Hertzian Fields:
Exploring WiFi microwave signals as a spatial and embodied sensing medium for art

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Abstract

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This dissertation is centered around a series of three artworks (*Hertzian Fields*) that explore WiFi as a spatial and embodied sensing medium. These works use a new sensing technique developed by the author that leverages the interference of the human body on WiFi signals to create highly responsive live performance and interactive systems.

Hertzian Field #1 (2014) is an augmented reality immersive environment using sound to explore the materiality of WiFi communication through its interaction with space and the human body. *Hertzian Field #2* (2016) is a 20'-25' augmented reality immersive performance for solo performer, WiFi fields, computers and surround sound that conjures a phenomenology of the hertzian medium explored through sound and movement. *The Water Within (Hertzian Field #3* and *#3.1)* is a reactive wet sauna: an intimate multi-sensory environment of complete immersion, combining WiFi sensing fields, machine listening software, embedded 3D sound, hot steam, and architectural design. Steered by the flows and

variable densities of water molecules traced in steam and bodies by (ab)using WiFi, it creates a regenerative post-relational experience that celebrates interference, signal-loss, and disconnecting. The piece exists in two iterations and formats: an interactive installation (2016) and a composed interactive experience (2018).

The dissertation describes the author's conceptual and technical approach in using WiFi microwave signals as an artistic medium. It also examines the background, context, ideas and research processes that led to the creation of these works. In doing so, it lays the foundation for developing a better and deeper understanding of microwaves and WiFi signals, investigates their artistic potential, and discusses related approaches by other artists.

Chapter One (*Introduction: The hertzian medium*) introduces core ideas and concepts regarding the medium. This includes: a discussion on the impact of wirelessness in contemporary living and how it has transformed our interactions with and understanding of the world; an overview of the physics of electromagnetism and the electromagnetic spectrum; and an investigation of the hertzian (i.e. radio and microwaves) as a multilayered medium consisting of seven interconnected layers: *physics, science, imagination, engineering, use, impact, regulation.*

Chapter Two (*The birth of a medium: Energy becomes technology*) introduces a media archaeological approach as a method for grasping what the medium affords, and how our imagination of what we can use it for has developed over time. It presents an overview of key developments in hertzian science, imagined and realized applications, and their impact. This chapter focuses primarily on the early years around Heinrich Hertz's discovery of electromagnetism, looking at the birth of wireless technologies relevant to the *Hertzian Field* series: communication, broadcast, hacking and electronic warfare, navigation, meteorology, radio astronomy, and radar, before closing with a section on the development of WiFi.

Chapter Three (*Radar and Direction-Finding in sonic art and beyond*) surveys musical instruments and artworks based on spatial and/or embodied uses of the hertzian as a sensing medium. The emphasis is on sound-centric practices and specific technologies that have been used to this extent: from capacitative / electric field sensing, to musical instruments utilizing direction-finding principles, to spatial uses of broadcast radio, to doppler radar systems. Instruments discussed include: *Theremin* and *Terpsitone; Pupitre d'Espace; Radio Baton; Marimba Lumina.* Artworks by the following artists are examined: *Max Neuhaus; Edwin van der Heide; Christina Kubisch; John Cage; Philippa Cullen; Liz Phillips; Sonia Cillari; Tetsuo Kogawa; Anna Friz; Edward Ihnatowicz; Steve Mann; Joe Paradiso / MIT Lab; Arthur Elsenaar; Godfried-Willem Raes*.

Chapter Four (*First hertzian explorations: From the network to the body, from WiFi to Radar*) turns to the author's own work. It presents the first phase (2010-14) of his research trajectory on the hertzian medium, and introduces three projects in which he explored WiFi and broadcast radio.

Chapter Five (*Ubiquitous sensing with radio waves and microwaves*) dives into the technological context influencing the author's research. It introduces the field of Ubiquitous Sensing and discusses relevant localization and device-free sensing techniques, concluding with a discussion on the physics and biological factors involved so as to comprehend how and why such techniques work.

Chapter Six (*Wireless Information Retrieval: Sensing with WiFi signals*) presents the device-free WiFi-sensing technique that the author developed for the *Hertzian Field* series. Combining elements from Ubiquitous Sensing and Music Information Retrieval, this technique performs multi-layered feature extraction on the Received Signal Strength Indication (RSSI) of WiFi Beacon frames to deduce a variety of information related to the movement of uninstrumented bodies, and to changes in environmental factors (e.g. humidity).

Chapter Seven (*Composing Hertzian Fields*) discusses strategies for creating works with this technique, and examines the three works of the *Hertzian Field* series in detail. It finally touches on ideas for future work by the author.

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Acknowledgements

This research trajectory took many years to complete and could not have been realized without the support, input, teachings, assistance and inspiration generously provided by many people. It is impossible to mention everyone as it is to do justice to all the different things those I do mention did to support me in just a few lines.

First, I want to thank my committee: I have heartfelt appreciation for my supervisor, Juan Pampin, for his invaluable advice, for granting me with absolute freedom and abundant time and trust, and for his most admirable ability to attentively listen and ask sharp, deep, and challenging questions which so often helped me clarify where I was heading to - even if I only had a faint idea of the general compass directions - instigating me to take a leap further. I also owe profound thanks to my first advisor, Richard Karpen, for his inspiring outlook on art, interdisciplinarity, and the artistic process which drew me to join the program already after our first chat at the Van Gogh museum, for always challenging me to grow as an artist over my years in Seattle, and for his vision in establishing the remarkably cross-medial pioneering program of DXARTS. I likewise deeply appreciate the two committee members who joined my process towards the end: Afroditi Psarra, who offered a rare and indisputable understanding of hertzian artistic practices together with a regard of their conceptual and socio-political underpinnings that resonates with my work, and whom I wish I had brought earlier into the fold; and Shwetak Patel whose feedback and comments, backed by years of insights and expertise on the subject as a computer scientist, feel very empowering to continue developing this artistic research thread with much confidence. I am honoured to have had you all be in my committee and I am grateful that you spent time with my work and writings.

Furthermore, I want to extend heaps of thanks to all the people that helped me grow as an artist during my years at DXARTS - faculty, colleagues, staff, but also my students. Among them, I want to express special thanks to: Josh Parmenter, SuperCollider guru whose code-fu and courses inspired me and taught me a language that radically changed my practice (and without which I could had never even thought about working on this subject); DSP wizard Jo Anderson for imparting his spectral-domain sorcery together with Juan, thus enabling me to implement the complex toolkit discussed in this thesis; Blake Hannaford, who gave me first-hand insights on the thought process and methodology of an impressively accomplished scientist and showed me how close artistic and scientific research can be, how to appreciate our differences but also recognize that in many ways we stand equal. To the extraordinary cohort of colleagues that I shared my years in Seattle with, and who formed an inspiring community of both awesome people and incredibly talented artists each with their own specialty like a group of superheroes, and particularly to: Nicolás Varchausky, Tivon Rice, Hugo Solís, Annabel Castro, Meghan Trainor, Robert Twomey, Ha Na Lee, Mike McCrea, James Hughes, Philomène Longpré, Maja Petric, Max Keene, Heather Raikes, Eunsu Kang: I have immense respect and gratitude for you all as friend, colleague, and artist. I am especially thankful to Nico and Tivon, first and foremost for their lasting friendship, for our many talks on art and life, your feedback and special efforts to see my works outside of Seattle, and for being amazing collaborators (I wish I had the energy to discuss our collective work that relates the Hertzian Field series, *Proxy Kabinet: Raamweg 47*). Finally, I am grateful to DXARTS's extremely kind, competent and helpful administrators, Billie Grace and Cynthia Caci, who were both always there helping navigate the - sometimes complex and stressful - pathways of the University.

I could not have realized the works mentioned in this dissertation without my collaborators, most of them dear friends, that worked with me in various capacities. I owe my warmest thanks to: movement artists Eugenia Demeglio, Joseph Lau, and Bridget Fiske for spending time with *Hertzian Field #1*, for their feedback, and for showing me what is possible through their mastery of the body, as well as to all the people interacting with the work during different sessions; to Ping-Hsiang Chen for his expert work in designing and helping build the steam room of *The Water Within (Hertzian Field #3)*; to Stephanie Pan for coming up - and sewing on the spot - a solution for the steam room's 'skin', and for masterly coordinating production matters; to my brother Dionysis for helping me design its speakers from back home; to the crew of amazing volunteers - Dave Kalle, Gijs Thermorshuizen, Johannes Fischer and Djurre Kooistra - who helped build it on site; and to Mara Wasiuta and Fazle Shairmahomed, our Modern Body Festival core team, for joining Stephanie in very strongly encouraging me to continue developing and to present the work when logistical issues, lack of time and sleep, and the difficulty of simultaneously organizing a festival were making me have doubts and feel overwhelmed. I also want to thank Stephanie (once more!) for being the voice of *'Act so that there is no use in a centre'*, as well as the two musicians whose sounds are included in that work, Jelte van and Andel and Garth Knox.

My sincere appreciation goes to the many curators that commissioned and supported making and presenting the works discussed in this thesis, but also to the organizers, producers and technical crews, and more expressly to: Peter Weibel - who very sadly passed away a day before my defense - for his support and enthusiasm, and to Ludger Brümmer and Marie-

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Though not directly connected to this trajectory, my teachers at the Institute of Sonology deserve recognition here for teaching me so many things and setting me on this path - Joel Ryan, Paul Berg, Kees Tazelaar, Konrad Boehmer, Johan van Kreij, Peter Pabon - together with the large group of talented colleagues and friends that I had the privilege to spend time around in the Hague, learning with and from, and who are just too many to name here individually.

I owe a very special thanks to my family for their unconditional love, continuous support, interest in my work, and for inspiring me with the uncompromisingly high standards they set for their own work: Angeliki Karathanasi-Manousaki, Vasilis and Dionysis Manousakis, and to my father Giorgis Manousakis whose love and support from the great beyond I can always feel accompanying me. Finally, but certainly no less importantly, I owe immeasurable gratitude to Stephanie Pan for her unwavering belief, support and patience, for her assistance under so many guises, for picking up the slack when I was too busy writing, and for inspiring me with her art - but most importantly for her love all these years; all this made it possible for me to see this long trajectory till the end, and I certainly could not had done it without you.

Dedication

To Stephanie and to my parents, Angeliki and Giorgis

One organ, more or less, in our machine, would have given rise to another kind of eloquence, another kind of poetry.

Charles de Secondat Baron de Montesquieu (Montesquieu, 1757)

Chapter 1. INTRODUCTION: THE HERTZIAN MEDIUM

1.1 INTRODUCTION

1.1.1 *Overview*

What kind of music would a deaf society make? What would a blind society's visual art look like? Would humanity ever develop perfumes without the sense of smell? What types of recipes would we concoct if we could not taste? How can we create with a medium we cannot sense or experience directly?

This dissertation is the result of several years of extensive research on the potential of radio waves and microwaves for the creation of art. Although these electromagnetic waves have always been around us, humans never evolved organs to sense them like they did with light, which is a similar form of energy oscillating at a higher frequency. As a consequence, we only truly started understanding the nature of these waves very recently, in the end of the 19th century, following a series of experiments by German physicist Heinrich Hertz. Since his discovery of *hertzian waves* (the name given to radio waves and microwaves by the scientific community early on) humans have been continuously devising new ways and instruments to tap into this otherwise inaccessible stratum of our universe.

I use the term *hertzian* as a shorthand for 'radio and microwaves' for its capacity to at once convey the scientific and artistic historical context of electromagnetism. Firstly, the term points to the discovery of electromagnetism by Heinrich Hertz about 130 years ago and subsequent investigations, thus underlying the relative novelty of the medium as far as humanity is concerned. The term is not anachronistic but borrowed from that period: While Hertz himself called these waves *electric* or *electromagnetic*, with the title of his 1893 treatise on the subject being *Electric Waves*, many of his contemporaries referred to them as *hertzian waves* or *hertzian rays* in his honour. For the first few decades after the discovery of electromagnetism, *'hertzian'* was one of the most prevalent terms used to describe not only the physical phenomenon but by extension also the new equipment and the technologies that deployed these waves. For instance, instruments were named hertzian oscillators, hertzian transmitters and receivers, wireless telegraphy was often referred to as 'Hertzian Wave Telegraphy' or simply 'hertzian telegraphy', wireless telephony as 'hertzian telephony', and so forth. This naming convention was not limited to communication technologies, as evidenced by Christian Hülsmeyer's patent of a proto-RADAR system titled *"Hertzian-wave projecting and receiving apparatus"* in 1904 (see 2.5.2) (Hülsmeyer, 1904). During these first decades of electromagnetic research there were numerous debates on terminology, as demonstrated for example by a 1901 article on the Western Electrician, titled *"Spark, Space, Wireless, Etheric, Hertzian Wave or Cableless Telegraphy—Which?"* (Collins, 1901). The term *hertzian* gradually fell into disuse, especially in English (though in some languages, such as Greek, it is still used to refer to radio waves used for broadcast). Figure 1.1 demonstrates the evolution of terminology referring to electromagnetic waves over time.

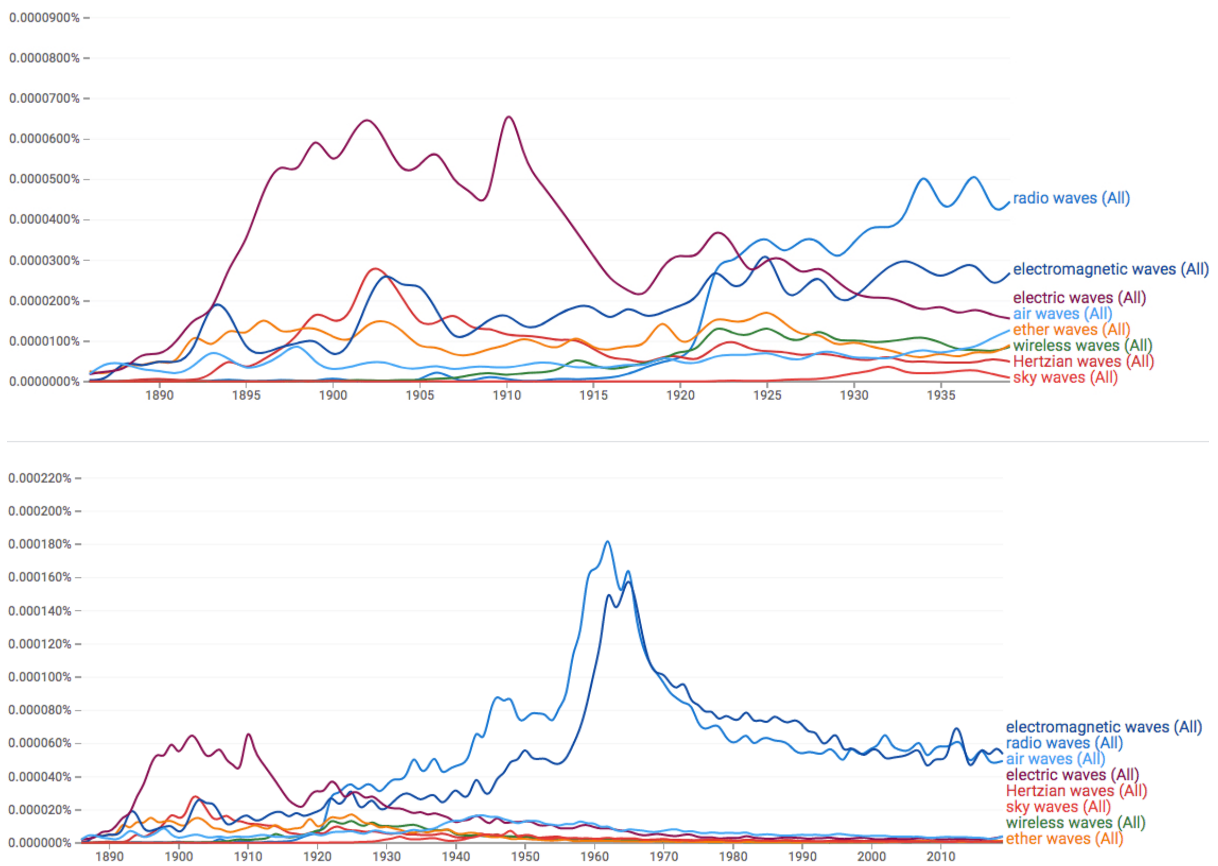

Figure 1.1. The rise and decline of the use of different terms to describe various types of electromagnetic waves in English language books published between 1886-1939 (top) and 1886-2019 (bottom) (Google, 2021).

Nevertheless, while mostly a fringe term in contemporary scientific research, the word *hertzian* still retains its original meaning and is used to refer to electromagnetic waves within the radio and microwave range. As such, Merriam-Webster defines "*hertzian waves*" as *"electromagnetic wave[s] produced by the oscillation of electricity in a conductor (as a radio antenna) and of a length ranging from a few millimeters to many kilometers"* (Hertzian

Wave, 2021). Encyclopedia Britannica defines them as "*electromagnetic waves in the radar and radio range*" (Burton, 2021).

My research in this field was initially fueled by a deep curiosity in understanding and utilizing these waves and the increasingly more ubiquitous technologies that involve them in my own work. The longer and more intimately I explored this medium, the more I was inspired to look wider and deeper in an effort to understand its true nature and artistic potential from a broader perspective. Thus, my research ended up extending far beyond my own personal practice to encompass a thorough investigation and exploration of hertzian waves as an expressive artistic medium, which I believe should be considered in similar terms as other traditionally established media, such as light waves or sound waves.

My research trajectory that led to this dissertation evolved over time in what I now identify as three phases:

The first phase of this research, and my personal fascination with microwaves, wireless infrastructures, and the inner workings of networks, essentially commenced in 2010. This led to an investigation of Wireless Local Area Networks (WLAN) as a kind of space with its own sui generis acoustics, which in its turn resulted in the installation *Observe, Recount, Distort!* (see section 4.1). That project was an experiment created as part of the Telematic Art graduate course at DXArts, led by Dr. James Coupe and was only presented within that context.

Diving deeper into the nature of microwave communication signals, I created the distributed interactive installation *The Network Is A Blind Space* in 2011-12 (section 4.2). For this piece, I devised a real-time system of ‘musical echolocation’ through which visitors with WiFi-enabled mobile devices could explore the invisible yet physical hertzian dimensions of a WLAN as it exists within an exhibition site. This piece considerably strengthened my interest in the – typically ignored - physicality of wireless communication. The installation was exhibited at the Jack Straw New Media Gallery in Seattle, where I created it during an artist residency.[1] I subsequently presented a paper on the work and the techniques I developed for it at the *New Interfaces for Musical Expression* international conference (NIME) in 2012 (Manousakis, 2012b).

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[1] See: https://www.jackstraw.org/exhibit/stelios-manousakis-the-network-is-a-blind-space/. Last retrieved 15 January 2023.

A third related distributed interactive installation followed in 2014. Titled *'Act so that there is no use in a centre'* and created during another residency (with Kultur Kontakt Austria in Vienna), it is an abstracted and deconstructed spatial radio play based on Gertrude Stein's text 'Rooms' (section 4.3). For this piece I moved away from microwaves and WiFi, using an array of low-powered FM radio transmitters and handheld receivers to fabricate an invisible radio-sonic web that is overlaid on the exhibition space. The sound and experience of the work emerges through the interaction of visitors with the physical and spatial nature of its transmissions. The piece has been exhibited three times so far: at the Gallery of the Austrian ministry of Arts & Culture in Vienna, Austria (2014); at the Faulconer Gallery of Grinnell College (recently renamed the Grinnell College Museum of Art) in Iowa, USA (2015); and at Korzo Theater in the Hague, the Netherlands, as part of the festival Musical Utopias (2019).[2]

This nearly 4-year research path prompted a new and more distilled second phase of artistic exploration, the result of which is a series of three sound and movement works that I created between 2014-2018. Named after Heinrich Hertz, these first works of the *Hertzian Field* series explore WiFi microwave signals as a medium for creating dynamic immersive environments that are driven by the full-body interaction of uninstrumented bodies in space. While the absence of both physical space and physical bodies has long been one of the dominant notions of the concept of wirelessesness – particularly when wirelessness is conflated with telecommunication media and promoted as something immaterial – the *Hertzian Field* series focuses exactly on this point: it brings the human body back into the wireless equation, situating it within the spatial reach of its wireless fields – i.e. in the empty and ignored spaces between transmitter and receiver - so as to examine and be inspired by the body's interactions with the wireless electromagnetic medium. The body thus becomes simultaneously an interface and a resonant space that is continuously pinged and scanned by wireless telecommunication signals, generating sound as evidence of the materiality of the hertzian. In this regard, it is important to point out that the relationship between body, space, and electromagnetic medium, although by and large disregarded for many decades, can be traced back to the earliest days of the medium's discovery when Hertz himself introduced the body as a dielectric agent to study how it affects transmissions and fields (see section 2.1.8).

[2] See: https://www.grinnell.edu/news/artistsgrinnell-stelios-manousakis, https://www.ensembleklang.com/sensing-sound-installations-musical-utopias2/. Links last retrieved 15 January 2023.

The series is based on a new sensing technique that I developed to leverage the interference of water molecules (mainly those in the human body) on WiFi microwaves. Inspired by technologies such as radio-frequency sensing, radar, and radar astronomy, it enables sensing bodies and their movement in space by capturing and carefully analyzing variations in the real-time flow of ordinary WiFi signals. I have named this technique *Wireless Information Retrieval* (*WIR* in short) and have used it to create and control complex, immersive sound environments (*WIR* is discussed in detail chapter 6). Rather than merely devising yet another interactive technology for sensing bodies in space - i.e. essentially a variant of computer vision - my goal in developing this sensing technique has been first and foremost to create a tool for revealing and understanding the materiality of wireless communication, for designing spaces and conditions through which this materiality can be interacted with, and for composing systems and situations in which it can be explored and experienced from within in a physical manner that involves the human body and the mediation of sound.

In this sense, I consider the *Hertzian Field* works created with this technique a form of augmented reality (AR) in which hertzian spaces become performative fields of energy that are sliced, distorted, and manipulated by the body within. It should be emphasized that with the term AR I mean something very different than the typical superposition of a computer-generated image over an image of the real world - a very limited vision-centric paradigm that has essentially managed to gain ownership of the term. As digital thinker and game developer Kevin Slavin made clear in a fascinating talk titled "*Reality is plenty, thanks*", augmenting reality does not necessitate adding new visual layers to our existing world (MoMoAms, 2011). Instead it should be understood as a broader strategy of devising methods that enable us to experience this very world in new and unknown ways. In short, *"[r]eality is augmented when it* feels *different, not when it* looks *different"* (Ibid). This is why in my descriptions of these works I chose to reclaim the term 'augmented reality' to describe environments in which sound becomes a medium for experiencing the hidden hertzian layers of reality that envelope us.

The first of these works, *Hertzian Field #1,* is an immersive augmented reality environment for microwave fields, computers, and surround sound that exposes the raw materiality of the WiFi communication medium, exploring its physical interaction with our spaces and our bodies through sound (section 7.2). It was developed in June 2014 during a month-long artist residency at ZKM Center for Art and Media Karlsruhe and was exhibited in the ZKM_Kubus theater on July 1st of the same year.[3] The piece was presented as a solo performance (featuring myself as performer) and as an interactive installation. A year later, in 2015, it was presented once more in this dual format at the Attenborough Centre Creativity Zone, University of Sussex in Brighton, UK, this time performed by dancer/choreographer Eugenia Demeglio.[4]

My following work involves a further developed iteration of the *Wireless Information Retrieval* system. *Hertzian Field #2* is an augmented reality immersive performance of about 25 minutes for solo performer, electromagnetic fields, computers, and surround sound that exposes the sympathetic resonance of the human body to the invisible flows of wireless communication (section 7.3). The piece was created between 2015-2016 for *GLOBALE,* a 300-day festival-of-festivals at ZKM Karlsruhe, as a response to its thematic exploration of the *Infosphere* - a concept that will be discussed in the following sections.[5] It premiered during *GLOBALE: Performing Sound, Playing Technology,* an event on contemporary musical instruments and interfaces (2016).[6] I performed it again at the closing concert of the GLOBALE festival (called in an event called *GLOBALE: Sonic Senses*) which took place within the context of the *New Sensorium* exhibition.[7] The piece has also been shown internationally in a number of other festivals and venues.[8]

The third and currently last work of the series exists in two iterations (section 7.4). *The Water Within (Hertzian Field #3.0*), created in 2016, is an interactive steam sauna: an intimate multi-sensory environment of complete immersion combining the *WIR* sensing system with embedded 3D sound diffusion, hot steam, and architectural design by collaborating architect Ping-Hsiang Chen. The piece was produced for and presented at the second biennial edition of the *Modern Body Festival* in The Hague, the Netherlands, a platform that I co-founded and

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[3] See: https://zkm.de/en/media/video/ima-lab-no-25-stelios-manousakis. Last retrieved 15 January 2023.

[4] See: http://www.emutelab.org/blog/interactive-music. Last retrieved 15 January 2023.

[5] See: https://zkm.de/en/project/globale-0. Last retrieved 15 January 2023.

[6] See: https://zkm.de/en/event/2016/02/globale-performing-sound-playing-technology. Last retrieved 15 January 2023.

[7] See: https://zkm.de/en/event/2016/04/sonic-senses. Last retrieved 15 January 2023.

[8] This includes performances at: *Wonderwerp* series (Studio Loos) in the Hague, the Netherlands (2016 - https://www.loosdenhaag.com/wonderwerp-2016/wonderwerp-68); *Audio Art Festival*, Krakow, Poland (2016 - https://www.audio.art.pl/2016/index.php); *Athens Digital Arts Festival* (theme: *Singularity Now*), Greece (2018 - https://2018.adaf.gr/events/hertzian-field-2/); *Gogbot Festival* (theme: *Future Flash 200, From Frankenstein to Hyperbrain*), Enschede, the Netherlands (2018 - https://2018.gogbot.nl/portfolio/stelios-manousakis/); *RIXC Art Science Festival* (theme: *Global Control*), Riga, Latvia (2018 - http://festival2018.rixc.org/performances/); *Latent City: Invisible Fields*, a festival by *Bergen Center for Electronic Arts,* Norway (2020 - https://bek.no/en/hertzian-field-2-by-stelios-manousakis/); *Flipchart* series, theme *Resonating bodies* (iii workspace @ WD4X), the Hague, the Netherlands (2022 - https://instrumentinventors.org/agenda/flipchart-2/). All links last accessed 29 December 2022.

co-direct together with frequent collaborator Stephanie Pan.[9] It was conceived as a response to the festival's theme *I/WE/THEY,* which centered around explorations of the 'social body'. In 2018 I created a new version of the work, titled *The Water Within (Hertzian Field #3.1).* Building on the previous iteration and taking place in the same structure and using the same equipment, this steam bath installation was composed as an intimate 20-minute interactive experience of complete multi-sensory immersion for groups of up to 6 visitors at a time. The work was shown at the exhibition of another Modern Body event, *Modern Body Laboratory #2: Intelligent artifacts and breathing spaces.*[10] It was also presented a few days later during *Azimuth #6*, an event focusing on spatial electroacoustic music.[11]

I began transitioning to the third phase of my research on the hertzian medium around 2016, after completing *Hertzian Field* #2, when I started working on this dissertation. While the dissertation's thematic nucleus had been formed during the process of developing the first two *Hertzian Field* pieces, my research path led me into a maze of deep, enthralling, and enlightening 'rabbit holes' which were too enticing for me not to explore. This was particularly true in my investigation of artworks that use the hertzian medium, as this practice proved to be much more vast, rich and intricate than I had originally anticipated. After dedicating several years in this investigation, with new discoveries leading me to make new connections which led me to new discoveries and so forth, my understanding of the subject in both its intricacies and its big-picture concepts and contexts has evolved and grown vastly. Instigated both by my own curiosity and the relative dearth of literature offering a comprehensive perspective on this new medium and related art practices, this resulted in a much more thorough review of the subject than I had originally planned. This meant that my research extended far beyond the scope that a PhD dissertation can have. Thus, in the end I decided to limit the focus of this text to a discussion of my own works and their more immediate context relating to spatial uses of the hertzian medium. I plan to dedicate a subsequent book to a more expansive investigation of the history and different possibilities afforded by radio waves and microwaves i.e. by what I call the *hertzian medium*, with a particular emphasis on their potential for creating art. In that text I plan to examine, explore,

[9] See: https://modernbodyfestival.org/2016/works/manousakis-chen/. Last retrieved 29 December 2022.
[10] See: https://modernbodyfestival.org/2016/modern-body-laboratory-2/. Last retrieved 29 December 2022.
[11] See: https://www.azimuthfoundation.net/6-1/. Last retrieved 29 December 2022.

and categorize a growing corpus of artistic practices, attitudes and artworks based on this medium, which I propose constitutes the emerging field of *Hertzian Art.*[12]

1.1.2 *The wireless shift: Living immersed in hertzian fields*

Heinrich Hertz's diary, Karlsruhe, 1886:
October 25
Obtained a spark-gap micrometer and started experiments with it.

December 2
Succeeded in producing resonance phenomena between two electric oscillations.

December 3
Resonance phenomena becomes clear, wave nodes, peculiar effect on sparks.[13]
(Quoted in Sato & Sato, 2006, 457).

Heinrich Hertz's Laboratory Notes, Karlsruhe, 1887:
October 5
First experiments performed on the effect of dielectrics and clear results obtained

October 10
Human body brought near

November 5
Work concerning dielectrics finished and results sent off to Helmholtz.
(Quoted in Hertz & Doncel, 1995, 233).

On an October day in 1886 Heinrich Rudolf Hertz, a 29-year-old physicist in his second year as a professor at the Technical University of Karlsruhe, began experimenting with an apparatus he had just devised and which could generate high frequency electromagnetic disturbances. Using this instrument, a rudimentary radio-transmitting oscillator, Hertz attempted to verify the validity and practical usefulness of a mental tool which up to that moment had remained purely conceptual: the electromagnetic theory of Scottish physicist James Clerk Maxwell. While testing his device, Hertz noticed that the spark it generated was accompanied by another, weaker spark in a similar circuit located some meters away – *"a peculiar effect",* indeed (Hertz quoted in Sato & Sato, 2006, 457)! This observation revealed something much more significant than some type of quasi-magical action-at-a-distance.

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[12] A significant difference between this artform and others, such as Visual Art or Sound Art, is that in order to create and experience works with the hertzian medium another process of mediation is typically required, in order to translate this form of energy into another form which the human senses can experience firsthand.

[13] Original text in German:
October 25: "*Funkenmikrometer erhalten und Versuche darnit angefangen.*"
December 2: "*Gelungen, Rezonanzerscheinung zwischen zwei elektrischen Schwingungen herzustellen.*"
December 3: "*Rezonanzerscheinung deutlicher, Schwingungsknoten, eigentiimliche Wirkung auf Funken.*"

Performing a series of experiments with this instrument, Hertz proved the existence of electromagnetic waves and the veracity of Maxwell's theory. He also provided a blueprint and an instrumentation for generating, transmitting, and receiving these waves wirelessly. In this manner, he expanded the strata of known physical reality to include a new invisible dimension, the electromagnetic spectrum, providing humanity with a map to chart and explore this new territory alongside a new sensing apparatus with which we could perceive the world around us - from celestial bodies in outer space to the worlds hidden inside our own human bodies.

The changes that this discovery brought forth in our society and everyday lives in just over 130 years are innumerable. We make wide use of radio waves, microwaves, and other electromagnetic waves, depending on them more and more every day. These waves are fundamental components of all kinds of telecommunication technologies that form the scaffolding of our society and with which we interface daily – TV and radio broadcast, cellphone telephony, WiFi and Bluetooth, and more - allowing us to wirelessly transmit and receive information of all sorts, for all sorts of uses. They are also the basis of a plethora of other contemporary technologies beyond telecoms, from RADAR and navigation systems (e.g. GPS), to radio telescopes, MRI scanners, contactless payment and ticketing systems, microwave ovens, and many more.

As a result, today's increasingly networked and digitized societies have flooded our spaces with a multitude of electromagnetic flows. The Earth's atmosphere has thus acquired an electromagnetic twin dubbed the *Infosphere*: layers upon layers of radio waves and microwaves carrying all kinds of information that keep our world in motion. We live engulfed in the fields these waves create, moving unaware through turbulent streams of data. Our wireless infrastructures have imposed their very physical presence in our spaces. While invisible they are as real as the air we breathe; and while we lack the capacity to feel them with our senses, they can feel our presence as our bodies block, reflect and displace their microwaves. As such, even though we typically think of wirelessness in an abstract manner - as something virtual, a concept more than a physical force - beyond merely distributing our data, the Infosphere has an inescapable side effect, a glitch: it transmits information about physical space and our bodies within it. Our data networks are in fact public radars, disclosing potentially sensitive information to anyone listening.

Despite relying on this invisible electromagnetic architecture that engulfs us, it can be difficult to truly understand its nature or even acknowledge its very physical presence –

unless our bodies become directly involved. If we look at the grand scheme of things, this is very reasonable; after all, mankind only tamed electromagnetic waves to do our bidding a handful of generations ago. Nonetheless, the physicality of radio waves and their relationship to space and the body did not elude Hertz all these years ago but was instead a fundamental component of his investigation from the beginning. This is evidenced by the spatial nature of his early experiments and the fact that already in 1887, less than a year after inventing the first radio transmitter, he introduced the human body into the radio field as a dielectric actor and as a conductor, studying its effects on the transmission and reception of signals (see sections 2.1.7 and 2.1.8). In many ways, the performative exploration of WiFi microwave fields in the *Hertzian Field* series echoes Hertz's performative actions when conducting his electromagnetic experiments between 1886-1889, as described in his book (Hertz 1893): moving attentively around the physics lecture room with various self-fashioned instruments to measure the wavelengths of static waves, their nodes and antinodes, their reflection, refraction and polarization, and the ways in which they interacted with his body and the body of his assistant.[14]

Even though wirelessness has crept into countless aspects of contemporary life, its material nature appears to be getting more and more obscured, increasingly hidden behind layers added by technological innovation. The generations growing in the era of analog radio and television have a more intuitive understanding of the physics of wireless than newer generations growing up as digital natives. The distant memories I personally have of tuning (analog) television and radio receivers through adjustable antennas, and the delicately shifting effects that the position of human bodies in the room had on transmission – moving around to find a place to seat where interference was minimal, or touching an antenna to boost the signal – are likely never going to repeat for future generations. Today’s experience is more typically a binary one – you are either connected or you’re not – like tapping a card on the correct spot of a reader so that information is successfully transmitted. The advancement of wireless digital technologies has obfuscated the hertzian medium, turning it more and more abstract in our minds.

[14] Hertz was by no means the only pioneer of electromagnetic research to use his body as a medium and interface through which to interact with and understand this force. A similar mentality led Wilhelm Conrad Röntgen to discover X-rays in 1895 after interjecting his hand (Röntgen, 1896) while Nikola Tesla – who had also x-rayed various parts of his body a few years earlier (see Baltić & Baltić, 2007) was famously using his body as a spectacular prop in his lecture-performances on electromagnetic technologies (see 2.2.4).

On the other hand, technological innovation is paying increasingly more attention to the spatial and material nature of the hertzian, coming up with new systems and new uses for telecommunication infrastructure. As wirelessness has become a crucial component of society, and as the Internet of Things and the advent of 5G networks promise to cast an ever-tightening electromagnetic web in our public and domestic spaces, this long forgotten and un-advertised feature - the physicality and spatiality of telecommunications - is emerging as an invaluable tool for advertisers, the surveillance industry, police forces, and other actors (see chapter 5). The Infosphere is being rediscovered as a continent rich in valuable resources ripe for mining: spatial information that is not initially inscribed in the message flows of telecommunications, but which materializes as some form of waste, a by-product of the process of transmitting data in a space occupied by people and things.

The *Hertzian Field* series points a magnifying glass to this attribute of wirelessness, examining the omnipresent WiFi fields in our everyday spaces from a spatial perspective as a radar technology that can sense what exists between transmitter and receiver. In doing so, it exposes the WiFi network as a potential decentralized panopticon hiding in plain sight, enabling the tracking, localization, and recognition of activities performed by any human within its range. What is fundamentally important is that there is no way to opt out from such technologies: even without carrying any electronics the human body interacts with the electromagnetic fields of our infrastructure. By pointing attention to this unintended feature, the *Hertzian Field* series makes clear that hertzian technologies like WiFi are not just invisible communication media but have a physical footprint, filling our spaces with a form of energy that can be manipulated to achieve different things than what the original design intended.

1.1.3 *Connectivity and the Infosphere as a process of exo-evolution*

The emergence of wireless technologies has made connectivity one of the defining aspects of contemporary daily life, from the way our economies are interlinked to the very daily and personal. As Adam Greenfield observes, "*we balance on the cusp of an era in which every near- or fully adult person on Earth is instrumented and connected to the global network at all times. Though we've barely begun to reckon with what this implies for our psyches, our societies, or our ways of organizing the world, it is no exaggeration to say that this capability - and all the assumptions, habits, relations of power and blindspots bound up in it - is already foundational to the practice of the everyday.*" (Greenfield, 2017, 48) In 2020-2021, the importance and pervasiveness of connectivity became even more evident during the COVID-19 pandemic and ensuing lockdowns, with the whole world relying on networking technology to stay virtually together while keeping physically apart.

Many decades prior, when the electromagnetic web of the Infosphere was just beginning to spread around Earth, Buckminster Fuller gave an interesting overview of connectivity from an architectural perspective in a short essay (Fuller, 1950). Fuller identified three distinct states in mankind's history on earth, relating to the infrastructures with which people connected to each other (figure 1.2). During the first era, lasting half a million years, humans lived in isolated societies struggling on their own against the forces of nature. In architectural terms, this is the time of independent dwellings. During the second state, societies began to connect to each other, linking their resources through transport and various forms of communication media. This is the era when architectural spaces became linked to each other via roads, cables, and pipes. For Fuller this state was merely *"transitional"* and lasted about a century (Ibid). The third, which he called humanity's *"natural*" state, was just starting at the time of his writing and was projected to introduce *"a new volumetric and dynamic dimension"*, a wireless flow of information and energy connecting everything and everyone together (Ibid). This vision of Fuller is evident in many of his architectural designs, such as the 4-D Tower: a building concept, first published in 1928, meant to be simultaneously an apartment block and telecommunication infrastructure, not only housing but also connecting the city's inhabitants through the use of radio transceivers (Wigley, 2015 and LaBelle, 2010). Through radio, *"every building became a spaceship"* for Fuller, as this medium connected it not only to the rest of the planet but also to outer space (Wigley, 2015, 22).

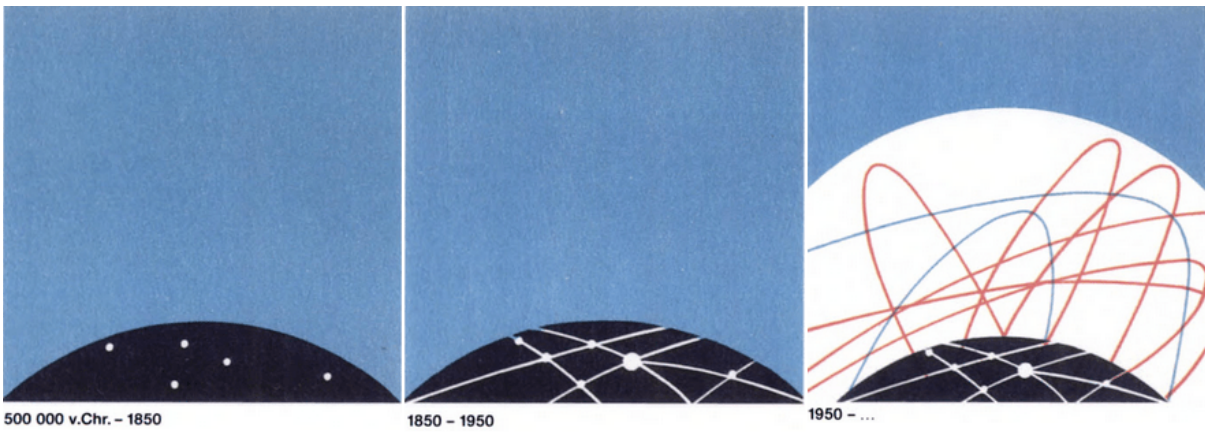

Figure 1.2. Buckminster Fuller's three states of mankind: Isolated (left), connected via physical lines of transport and communication (middle) and connected via wireless media (right) (from Fuller, 1950).

The gist of Fuller's ideas clearly resonates with the thoughts expressed by Marshall McLuhan a few years later, in 1964, when connectivity was no longer a vision of the near future but a burgeoning reality. McLuhan wrote: *"During the mechanical ages we had extended our bodies in space. Today, after more than a century of electric technology, we have extended our central nervous system itself in a global embrace, abolishing both space and time as far as our planet is concerned"* (McLuhan, 1964/2017, 5). McLuhan's vision of an extended central nervous system for the whole humanity has become by and large wireless and invisible today, enveloping the world with radio and microwaves.

More recently, and further building on the same concepts, artist and ZKM director Peter Weibel put this "*global network of wireless radio connections"* at the center of the exploration of the GLOBALE festival, arguing that it has become "*as necessary for the life of seven billion people on earth as the atmosphere"* – hence the name Infosphere Weibel, 2015a, 10-11). While natural radio has always surrounded the Earth, the Infosphere has created a 'radioscape' that is 'louder' by multiple magnitudes; the amount of electromagnetic energy emitted by man-made communication and other technologies has all but drowned natural emissions (similarly to what urban environments have done to natural soundscapes). This prompted Weibel to declare that the Infosphere should be regarded as the electromagnetic footprint of the Anthropocene, the era in which man has become a geological force (Ibid).

Further echoing McLuhan, Weibel considers the development of the Infosphere to be the result of a process of exo-evolution, i.e. "*the evolution of artificial organs and tools that are man-made and controlled by humans"* (Ibid, 10). A contemporary iteration of such an organ – and one defining our era of connectivity - is the smartphone, which Greenfield regards "*not even so much an extension of our bodies as a prosthesis grafted directly onto them"* (Greenfield, 2017, 62). This man-made network-organ is a complex object. It belongs to a family of electronic objects whose physical existence seemingly *"dematerializes"* into electromagnetic radiation and software abstraction (Dunne, 1999/2005). Such objects are essentially hybrids that exist *"on the threshold of materiality",* combining "*conceptual models, symbolic logic, algorithms, software, electrons, and matter"* (Ibid, 11 & 7). Through networked instruments like the smartphone, McLuhan's vision of humanity as a network of neurons has now become humdrum reality. As Greenfield points out, *"[w]e need to understand ourselves as nervous systems that are virtually continuous with the world beyond the walls, fused to it through the juncture of our smartphones"* (Greenfield, 2017, 64). This expansion of the self means that *"[o]ur very selfhood is smeared out across a global mesh of nodes and links; all the aspects of our personality we think of as constituting who we are - our tastes, preferences, capabilities, desires - we owe to the fact of our connection with that mesh, and the selves and distant resources to which it binds us (...) Now we make networks, and they shape us every bit as much as any building ever did, or could"* (Ibid, 62-63).

All this is a resounding confirmation of McLuhan's famous aphorism that *"the medium is the message",* with which he proclaimed that the effects of the medium – i.e. the changes it causes to its users and to mankind at large - are more important than its content, "*[f]or the 'message' of any medium or technology is the change of scale or pace or pattern that it introduces into human affairs"* (McLuhan, 1964/2017, 20). As he further declared, "*[o]ur conventional response to all media, namely that it is how they are used that counts, is the numb stance of the technological idiot. For the 'content' of a medium is like the juicy piece of meat carried by the burglar to distract the watchdog of the mind. The effect of the medium is made strong and intense just because it is given another medium as 'content'"* (Ibid, 31).[15]

1.1.4 *Instruments make worlds*

During humanity's continuous struggle to augment our capabilities and the ways in which we interface with the world, we have been ceaselessly developing instruments, both physical and mental, with which to perceive and act upon our surroundings. Discussing the notion of exo-evolution, another of GLOBALE festival's themes, Weibel writes: "*From the hammer to language, over the course of thousands of years human beings have created a culture of tools, an engineering culture that has expanded the boundaries of perception and of the world"* (Weibel, 2015b, 74). Through these tools, we have exteriorized or outsourced our natural organs and functions - "*the hand handed over to the hammer, the foot to the wheel, the eye to the microscope or telescope, the voice to the microphone, etc."* (Weibel, 2015a, 10). These tools help us navigate the world as much as they help us understand it, inevitably shaping our concept of what reality is. Our tools and our notions of reality are thus inherently intertwined. Paraphrasing philosopher Ludwig Wittgenstein, Weibel observes that *"it is hard not to think that the limits of our world coincide with the limits of our tools"* (Weibel, 2015a,

[15] For McLuhan, the content of our media always consists of other media: Thought is the content of speech, speech is the content of writing, writing the content of print, and print that of the telegraph. Similarly, tapes and records are the content of radio (at least in his time), tapes combined with silent film the content of cinema, and so forth (McLuhan, 1964/2017).

7).[16] Tools help test, develop, and evolve our ideas about the world. This development of our ideas, in its turn, has the effect of producing more advanced tools, and so on and so forth, resulting in an ever-evolving genealogy of tools, ideas and – essentially – an ever-evolving conceptualization of reality and the world around us.

The complex relationship between our tools and our conception and perception of reality and the world has come at the forefront of science studies since the 1970s. Breaking with past models, philosopher of science Bruno Latour in his Actor-Network Theory, and Andrew Pickering in his further development of this theory's ideas, consider the scientific activity to be performative. According to them, this activity is less about creating static, 'objective' representations of reality (i.e. 'knowledge') through laws of nature, and more about constructing plausible models of reality through experiments in the laboratory and a process of continuous 'tuning'.[17] They replace a static view of knowledge with a dynamic one that is influenced by ever-changing contexts and by the continuous development of new instruments (Salter, 2015).

Key to Actor-Network Theory is the idea that *"[h]uman and nonhuman agents are associated with one another in networks, and evolve together within those networks"* (Pickering, 2010, 10).[18] As such, both human and nonhuman components have to be considered when talking about science. The original theory assumes a symmetry between these two agencies. Pickering, however, diverges from this view pointing out that the relationship between the two is not completely symmetrical because human agency has an inherent intentionality that makes it fundamentally different. Scientists have plans and goals, something that cannot be attributed to matter.

In his search to grasp how knowledge is produced, Pickering is interested in understanding the scientific practice at the moment it occurs rather than retrospectively. He proposes that instead of looking at facts, observations, and static results to describe the world, one should look at the world's dynamic way of 'doing things', its agency. This means focusing on *action* and *forces* rather than *matter*. He proposes that the scientific process should be viewed as a

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[16] Weibel refers to the famous quote from Ludwig Wittgenstein's *Tractatus logico-philosophicus* (1921) that *"[t]he limits of my language mean the limits of my world"*.

[17] This view opposes the representational model of science of the 1950s, according to which science is a corpus of knowledge about the world, theoretical and empirical, that aims to decode and represent reality in an objective manner. This older model is still a foundational element of contemporary discourse on the nature of science.

[18] Both Latour and Pickering follow a post-humanist perspective (as opposed to an anthropocentric one) in which human and non-human actors interact with each other without either being at the center.

way of interacting with the nonhuman material agency of the world. To achieve this, humans have built innumerable tools that allow us to *"capture, seduce, download, recruit, enrol, or materialize that agency, taming and domesticating it, putting it at our service, often in the accomplishment of tasks that are simply beyond the capacities of naked human minds and bodies, individually or collectively"* (Pickering, 2010, 7). As he writes, *"[s]cientists are human agents in a field of material agency which they struggle to capture in machines"* (Ibid, 21). Beyond its applicability in science, Pickering's approach feels particularly relevant when regarding the production of knowledge within a performative artistic practice. At the very least, it feels especially relevant to me in helping me understand my own personal practice with radio, microwaves, and software.

Having this in mind, it becomes evident that the instruments and machines we use play an extremely important role in how we produce knowledge. We glimpse reality through them and use them to grapple with the *"nonhuman material agencies that produce those realities"* (Salter, 2015, 8). This causes Pickering to describe the scientific practice as a *"mangle"* performed dialectically through *"an assemblage of multiple and heterogeneous elements"* – an ecosystem of instruments, devices, infrastructures and other tools through which facts and knowledge about the world can be produced (Pickering, 2010, x). These tools act as 'transducers' of reality, but also as performative partners. They extend our capacities through a *"performativity"* that depends on *"the gestures, skills, and whatever required to set machines in motion and to channel and exploit their power"* (Ibid, 16). They are the interfaces between human and non-human agencies, enabling their interaction and helping establish a balance between them.

These tools are not the products of an external process (like a god-given gift) but are instead developed iteratively through a dialectic process which involves creating a machine/instrument/tool, monitoring its success in capturing material agency, then evaluating its performance to further tweak it, while revising the model and the ideas that birthed it if necessary (Ibid). Material agency is not a given, but a force to be explored through continuous experimentation. When it resists capturing, human agents accommodate by correcting the model, the machine, and/or their way of performing with the machine. The process of 'tuning' is thus not reserved for the tools, but may be applied to the ways people operate them, or even to the goals of an experiment. In this *'dance of agency',* as Pickering calls it, human and material agencies perform together, stabilizing and defining each other through real-time interaction that is shaped by culture, technology, and context. New instruments often result in new models and new ways of understanding reality, leading to potentially radically new conclusions. Inevitably, our reality changes together with our instruments because, as Weibel remarks, “*we do not interact with the world - only with the interface to the world”* (Weibel, 1996, 343)

The invention of electromagnetic technologies is a clear example of this culture of mental and physical tools evolving together, at times piecemeal and at times with large jumps and radical shifts, to the point of creating a new set of ‘prosthetic organs’ that have allowed mankind to sense and act upon a layer of reality that was previously unknown. As will be shown in the following chapter, stepping on previous work by Faraday and many others, Maxwell offered a new way to understand electromagnetism – and our reality - with his theory. Hertz used this theory as a compass that enabled him to make the passage from the world of theories and equations to measurable facts using a set of new instruments and experiments he devised. The subsequent discovery of electromagnetism caused a radical *“paradigm shift”* (Kuhn, 1962/2012), not only in science but also in everyday life – both in the material world of objects, with a flood of new technologies taking over the world, but also in the human psyche and our understanding of the world. Electromagnetism created the certainty that there is *physically* more than what we, humans, are able to sense. While this is not a new concept, such beliefs had been limited to the realm of faith and religion in the past.[19] Following Hertz’s electromagnetic experiments, this became a scientifically proven fact that could be harnessed to develop innovative technologies.

1.1.5 *Malfunction, glitch, and errors showing the path forward*

It is important to recognize that instruments and tools are not only valuable in their success, but can prove pivotal in their failure as well. Similar to how random mutation is a catalyst of biological evolution, chance has always been a driving factor for the production of knowledge and for innovation – scientific, technological, but also artistic. Accidents, errors, malfunctions, glitches, and unexpected results have proven time and time again to fuel imagination towards new paths, offering glimpses into the unknown and opening up new perspectives that lead to new knowledge and new tools. They should thus be considered an essential part of the process of ‘tuning’ that Pickering writes about.

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[19] An example of the deep mental impact of this paradigm shift is how it is directly connected to the wide spread of spiritualism in the late Victorian era, often practiced by eminent scientists.

The history of electromagnetic science, in particular, is full of breakthroughs sparked by observations and inquiries into instruments and tools that did not work as they should – or, perhaps, that did not work the way their designer *thought* they should. The examples are countless. Hans-Christian Ørsted realized that electricity and magnetism are intrinsically connected after noticing the interference of an electric circuit on a nearby compass in 1820 (see 2.1.3). In 1885, Hertz's world-changing experiments started with the puzzling observation that generating a spark in one circuit caused another spark to materialize in another circuit far away (see 2.1.7). The broadcast of the first ever 'radio show' by Reginald Fessenden in 1906 came about after one of his engineers informed him about a glitch in their transatlantic Morse telegraphy system, namely that it picked up and transmitted another engineer's voice (see 2.3.5). Broadcast radio itself, a medium that defined the 20th century, was considered a 'bug' of wireless telegraphy for many years; this potential of the radio medium was in fact hidden from the public for decades. More recently, Ubiquitous Sensing researchers (Woyach et al., 2006) discovered that radio and microwave telecommunication signals could be harnessed to sense human bodies in space after analyzing the noise that produced connectivity errors in their systems (see 5.4.1).

Naturally, only a small portion of such mishaps leads to breakthroughs. One can readily assume that there must have been innumerable other potentially fruitful accidents that have passed unnoticed in the history of mankind. There were also many other accidents that nearly led to something before reaching a dead end, causing enough of a stir to at least become part of written history. For example, the investigation of a faulty connection in his new microphone prompted David Edward Hughes to invent a radio receiver already in 1878, before Hertz's experiments. Nevertheless, nothing came of it as neither Hughes nor any scientists informed about his achievement could properly identify the phenomenon (see 2.1.6). Hertz essentially invented radio frequency sensing of human bodies between 1887-88 but, being interested in conducting science rather than conceiving new technologies and having so much ground to cover in the study of electromagnetic phenomena, he did not proceed in applying his findings towards technological innovation (see 2.1.8). About a decade later, in 1897, Alexander Popov nearly invented radar after noticing that his radio signals were reflected by the hull of a boat (see 2.3.1). Nonetheless, this ground-breaking finding did not result in a new technology as Popov's attention was consumed with creating a wireless telegraphy system instead. In all these cases, the paths to new knowledge opened by these errors was left unexplored.

The evolution of my own artistic practice with WiFi and FM radio – or better, with microwaves and radio waves - can also be described through Pickering's model as a performative 'mangle'. The dialectic interaction of my own agency as an artist with the material agency of the hertzian medium has led to a continuous tuning, expanding, and transforming of my ideas about this medium, its potential, and its experiential qualities. It did the same to the tools and instruments I developed and - no less importantly - to the knowledge produced through these works about the world and, more specifically, about the material nature of the hertzian medium and the ways in which it can be used to produce engaging artist experiences. Grappling with noise, errors, and unexpected results has been a critical element of my process. Whereas the material mechanism of a technology like WiFi is opaque when it works, it begins to become transparent as soon as the technology starts to malfunction. In fact, as will be discussed in section 4.2.6, my entire trajectory in working with radio and microwaves was significantly inspired by things that went wrong - or simply seemed odd – in my WiFi-based installation *The Network Is A Blind Space.* The 'glitching' of this technology became a revelatory process that enabled me to glimpse beneath its surface layers. Observing and analyzing connectivity errors and their provenance began to reveal to me the physical nature of wireless communication, thus hinting on the technology's potential use not to communicate but to sense. This resulted in creating a radar-like system that is in and of itself a 'glitch' of WiFi, an abuse of its intended purpose that is not meant to be possible, but which is physically unavoidable. By focusing my attention on this unintended feature and digging deep into the hidden layers of this technology, I started understanding WiFi not just as a communication medium but as a form of measurable physical energy.

1.1.6 *Discovering the medium behind the technology*

Hertz's discovery of electromagnetic waves should be regarded as an integral element of a broader process of *"intense dematerialization"* of everyday life that has been taking place since the mid 19th century (Baumgärtel, 2005, 61). In regard to communication, this discovery marked the beginning of the telematic era, in which wireless media appear to collapse space-time, instantaneously connecting remote locations together through a *seemingly* – but not truly – immaterial medium (Ibid). Messages no longer require a corporeal messenger to transport them (whether that is the human body of a messenger, the envelope of a letter, or the wire of a telephone is beyond the point) but flow 'in the ether', as it were, in the form of invisible energy moving through space at the speed of light. The material of wireless communication, radio waves and microwaves, literally escapes our senses, creating "*a space, or rather, nonspace, that was previously beyond the imagination: a (non)place in which time and space collapsed into one another and which was accessible potentially from everywhere, by everybody, and at all times"* (Ibid, 61). Our inability to perceptually access this space has its dangers, inhibiting our very understanding of the medium and its materiality. As Dunne points out, *"[t]he extrasensory nature of electromagnetic radiation often leads to its treatment as something conceptual—which easily becomes confused with the notional, although of course it is physical and exists in space."* (Dunne, 1999/2005, 102). This confusion often results in a fundamental misrepresentation or misunderstanding of the nature of wirelessness.

As wireless media become abstracted and dematerialized in our minds, it is easy to become so focused on their content (i.e. on the data distributed by our Infosphere) that we forget about their very physical materiality. However, to better understand the *dance of agency* involved in creating artworks with wireless technologies like WiFi and broadcast radio, it is necessary to understand what exactly the medium is, what is its material, and what is the kind of agency that can be attributed to it. The obvious first answer in regard to the nature of a wireless communication medium such as WiFi would be that it is a telecommunication technology designed to relay messages from a transmitter to a receiver. This simplification is however misleading as, in this manner, our understanding of the medium's nature becomes conflated with our understanding of its content or of its function and purpose of use. Communication becomes the lens through which we regard the phenomenon of transmission and reception, rendering radio synecdochically synonymous to broadcast, and WiFi to wireless internet access.

Regrettably, this is a pitfall that many media theorists and artists tend to fall into. In fact, discussing wireless electromagnetic media through communication has been the single most dominant perspective for a very long time. Nevertheless, we may end up with a radically different understanding of radio waves and microwaves when we disregard the notion that they are mere carriers of man-made information encoded into them (a notion that has become engrained to our understanding of these waves since the publication of a visionary article on wireless telegraphy by Sir William Crookes in 1892 - see section 2.2.2). First of all, wireless communication does not necessarily need to happen between humans but it may be a means to control machines, such as drones for instance, or it may even dismiss the human element altogether. Moreover, apart from communication the same radio waves and microwaves can also become tools for perceiving reality in different scales: from listening to the cosmos (such as in radio astronomy), to sensing weather (in radar meteorology), to sensing space from afar (radar), to navigating (such as with GPS), to peering inside the body (with MRI scanners), and more. Although all these applications are based on the same hertzian material, their content is very different. In radio astronomy, the content is discovered by analyzing the cosmic noise carried by the waves. In radar meteorology the content is found in interference, in the electrical perturbations of the atmosphere and how they affect waves passing through it. Similarly, in radar and radiology the content is also found in the interferences caused by objects inhabiting the space between transmitter and receiver – boats, aircrafts, or the human body. The fact that, despite the radical differences between these applications the nature of the waves they use at their core remains the same is extremely useful to keep in mind when examining the possibilities afforded by specific wireless technologies.

The versatility of the hertzian medium brings forth a set of questions: Are the possibilities afforded by a technology limited to those planned by its design? Meaning, should for instance WiFi, radio, TV and their like be considered telecommunication technologies and nothing else? Is that all they can be used for? Furthermore, does the purpose with which a medium is designed coincide with its material agency? Meaning, is the material agency of a technology like WiFi limited only to telecommunication?

As will be shown in this dissertation, the history of electromagnetic science, technology, and art indicates that the answer to these questions is resoundingly negative. In the case of my own *Hertzian Field* series of works, WiFi is used not as a telecommunication technology but as a spatial sensing system, a kind of radar. In this application, the content of the WiFi network is found in the electromagnetic interference caused by the human body and its movements, and in the sound that the system produces in response to this interference. This makes it clear that the prototypical purpose of technologies like WiFi – i.e. their intended use - is not as much defined by their material agency but by the human agency of its designers. In their turn, the possibilities afforded by the hertzian medium are not factually limited by the design of a specific technology but by the medium’s physics - essentially its material agency - and the ability of the human agency to imagine and implement possible uses for this medium that may go beyond its original intent. To better understand telecommunication and other wireless electromagnetic media, to grasp the possibilities afforded by them – not in their design but in their nature - and to imagine new uses for them, it is crucial to first comprehend their underlying materiality as that is what primarily defines their agency and their potential.

1.2 FUNDAMENTAL PHYSICS OF ELECTROMAGNETISM

1.2.1 *Forces, fields, waves and particles*

The raw matter of wireless electromagnetic media is electromagnetic radiation. In its purest most abstract form to communicate via electromagnetism means to vibrate together, to bring a 'transmitter' and a 'receiver' in sympathetic resonance through the electromagnetic force. In order to describe this newly invented communication modality Oliver Lodge, one of the pioneers of electromagnetic science and technology, came up with the term 'syntony' in the late 19th century, which was eventually replaced by the term 'tuning'.[20] To understand the processes involved in making transmitter and receiver vibrate together a brief overview of the physics of electromagnetism is necessary.

The electromagnetic force is a form of physical interaction between particles that are electrically or magnetically charged. It is one of the fundamental forces of nature, playing a crucial role in the formation of matter, life, and the world as we know it (Feynman et al., 2013). All things that make up matter – protons, neutrons and electrons, atoms and molecules – have some kind of inherent electrical charge (positive, negative, or zero).[21] These charges produce electric and magnetic forces that make the building blocks of matter attract or repel each other, depending on the relationship between their charges.[22] Among other things, the electric force is the reason why negatively charged electrons are bound to positively charged nuclei, thus forming atoms, why atoms chemically bind together to form molecules, and why molecules interact with each other to build biological cells. On the other hand, the magnetic force is the reason why magnets attract iron and why compasses can be used for orientation on Earth, because moving electric charges in our planet's core make it behave like a massive magnet. On a much more minuscule scale, the motion or spin of electrons in the atoms of minerals such as lodestone generate naturally occurring magnetic fields that surround these stones causing them to be magnetic.

[20] Radio historian Hugh Aitken laments the replacement of 'syntony' with 'tuning', stating that *"our language is the poorer as a result, because 'syntony' carries with it none of the associations of melody or tunefulness that 'tuning' has."* (Aitken, 1976/2014a, 34)

[21] The discovery of the electron by J. J. Thomson in 1898 proved the electric nature of matter, resulting in electromagnetic theory becoming integral to theories concerned with the structure of matter from the atomic to the subatomic and subnuclear level (McGrayne et al., 2020).

[22] Similar charges (positive or negative) repel each other, opposite charges are attracted to each other, and neutral ones are attracted to both positive and negative.

Long thought to be separate phenomena until the 19th century, electricity and magnetism are essentially two sides of the same coin: electromagnetism. Typically, phenomena which do not involve changes in electric charge – such as static cling - are interpreted as electric/electrostatic. Phenomena which involve a change in electrical charge but no change in the rate with which this charge flows through a surface (i.e. when the magnitude of the current remains unchanged) are typically classified as magnetic/magnetostatic. Phenomena in which both the electric charge and the magnitude of a current are fluctuating are typically interpreted as electromagnetic.

Whereas electric or magnetic charges at rest (i.e. *electrostatics* and *magnetostatics*) only produce one type of force, when they are in motion they produce both electric and magnetic forces. These forces radiate through space and time via electric and magnetic *fields*. Broadly defined, a field is *"any physical quantity which takes on different values at different points in space"* or at different points in time (Feynman et al., 2013). Placing one charged object within the field of another will create an interaction between the two, attracting or repelling them from each other according to the relationship of their polarities.

Whenever a particle with a charge changes velocity, part of its energy is transferred into electromagnetic radiation that propagates as a time-varying fluctuation in both electric and magnetic fields.[23] This occurs because the change in the velocity of the charge creates an oscillation in the electric field around the charged particle. In its turn, this creates an oscillation in the surrounding magnetic field, which creates another oscillation in the electric field, and so forth.

Classical electromagnetic theory, formalized by James Clerk Maxwell and experimentally proven by Heinrich Hertz, describes electromagnetic radiation as a wave of electric and magnetic fields and explains how its energy and momentum propagate in time through space. Maxwell described the properties of electromagnetic fields through a number of equations that built on previous knowledge. Without diving into the mathematics involved, the physical laws resulting from these equations can be summed as follows:

- Electrical fields are caused by an electrical charge (Gauss's law). This law stems from the investigation of objects with electrical charge and the forces that make them attract or repel each other. Its roots can be found in ancient Greece and the study of the

[23] This typically occurs through acceleration, though deceleration is also possible such as in the case of *Bremsstrahlung* or *Braking radiation,* which will be explained further below.

properties of amber by Thales of Miletus (Elert, 1998/2022).

- Magnetic monopoles do not exist (Gauss's magnetism law). Also called, 'no one's law', because no one has ever seen a magnet without both a north and a south pole. The roots of this law also extend to ancient times.
- A fluctuating magnetic field will induce an electric field (Faraday's law). Practically put, this law states that it is possible to induce an electrical field on a loop of wire by either moving a magnet around it or moving the wire around the magnet.
- A fluctuating electric field and/or electric current will induce a magnetic field (Ampère's law). This law states that moving an electrical charge through a wire will induce a magnetic field on a magnet.

Faraday's and Ampere's laws reveal the relationship between electric and magnetic fields, and how they can induce and sustain each other to create a fluctuating, self-perpetuating electromagnetic field that propagates in space as an electromagnetic wave. Beyond bringing electricity and magnetism together, Maxwell and Hertz also made evident the fact that visible light is a form of electromagnetic radiation as well; thus, they incorporated the study of optics into the broader field of electromagnetic science.

Maxwell's theory deals with the macroscopic scale. It is not concerned with the transfer of matter but with the transfer of energy. The advent of quantum mechanics in the 20th century revealed the nature and behavior of electromagnetism in the quantum scale. As such, electromagnetic radiation is now thought of as both a wave (radiation of energy) and a particle (displacement of energy-carrying minuscule matter, such as the flow of light quanta or photons through space at the speed of light). This is called the wave-particle duality of electromagnetism. Having two different perspectives to describe the same force is not redundant, because some properties of electromagnetism are better explained when regarding it as consisting of particles and others as consisting of waves. The particle model is useful for describing how matter is transported – such as photons in the case of light – whereas the classical wave model is more versatile for describing the transfer of energy and electromagnetic radiation below the frequency of light, like with radio waves and microwaves. This is mainly because the first case (light) involves smaller numbers of high energy photons whose individual trajectories can be predicted with the quantum model, whereas in the latter case (e.g. radio), a higher-level abstraction is more effective in describing the wave-like propagation of masses of lower-energy particles through the use of statistics and stochastic probabilities. Furthermore, Maxwell's equations are only pertinent for distances down to 10^{-10} cm (i.e. about 1/100 of an atom's size). To accurately describe the electromagnetic force in yet more microscopic distances that can account for quantum effects, the equations were modified according to quantum theory with the development of Quantum Electrodynamics (QED) between 1945-55 (McGrayne et al., 2020). Nonetheless, given that this thesis is primarily concerned with radio waves and microwaves at the macroscopic scale, it will primarily discuss electromagnetic phenomena as waves rather than particles.

Mathematically, electromagnetic waves are commonly described by their velocity, which equals the speed of light, by their wavelength, and by their frequency. The wavelength is the physical distance between the peaks of two adjacent cycles of the wave and is measured in meters (figure 1.3); its length depends on how long the acceleration of charge lasts. Frequency is the number of cycles that pass a given point in space per second and is measured in Hertz. Frequency and wavelength are inversely proportional, a relationship described by the following equation:

$$f = c / \lambda$$

where f is Frequency in Hertz, i.e. oscillations per second, c is the speed of propagation in meters per second (which for electromagnetic waves equals the speed of light) and λ is the wavelength in meters.

Like all waves, electromagnetic waves are also characterized by their phase, amplitude and energy. The phase of a wave is a measure of its position at a specific time in a cycle of its oscillation. Phase becomes particularly relevant when waves of the same frequency encounter each other (which occurs, for example when a wave is reflected on a surface) as, depending on the relationship between their phases, these waves may amplify, attenuate, or even cancel each other out. This is a natural effect of the interaction between waves that I make use of in the *Wireless Information Retrieval* (WIR) sensing system, as will be shown in chapters 5 and 6. Another characteristic of waves that is fundamental to the *WIR* system is amplitude. The amplitude of a wave is the magnitude or range of its variation within a single cycle (from its maximum to its minimum). This relates to the energy a wave carries. In the case of sound waves, for instance, a wave with a higher amplitude exerts more acoustic pressure and is thus typically perceived to be louder than one with a lower amplitude. In electromagnetic waves the effects is similar; for instance, higher amplitude radiation from the Sun will be experienced as brighter light and produces more heat.

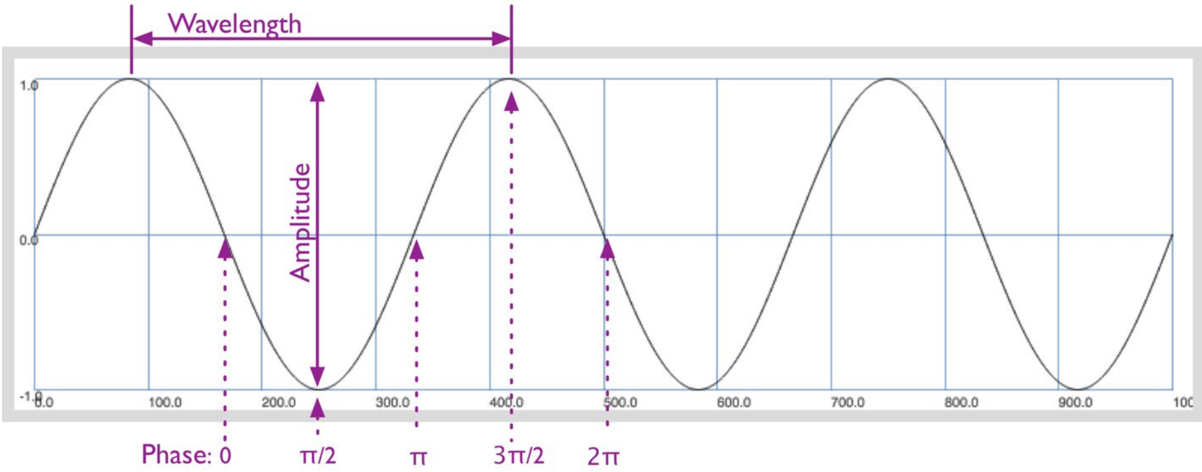

Figure 1.3. Wavelength, amplitude and phase of a wave.

The energy carried by an electromagnetic wave in a vacuum is equally distributed to its electric and magnetic components and is proportional to the square of the force induced by each field. The amount of energy also depends on the frequency of oscillation: the higher the frequency of an electromagnetic wave, the more energy it carries. There are many different ways to measure the energy of a wave. Among others, the *power* or *radiant flux* of a wave corresponds to how much energy is transferred over a unit of time (i.e. measuring what the rate of transfer is) and is calculated in Watt or Joule per second. The *intensity*, *flux density* or *irradiance* of a wave corresponds to how much power the wave delivers on average during a cycle over an area unit and is measured in Watt per square meter. Many more types of measurement exist, often with variations established for different scientific fields (see “Radiometry”, 2021). .

Instead of measuring the properties of an electromagnetic wave in its entirety, it is also possible to focus on its properties at specific frequencies. This is achieved by describing the wave mathematically in the frequency domain rather than in the time domain. Using the Fourier transform, any kind of wave can be analyzed into a series of sinusoidal components described individually by their frequency, amplitude, and phase. In this manner, it is possible to pinpoint the frequencies in which the energy of a wave is concentrated. If the energy is concentrated in one single frequency, the wave is called *monochromatic*, owing to the fact that such a wave in the frequency range of light appears to the human eye as a single color.

1.2.2 *The electromagnetic spectrum and the various types of radiation*

The span of frequencies and wavelengths of electromagnetic waves vary immensely - over 26 orders of magnitude - from the size of an atom to nearly the size of the universe. The energy amounts carried by waves in different ranges vary in a similar fashion, from levels below what our equipment can measure to levels that are deadly to humans and other lifeforms. In the first decades following Hertz's discovery and up to the mid 20th century, the vast range of possible frequencies of electromagnetic waves was conceptualized similarly to sound, with scientists and engineers borrowing the musical term 'octave' to demarcate a doubling of the frequency of oscillation (Joyce, 2008). Today, the prevalent term to describe the entirety of possible frequencies of electromagnetic radiation is that of the 'electromagnetic spectrum'. Nonetheless, as a musician I find the notion of an octave still useful to grasp the broad range of the spectrum in its entirety, as well as the ranges of different types of electromagnetic waves. Following this concept, the span of the electromagnetic spectrum practically extends over 80 octaves (from 3Hz to $3x10^{25}$Hz), although theoretically it is near-infinite.[24]

Waves of different frequencies are generated in different manners, have different properties, interact with matter in different ways, and hence are used by humans in different types of applications. Overall, there are seven principal bands, each with its own set of characteristics. From slowest to fastest, these bands are: *Radio waves, microwaves, infrared light, visible light, ultraviolet light, X-rays,* and *gamma rays* (figure 1.4). The exact terminology for some of these bands is dependent on context and perspective; for instance, one may speak of *infrared light, infrared radiation, infrared rays, infrared waves,* or *infrared photons*. These seven bands do not split the spectrum in equal chunks. Radio waves stretch out over $26\frac{2}{3}$ octaves, microwaves just short of 10 octaves, infrared about $10\frac{1}{2}$, visible light is limited to less than an octave, ultraviolet about $5\frac{1}{3}$, X-rays about $6\frac{2}{3}$, and gamma rays over 20 octaves.[25] It should be noted that these are approximate ranges, as there are no firm divisions between these bands. Instead, much like the colours of a rainbow, these bands smoothly fade into each other with no clear beginning or end. Electromagnetic waves whose frequencies are around these boundaries exhibit a mixture of properties from both of the bands they straddle. For this reason, the exact boundaries of all these bands vary in the literature.

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[24] The lowest possible frequency corresponds to a wavelength with the size of the universe and the highest possible frequency corresponds to the so-called Planck frequency of about $1.885x10^{43}$ Hz. This is an oscillation whose wavelength is the Planck length: the smallest meaningful unit of measurement estimated to about $1.616255x10^{-35}$ meters (Padmanabhan, 1985).

[25] As a comparison, the keyboard of a piano extends to 7 and 1/3 octaves.

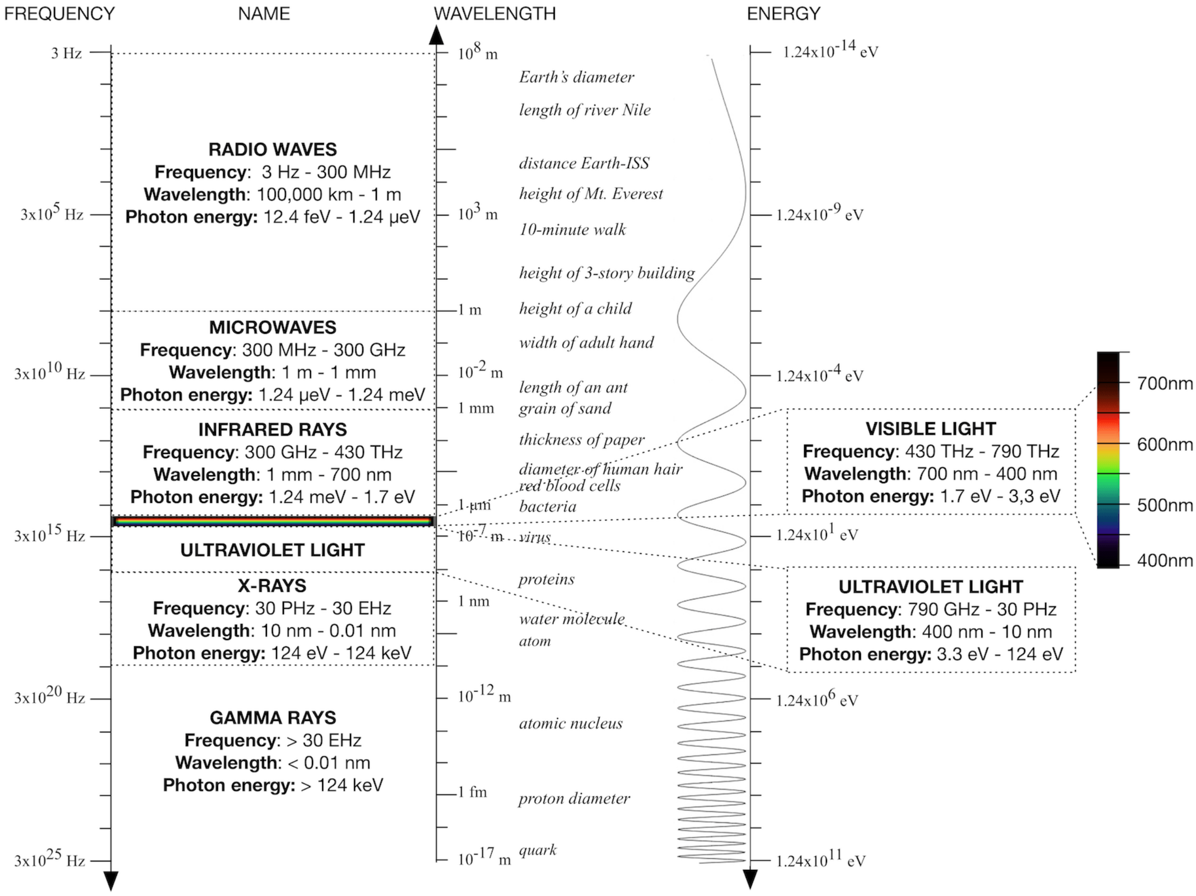

Figure 1.4. The electromagnetic spectrum in terms of frequency, wavelength, and energy.

Electromagnetic radiation is both natural and man-made and can be produced in a variety of environments and conditions. Radio waves and microwaves, i.e. electromagnetic radiation with a wavelength between 100,000km-1mm and a frequency between 3Hz-300GHz, are generally produced by electrons and ions moving freely in space, or by free-moving electrons in metallic antennas (Fritzche & Phillips, 2020). 'Natural radio' signals are abundant in the atmosphere and were already the object of investigation before Hertz's discoveries (by Thomas Watson and others) and prior to the establishment of electromagnetic science as we know it (Kahn 2013). Hertz was the first to investigate man-made radio signals as well as waves in the lower microwave range with his experiments reaching up to about 500MHz (Cichon & Wiesbeck, 1995, and Aitken, 1976/2014a). Following on Hertz's footsteps, most early electromagnetism researchers concentrated on radio waves, however there were a few pioneers who surveyed higher frequencies in the microwave range. This includes Augusto Righi, who experimented with waves between 1.5 - 12GHz, and more importantly Jagadis Chandra Bose who reached up to 60GHz (see 2.3.1 and 2.2.6 respectively).

The seven principal bands can be further divided into sub-bands. These subdivisions are typically established for practical reasons that relate to specific physical characteristics of the waves, to how matter responds to them, and to specific technologies, applications, and legal frameworks. As such, each band can be divided in different manners that are context-specific. Figure 1.5 shows the most standard subdivision of the radio and microwave bands.

	FREQUENCY	NAME	WAVELENGTH		ENERGY	
3Hz	3-30 Hz	Extremely Low Frequency (ELF)	100,000-10,000 km	10^8 m	12.4 feV	1.24×10^{-14} eV
	30-300 Hz	Super Low Frequency (SLF)	10,000-1,000 km		124 feV	
	300-3000 Hz	Ultra Low Frequency (ULF)	1,000-100 km		1.24 peV	
	3-30 kHz	Very Low Frequency (VLF)	100-10 km		12.4 peV	
	30-300 kHz	Low Frequency (LF)	10-1 km		124 peV	
	300-3000 kHz	Medium Frequency (MF)	1000-100 m		1.24 neV	
	3-30 MHz	High Frequency (HF)	100-10 m		12.4 neV	
	30-300 MHz	Very High Frequency (VHF)	10-1 m		124 neV	
3×10^8 Hz	300-3000 MHz	Ultra High Frequency (UHF)	1000-100 mm	1m	1.24 μeV	1.24×10^{-6} eV
	3-30 GHz	Super High Frequency (SHF)	100-10 mm		12.4 μeV	
3×10^{11} Hz	30-300 GHz	Extremely High Frequency (EHF)	10-1 mm	10^{-3} m	124 meV	1.24×10^{-3} eV

Figure 1.5. The Hertzian medium: Radio wave bands and microwave bands (in white and grey respectively).

The above categorization is rather telecommunications oriented. A more radar-oriented standardized categorization of microwaves in bands according to their frequencies and wavelengths can be seen in Figure 1.6.

FREQUENCY	NAME	WAVELENGTH
300 MHz -1 GHz	P-band	1 m - 30 cm
1 - 2 GHz	L-band	30 - 15 cm
2 - 4 GHz	S-band	15 - 7.5 cm
4 - 8 GHz	C-band	7.5 - 3.8 cm
8 - 12.5 GHz	X-band	3.8 - 2.4 cm
12.5 - 18 GHz	Ku-band	2.4 - 1.7 cm
18 - 26.5 GHz	K-band	1.7 - 1.1 cm
26.5 - 40 GHz	Ka-band	1.1 - 0.75 cm
32 - 50 GHz	Q-band	9.38 mm - 6 mm
40 - 60 GHz	U-band	7.5 - 5 mm
50 - 75 GHz	V-band	6 - 4 mm
75 - 100 GHz	W-band	4 - 3.33 mm

Figure 1.6. Radar-oriented division of microwave bands (after Whitaker, 2002).

The radio and microwave portion of the spectrum is also divided by law, with different frequencies assigned to distinct licensed and unlicensed technologies and communication protocols. Figure 1.7 shows how the radio and microwave portions of the spectrum are allocated in the US by the National Telecommunications and Information Administration (NTIA) and the Federal Communications Commission (FCC) as of 2016.

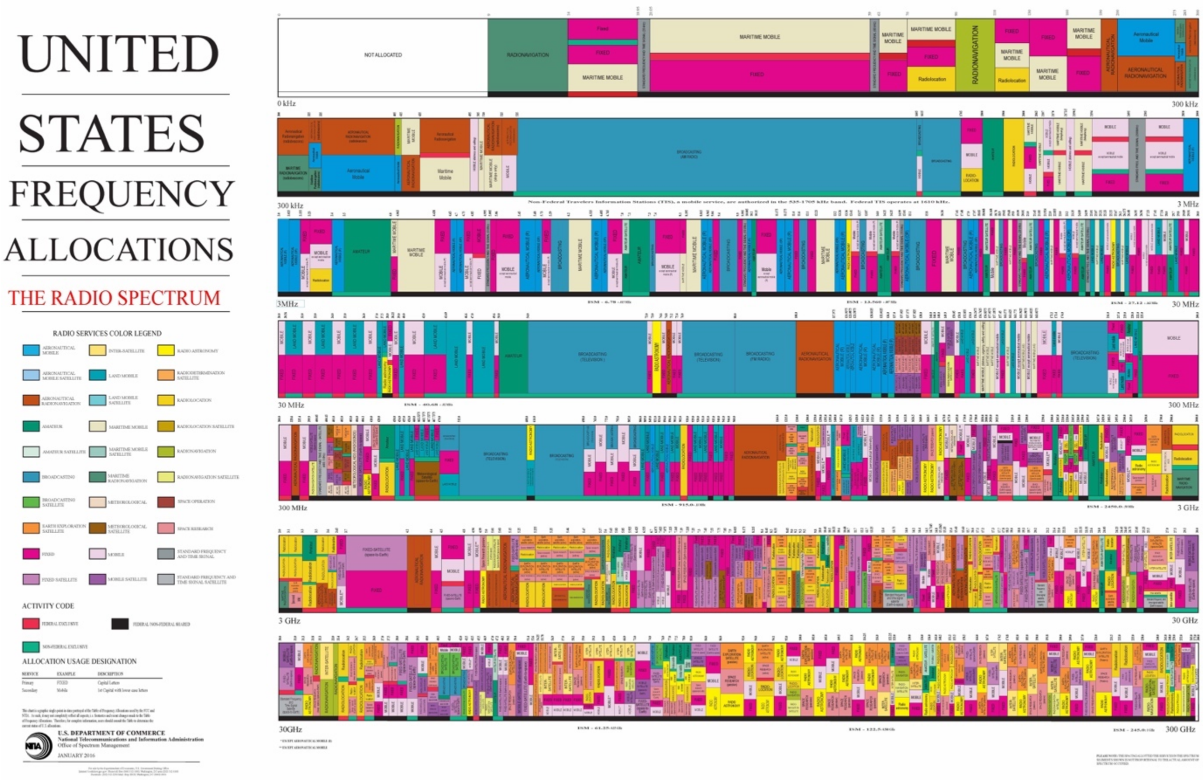

Figure 1.7. Allocation of frequencies in the radio spectrum in the United States (National Institute of Standards and Technology, 2016).

Above microwaves is the infrared band, with frequencies ranging between 300 gigahertz to 430 terahertz, and wavelengths between 1 millimeter to 700 nanometers. This band reaches up to the wavelength of visible red light - hence the name ‘infra-red’ which means ‘below red’. Infrared radiation is mainly produced by charges originating from molecules rotating or vibrating, or from the movement of bonded atoms. With the exclusion of visible light, these were the first type of electromagnetic waves to be discovered as a result of William Herschel’s investigation of the Sun’s spectrum in 1800. Infrared radiation is invisible to the human eye but can be sensed by the skin as heat. Objects that emit moderate amounts of heat also emit infrared light - the hotter the temperature, the shorter the wavelength and the higher the frequency. From low to high frequencies, the infrared band is typically divided into *Far Infrared* (FIR), *Mid Infrared* (MIR) and *Near Infrared* (NIR), with the exact division points diverging between scientific fields. The *Far Infrared* sub-band that follows microwaves is also known as *terahertz radiation* (owing to the frequency of its waves) or the *terahertz gap* (owing to the fact that these waves are too slow for optical equipment and too fast for electronics, making their examination difficult). This form of radiation is thought to account for 98% of all photon emissions since the Big Bang. Higher in the spectrum, *Near Infrared* is divided in two subcategories, short-wave and very-near infrared. The latter can be captured by photographic film and is thus also called *photographic infrared*. While human ability to sense infrared radiation is limited, there is a number of animal species that have developed advanced infrared sensing capabilities, such as pit vipers and some kinds of boid snakes (Macpherson, 2011). These animals have specific organs under their eyes with cells that respond to infrared radiation. This infrared sense allows them to perceive the presence and general shape of prey – enough to target the more vulnerable areas in its body – as well as to sense trails of heat. These infrared organs and the representation of the environment they produce display both similarities and differences to our more familiar sense of vision that is based on visible light (Ibid).

In the higher parts of the spectrum, from visible light to X-rays, the frequency of radiation correlates to charges moving inside atoms. Visible light is the small slice of the electromagnetic spectrum that humans can see with our eyes, with frequencies of oscillation between 430-790 terahertz and wavelengths between about 700-400 nanometers. Owing to our innate sensitivity to it, visible light is by far the most studied electromagnetic phenomenon, with the science of optics – i.e. the study of the properties and behaviour of light – long predating all other electromagnetic science. Visible light is produced by the excitation of electrons in molecules and atoms and is generated in nature by very hot objects such as fire, the Sun and other stars. Our retinas contain special cells sensitive to light that sense these electromagnetic waves as they propagate in space and as they reflect off objects. Humans have 3 kinds of receptor cells tuned to perceive different wavelengths – long, medium, and short. When light falls on these cells, they produce electrical signals in response which they send to the brain through a complex path that involves various types of other cells located in the eye, the optical nerve, and the brain (Macpherson, 2011). The range of wavelengths we are able to sense corresponds to different levels of electron excitation. In succession from cooler to hotter, our brain interprets these wavelengths as red, orange, yellow, green, blue, and violet light. The way we visually experience our surroundings is a combination of the physical properties of the world around us, of the makeup of our light sensing organs, and of the processing of light-related stimuli by our brain and nervous system

(Ibid). As mentioned above, our eyes are only able to see less than an octave of electromagnetic radiation. This is a very small bandwidth when compared to the range of human hearing, which nominally covers up to 10 octaves of mechanical vibrations (20Hz-20kHz). It should be noted that, similarly to our hearing, the exact boundaries of vision differ for every person, with some people having a more extended range in the frequencies they perceive towards the bottom end (infrared) or the top end (ultraviolet) of visible light than others.

Electromagnetic radiation with frequencies just above visible light (790 terahertz to 30 petahertz) and shorter wavelengths (between 400-10 nanometers) is called *ultraviolet* or UV in short (meaning 'beyond violet'). This form of radiation is produced by electrons in atoms and molecules with an even higher excitation than that which produces visible light. Ultraviolet light / radiation was discovered in 1801. A year after Herschel expanded the range of the light spectrum below the visible colours of the rainbow with his discovery of infrared, Johann Wilhelm Ritter did the same with light's upper range, discovering an invisible form of radiation above violet light through the use of an electrochemical process (Joyce, 2008).[26] Although the ultraviolet band extends beyond the wavelengths our human eyes can capture, there are many species of animals whose eyes can see it, from birds, to fish, reptiles, amphibians and invertebrates (Douglas & Jeffery, 2014). Bees, for instance, have sensing organs - classified as eyes - with which they can see ultraviolet light. This enables them to perceive markings on flowers that guide them to the flower's nectar (Macpherson, 2011). Recent studies have also shown that UV sensitivity in mammals is likely much more widespread than previously believed (Douglas & Jeffery, 2014). Ultraviolet light can be divided into four main categories: *near ultraviolet* (NUV, with wavelengths between 400-300nm), *middle ultraviolet* (MUV, between 300-200 nm), *far ultraviolet* (FUV, 200-122nm) and *extreme ultraviolet* which is nearly X-ray radiation (EUV, 121-10nm).[27] A more widely known classification of UV light follows the effects of these rays on human skin and consist of three categories: *UV-A* (400-315nm) are rays that make up about 95% of the Sun's radiation hitting the earth and include so called 'black light'. Exposure to these rays tans and ages the human skin. *UV-B* rays (315-280nm) can burn the skin, cause cancer, and even burn the cornea of our eyes through over-exposure. *UV-C* rays (280-100nm) are absorbed by

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[26] Ritter also left us a very interesting aphorism that helps explain the relationship between vibration and light: *"When bodies vibrate* extremely fast*, they* glow*"* (quoted in Zielinski 2006, 181).

[27] *Far* and *extreme ultraviolet* can also be bundled into a single category, named *vacuum ultraviolet* (VUV, 200-10nm).

ozone in the atmosphere and do not reach the Earth's surface. Owing to their adversary effects on lifeforms, special *UV-C* lamps are often used to kill germs and bacteria.

The next band in the electromagnetic spectrum is that of X-rays, a form of radiation discovered and named in 1895 by Wilhelm Conrad Röntgen (Röntgen, 1896).[28] X-rays are produced when electrons inside atoms become highly excited, oscillating at extremely fast frequencies between 30 petahertz (3×10^{16} Hz) to 30 exahertz (3×10^{19} Hz), and at extremely short wavelengths, between 10 and 0.1 nanometers – i.e. about a thousand times shorter than visible light. Due to their high frequency and high energy, X-rays are better described as particles rather than as waves. From longer to shorter wavelengths, they can be distinguished into *soft* and *hard X-rays*, with the latter able to penetrate deep inside biological tissue. X-rays can be produced in several manners. In his 1895 experiments, Röntgen discovered 'braking radiation' (*bremsstrahlung* in German), which is generated in an X-ray tube by firing electrons with very high energy onto a metal target. Upon collision, the electrons suddenly decelerate, emitting broadband electromagnetic radiation with a peak in the X-ray band as a result (Stark, 2020). Another form of X-rays, synchrotron radiation, is produced in a special type of particle accelerator called a synchrotron. This device speeds up particles such as electrons to very high frequencies and uses powerful magnets to restrict their movement to a circular orbit. The deflection of the particles' path caused by these magnetic fields generates X-rays. X-rays are also emitted by radioactive objects. When an atom's nucleus captures an inner shell electron – a process of *transmutation* through which a chemical element is converted into another type - an outer shell electron takes its place, thus emitting X-ray radiation (Ibid). X-rays are also abundant in the cosmos, emitted by extremely hot objects, like the hot outer atmospheres of the Sun and other stars, as well as by supernovas and quasars.

Finally, in the top range of the spectrum we find gamma rays, the fastest type of radiation with the shortest wavelength and most energy. Gamma rays were given their name by Ernest Rutherford. in 1903. At the lower end of the band, the dividing line between X-rays and gamma rays is particularly diffuse. Generally speaking, electromagnetic waves with frequencies higher than about 30 exahertz and wavelengths shorter than about 0.01 nanometers are considered gamma rays. Whereas in the other high-frequency bands the frequency of radiation correlates to electron charges inside atoms (from electrons in the outer-shell of an atom in visible light, to inner-shell electrons in X-rays), gamma rays are

[28] In many languages, such as German and Dutch, X-rays, are known as Röntgen rays.

generated deeper within the atomic structure, with their frequencies correlating to charges inside atomic nuclei (Fritzche & Phillips, 2020). Gamma rays are generated by a phenomenon called *radioactive disintegration* or *radioactive decay* of atomic nuclei and subatomic particles. When the nucleus of an atom shifts from a high-energy state to a state with lower energy, it emits a gamma ray photon which carries the energy lost from the nucleus (Stark, 2020b). High energy gamma ray photons are also emitted when two antiparticles - an electron and a positron - collide and vanish (a process called *annihilation*).

Electromagnetic energy can be transferred to any object placed within the field of radiation. An important difference between electromagnetic waves of different frequencies is how they affect matter when this energy transfer occurs. Waves that contain high amounts of energy can ionize matter, meaning that the ions or electrons of molecules and atoms within the field can be released in this process of energy transfer, thus causing the chemical binding of matter to break down. The amount of energy of a wave depends on both its frequency and intensity. This means that waves with frequencies above visible light – particularly short-wavelength UV light, X-rays and gamma rays - or extremely high powered waves at lower frequencies can be ionizing. Ionizing radiation is not only directly damaging to living organisms, but exposure to it also has cumulative effects that are not immediately detected. These effects can range from breaking down biological tissue to causing DNA mutations and cancer (which is why, for instance, years-long exposure to the Sun may cause skin cancer). Waves with higher photon energy also penetrate deeper into biological tissue and may thus cause additional health problems. In contrast, lower energy radiation does not cause ionization, and thus brief exposure to it is considered not dangerous. Nevertheless, prolonged exposure to such waves may have other adversary health effects. For one, low energy non-ionizing radiation still causes some form of temporary molecular change, as electromagnetic energy is transduced into heat within a molecule. This is the well-studied *thermal effect* of radiation, which at low levels does not break the chemical binding atoms. Beyond this effect, there are other potential non-linear effects of radiation on living organisms that have not been investigated to the same extent. More on this subject will be discussed in section 5.6.

1.2.3 *Generation and propagation of hertzian waves in space*

Let us return to hertzian waves and their generation and propagation. Typically, a man-made radio or microwave system uses a special signal-generating electrical circuit, called an oscillator, to generate an acceleration of charge that produces a rapid oscillation of electrons.

This oscillator is nearly always coupled with a conductive - usually metallic – radiating element called an antenna. The two components are connected together with a wire (called the transmission line, usually a coaxial cable), that feeds the oscillating signal to the antenna. The antenna is a unique kind of object that functions as a connecting interface between the visible world of 3-dimensional objects and the invisible world of electromagnetic waves and dynamic energy flows (Medosch, 2006). Any object fabricated by conductive materials will function as an antenna if it is placed within an electromagnetic field. Depending on its shape and size, the antenna will resonate when waves of certain wavelengths pass through it. Antennas are typically designed to resonate in the frequency band of the oscillator they are coupled to (Fritzsche & Philips, 2020).

Delving deeply into the field of antenna design – a practice often referred to as one of the 'dark arts' of engineering – is beyond the scope of this thesis (for a detailed overview, see Poisel, 2012). Nevertheless, it is useful to have an overview of the lay of the land. There are numerous families, types and variations of antennas with different characteristics (see figure 1.8 for a comparison of the physical configuration and radiation patterns of four different types of antennas). *Wire* antennas consist of a wire that can be shaped in various ways: in a straight line (*monopole*), two straight segments (*dipole*), in a loop (e.g. *circular, square, biquad, cloverleaf, triangle*, etc.), or a *helix*. More advanced variants of these designs have been developed as well.

For instance, a monopole may be connected to a set of wires to form a *radial* antenna, or to a conical structure to form a *conical*, a *biconical* (e.g. *bowtie*, or *butterfly* antenna) or a *discone* antenna. *Aperture* antennas constitute another design family. These types of antennas work by creating electromagnetic fields across precisely designed openings. They are highly directional and can take the form of a horn (with many different horn geometries possible), a tube (such as the WiFi *cantenna*, a design infamous in the DIY community) or a flat surface with slot cutouts (*slot* antenna). Antennas may also be combined with a reflector, such as a parabolic dish (*parabolic* antenna), an angled metal plate (*corner reflector* antenna), or a lens (*lens* antenna). Another type of directional antenna for frequencies above the UHF band is the *microstrip patch* antenna. This design has become very popular recently because it is both very lightweight and easy to manufacture as it can be printed in a variety of 2-dimensional shapes using conductive material on a flat circuit board.

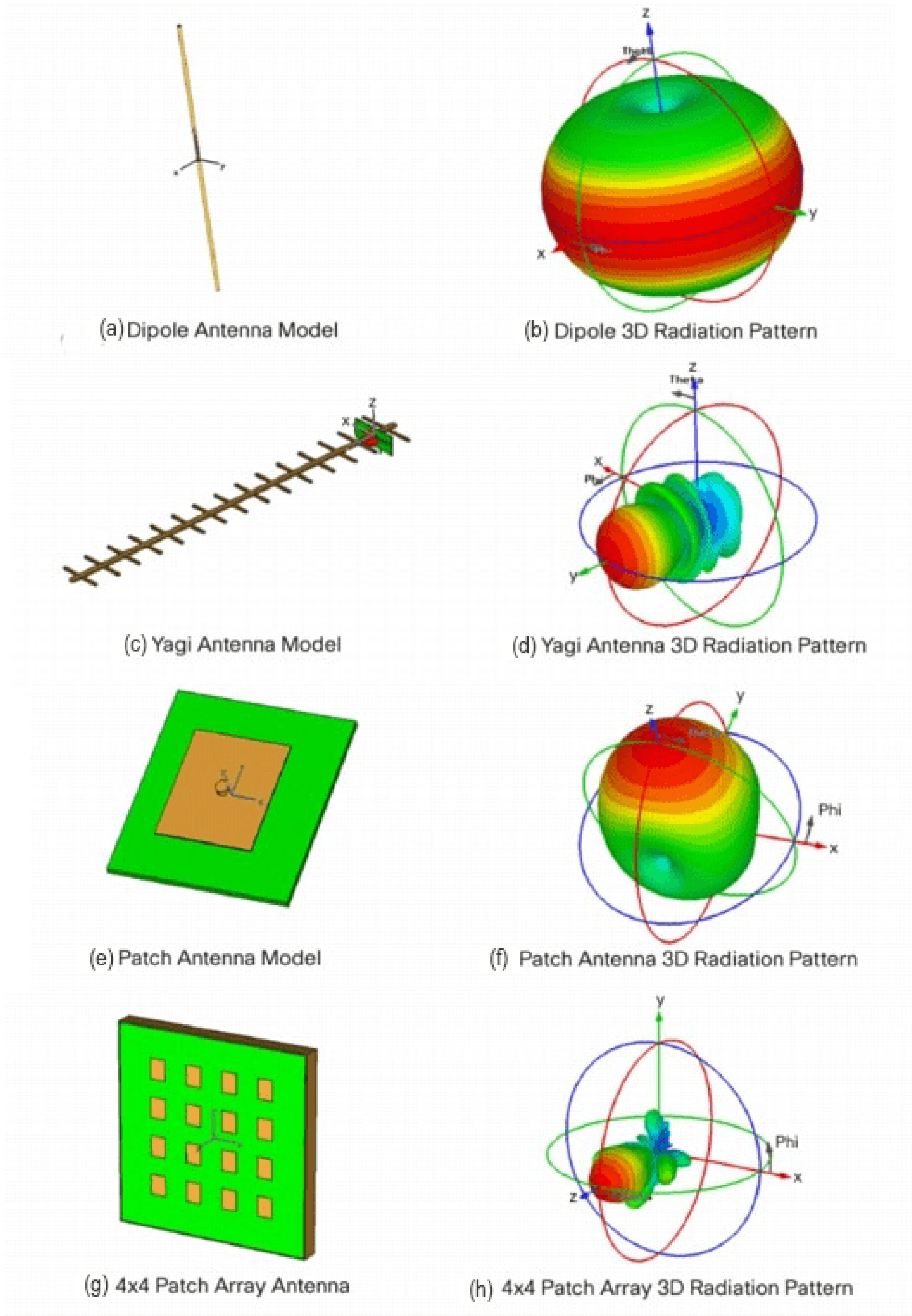

Figure 1.8. Comparing four different types of antennas: their physical configuration (left row) and their 3-dimensional radiation patterns (right row) (from Cisco, 2007).

Conductive elements with particular radiation patterns may also be combined together in specific geometries to produce new radiation patterns. These designs are called *antenna arrays*. Their configuration can be geometrically simple – such as multiple elements in a line, a circle, or a plane – or more complex, as is the case for *conformal arrays* that are mounted on surfaces with more intricate geometries, like the outer shell of an airplane or a tank. Another type of directional array is the *Yagi-Uda*, which was often installed on rooftops in the recent past to capture analog television signals. The Yagi-Uda is a narrow-band system that consists of a dipole wire and a number of so-called *parasitic elements* that absorb and radiate its energy. These elements include a reflector and a number of wires, all placed in specific distances parallel to the dipole. Another family of arrayed designs is that of *log-periodic array* antennas. These are broadband directional antennas designed to resonate effectively at various bandwidths. Log-periodic monopole and dipole designs resemble a Yagi-Uda but consist of an array of parallel monopoles or dipoles of decreasing lengths, giving them a characteristic triangular shape (such designs are sometimes referred to as *shark-fin* antennas). This family also includes various types of *log-periodic spiral* antennas that operate in similar manner. The characteristic spiral elements of these antennas generate fields with a circular or elliptical polarization.

Finally, the use of more advanced computational tools has produced some more exotic designs in recent decades. For instance, moving away from the Euclidean geometrical model of the antenna families mentioned above, *fractal* antennas are designed algorithmically with the use of iterated function systems as self-similar space-filling curves. Fractal antennas can be monopoles, dipoles, or loops, and can have directional or omnidirectional radiation. Most importantly, their fractal geometry maximizes operational bandwidth while reducing their size at a minimum. Genetic algorithms and evolutionary computation are also being used to develop new antenna designs and configurations for specific applications.

Generally speaking, a system capable of radiating electromagnetic energy at certain frequency is also capable of absorbing energy at that same frequency (Fritzsche & Philips, 2020). As such, antennas are reciprocal systems, meaning that an element capable of transmitting electromagnetic waves can also be used to detect them, and will exhibit similar characteristics in both uses (Poisel, 2012). When the electromagnetic wave – originating from a connected oscillator or free space - meets an antenna, its oscillating fields bring the electrons in the antenna into motion through sympathetic resonance or syntony, creating an oscillating current whose vibration patterns copy those of the originally transmitted wave.

As the oscillating current flows through an antenna, it creates a time-varying electric and magnetic field around it. The two fluctuating fields – electric and magnetic - are orthogonal, meaning that they are at a 90° angle with each other (figure 1.9). They have the same phase, meaning that their peaks and valleys occur at the same time, and they carry equal amounts of energy. Together they form a transverse electromagnetic field wave that radiates away from a transmitting antenna at the speed of light and at a direction perpendicular to the oscillation. The oscillation of the electromagnetic field can have different (angular) orientation in relation to the direction of its propagation; this is called the wave's polarization. Polarization can be linear (when it follows the vector of motion), circular (when it rotates in a plane perpendicular to it), or elliptic (when both its direction and amplitude vary) (Vander Vorst et al., 2006).

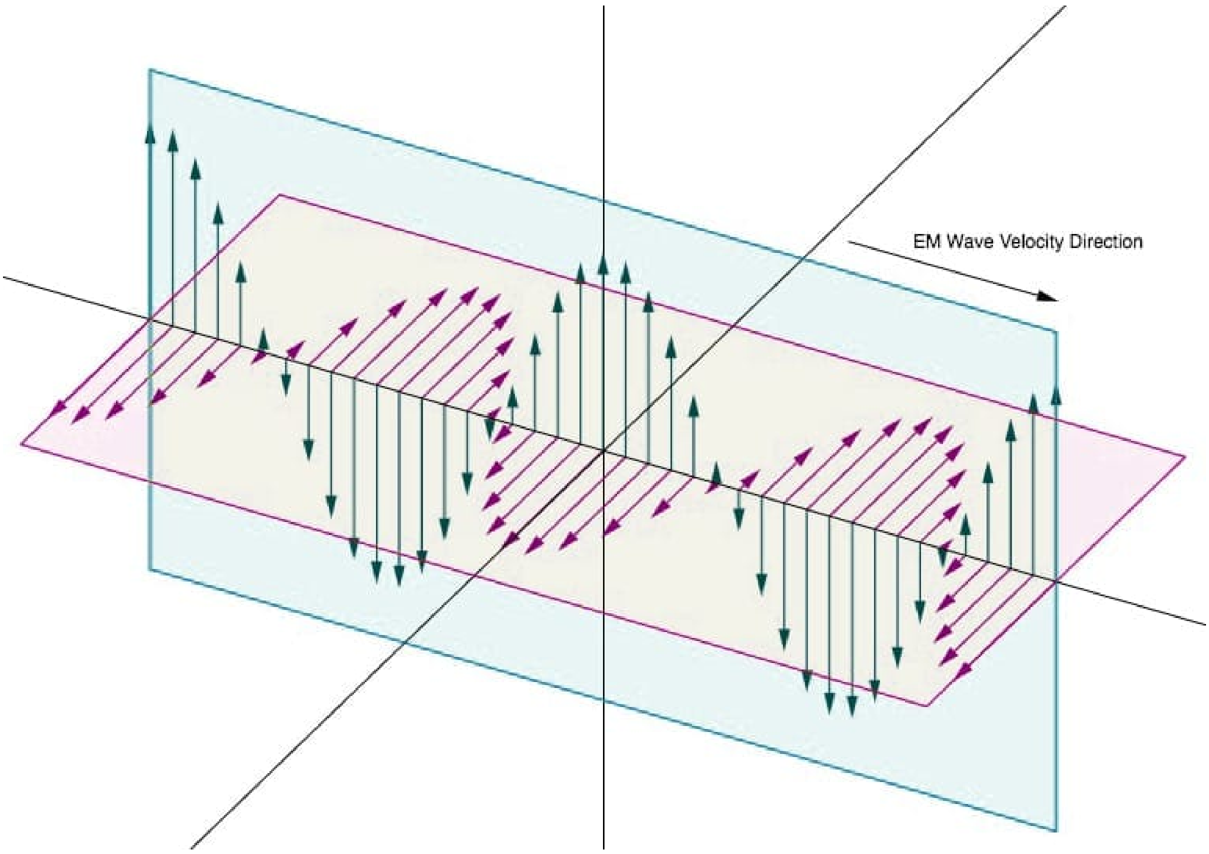

Figure 1.9. Electromagnetic wave visualization, showing the electric field component and its propagation plane in blue, and the magnetic field component and its propagation plane in purple.

Yet another characteristic of electromagnetic waves is the geometry with which they propagate. The shape of a radiating wavefront depends on the geometry of its source (i.e. the transmitting antenna) and can be classified as spherical, cylindrical, or planar (see again figure 1.8). A wave emitted from a perfectly omnidirectional point source propagates outwards in the shape of a sphere, its wavefront expanding concentrically with the point source in the center. A wave emitted from a line source propagates as a cylinder – circular along two dimensions and flat along the third. A planar source emits waves whose wavefronts propagate along a plane parallel to the source; in this case propagation happens along only one dimension. In real life, antennas are 3-dimensional objects with more complex geometries than a point, line, or plane and thus the waves they emit propagate more intricate 3-dimensional patterns. Waves are considered uniform or non-uniform depending on whether their amplitude and phase remain constant throughout the surface of the wavefront.

Electromagnetic waves exhibit typical wave properties. They propagate similarly to other waves, however, they can travel much further than mechanical waves, such as sound, because they do not require a medium but can travel in a vacuum. This allows electromagnetic waves from outer space - such as light from the Sun and other stars, and cosmic electromagnetic radiation from around the universe - to reach us here on Earth. Propagation is unbounded in free space, but the further a wave travels the less energy it will deliver at any given point in its path. This phenomenon is called path loss and occurs primarily because the longer a wave propagates, the larger the surface volume its wavefront has to cover becomes. For example, as mentioned above, a pulse of energy emitted from a perfectly omnidirectional antenna will take the form of a sphere; as the pulse moves away from its source, the outer surface of that sphere constantly grows in size. The reduction in energy strength at any given point on the sphere's surface can be described by the inverse-square law, according to which the intensity or surface power density of the radiating wave is inversely proportional to the square of the distance from a static transmitting source. Thus, to limit energy loss and consequently to transmit a signal further, the radiation pattern of a transmission can be modified so as to cover less volume. This can be achieved by using a directional antenna that focuses energy in a particular direction, or by using an array of antennas that can be combined to 'sculpt' the beam of radiation (a technique called beamforming).

Traveling electromagnetic waves can interact with objects in their environment in a number of ways. Upon encountering an object in space, electromagnetic waves may be *absorbed* or dampened, losing their energy. They may be *reflected* - which means that a secondary wave containing part of the original wave's energy bounces off the object to another direction - or *scattered*, in which case many secondary waves are reflected in multiple directions. Waves may also bend and spread around an object, a phenomenon called *diffraction*, or they may change direction when encountering a sharp edge or corners (*refraction*). Furthermore, the orientation of the field (i.e. the wave's polarization) field may change. Electromagnetic waves can also pass through obstacles with certain characteristics.

Overall, the nature of the wave's interaction with objects in its environment depends on the relationship between the wavelength of the wave and an object's size, shape, relative angle to the wave, and on the dielectric properties of its materials, such as its permittivity, conductivity, and permeability (these terms will be discussed in more detail in section 5.6). It is important to note that the dielectric properties of an object may vary at different frequencies. Most materials are *opaque*, acting as barriers to the propagation of electromagnetic fields by absorbing their energy, at least to a certain extent. When encountering such media, the amplitude of a wave decays as it propagates through the medium. In contrast, vacuum is considered *transparent*, as it is an ideal dielectric material through which all electromagnetic waves can propagate without any conduction and thus without any energy loss. A number of materials are opaque at some frequencies and transparent at others. Water, for instance, is absorbent in most wavelengths of the electromagnetic spectrum except for the narrow band of visible light - a physical effect that is largely responsible for the evolution of life on Earth as we know it.

In a real-life scenario on our planet, a combination of all the above phenomena incurs on an electromagnetic wave that propagates through space. The effects of the environment are particularly noticeable in indoor propagation, as the complex interactions of waves with architecture and other obstacles result in multiple copies of a transmitted signal reaching a receiver antenna, each copy arriving with a slightly different delay as well as phase and amplitude variations. This phenomenon is called *multipath propagation* and is analogous to the effects of reverberation on acoustic signals. Multipath propagation has an effect on transmitted signals because, like acoustic waves, electromagnetic waves are additive. Consequently, when the multiple delayed copies of a signal are added together, they cause constructive or destructive interference, amplifying or attenuating the original signal respectively, depending on their phase relationships. Such attenuating effects are called *signal fading*. Furthermore, when a transmitted wave encounters a moving object its frequency will be shifted – a phenomenon called *Doppler shift*. The amount of change depends primarily on the signal's frequency, the object's speed, and its movement angle in relation to the wave's propagation.

1.3 THE HERTZIAN AS AN ARTISTIC MEDIUM

1.3.1 *Defining the hertzian medium*

What does creating art with an electromagnetic radiation technology, like WiFi or broadcast radio, entail? What exactly is the medium, and what are the elements involved? Answering these questions will significantly contribute to a better understanding of how hertzian technologies can be used to create art and, conversely, to a better understanding of artistic practices that make use of these technologies.

The materiality of the medium and the way in which it interacts with other physical media (structures, objects, bodies, molecules, atoms) is of fundamental importance, but only defines the medium’s essence in part. Like sound and light, the hertzian medium is agnostic and has no inherent content by itself. Radio and microwaves are fluctuations of energy over time that only become signals – i.e. carriers of some kind of information – through their interaction with human agency. It is only through the intervention of this agency that a wave acquires a *meaning* that can be encoded into it, or decoded from it. Therefore, beyond the materiality of the medium, another crucial element that defines it is the way in which human agency interacts with the medium’s material agency. This extends far beyond the technicalities of a specific technological implementation. It includes the knowledge we have developed about the physical nature of the hertzian medium, the types of applications we have imagined for it (such as tele-communication, radar, radio astronomy, radiology, etc), and the specific technologies and instruments we have devised to implement these applications. It also includes the ways in which these technologies are actually used in the real world, the impact they have on their users and society, and the ways in which their use is regulated.

Taking the above into account, the hertzian medium is thus best described as a hybrid that combines the raw material and its agency – that is, waves/radiation and their interaction with the physical world – together with our own human agency and the mental and physical tools we have devised to interact with and utilize this material. Given that both our human agency and our tools continuously evolve, the medium itself should thus be thought of as being in a process of constant evolution, not as much a static entity but more like a living organism or, perhaps more aptly, more like a language.

Furthermore, the hertzian medium should be thought of as consisting of multiple layers or strata, owing to the fact that the interaction between human and material agency occurs in multiple distinct layers. In broad strokes, the principal layers of the medium are the following:

a) The medium's *physics*. This can be thought of as the answer to the question, *'what is it?'*. At the most fundamental stratum, we find that which exists regardless of our presence: the raw physical material/energy.[29] In its purest, most fundamental form, the hertzian medium is natural or man-made electromagnetic radiation in the radio and microwave range, i.e. electromagnetic waves (or radiating particles) with frequencies between around 3Hz-300Ghz and wavelengths between around 100,000km-1mm. The nature of the medium's materiality is immutable as it is entangled with the physical laws that govern our universe, which remain unchanged over the lifespan of the human species.
b) Our *science* on the medium, i.e. *'how do we understand it?'*. The next layer branching out of this root stratum consists of humanity's scientific knowledge about the medium and its nature. While the previous layer is timeless and fixed, this layer and the ones following it are in a process of continuous evolution that involves both the refinement of existing theories and radical paradigm shifts. The role of this layer is crucial, because it is the foundation that defines how we interact with the material. As will be made evident in chapter 2, the more our knowledge of the medium's nature advances through science, the more we can imagine new uses for it, and thus the more things we manage to do with it. The theoretical and experimental work of scientists like Faraday, Maxwell and Hertz, falls squarely within this layer.
c) Our *imagination* on how to use the medium, i.e. 'what can we do with it?'. Humans are curious creatures. Thus, any new knowledge acquired on the medium's physical nature inevitably feeds our imagination, leading us to think of new things to learn and new practical applications to use it for. This is the layer of conceptualization, theoretical innovation, and blue-sky ideas on how the medium could potentially be used; it connects scientific knowledge to the engineering of technological solutions. The physics of radio and microwaves support a large variety of applications, such as to communicate from afar, to control machines, to assist navigation, to sense space, to listen and peer into the cosmos or within our bodies, and many more. All these inherent capabilities of the medium had to first be imagined by someone before becoming implemented as a technology. The period following Hertz's discovery of

[29] As mentioned earlier, electromagnetism can be described as both energy and matter.

electromagnetism is characteristic of activity in this layer. Between 1890-1894 several visionary engineers – such as Richard Threlfall, Alexander Pelham Trotter, Captain Henry B. Jackson, Sir William Crookes, Nikola Tesla - proposed potential uses for the new wireless medium that would eventually make their way from theory into practice, such as using it for navigation, tele-communication, and tele-control (see 2.2.2).

d) The *engineering* of specific instruments, tools, systems and technologies through which the material can be manipulated to achieve certain tasks, i.e. *'here is a thing to perform that task with'*. Once an idea for a potential use has found its way into the world, someone will inevitably attempt to implement it as a technology. Often these ideas are taken up by many people at once as is evidenced, for instance, by the near-simultaneous invention of wireless telegraphy by several innovators between 1894-1895 (Roberto Landell De Moura, Oliver Lodge, Jagadish Chandra Bose, Alexander Popov and Guglielmo Marconi, see sections 2.2 and 2.3) and by the parallel re-invention of radar in several countries during the early to mid 1930s (see 2.5.4). Whereas the previous layer is about theoretical possibilities and general principles of operation, this one is about specific technologies and their many iterations (e.g. FM radio, GPS, WiFi, MRI scanners, etc.), about the way they deploy hertzian waves to achieve the task they were designed for, their hardware and software (where applicable) with all their intricacies of implementation, their technical protocols of operation, and everything specific to the technology from a technical standpoint.

e) Our *everyday use* of these tools, i.e. *'here is how we actually use this thing'*. While the layer above is concerned with the design and implementation of specific technologies, this layer regards their actual use in the real world. This distinction is important, as once technologies become disseminated through society it is quite common that users deploy them in ways that diverge or expand upon what was originally planned by their designers. The gaps between intended design and actual use may even lead to the invention of new tools and technologies. As mentioned in a previous section, there are innumerable examples in which imperfections in a technology or unaccounted features had such results. For instance, radio broadcasting emerged after users noticed a physical flaw in wireless point-to-point communication and took advantage of it (the flaw being that transmitted messages can be intercepted by anyone with a receiver within the transmitter's range, see 2.3.5).

f) The *impact* of this use, i.e. *'this is how using this thing changes us'*. The dissemination of a technology through society and the ways in which it is being used inevitably has an effect on its users and on society at large. McLuhan's writings made evident how significant the impact of media like radio and television is. Therefore, this should be considered as another important layer that defines the hertzian medium.
g) The *regulation* of the medium and its technologies, including laws, standards and protocols developed around it, i.e. *'this is how this thing should be used'*. Once the use of a technology has reached a critical mass that makes its impact noticeable, commercial and state actors typically rise to impose restrictions, regulations, and frameworks on its use. The very notion of the electromagnetic spectrum is not only a conceptual tool, but also a regulatory device conceived to formulate and govern how this resource is shared between different users and uses, dictating who has rights to exploit each part of the spectrum and for which purpose (section 2.3.3 will discuss how this type of regulation was first established). This layer is primarily political and could be thought of as the equivalent of city planning for the hertzian medium and hertzian space. Through the use of regulation, the vast space of the radio and microwave spectrum has been converted into a stratified information highway in which different bands are reserved for specific types of uses (e.g. navigation, communication, radar), specific technologies (e.g. FM or AM radio broadcast, cellphone telephony, etc.), and specific users (e.g. the military, satellite networks, broadcasting corporations that have purchased rights to a specific frequency, etc.). As can be seen in figure 1.7 there are only a handful of unregulated bands left that do not require an official license to operate. It should be stressed that this layer is not only concerned with legal frameworks but also with standards and protocols (see, for example, section 2.3.2 on how the Marconi company introduced the first protocol for wireless telegraphy communication to exclude other operators when it began facing competition). The frameworks, protocols and standards that have been formulated and agreed upon in regard to how radio waves, microwaves and the technologies that deploy them can be used are a significant component of the hertzian medium. Though arbitrary and external to the medium's physicality, they define how human agency is allowed to engage with this medium and its technologies in the context of an organized society.

The strata that constitute the hertzian medium can be conceptualized in the form of a tree structure diagram to map out how the medium evolves over time (figure 1.10). The tree metaphor can portray how new developments in a particular layer may branch out into multiple new developments in subsequent layers. For instance, newly produced scientific knowledge (2nd layer) may lead to new ideas for potential uses (3rd), which in their turn may lead to new technologies (4th) and new ways to use the medium and these technologies (5th), that may incur new types of societal behaviors (6th), which may lead to new regulatory frameworks (7th layer). The relationship between the different layers is not unidirectional; there can be significant crosstalk and feedback between and within them. For example, regulation may contribute to the development of alternative technologies which may encourage different types of use, which in their turn may require further regulation, and so forth. Or, the development of a technology may lead to more extended or focused scientific exploration, which may lead to new technologies that take advantage of new scientific findings on the material's nature. This is essentially what happened with the development of radar contributing to the study of microwave physics, which in its turn contributed to the evolution of radar technology.

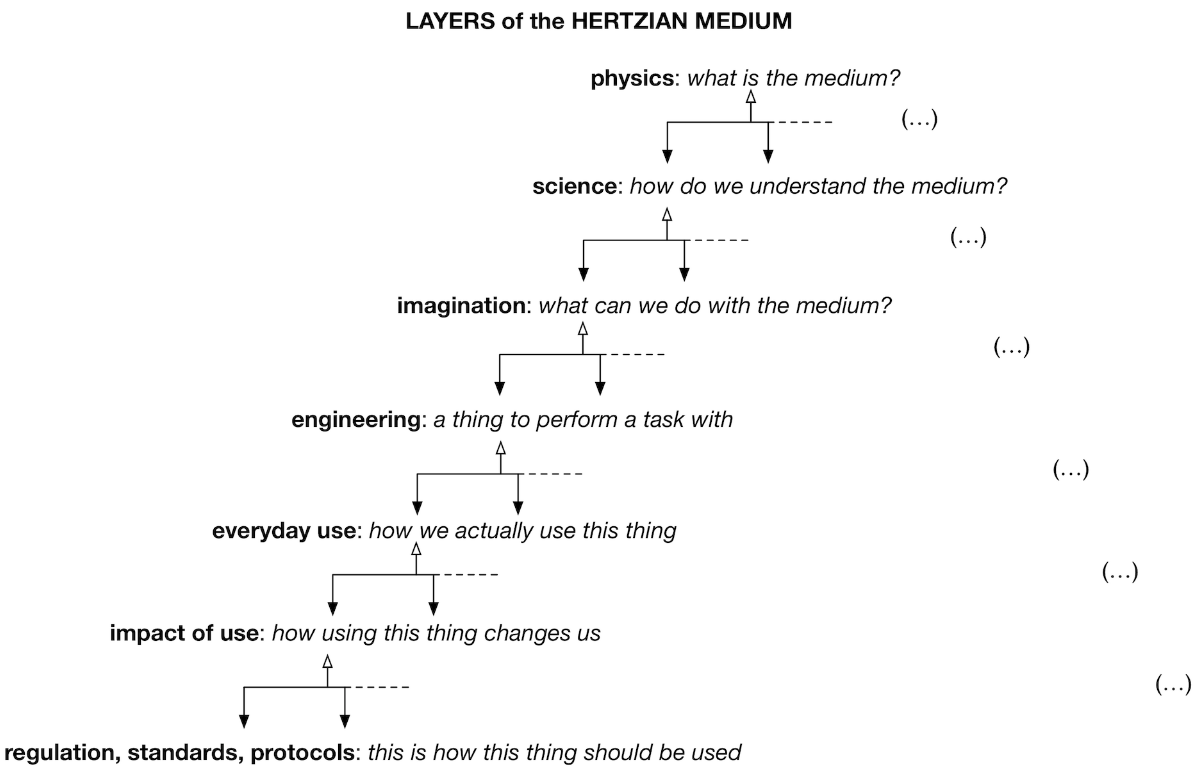

Figure 1.10. A tree structure diagram of the different layers of the hertzian medium.

To summarize, the hertzian is a hybrid medium continuously evolving over time and consisting of seven different layers: (a) physical matter and energy; (b) scientific theories, experiments, and the knowledge they produce on the material; (c) concepts and ideas about the material's potential uses; (d) the implementation of these concepts in tangible technologies; (e) the actual use of these technologies in the real world; (f) the impact of that use and the ways in which it affects society and everyday life; (g) the legal frameworks, standards, and protocols created to regulate the use and impact of those technologies. My strategy in this thesis involves addressing all these layers to better understand the medium in all its aspects.

1.3.2 *Excavating the medium's layers: a media archaeological approach*

The first two layers, i.e. the medium's physics – or better, our current understanding of it – were discussed in section 1.2. However, this is only part of the story; the ways in which humanity arrived at this understanding and the paths through which our knowledge evolved is another important element. As Auguste Comte, the first philosopher of modern science, stated: *"On ne connaît pas complètement une science tant qu'on n'en sait pas l'histoire"* (translating to *"We do not completely know a science as long as we do not know its history"*) (Comte quoted in Sarkar et al., 2006, xiii).

Inspired by Thomas Kuhn's theory on the structure of scientific revolutions (Kuhn, 1962/2012), the evolution of our scientific knowledge on the hertzian medium can be roughly outlined in the following manner (figure 1.11): Phase 1, or 'pre-paradigm', was the period in which humans speculated about the nature of individual electrical and magnetic phenomena without having a unified theory to guide them (see 2.1.1). This period dates from the ancient era up to the 17th century, reaching its scientific apex with William Gilbert's publication *De Magnete* (1600). Newton's establishment of a classical theory of mechanics in 1687 with the publication of his *Philosophiæ Naturalis Principia Mathematica* led to phase 2, or the phase of 'normal science', in which Newtonian principles were used for understanding electromagnetic phenomena. This way of thinking produced texts such as Franz Maria Ulrich Theodor Hoch Aepinus's publication of the first mathematical treatise attempting to explain electricity and magnetism through Newton (1759) (see 2.1.2). Phase 3, or the period of 'crisis', began around 1820 with scientists hitting a wall, finding more and more anomalous phenomena that could not be explained with strict Newtonian mechanics. While Hans-Christian Ørsted and André-Marie Ampère contributed to the creation of a more solid foundation for electromagnetic science, the need for a new and unified theory of electromagnetism was becoming evident (see 2.1.3 and 2.1.6). A few years in this phase, the seeds for the next phase were planted by the conceptualization and visualization of electrical fields by Michael Faraday and by Lord Kelvin's subsequent mathematical explanations. Jumping off their work, James Clark Maxwell initiated phase 4, the 'paradigm shift', in the 1860s by proposing a mathematical theory that forms the basis of classical electromagnetic science up to today (see 2.1.4). Maxwell's theory was purely mathematical and remained relatively in the fringes until Heinrich Hertz's experiments in the late 1880s verified its accuracy (see 2.1.5, 2.1.7). This firmly established a radical paradigm shift in both our science on the subject and our view of the world as a whole – or, to borrow Kuhn's term, it brought forth a *"scientific revolution"* (Kuhn, 1962/2012). The post-revolution period, following Hertz's experiments and extending to the present, is a new phase in which the new paradigm is being constantly refined and has taken the place of 'normal science'.

Continuing with the 'tree' metaphor of the hertzian medium's layers expressed above, Maxwell's theory and Hertz's experiments created a new branch in layer (b) that enabled many subbranches to rapidly spring up in layers (c) through (g). Within just the first two decades after Hertz's discovery of electromagnetic waves, numerous innovative uses for them had been proposed or were in various stages of implementation: from telecommunication (wireless telegraph) and radio broadcasting (see 2.2 and 2.3) to remote control and wireless power transmission, radiology and electro-medicine, radio navigation (2.4.1), radar (2.5) and radio-frequency sensing (2.1.8), weather prediction (2.2.7) and atmospheric sciences, radio astronomy and search for extraterrestrial intelligence, and more. Looking more closely, one will also notice the emergence of some - nowadays familiar - practices in the fringes that are not media in and of themselves but ways of *operating on* wireless media, such as radio jamming (2.3.3), wiretapping and hacking (2.3.4), but also (multi)media performance (2.2.4). To all this, we should also add a number of imagined but unrealized – or unrealizable – technologies typically associated with the occult: telepathy, mind control, conversing with the dead, even the development of 'superpowers'. Thus, it is especially informative to investigate this fertile period, as it gives many insights into:

- how our human agency towards the medium developed, and when and how innovative concepts, ideas and potential uses were imagined, formulated, disseminated and developed or abandoned - i.e. tracing the evolution of our imagination in regard to the hertzian (layer c);

- the ways in which this imagination materialized in tangible technologies and the context and conditions that influenced this process (i.e. how layer d branched out of layer c);
- the affect that the newly discovered medium and emergent technologies had on society (layer e);
- the regulations, standards and protocols that were implemented as a result (layer g).

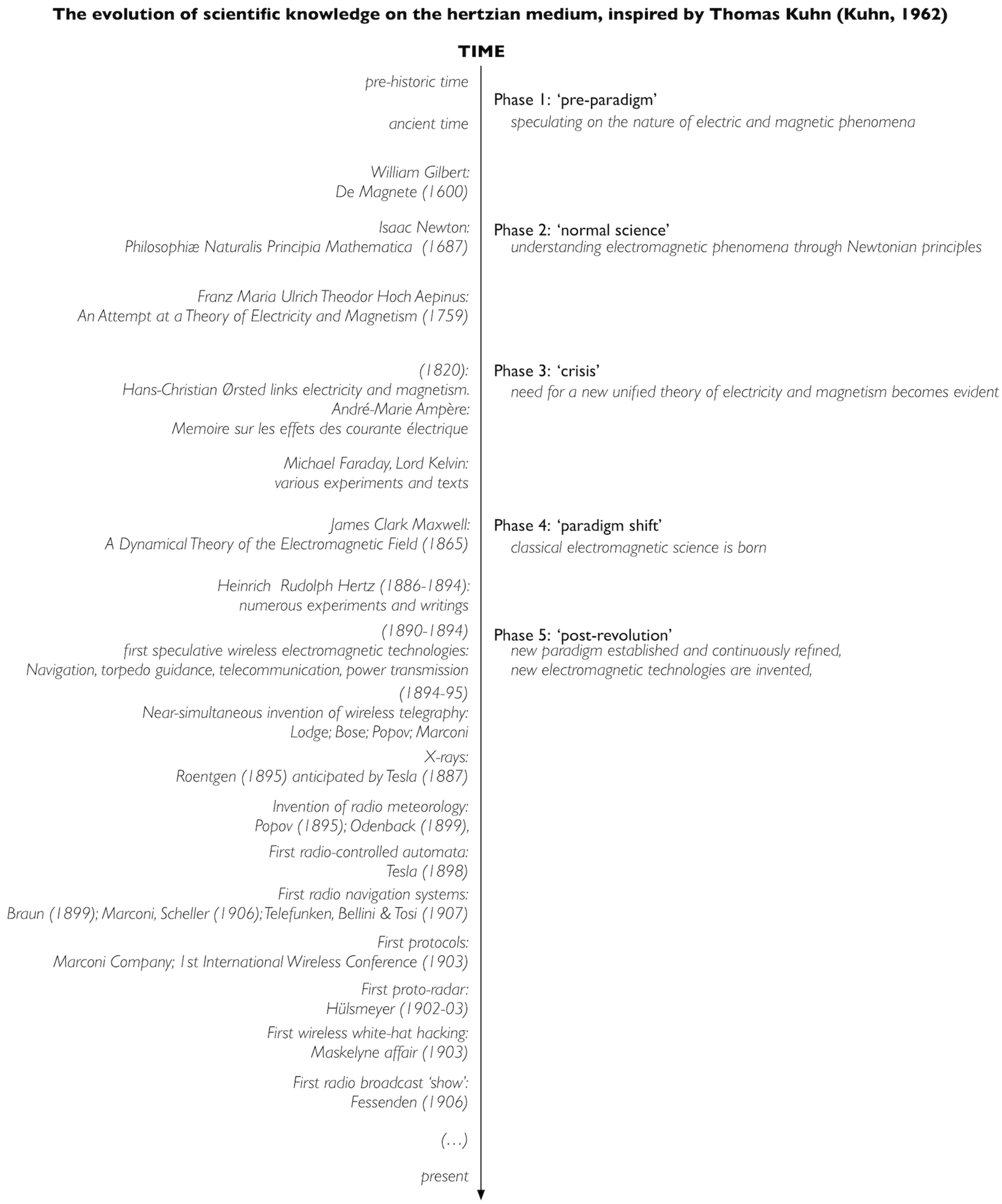

Figure 1.11. The evolution of scientific knowledge on the hertzian medium with Maxwell and Hertz at the center of a paradigm shift (inspired by Kuhn 1962/2012). Milestones are displayed on the left of the time axis with the corresponding phase on the right.

In this regard, my approach and methodology is related to and informed by media archaeology, an interdisciplinary field of research that began emerging in the 1980s-1990s. Media archaeology is "*interested in excavating the past in order to understand the present and the future*" of media and the culture around them (Parikka, 2012, 2). Parikka, a preeminent media archaeologist, summarizes the core question of the field as follows: "*what are the conditions of existence of this thing, of that statement, of these discourses and the multiple media(ted) practices with which we live?*", noting that "*such questions are political, aesthetic, economic, technological, scientific and more - and we should refuse attempts to leave out any of the aspects.*" (Parikka, 2012, 18). I believe that this outlook is particularly relevant for investigating the various layers of the hertzian medium as described above, the role and impact of hertzian science and technologies in contemporary society, and how this all influences the medium's potential for art. I thus have adopted a number of strategies from this field, which I will briefly discuss below.

The field of media archaeology is situated between history, theory and practice and has developed through contributions from both academia – especially fields related to media studies - and the arts, particularly practices related to so-called 'new media art' and sound art.[30] The discourse on 'new media' from the 1980s and onwards significantly contributed to the establishment of the media archaeological method as a way to examine, challenge, and dismantle conventional notions on the supposed radical originality of our contemporary 'new media', on the myth of frictionless technologies, and on the notion that the world's problems will be solved simply by engineering innovative technologies. As such, media archaeology has contributed significantly to a more critical, in-depth, and well-informed perspective on technology, media and their novelty. This counteracts the more widespread uncritical and celebratory views on this subject - in large part driven by the forces of marketing, and widely popular in the world of new media art and even more so in engineering and technology-

[30] Parikka (2012) traces the roots and inspirations of the field in a combination of sources dating since the first half of the 20th century: a) Walter Benjamin's multi-layered investigation of modernity through its ruins, and his research into the influence of urban environments and emerging media technologies (telephone, photography and cinema) into contemporary life and into the development of new modes of sensation and ways of being - thinking, feeling, seeing, hearing; b) Michel Foucault's archaeological inquiries into knowledge and power through a methodology that involved peering into the roots of things and ideas to find how and why they emerged and proliferated. McLuhan and Kittler – two media theorists whose work has significantly contributed to the field of media archaeology and who were an influence for this thesis - extended Foucault's approach from the written word (documents, books, and archives) to the world of technical media; c) the conceptually, historically, and contextually rich ways of studying cinema developed by film theory and New Film History since the 1970s and particularly the 1980s, which were consequently adopted by media archaeologists to study other media; d) numerous studies of digital and software cultures through their past, particularly since the 1990s.

related fields - which could be described as a form of *"technological determinism"*, according to which technology drives practice instead of being driven by it (Kelly, 2009, 38).

Witnessing a radical shift in the media cultural landscape in the 1960s, McLuhan searched for perspectives that would enable looking at established familiar media and their use and context with fresh eyes. Investigating the past was one potential strategy for inspiring such perspectival shifts. As McLuhan wrote, *"[t]oday when we want to get our bearings in our own culture, and have need to stand aside from the bias and pressure exerted by any technical form of human expression, we have only to visit a society where that particular form has not been felt, or a historical period in which it was unknown"* (McLuhan, 1964/2017, 32). This strategy was adopted, expanded, and refined in later years by media archaeologists who often centered their attention to the science, technologies, and socio-economic developments of the 19th century to examine the roots of modernity.

Nevertheless, the media archaeological method does not dig into the past aiming to create histories of linear progress; instead it does so to develop insights on the present and think about our current situation, with the primary goal being to decipher, re-imagine, and shape the present and future rather than to wallow in the past. As Parikka states, the media archaeological method "*is always, implicitly or explicitly, about the present: what is our present moment in its objects, discourses and practices, and how did it come to be perceived as reality?"* (Parikka, 2012,10). I find this particularly relevant and inspiring both as a practicing artist and as a researcher attempting to decipher the nature of the hertzian medium.

Acknowledging that the history of media is not a straight line of constant progress but a complex and dynamic maze (a network full of connections between nodes that are entangled with each other), media archaeology seeks inspiration in the construction of genealogies - another idea borrowed from Foucault, as Parikka reminds us. It aims to understand why and how particular media concepts, beliefs, designs, solutions and practices persevere while others become extinct, as well as to discover alternative pasts, presents and futures: what *could* have been but is not. This involves considering media from a broader perspective, deploying out-of-the-box thinking, questioning, and reconsidering "*what even counts as media"* (Parikka, 2012, 79). To achieve this, media archaeology often looks outside of the mainstream and the status quo, paying attention to the margins, to weird applications and dead ends, to what has been abandoned, neglected, forgotten, or merely conceived in theory but never implemented in practice. This includes researching *"imaginary media",* which Siegfried Zielinski – another stalwart of media archaeology and critical influence on this thesis - divides into three basic categories: "*Untimely media / apparatuses / machines",* conceived and planned centuries before or after they were implemented as functioning technologies; *"conceptual media / apparatus / machines"* that were only imagined and sketched out but never actually realized; and *"impossible media / apparatus / machines"* whose design acknowledges that they cannot be actualized but which, regardless of their purely fictional existence, exert influence on *"the factual world of media"* merely by being conceived (Zielinski, 2006b, 30). Huhtamo calls the latter *"discursive inventions",* because their purpose is not practical application but initiating a discourse (Huhtamo 1997).

For Zielinski and other media archaeologists, the relationship between existing and imaginary media is fluid, revealing a close connection between imagination, invention, and innovation. Therefore, media archaeological excavation does not only occur in the fields of science and engineering, but also in literature (especially science fiction), art, philosophy, and every field that may nurture imaginary media - even magic. Beyond probing diverse and at times unexpected fields, this practice also involves digging into what Zielinski calls the *"deep time of the media"* (a concept he borrows from geology and paleontology) to unearth ways of sensing the world with technical means that go further back in the past than one would normally expect when examining particular media technologies (Zielinski, 2006a). For instance, he detects traces of electromagnetic telematic communication and the concept of a proto-telegraph back in the 16th century in Giovani Battista della Porta's *Magia naturalis* (1558). Having observed that two compass needles exerted influence on each other even from afar, della Porta described a speculative system of instant and stealthy wireless messaging based on this magnetic effect that would allow communicating with *"a friend who is far away or even in prison"* (Ibid, 75-76). Zielinski calls this practice of unearthing and collecting curiosities *an-archaeology*, and uses it to inspire what he calls a *variantology* of media: a mapping of media and our imagination not through hegemonic masterplans but through oddities, variations, fractures, accidents, turning points and the sketching out of new counter-histories and minor genealogies.[31]

Erkki Huhtamo follows a related approach, being particularly interested in examining the notion of *topoi* (plural of the Greek word 'topos', meaning place), which he describes as "*cyclical phenomena which (re)appear and disappear and reappear over and over again in*

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[31] Although Zielinski's methodology is certainly inspiring, Parikka finds some contradictions and blind spots in it, namely that at times it resembles a somewhat 'romantic' *"celebration of heroes"* which are mostly male and European, despite Zielinski's self-proclaimed effort to focus on what happened in the peripheries. (Parikka, 2012, 52)

media history and somehow seem to transcend specific historical contexts" (Huhtamo, 1997, 222). While the re-emergence of such *topoi* far apart in space or time may seem random or unconnected, Huhtamo posits that they reflect *motifs* that are integral to cultural traditions, similarly to how certain topics or formulas reappear in literary traditions. Hence, such motifs repeatedly resurface through history in conscious or subconscious manners.[32] The recurring connection of wireless technologies with the paranormal and the world of ghosts and spirits could be seen as one of the most notable *topoi* of the hertzian medium. Huhtamo is particularly interested in locating these *topoi* in "*false starts, seemingly ephemeral phenomena and anecdotes about media"* rather than in the histories of widely disseminated technologies and the biographies of their makers, believing that in the margins one can better discover how technological use and related social practices create habits, processes, beliefs and meanings (Ibid, 222).

1.4 THESIS OVERVIEW

1.4.1 *Gaining insights through an archaeology of the hertzian medium (Chapter 2)*

Chapter Two provides a media archaeological perspective of the electromagnetic medium and how related concepts, scientific knowledge, and technologies developed, with a particular focus on the first few decades after Hertz's experiments.

It begins (2.1) with a brief historical overview of humanity's relationship to electricity and magnetism before Hertz's discovery and the ensuing paradigm shift, i.e. the 'pre-paradigm' period when these energies were linked to magic stones and forces of the occult. It continues with the period of 'normal science' that included Gilbert's *De Magnete*, the Newtonian model of action-at-a-distance, and Galvani's near-invention of radio. It proceeds with the 'crisis' period of the 19th century, when further connections between electricity and magnetism were continuously discovered (by Ørsted, Ampère and Faraday among others), leading to J. C. Maxwell laying the foundation for the paradigm shift with his theory on electromagnetism. This is followed by an introduction to the scientific models within which Hertz operated, and the numerous near-discoveries of electromagnetism by a number of scientists and inventors predating his work (Joseph Henry, Thomas Edison, Elihu Thomson, Silvanus Thompson, David Hughes and Amos Dolbear). The section ends with a discussion

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32 Huhtamo notes that "in *the era of commercial and industrial media culture it is increasingly important to note that* topoi *can be consciously activated, and ideologically and commercially exploited."* (Huhtamo, 1997, 222).

of the experiments through which Hertz managed to break through, giving particular attention to his investigation of the human body's dielectric properties, with which he essentially laid the foundation of radar and radio-frequency sensing.

The subsequent section (2.2) is concerned with the years following Hertz's discovery: how the newfound scientific knowledge led to the imagination and then realization of new technologies, why some of these technologies failed to develop at that early stage, and why the wireless telegraph was the first to eventually emerge. This section includes an introduction to the work of a handful of scientists that played a crucial role in the development of electromagnetic science and technologies in the 1890s: Nikola Tesla - and his spectacular electromagnetic lecture-performances, often involving his own body - Oliver Lodge, Jagadis Chandra Bose, and Alexander Popov.

The chapter then turns to the first hertzian technology to emerge: wireless telegraphy Section 2.3 introduces Guglielmo Marconi, how he transformed the new electromagnetic science into a thriving business, and how that business quickly became the Earth's first wireless infosphere. This leads to a discussion on how the success of Marconi's telegraph made evident the necessity of regulation, and how it also produced the first incidents of wiretapping and hacking. The section ends by addressing how a hidden 'bug' of wireless telegraphy – the broadcasting of its signals allowing anyone within range to capture them – was eventually re-imagined as a feature thus producing a new medium: broadcast radio.

Section 2.4 first discusses how radio became a spatial medium with the invention of navigation systems like early Direction-Finding (D/F) technology, the predecessor of radio navigation aids like GPS. It then describes how observing the increasingly more pervasive flows of wireless telecommunication and navigation technologies led to the realization that the noise found in their signals can itself be a source of rich information if properly analyzed - much like the interference of WiFi signals that I analyze in the WIR system. This is exemplified by the emergence of a new form of electronic warfare preoccupied with capturing and analyzing radio signals, and new scientific fields, like atmospheric sciences and meteorology on one hand and radio astronomy on the other.

The penultimate section of the chapter (2.5) establishes the hertzian as a medium for sensing objects in space. It first introduces the basic principles of RADAR technology before conducting a brief survey of the several incomplete, failed, or speculative attempts to create such a technology by scientists or engineers like Hertz (in 1887), Tesla (in 1900 and 1917), Christian Hülsmeyer (1902-05), and Marconi (1922), and imaginative sci-fi writers like Paul d'Ivoi (1900), Jules Verne (1908), Hugo Gernsback (1911), Hans Dominik and Richard Scherl (1916). The section closes with an account of the numerous near-simultaneous inventions of RADAR in the 1920s-30s.

Finally, the chapter closes (2.6) with a historical review of the development of WiFi technology and provides the tools to better understand the technological foundations behind the *Hertzian Field* series. This section touches on: the provenance of WiFi, originating from a 1970s wireless network (ALOHAnet) that was quickly adopted by DARPA and a couple decades later by the commercial world; why the 2.4GHz frequency band was chosen; the problems of transmitting in physical space and how that inevitably makes wireless technologies stochastic; the strategies borrowed from other fields, such as radio astronomy, to solve these problems; some techniques, algorithms, and protocols devised to improve the technology. The section concludes with a conceptual model of networking.

1.4.2 *Artistic context: sensing through the hertzian medium in the sonic arts (Chapter 3)*

Chapter Three discusses the use of technologies inspired by radar and direction-finding in the sonic arts (music and sound art) and beyond.

Section 3.1 chronicles Lev Termen, a.k.a. Leon Theremin, and his 1920 invention of the first radio-sonic instrument for gestural performance, the *Etherophone,* a.k.a. *Thereminvox* or simply *Theremin.* Beyond being both radical and exceptionally influential, the technology for this instrument was first developed by Termen as a surveillance tool (fittingly, my inspiration for the WIR system also originated in surveillance research). The chapter proceeds with addressing how the instrument was initially received and how it was used by Termen/Theremin and his contemporaries; it also describes the many variants the inventor created, focusing on the most pertinent of all for this thesis: the Terpsitone, a capacitative platform capturing full body motion, through which Theremin aimed to bridge the gap between dance and music. The entanglement of wireless music and wireless espionage is further documented through the double life of Theremin (famous US-based wireless technology inventor, entrepreneur and musician) and Lev Termen (soviet spy and then gulag inmate who created numerous wireless technologies for the soviet military and secret services, before finally being allowed to return to conducting innovative research on music expression). The legacy of the Theremin and its influence on the work of a select few avant-garde composers – Joseph Schillinger, Percy Grainger, Edgard Varèse, and Henry Cowell – concludes this section.

Section 3.2 presents a handful of trailblazing musical instruments based on the principles of Direction-Finding (DF) technology, i.e. tracking a device in space through its electromagnetic emissions. This includes:

- *Pupitre d'Espace*, an instrument developed in 1951 on behalf of composer Pierre Schaeffer, which directly borrowed D/F techniques for the live spatialization of electroacoustic music;
- the *Radio Drum,* developed by Max Mathews in the mid 1980s, and its successor the *Radio Baton* from a few years later – both controller devices using capacitative sensing and initially developed with the goal of performing the computer like a conductor conducts an orchestra;
- finally, interfaces based on RFID near-field sensing, such as *Marimba Lumina*, a marimba-style control interface developed by Donald Buchla in 2000, and a couple other systems developed at MIT around that time.

Section 3.3 examines the use of innovative D/F-style systems in sound art. It begins with Max Neuhaus' pioneering installation *Drive In Music No. 1* from 1967, most likely the first work to use a system similar to the one I used in my own work *'Act so that there is no use in a centre'*: an array of low-power radio transmitters all broadcasting on the same frequency. A more recent work using radio transmission as an interactive mechanism is then discussed: Edwin van der Heide's *Radioscape* from 2004, in which an array of unmodulated transmitters spread throughout a neighborhood create an immersive soundscape navigable with custom handheld receivers. The section closes with Christina Kubisch's trailblazing work using electromagnetic fields and induction. It first discusses her *Electrical Drawings* – a large series of installations using coil loops and special boxes or headphones to transmit sound, which she began in 1980; then, it continues with her *Electrical Walks,* another expansive series of nomadic works she has been developing since 2004, which use similar technology to capture electromagnetic signals already existing in the urban environment.

The following section (3.4) returns to the Thereminvox to examine how the instrument and its technology have been re-imagined, with a particular focus in its use as a full-body sensing system. It starts in 1965 with *Variations V*, a pioneering interactive multimedia performance led by John Cage and Merce Cunningham in which an array of theremin antennas captured the movement of dancers converting them to control data. An introduction to the work of Philippa Cullen follows – an innovative dancer who turned to the Theremin around 1970 as a way to transform movement directly into sound. Subsequently, the extensive oeuvre of Liz Phillips with self-made capacitative sensing systems and sound is discussed, introducing her many such works created between 1970-2012. This is followed by an overview of Human-Computer Interaction research conducted at MIT Lab in the 1990s on theremin-related sensing techniques, the resulting proposal for a broader typology of likeminded techniques (under the term *Electric Field Sensing*), and the interactive systems developed with this technique at the Lab. The section closes with a brief presentation of two interactive multimedia works by Sonia Cillari featuring a system inspired by this MIT Lab research.

Section 3.5 focuses on the ideas and artistic practice of sonic artists Tetsuo Kogawa and Anna Friz - most pertinent in relation to my work *'Act so that there is no use in a centre'*. Their emphasis on the materiality of broadcast (FM) radio enables them to redefine it as a spatial medium that can be used for the embodied and expressive manipulation of sound. Some related works by the two makers are briefly presented: from Kogawa's pioneering of the *Mini-FM* movement in the 1980s, to his subsequent performances with self-made low-powered FM instruments, to Friz's radio array installations and performances. The section ends with Friz's observations and advice on working with low-power FM radio.

Continuing the voyage through different radio/microwave sensing technologies, the last two sections of the chapter (3.6 and 3.7) examine the sparse artistic uses of a more niche technology: microwave doppler radar. Because of the rarity of this technology, this section expands beyond the sonic arts. It starts with Edward Ihnatowicz and his *Senster*, a momentous cybernetic kinetic work from 1970 through which this technology was introduced to the arts. As doppler radar technology became more readily available in the early 1990s, a handful of artists incorporated it into their work. These doppler systems are introduced here, with brief accounts of Steve Mann's *DopplerDen* (1991) *DopplerDanse* (1992), MIT Lab's *Magic Carpet* (1997), and Arthur Elsenaar's *Body Convention* (1993).

The last section of the chapter (3.7) examines in detail Godfried-Willem Raes's substantial – and technically impressive – work with doppler radar. This includes an overview of the many doppler radar systems he has been developing since 1993, before zooming into some technical details of his implementation and particularly the ways in which he analyzes doppler signals to derive motion data and to recognize a set of predefined gestures. This is followed by the strategies he has developed for learning how to perform with these systems, before turning to his expansive artistic output with microwave doppler radar. The chapter concludes with a critical discussion on Raes' approach, particularly in regard to his performance series *Namuda* (a portmanteau meaning *Naked Music Dance*).

1.4.3 *The first phase of my hertzian explorations (Chapter 4)*

Chapter Four turns to my own work, presenting the initial phase of my research trajectory on the hertzian medium through three related projects I completed between 2010-14.

It begins (4.1) with a brief account of *Observe, Recount, Distort!* (2010), an experiment which granted me the first glimpses into the medium's fascinating materiality.

A more substantial section on *The Network Is A Blind Space* (2011-12) follows (4.2), discussing the work's concept and the fundamentals of its technology, its functional components and their spatial configuration, and giving an account of the modes of interaction and resulting visitor experience. The section continues with a more in-depth presentation of the technology I developed for that work – what I call a 'network echolocation toolbox' – and a discussion of the compositional strategies, sound synthesis techniques, and general mapping strategies used. It closes with some observations and conclusions arising from the work's exhibition.

The final section of this chapter (4.3) describes in depth my work *'Act so that there is no use in a centre'* (2014), a spatial interactive radio-play based on Gertrude Stein's 'Rooms' (from her 1914 book 'Tender Buttons') and using an array of low-power FM radio transmitters and portable receivers. As discussed in this section, this work brought me considerably closer to the physicality of the hertzian medium, thus laying the foundation for my later explorations of the *Hertzian Field* series. Subjects discussed include the context in which I created the piece, the work's concept, and my process in creating it, and more specifically my treatment of the text as a system through which I could derive artistic decisions while making the piece. A discussion on the composition, sound material and playback system follows, before turning to visual aspects of the work and my thought process behind them. Finally, the section concludes with observations and remarks relating to visitor experience.

The chapter closes with a brief autoethnographic section of failure becoming inspiration (4.4), briefly documenting my thwarted plans for a subsequent work which I was – very fortunately! – unable to realize. This required me to shift to a different approach, extending the field of my research and finally discovering a very fertile path that led me to create the *Hertzian Field* series.

1.4.4 *Technological context and state-of-the-art (Chapter 5)*

Chapter Five dives into the technological context of the *Wireless Information Retrieval* sensing technique I developed, discussing the state-of-the-art in the field of Ubiquitous Sensing, as well as the physics behind how radio-frequency sensing techniques work.

The chapter begins (5.1) with a discussion of the context in which Ubiquitous Sensing technologies are being developed. It introduces the *Quantified Self* movement and touches on the shift from simpler localization technologies to the more complex goals of activity recognition and sentiment sensing, and from using specialized sensors to taking advantage of already existing infrastructure - like the radio and microwave signals of telecommunications - for the purpose of sensing.

Section 5.2 introduces two main modalities of radio-frequency sensing: device-bound and device-free sensing. The former is used primarily to localize wireless devices connected to a network. Differences between outdoor (e.g. GPS) and indoor models (e.g. WiFi-based) are presented, together with a discussion on how indoor localization became a business, thus leading to further technological developments.

The following section (5.3) presents the diverse techniques used in indoor-localization, from ranging techniques based on measurements of time, angle, or signal strength, to range-free techniques such as proximity-based systems and fingerprinting.

Device-free sensing, a modality in which the *WIR* system belongs and which is used to track the location and activities of uninstrumented bodies is discussed in section 5.4. This includes how device-free sensing emerged and the different techniques used to localize bodies (Device-Free Localization, or DFL) and to recognize activities (Device-Free Activity Recognition, or DFAR). A number of more advanced technical approaches and recent trends are briefly presented, as well as examples of real-world applications of DFAR. This is followed by a consideration, evaluation, and critique of these technologies from my personal artistic viewpoint, with a discussion of how my own goals and experiences in developing WIR relate or diverge from technologies developed within the context of Ubiquitous Sensing.

The chapter then turns to an investigation of how and why such systems work. Section 5.5 reviews the propagation and reflection of radio waves and microwaves. It describes how fields radiate from an antenna and introduces the concept of Fresnel zones, which I found particularly relevant and revealing in understanding how systems like WIR relate to space.

The chapter then closes (5.6) with an examination of the body as a dielectric space, providing insights on the relationship between hertzian fields and the human body so as to gain a deeper understanding of the operational principles behind hertzian sensing systems like WIR. This includes: a discussion on how researchers study and model the interaction between body and electromagnetic fields; how these fields and their waves propagate inside the body; how the body can be understood as a propagation medium; what the electromagnetic properties of different types of tissue are and how this complex composition of the body affects propagating signals. To conclude, the chapter opens a discussion on the effects of electromagnetic fields on the body and finishes by reviewing the recent development of a new and obscure kind of weaponry using microwaves.

1.4.5 *The technology developed for Hertzian Fields (Chapter 6)*

Chapter Six discusses *Wireless Information Retrieval* (WIR), the WiFi-based sensing technique that I began developing during the second phase of my research, and which constitutes my technological contribution to the field.

The chapter begins (6.1) with a brief account of how I arrived at this sensing technique and how it relates to research in the fields of Ubiquitous Sensing and Music Information Retrieval.

Section 6.2 then examines a series of technical aspects of the system: how it is configured (in both hardware and software), how a WiFi card can scan the 'air interface', and how software can capture data that can later be used for sensing and other purposes. It then dives into the details of 'packet sniffing' on the so called Physical layer of WiFi communication, discussing the different types of transmitted frames - data, control, management, and special frames - focusing on Beacon frames, which form the basis of the WIR sensing system. After examining these Beacon frames in detail and how they can be used as radar pulses, the chapter discusses specific techniques for enhancing their usability for sensing: resampling signal strength data (RSSI) that does not arrive at a fixed rate, using a WiFi card simultaneously as a transmitter and receiver, and strategies for calibrating and tuning the system. Then it describes the method I developed for parsing and conditioning captured data - a multi-step process that involves registering data by the Access Point that transmitted them, filtering spurious values, then logging, shaping, and finally passing the resulting values further down the system's chain where they can be mined to extract sensing data out of them. The following section (6.2.9) discusses in detail the many different ways in which incoming RSSI data can be analyzed to extract 'features' from them, which in their turn can provide insights on what takes place in the physical space between transmitter and receiver (e.g. the ways in which a body moves). The current implementation of the WIR system can extract several dozen different features in three separate domains: time, frequency, and quefrency. All these features, and what they indicate in terms of sensing, are presented in this section, together with strategies for combining them to extract even higher-level information.

1.4.6 *Artistic outcomes: the Hertzian Field series (Chapter 7)*

Finally, Chapter Seven focuses on the *Hertzian Field* series.

It opens (7.1) with a broader reflection of my creation process, including the methodology, strategies, and elements involved in using the WIR system and creating a *Hertzian Field* work. It first breaks down the compositional process into multiple separate but interconnected steps concerning the composition of space, sound, interaction, and movement as well as touching on practical subjects such as tuning, scoring, rehearsing, observing others interact, and creating tools that can streamline the creation process. A number of specific subjects are discussed in more detail and with a practical outlook, including:

a) Sculpting hertzian topologies, i.e. using microwaves to design interactive spaces, and the various technical elements and physical aspects that must be taken into account.

b) Composing interaction, i.e. devising ways to perform with a microwave sensing system. In my personal practice this involves two complementary perspectives: that of the instrument designer, i.e. creating a system that can produce expressive performative data from the motion of an interacting body, and a more conceptual/philosophical approach (technically related to the field of Sonification) in which the system reveals qualities of the hertzian medium, thus producing knowledge on this invisible layer of reality that surrounds us.

c) Devising mapping strategies, i.e. how extracted RSSI features – which may, for example, relate to movements with specific characteristics or occur in specific areas – are used to control sonic parameters. This is a fundamental part of the creative process.

d) Designing performance environments as second-order cybernetic systems in which system and interactor become intricately entangled, thus producing a radically distinct way of experiencing space.

e) Considering the broader context and socio-political significance of the technology, i.e. perspectives that venture beyond the purely sonic or expressive potential of the system.

The three existing works of the *Hertzian Field* series are then presented in sequence. The first is *Hertzian Field #1* (7.2)*,* with subjects including a discussion on its concept and presentation context, the configuration of the system and space, the sound synthesis and spatialization methods deployed, and how sensing data is extracted and mapping. The section closes with some observations from this work that helped my practice with the WIR system evolve, including remarks on performing with the system, outcomes from further experiments with dancers/choreographers conducted after the work's premiere, and observations from how untrained visitor interacted with the work.

The following section (7.3) reviews *Hertzian Field #2* in a similar manner, presenting the concept and context for which it was developed and the configuration of system and space. This is followed by a more thorough discussion on spatialization and sound synthesis, the extraction of control data, their mapping to sound, and my interaction strategies. The section concludes with the score for the work's sound and movement, scene by scene

Section 7.4 examines the third work of the series, *The Water Within (Hertzian Field #3),* in its two iterations. The concept behind the work and the context of its creation and presentation is discussed first, introducing the ideas of the *social body* and *post-relational aesthetics.* This is followed by a survey of the broader socio-historical context of steam rooms and sweat bathing practices. Shifting to more practical matters, the chapter describes my process of learning how to work with hot steam and designing the structure for the steam room with a collaborating architect. It then discusses the configuration of the sensing system and of the immersive sound diffusion system and the choices involved in both, before proceeding to a presentation of the sound processes and how sensing data is mapped to it. This is followed by an introduction to my scoring method and lighting design, accompanied by a discussion of the strategies I developed for using sensory stimuli (sound and light) to help participants withstand the extreme heat of the installation environment. The section on this piece concludes with a discussion of the multi-sensory experience of the work, observations on visitor behaviors, a time-based synopsis of the experience of the 2018 iteration, and some final thoughts and remarks on visitor responses to the work and on creating post-relational art.

Finally, the thesis ends (7.5) with a brief overview of my future plans concerning both technological improvements to the sensing system and touching on my ideas for future artworks with it.

Chapter 2. THE BIRTH OF A MEDIUM: ENERGY BECOMES TECHNOLOGY

Where observation is key, chance only favors the prepared mind.
Louis Pasteur, 1854 [33]

2.1 MAPPING ELECTROMAGNETIC EXPERIENCE

2.1.1 *Electromagnetic prehistory: Occult forces and magic stones*

Natural phenomena related to electricity and magnetism have been known to mankind for millennia. Lightning, a natural phenomenon of electrostatic discharge in the Earth's atmosphere, was deified or believed to have a godly provenance in a large number of ancient cultures all over the globe (Gomes & Gomes, 2014). Ancient people did not only encounter electricity in the atmosphere but also in animals. Ancient Egyptians were likely aware of bioelectricity already in the 25th century BCE 4.5, as evidenced by the imagery of electric catfish of the Nile found in tombs (Finger & Ferguson, 2009) (for an example, see figure 2.1). About two millennia later, ancient Greek philosophers such as Plato described the paralyzing capacities of electric or torpedo rays while their contemporary physicians suggested consuming their flesh as medicine. The Romans expanded on this knowledge, with physician Scribonius Largus noting in the 1st century CE that these rays could numb the hands of fishermen from a distance. The nature of this shock remained unknown - attributed to a venom (e.g. by eminent physician Claudius Galenus) or explained through magic and the supernatural up until the 17h century (Finger & Ferguson, 2009). Discharges from electrical fish were reportedly used in medicine by the Romans since the 1st century CE, and in the Arab world some 15 centuries later (Benz, 1989). Today we are well aware that electrical activity is not limited to special animals but is also present in the human body. For thousands of years, Eastern philosophy has viewed the human body as a space of electromagnetic flows. This is evidenced by the Indian concept of Chakras, which represent nodal points of electromagnetic energy along the human spine (Halary, 2003), as well as by Chinese acupuncture, a medicinal practice dating almost 5000 years and which also aims to restore the

[33] "*Dans les champs de l'observation le hasard ne favorise que les esprits prepares*" (translated in English by the author) Louis Pasteur, on Ørsted's discovery. From a lecture at the University of Lille in December 7 1854, in *Œuvres Complètes. Textes recueillis par Louis Pasteur Vallery-Radot, petit-fils de Louis PASTEUR, tome VII.*

flow of energy through the body using needles (or needles and electricity in the case of the modern practice of electro-acupuncture).

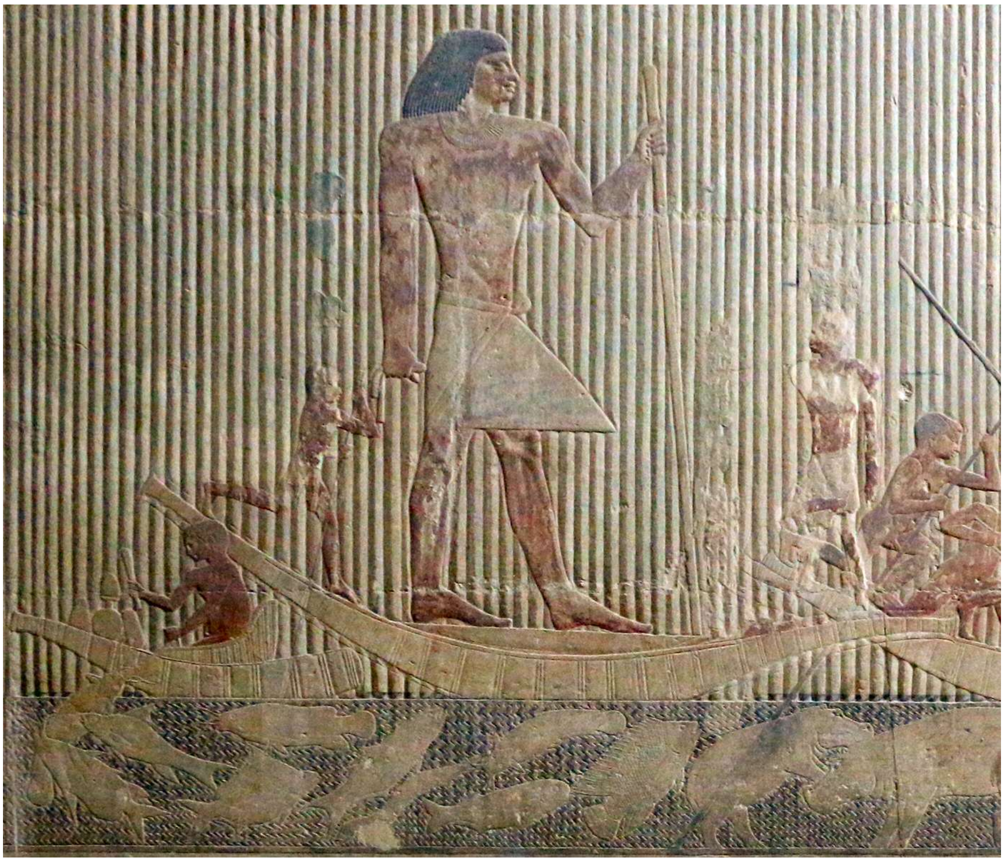

Figure 2.1. Fishing scene from a bas-relief at the Mastaba (tomb) of Ti in Saqqara, Egypt, circa the middle of the 3rd millennium BCE. An electric catfish (*malopterurus electricus*) is third on the left, close to the water surface and crossed by the boating pole (see Kellaway 1946) (photo by Sailko, Wikimedia Commons).

Humans also encountered electricity and magnetism through two strange stones with a peculiar capacity to affect objects from afar: amber and lodestone (figure 2.2). Amber is fossilized pine resin which, after being rubbed, becomes electrostatic thus attracting lightweight objects. Its Greek name, *elektron*, inspired William Gilbert to name the electrical force after it in 1600. The first surviving documentation of its attractive properties came in the beginning of the 6th century BCE by Greek philosopher Thales of Miletus who, as Aristotle wrote, rubbed amber with cat fur to pick up feathers (Sarkar et al., 2006). Owing to its beautiful appearance, people have been using amber as an ornamental stone and were trading it already in the Stone Age, with deposits from the Baltic Sea spreading to Europe, the Mediterranean (e.g. Mycenae and Troy), even Egypt and Babylon (Habashi, 2003 and Riddle, 1973). The Romans intensified the trade through an 'Amber Route' increasing the stone’s availability to everyday people. This interest was likely influenced by the mineral's properties - which must have revealed themselves early on - with people widely believing it to have magical or medicinal powers up until the 19th century (Riddle, 1973). For instance, Pliny the Elder (1st century CE) mentioned various uses for amber, such as a protective amulet, medication, or cleaning implement by Syrian women who used it to attract leaves and debris (Riddle, 1973 and Sarkar et al., 2006).

Lodestone is magnetite (iron ore) that has been naturally magnetized thus attracting iron. It is a much plainer looking rock than amber, but with a more significant role in the history of mankind as it can be used to create a rudimentary magnetic compass. The word 'lodestone' means 'leading stone' in Middle English. This is very appropriate as the compass can be thought as a basic direction-finding system in which the lodestone needle is the receiver showing the way to the transmitter, i.e. the Earth's magnetic poles. [34]

Figure 2.2. Amber (left) and lodestone (right) (photos by Hans Grobe and James St. John respectively, Wikimedia Commons).

One of the first likely uses of lodestone was to help orient the dwellings of the living and the dead. Archaeomagnetic and archaeoastronomical research suggests that the ancient Minoans, an important seafaring culture from ancient Crete, may have used magnetic loadstone compasses since around the 20th century BCE (Downey, 2011). This is evidenced by the alignment of several palaces and other significant buildings across the island, which appear to face towards the location of the magnetic North at that time and place. Furthermore, the 'Minoan Kernos', an enigmatic circular holed stone structure from a century later, may have

[34] The words magnet and magnetite most likely derive from 'Magnesia', the place where ancient Greeks found a rich supply of these stones.

been designed to predict solar eclipses using a magnetic compass made with loadstone floating in water (Downey, 2015). This speculation is supported by the similarities of its design with an instrument created by Hipparchus to predict solar eclipses in the 2nd century BCE. Similarly to the Minoans, but over 10,000km away and about a thousand years later, the Olmec civilization of Mesoamerica seems to have used lodestone to orient houses and graves, as archaeomagnetic studies of ceremonial edifices and offerings suggest (Carlson, 1975). This is supported by an Olmec artefact dating from around the 10th century BCE which appears to have been part of a lodestone compass. The first verified use of loadstone compasses is from yet another part of the world, China, dating almost another thousand years later, between 2nd century BCE and 1st century CE. *South-pointing* lodestone compasses were used in Taoist geomancy, known as Feng Shui, to orient homes and tombs to the cosmic forces and the chi of the Earth (Ibid). There are prior speculative appearances of compass technology in China, already circulating in Europe since the Age of Enlightenment. The earliest of them is the South-pointing chariot, a ‘magic’ vehicle used by king Huangdi (known as the Yellow Emperor) to lead his troops to victory through a dense fog created by his wizard opponent in the 27th century BCE (Statman, 2019). Chinese historians hypothesized that this was based on either a compass or a gear mechanism, which is more likely (Ibid). Many centuries later, in the 11th century BCE, a south-pointing machine (named with the same syllables used for ‘compass’) was reportedly given as a formal present from a duke to a legate.

Though lodestone was not used as a compass by the ancient Greeks and Romans, the attraction of iron to it was well known to them. Thales of Miletus produced the first scientific theory of magnetism and, according to Aristotle and Diogenes Laertius, believed that lodestone and amber had a soul – i.e. a non-material living essence – due to their ability to make things move from a distance. Empedocles of Agrigentum (5th century BCE) also thought that magnetite was animate; furthermore, he conceived of attraction and repulsion as fundamental forces between the elements that make up the world (Emerson, 2014). Several more ancient Greek philosophers referred to the properties of this strange rock, followed by several Romans who built on that knowledge. For example, fascinated by how lodestone attracted iron from a distance Lucretius discussed this rock as an explicable marvel in his *De Rerum Natura* (On the Nature of Things, 1st century BCE), explaining its power through a description of its ‘agencies’. Two centuries later, Pliny the Elder described how an architect hoped to make an iron image levitate mid-air using this mineral (Emerson, 2014). In the same book, Pliny traced the mineral to Magnes, a mythical Greek shepherd in Asia Minor who allegedly discovered magnetic stones and their effects when the iron tip from his staff and nails from his shoes were pulled while walking across a field.

As mentioned above, magnetic compasses were first used for navigation by the Chinese, with a text from the 11th century CE clearly describing the use of a lodestone to magnetize a needle (Statman, 2019). There is evidence that such compasses were used to navigate even earlier. In Europe, the compass is first mentioned by English monk Alexander Neckam in his treatise *De Utensilibus* from 1187CE as a tool for crossing the – notoriously cloudy – English Channel (Nelson et al., 1962). Many more writers across Europe mentioned the use of a floating magnetized needle in subsequent years to guide ships in conditions unfavourable for celestial navigation, with the use of this technology quickly spreading to other Europeans, the Vikings, and Arabs.

2.1.2 *Electromagnetic phenomena as actions-at-a-distance*

Apart from this early practical knowledge, humanity's understanding of the two phenomena would only start developing further around the 17th century (Lindell, 2006a). The first systematic research can be found in William Gilbert's *De Magnete* (1600), where he emphasized the differences between the electric and magnetic forces and deduced that the Earth is a giant magnet (figure 2.3). Gilbert's experimental proof involved a lodestone orb in place of a miniature earth and shreds of iron (Emerson, 2014). For nearly a century, only sparse studies in the fringe of main discourse in natural philosophy built on this controversial work. Its condemnation during the trial of Galileo in 1633 certainly did not help. In 1687, Newton's Law of Universal Gravitation gave humanity a new wonderful mental tool for understanding the invisible forces around us. Nonetheless, and despite its significance in advancing science, the Newtonian model was not able to explain electromagnetic phenomena since, as McLuhan pointedly notes, "*Newton, in an age of clocks, managed to present the physical universe in the image of a clock.*" (McLuhan, 1964/2017, 41).

Following the unveiling of the nature of gravity, natural philosophers become increasingly more preoccupied with magnetism and electricity, which these forces becoming a central subject of research in the 18th century. In 1729, Stephen Gray performed an experiment in which he successfully transmitted 'the electric force' through a wire over a distance of 270 meters (a forewarning of the wired landscapes that the telegraph would start creating a hundred years later across the globe). In 1759, Franz Maria Ulrich Theodor Hoch Aepinus published the first mathematical treatise of electricity and magnetism titled *Tentamen theoriae electricitatis et magnetism* (*An Attempt at a Theory of Electricity and Magnetism*) with a theory based on Newton's law. The first convincing measurements of the two forces were made by Charles-Augustin Coulomb in 1785. Since then, their study became an exact science even though they were still treated as two separate phenomena.

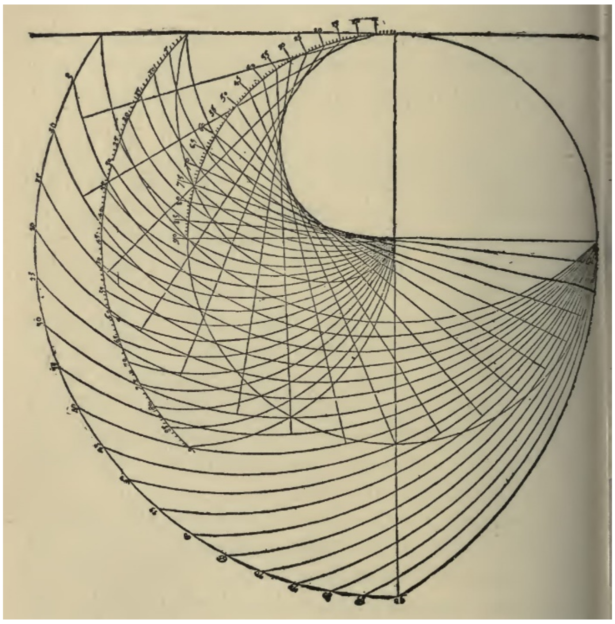

Figure 2.3. A compass diagram by William Gilbert which *"[s]eamen tossed by the waves"* could use together with a magnetic needle and a *"dip instrument"* to *"ascertain the latitude of the place where they happen to be"* (Gilbert, 1600/1893, 297-298).

In 1789, Luigi Galvani became the first person to almost invent radio (Lindell, 2006b). A doctor of medicine and anatomy, he had been developing his own branch of bio-electrical research since 1780, primarily experimenting with the electrical stimulation of dissected frog nerves and muscles to release the animal electricity he believed they contained. During these investigations, Galvani observed that sparks from an electrostatic generator induced spasms on a dead frog's leg a few meters away when he touched a nerve with a metal scalpel (figure 2.4). This was similar to what he had previously observed in his outdoors experiments, when frog legs hanging from iron hooks would begin to twitch during thunderstorms (Zielinski, 2008a). Unbeknownst to him, Galvani had created a unique bio-electrical radio system, with an electromagnetic transmitter (the electrostatic generator), an antenna (the scalpel), and a receiver (the dead frog's leg). Unfortunately, however, his focus being on the electrical properties of animal bodies and not on electromagnetism made him misinterpret this puzzling effect, believing it to be inherent to the animal. It would be up to other researchers to follow in his footsteps and investigate this phenomenon further over 100 years later, after radio transmission had already become a reality (for more regarding early experiments on biological radio receivers see Philips, 1980).

Figure 2.4. Luigi Galvani's accidental radio apparatus, showing the spark of an electrostatic generator exciting a dead frog's leg from a distance when the main nerve was touched with a scalpel (from Galvani 1791).

2.1.3 *Electricity and magnetism as connected flows of energy*

Electricity and magnetism came together as a single phenomenon through two experiments in 1820. Hans-Christian Ørsted had been exploring the relationship between the two forces for years and was investigating them through the perspective of the - still developing - concept of conservation of energy. During a lecture, he noticed that switching a battery on and off was causing magnetic interferences on a nearby compass – meaning that magnetic force could be created with electricity (Lindell, 2006a). Inspired by Ørsted's finding, André-Marie Ampère verified the inseparability of electricity and magnetism with an experiment of his own. In it, he succeeded in demonstrating a magnetic relationship of attraction and repulsion between two parallel electrically charged wires, thus proving that *"magnetism is merely electricity in* *movement"* (Ampère, 1820, quoted in Perelló, 2011). Ampère generalized his results mathematically and set a firm foundation for the study of electrodynamics.

With the intensification of research and experimental investigation of various phenomena that appeared to be related, the need for a unifying theory was becoming more and more evident. In the beginning of the 19th century, electromagnetic research had split in two main schools separated by the English Channel. The continental approach was primarily through mathematics. It followed Coulomb and investigated electromagnetism through a mechanical model that built upon Newton's action-at-a-distance. Researchers in the British Isles followed a different method and paradigm that had taken its roots with an induction experiment by Michael Faraday in 1831. In this pivotal experiment, Faraday navigated the opposite route from Ampère, aiming to create electricity through magnetism. The way to do this was found by inverting Ampère's statement: if magnetism is merely electricity in movement, then it should be possible to create electricity using a moving magnetic force.

Faraday made another decisive leap that would cause a radical shift in understanding electromagnetic forces: developing the concept of the electromagnetic field and a method to visualize it. At the heart of this breakthrough was Faraday's idea of translating the invisible electromagnetic force into a medium that he could observe. Fascinatingly, the reason behind this was his limited knowledge of mathematics. Seeking to study the attraction and repulsion patterns in the area around a magnet's pole, Faraday devised a visualization system whose origins have an interestingly winding provenance. This method started with the electrical studies of Georg Christoph Lichtenberg in 1777, who had managed to create an imprint of the effects of positive and negative electrical discharges on plates coated in dark resin by spreading by spreading sulphur and red lead powder on them (Zielinski, 2008) (figure 2.3a). Ten years later, Lichtenberg's work inspired Ernst Florens Friedrich Chladni, a physicist and musician, to apply this idea to the study of acoustic vibrations. Chladni would spread fine sand over thin plates of glass or metal and excite them with a violin bow to visualize different modes of vibration and their patterns (figure 2.3b). Faraday was very familiar with Chladni's figures from his own research in acoustics, and was impressed by both the effectiveness of the method as well as its beauty (Faraday, 1831).[35] Transposing this concept from the study of sound to that of magnetic forces, he placed iron fillings near the poles of magnetized

[35] Faraday wrote on the matter: "*The beautiful series of forms assumed by sand, filings, or other grains, when lying upon vibrating plates, discovered and developed by CHLADNI, are so striking as to be recalled to the minds of those who have seen them by the slightest reference. They indicate the quiescent parts of the plates, and visibly figure out what are called the nodal lines."* (Faraday, 1831).

circuits and observed that the fillings formed patterns reminiscent of those found in Chladni's plates (figure 2.3c). He then intuitively postulated a theory of *magnetic force lines,* with the poles of the electromagnetically charged body being at the center. These force lines, later named *field lines* by James Clerk Maxwell, were to be understood analogously to rays of light. Faraday would hypothesize 15 years after this experiment, in 1846, that light radiates along such magnetic force lines and that it is actually a kind of electromagnetic oscillatory wave. This was a breakthrough with major ramifications that would completely change the way electricity was understood.

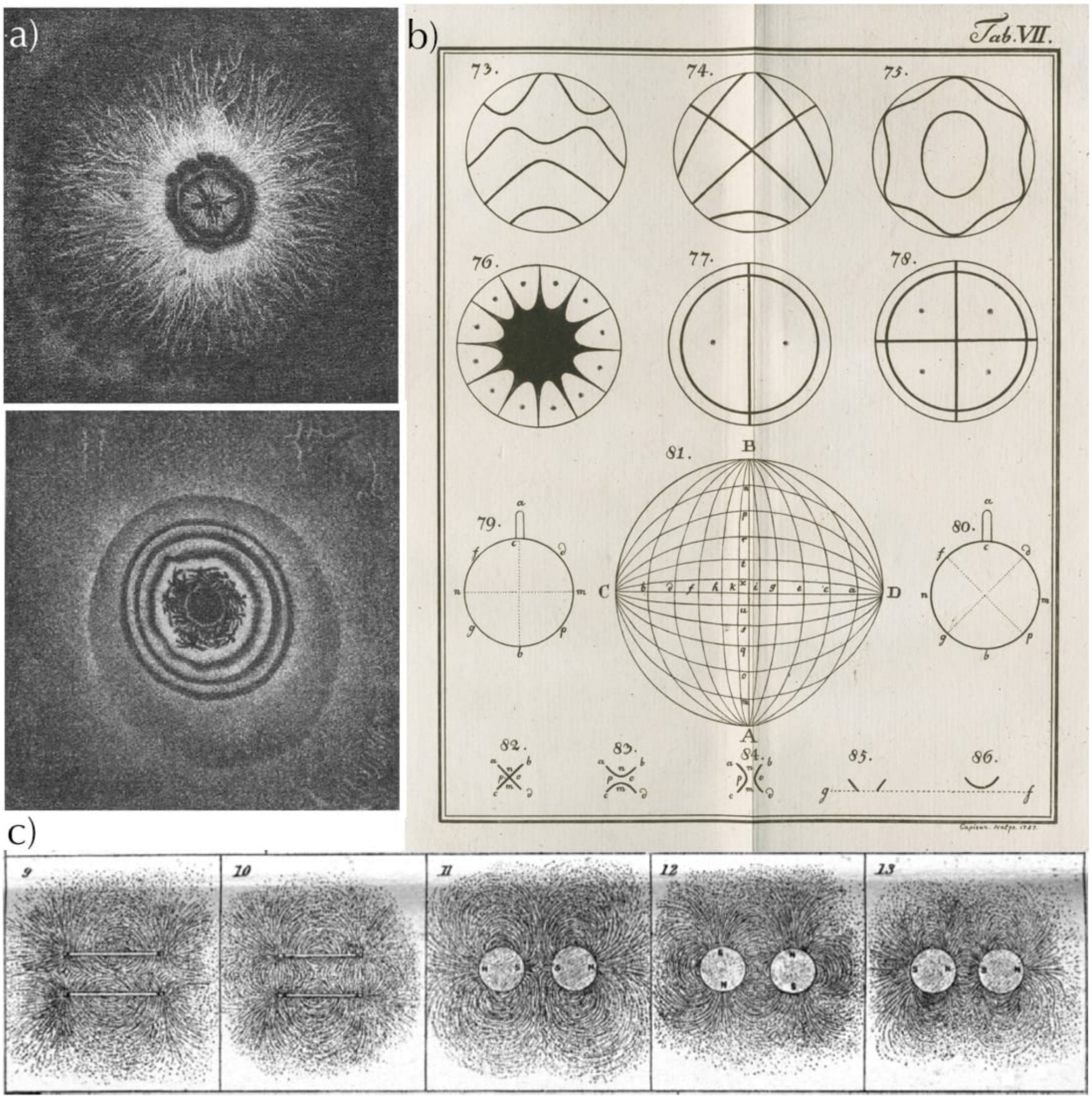

Figure 2.5. A new visualization language developed during the 18th and 19th century, and how it was applied to study different dynamic phenomena: (a) imprint of electrical discharges by Licthenberg (in Lichtenberg, 1806); (b) visualization of acoustic vibrations by Chladni, inspired by Lichtenberg (in Chladni, 1787); (c) diagrams of magnetic lines of force by Faraday, inspired by Chladni (in Faraday, 1852).

Nevertheless, while Faraday's experimental findings were groundbreaking, it was very difficult to construct a mathematical basis for them. Still, the concept of magnetic field lines proved useful to designers of electromagnetic generators, who applied it towards the grand project of urban electrifications towards the end of the 19th century (Lindell, 2006a). Beyond its scientific and engineering implications, Faraday's visualization method should also be recognized as an invaluable new medium. This type of direct transduction of electromagnetic signals into stimuli of a sensory modality that humans can experience has become a fundamental strategy for understanding such phenomena. In the arts, they are the indubitable precursors of a sizeable branch of 'hertzian art practice that is concerned with rendering the invisible forces of electromagnetic energy visible.

2.1.4 *Maxwell's mathematical electromagnetism sparks a paradigm shift*

> *"Throughout its eighteenth-century infancy, electricity* streamed*: it was a fluid. In its early nineteenth-century adolescence, jumping between voltaic piles, or leaping from electrostatic generators, or from lightning bolts into Leyden jars, it* hurtled*: it was a force, acting (like gravity) at a distance across the aether. In its young adulthood, induced to follow a wire, it* flowed*: it was a current, a hybrid of fluid and force. How exactly a current arose was uncertain, in part because time had not been looped into the analysis. Once Faraday proposed in the 1840s that electricity was rather an event than a thing, time became a critical variable and electrical phenomena could be conceived to arise from strains in an ambient 'field' traced by lines of force"* (Schwartz, 2011, 408)

In 1840, Lord Kelvin (a.k.a. William Tomson) proposed a mathematical explanation of Faraday's field lines through an analogy between heat and electrostatic fields. Electromagnetism should thus not be regarded as a type of action-at-a-distance analogous to gravity, like Kelvin's continental colleagues hypothesized, but as flow through a medium. Building on this concept, James Clerk Maxwell - a Scottish scientist and student of Kelvin - would become the catalyst for understanding and later conquering the electromagnetic strata of our universe.[36]

For Maxwell, electricity and magnetism were physical entities that could be related to each other mathematically. Unlike Faraday, his approach was not fueled by hands-on experiments;

[36] Maxwell would be considered a key figure for the development of the science of physics even disregarding his contribution on the study of electricity and magnetism. However, the impact of his work on the nascent science of electromagnetism has put him in the company of Newton and Einstein. As Ovidio Bucchi notes, our contemporary view of a world *"made of particles interacting through fields, have their conceptual foundation in Maxwell's two main contributions: the lunetic theory of gases and the theory of the electromagnetic field*" (Bucci, 2006, 189).

instead he aimed at developing an understanding of the many experiments already performed and providing a model that could unite the different theories that existed. In 1856, following two years of surveying the literature and having remained unsatisfied by the Continental approach and the overall fragmentation of knowledge, Maxwell began focusing on Faraday's work. His initial goal was to provide a mechanical model for Faraday's force lines. Over a decade later, and despite remaining a Newtonian himself, he arrived at something much more revolutionary: a new way of thinking about electricity, magnetism and light, together with the mathematical tools to explain and integrate most of the corpus of past research.

Adopting Kelvin's idea of understanding through analogies, Maxwell's method consisted of fabricating a 'physical reality' as a plausible conceptual model for explaining what intuitively made sense, modifying it, and in the end discarding it if it was impeding his mathematical explanations. As such, in 1861 Maxwell's theory of electromagnetism was founded on a physical model he had constructed, based on the flow of electromagnetic forces through the invisible medium of *aether*. The concept of aether had been introduced before Newton by Descartes, in his Principia Philosophiae in 1644, to explain action-at-a-distance. The concept of the *luminiferous aether* had been introduced over 30 years later by Christiaan Huygens as a medium through which light travels – a parallel to how sound waves propagate in air. The need for an electromagnetic medium that could support a Newtonian explanation of electromagnetism had already been introduced with the works of Faraday and Joseph Henry on induction. Maxwell's aether was first presented as an incompressible fluid without mass – a sort of clockwork-like mechanism displaced by electromagnetic charge. His theory's focus was not on what that medium was, but on its function and inner workings. In a later development of Maxwell's theory, and to account for more electromagnetic phenomena, the aether became an elastic jelly in which disturbances in electromagnetic charge propagate like waves. An essential part of this concept of radiation through a medium was the realization that electromagnetic waves propagated with a finite speed and not instantaneously. This idea had already been expressed by Faraday in the past, but without experimental proof (Sengupta & Sarkar, 2006). Maxwell measured this speed to be practically the same as that of light, a discovery which suggested combining the concept of the luminiferous and the electromagnetic aether. The consequence was that *"[w]e can scarcely avoid the inference that light consists in the transverse undulations of the same medium which is the cause of electric and magnetic phenomena."* (Maxwell, 1861).

Continuing on this revolutionary path, Maxwell dispensed with the physical model altogether in 1864, replacing it with a purely mathematical one. The properties of the aetheric medium could be simply represented by a constant, equal to the speed of light. Relationships between electricity and magnetism were defined with a set of differential equations with a solution that is periodic in both space and time and can therefore be considered a wave. Faraday's force lines had thus become an electromagnetic radiant field in motion. With his subsequent publication, *A Dynamical Theory of the Electromagnetic Field* (1864), Maxwell finally unified the experimental results, fragmented observations, and theories of Ørsted, Ampère, Gauss, Faraday and others under a single mathematical model. His *Treatise on Electricity and Magnetism* (1873) presented a complete set of equations and variables to explain electromagnetic phenomena, which, in a modified form, are still in use today.

Despite the potential of Maxwell's theory, it also presented a few of problems. Like many new theories, it was a bit awkwardly formed at first and more complicated than it needed, and there were also a few errors. More importantly, however, its concepts were radically novel and most of Maxwell's contemporaries had difficulty comprehending them. They had even more problems making sense out of his equations. This was all exacerbated by Maxwell's modesty in promoting his theory. After his death in 1879, a small group of devoted scientists who could grasp it and understand its implications begun making adjustments to Maxwell's equations and theory. This included firm believers from the British Isles, such as George Francis FitzGerald, Oliver Lodge, Oliver Heaviside (called the Maxwellians by some), and John Henry Poynting. It also included a young German scientist, Heinrich Hertz, who would begin developing his own understanding of Maxwell's theories independently a few years later, and would perform experiments to test their validity.

2.1.5 *Hertz bridges the channel*

The continental model had reached a dead-end after Wilhelm Eduard Weber's Electrodynamic Force Law (1846), which was initially thought as the beginning of a unified theory of electromagnetism until Hermann von Helmholtz proved otherwise with his influential work on the conservation of energy a year later. Helmholtz was spearheading an effort to consolidate and advance the different incomplete and incompatible electrodynamic theories of the time, believing - like his German peers - that electricity, magnetism, and light could be explained by laws of Newtonian mechanics that were yet to be revealed.

Helmholtz was a leading German physicist, *"perhaps the last real 'Universal Scientist' in the tradition of Gottfried Wilhelm Leibniz"* (Thumm, 2006, 329). He had made numerous contributions in many scientific fields, including the studies of psychophysiology and vision, acoustics and sound perception. As he had told an audience in 1857, he was mystified by the fact that mathematics, *"the science of purest and strictest thoughts",* would be so suitable in the study of music – particularly its physical and technical foundation – more so than any other artform, despite it being the most *"immaterial, evanescent and tender creator of incalculable and indescribable states of consciousness.* (...) *Mathematics and music! The most glaring opposites of human thought! And yet connected, mutually sustained!"* (Helmholtz quoted in Schwartz, 2011, 325). In 1863, he delivered his authoritative treatise *On the Sensations of Tone as a Physiological Basis for the Theory of Music*, presenting sound as an acoustic wave that makes air vibrate. With his theory he believed to have reached *"the heart of the theory of harmony"*, having brought together music, philosophy and physics and an understanding of harmony and dissonance through physical states that can be mathematically predicted (Ibid, 326). This approach, stripped of its musical connotations, had a profound effect in the development of electromagnetic technology.

It was through Helmholtz's guidance that his young and talented doctoral student Heinrich Hertz begun to work on electromagnetism. In 1879, Helmholtz initiated an international competition at the Berlin Academy for an experimental study on the effect of dielectrics on electromagnetic processes - a problem that Maxwell had encountered as well. Helmholtz encouraged Hertz to participate and gave him access to his lab as he believed him to be one of the most equipped to solve that problem. To Hertz's deep disappointment the results were inconclusive. This was unsurprising, however, as the instruments that the experiment required did not yet exist, nor did Hertz have the right conceptual framework to devise them yet.

In 1884, Hertz began to focus on electromagnetism again, and in particular to the concepts of rays and fields. His goal was to better understand the '*Faraday-Maxwell'* theory, as he then referred to it, and how it compared to other theories (Appleyard, 1927).[37] The biggest problem that Hertz encountered was that Maxwell never proposed any experiments nor he designed any instruments that could verify – or disprove – his theory. His equations supported the existence of electromagnetic waves that are not light, but he never wrote anything about generating or detecting such waves. Maxwell's motivation had been

[37] A January 27, 1884 entry from Hertz's diary *reads: "Thought about electromagnetic rays. Reflected on the electromagnetic theory of light".* And then again in May: *"Hard at Maxwellian electromagnetics in the evening. Nothing but electromagnetics. Hit upon the solution of the electromagnetic problem this morning."* (Quoted in Appleyard, 1927, 64-65)

philosophical, *"even metaphysical"* as Bucci writes, aiming to create an alternative model of what reality is that would allow finding its deep structure and expressing it mathematically (Bucci 2006, 189). Hertz would reflect in 1890 that *"[f]rom the outset Maxwell's theory excelled all others in elegance and in the abundance of the relations between the various phenomena which it included";* however it was impossible for it to displace opposing theories until there was "*evidence of decisive experiments*" (Hertz 1893, 20). Thus, the only way forward would be for someone to invent an instrument for generating electromagnetic waves, another instrument to measure those waves, and then to formulate and execute appropriate experiments that prove whether this theory reflects reality.

2.1.6 *Fleeting transmissions misidentified without a map*

Hertz was exploring uncharted waters. However, there had already been other explorers before him who had produced fleeting glimpses of the electromagnetic world – though without recognizing what they had done. As mentioned earlier, Galvani had managed to transmit and receive electromagnetic signals wirelessly with his bio-electric apparatus already in 1789. American scientist Joseph Henry was possibly the second to achieve this. Henry had reached similar conclusions with Faraday on induction around the same time, although Faraday was first to publish. In 1832, Henry demonstrated a proof of concept of a magnetic telegraph, with which he could ring a bell through a mile-long coiled wire. Ten years later, in 1842, he made two extraordinary discoveries: electrical discharges were producing an electrical oscillation, which would be a fundamental observation for the generation of electromagnetic waves. Henry also discovered that magnetization can occur over a considerable distance (more than 65 meters, in his experiments) and through walls.[38] In his effort to explain the phenomenon intuitively, he came very close to discovering the electromagnetic nature of light and making an important breakthrough.[39] However, he did not correctly identify it, thinking that the phenomenon was caused by induction, nor was he able

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[38] Henry wrote: *"A single spark from the prime conductor of the machine of about an inch long, thrown on the end of a circuit of wire in an upper room, produced an induction sufficiently powerful to magnetize needles in a parallel circuit of wire placed in the cellar beneath, at a perpendicular distance of thirty feet with two floors and ceilings, each fourteen inches thick, intervening."* (Henry quoted in Süsskind, 1968, 94). Originally in Proceedings of the American Philosophical Society vol 2, 1842, 193-196.

[39] "*The author is disposed to adopt the hypothesis of an electrical plenum, and from the foregoing experiment it would appear that the transfer of a single spark is suficient to disturb perceptibly the electricity of space throughout at least a cube of 400,000 feet of capacity; and when it is considered that the magnetism of the needle is the result of the difference of two actions, it may be further inferred that the diffusion of motion in this case is almost comparable with that of a spark from a flint and steel in the case of light."* (Henry quoted in Süsskind, 1968, 93). Originally in Proceedings of the American Philosophical Society vol 2, 1842, 193-196.

to put the different pieces of his research together as he lacked the mathematical background (Süsskind, 1968). Thus, the era of wirelessness was once again delayed.

Three decades later, Thomas Alva Edison was another pioneer that failed to grasp the nature of his achievement. In 1875 he noticed that sparks from a circuit were picked up by what later would be recognized as a rudimentary antenna - a wire attached to a plate in proximity with other metal objects. Edison was convinced the phenomenon was not electrical but that he had discovered a new 'etheric force' instead. He then went as far as to fabricate a primitive wireless telegraphy apparatus, with which he could tap into the wired telegraphy system and retrieve messages at a small distance. While Edison's relentlessly entrepreneurial approach is legendary, this time his scientific ambition to prove he discovered a new force blinded him from the practical and commercial implications of his discovery.[40]

Edison's claims where widely published and reached a young science teacher in Philadelphia, Elihu Thomson. Thomson had encountered a similarly odd phenomenon a few years prior, in 1871, when he was just 18 and starting his career. Using simple classroom demonstration equipment he had fabricated a circuit that generated a spark, which he could transfer anywhere in the room with his metallic knife (which acted as an antenna). Thomson mentioned this phenomenon in a paper but did not properly identify it.[41] After reading about Edison's 1875 findings, and convinced that the sparks were actually electric, Thomson performed his experiment again, this time using a primitive detector like Edison to prove that the inventor was mistaken. Thomson succeeded in detecting the sparks from his electric circuit across the room, then in another room, then in another floor and all the way up to the top of the building. This produced a new report which focused on disproving Edison's claims, sidestepping the importance of the discovery that lay in front of the author's eyes. The report created a long public debate, but nothing else came out.[42]

Edison's claims made it across the pond as well. A 24-year old Londoner by the name Silvanus Phillips Thompson performed his own systematic experiments between 1875-76, following encouragement by his teacher Frederick Guthrie (Süsskind, 1968). Thompson

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[40] Edison regretted not understanding the implications: *"What has always puzzled me since is that I did not think of using the results... If I had made use of my own work I should have had long-distance wireless telegraphy."* (Edison quoted in Süsskind 1968, 94)

[41] Thomson co-wrote this paper with an older colleague who published it under his own name.

[42] The report was co-authored and co-signed by Thomson this time. As Thomson's biographer wrote: *"Elihu Thomson never regretted his failure to be the father of wireless. In later years he said frankly that in those experiments of 1875 he had fully realized that he had discovered the germ of a new system of communication, but had not been wise enough to exploit it.*" (From Woodbury, D. (1960). *Beloved scientist.* Harvard University Press - quoted in Süsskind 1968, 94).

devised a rather sophisticated and quite precise instrumentation with which he succeeded in detecting the wirelessly transmitted electrical energy. However, he thought the phenomenon was inductive - just like Henry had before him - thus yet another chance to jumpstart electromagnetic science and wireless communication was thwarted.

A few years later, in 1879, British-American musician and inventor David Edward Hughes came even closer to inventing radio technology when he noticed that a loose contact in his new invention, a carbon microphone for the telephone, was reacting to electric current flowing in a nearby coil. Hughes quickly realized that, due to a faulty connection, his microphone had accidentally become a detector of electromagnetic sparks. Curious, he explored how his device reacted to the world around him by moving and listening (figure 2.6):*"After trying successfully all distances allowed in my residence in Portlandstreet, my usual method was to put the transmitter in operation and walk up and down Great Portland-street with the receiver in my hand, with the telephone to the ear (...). The sounds seemed to slightly increase for a distance of 60 yards, then gradually diminish, until at 500 yards I could no longer with certainty hear the transmitted signals. What struck me as remarkable was that, opposite certain houses, I could hear better, whilst at others the signals could hardly be perceived*." (Hughes in an 1899 letter, quoted in Süsskind 1968, 97). In many ways, Hughes' ambulatory exploration of the hertzian landscape as a soundscape foreshadowed the interactions of Direction-Finding and Signal Intelligence units with their own electromagnetic surroundings in the war zones of WWI over 35 years later. For that matter, it can also be read as the forebearer of many locative practices, particularly sound-based ones, as they explore hertzian landscapes and their relationship to architecture in a somewhat similar manner to Hughes, and more importantly with a similar curiosity. This certainly rings true for my own Hertzian art practice, which will be discussed in following chapters.

Unfortunately, nothing came of Hughes' findings, as he was not a scientist and therefore lacked the knowledge to correctly identify what he had come across. Therefore, instead of recognizing that he had created an apparatus for radio reception and that he had observed static electromagnetic waves arising from the interference of architectural structures, he attributed it all to electrical conduction through air. More knowledgeable scientists also failed to correctly interpret the phenomenon when he demonstrated his discovery. An early attempt to communicate his findings produced a disheartening response, likely because he was an outsider to the scientific community. As such, Hughes kept his experiments to himself for many years (Süsskind, 1968).[43]

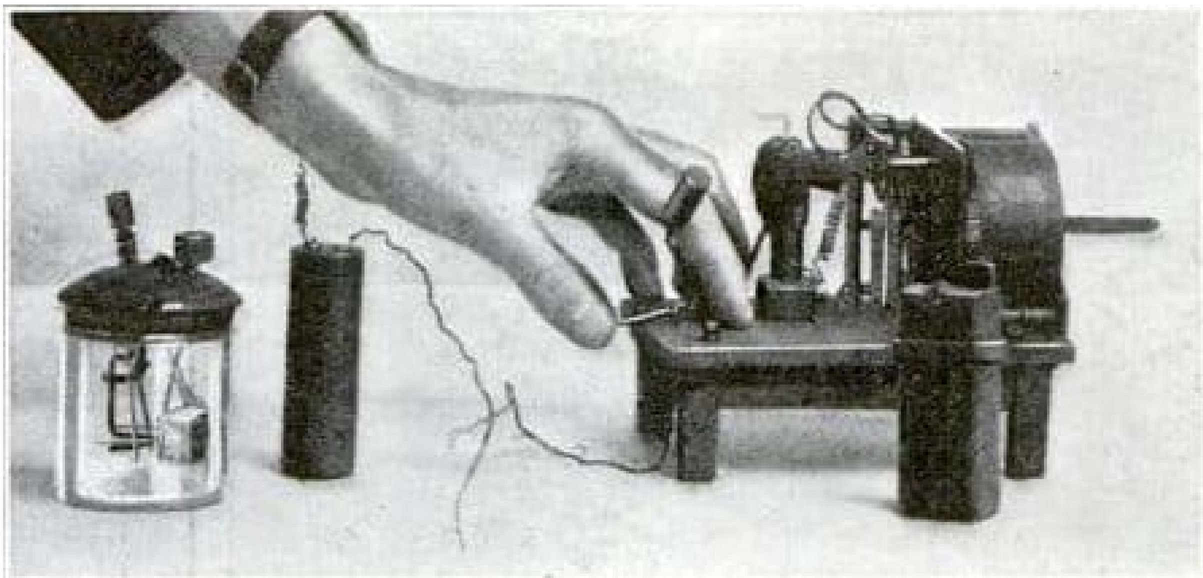

Figure 2.6. The apparatus with which David Edward Hughes transmitted and received electromagnetic waves in 1879. It consisted of a spark gap transmitter controlled by a clock for transmitting sparks periodically (right) and a variant of his carbon microphone acting as a mobile receiver, similarly to the *coherer* devices deployed for the same purpose years later (image from “World's first wireless outfit found in London tenement”, 1922).

Finally, Amos Emerson Dolbear was a physics professor and inventor who went far beyond merely sending simple signals. Having invented a sensitive microphone as a telephone receiver like Hughes, Dolbear applied for a wireless telephone system patent in 1882. That same year, and to his audience’s astonishment, he became the first to transmit the sound of voice and music wirelessly via electromagnetic waves in a demonstration in London. While this was only over a small distance, he claimed that in a subsequent experiment he managed to communicate at distances of up to 20km. Like other pioneers in this section, and like most of his contemporaries, Dolbear had possibly never heard of Maxwell and his innovative theory. Therefore, his own reasoning was that signals were conducted through earth; most others believed his system was inductive. As a result, Dolbear’s invention was another technology that lead to a dead end, becoming forgotten without bringing forth the wireless revolution that it could.

The stories of these several failed beginnings of wirelessness exemplify that a combination of theoretical understanding, inventive experimentation and the right conditions was needed to

[43] Years later, Hughes would refuse any credit for the invention of wireless telegraphy, stating: *"At this late date I do not wish to set up any claim to priority, as I have never published a word on the subject and it would be unfair to later workers in the same field to spring an unforeseen claimant to the experiments which they have certainly made without any knowledge of my work."* (Hughes quoted in Süsskind, 1968, 97).

make the idea of radio transmission a reality and to provide a map for others to reliable access the electromagnetic spectrum. On the other hand, the exponentially increase of these events towards the last quarter of the 19th century clearly indicates that humanity was at the cusp of a paradigm shift. It was only a matter of time until someone put all the pieces together.

2.1.7 *Hertz reveals an invisible world and how to access it*

In 1885, Hertz became a professor at the University of Karlsruhe where he finally got access to the right technical building blocks – simple equipment that any respectable university laboratory of the time had – together with a large enough space to experiment (the physics lecture room). While *"rummaging through the school's cabinets of old apparatuses"* he found two Riess spirals - flat coils of insulated wire acting as conductors (Schwartz, 2011, 410). He made a simple circuit wiring them up to batteries and noticed that a spark leaping across the gap of one coil was causing a similar spark to appear on the faraway coil. Intrigued, he incrementally refined this circuitry, experimenting, building, and fine-tuning. As Appleyard writes, *"[w]hat further was needed he made, after the manner of the pioneers, with his own hands, out of bits of wood and wire and sheet-zinc, so that all was infinitely adjustable"* (Appleyard, 1927, 74). By 1886, Hertz had devised a spark gap circuit capable of transmitting high frequency disturbances electromagnetically; this was the first 'Hertzian oscillator'. Five months later, he submitted a paper documenting his experimental results together with his instrumentation and setup (figure 2.7).

Hertz was now free to focus on the puzzling side effect, the *"reciprocal action between simultaneous electrical sparks"*, that seemed to justify Maxwell (Hertz, 1893, 4). Like Edison before him, he was not certain of the nature of the sparks. *"For some time, indeed, I was in doubt whether I had not before me an altogether new form of electrical action-at-a-distance"*, he wrote, diving head-first into a series of experiments through which he hoped to understand the phenomenon (Ibid). A new paper in June 1887, titled *On an Effect of Ultra-Violet Light Upon the Electric Discharge,* presented to the world a preliminary proof of Maxwell's theory. Perhaps as importantly, it also described the instrumentation and an experimental procedure not only for generating, but also for wirelessly detecting electromagnetic waves. Hertz had brilliantly realized that an open circuit like the spark-gap, usually considered a nuisance like the loose contact in Hughes' microphone, could be used as a generator of electromagnetic energy, and that a similar circuit in the vicinity would resonate with it and could thus be used to detect this energy.

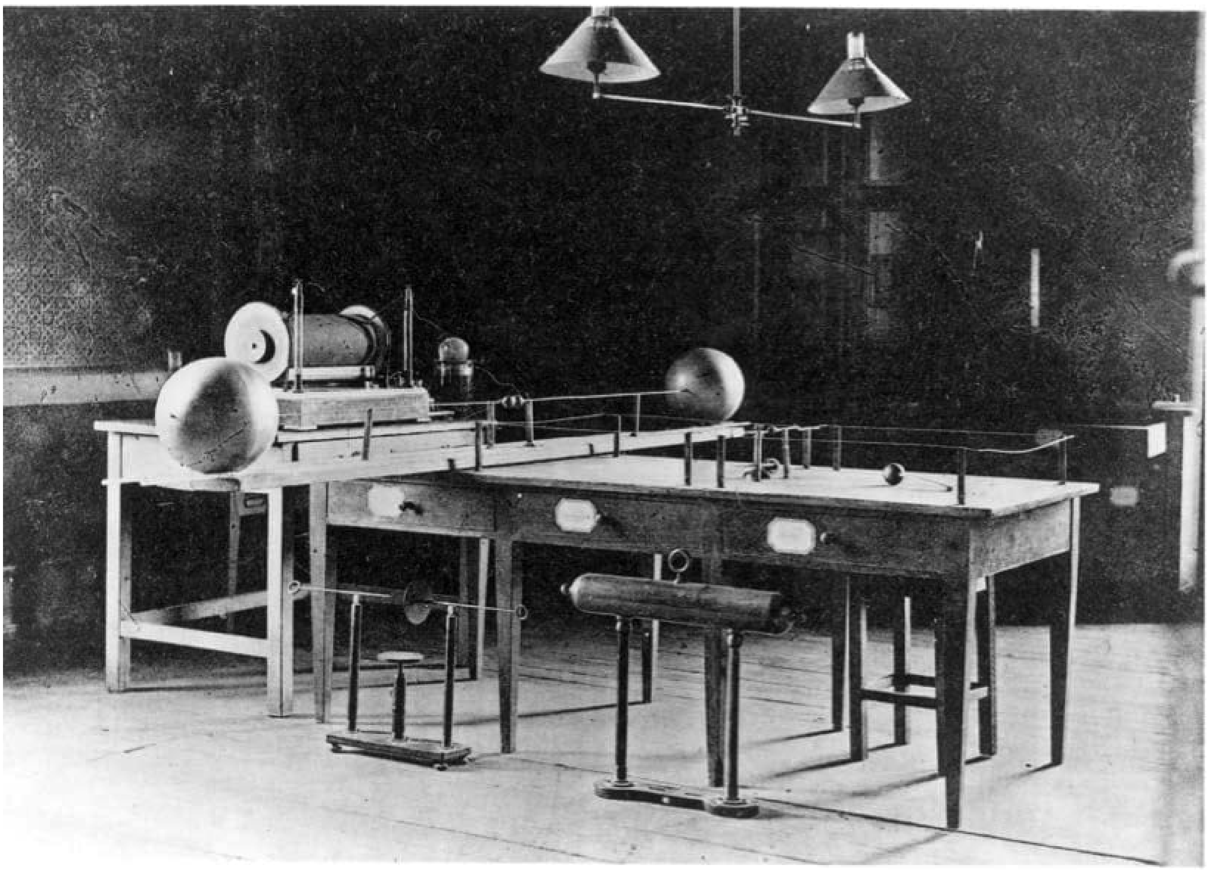

Figure 2.7. A photo of Hertz's self-fashioned equipment in the Karlsruhe physics room (Physicalisches Institut of the Technische Hochschule) where he conducted his groundbreaking experiments, taken by Hertz himself. It displays on a table from left to right: a large high-voltage induction coil, a Meidenger cell (battery) and a spark gap functioning as the transmitting oscillator; two rectangular loop receivers and a metal sphere with insulated handle for probing the field on these loops; a conductor and discharger are placed on the floor (for a detailed description of all instruments, see Bryant, 1998).

Hertz's understanding of electromagnetic waves was clearly influenced by Helmholtz's work on sound. As Schwartz remarks, Hertz *"saw, and* heard*, the parallel sparking as a type of resonance akin to the sympathetic vibrations analyzed in 'On the Sensation of Tone'; indeed, he termed the interaction between the two circuits 'symphonic relations'"* (Schwartz, 2011, 410). Hertz had noticed that the sparks were amplified when his two circuits had the same size, meaning that the transmitter was bringing the receiver into resonance at the frequency of the wave's fundamental oscillation. Thus, he turned to the concept of sympathetic resonance to prove Maxwell's theory. This was essentially the same strategy that Helmholtz had used in his own effort to experimentally prove Fourier's mathematical theory that complex sounds can be broken into a series of sinusoidal waves.[44]

After this crucial breakthrough, Hertz embarked on a long series of inventive experiments, with stalemates followed by progressive breakthroughs followed by more papers. As he put it: *"The object of these experiments was to test the fundamental hypotheses of the Faraday-Maxwell theory, and the result of the experiments is to confirm the fundamental hypotheses of the theory"* (Hertz, 1893, 20). In February 1888 he published a paper titled *On the finite velocity of propagation of electromagnetic actions* where he proved that electromagnetic waves can be generated and detected, that they radiate with a finite speed like light, and that light is an electromagnetic phenomenon itself. Maxwell was correct and the world would have to begin changing its ideas on the nature of reality to include a vast universe of electromagnetic oscillations surrounding us. Hertz had all the proof he needed for himself, writing to Helmholtz in March of that year: *"I believe that* the wave nature of sound *in empty air space cannot be demonstrated so clearly as the wave nature of this electrodynamic propagation"* (Hertz quoted in Schwartz 2011, 411).

While conducting these experiments, Hertz noticed *"something like a formation of shadows behind conducting masses"* but also *"a peculiar reinforcement of the action in front of such shadow-forming masses, and of the walls of the room"* (Hertz, 1893, 11). This led to a paper on the reflection of waves through the use of electromagnetic mirrors and reflectors (figure 2.8). At this point, the scientist faced another technical stalemate before he could continue exploring the interaction between objects and electromagnetic waves: the wavelengths he could produce were too large for the physics lecture room. The way forward was paved by the instrumentation he developed for another experiment in which he investigated the electromagnetic fields of wired circuits. His spark gap oscillator was producing a broadband train of damped pulses: a signal full of harmonics that could be tuned to other frequency ranges in the radio spectrum through resonance. Mirroring Helmholtz's work in acoustics, Hertz fabricated a set of electromagnetic resonators that could filter and tune these broadband signals. Coupling his spark gap with the new resonators, Hertz discovered he could alter the wavelength – and thus the frequency - of the waves (figure 2.9). Using his new instrumentation and a new set of smaller reflectors for these shorter waves, Hertz went forth

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[44] Inspired by Chladni, Helmholtz had employed physical objects to visually and audibly separate (i.e. filter) sonic vibration patterns of different frequencies, the former with Chladni plates and the latter with a set of resonators (hollow spheres of specific sizes and shapes out of metal or glass that are now called Helmholtz resonators) (Salter, 2015).

to perform, with ease this time, a set of systematic experiments to reveal the nature of electromagnetic waves, and how they radiate, propagate and interact with their environment.[45] With these experiments he demonstrated that, once the differences in wavelength are taken into account, electromagnetic waves demonstrate the exact same behavior as light.

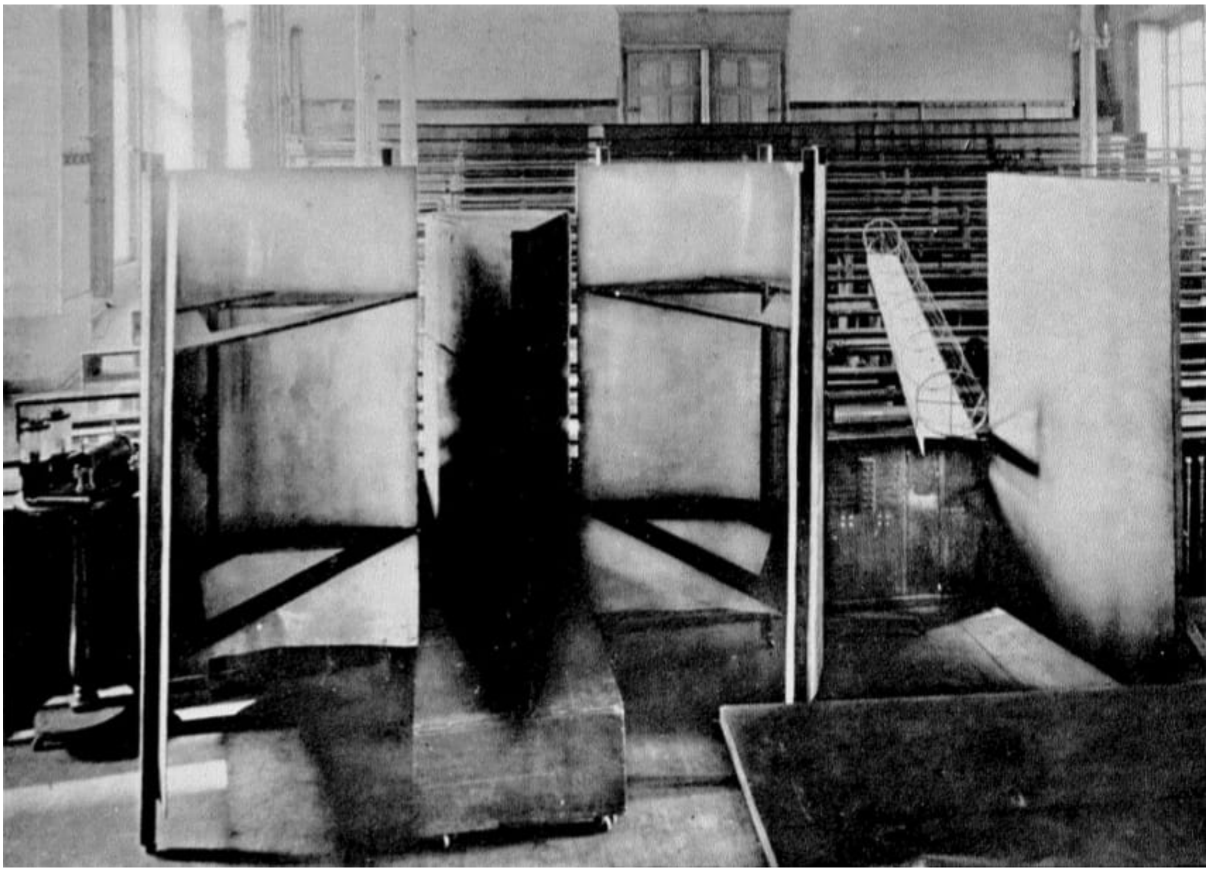

Figure 2.8. Another photo taken in the Karlsruhe physics room, featuring Hertz's equipment arranged in a similar fashion as in his 1885-89 experiments. From left to right: small table with bichromate cells (a type of battery) and induction coil; parabolic zinc mirror with transmitting oscillator; prism for the study of refraction; receiving parabolic mirror (the two mirrors were exact copies fabricated by Hertz's assistant, Julius Amman); wire cage for experimenting on the skin-effect; plane zinc mirror sheet. (Appleyard, 1927).

[45] More specifically, he wrote about the properties of rectilinear propagation, polarization, reflection, and refraction.

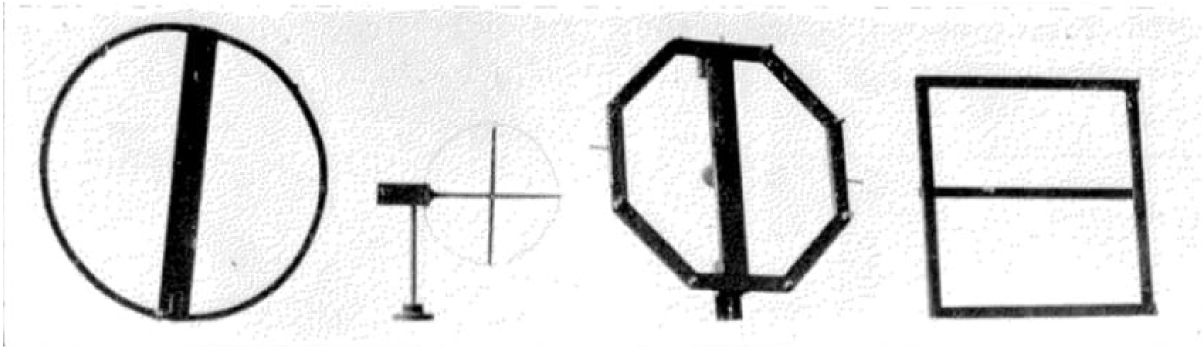

Figure 2.9. Four different resonators (antennas) used by Hertz in his experiments with dimensions (left to right) 70, 35, 67 and 60 centimeters (Appleyard, 1927).

2.1.8 *Hertz's performative exploration of the dielectric body with a proto-radar*

Hertz inserted the human body as part of his experiments very early in his experiments. In an 1887 paper he reported touching the detector circuit to feel the strength of its spark.[46] According to his laboratory notes, he started investigating the effects of dielectric materials on the 5th of October of that year (Hertz quoted in Hertz & Doncel, 1995, 233). Five days later, on October 10th, he started studying the effects of the human body when brought near the receiving circuit. In a subsequent paper, also published in 1887, he noted that *"[a] little attention shows that even the body of the observer exerts a perceptible influence"* (Hertz, 1893, 99).[47] A year later, Hertz offered a glimpse on his exploratory process when discussing his experiments with static waves,. With antenna in hand, he moved around the lecture room seeking to discover nodes and antinodes and measuring wavelengths, always with the help of an assistant to account for the *observer effect* (figure 2.10). In his own words: "*For the most part it does well enough for the observer to hold the circle, mounted in an insulating wooden frame, in his hand, and then to bring it as may be most convenient into the various positions. But, inasmuch as the body of the observer always exercises a slight influence, the observations thus obtained must be controlled by others obtained from greater distances."* (Ibid, 126) (figure 2.11).[48]

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[46] He wrote: *"No physiological effects of the induced current could be detected; the secondary circuit could be touched or completed through the body without experiencing any shook,"* (Hertz 1893, 38, from the paper *On very rapid electric oscillations* (1887)).

[47] From the paper *On electromagnetic effects produced by electrical disturbances in insulators,* originally published on November 10, 1887.

[48] From the paper *On Electromagnetic waves in air and their reflection,* originally published in 1888.

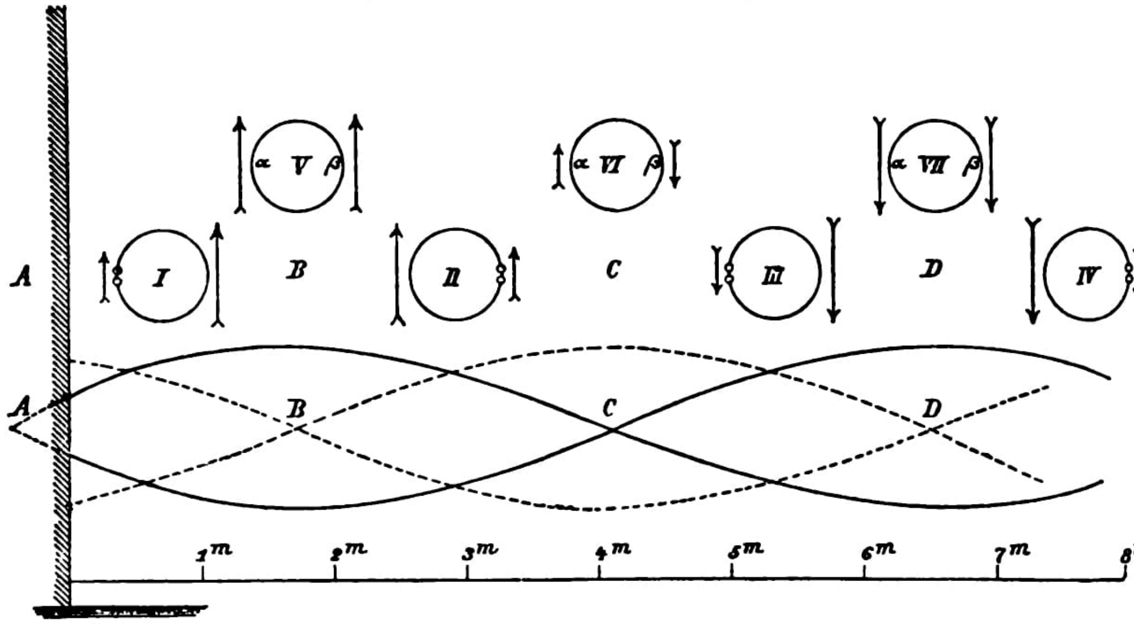

Figure 2.10. Hertz's diagram mapping out the presence of nodes and antinodes formed by static waves inside the physics room in Karlsruhe, following an experiment in 1888 (Hertz, 1893).

The deep roots of my own *Hertzian Field* series and the WiFi sensing system I developed - the deep media ancestor of this work, if you will - can be traced in the experiments conducted by Hertz in 1887-88. Of particular note is his process for investigating the nature of electromagnetic radiation and its propagation in space in 1888. The human body became part of these experiments, inserted between transmitter and receiver to discover its influence on the propagation of waves. Hertz wrote: *"If an assistant walks across the path of the ray, the secondary spark-gap becomes dark as soon as he intercepts the ray, and again lights up when he leaves the path clear"* (Ibid, 176).[49] With this experiment, Hertz and his assistant, Julius Amman, became the first humans to intentionally scan their bodies with electromagnetic waves. Not only that, but by doing so they became the first actor and first witness of an embodied multimedia electromagnetic performance in which the interactions between radio field and moving body were transduced into an experience of sound and light. The setting was the University's physics lecture room, pitch dark and silent. The transmitter's sparks, bright and noisy, were radiating at the speed of light to its receiving twin, causing a tiny flicker that *"could be better heard than seen"* (Cichon & Wiesbeck, 1995, 3). Hertz was hunched over the receiver, observing the effects of Julius's body on the spark and adjusting the gap's width to measure its influence, and thus its radio resonance: *"In the dark and cold of*

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[49] From the paper *On Electric Radiation,* originally published in 1888.

the college's main secure hall, which he had cleared of the obstruction and hiss of gas chandeliers, Hertz watched and listened for changes in the sparking behaviour of his oscillator that he could correlate with the sparking in his resonator. He would not have been able to engage in conversation over the noise of the Ruhmkorff coils he was using to power his apparatus, but in the dark he may have adjusted his receiver at first by cues from the crackle of sparks, then by changes in luminosity and length" (Schwartz, 2011, 410). This scene of waiting, testing, moving, observing, listening, calibrating, and repeating as a means to discover and tap into the hidden electromagnetic layer is not unlike what one can find in the artist's studio; it certainly is a scene that strongly resonates with my own process in creating and performing the *Hertzian Field* works.

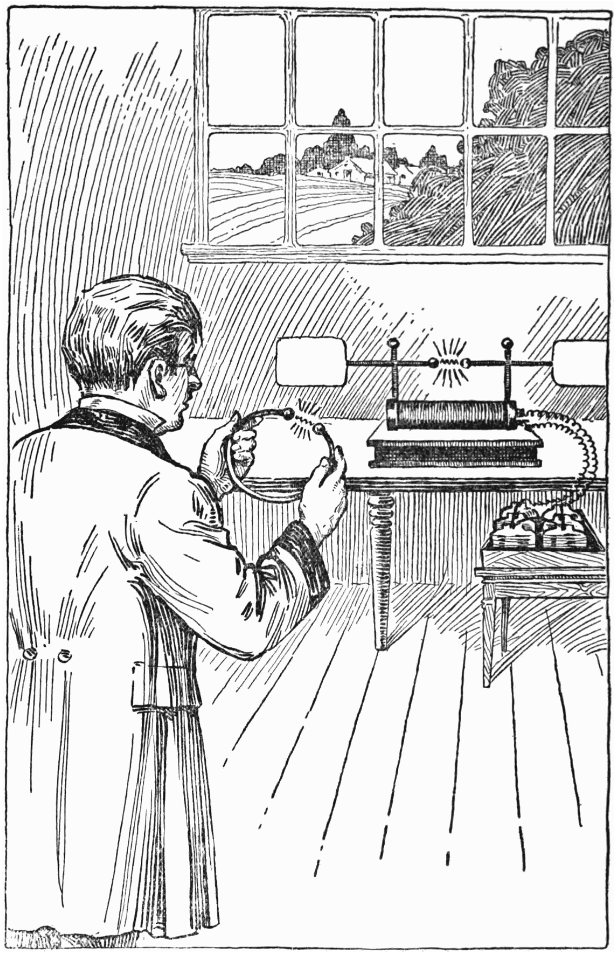

Figure 2.11. A 1922 artist's rendition of Hertz experiments, showing him moving around the physics room while holding his receiver antenna and pointing it to his spark gap transmitter (Yates & Pacent, 1922).

The paper that came out of these experiments, *On Electric Radiation,* was extremely well received and became widely distributed in the scientific community to the extent that electromagnetic waves begun to be called *Hertzian waves* - a name they would keep for the next few decades until the advent of radio broadcast. As we have seen, Hertz was neither the first human to generate radio waves, nor the first to ever detect them. He was, however, the first to purposefully and systematically do it all - synthesizing, transmitting and receiving electromagnetic waves and explaining the physics behind his findings through Maxwell's mathematical theory.

Hertz kept refining the theory to the point of removing the mathematical need for aether.[50] In an exemplification of Pickering's concept of the *mangle of practice,* he was also continuously developing his instrumentation as he tackled different problems, advancing his technology together with his knowledge with each experiment. He remained productive, experimenting and publishing until his premature death in 1894, at the age of 37, from a painful bone disease that had him suffering since he started solving the riddle of electromagnetism in 1886 (Schwartz, 2011, 412).

While no one can say what Hertz would have achieved and what he would had worked on had he lived longer, it is clear that he was only interested in the scientific implications of his work, and there is no evidence that he entertained any ideas for implementing practical uses of his findings.[51] With the generation of electromagnetic waves proven possible, it would be up to others to carry on the electromagnetic torch and begin filling the spectrum with man-made noise and man-made signals. Owing to a combination of economical, political, social - but also circumstantial - reasons the exploration of wireless technology would initially become focused on the transmission and reception of messages. As a compass for the future, however, Hertz's work and in particular his 1888 paper also produced the foundational knowledge and planted the seed of the possibility of embodied interaction between body and electromagnetic waves. It also implied, when reading between the lines, that it is possible to

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[50] The experimental verification of the non-existence of luminiferous aether began with Albert Michelson, an American musician and mathematician, attempting to measure how much light was slowed down by its supposed carrying medium, aether. To achieve this - with advice from Helmholtz and a grant by A. G. Bell - he devised an interferometer apparatus with which to measure *aether-drag*. The interferometer was extremely sensitive; nonetheless the results were unexpected, showing that the aether had no effect. In 1885 Michelson started working together with chemist Edward Morley on the matter, and between April-July 1887 they performed a new improved experiment. Once again, the results showed no traces of aether. Schwartz places this experiment within the context of the cultural history of sound (as they *"drew upon acoustical analogies"*), the context of the study of noise (because of the painstaking efforts Michelson-Morley took to filter out extraneous vibrations), and the context of a growing curiosity on the 'just noticeable differences' of perception and sensation (Schwartz, 2011, 321).

[51] For instance, Appleyard mentions Hertz's response in December 3rd 1889 to a question from a certain 'Herr Huber' who worked in the electric power station in The Hague, the Netherland, about the potential of this technology for wireless communication. Hertz's reply was that it would be possible but impractical because the slow oscillation of the telegraph would need a mirror as large as a whole continent (Appleyard, 1927, 76).

gain information on the environment of transmission by using radio waves to touch or sense space - another hint for future explorers of the electromagnetic spectrum to discover. As Cichon and Wiesbeck observed, *"Heinrich Hertz developed for the first time a complete pulsed radar, an indoor communication link and a material test set, all in one"* (Cichon & Wiesbeck, 1995, 1).

2.2 WIRELESS IMAGINATION AND ELECTROMAGNETIC REALITIES

2.2.1 *Historical context, or why wireless telegraphy and tele-control became the first electromagnetic technologies*

The 1890s was a pivotal decade for electromagnetic research, bringing about a concentrated focus on the development of wireless communication. Several visionaries imagined and invented technologies that used these newly discovered 'Hertzian waves' to tackle real-world problems. A few of these inventions would become disseminated to society as innovative products, a complex process that was tied to the social, economic and cultural systems of the time (Lochte, 2000). Before reviewing these technological visions and developments following Hertz, and before seeking to identify the origins of different electromagnetic applications and the development of wireless imagination and wireless practice, it is first important to briefly consider the overall context of the period as it will shine light on the reasons why electromagnetic technologies developed the way they did. As radio historian Aitken notes about the roles of some key figures of early electromagnetism, *"Hertz, Lodge, and Marconi were, each in his own way, actors in historical processes that stretched far back in time and that still shape our lives today"* (Aitken, 1976/2014a, 298-299).

Hertz's discoveries came in the midst of a long economic recession that had begun in 1873. It was called the 'Great Depression' until the crash of 1929 and lasted longer than two decades in many countries, including Great Britain. Prices were continuously dropping as supply exceeded demand and the great powers of the time begun to seek new markets as well as new resources. This brought a rise of nationalist ideas and the era of *New Imperialism*, in which colonizing Africa - still largely unexplored and unexploited by European powers - became a core policy in many countries aiming to build large empires and to strengthen their position on the global stage. In the Berlin Convention of 1885, the great powers of the time came together to lay out the rules of engagement for conquering the continent, thus beginning the 'Scramble for Africa' (figure 2.12). Besides the financial ramifications of colonizing lands with resources and a population that could be treated as a monopolized market, promoting the grand ideal of creating empires was also seen as a way to control and divert internal problems that had come from industrialization and rising inequality.

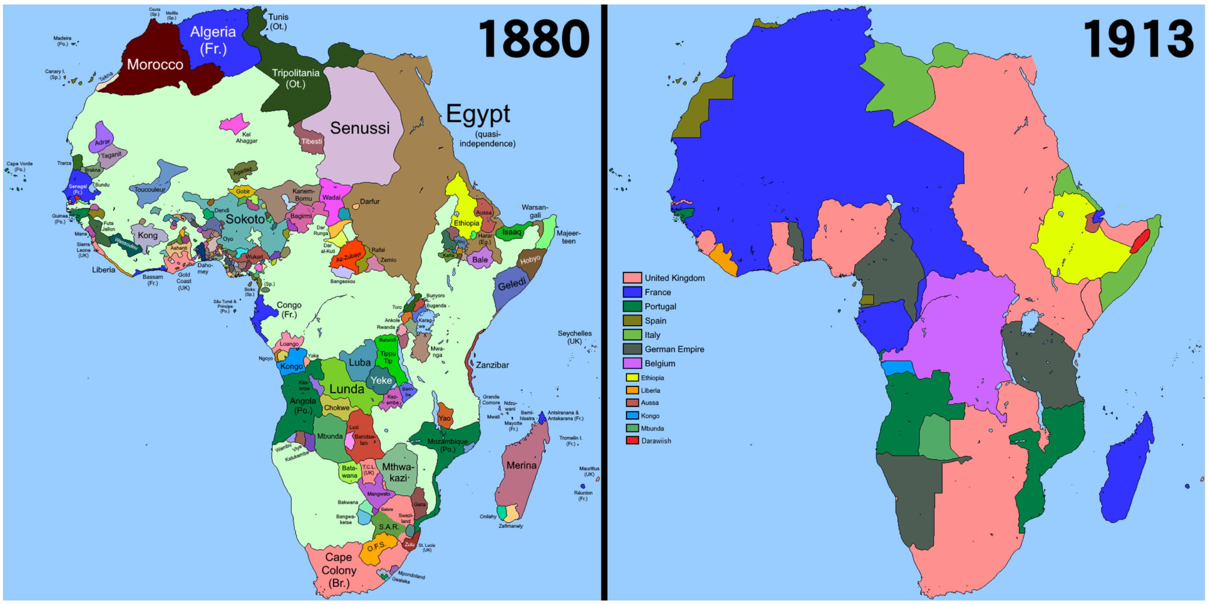

Figure 2.12. Map depicting the results of the colonial *Scramble for Africa*, showing how the many sovereign lands of 1880 had become colonies by 1913 (by Somebody500, Wikimedia Commons).

Within that context, many countries were very interested in new technologies and their potential in providing military or financial advantages. Great Britain, in particular, was the leading industrialized nation and still ahead of its competition, but was beginning to feel other powers catching up. Control of the seas was especially important, with the recently formed German state attempting to challenge Great Britain's marine supremacy. While telegraph wires had connected many parts of the world, contributing to rapid economic growth and radically accelerating military communication, they were still of no help when it came to communicating with ships - a crucial part of the global economy and even more so for the British. Towards the end of the 19th century there was increasing pressure in Britain from the Admiralty, the Trinity House (a corporation responsible for various coastal and deep sea navigational aids) and Lloyd's (an insurance company providing maritime intelligence to interested parties) for a new communication system that could connect boats, lightships, and lighthouses, especially around the traffic-packed British coast.

As such, commercial wireless telegraphy was the first field in which the newfound radio technologies were applied. Military applications, and torpedo guidance in particular, followed as a close second. While the application of radio for communication is well known and the reasons behind it seem rather obvious, the second application may come as somewhat of a surprise. Torpedoes were a recent evolution of fire-ships, explosive-filled boats that had been used in naval battle since the 16th century. Since the 1860s many types of wired torpedoes that could be guided remotely had been developed, but their tethering only made them suitable for coastal defense as a more advanced version of harbor mines (Everett, 2015). The fast torpedo boats introduced in the British Royal Navy in the 1880s required a visible signal link with their parent ships.[52] Before radio, various methods had been employed, each with its own limitations - submarine cables used for acoustic signaling of hazards to ships equipped by hydrophones, visual signaling, and inductive or conductive wireless telegraph.

2.2.2 *1890-94: From theory to speculative applications and technological dead-ends*

The passage from approaching electromagnetic waves as a scientific phenomenon to harnessing them for practical use was first crossed by several visionaries between 1890-92. In 1890, British engineer Richard Threlfall suggested in a meeting in Sydney to use electromagnetic waves as a radio beacon for guiding ships: *"A Hertzian transmitter in a lighthouse would act like a torchlight, which would be visible also through a thick fog when a Geissler tube is used as a detector"* (quoted in Lindell, 2006b, 264). Although Threlfall’s concept would eventually be implemented in the early 20^th^ century in direction-finding and radio-homing systems like the 1907 Kompass-Sender (see section 2.4.1) his proposal did not have an immediate impact.

The following year, in 1891, Alexander Pelham Trotter - another British engineer - proposed a different radical idea: to use electromagnetic waves for ship-to-shore communication on foggy days. While electrical wireless communication predated Hertz, those techniques used induction or conduction rather than transmission of radio waves and thus had many shortcomings (Süsskind, 1968).

That same year, a young British officer at the Torpedo School (who would later become a knighted Admiral), Captain Henry B. Jackson, proposed to use 'Hertzian waves' for the control of torpedoes. Jackson created the first prototype of radio communication, sending Morse signals at a distance of a few hundred meters (Mallik, 1986 and Hackmann, 1988). His demonstration convinced an initially skeptical Admiralty about the feasibility of his idea and moreover proved that such a system would be safe (it had been feared that the transmitted

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[52] Because of that, Torpedo Schools were important R&D branch/facility of the Navy (in Britain but also Russia), teaching physics and electricity already from the 1870s (Everett, 2015).

signal could detonate the torpedo). A decision was made to proceed with the research for such a system, but a fully working solution was never produced.

The most resonant idea was published by Sir William Crookes in the *Fortnightly Review* in 1892, inspiring many scientists and inventors around the world - including young Guglielmo Marconi who started experimenting with radio waves in Italy because of it (Crookes, 1892).[53] Crookes was a British physicist and chemist, and also very knowledgeable in the science and practice of electromagnetism, having invented the Crookes tube (the core instrument for the discovery of cathode rays and X-rays). He was also a passionate spiritualist who saw many connections between electromagnetism and various occult notions, believing for example that telepathy could be explained through radio. In his seminal article, titled *Some Possibilities of Electricity*, Crookes remarked that 'Hertzian waves' would be a perfect telecommunication medium, dispensing the need for infrastructure like wires and poles and overcoming obstacles that limit optical communication, like fog or walls. Moreover, they could allow the simultaneous use of many parallel communication channels and would be ideal for establishing secret communication links, as one could easily make the transmission frequency narrow and direct the radiation beam to a target.

Finally, around the same time but thousands of miles away, Father Roberto Landell De Moura invented an early electromagnetic communication prototype. De Moura, a Brazilian roman-catholic priest with Jesuit and polytechnic education in Brazil and Rome and a deep interest in science and engineering, is one of the lesser-known radio inventors, largely because he lived and worked in the periphery isolated from the rest of the scientific community. De Moura conceived of a theory based on Maxwell's work which he named *The Unity of Forces and Harmony in Nature*. De Moura was also aware of Hertz's experiments with electromagnetism and Alexander Graham Bell's *Photophone*, a communication device that transmitted sound as light, and which Bell had hoped could act as a kind of telescopic transducer allowing him to listen to the sound of the sun in real time.[54]

In 1893, De Moura built a hybrid wireless communication system that combined three different modalities: acoustic, optical and electromagnetic. The user could select which mode was appropriate for a given situation. This triple system consisted of the *Esophone*, a wireless

[53] This visionary article and its impact in shaping the wireless technologies could be compared to Vanevar Bush's seminal essay *As We May Think* and its influence on information technologies and the digital revolution (Bush 1945).

[54] Bell had published a paper in 1880 recounting his failure to achieve this, titled *Application of the Photophone to the Study of the Noises Taking Place on the Surface of the Sun* (see also Kahn, 2013)

acoustic system using parabolic reflectors that amplified and directed the signal, the *Photophone* - named after Bell's device - which used a beam of sound-modulated light, and the *Radiographone*, which was the first mobile radio system, based on electric arcs. The parabolic acoustic reflectors were coupled with radio antennas to create a directional beam of radio waves (figure 2.13). An early test of De Moura's system in 1894 revealed it was capable of communicating at a distance of up to 8 kilometers. Later on, De Moura claimed that *Esophone* could reach 6-8km, the *Photophone* 8-11km, and the *Radiographone* 16-25km. Unfortunately, de Moura's Brazil was not as open as Europe to such innovations. A bishop above him in the ecclesiastic hierarchy deemed his work akin to witchcraft and believed that the device transmitted Satan's voice. De Moura was ordered to stop this work, and a year later his lab was broken into and vandalized by christian fanatics (Lochte, 2000). It took him 5 years to recreate the apparatus, for which he then received a Brazilian patent in 1901. In the same year he filed for a US patent as well; 3 years later and after many tribulations he received 3 patents. By then, however, he was too late. The Marconi Company had already become too powerful and his technology was becoming rapidly obsolete.

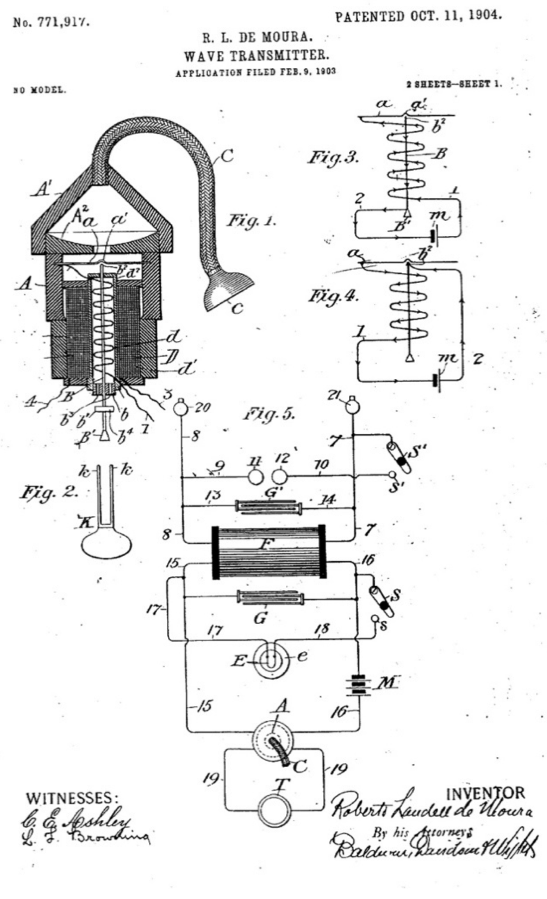

Figure 2.13. Diagram of De Moura's wave transmitter submitted in support of the US patent he was granted many years after his original 1893 invention, in 1904 (De Moura, 1904).

2.2.3 *Nikola Tesla's early electromagnetic vision (1889-1893)*

Nikola Tesla was another visionary who, among many other things, created an early prototype of wireless communication. While his work on the subject was sporadic, it was significant. As Aitken points out: *"Whenever you look in the early history of radio technology, you run into the name of Nikola Tesla. Tuning circuits, high-frequency alternators, rotary spark transmitters-name almost any device that became important in the later history of radio, and you can find an anticipation by Tesla"* (Aitken, 1985/2014b, 170). Born a Serb in the Austrian Empire and living in the United States since 1884, Nikola Tesla was an extremely talented and prolific inventor who opened up many new technological fields (Marinic, 2006). He published hundreds of articles and acquired almost 300 hundred patents. Many of them were fundamental for the development of various wireless technologies, although his work was often blatantly copied or re-invented by others without giving him any credit. The scope of Tesla's vision went far beyond that most of his scientist and inventor peers, encompassing radical ideas about mankind and its future that were often ahead of his time - to the point of getting repeatedly ridiculed. For instance, and among many other projects, one of his grand enterprises was creating a network that could deliver unlimited electrical power wirelessly across the globe at a low cost. He also believed that weather could be controlled, and that communication with intelligent life in other planets was possible (he in fact claimed at some point to have captured encoded signals from Mars). He worked on numerous different projects in his life, taking on new ideas and pausing others at whim when a new subject captured his attention. Tesla's vision of the future was radical. While he was not alone in his dreams of empowering humanity through electricity at the time, he was the one to come closest in making this a reality.[55]

Tesla learned of Hertz's experiments during a trip to Paris in 1889 owing to the German's research having *"caused a thrill as had scarcely ever been experienced before"* (Tesla, 1919). He mentioned being *"fairly burned with desire to behold the miracle with my own eyes"* but had to wait until 1891 to conduct his own experiments as he was busy with setting up a power transmission system for Westinghouse, the company licensing his alternating current patent (Ibid). Finding Hertz's original instrumentation limited, Tesla began to construct his

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[55] Schwartz writes: *"While Edvard Munch and his circle of anarcho-socialist friends in Berlin were speculating in 1893 on how to convert atmospheric electricity into free power for the planet, six-foot-six Nikola Tesla had been standing tall in London and New York theaters, dapper and unruffled amid balls of electric flame on platforms charged with hundreds of thousands of volts, proud that his alternating currents, safe and efficient, were about to light up the White City of Chicago's Columbian Exposition."* (Schwartz, 2011, 413)

own version, first building several variants of a 15KHz alternator to generate electromagnetic waves. He subsequently made an important breakthrough with the invention of the resonant transformer and the Tesla coil. With this superior instrumentation he reproduced the same phenomena as Hertz *"greatly magnified in intensity"* but thought they were *"susceptible of a different and more plausible explanation"* – a form of conduction rather than radiation (Ibid). Tesla decided to confer with Hertz on the matter and visited him in Bonn in 1892. However, the meeting did not go very well as Hertz *"seemed disappointed to such a degree that I regretted my trip and parted from him sorrowfully"* (Ibid). Tesla would continue to disagree with Hertz's interpretation of the phenomenon, arguing against the existence of radio waves. The key point of the misunderstanding was that the aether – which was part of Hertz's model – was according to Tesla not a solid but a gaseous substance that could only transmit longitudinal waves, not transverse ones (Secor, 1930). He believed that his own work was based on different principles, stating that *"[i]n reference to Herzian telegraphy, I have been a disinterested overlooker, as I devoted my self to my own system"* (Tesla quoted in Thompson, 1902). He promoted his system as *"the direct opposite of Hertzian wave transmission"* claiming that in it *"the Hertz waves"* – which pass through air, are *"effected by rays akin to light"*, and *"cannot be transmitted through the ground"* – are *"practically suppressed"* and instead transmission occurs entirely *"through the ground"* which acts likes *"a big wire"*.(Bottone, 1909). Today we know that the aether does not exist, and that Hertz was the one to correctly identify the phenomenon, not Tesla.

In February 1892 Tesla gave a series of lectures in London and Paris titled *Experiments with Alternate Currents of High Potential and High Frequency* (figure 2.14).[56] In these lectures he set the foundation of radio engineering, as he went on to describe resonance, tuning circuits and antenna circuits (Marincic, 2006). He also spoke about "*no-wire"* motors, and gave his vision of a future, where "*'ere long intelligence - transmitted without wires—will throb through the earth like a pulse through a living organism"* (Tesla, 1892). These were presented as "*starting points of new departures"* that were already possible with *"the present state of knowledge and the experiences gained"* (Ibid).

Twelve months later, Tesla gave two lectures in the US (in Philadelphia and St. Louis) titled *On light and other high frequency phenomena,* elaborating on the subject of wireless

[56] On February 3 1892 he spoke in front of the Association of Electrical Engineers (London), on February 4 at the Royal Society (London), and on February 19 in front of the International Association of Electric Engineers and the French Society of Physicists (Paris).

telegraphy and the instrumentation required:[57] *"In connection with resonance effects and the problem of transmission of energy over a single conductor which was previously considered, I would say a few words on a subject which constantly fills my thoughts and which concerns the welfare of all. I mean the transmission of intelligible signals or perhaps even power to any distance without the use of wires. I am becoming daily more convinced of the practicability of the scheme. (...) My conviction has grown so strong, that I no longer look upon this plan of energy or intelligence transmission as a mere theoretical possibility, but as a serious problem in electrical engineering, which must be carried out some day. The idea of transmitting intelligence without wires is the natural outcome of the most recent results of electrical investigations"* (Tesla, 1893).

Figure 2.14. Illustration of Nikola Tesla's famous 1892 Paris lecture for the French Physical Society and the International Society of Electricians, showing him illuminating Geissler tubes (a kind of gas discharge tube similar to fluorescent lights) without using any wires (Hospitalier, 1892).

2.2.4 *Tesla the electr(omagnet)ic performer*

Tesla was not only a scientist, engineer and inventor; he was also a riveting performer drawing and captivating large crowds with his extravagant demonstrations of scientific

[57] These took place on February 24 1893 at the Franklin Institute in Philadelphia, and on March 1 before the National Electrical Light Association in St. Louis.

effects and inventions. His lectures would be best described as lecture-performances today – an idiosyncratic mix between a TED talk, a high-tech new media performance, and a magician's show full of theatrics. Tesla would typically start by presenting an aspect of his wild technocratic vision of humanity's future, then discuss the science required for it, and demonstrate the innovative, quasi-magical devices and technologies he had created and through which this vision would become a reality. The human body was often an interface or instrument integral to the experiment, and audience interaction was often involved. These demonstrations were about concepts as much as they were media-centric performances designed with an unmistakable penchant for showmanship. They seem rather odd when regarding them from the perspective of contemporary science, as today we have become accustomed to such lectures and demonstrations being presented in a rather dry and ascetic style – likely because this is deemed more 'objective' today. Instead, Tesla's lectures should be understood within a historical tradition and the context of his era, and in particular through their relationship to their contemporary scientific demonstrations and electrical wonder shows.

The demonstration of wondrous effects was thought to be a successful device for inciting explorations by natural philosophers during the Renaissance, producing a sense between feeling and knowing and stirring both passion and intellect. By the 19th century however, as the laws of nature were thought to be precise like clockwork, wondrous irregularities were no longer thought conducive to sublime experiences, which were now to be induced by nature and art rather then mechanistic, technological marvels (Nadis, 2014). Natural philosophers shifted to a more detached presentational mode, leaving wonders to magicians who used them as a means to both entertain and educate the masses. Stage performers began mixing magic with natural philosophy and scientific experimentation to demonstrate the wonders of science within the context of spectacle. Renowned stage magicians would stress the rational nature of their tricks, positioning themselves as patrons of science while often denigrating their opponents as spiritualist quacks. As Nadis remarks, at that time *"[t]he separation between highbrow and lowbrow culture, the divide between education and entertainment, and that between "good" science and "bad" science were not that clear-cut."* (Nadis, 2014, 45).

The mid of the 19th century saw an increase of publications, lectures, and exhibitions on electricity. In Britain, electrical experimentation was disseminated to the public through lectures and demonstrations by natural philosophers from the higher classes, as well as by inventors from the lower classes. Such lectures were necessary for audience cultivation, which was in itself necessary to support one's research; thus, *"[t]he natural philosopher's performances were often highly theatrical affairs"* (Nadis, 2014, 24). For example, Faraday's status had grown from that of a handy tinkerer to that of an important natural philosopher partly because of his fascinating and widely popular lectures at the Royal Institution and demonstrations for the elite. The middle and working class would instead frequent venues akin to contemporary science and technology museums, where artisan engineers from the lower classes offered "*spectacles and examples of industrial arts and working machinery"* focused on practical applications rather than science for its own sake (Ibid, 25).

The situation in the US was quite different. Itinerant shows were the norm, as very few institutions looked to educate the public by hosting performers that popularized science. Electrical wonder shows, in particular, were beginning to take the place of medicine shows, focusing on electrical technology in both scientific and speculative applications, such as electro-medicine.[58] Popular celebrations of the *technological sublime* became more and more common in the wonder shows that were thriving in the US by the 1830s. Automata, visits of the dead, electrical healing, and more were there to satisfy the increasing public interest on science, pseudoscience, and the new technologies that were changing people's lives. As Nadis writes, *"[w]onder showmen worked at the boundary of science and magic, relying on wonder to help their audiences suspend disbelief. To prop up their version of the fantastic, they continually cast scientific and technological breakthroughs in magical terms and remnants of a magical worldview in scientific terms"* (Nadis, 2014, 14). Electricity was a particularly successful medium: highly technological and futuristic, but also connecting to ancient ideas of invisible unknown powers and magic. This was exacerbated by the fact that, even by the end of the 19th century, the maxwellian understanding of electromagnetism was hard for people to grasp. At the same time, renowned scientists like Crookes, Lodge and Edison believed there was a connection between electromagnetic and psychic research. Tesla, being utterly rational and a materialist but also having an extremely intuitive grasp of electromagnetism, believed in the therapeutic powers of high-frequency electricity and had constructed an instrument with which he self-medicated (Tesla, 1898).

Towards the end of the 19th century, electricity was becoming a lived reality and was a

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[58] Electromedicine was not a fringe concept and it had led to some significant findings. For instance, the idea of electricity as a life force had been behind Galvani's experiments and behind Volta's development of the first battery. The concept also had deep roots in human history, as amber and lodestone were believed to have medicinal value for millennia due to their electric and magnetic properties.

central feature of many spectacles.[59] Its advent brought forth endless debates on the nature of technological innovation and whether it was an inevitable part of progress or a diabolical destructive force. While the connection between magic and science was old, it was also strongly encouraged by corporate propaganda, by the inventors themselves, and by the press. Nadis explains: *"Just as wizards might be practitioners of "black magic" or "white magic," so could the modern technical elite be envisioned as wizards or destructive mad scientists (...) The inventor as wizard was a favored journalistic motif from the 1880s through the 1930s, and it implies the priestly esteem the public then granted the technical elite. In the public eye, the inventor could blend the traits of the scientist, the artist, and the mystic"* (Nadis, 2014, 50-51). Edison was called 'the wizard of Menlo Park' after inventing the phonograph in 1878 and, similarly, Tesla was hailed a wizard after demonstrating his alternating current inventions ten years later. His patents would make him a key player in the so-called *war of the currents* and an adversary to Edison - under whom he had worked briefly - pitting Westinghouse's alternating current against Edison's direct current. While Edison encouraged a sinister campaign that led to the execution of horses, calves, an elephant, and finally human convicts to prove that his competitor's technology was deadly, Tesla - a natural born showman - was the perfect promoter of alternating current's safety and miraculous applications (Hagen, 2008, 56). There is no doubt that his thrilling performances were excellent for marketing purposes and that they had an effect in making his achievements widely known to the public. To amplify his message, Tesla consciously used his seductive persona to lure his audience, as is evident in people's accounts and photographic documentation (Czegledy, 2008a). He was also very capable in using the press to his advantage. In this respect he was quite like Marconi, who soon succeeded him as the new wireless wizard, portraying a very different type of entrepreneurial showmanship that would bring him immense commercial success.[60]

Tesla gave his first such 'show' at Columbia University in 1891 for the American Institute of Electrical Engineers (figure 2.15). He presented his coil, the principle of tuning, and lights and motors that he powered wirelessly. More spectacularly, he passed hundreds of thousands of volts through his own body, giving it a violet electric glow and shooting sparks from his fingertips. This debut was followed by two lectures in London on February 1892, which also

[59] For more information on the electrical parties, electrical weddings and electrical haunted houses of the 1880s-1890s, as well as on an electrical ballet and Edison's electric float from the same time see Nadis (2014, 48-57).
[60] Marconi gave a 'Tesla-esque interview' in 1912, presenting many of Tesla's visionary ideas as his own and gaining for himself the title of a 'wizard'. (Nadis, 2014).

gathered large crowds, impressing public and scientists alike and earning him the status of a celebrity back home.

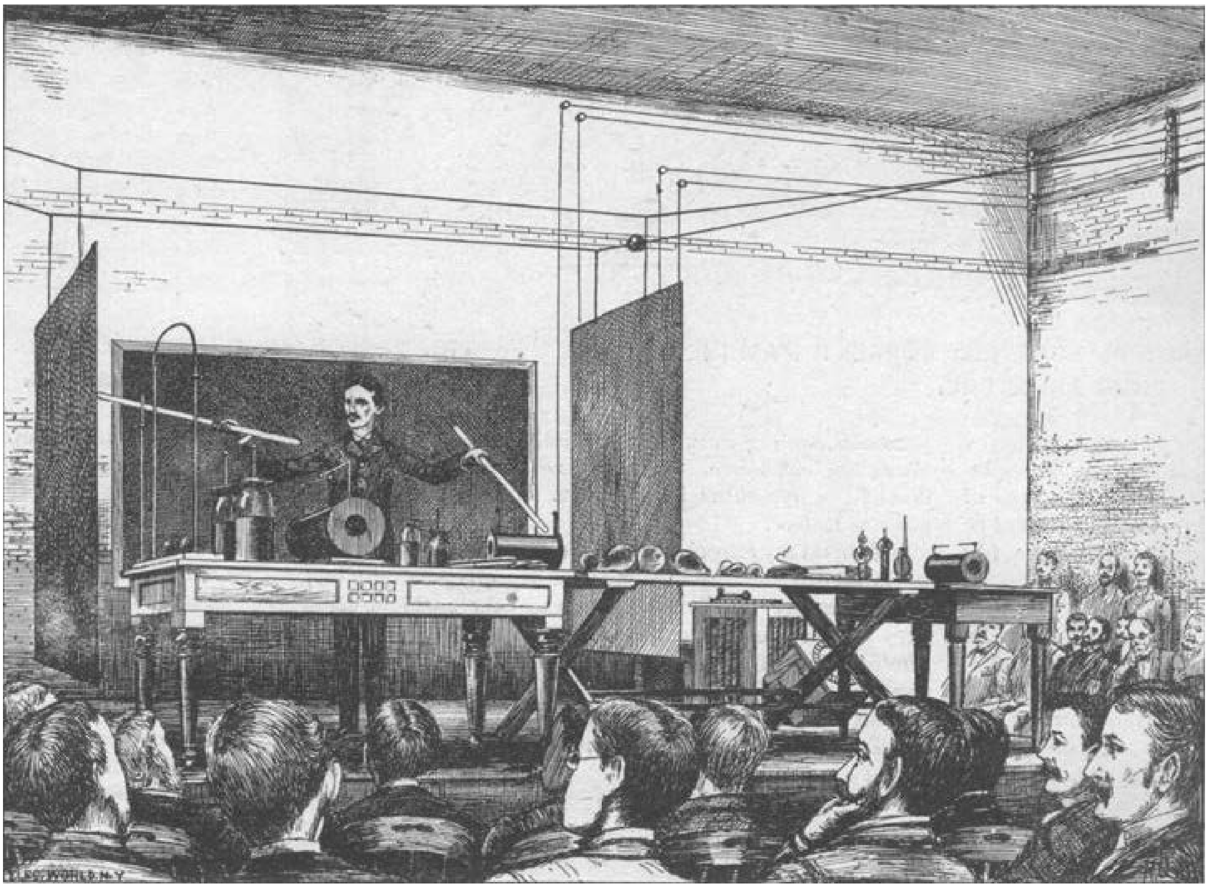

Figure 2.15. Illustration of Nikola Tesla’s 1891 lecture before the American Institute of Electrical Engineers at Columbia University, showing him performing experiments behind tables full of equipment (from Tesla 1891).

In 1893, he gave his St. Louis lecture-performance in a sold-out 4000-seat auditorium, spectacularly demonstrating how his concept of transmitting intelligence worked. He began with an elegy on Nature, the senses, and the eye. This was Tesla’s 'big-picture' introduction to the subject of electricity, brimming with scientific explanations but *"at the peril of treading upon metaphysical ground"* (Tesla, 1893). He then proceeded with a series of experiments - some performed for the first time - presenting the ideas and phenomena behind each one. Tesla spoke in detail about his instrumentation, setup and results, then performed what would have seemed like magic tricks without this explanation. An article from The Electrical Engineer magazine reports: *"He received, unhurt, currents of hundreds of thousands of volts, lit up tubes and lamps through his body, rendered insulated wires several feet long entirely luminous, showed a motor running under the influence of these million-frequency currents, obtained a number of effects with phosphorescent lamps (...). His ability to produce such* *effects, either with a single wire and no return, or without any wires at all, aroused the utmost interest and enthusiasm and the concluding demonstration literally brought down the house, when he showed how by simply carrying lamps or tubes into a room or hall where those currents were being developed, illumination was the immediate result"* (Martin, 1893). In this visually stunning experiment, "*a number of tubes were taken and flourished or flashed in various ways, and with the current made intermittent at longer intervals by adjusting the spark-gap. Wonderfully beautiful effects were thus produced, the light of the whirled tube being made to look like the white spokes of a wheel of glowing moonbeams. Then some rectangular tubes were taken and flashed or whirled so as to produce curious designs of luminous lines"* (Ibid). Tesla's arsenal of visual effects concluded with a filamentless bulb that produced *"a most dazzling light, far beyond that yielded by any ordinary phosphorescence",* and a rectangular frame with thin wires stretched on it that he would illuminate *"so that in the dark they looked like attenuated violet caterpillars yards long; and then within a large rectangle formed by such wires he flourished tubes in the interspace, these tubes flashing with light wherever waved."* (Ibid).

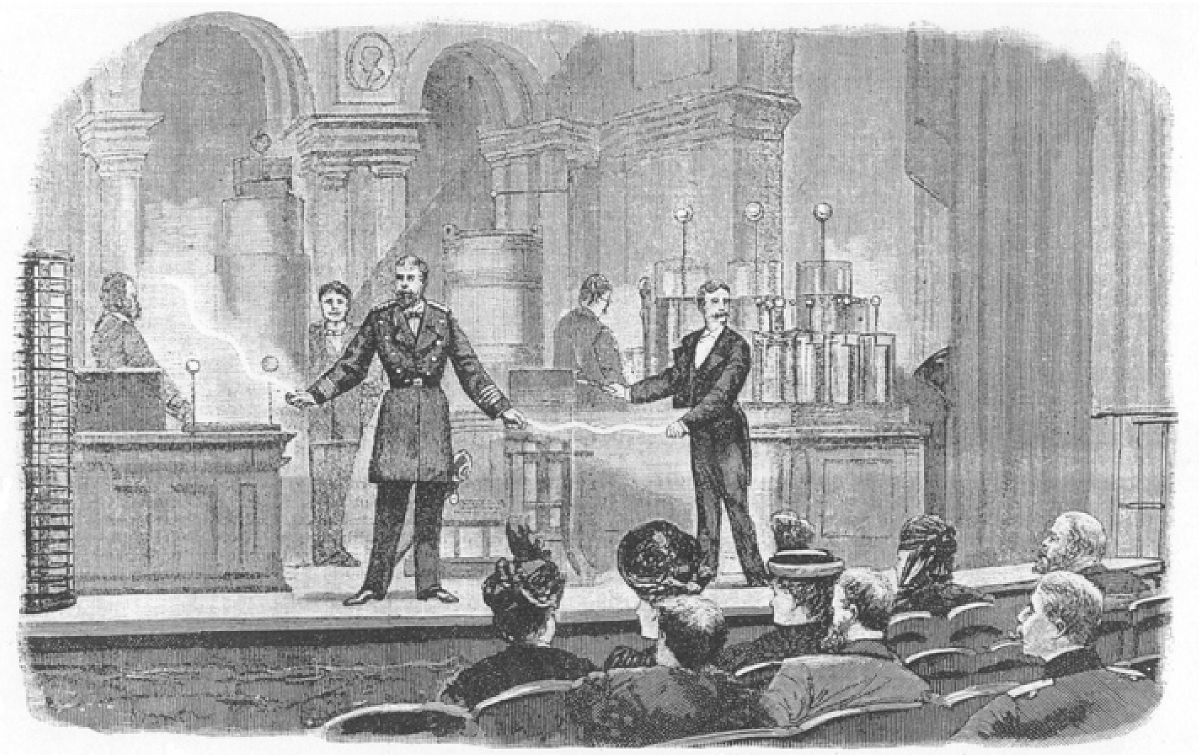

Figure 2.16. Illustration of an 1895 Tesla lecture in Berlin, showing an experiment in which Prince Henry, the German Emperor's brother, became a living conductor as he stood between high tension terminals while holding glowing Geissler tubes (from "Inventor Tesla's loss" 1895).

Tesla's sensational lecture-performances continued during the Chicago World's Fair, an international event promoting Westinghouse's alternating current. The fair was a massive spectacle on electricity whose success finalized the victory of Westinghouse over Edison, earning Westinghouse a contract for a new power station at Niagara Falls and keeping Tesla fully occupied for some time. Tesla continued giving lectures around the world, occasionally in a participatory format that involved audience volunteers (figure 2.16). His performative vision was not limited to lectures, however. At the turn of the century, he would speak of turning war into a spectacle of extreme proportions where humans are removed and machines fight against machines in *"a mere spectacle, a play, a contest without loss of blood"* (Tesla, 1900).

2.2.5 *Oliver Lodge transmits the spark (1894)*

Another key figure for the development of electromagnetic science and technology was British physicist Oliver Lodge. He was an esteemed scientist and teacher with an eminent social standing and many connections that earned him a knighthood in 1902. His work was well known and very influential, starting from a diametrically opposite point than Hertz's: While Hertz proceeded with great care to verify whether Maxwell was correct (as, in his circle, this was not at all evident), for Lodge the theory was undoubtedly correct so he created his experiments with that as a given. In 1879, a few months before Maxwell's death, Lodge begun to investigate how to generate electromagnetic waves. Together with George Francis FitzGerald he produced the *"first unambiguous description of how to generate electromagnetic waves other than light"*, but without knowing how to detect them yet (Sengupta & Sarkar, 2006, 224). Lodge therefore focused on wired experiments. In 1888 he presented his research to the British Association for the Advancement of Science, verifying Maxwell's equations with results very similar to Hertz's wireless experiments, which he learned about soon thereafter. Immediately recognizing their importance, he repeated them in 1890 with similar results. From that point on, Lodge became pivotal in disseminating Hertz's work, giving him complete credit and even stating that "*Maxwell and Hertz are the essential founders of the whole system of wireless*" (Lodge quoted in Aitken, 1976/2014a, 82).

A gifted inventor himself, Lodge adopted Hertz's instrumentation and made a key improvement that would foster the birth of wirelessesness: He replaced Hertz's spark detector with the more sensitive Branly coherer. This device was essentially a self-contained version of Faraday's electromagnetic visualizer: a tube made from insulating material (glass) that contained iron fillings between two conductive plates. The instrument was developed in 1890 by French physicist Edouard Branly after his rediscovery of the cohesion effect, in which small particles increase their conductivity under electrical influence – such as from a nearby spark.[61] Branly's 1891 publication caught Lodge's attention. He was the first to recognize the potential of this device (which he named 'coherer') as a detector of electromagnetic energy. Lodge thus produced the instrumentation that would be at the foundation of many radio innovations to come, as Branly's coherer was able not only to detect electromagnetic radiation, but also to differentiate between patterns, such as the dots and dashes of Morse code [62]

Hertz's death in January 1894 would, in a way, become the catalyst for the birth of radio communication. On June 1st, Lodge gave a memorial lecture at the Royal Society, titled *The work of Hertz and some of his successors*, to honor the deceased scientist and to present the state-of-the-art in electromagnetism. As part of this lecture, Lodge presented his own improved system for transmitting and receiving signals with 'hertzian waves'. Placing transmitter and receiver in different rooms, he successfully demonstrated wireless communication at a distance of about 40 meters and through several walls (Mallik, 1986 and Hong, 2001). The flicker of a spark and the ringing of a bell were not enough to excite his audience, however, despite the potentially groundbreaking applications - which Lodge did not spend time elaborating on. The dry delivery of the experiment, the lack of groundbreaking vision and the absence of any spectacular theatrics were a stark contrast to what that audience had witnessed in Tesla's lecture a couple of years earlier (Hong, 2001). Lodge followed with three more lecture-demonstrations in Oxford in August and September, in which he used a Morse instrument to automatically reset the coherer so it could receive again (figure 2.17). This would allow Lodge to later claim (after a suggestion of Alexander Muirhead, his future partner in the wireless telegraphy business) that he had been the first to invent wireless telegraphy that summer using Morse code to send letters of the alphabet rather than pure signals, and that he merely chose not to demonstrate the technique in his

[61] This effect had already been observed by a number of scientists in the past: Guitard (1850), Samuel Alfred Varley (1866), Lord Rayleigh (1879) and Temistocle Calzecchi-Onesti (1884-85) who, unbeknownst to Branly, had performed very similar experiments to his (Lindell et al., 2006).

[62] Hughes' electromagnetic detector from 1879 was quite similar to the Branly coherer but used powdered carbon instead. Nonetheless, it was practically unknown to the scientific community.

lectures because the audience was too large - a claim that is likely untrue (Hong, 2001).[63] Nevertheless, Lodge's June 1894 lecture would have a long-lasting resonance as it was published around the world, inspiring many theorists and practicians alike to work with electromagnetic waves.

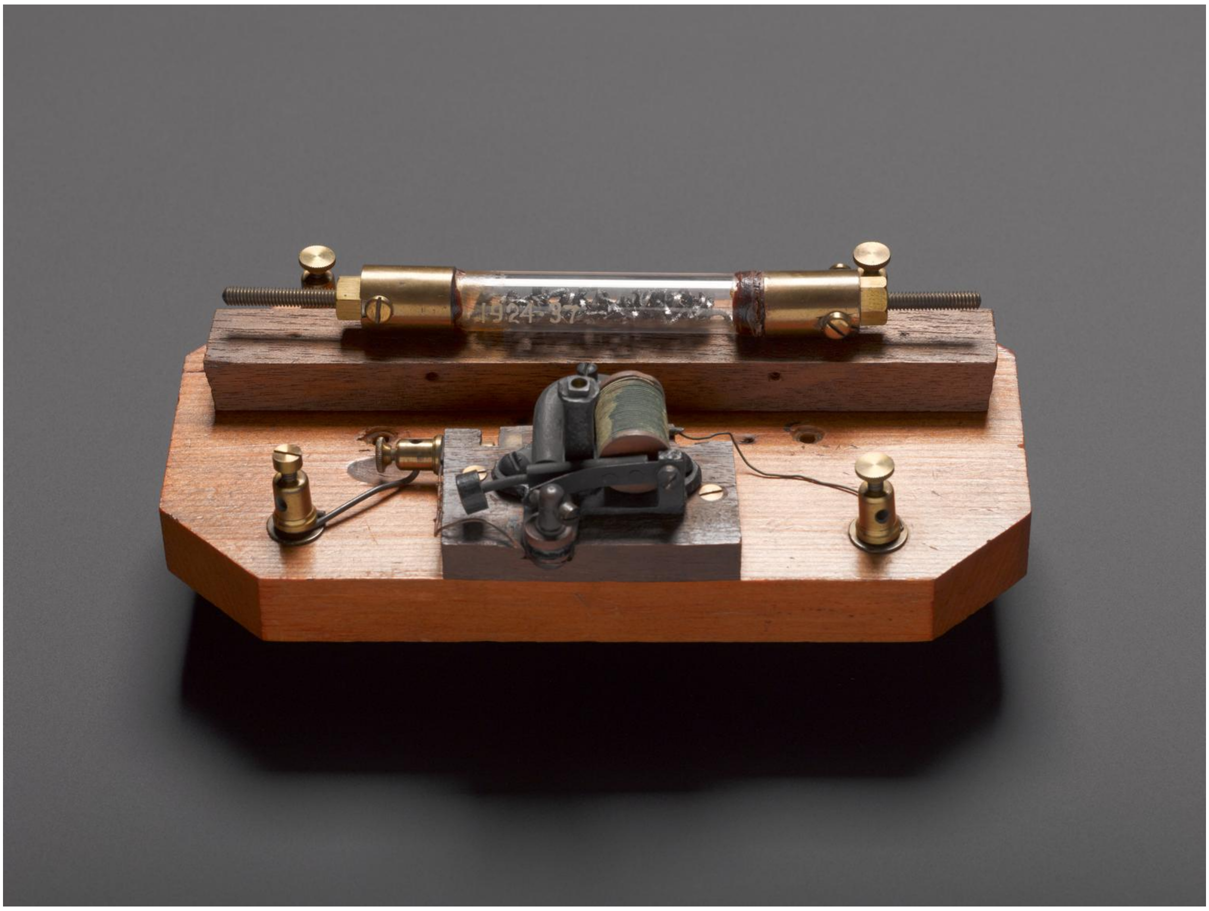

Figure 2.17. The Branly coherer (i.e. a hertzian wave receiver) used by Oliver Lodge in his August 14th, 1894 lecture at the British Association, likely self-fabricated by him. The iron borings inside it were restored to their original state by the vibrations of the Morse electric bell mechanism ("Two iron boring coherers (Branly type), 1894", 2021).

2.2.6 *Jagadis Chandra Bose's microwave transmissions (1894-95)*

One of the scientists inspired by Lodge's lecture was Jagadis Chandra Bose, a physicist and biologist from Bengal, India. Bose was a pioneering figure of early electromagnetic studies (and later biophysics and bioelectricity) though he remained largely unknown due to him working from the periphery – and most likely also because he was a brown man from the

[63] This is a continued source of confusion in the literature, and understandably so as the question of who was the first to invent wireless telegraphy had important legal and financial implications. For more details, see Hong (2001, 28-36).

colonies.[64] After his studies in India, Bose moved to London to study medicine. However, because of a health problem, he turned to science and became a pupil of Lord Rayleigh in Cambridge (Yadugiri, 2010). Bose read Lodge's lecture in Calcutta, where he had returned to teach physics. Working in significantly more challenging conditions than his European and American peers, he converted a small storage space adjoining a bathroom into his laboratory and began researching small wavelength phenomena in the microwave band (Emmerson, 1997). This frequency range was completely un-studied at the time, but was the only range physically possible for Bose to study in his tiny lab space - as Aitken (1976/2014a) points out, the sizes of the spaces that researchers had available for their radio experiments played an important role in the wavelengths they studied, and consequently in the results they produced.

The materials and equipment available to Bose were also meager, so he proceeded to fabricate his own instruments. He improved Hertz's transmitter design early on, and managed to tune it to a narrower band. He introduced a waveguide to aid with transmission and developed the horn antenna, a more sensitive mercury coherer (detector) and many other circuits (figure 2.18). He also invented a set of measurement instruments such as a millimeter wave spectrometer with which he studied the reflection, refraction, diffraction, and polarization of electromagnetic waves, particularly between 12-60GHz (Sarkar & Sengupta, 2006 and Ghosh, 2000).

While Bose's primary focus was on the study of the optical properties of electromagnetic waves, he was also one of the very first to perform wireless signaling experiments and demonstrations. There are conflicting reports on when exactly his first public demonstration of microwave signaling occurred - November 1894 or May 1st 1895 (see Indian National Science Academy, 2001 and Ghosh 2000 respectively). Most likely, Bose gave several such lecture-demonstrations in various venues, such as his college and the Calcutta Town Hall. In them, he reportedly transmitted 6mm radio signals (around 50GHz), receiving them at a distance of over 20 meters and after they had passed through multiple walls and bodies (such as that of the Lieutenant Governor of Bengal in a Town Hall lecture), activating circuits that rang a bell, that fired a pistol, or that detonated a miniature mine (Sarkar & Sengupta, 2006).

[64] Bose also wrote the first Bengali work of science fiction.

Figure 2.18. Photo of the 60GHz microwave transmitter and receiver devices invented by J. C. Bose and used in his innovative experiments in 1897. The box on the right contains a spark gap transmitter and is made of metal to shield its coil, preventing its EMF noise to reach the receiver; its microwave transmissions radiate via a tubular waveguide. The receiver is on the left and also uses a tubular horn antenna with a galena point crystal rectifier in it and a galvanometer to display wave detection. All equipment pictured is original, besides the battery and galvanometer (photo by Biswarup Ganguly, Wikimedia Commons).

2.2.7 *Alexander Popov: from radio meteorology to communication (1894-95)*

Russian Aleksandr Stepanovich Popov was another physicist influenced by Lodge’s 1894 lecture. At the time, Popov was working as an electrical engineering teacher and researcher at the Naval Department’s Torpedo School in Kronstandt. The Torpedo School, located in the main Russian naval base near St. Petersburg, offered courses in electricity, galvanism, magnetism, explosives and submarine mines. It also had a library and one of the best physics laboratories in Russia at the time (Radovsky, 1957/2001). Popov had studied Maxwell’s theory at the University and had been keeping up to date with electromagnetic research conducted by scientists around the world, like Hertz, Tesla and Lodge. In 1890 he repeated Hertz’s experiments and taught his first course on electromagnetic waves. Following a visit to the 1893 Chicago World's Fair, he began to focus on 'hertzian waves'. A year later, after reading Lodge's lecture, he created his own apparatus – developing a variant of Hertz’s transmitting oscillator – and replicated Lodge's coherer experiments.

Popov's background, as opposed to Hertz's and Lodge's, favored practical applications of scientific achievements (Radovsky, 1957/2001). As such, he conducted research with a practical application in mind: to develop an instrument for detecting approaching thunderstorms. Aitken, unfairly regarding this idea through a lens that put communication above other wireless applications (a perspective shared by many radio historians), commented critically: "*Popov knew as much about Hertz's work as Lodge did and was well acquainted with Lodge's experiments, yet the only immediate utility he saw in the new technology was a meteorological one*" (Aitken, 1976/2014a, 305-06). Nevertheless, considering Popov's occupation with marine matters and navigation, this approach was both imaginative and useful. Proof to that is that the lightning detector he devised in 1895 remained in use until 1922.

Popov's device, dubbed the *Thunderstorm Recorder*, and also referred to as *Lightning Detector*, was completed in April 1895. The instrument consisted of an electromagnetic detector connected to ground and to an *"ordinary lighting conductor"* (essentially an antenna) (Zolotinkina, 2008, 116). This configuration allowed the operator to listen to natural radio signals produced by lightning, with the atmosphere functioning as the transmitter of this one-way communication system. Popov made improvements to the antenna circuit; he also developed a refined version of the Branly/Lodge coherer that featured a way to automatically tap and reset it with the use of an electric bell that produced long and short sounds in response to the received signal (Ibid). By July of the same year, he had further developed the instrument to automatically inscribe the atmospheric radio signals on a paper strip (Zolotinkina, 2009).

Popov's system was radically new, although he was not the first to attempt weather forecast. British Admiral Robert FitzRoy had created a storm-warning network already in 1860, analyzing weather information obtained via coastal telegraph stations. While FitzRoy's forecasts were sanctioned by the government, they were harshly ridiculed by the press when mistaken, with claims to predict the island's notoriously chaotic weather seen as a hubris by Brits at the time (Schwartz, 2011, 400-401 and Moore, 2015). A few years after Popov, in 1899, priest, meteorologist, and physicist Frederick L. Odenback from Cleveland, US invented a similar instrument to the *Thunderstorm Recorder*: A radio receiver captured electrical disturbances in the atmosphere, which were subsequently visualized with an apparatus that recorded them in a revolving drum (the *Ceraunograph*). This was accompanied by the *Ceraunophone,* an instrument that made atmospheric activity audible not as a binary signal, like Popov's bell, but by directly transducing those disturbances into sound. As Schwartz comments, *"[t]elephone and telegraph* operators *had heard these 'sferics' for decades as awful pops and cracklings on the line; now meteorologists would make something meaningful of that static"* (Schwartz, 2011, 392).

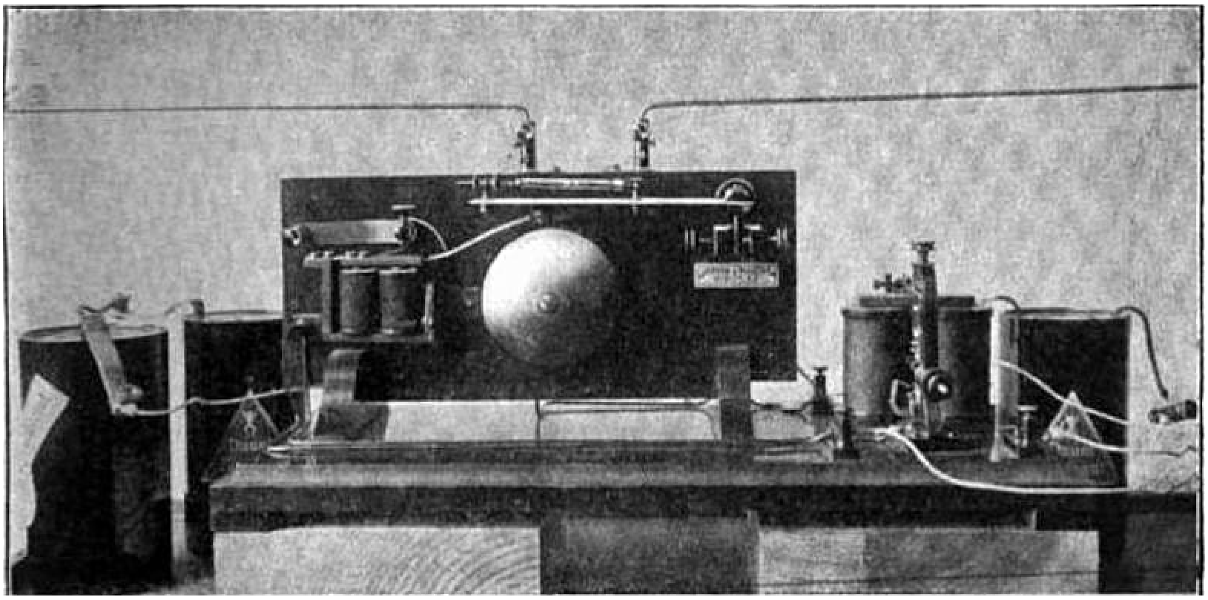

Figure 2.19. Photo of Alexander Popov's wireless receiver invented in 1895 by adapting his *Thunderstorm Recorder*, possibly featuring the original device (from Partheil. 1907). The dipole antenna (top) receives radio waves which are passed through to the Branly coherer (the horizontal tube right below it). As the metal powder inside it coheres, it powers a DC circuit that rings the bell below. The bell's vibration resets the coherer.

The technology's potential for communication did not escape Popov. In April 1895, during a presentation of his invention to the Russian Physical and Chemical Society, he stated that his device was not limited to meteorology but could also function as part of a wireless communication system when paired with a transmitter and a powerful enough generator (figure 2.19). Testing this idea earlier, he had achieved successful signaling at distances of up to 64 meters at the Torpedo School garden using a special portable device (Schwartz, 2011). One can picture Popov holding his receiver and bell, listening attentively for a ring as he walked in the garden further and further away from his transmitter. This ambulatory exploration is a common trope of investigating electromagnetic fields and their strengths, resembling Hughes's 1879 exploration, Signal Corps soldiers engaging in Direction-Finding operations in WWI, but also several Hertzian artworks, like Christina Kubisch's *Electrical Drawings* (section 3.3.3) and *Electrical Walks* (section 3.3.4), Edwin van der Heide's *Radioscape* (3.3.2), and my piece *'Act so that there is no use in a centre'* (section 4.3). On

May 7, Popov accompanied the presentation of another paper on lightning detection with a successful demonstration of message transmission. According to an article in the *Kronstandt Herald* (*Kronstadtskiy Vestnik*) from May 12, Popov rang a bell using 'hertzian waves' from a distance of about 12 meters (Michaelis, 1965, Zolotinkina, 2009 and Zolotinkina et al. 2009). This was a groundbreaking feat, making Popov one of the very first to demonstrate a functioning radio communication system. Nonetheless, the news did not cause much sensation in Russia or abroad. It would take 50 years and the beginning of the Cold War for the Soviet Union to start celebrating Popov as the inventor of radio, declaring May 7th as 'Radio Day'.

2.3 The Business of Wireless Communication

2.3.1 *Marconi and the wireless telegraphy race (1894-97)*

Augusto Righi, a scientist teaching at the University of Bologna and one of few around the world to understand Hertz's work at the time, was another important pioneer of 'hertzian wave' exploration. Righi focused on microwave optics, like J.C. Bose in India. He had designed a smaller apparatus than Hertz's with several innovations and alterations better fitting to investigate higher frequencies (figure 2.20). His research was centered between 1.5-5GHz (wavelengths of 7.5-20cm) near the range of today's WiFi, making him the first to explore that band (Kostenko et al., 2006).

Following Hertz's death in 1894, Righi wrote an obituary for an Italian journal and explained his experiments. This article reached the hands of a 20-year old by the name Guglielmo Marconi, the son of a rich Italian land-owner and the Irish/Scottish Annie Jameson, daughter of the Jameson whisky distillery founder and related to the Haig and Ballantyne families who owned their own distilleries in Scotland. These family connections would later prove very important (Aitken, 1976/2014a). Marconi had been interested in electromagnetic phenomena for some time already and was likely familiar with Tesla, having possibly read his book in 1894. He would later claim that as a youth, inspired by Benjamin Franklin's kite experiments, he had built an alarm that would sound a bell when it collected enough electricity from an approaching storm – an apparatus very similar to Popov's thunderstorm recorder (Dunlap, 1937).[65] Reading Righi's article made it clear to him that he could achieve wireless

[65] It is certainly not out of the question that Marconi fabricated this story during the many trials on his intellectual property, especially given that Marconi habitually claimed ideas of his pioneering peers as his own.

telegraphy with hertzian waves, an idea *"so simple in logic"* that he thought there had to be more *"mature scientists"* working on it (Marconi, quoted in Dunlap, 1937, 12). Indeed, Marconi was not the only one attempting to develop this technology, however he was certainly the only one with the entrepreneurial prescience to approach wireless as a business.

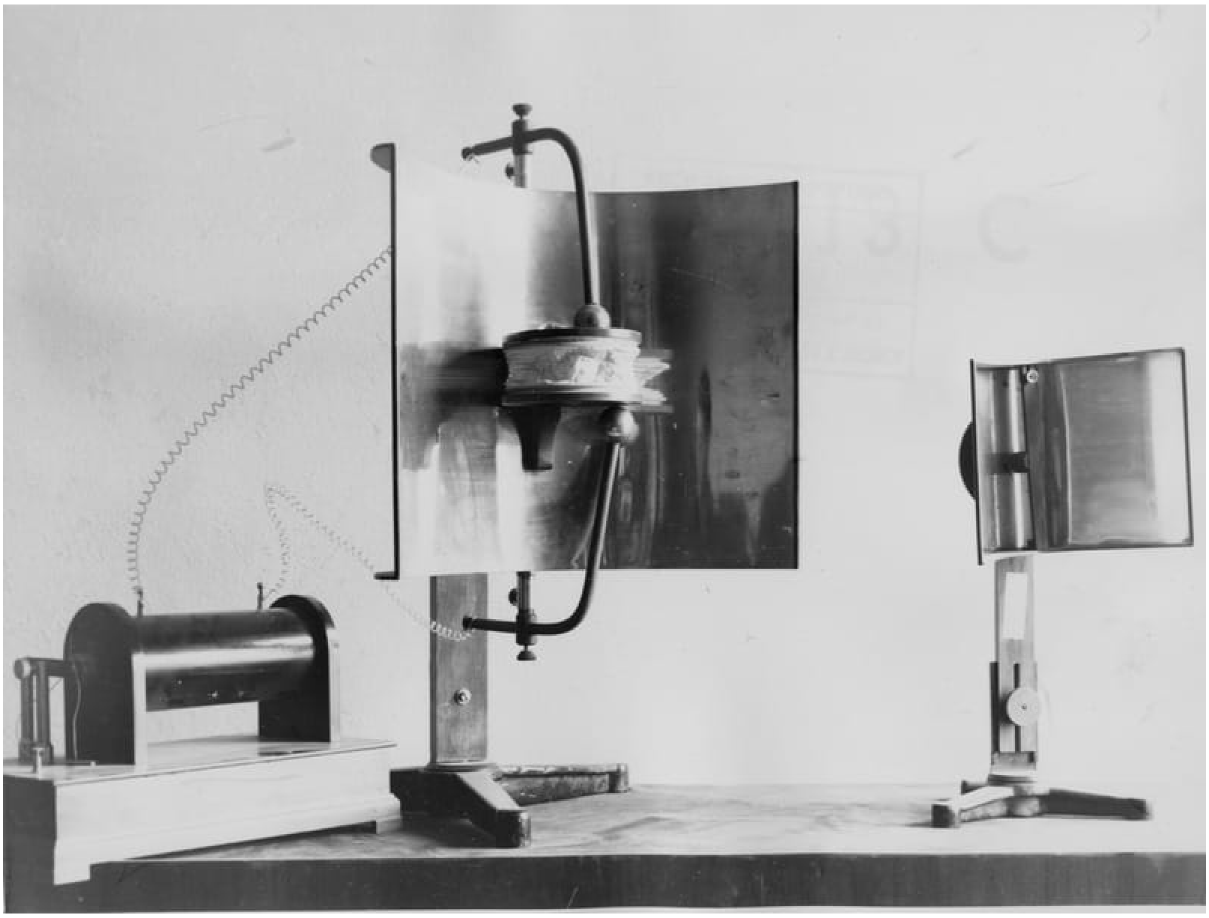

Figure 2.20. Photo of Augusto Righi's microwave apparatus, originally invented around 1894 and used in his experiments of the same year. High voltage pulses produced by the induction coil (left) generated sparks in the four-ball spark gap oscillator whose radiations was focused by the parabolic reflector (middle). The receiver (right) is also equipped with a focusing reflector thinly lined with a silver sheet that was incised with a razor blade to act as a dipole antenna; captured waves created sparks that rang a bell. The photo was taken by Augusto Righi himself between 1900-1955 (Wikimedia Commons).

By spring 1895, Marconi had built an apparatus that could send and receive Morse messages wirelessly (figure 2.21). He conducted his first tests indoors in his attic in Bologna – the same city where Galvani had made his frog leg experiments – at around the same time when Popov and Bose were demonstrating their own wireless communication systems in St. Petersburg and Calcutta respectively. By the summer he had moved outdoors, working on extending the range of transmission (a goal that would drive much of his research for his entire life) and negating the adversary effects of the landscape. Soon enough, Marconi managed to reach a distance of 2.4km; more importantly, he succeeded in sending messages to a receiver behind a hill, thus convincing his skeptical and stern father that this was a financial opportunity worth investing on (Aitken, 1976/2014a).

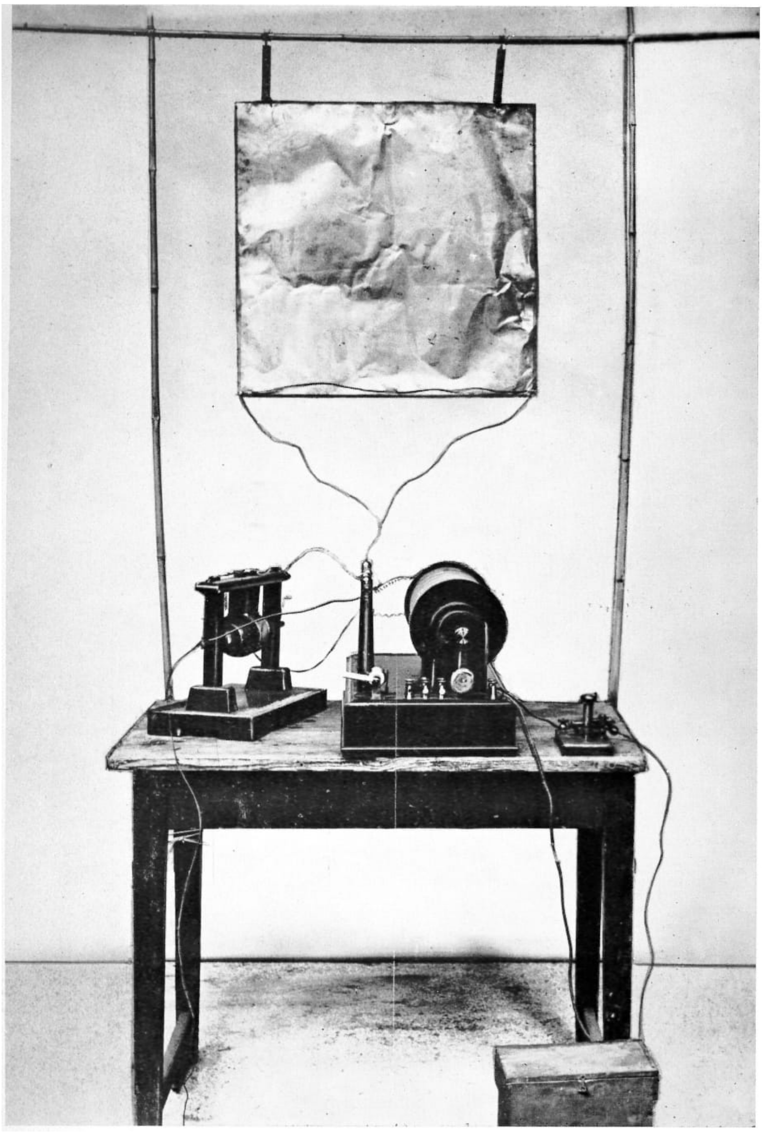

Figure 2.21. Replica of Guglielmo Marconi's first radio transmitter originally built in August 1895. It used a Righi spark gap connected to an induction coil (left side of table), powered by a battery (floor); the circuit was switched on and off via a manual switch (right of table) thus permitting the transmission of Morse signals. The transmitter was connected to Marconi's e monopole antenna invention, which involved connecting the transmitter to an elevated copper sheet (top) and to ground. This lowered the frequency of transmission and produced vertically polarized radiation with much increased range (photo from Marconi, 1926).

As luck had it, Righi happened to be a neighbor and a family friend, so Marconi began attending his lectures and consulting him, even though he did not have the formal qualifications to enter university. This gave him access to crucial theoretical and practical state-of-the-art knowledge that would otherwise be inaccessible to him. Marconi was very focused in solving the practical problems of tele-communication. While he was not a groundbreaking inventor, he was a meticulous experimenter and engineer, constantly tweaking and refining. Following Righi's suggestion, he started off with an instrumentation similar to Lodge's: Hertz's oscillator as a transmitter and Lodge's modified Branly coherer as a detector. Tesla's work was also added in the mix, with the transmitter complemented with a long vertical antenna connected to the ground (Marincic, 2006).

Marconi first approached the Italian government, but could not garner any interest in his invention. He therefore decided to go to England with his mother, who could put pressure through her family's connections. He arrived there in February 1896 with a complete technological solution to a pressing problem occupying many of the great minds of the largest naval power of that era: how to communicate with ships at sea. In spring, Jameson Davis - his mother's cousin - arranged him a meeting with William Preece, chief telegraph and telephone engineer for the British Post Office. Preece had long worked on the problem of wireless telegraphy himself and thus quickly recognized Marconi's achievement and knowledge. He was enthusiastic, even though he knew Marconi's system was based on already existing knowledge, commenting that *"Columbus did not invent the egg, but he showed how to make it stand on its end, and Marconi has produced from known means a new electric eye more delicate than any known electric instrument"*. (Preece in 1897, quoted in Lochte, 2000, 101). Preece's own experiments with inductive telegraphy had not produced a usable solution, and he was well aware that no other systems were even close to Marconi's. He also presumed it was only a matter of a few years until competing powers, such as Germany and France, developed such a technology. He therefore greatly supported the contact between Marconi and the Post Office, giving the Italian inventor equipment, personnel and space, and organizing numerous tests and demonstrations with the Post Office and the War Office. Preece was proud of having 'discovered' Marconi and his support to the young newcomer became a point of increasing tension with Oliver Lodge (Weightman, 2003). As Hong comments, Preece and the Maxwellians were in the midst of an ongoing rivalry which unfolded into a *"battle for electrical hegemony"* between scientists and engineers, theory and application, with the prize being both honor and research funds (Hong, 2001, 37). Having this talented foreigner, who had not even gone to the university and barely knew of Maxwell's theory, land in front of his door with a fully usable wireless system was a coup de force. It gave Preece an immense opportunity to claim victory for the side of the 'practicians' - electricians like him who thought with their hands first and empirically produced instruments that could be put into practical use - over scientists who seemed to be caught up in their mathematics arguing endlessly about things that contradicted experience.

News of Marconi's system – and an instrument near identical to his – reached Popov by the end of the summer of 1896, intensifying his work on wireless transmission (Schwartz, 2011). Popov had continued to develop his system giving several demonstrations that year, but his attention had been diverted by Willem Conrad Röntgen's discovery of X-rays early that year. Like many of his peers, he had spent a good amount of time exploring that new and exciting phenomenon with a self-made Crookes vacuum tube. Nonetheless, Popov's progress in wireless communication had still been significant. On January 31st, 1896 he achieved distant transmission at sea using directional parabolic antennas. Then, on March 24th, he demonstrated his new system's potential for wireless Morse telegraphy, transmitting and receiving the letters 'HEINRICH HERTZ' over a distance of more than 250 meters (Thumm, 2006; Zolotinkina, 2009, and Zolotinkina et al., 2009). The event, however, was not published: Popov's research fell under the umbrella of the Russian Navy, so he was forbidden from divulging any information as it was considered a military secret (Vendik, 2009). In addition, Marine Department specialists had cautioned him in a January 1896 meeting that it was *"undesirable to spread information on a new means of communication"* (Zolotinkina, 2008, 116). Thankfully, we have a record of his pioneering work as his system made the news in a local paper in April, owing to a demonstration by a teacher at the Electrotechnical institute (Zolotinkina et al., 2009).

By spring 1897 Popov would increase operational distance to 600m (Zolotinkina, 2009). The Russian Navy became interested in fitting its boats with the system, so in the summer he was asked to perform more experiments in the Kronstandt harbor with one of the goals being to increase distance to 5km. While he succeeded in that task, in hindsight the most groundbreaking outcome of the experiments was something else altogether: Popov and his crew noticed that the large metallic hulls of boats reflected radio waves as they passed between the ships carrying the transmitter and receiver, acting as electromagnetic barriers. Unknowingly, Popov had repeated Hertz's 1888 indoor experiment with bodily interference but on a larger scale, replacing the human body with metal ships. In doing so he had discovered radar. Regrettably, everyone was focused on the resonance of the system (i.e. improving wireless communication), not on the noise that the environment injected to it. As such, even though serendipity hinted towards a brand new application that would had been truly revolutionary at that time, nothing came out of it and it would not be until many years later that we would learn about Popov's unprecedented observation.

In the meantime, during the various tests with the Post Office, Marconi met in person some of his peers - or rivals - in hertzian telegraphy. In September 1896, during a demonstration in Salisbury, he discussed with Captain Henry B. Jackson who informed him of his own past success with hertzian telegraphy. According to Jackson, Marconi was visibly shaken from the news until assured that the project was considered a military top secret and that Jackson had no plans to patent or commercialize it (Weightman, 2003). This was certainly good news for Marconi who had just applied for his first patent on June 2nd. In any case, his system was much more advanced, as was his ambition. Jackson continued to work on wireless telegraphy, joining Marconi and becoming a close friend (Hackmann, 1988). Marconi also met J. C. Bose, who arrived in London from India that same month (September) with a portable apparatus that reportedly achieved wireless communication at a miles' distance (Emmerson, 1997). Bose presented his research at the British Association in London and gave several lectures in England and in Europe. Nevertheless, even though he was one of the very first to work on hertzian communication, he did not pursue the subject as an entrepreneur, as he was not interested in commercial applications. The field was thus clear for Marconi.

2.3.2 *The first global wireless infosphere*

Marconi's invention reached the public consciousness after two open presentations organized by Preece in December 1896. His fame started to grow, but the Post Office was still asking for more tests and his patent application was still pending. In May 1897, Marconi passed yet another trial, establishing a link across the Bristol Channel (figure 2.22). This demonstration was attended by German physicist Adolf Slaby, who returned to his country enthusiastic and would later develop his own competing hertzian telegraphy system (Aitken, 1976/2014a). That April, Marconi had been approached by Jameson Davis with a proposal: establishing a private company with family funds that would allow Marconi to develop his technology and stop wasting time with the Post Office's seemingly endless tests while competition – like Lodge, Tesla, or others – catches up. Despite many deliberations, the Post Office never made an official counter-offer hence, in July 1897, the Wireless Telegraph and Signal Company Limited was founded, backed by the Jameson, Davis and possibly Haig and Ballantyne families (Ibid).

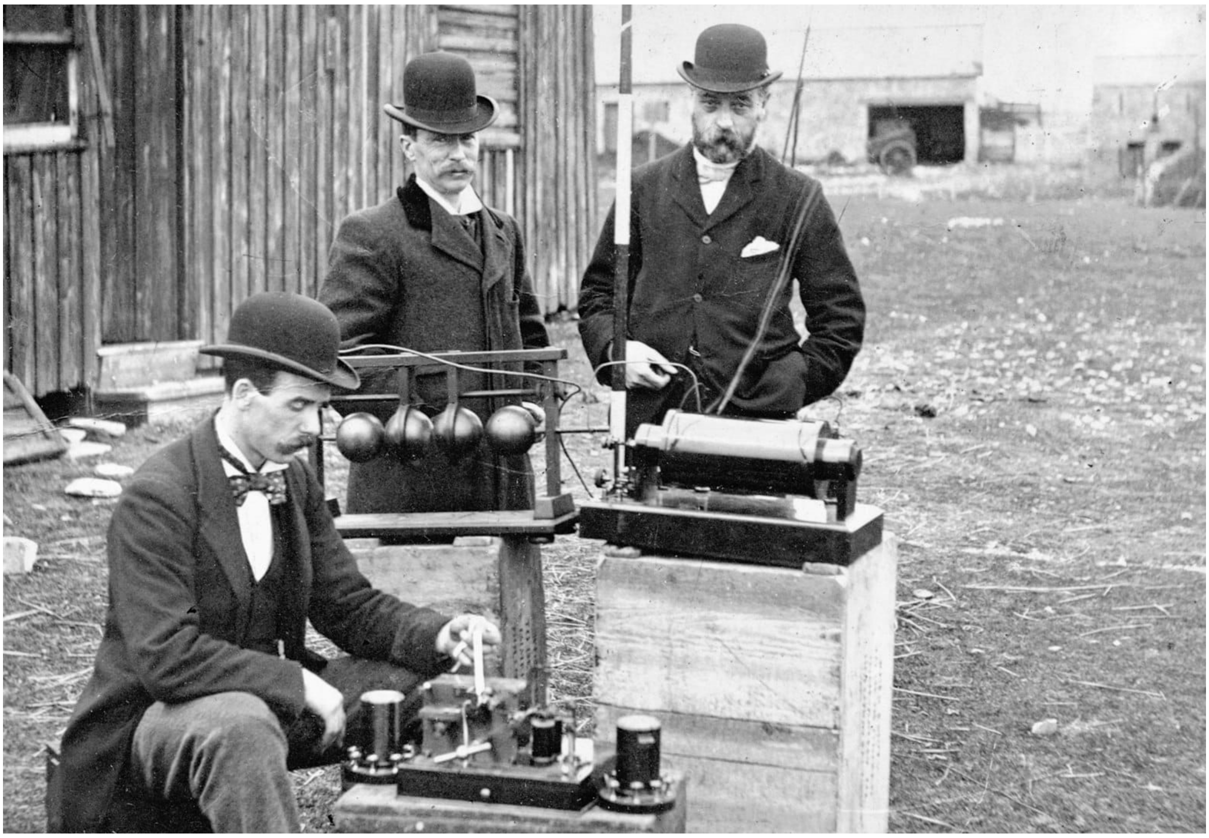

Figure 2.22. Photo taken on May 13th, 1897 during Marconi's demonstration of radio transmission over open sea at the Bristol Channel, showing British Post Office engineers inspecting Marconi's wireless telegraph apparatus which consisted of: a Righi spark gap (top left), a transmitter induction coil (top right), a wire antenna mounted on the pole between the two, and a receiver unit (bottom) (photo by Cardiff Council Flat Holm Project, Wikimedia Commons).

The company soon signed its first contracts selling equipment. The Italian Navy adopted Marconi's system in 1897. Then the British War Office bought it for the Anglo-Boer War in South Africa in 1898 - the technology was perfect for military applications, leaving no wires for the enemy to cut (Hong, 2001) (figure 2.23). In 1899 the system was installed on a passenger ship, and in July 1900 a more significant contract was signed with the Admiralty that involved creating a small communication network to connect 6 coastal stations and a few dozen ships (Mallik, 1986 and Aitken, 1976/2014a). The company's business model however soon shifted away from the sale of equipment. In 1900, renamed into *Marconi's Wireless Telegraph Company*, it begun offering subscriptions to its own private communication network as a service: equipment and personnel could be rented with stations on land or on-board remaining the company's property. This allowed for the standardization of equipment and operation, and created a functional and completely integrated system. The system was also an exclusive one specifically designed to 'tune out' messages from non-members. This was not implemented in a technical manner but through an administrative process dictated by the company that obliged technicians to ignore any messages from non-Marconi operators. The Company had thus created the first wireless communication protocol.[66]

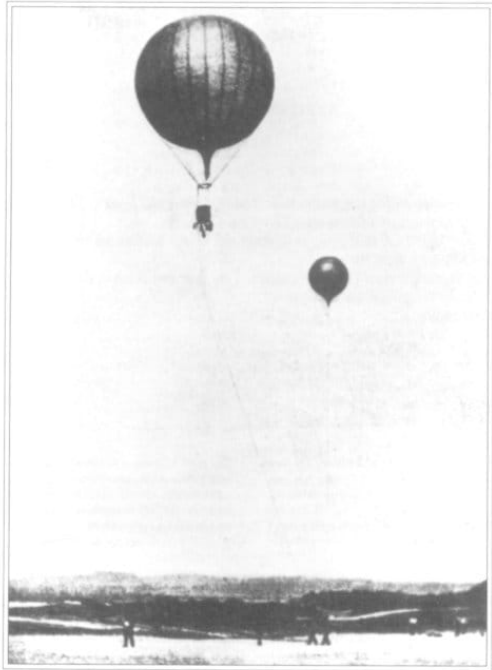

Figure 2.23. Photo from the Anglo-Boer War, showing Marconi Company's wireless telegraphy antennas suspended from airborne balloons. The steel masts that the long wire antennas were meant to be suspended from were quickly abandoned as they were conceived for ships and were thus impractical for use on the battlefield. The British first replaced them with bamboo poles, but as those quickly split due to the dry climate they eventually turned to kites and balloons (Baker, 1998).

In hindsight, this change of model was instrumental in catapulting the Marconi Company as a major player in the international scene (Aitken, 1976/2014a). However it was not entirely the result of a wise business strategy; in many ways, Marconi's hand was forced by the particular legal and economical context of Great Britain. Law forbade any for-profit public communication systems that were not part of the Post Office, but it allowed a company to transmit and receive messages for internal use. By providing a membership at a fixed rate and not charging per message, and by not communicating with anyone outside the company, a loophole was found that helped the company grow immensely. In September 1901, Marconi signed an exclusive contract with Lloyd's, a marine insurance company that employed 1000 agents stationed in ports all over the world, tasked to handle its affairs and update its

[66] Protocols *"are all the conventional rules and standards that govern relationships within networks* and are used to understand, facilitate, organize, regulate and control communication. Different applications use different protocols " (Galloway & Thacker, 2004).

international registry of ships with current locations and travel plans. This coming together of Lloyd and Marconi created the first wireless infosphere of our planet, allowing ships around the world to be informed in real-time through Lloyd's intelligence network and to communicate with each other even in the remotest of seas.[67] Echoing a behavior common today with people's involvement in contemporary social networks – one of today's many infospheres - interested parties (ships in that case) were increasingly more likely to choose to become members of this network, as otherwise they would be excluded from information and communication. By the time other companies offered competing wireless systems, like Oliver Lodge's Lodge-Muirhead Syndicate, it was too late; Marconi-Lloyd had a stronghold.

2.3.3 *Regulation*

The discovery of electromagnetism and the electromagnetic spectrum in the end of the 19th century - that is, during the last throes of expansive imperialism - was in many ways treated analogous to the discovery of a new continent (Aitken, 1976/2014a). The landless territory of the spectrum was recognized early on as a resource with rich economic and military implications, in particular because of its potential for communication. While the spectrum was discovered by science and explored through technology, the problem over who had the rights to use it and under what conditions presented many parallels to the discovery of new lands and continents. Individuals, companies, and nations competed to take hold of this new resource; like with colonial conquest, *"[w]hoever occupied a portion of spectrum came to own it"* (Mackenzie, 2010, 197). However, land can be mapped; it can be demarcated by clear borders, and protected by armies. In contrast, the electromagnetic spectrum had no identifiable limits at that early point in in its exploration. In addition, the technology of the time did not allow placing transmissions in a specific part of the spectrum with precision, relying instead on the broadband bursts of the spark-gap transmitter. In order for laws and regulations to administer this resource, the technology first had to be improved. A few years down the line, with syntony possible, it became feasible to divide, regulate, and license the spectrum, and to lay a map that defined which frequencies were to be used by whom and for what purpose.

The communication protocol set by the Marconi Company, in which communication with non-Marconi operators was forbidden, was seen by many as a way for British interests to gain control over this new resource and establish a monopoly on communication. This

[67] For more information, see Chapter 5 in (Aitken, 1976/2014a).

approach (known by the name *Marconism*) was challenged by Germany, who summoned the first *International Wireless Conference* in 1903. The conference established an international protocol of communication which was signed by 6 of 8 attending countries – but not by Britain and Italy who were using Marconi's system. A 1906 conference attempted to make this protocol enforceable, legally forbidding Marconi operators to ignore others' messages. It also established the first formal division of the spectrum in four tiers, following a proposal by the German delegation. The sections of the spectrum considered best were assigned to the military and the navy, leaving wavelengths considered inferior to Marconi and commercial use in general.[68] While still partial and notional, this set a precedent that is still observed today and which has turned the radio spectrum usable but also less flexible at the same time. Soon thereafter, various states established power structures to allocate and regulate the hertzian resource. Different countries took different approaches; for example, in New Zealand the radio spectrum became state property already in 1903, while in the US the government only took control of it the 1920s (Joyce, 2008).

Once more ships were equipped for wireless telegraphy, the combination of ineffective regulation and imprecise technology created a radioscape full of noise. This was partly due to the fact that '*wireless'* was a marvelous new toy for operators who could fight the boredom of the seas by endlessly chatting each other (Michaelis, 1965). Regrettably, while the gadget had allowed the formation of a remarkable prototypical social network extending over the globe, its technical limitations were causing a rift among its members. The broadband transmitters used at the time made it impossible for anyone to conduct a conversation within a 100 km radius of a transmitter in operation. To make matters worse, Michaelis notes that *"no operator admitted any precedence to any other, and those on liners were particularly contemptuous of those on freighters and smaller vessels"* (Michaelis, 1965, 139). Unsurprisingly, the wireless channel was full of *"feuds and quarrels, filling the air with curses, aspersions, and choice obscenities"* (Ibid, 141). This resulted in countertactics such as 'dropping a book on the key', a trailblazing form of radio jamming that, quite literally, involved placing a heavy object on a Morse key. The constant noise made it impossible for those chatting about - or anyone else for that matter - to continue using their *wireless.*[69]

The benefits of wireless together with the problems of its unscrupulous use were made

[68] For more information see Joyce (2008, 38-45) and Michaelis (1965, 142-157).

[69] Radio jamming had been known to Marconi Company operators already since 1899; they used it as a tactic to fight new antagonists (Schwartz, 2011, 427).

dramatically clear in 1912 with the sinking of the Titanic. On one hand, many passengers were saved after nearby ships received calls for help from the Titanic's wireless operator (figure 2.24); more would had survived had more of the ships in the area been equipped with wireless. On the other hand, a few hours before the catastrophe, the wireless operator of another boat had attempted to warn the Titanic that it was about to enter a field of icebergs. Rather than listening to what a colleague on an 'inferior' vessel had to say, the Marconi system operator of the Titanic's asked him to 'shut up' as he was busy chatting with a Cape Cod colleague (Michaelis, 1965, 139). Furthermore, once news of the disaster broke out, rescue efforts were hindered by an abundance of telegraphic queries clogging the airwaves. As a result of the disaster, the 1912 Radio Act was voted in the US, thus implementing the regulations proposed by the *International Wireless Conference* in 1906 and requiring licenses for wireless transmission. The spectrum was split hierarchically in four bands, separating governmental and maritime use from emergency and private station transmissions. Short waves remained available for amateur use as they were deemed practically useless due to technological limitations (Joyce, 2008).

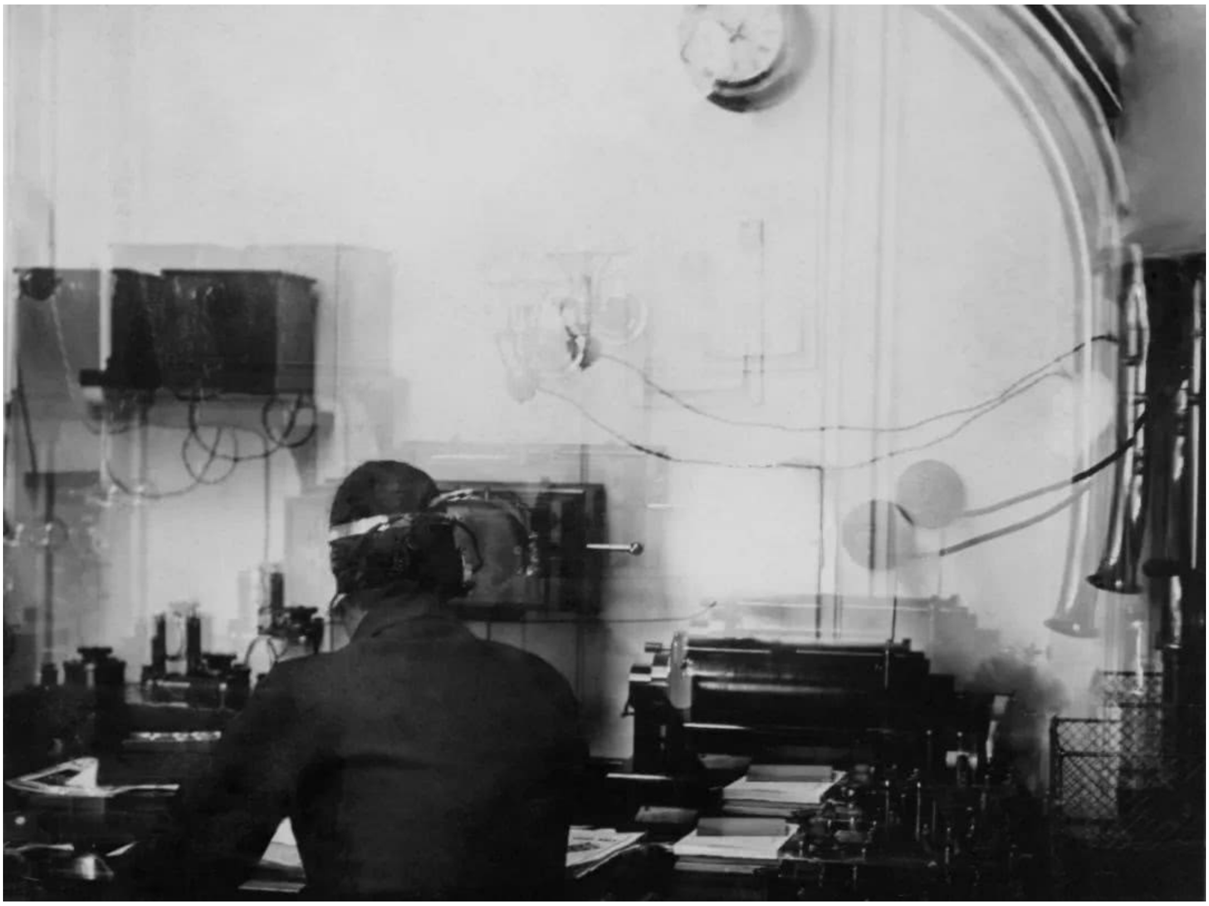

Figure 2.24. The only photo of Titanic's wireless telegraphy room, showing junior wireless operator Harold Bride at work (photo by reverend Francis Browne, Public Domain).

2.3.4 *Wireless troll or white-hat hacker? Man-in-the middle attacks of a 'scientific hooligan'*

Marconi was very competent in manipulating the power of the press to promote his work. Many of his experiments were performed for the public, for esteemed members of the scientific community, or for Kings and other high ranking officials who reported the success to the press confirming both the effectiveness and practical usability of his instruments (Hong, 2001). Marconi's R&D process had been a core element of the company's marketing since the beginning. Once a large station was completed in Poldhu Cornwall in 1901, it became the center of a campaign advertising the superiority of the Marconi system both in range and security, owing to its patented tuning. However, a series of events in 1902-1903, known as the Maskelyne affair, raised many questions regarding Marconi's claims about security. More importantly, it proved that wireless communication can be both tapped into and interfered with. To many, this meant that more regulation was needed.

The October 1902 issue of *The Electrician* contained a claim that messages from one of Marconi's long-range transmission experiments had been received by a third party using non-Marconi instruments, thus demonstrating that the system was not in fact secure. A swift denial of this claim by the Marconi Company was subsequently dismissed in a thorough a report by Nevil Maskelyne (Maskelyne 1902). Maskelyne was a wireless autodidact and magician, the son of theater-owner, illusionist and stage magician John Nevil Maskelyne. He had several patents to his name and was likely the designer of a wireless communication apparatus used in a 'mind-reading' act by his father (Aitken, 1976/2014a, 295). Some of his public demonstrations had caused quite a stir; for instance, he had used wireless to detonate gunpowder, and had established communication with people on a balloon. Maskelyne nearly made the passage from engineer to entrepreneur when Lloyd's asked him to develop a radio beacon system for use in the Thames. His plans were however thwarted by Marconi's overreaching patents. After that point, Maskelyne became a vocal critic of the company's monopolist practices (Ibid).

In his report, Maskelyne recounted how he had tapped into Marconi's system and included the captured message as proof to his claim (figure 2.25). Furthermore, he stated that he had easily intercepted messages from Marconi stations across the country wondering *"what has become of that syntony of which we have heard so much?"* (Maskelyne, 1902, 108). This set-off a polarizing debate. The Marconi side downplayed the problem, stating the transmission was not meant to be secure to begin with. Instead, they highlighted the technology's success in combating interference: This was proof that messages would always be received even at remote distances. The fact that an expert could intercept them should not be held against Marconi's wireless, as this was a known problem for wired communication as well.

Thereafter, the Marconi Company organized a public 'show' at the Royal Institute to settle the argument. John Ambrose Fleming would give two lectures on the science and technology of the system, and would subsequently prove its security and robustness with a complex demonstration involving Poldhu, another station, and a receiver in the lecture hall. The receiver would be connected to a Morse sounder so that the messages would be audible to everyone in the room. Fleming was an established scientist straddling the worlds of science and engineering and one of Marconi's most credible advisors; he would also be the one whose reputation suffered the most from this episode.

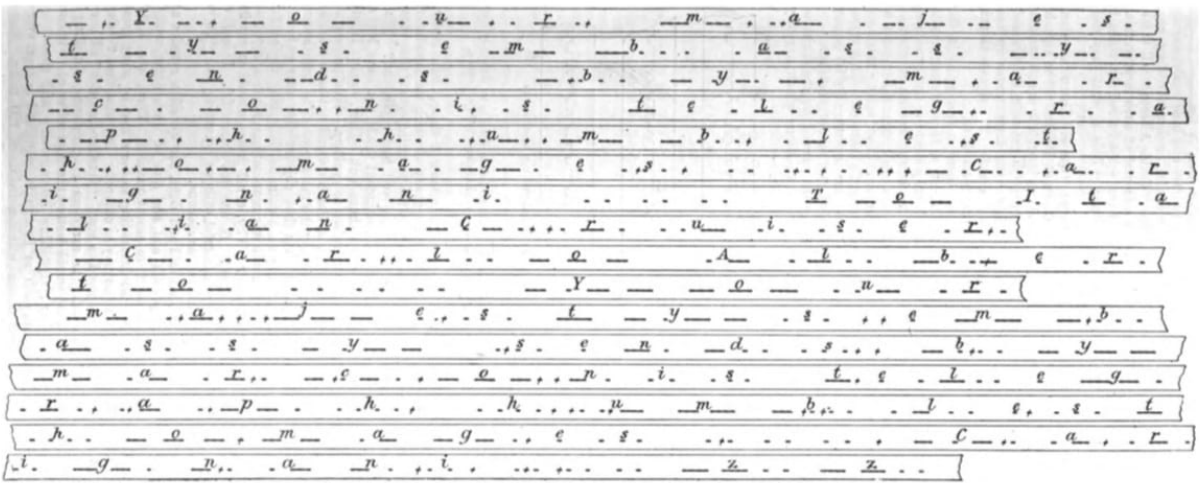

Figure 2.25. Maskelyne's publication of a Marconi Company - supposedly untappable - telegram sent by the Italian Embassy, which he had captured with his own receiver (Maskelyne, 1902). The message read: *"Your majestys embassy sends by marconis telegraph humblest homages Carignani To Italian Cruiser Carlo Alberto"* (sic). The dots with vertical lines in the published image showed that there was a simultaneous interfering transmission meant to obfuscate the message. The image was also proof that the message was repeated multiple times in order to come through, despite claims by the Marconi Company that it only had to be transmitted once.

Maskelyne felt *"it was a duty*" to expose the system's flaw and his adversaries false claims (Maskelyne, quoted in Hong, 2001, 108). He thus set up a crude short-wave transmitter on the rooftop of his father's London theater, which he used to hijack the Morse sounder by sending messages to its receiver. In this manner he made his opinions loud and clear in the hall. Maskelyne's *man-in-the-middle* attack ("Man-in-the-Middle Attack," 2022) was introduced with the march-like sound of the word 'rats' repeating time and time again:

.-. .- - ...

.-. .- - ...

.-. .- - ...

As reported by one of Fleming's assistants, this *"unbelievably gave place to a fantastic doggerel (...) There was a young fellow of Italy / Who diddled the public quite prettily"* (Arthur Blok quoted in Hong, 2001, 110). Maskelyne was dubbed a 'scientific hooligan' but he defended his use of 'foul language' declaring that he merely wanted to provoke a visible reaction so that his assistant, who was present at the lecture, could verify the success of his intervention. In any case, he claimed, he was justified as this was *"the only possible means of ascertaining* fact *which ought to be in the possession of public"*, i.e. that a non-syntonic transmitter can take over Marconi's receivers (Ibid). The scandal soon took a different course, when it became clear that Marconi had faked the reception of messages on this occasion, and possibly on others. After that event, Marconi's public performances became more rare. A few years later, in 1907, he was pressing for laws against eavesdropping on wireless communication (Schwartz, 2011).

Considering Maskelyne's actions and reasoning from a contemporary perspective, we could very well describe the affair as the first known white-hat hacking of radio communications, or perhaps the first 'critical engineering' intervention performed with the attitude of a heckler or a troll ("White Hat (Computer Security)," 2022).[70] In any case, this episode should be earmarked as a tipping point in the history of wireless, making the need for encrypted transmission evident.

2.3.5 *Radio Broadcasting: from bug to feature*

The Maskelyne affair exposed a glitch of the wireless telegraphy technology: While advertised as a *unicasting* system linking one transmitter to one receiver, messages could actually be intercepted by anyone with a receiver tuned to the transmitting frequency. This *broadcasting* of signals was a critical problem that Marconi had been well aware of. In a radio transmission after his death the Italian radio played a recording of him stating: "*forty-two years ago, when I achieved the first successful wireless transmission in Pontecchio, I already anticipated the possibility of transmitting electric waves over large distances, but in spite of that I could not hope for the great satisfaction I am enjoying today. For in those days a major shortcoming was ascribed to my invention: the possible interception of*

70 For more on critical engineering see (Oliver, Savičić, Vasiliev 2011-21).

transmissions. This defect preoccupied me so much that, for many years, my principal research was focused on its elimination. Thirty years later, however, precisely this defect was exploited and turned into radio-into that medium of reception that now reaches more than 40 million listeners every day." (Marconi from 1937, quoted in Kittler, 1999, 251).

It should come as no surprise that broadcasting was initially seen as a bug and not a feature. As we have seen, wireless technologies in Europe developed within a militaristic and colonialist context and as such were designed to transmit information that was crucial for the control of armies, colonies, and the global economy (Hagen, 2008 and Kittler, 1999). This was part of the reason why Hertz's wireless technology was used to re-invent cable telegraphy in the 1890s rather than, for instance, to invent a new form of entertainment through radio broadcast. The obsession of Marconi and his contemporaries with increasing range must be seen within this context as well. The possibility of willingly broadcasting was not mentioned in the 1903 and 1906 wireless conferences, even though the delegates imagined a number of different potential uses of the spectrum in order to regulate it (Daniels, 2008). Eventually, the 'leakiness' of wireless information led to the development of machines addressing this defect through encoding and encryption, like the famous ENIGMA device from WWII (Kittler, 1999).

It should also not be too surprising that Tesla was the only pioneer whose all-encompassing electromagnetic vision included broadcasting. The concept was in fact central to his World Wireless System. In 1904 Tesla wrote about a kind of 'World Telegraphy' that would enlighten the masses and connect people – a vision very reminiscent of today's Internet. His system would consist of a network of transmitters that would reach even the most remote places around the globe; one would access these transmissions through *"a cheap and simple device, which might be carried in one's pocket",* receiving news or any other special messages. *"Thus the entire earth will be converted into a huge brain, capable of response in every one of its traits"* (Tesla from 1904, quoted in Daniels, 2008, 35).

Spark-gap transmitters were far from ideal for transmitting voice or music, as they generated a pulsed signal full of harmonics. Early wireless transmitted binary Morse code sounds, and thus was "*literally digital before it became, through speech and music modulation, an analog medium"* (Ernst, 2008, 421). Still, Canadian inventor and Pennsylvania University professor Reginald Aubrey Fessenden managed to coax a spark-gap to transmit his voice over a mile's distance in Cobb Island on December 23rd, 1900 (Fry, 1973). He did so by adding a microphone in the transmission circuit to modulate the current in the antenna. The quality was very low, but radiophony was born with the following words: *"One, two, three, four. Is it snowing where you are Mr. Thiessen? If it is, telegraph back and let me know."* (Mallik, 1986, 496). Four years later, on June 15th 1904 in Graz, Austrian professor Otto Nussbaumer used his own special apparatus to transmit music for the first time, yodeling a folk song which was received in a nearby room (Fantel, 1990).

In the beginning of the 20th century, transmission of sound was becoming reality owing to the invention of a number of devices that could create continuous and even waves, such as Valdemar Poulsen's arc transmitter, Reginald Fessenden's high frequency alternator (which improved on earlier work by Tesla) and vacuum tube oscillators. The signals of these instruments could be further processed to create an interrupted signal for telegraphy, or an amplitude-modulated signal that could transmit audio, such as voice or music (Aitken, 1976/2014a). Fessenden patented 'heterodyning' in 1902, an analog processing technique that allowed shifting a signal in different frequency ranges.[71] The technique was necessary for grafting sound into a radio transmission by the process of modulation. Since radio transmitters operate in much higher frequencies, direct *radio-fication* (the opposite of the '*audification'* of natural radio on telephone lines, heard by Thomas Watson in the 1870s, see Kahn (2013)) was not an option. Heterodyning made it possible to transmit humanly audible sounds electromagnetically (Mallik, 1986).

Fessenden had the idea to wirelessly broadcast sound instead of Morse signals - in a format foreshadowing radio broadcast - after an accidental discovery that he made during his own experiments with transatlantic telegraphy. In November 1906, one of his engineers reported that while listening to his wireless receiver for Morse messages from Plymouth, England, he was astounded to hear the actual voice of the chief engineer at that remote station instructing his crew. Consequently, Fessenden scheduled the first ever 'radio show' for Christmas Eve as a present to his wireless telegraphy clients at sea and on land - a good way to promote his 'wireless telephone' invention. This would be the first time that radio technology was used to broadcast sound to multiple receivers in many locations. Fessenden advertised this event via the telegraph, prompting operators to tune in for *"something different"* (Fessenden quoted in Stewart, 1975, 9). It included broadcasting speech as well as live and pre-recorded music from his laboratory in Brant Rock Massachusetts.[72] Even though his audience had been

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[71] As Mallik writes, Fessenden was also the one who introduced the term 'modulation' in a 1907 article.

[72] The event was reported by Fessenden decades later, and while there is some debate whether it actually occurred, it has been confirmed by earwitnesses (Hagen, 2008). The program included a recording of Handel's Messiah, Fessenden playing Gounod's 'O Holy Night' on the violin and singing, and a Gospel recitation

notified about the broadcast, they were astonished to hear the sound of voice and music coming to them through the ether instead of the all-familiar Morse dots and dashes. The event was a big success, and a repeat performance was given on New Years Eve.

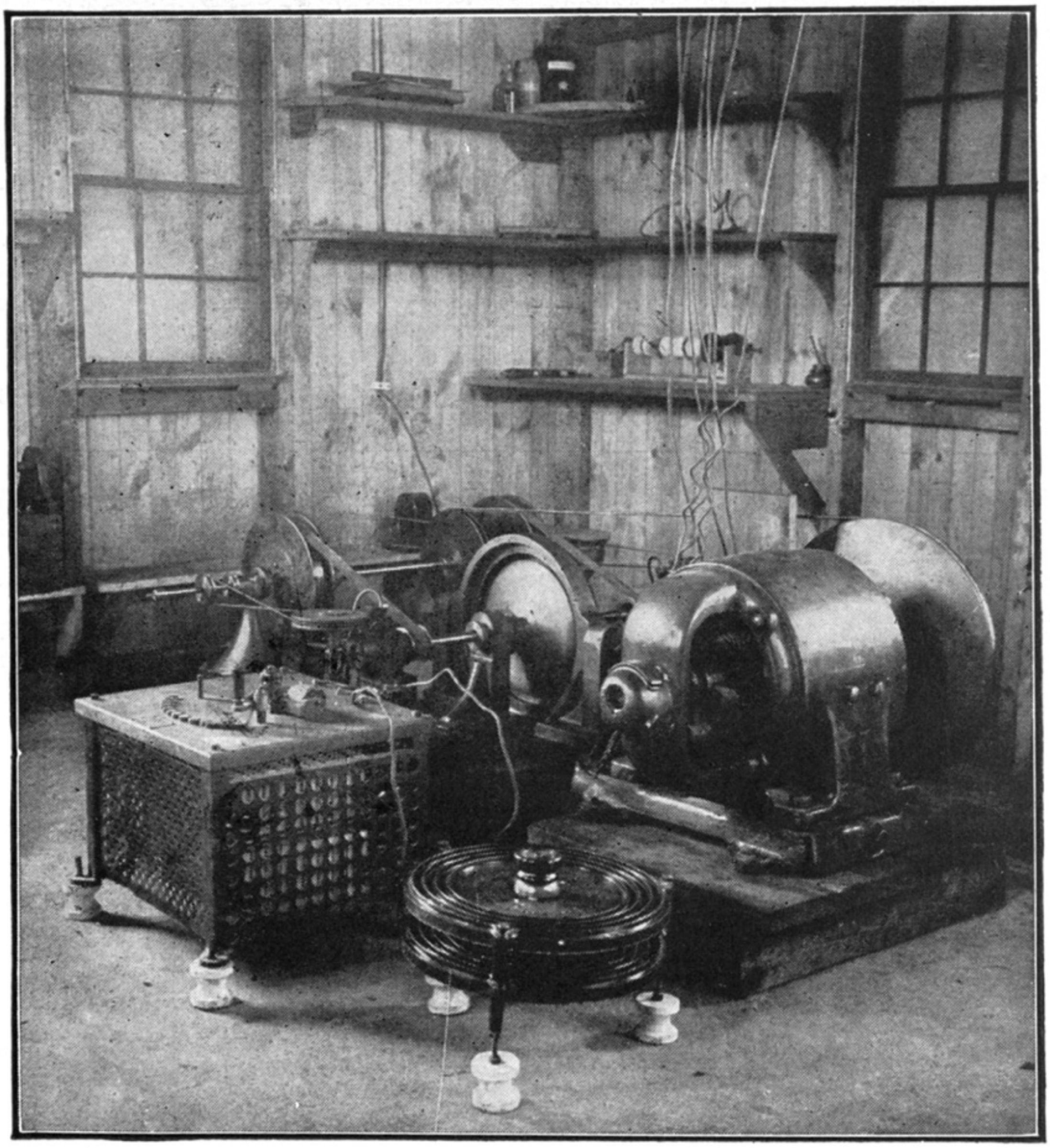

Figure 2.26. Fessenden's alternator transmitter which he coupled with a microphone to transmit sound via radio waves and create the first ever broadcast radio 'show' in 1906.

To achieve this remarkable feat, Fessenden used a steam-operated alternating current transmitter that broadcast long waves at about 100KHz amplitude-modulated by the sound of a microphone (figure 2.26). As Hagen points out, *"[i]f Fessenden's lips had touched this device he would have been dead on the spot"* (Hagen, 2008, 54). A much safer

(Daniels, 2008; Kittler, 1999). Fessenden's wife and secretary were scheduled to recite the Bible, but were paralyzed from 'mic fright', so he spoke instead (Stewart, 1975).

instrumentation would be used later, having at its core Lee De Forest's *Audion*, a vacuum tube whose name was a combination of the words audio and ionize (figure 2.27). [73] The Audion could be used as both amplifier and oscillator and would revolutionize wireless technology, making large-scale broadcasting possible. In 1912, Edwin Howard Armstrong discovered that by feeding the Audion's output back to its input he could turn it into an amplifier. Further experiments revealed that pushing feedback amplification caused the Audion to self-oscillate, generating high-frequency signals without any input. This meant that the same vacuum tube could be used not only as a detector, but also as an amplifier and as a transmitting oscillator through the principle of positive feedback. As an oscillator, the Audion permitted transmitting much stronger, narrow-band continuous waves. As a radio receiver, it used the cybernetic principle of feedback to amplify weak signals. Radio waves would be iteratively fed back through the audion making it resonate on the strongest of the signal's frequencies to improve reception. Later on, De Forest realized he could amplify signals before transmitting them as well.

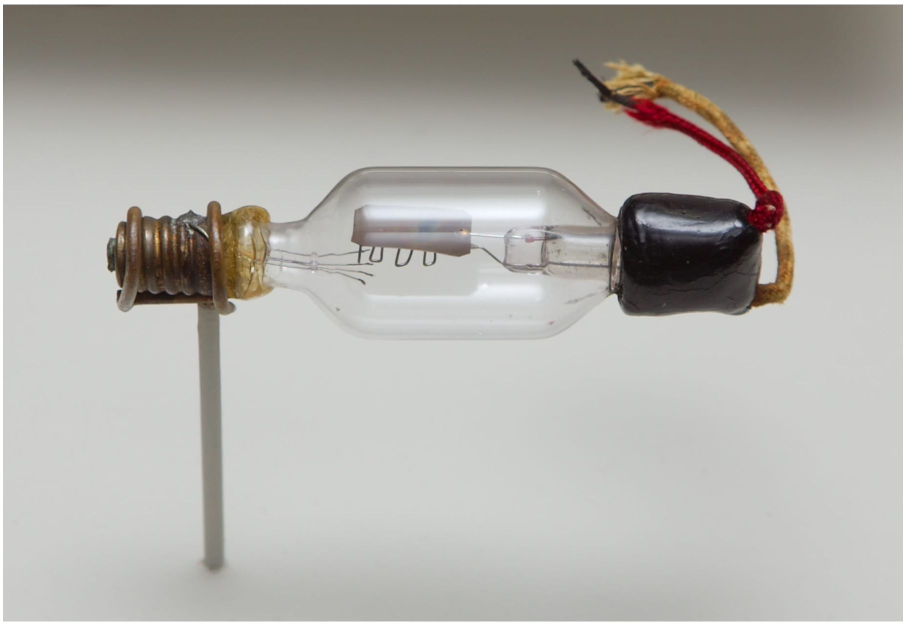

Figure 2.27. Early iteration of an Audion tube from 1908 (photo by Gregory F. Maxwell, Wikimedia Commons).

By the time the 1912 US Radio act was voted to regulate the spectrum, a grassroots community of about 100,000 wireless amateurs had already emerged, like settlers in an

[73] De Forest was an American inventor who believed in the spirituality of electricity, having gotten inspired by Tesla's writing *"to myself enter into that tenuous realm that is the connecting link between God and mind and lower matter"* (De Forest quoted in Daniels, 2008, 35). He was also the first to use the term 'broadcasting' - a metaphor from agriculture – in the context of wireless in a 1907 love letter (Ibid). The term *radio* was standardized in 1913 by the Institute of Radio Engineers (Mallik, 1986).

electromagnetic Wild West. Enthusiasts communicated with each other mainly using Morse code on self-made equipment, although some also broadcast voice and music to their peers in *“small but periodic”* radio shows (Daniels, 2004, 146). The community was growing, and as it did it was helping further develop wireless technology. Before WWI, the American Radio League proposed to create a national network of radio amateurs as a backup for a possible sabotage on telecommunications. Nonetheless, the US government decided to take control of the airwaves and shut down all amateur wireless transmissions for security reasons, a moratorium that lasted until 1919, thwarting the emergence of mass broadcast (Daniels, 2008). Radio could have become a commercial reality in 1916, but a proposal for a *“music box in the home”* from David Sarnoff of the American Marconi Company was disregarded (McLuhan, 1964/2017, 407). That same year, broadcast radio was re-invented as a revolutionary medium – an augur of the medium’s critical role in politics in the years to come: During the Easter Rising in Ireland, rebels took over a ship’s wireless transmitter to broadcast the establishment of a new independent republic with Morse messages, succeeding to get the news out (Ibid).

During WWI, wireless technology was of outmost importance in the battlefield. Owing to the wide availability of radio equipment in the front, radio broadcast was re-invented not as a tactical tool but to respond to simpler human needs: fighting boredom and sensory deprivation in the trenches. From May 1917, a former AEG engineer by the name Hans Bredow started a pirate radio show, playing records and reading the news for his fellow German soldiers. The show was quickly stopped once higher ups found out, prohibiting this *"abuse of army equipment”* (Kittler, 1999, 96). After the end of the war, in November 1918, 190,000 German radio operators were sent home with their radio equipment. By the end of the month, a Central Broadcasting Bureau was founded with support from the Independent Socialist Party prompting as immediate response the founding of the German Radio network to keep the airwaves in the hands of the government and industry (Ibid). Radio remained in the control of the army for a few more years, until civilian radio entertainment became a reality in 1923 - though with a strict prohibition on transmitting. Beyond Germany, broadcast radio was beginning to be treated as a national resource all over Europe.

In the US, on the other hand, the end of the wireless moratorium in 1919 brought about an explosion of amateur use. The technology had improved significantly during the war and used army equipment was easy to find. A vibrant community of amateurs begun filling the airwaves with the sounds of recorded and live voice and music coming from their DIY stations. Within a few months it had grown to such extent that many early adopters of radio would tune in not to discuss but just to listen, thus bringing the concept of a radio audience into public discourse. Broadcast in the US was thus not invented by any individual or company but by the listeners, emerging as a grass-roots phenomenon fueled by the socio-technological situation after WWI (Daniels, 2008). The realization that radio was a potential market came around 1920, the year of a 'radio boom' for both US and Canada. The first commercial broadcast was a report on the results of the US elections on November 2nd 1920 - even though there were no commercially available radio sets yet. By 1922 consumers could buy a receiver to listen to the several hundred stations broadcasting in the country. Within a few years, radio had taken over the world. Its commercialization, together with the acknowledgment of its power as a mass communication medium, marginalized the amateur community although it never extinguished it.[74]

In Britain, the first public radio shows were broadcast by the BBC in 1922. In the beginning, listening was a solitary experience due to most receivers using headphones. Within a few years, the advent of loudspeakers made it possible to experience the new medium in groups. Subsequently, listeners begun pumping up the volume of their receivers more and more, giving the decade the nickname of the *roaring '20s*. Wilson notes on the matter: *"A quirk of early valve radios meant that increasing volume beyond a certain threshold created an electronic feedback frequency that would energise the aerial, and the oscillation interference would be reproduced in other radio sets tuned to the same frequency in the locality"* (Wilson, 2017, 158). Meaning that when the volume was too high, radio receivers would start to self-oscillate and heterodyne with the carrier wave of the broadcast - a howling noise that would be picked up by neighboring receivers.[75] "*Prevalent at the time was an inconsiderate method of tuning in to a radio station: the radio's volume would be pushed into self-oscillation, which would remain inaudible until a radio station frequency was approached. The vicinity of the broadcast wavelength would be heralded by a high-pitched tone that lowered as the wavelength was reached, and at the lowest point the volume dial would be ducked in order to*

[74] Daniels compares the amateur radio communities of the 1920s with the Internet communities of the 1990s, populated by *"experts, initiates and hackers"* before the Internet was transformed into a commodity (Daniels, 2004, 146). He posits that the radio amateurs "*are the predecessors of hackers and tech-nerds and without intending to, sparked the first "hype" in the history of media"* "*the radio boom"* (Ibid). Daniels also identifies a similar type of technologically-fueled economic boom/crash cycle between the two periods, the former ending in the 1929 crash, and the later in the dot com bust.

[75] Heterodyning is a radio frequency shifting technique invented by Fessenden. It involves a circuit that combines an incoming radio signal with an internally generated one to produce two output signals at different frequencies, one at the sum of the two original signals and the other at their difference.

hear the broadcast. Many people tuning radios in this way meant that these wild electronic tones locally intruded upon radio broadcasts" (Ibid).[76] This terrible noise was an unwanted glitch in the system, ruining the broadcast and the listener's experience. In Britain, producing such sounds was presented as a 'moral failing' and a 'disgraceful habit' that would be stomped with 'detector vans' if need be (figures 2.28 and 2.29). While mostly a result of ignorance, local papers "*revealed instances of gratuitous oscillation such as beating in time with music and, notably, in 1925, a broadcast religious sermon where the 'air was full of oscillators' warring to 'chase one another off the ether' (a possible manifestation of the tit-for-tat revenge oscillation – the 'howl for a squeak terror'), and most extraordinarily, in 1930, 'three or four' oscillating 'fanatics' apparently orchestrated their interference over a vaudeville broadcast – 'there is no doubt these pests had an arranged plan'"* (Ibid, 159). These type of radio effects were audible until the 1930s when better circuits, transmitters and antennas were introduced.

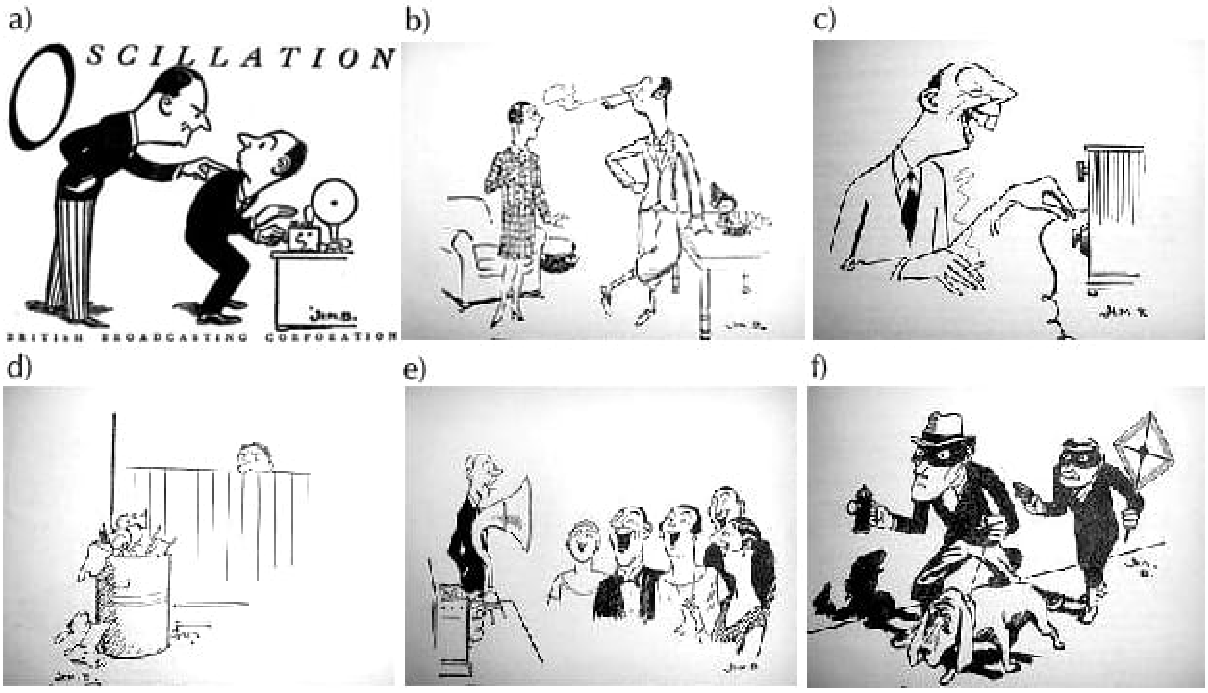

Figure 2.28. Images from a 1927 BBC booklet against oscillation: (a) Cover page. Original captions: (b) *"This man boosts he can get Timbuctoo on one valve";* (c) *"Don't try and communicate with your neighbours";* (d) *"It is just as bad form as if his garbage were not removed";* (e) *"There are regrettably some who make whistling noises in their loud speakers in order to produce amusement";* (f) *"Detective work on locating an oscillator"* ("Early Wireless", 2007).

76 To portray how poor reception sounded in the 1920s, Wilson turns to contemporary reports of 1924 BBC production emulating such effects acoustically. As he writes, *"the sounds comprised 'lead shot on a kettle-drum, paper rustled before the microphone, the breaking of matchwood, and an oscillating valve"* (Wilson, 2017, 158).

Figure 2.29. Interference-tracking lorry with manually operated directional loop antenna used by the British Post Office to locate unlicensed amateur transmissions and self-oscillating radio sets, 1927 (public domain, Wikimedia Commons).

2.4 ENERGY RADIATING IN SPACE: LISTENING THROUGH THE NOISE UNTIL IT BECOMES THE MESSAGE

2.4.1 *Early radio navigation and Direction-Finding*

"D/F should remind us that wireless telecommunications have always been concerned with positions as well as messages."
Douglas Kahn (Kahn, 2013, 22)

Once more ships were connected to land via radio, the prospect of using hertzian waves as a navigational aid - already expressed in 1890 by Threlfall as we saw in section 2.2.2 - became attractive in commercial and military circles alike. Overcoming the problem of low visibility was an important affair and soon became the main impetus for the development of radio as a sensing technology. Radio navigation was implemented using two main techniques: Deploying directional antennas during transmission to encode signals with embedded spatial information, or deploying directional antennas upon reception to deduce where a transmission was coming from.

Marconi had become an expert in directional antenna design throughout the years. One of his observations was that an antenna consisting of two elements, a short vertical one and a longer horizontal - dubbed an *inverted-L antenna* - would receive a stronger signal when it was directly opposite a transmitter (figure 2.30). Thus, in 1906 he patented a design in which an array of such antenna modules fanned out of a central point. The element with the strongest signal would point to the transmitter's direction. This was an early Direction-Finding (D/F) antenna.

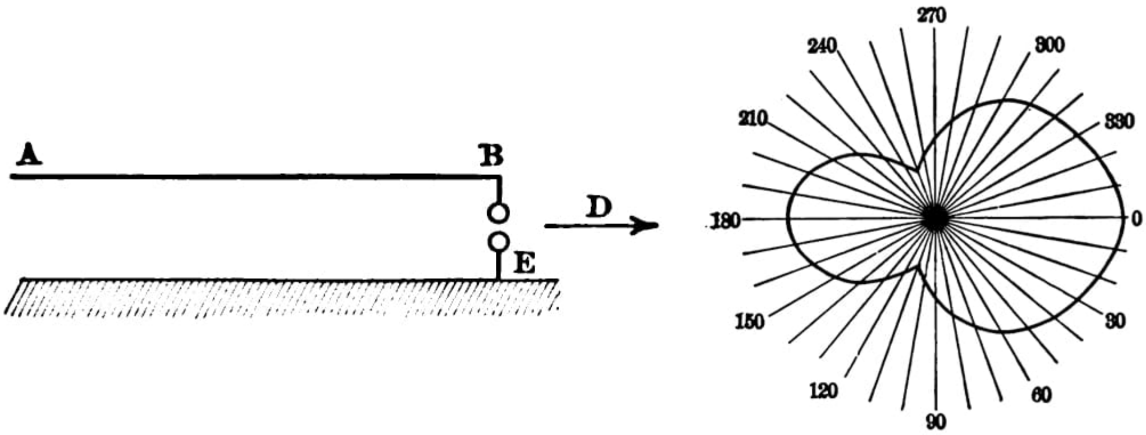

Figure 2.30. Marconi's 'inverted-L' directional antenna: diagram (left) and horizontal radiation pattern (right) (from Pierce, 1910).

The Marconi Company - responsible for 2/3rds of global marine communications by 1909 - was not alone in working on direction-finding technology. In the US, John Stone Stone had received a patent for determining the direction of a transmitter using a rotatable loop antenna already in 1902 (Stone, 1902). German firms were also developing their own, eventually superior, technologies and were gearing to challenge Marconi's rule (Quilter, 2010). This was encouraged as much by Germany's imperialist plans, as it was by the Marconi Company's aggressive patent protection policy compounded to its complacency stemming from having a near-monopoly that made innovation less critical for its survival.[77]

Karl Ferdinand Braun had received a British patent for an antenna that could identify the direction of wireless transmission already in 1899. Another system patented in imperial Germany in 1907 was Otto Scheller *Course-Setter* (Scheller, 1907). This system, produced

[77] In contrast, German companies poured much energy into innovation directed to cater military needs, thus giving Germany a technological advantage in the beginning of WWI (Quilter, 2010).

by the Lorenz Company, was designed to guide boats equipped with a receiver along a safe line until they reached close enough to shore to see landmarks (Quilter, 2010 and Rohde & Schwartz, 2016). The *Course-Setter* used sound to guide operators through an invisible line created by radio waves. The apparatus transmitted Morse signals using two antennas with intersecting radiation patterns (figure 2.31). While one sent dots, the other sent dashes. When the receiver was directly on the line between the two, the operator heard both sounds equally loud, whereas one sound would overpower the other when veering off-course. This type of system was used by the German Airforce in both WWI and WWII to guide bombers to their target through the guise of night or fog – something that became necessary with the tightening of anti-aircraft defenses (Quilter, 2010). Kittler describes a more advanced version of the *Course-Setter* deployed in the Battle of Britain that made clever use of triangulation, stereophonic sound, and psychoacoustics: *"Radio beams emitted from the coast facing Britain, for example from Amsterdam and Cherbourg, formed the sides of an ethereal triangle the apex of which was located precisely above the targeted city. The right transmitter beamed a continuous series of Morse dashes into the pilot's right headphone, while the left transmitter beamed an equally continuous series of Morse dots-always exactly in between the dashes-into the left headphone. As a result, any deviation from the assigned course resulted in the most beautiful ping-pong stereophony (of the type that appeared on the first pop records but has since been discarded). And once the Heinkels were exactly above London or Coventry, then and only then did the two signal streams emanating from either side of the headphone, dashes from the right and dots from the left, merge into one continuous note, which the perception apparatus could not but locate within the very center of the brain. A hypnotic command that had the pilot- or rather, the center of his brain-dispose of his payload"* (Kittler, 1999, 100). After cracking the encryption of the German *Enigma* machine, the British became aware of the existence of such a *"bomber beam"* (Ibid). However, it remained completely invisible to them as it operated in frequencies above the VHF band, a slice of the spectrum unknown to the Secret Service at the time. It was only after the capture of an enemy bomber that they identified and localized the signal. This initiated a *Battle of the Beams*, with the British initially deploying jammers to counteract with noise and interference and later broadcasting their own dots-and-dashes to contaminate Luftwaffe's binaural signal and 'bend' the beam away from its intended target.

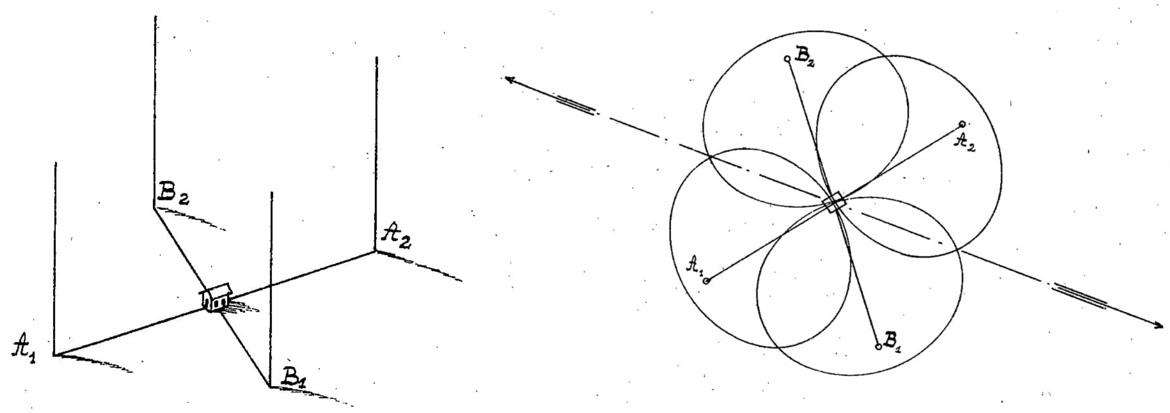

Figure 2.31. Graphs from Otto Scheller's *Course Setter* patent from 1907. The system deployed two co-located orthogonal vertical antenna systems operating on the same frequency (left) with complementary directional 'figure-8' patterns (right) (from Scheller, 1907).

Yet another German radio navigation instrument was patented in 1908 and developed in the following four years by Telefunken, a company founded in 1903 from a merger of Slaby-Arco and Braun-Siemens (Quilter 2010). Named the *Kompass-Sender* (translating to *Compass-Transmitter*), it was an umbrella-shaped object consisting of 32 compass-aligned antennas with an omnidirectional antenna in the middle (figure 2.32). The *Kompass-Sender* was a radio beacon; it essentially reversed Marconi's concept of a D/F receiving antenna into its transmitting twin. Originally designed to provide navigational aid to marine mobile receivers, it was also used to guide Zeppelin after successful experiments in land-to-air communication in 1908. The *Kompass-Sender* worked as follows: it first transmitted an identifying signal from the central antenna, waited for a fixed time, and then sequentially transmitted from each element at a fixed interval. The receiver captured and sonified the signal through headphones, allowing the operator to deduce the transmitter's compass direction by comparing the loudness of the different signals, which corresponded to their strength. The device had a nominal resolution of 11.25°, which operators with sharp ears could increase (Quilter, 2010). Telefunken's goal was to create a network of *Kompass-Sender* stations across Northern Europe, but in the end the system was mostly used during WWI as a homing beacon.

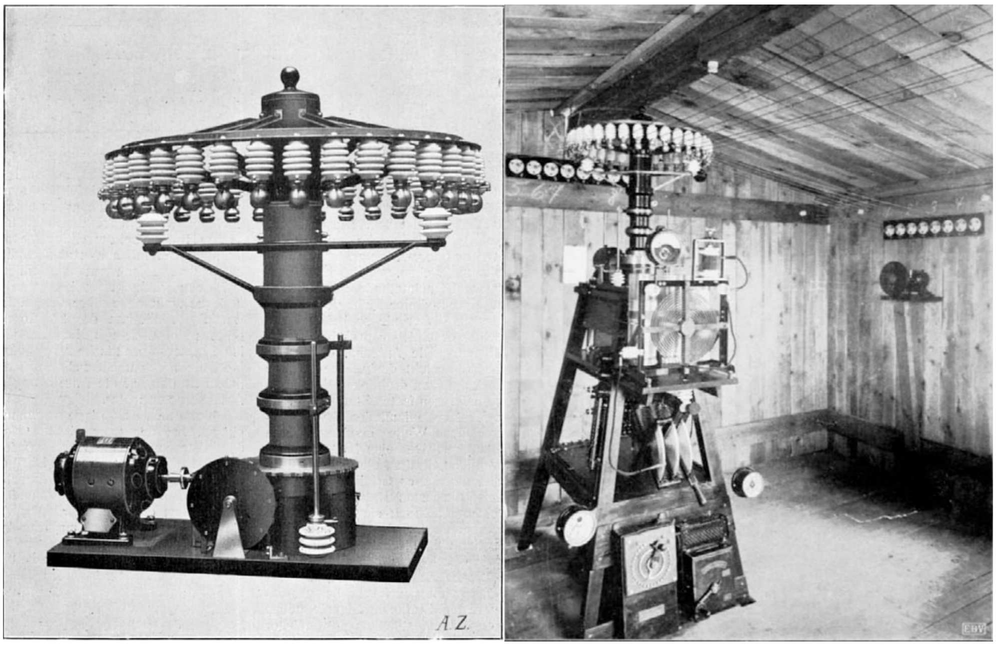

Figure 2.32. Photos of the *Telefunken Kompass-Sender* device: the device on its own (left) and installed in the *Telefunken Kompassstation* in Gartenfelde (right) (from "Telefunken-Kompass", 1912).

An alternative direction-finding system that became very popular was developed in 1907 by Ettore Bellini and Alessandro Tosi and patented in the US a year later ("Bellini-Tosi direction finder", 2022). The B-T system (BTDF) could be used as both a directional transmitter and a D/F receiver. Using a similar configuration to Scheller's *Course-Setter*, it deployed two directional loop antennas of the same size, insulated from one another and fixed at right angles – a configuration that can be thought of as the radio equivalent of stereoscopic vision or binaural hearing. The antennas were connected to a *radiogoniometer*, an instrument that permitted finding the transmission angle and thus its direction without having to rotate the antenna itself. The radiogoniometer consisted of twin antenna coils wound at right angles and fixed to a frame together with a rotatable 'search coil' (also called 'sense coil') (figure 2.33). This system was connected to a 'tuning buzzer'. The electric field produced by the two coils was a copy of the field received by the two antennas - slightly attenuated, but perceptually stronger, as it was concentrated in a smaller area. After tuning to the desired frequency, the operator would start rotating the search coil and could identify the angle on which the radio wave hit the plane of the two antennas by listening to the sound of the tuning buzzer - strongest when directly opposite the transmitter, and completely silent when turned 180° from that point (Donisthorpe, 1925). The rights to the patent were acquired by Marconi, Telefunken and others in 1912, and the system was first deployed in France to facilitate commercial navigation. (Donisthorpe, 1925 and Quilter, 2010).

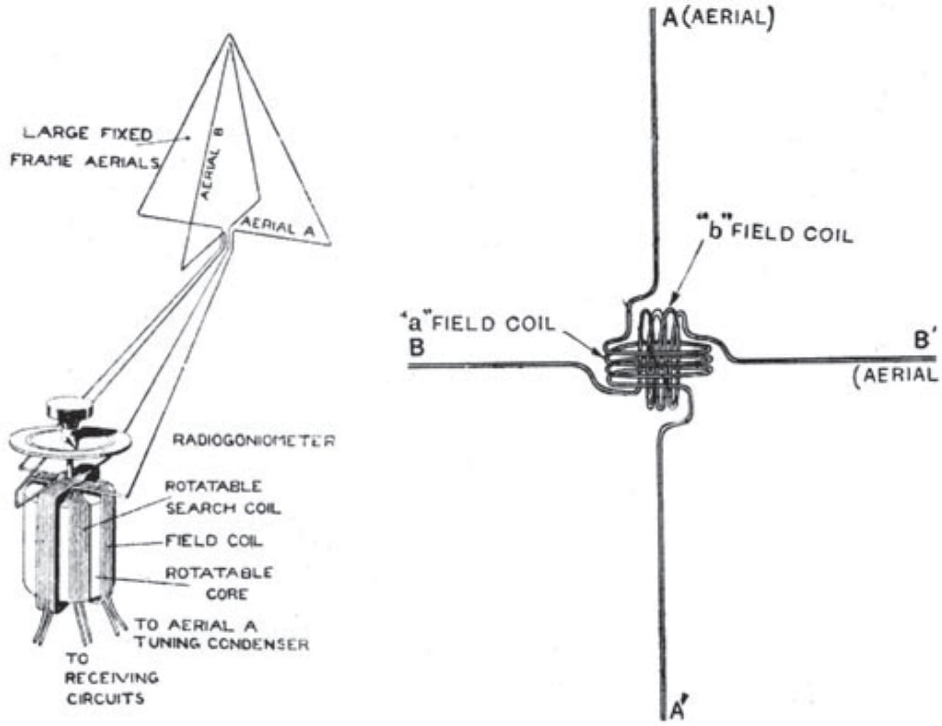

Figure 2.33. Graphs demonstrating the principle of operation of the *Bellini-Tosi Direction-Finder* and its use of a radiogoniometer (from Kendall, 2011).

Trailing by just a couple of years, Reginald Fessenden received a patent for his own *Method for Determining the Position of Vessels* in November 1909 (an application he first submitted in 1904) (Fessenden, 1909). Whereas the systems mentioned above used localization techniques based on *Angle-of-Arrival* or *Time-of-Flight*, his system relied on *Received Signal Strength* (for an explanation of these techniques see section 5.3). Fessenden mistakenly believed radio signals to fade linearly, so he thought that by measuring the strength of two transmitters placed at known coordinates he could simply deduce the receiver's location (Kendall, 2011).

As the overview of all these systems reveals, the fundamental techniques of radio navigation had already become established by 1910. Through a continuous refinement, evolution, and combination of these simple systems we have arrived to the much more complex and sophisticated navigation and direction-finding systems of today. Beyond these basic techniques, we have also inherited some networking standards from this early period. For instance, due to the difficulty of having large heavy transmitters on board of a cramped boat or aircraft, Telefunken decided that it was best to have fixed infrastructure on the ground transmit and mobile stations to receive, a standard used today by GPS and many other localization technologies (Quilter, 2010).

2.4.2 *Electronic warfare and TEMPEST*

The Great War made the practical applications of radio obvious rendering wireless communication a critical tool for military operations. This led to the formation of a new branch of special forces, the Signal Corps, who dealt not only with the coding, transmission and decoding of messages but also included Direction-Finding units, whose task was to locate the enemy's transmission infrastructure. Finding where intercepted signals where transmitted from became part of a newly discovered field, often referred to today as *electronic warfare*. Electronic warfare activities can be summarized under 3 basic principles (Quilter, 2010):

- Any transmitted signal can be intercepted with the right receiver.
- Signals can be interfered with (*Funkstörung*) to either make it impossible for the enemy to utilize them by adding noise (*jamming*), or to deceive them by adding false information (*active electronic warfare*). As we saw earlier, the British used both of these strategies during the 'Battle of the Beams' in WWII.
- Through analysis, the function of any signal can be deduced, i.e. the interceptor can infer whether it is used for communication, navigation, or radar-sensing. This process is called *electronic intelligence*. Signals can also be exploited to reveal their content. Even when encoded, they can be decoded with the right tools and knowledge (*signal intelligence*). The source of the signal can also be traced using direction finding (*passive electronic warfare*).

The field of electronic warfare took its first steps in WWI. By the time WWII came, it had become a crucial part in both war and peace. Since then, its importance has kept growing at a rapid pace.

Recently declassified - though heavily redacted - documents of the US National Security Agency (NSA), in conjunction with reports by NSA trained and certified cryptographists, help put together the pieces of this field's evolution on the American side. One of the most notable discoveries leading to the field's inception was made by accident towards the end of WWI. In 1918, Signal Corps officer Herbert Yardley was investigating how to detect, intercept and decipher signals from enemy telephone lines and clandestine wireless communication for the US government (Atkinson, 2000). In doing so, he discovered that Allied communication devices were in fact leaking classified information via electromagnetic radiation. As a result, shielding, grounding and encryption were implemented to protect transmissions. An advanced iteration of this problem resurfaced in WWII. In 1943, Bell Labs technicians accidentally discovered that encryption equipment that the company rented and sold to the military was transmitting traces of its own mechanical decryption actions (Friedman, 1972). Electromagnetic signals were radiating away from the devices, allowing anyone in range to remotely capture and read the decrypted message. The Signal Corps formulated some simple countermeasures against this, but the problem was forgotten until the Cold War. In 1951 it was rediscovered by the CIA and by 1955 a lot of work had been made for suppressing as well as detecting and analyzing such signals leaks. Broad protection policies were established in 1958, and were adopted by the UK and Canada the following year. In 1959, the problem began to be acknowledged outside of Communications Security and Signal Intelligence as well. As a result, in 1960 the first permanent committee and *"a multi-million dollar program aimed at the full range of information-processing equipment"* was formed in the US to deal with such problems (Boak, 1973, 93).

The above is the pre-history of a secret program, codename *TEMPEST*, as presented to NSA employees in 1966 in a series of in-house lectures by David G. Boak.[78] These lectures were meant to educate them on key concepts of Communications Security and to introduce the concepts and techniques behind TEMPEST - a Shakespearean acronym standing for *Telecommunications Electronics Material Protected From Emanating Spurious Transmissions* (Atkinson, 2000).[79] The fundamental idea was that electronic equipment radiates electromagnetic energy, and that this energy can be analyzed to reveal sensitive information: *"[A]ny time a machine is used to process classified information electrically, the various switches, contacts, relays, and other components in that machine may emit radio frequency or acoustic energy. These emissions, like tiny radio broadcasts, may radiate through free space for considerable distance (...). When these emissions can be intercepted and recorded, it is frequently possible to analyze them and recover the intelligence that was being processed by the source equipment"* (Friedman, 1972, 27). TEMPEST research was of special value for the intelligence community as it provided information that was *"generally accurate, reliable,* authentic*, continuous, and most important of all,* timely*"* (Boak, 1973, 9). Unsurprisingly, this meant it was a highly classified matter and thus hidden to the public. A first mention in non-secret literature appeared in 1967 (Kuhn & Anderson, 1998); but it was

[78] An article summarizing these lectures (Friedman, 1972) and the lectures themselves were partially declassified in 2007 (Boak, 1973).

[79] The acronym has also been said to stand for other names, such as *Transient ElectroMagnetic Pulse Emanation Standard,* or *Transient EManations Protected from Emanating Spurious Transmissions*.

not until 1985 that the problem of information leakage became widely known, thanks to Dutch engineer Wim van Eck and his presentation of *van Eck 'phreaking'*, a technique for capturing the image of a video display using cheap, off-the shelf equipment (Van Eck, 1985). In more recent decades, TEMPEST concepts have been slowly making the passage from intelligence agencies to the private sector and the commercial world, becoming more commonly known under the acronyms EMSEC (*Emissions Security*), and COMSEC (*Communications Security*).

A key countermeasure against compromising emissions is the *Red/Black* separation of equipment: Equipment that carries confidential data, such as computers, is considered *Red* and needs to be electromagnetically isolated from *Black* equipment, which is used to transmit or process unclassified data (Kuhn & Anderson, 1998). This is similar to the problem described by Boak as *"cipher signal modulation"* or *"cipher signal anomaly"*: *[S]uppose, when a cryptosystem is hooked to a radio transmitter for on-line operation, compromising radiation or conducted signals get to the transmitter right along with the cipher text and, instead of just sending the cipher text, the transmitter picks up the little compromising emissions as well and sends them out full blast. They would then "hitchhike" on the cipher transmission, modulating the carrier, and would theoretically travel as far as the cipher text does. Alternatively, suppose the compromising emanations cause some tiny variations or irregularities in the cipher characters themselves, 'modulate' them, change their shape or timing or amplitude? Then, possibly, anyone intercepting the cipher text (and anyone can) can examine the structure of the cipher signals minutely (perhaps by displaying and photographing them on the face at an oscilloscope) and correlate these irregularities or anomalies with the plain text that was being processed way back at the source of the transmission. This process is called 'fine structure analysis'"* (Boak, 1973, 93). The *Wireless Information Retrieval* technique that I developed to analyze WiFi signals for the *Hertzian Field* series does precisely what Boak mentions: It intercepts publicly available beacon signals and performs a multi-layered analysis of the fine structure of their amplitude to reveal embedded interference patterns, thus producing knowledge on the activities of bodies in the physical space between transmitter and receiver.

2.4.3 *From Direction-Finding to meteorology*

This focus on signal analysis, closely examining its minute fluctuations to extract information, strongly relates to the practice of attentive listening exercised by Signal Corps during WWI, a military branch that grew significantly during the war (figure 2.34). Much of the art of being a radio operator in those days involved discerning which signals were intended for one's station and which were not. This skill was much more important for Signal Corps decoders and direction-finders. Natural radio research, in fact, built upon observations made by radio operators in the trenches and war zones of WWI after endless hours of listening.

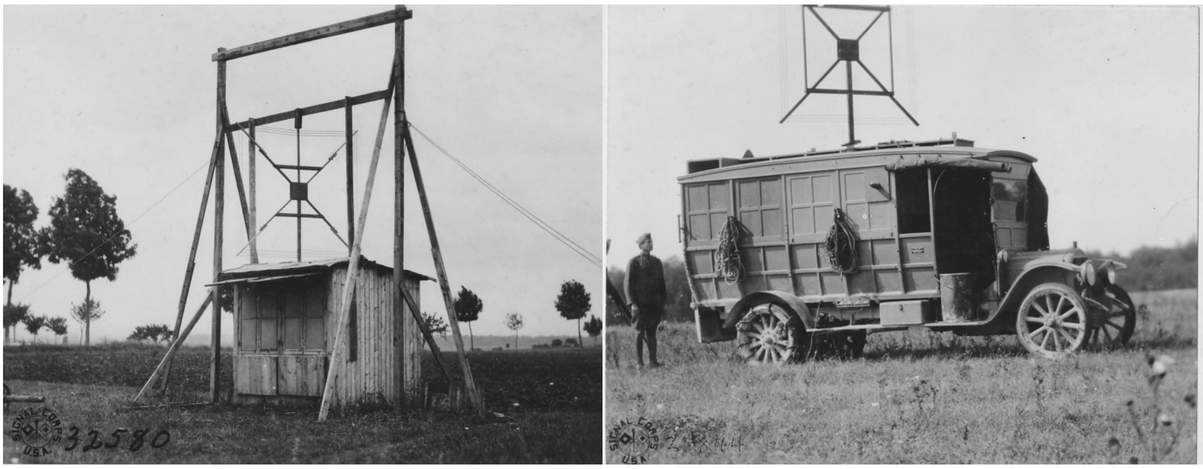

Figure 2.34. Photos of WWI US Signal Intelligence systems taken in France in 1918. Left: an *'Aero Gonio Station'* or '*airplane compass'* at Royaumeix, France, tracking the direction of enemy aircraft via their radio emissions. Right: radiogoniometric truck near Verdun, conducting direction-finding on enemy radio communications (Smoot 2020) (photos from National Archives, public domain).

Heinrich Barkhausen's job at the German Signal Corps was to intercept and decode allied communication in the field. He used a telephone receiver connected through an amplifier to two electrodes/dipoles placed in the earth hundreds of meters from each other. This apparatus, named *Erdsprechgerät (Earth speech device),* amplified inductive currents in the Earth as well as natural radio signals (Kahn, 2013). After the war ended, Barkhausen published the first scientific report on whistlers in 1919. He wrote in a later summary: *"At certain times a very remarkable whistling note is heard in the telephone. At the front it was said that one hears 'the grenades fly.' (...) These whistling tones were so strong and frequent on many days that at times listening in was impossible. This phenomenon certainly was related to meteorological influences"* (Barkhausen, 1930, 1155).

At the opposite camp, Thomas L. Eckersley from the British D/F Corps, detected the same strange whistling sounds with his directional loop antennas and hypothesized that the Heaviside layer of the atmosphere (ionized gas between 90-150km) was causing interference (Kahn, 2013). After the war ended, Eckersley joined the Marconi company and like Barkhausen began investigating the phenomenon scientifically, helping discover the ionosphere and reveal its properties. This type of research was pivotal for the further development of telecommunications in the 1920s, allowing to bounce signals off the ionosphere and achieve longer range transmission.

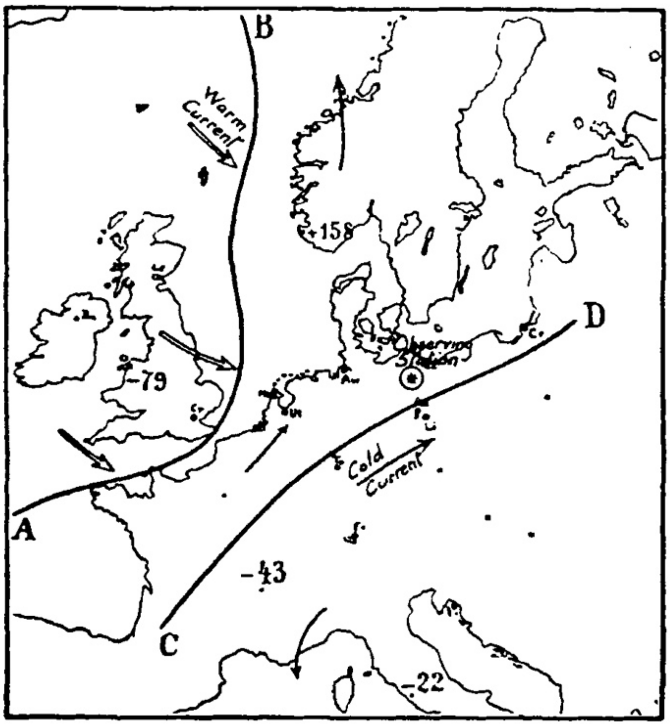

FIG. 16.—Effect of discontinuity surfaces on signal strength.
[Numerals represent the percentage increase or decrease in received intensity at Strelitz-Alt of the transmission from the Station covered by the numerals.]
22nd December, 1920.

Figure 2.35. Thunderstorms and signal strength: image illustrating that *"[s]urfaces of discontinuity between sender and receiver diminish the received energy"* whereas *"[s]urfaces of discontinuity over the sender increase the received energy"* (Watson-Watt 1929, 294).

Robert Watson-Watt's work for the British airforce during WWI involved tracking the electromagnetic emissions of a different type of enemy: thunderstorms (Sim, 2014) (figure 2.35). As he reminded the audience of his 1929 lecture, *Weather and Wireless,* the lineage of such work, i.e. using *"wireless communication as a tool of the forecaster",* started with Popov in the early days of wireless communication when the disturbing effects of atmospherics where first observed; it was further developed with a foundational paper *"on the relation between wireless and weather"* by Captain Henry Jackson in 1902 (Watson-Watt, 1929, 273). In 1911, James Robert Erskine-Murray suggested locating meteorological disturbances with a radio compass. Experiments at the Meteorological Office demonstrated already in 1915 that *"actual thunderstorms could be located by direction-finding on atmospherics"* (Watson-Watt, 1922, 680). This initiated a more thorough investigation between 1916-18, involving a network of coastal stations, on which Watson-Watt published some preliminary results in 1922. This path of research would eventually lead him to re-invent the principle of radar in the mid 1930s, as we will soon see.

2.4.4 *Listening to outer space, and the birth of radio astronomy*

Direction-Finding units and Signal Corps soldiers were not the only ones becoming familiar with the strange sounds of radio around that time. Many radio engineers and enthusiasts had also developed an ear for identifying the provenance of strange sounds like atmospherics. However, there were still a lot of unidentified noises – "c*licks and scratches on telephone and telegraph lines; 'sudden uncontrollable variations in the strength of reception'; hissing everywhere"* (Schwartz, 2011, 817). In 1925, physicist Robert Millikan proposed that these sounds were caused by *"cosmic rays"* originating from *"everywhere in interstellar space",* an idea that was supported by Marie Curie's finding of *"a penetrating radiation disseminated through the universe"* (Millikan and Curie quoted in Schwartz, 2011, 817).

Equipped with a sensitive direction-finding antenna, a 28-year old by the name Karl G. Jansky would be the first to listen to sounds beyond our solar system in 1933. Jansky was a trained physicist from a family of engineers. His father was a distinguished electrical engineer and his older brother a radio engineer and businessman since the early days of radio (Schwartz, 2011). In 1928, Jansky was hired by Bell Laboratories to study radio static and to measure electromagnetic noise in different frequencies so as to improve communication fidelity. Soon thereafter he was charged with profiling the atmospheric noises that hindered commercial trans-oceanic short-wave transmissions. In spring 1929, he started designing the instrument for this assignment (Jansky, 1979). By fall 1930 it was complete and was placed at a company-owned potato field in New Jersey (Kraus, 1981). The instrument consisted of a 14.6-meter directional and rotatable antenna array system on wheels, coupled to a 20.6MHz double receiver - very sensitive and as noise-free as possible at the time - and a self-adjusting recorder which transcribed received signal intensity on paper (Jansky, 1932 and Schwartz, 2011) (figure 2.36).

Within less than a year, Jansky's instrument had detected a strange new type of noise. After a long process of data gathering and observations, Jansky presented a paper in 1932 in which he distinguished between three types of 'static': a) *"crashes",* caused by local thunderstorms; b) a *"very steady weak static",* which *"aural observations"* revealed to be *"of the crash and rumble type",* and therefore attributable to energy from remote storms bouncing off the ionosphere; c) a *"very steady hiss type static"* that was hard to identify, and which he first thought may be coming from the sun (Jansky, 1932). After more data-gathering and research on astronomy, Jansky corrected himself a year later: the hiss was coming from a fixed point in the middle of the Milky Way in the direction of Sagittarius (Jansky, 1932). While Jansky had set to scan the skies and map the received radio energy of high-frequency atmospherics, he had instead performed the first radio cartography of outer space and had set the foundations of radio astronomy.

His findings made headlines around the world. A New York Times article on 5 May 1933 led to a very special broadcast on the New York radio 10 days later ("New Radio Waves Traced", 1933, 1). A live feed of Jansky's receiver was broadcast during the show *Radio Magic* (episode: *Hearing the Radio of the Stars)* with the host encouraging his audience to listen closely to the static for this most faraway of all signals, a noise that comes "*from the depths of the universe"* (quoted in Kahn, 2013, 119). Kahn describes this as *"an extraordinary historical moment for many reasons: a socialization of the cosmos, extra-terrestrial radio on the radio, a lesson on listening to radio within radio"* (Kahn & Macauley 2014). As he noted elsewhere, radio was *"finally taking astronomy out of its silent film period"* (Kahn, quoted in Harger, 2008, 468).[80] The eye was no longer the sole organ for examining the universe. Unfortunately, happy to realize that this nuisance was both unavoidable and minor, Bell Labs reassigned Jansky to develop a systematic way to measure static. Jansky would continue pondering on the provenance of the hiss but in his own time, while Bell Labs continued to assign him to more mundane tasks. Regrettably, astronomers were also oblivious to Jansky's finding – how significant could the work of a young Bell Labs engineer be to change our view of the cosmos, after all?

Another outsider, Grote Reber from Illinois, would soon come to similar conclusions as Jansky. Reber, a designer of radio receivers and true DIY-er, had fashioned *"the world's first parabolic telescope"* in his back yard in 1937 (Schwartz, 2011, 820 and Joyce, 2008). Its dish was made out of discarded wood and car parts and was coupled to a receiver operating at a higher frequency than Jansky's, around 160MHz (Haddock, 1958) (figure 2.36). Reber would spend his nights listening to the noise of the stars, using sound to sense the universe from afar. By 1939 he had heard the same noises as Jansky. He began mapping the radio noise of the sky and identifying peaks of static from certain constellations, publishing a first radio

[80] From a lecture by Kahn titled *Radio was discovered before it was invented* at the RIXC festival *Art + Communication: Waves*, in Riga, Latvia, 2006.

map of the sky five years later in 1944 (Mezger, 1984). Like Jansky, Reber's work went unnoticed until after the war, when the vast experience amassed by technicians, engineers, physicists and astronomers led to the construction of new radio telescopes and the birth of radio astronomy as a science.

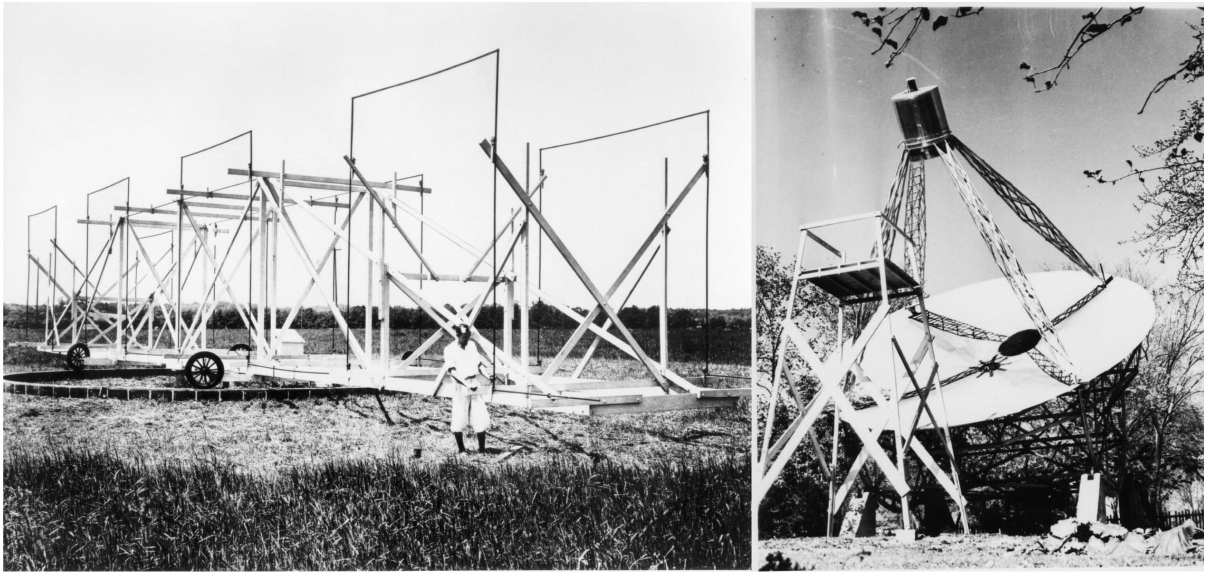

Figure 2.36. Radio astronomy was founded on the work of two outsiders in the 1930s. Left: Photo of Karl Jansky in front of his rotating directional antenna – nicknamed 'Jansky's Merry-go-round' - with which he discovered radio emissions from the Milky Way; photo taken in New Jersey in the early 1930s. Right: Grote Reber's parabolic radio telescope from 1937, a 9-meter antenna he built in his backyard. (Public domain images, courtesy of National Radio Astronomy Observatory / Associated Universities, Inc).

2.5 SENSING SPACE

2.5.1 *Radar principles and contemporary systems*

Another electromagnetic application that emerged due to an increased ability in distinguishing hidden patterns within radio noise is RADAR. The term was introduced by the US Navy in 1940 as an acronym for *RAdio Detection and Ranging*. Before presenting an overview of the technology's historical development (sections 2.5.2-2.5.4) it is useful to first discuss the basic of its operation (for more detail, see Yavari et al., 2016).

Radar works by transmitting electromagnetic waves in free space and listening for received echoes. Objects within the path of transmission that have a different relative permittivity than vacuum will reflect parts of the transmitted energy (figure 2.37). This effect allows deducing a variety of information about these objects. A typical contemporary radar system is composed by a transmitter, a receiver, an antenna or antenna array, and a signal processing module implemented in hardware, software or both. Depending on their spatial configuration, radars can be monostatic or bistatic. In the first case, the same antenna is used by both transmitter and receiver. In the second case, the transmitter and receiver antennas are separated by a distance as large as the expected distance between target and radar (this is the case, for example, for semi-active missiles). Other variants are pseudo-monostatic radars, which utilize two antennas in proximity, and multistatic radars which employ more than one transmitter and/or more than one receiver separated in space. Antennas are commonly directional so as to facilitate tracking the target's direction.

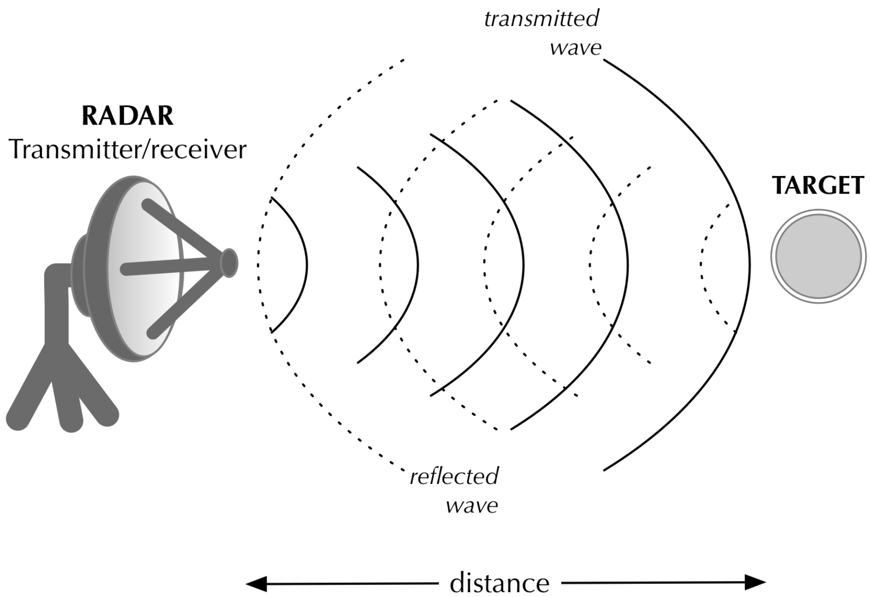

Figure 2.37. Simplified graph of the basic operating principle of a radar system: Its transmitter sends out waves in free space and its receiver listens for returned echoes that reveal the presence of an object and which, through signal analysis, can also reveal its distance as well as its angle, direction, velocity, and altitude.

Radar technology can be implemented in different parts of the electromagnetic spectrum, although it is usually located between 3MHz to 300GHz – i.e. the radio and microwave range - and more often in the upper area of that range (see again figure 1.6 for the naming of the different radar bands). The choice of frequency depends on design factors such as the size of the antenna, transmission power, desired range, resolution and other application-specific requirements. Atmospheric conditions are also a consideration, as the range of radars is affected by the presence of water molecules absorbing part of the radiated energy. To avoid such interferences higher frequencies are preferred because they are less susceptible – the electromagnetic resonance of water is not flat across the spectrum. In contrast, weather radar is specifically tuned to harness the interference of water.

Early radar instruments could only detect the presence and estimate the distance of a target. Since the 1950s, the capabilities of radars have expanded beyond detection and ranging, allowing to track direction, angle and velocity of motion of several objects at once, their altitude, as well as to classify them and create an image of the radio field. Distance can be calculated by measuring time-of-flight, meaning how long it took the transmitted signal to travel back to the radar. Information about the size, shape and material composition of the object can be deduced by the amount of reflected energy. The velocity of motion can be calculated by measuring the shift in frequency between transmitted and reflected signals. This phenomenon, discovered by physicist Christian Doppler in 1848, occurs with all types of waves, e.g. sound, when the distance between source and receiver is changing - i.e. when either of the two is moving relatively to the other. When the distance is reduced, frequency rises; when it increases, frequency drops. Motion also effects the rate of change of the received signal's phase, or its angular frequency (for doppler equations see Yavari et al., 2016). Doppler is particularly useful for atmospheric imaging of weather patterns as it can track water vapor movements, and for detecting the speed of vehicles, aircraft and boats. Doppler-based direction finders were first introduced in 1941, initially operating in the shortwave range but soon extended to higher frequencies. After WWII, airports became equipped with such VHF and UHF systems to control air traffic (Rohde & Schwartz, 2016). Doppler modules are also commonly used for various motion detection applications involving the human body, such as in security systems, door openers, etc.

Doppler radar modules commonly operate in the microwave range; they typically combine transmitter and receiver in the same unit and employ directional antennas. Several types of Doppler radar exist, categorized by the type of signal or waveform used:

• *Continuous Wave* (CW) systems utilize a continuous, narrow band signal, making it easy to detect Doppler shifts and thus infer velocity. CW radars use the transmission oscillator on the receiver end, employing the heterodyne or homodyne principle to mix transmitted and received signals and detect shifts. CW doppler radars may use separate antennas for transmission and reception, or the same antenna with some added circuitry to isolate the two received signals. A drawback of CW systems is that there can be energy leakage from the transmitter to the receiver, resulting in strong unreflected signals at the radar frequency which produce DC offset and low frequency noise that needs to be filtered out. Simple CW systems cannot distinguish between motion towards or away from the antenna. To achieve such differentiation the circuitry must involve either a quadrature homodyne or a coherent heterodyne receiver.

• *Frequency-Modulated Continuous Wave* systems (FM-CW) can detect velocity, like any CW system, as well as distance. This is achieved by encoding a timing marker through frequency modulation so that the time-of-flight between transmission and reception can be measured. Typically, the modulator wave is triangular, so that frequency is varied linearly in time. The system's resolution depends on the amount of modulation i.e. the bandwidth of the FM-CW signal; the larger the bandwidth, the more accurate the measurement. Maximum range depends on the modulator's frequency. The transmitted and received signals are multiplied to find the difference in frequency, which allows finding the time delay between transmission and reception. Frequency modulation is one of several alternatives available for this type of encoding; other techniques include Amplitude modulation (AM), coded modulation (CM), noise modulation (NM), stepped frequency continuous wave (SF-CW), synthesized pulse modulation (SPM), or holographic modulation (HM).

• *Pulsed Doppler* systems are the most common radar type, combining features of continuous wave and pulsed systems. They transmit a train of narrow-band, high power pulses at a constant frequency. The received pulse-train is compared to the transmitted signal to infer distance by measuring the time delay between the two. Velocity is inferred by measuring the reflected signal's doppler shift; high velocities will cause a shift within a single pulse whereas lower velocities can be detected by looking at the modulation caused in several periods of the pulse train. A significant advantage of pulsed techniques is that energy leaks from the transmitter and loud echoes from nearby objects can be easily ignored, as they occur before the softer reflections of longer range objects reach the receiver. Typically, pulsed radars switch between transmit and receive modes, which makes energy leaks from transmitter to receiver a non-issue.

2.5.2 *The forgotten births of radar technology*

Like direction-finding, the first radar instruments were developed as a response to maritime needs. However, as we saw earlier (section 2.1.8), Hertz had planted the seed of the concept already in 1887 with what should be regarded as the *"*ur-*experiment of radar"* (Süsskind, 1985, 92). Nevertheless, this seed remained dormant for a long time. While indoor radio sensing is a rapidly growing field today, at the time there was no need for – or even the concept of – sensing human bodies in domestic spaces like the Karlsruhe physics lecture hall. Therefore, there was little incentive to investigate the interaction between body and radio. The next time the artifact of interference-as-sensing showed its face was 10 years later and by accident, during Popov's wireless experiments (section 2.3.1). Radar was almost born in the bay of St. Petersburg, but Popov was too absorbed with implementing a working telecommunications system and did not follow up on his discovery.

Tesla was another inventor that came near making radar a reality. In 1900, he exclaimed in a juggernaut of an article titled *The problem of increasing human energy*: *"When we raise the voice and hear an echo in reply, we know that the sound of the voice must have reached a distant wall, or boundary, and must have been reflected from the same. Exactly as the sound, so an electrical wave is reflected, and the same evidence which is afforded by an echo is offered by an electrical phenomenon known as a 'stationary' wave–that is, a wave with fixed nodal and ventral regions. Instead of sending sound-vibrations toward a distant wall, I have sent electrical vibrations toward the remote boundaries of the earth, and instead of the wall the earth has replied. In place of an echo I have obtained a stationary electrical wave, a wave reflected from afar"* (Tesla, 1900). While this was more than a mere theoretical vision, Tesla likely never concentrated on the subject enough to produce an instrument, as he never published any technical details about such a technology.

Between 1902-3, radar technology would actually come to briefly exist, but it would soon become forgotten. The inventor was 22-year old German physicist and inventor Christian Hülsmeyer who came of age in the midst of a wireless communication arms race and at a time when it was too late for a young newcomer to claim his space in that field. Hülsmeyer had started out working with optical and sound technologies. His first invention, with which he applied for a patent in March 1902, was the *telephonogram*. [81] This was an apparatus that converted electric fluctuations from telephone speech *"into variations in the intensity of light"* (Hülsmeyer, 1904a) and then imprinted them on a plate to create a *"sonic telegram"* (Bauer, 2005). Hülsmeyer had an entepreneurial spirit, however he lacked funds to commercialize his designs and as such had been searching for capital since at least April 1902. In September1 1902 he submitted another invention to the patent office: an optical film projection apparatus that could be mounted on advertising vans (Ibid).

Hülsmeyer begun working with electromagnetic waves that same year. In November, he submitted an application for an interference-free radio detonator. It is possibly this work that made him pay attention to Hertz's comments on electromagnetic waves being reflected by metal. This gave him the idea to use radio waves not for communication, as was the norm at

[81] Hülsmeyer received 160 patents in his life.

the time, but to detect large metallic objects such as ships (Thumm, 2006 and Ender, 2002). Having grown up in Cologne and living in Düsseldorf meant that he was familiar with navigation problems in the Rhein river and that he recognized the commercial potential such an instrument could have. Intrigued, he focused his attention to exploiting the phenomenon and proceeded to build the first device harnessing this effect: an instrument for *"[s]eeing ships through fog and darkness by transmitting waves and detecting the echoes"* to prevent collisions (Thumm, 2006, 334 and Quilter, 2010).

Hülsmeyer finished a first version of this device in 1903 and named it *Telemobiloskop* (*Telemobiloscope*), i.e. a device for seeing movement from afar or while moving. There is no information on this early prototype and the patent he filed on 21 November 1903 was rejected (Bauer, 2005). More wireless invention applications followed, such as one in March 1904 on an interference-free *"wireless transmitting and receiving mechanism for electric waves"*, whose suggested uses were communications or the secure actuation of mechanisms at a distance (i.e. remote detonation) (Ibid). On April 30th 1904 he received a German Imperial patent for a new version of the *Telemobiloskop.* He subsequently applied for a British patent - granted on September 22nd - titled *"Hertzian-wave Projecting and Receiving Apparatus Adapted to Indicate or Give Warning of the Presence of a Metallic Body, such as Ships or Trains, in the Line of Projecting of such Waves"* (Hülsmeyer 1904b) (figure 2.38). The texts of these patents demonstrate a clear understanding of the radar principle. As Hülsmeyer explained, *"My invention is based upon the property of electric waves of being reflected back towards their source on meeting a metallic body (...) My apparatus comprises a transmitting and a receiving station similar to those used in wireless telegraphy, with this difference that the two stations are situated in close proximity to each other and are so arranged and constructed that they cannot directly influence one another"* (Hülsmeyer 1904b, 1).

The *Telemobiloskop* consisted of a double spark-gap transmitter generating a continuous wave around 650MHz, coupled to an array of simple dipole antennas and a 'projector screen' to further focus the beam (Sarkar et al. 2016; Guarneri, 2010; Ender, 2002). The receiver was also directional and was comprised of a coherer coupled to a parabolic antenna that could mechanically rotate in 360° (Sarkar et al., 2016). A compass pointer was integrated to this mechanism. Reflected signals activated a relay; the relay activated a hammer that tapped a bell - one of the most common ways of the time to demarcate a successful transmission, used by Hertz, Bose, Popov and many others, as we have already seen. The hammer also reset the coherer (Bauer, 2005). Stepping on his previous work, the instrument also had the capacity to filter out false signals (Sarkar et al., 2016). Initially, this rudimentary radar could not determine distance, only direction like its early D/F cousins (Ender, 2002). A subsequent patent application from 1904 - titled *Improvement in Hertzian-wave Projecting and Receiving Apparatus for Locating the Position of Distant Metal Objects* and granted on March 23rd 1905 - attempted to tackle the issue by adding a second vertical measurement that could be used to triangulate (Hülsmeyer, 1905).

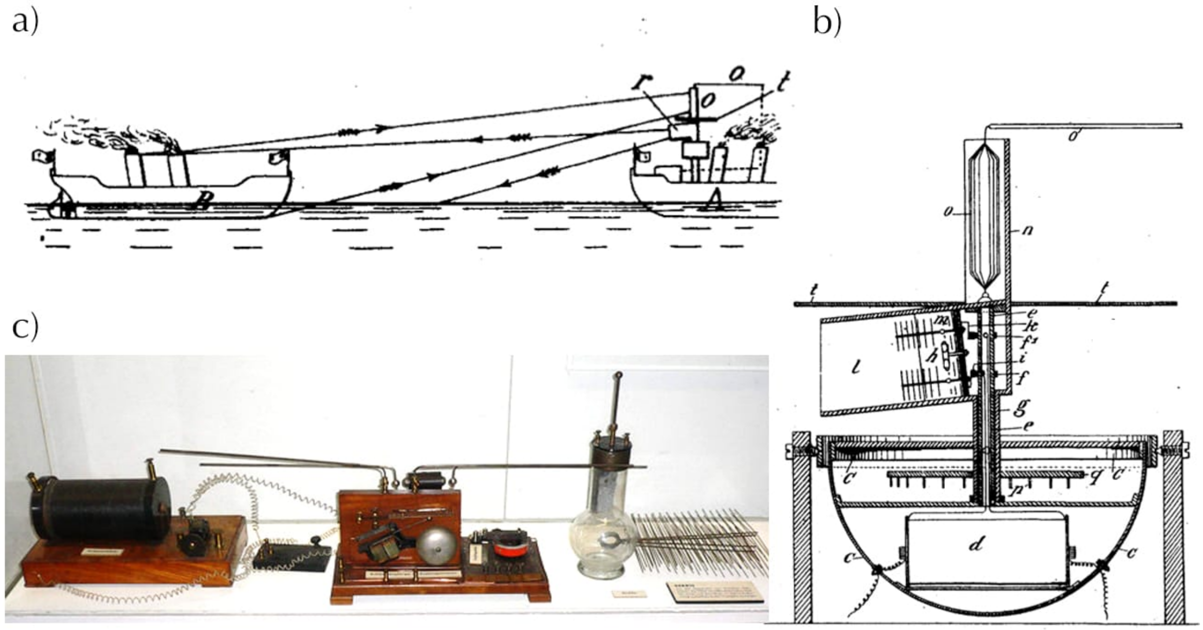

Figure 2.38. Christian Hülsmeyer's *Telemobiloskop,* the first radar apparatus from 1904: (a) Diagram from Hülsmeyer's patent application showing a ship fitted with his device on the right detecting another ship on the left, and (b) sectional view of the *Telemobiloskop* (from Hülsmeyer 1904b); (c) photo of the apparatus from a contemporary exhibition (by Deutches-museum.de).

Soon after inventing the *Telemobiloskop,* Hülsmeyer approached Telefunken to sell his patent and set the system in production; however, the company was not interested in it (Thumm, 2006). Instead, in March 1904, Hülsmeyer received a starting capital from a Cologne leather merchant, Heinrich Mannheim; a couple of months later the company *Telemobiloskop–Gesellschaft Hülsmeyer & Mannheim* was incorporated (Sarkar et al., 2016). The first public demonstration of the invention took place on 17 May 1904, in the courtyard of the Cologne Dom hotel. In an interesting simulation of its intended use, the target was the courtyard's metal gate; the apparatus itself was placed behind a curtain to showcase that visibility was not a requirement (Ibid). Reports of the demonstration made rounds in the press, and reached the director of the Netherlands-based shipping company Holland-Amerika Lijn (HAL). Hülsmeyer was subsequently invited to a conference held in Scheveningen, the Netherlands.

He presented his *"anti-ship-colliding system"* to the main Atlantic shipping companies (Bauer, 2005, 1) and successfully demonstrated it in action on June 9th in the nearby Rotterdam harbor (Sarkar et al., 2016). A report on the Dutch newspaper De Telegraaf two days later made a prophetic remark on the future of radar: *"Because, above and under water metal objects reflect waves, this invention might have significance for future warfare"* (translated quote in Bauer, 2005, 36). Hülsmeyer had already demonstrated his device to the German Navy, but there was no interest. The argument of the experts was that *"[s]ince the steam pipes can be heard over a longer range than Herrn Hülsmeyer's device can detect, his invention is absolutely useless"* (quoted in Ender, 2002, 6).

The *Telemobiloskop* was the earliest radar application described and produced, but not much came of it, even though Hülsmeyer lived until 1957. The device was invented when wireless technology was at its very early stages, and was thus rudimentary. No transmitting tube amplifiers or matched filters were available to its inventor, and the coherer was certainly not the optimal detector. Furthermore, while revolutionary in its application, the underlying technology was not state-of-the-art even by that era's standards (Bauer, 2005). Its spark-gap transmitter made it a not very efficient device. Its range was limited to only about 3km, it was insensitive to movement, and could not measure distance reliably. Perhaps more importantly, because of its lack of proper tuning circuitry – already in use by Marconi, Lodge and Telefunken at the time – it did not implement true frequency separation or tuning. This meant that the *Telemobiloskop* would be problematic if more ships used the apparatus without further refinements. In this regard, it was closer to a prototype than a device ready for commercial deployment.

After his presentation in Rotterdam, Hülsmeyer kept contact with HAL. He also continued improving his invention and applying for patents in other countries. As the minutes of the next yearly Nautical Meeting disclose, a subsequent test of the *Telemobiloskop* at Hoek van Holland had failed (Bauer, 2005). The problem was likely interference: a contemporary report put the blame on mechanical vibrations from the boat, but Bauer suggests the Telemobiloskop and the many wireless stations on the coast might have interfered with each other. To make matters worse, *"[o]ne of the Delegates reported also that the principle on which the apparatus is based has been proved to be an error, so that probably nothing more will be heard of it"* (from the meeting's Minutes, quoted in Bauer, 2005, 47). The result was that in October 1905 Hülsmeyer disbanded the company and pursued other ventures unrelated to wireless. The concept of radar would have to be re-invented once again in later years and by someone else. The *Telemobiloskop* would be forgotten until 1948 when its existence was stumbled upon, thus starting a debate on who first invented radar (Ender, 2002).

2.5.3 *Radar as science fiction and speculative technology*

Radar-like devices stirred the imagination of sci-fi writers long before becoming an actual technology. The hero in Paul d'Ivoi's *Le Doctor mystère* (1900) is a doctor in possession of many unknown electrical devices. Among them, a kind of panoramic radar system whose 'eyes' could penetrate clouds and hills, and which displayed everything that occurred in the world. The principle of radiolocation also appears in Jules Verne's *La Chasse au météore* (1908) (*The Chase of the Golden Meteor*), which features a competition between two amateur astronomers who discover a golden asteroid about to fall on Earth (Süsskind, 1985).[82]

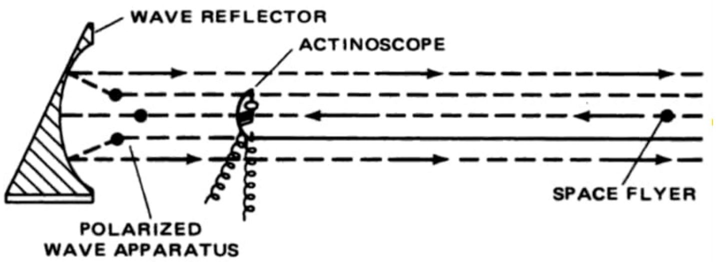

Figure 2.39. Hugo Gernsback's diagram of a speculative radar technology from his space travel story *Ralph 124C 41+: A Romance of the Year 2660,* first published in 1911 (Gernsback, 1925).

A rather detailed description of radar principles, accompanied by a diagram, can be found in a space travel story by Luxembourgian science fiction writer Hugo Gernsback (figure 2.39).[83] Titled *Ralph 124C 41+: A Romance of the Year 2660* (spelled out: *One Two Four See Four One Plus*, i.e. 'One to foresee for many'), it was first published in 1911 as a series in a technical magazine for radio enthusiasts (*Modern Electrics*). The hero is a scientist who, in 2659, invents a radar device that works in outer space; it uses signal strength and time-of-flight measurements and can distinguish between different materials (Sarkar et al., 2016). The narrator explains how this speculative technology works: "*At first thought it might be considered a difficult feat accurately to locate a machine thousands of miles from the earth, speeding in an unknown direction somewhere in the boundless universe (...) A pulsating polarized ether wave, if directed on a metal object can be reflected in the same manner as a*

[82] The novel was rewritten by his son and published posthumously.
[83] The sci-fi/fantasy literature Hugo Awards were named after him.

light-ray is reflected from a bright surface or from a mirror (...) By manipulating the entire apparatus like a searchlight, waves would be sent over a large area. Sooner or later these waves would strike a space flyer. A small part of the waves would strike the metal body of the flyer, and these waves would be reflected back to the sending apparatus. Here they would fall on the Actinoscope, which records only reflected waves, not direct ones. From the actinoscope the reflection factor is then determined, which shows the kind of metal from which the reflection comes. From the intensity and the elapsed time of the reflected impulses, the distance between the earth and the flyer can then be accurately calculated" (Gernsback, 1925, 125-126). Beyond radar, in this novel the author also predicted numerous other technologies: video conferencing, social networks, electrical cars, sound film and sound recording, solar power, long-distance flight, space flight, and more (Süsskind, 1985).

German sci-fi writer and engineer Hans Dominik, in collaboration with Richard Scherl, son of a newspaper publisher, went one step further, turning a similar figment of their imagination into an existing radar-type instrument (Petersen, 2012). In February 1916, with the Great War in full swing, they finished a working prototype of their *Strahlenzieler* (*Ray pointer*): a spark-gap based instrument which listened to radio echoes around 3GHz (Sarkar et al., 2016). Scherl offered the device to the German army but the technology was deemed *"unimportant"* (Petersen, 2012 and Sieche, 1982). Like the *Telemobiloscope*, it would become rapidly forgotten.

The opposite camp came close to having radar technology towards the end of WWI as well. In 1917, an American technical magazine co-edited by Gernsback (*Electrical Experimenter*) published an interview with Nikola Tesla on the war which prominently featured the Serb's scheme for *"Locating Submerged Submarines"* using a *"Reflected Electric Ray"* (Secor, 1917) (figure 2.40). U-boats were *"the all-absorbing topic of daily conversation at the present time"* according to the interviewer, Winfried Secor (Ibid). Tesla described how, many years earlier in 1882 when he was working for Edison in France, he had observed how *"the small iron-hull steam mail-packets (ships) plying up and down the river Seine at a distance of 3 miles would distinctly affect the galvanometer"* (Ibid). He hypothesized that *"[i]f we can shoot out a concentrated ray comprising a stream of minute electric charges vibrating electrically at tremendous frequency, say millions of cycles per second, and then intercept this ray, after it has been reflected by a submarine hull for example, and cause this intercepted ray to illuminate a fluorescent screen (similar to the X-ray method) on the same or another ship, then our problem of locating the hidden submarine will have been solved (...)*

The ray would be reflected, and by an appropriate device we would intercept and translate this reflected ray, as for instance by allowing the ray to impinge on a phosphorescent screen, acting in a similar way to the X-ray screen” (Ibid). The visualization system of Tesla’s speculative apparatus strongly resembles radar as we know it today. While he certainly had the knowledge and capacity to attempt executing such a design, his plan remained a theoretical exercise.[84] Perhaps partly to blame is that his proposal from that same year offering the War Department a similar invention for deducing the position of enemy aircraft was met with ridicule and thus never materialized (Czegledy, 2008b).

Figure 2.40. An artist’s rendering of Tesla’s proposal for *“locating submerged submarines”* by reflecting *“electric rays”* on them to cause *“phosphorescent screens (...) to glow”,* thus rendering them visible (Secor 1917).

A few years later, on 20 June 1922, it was Marconi’s turn to share his vision of radiolocation. In his address to a joint meeting of the American Institute of Electrical Engineers and the Institute of Radio Engineers in New York (the predecessor of IEEE), he said: *“As was first shown by Hertz, electric waves can be completely reflected by conducting bodies. In some of my tests, I have noticed the effects of reflection and deflection of these waves by metallic objects miles away. It seems to me that it should be possible to design apparatus by means of*

[84] Tesla’s concept did not account for energy loss caused by water, something he would have had to address had he tried to implement such a system.

which a ship could radiate or project a divergent beam of these rays in any desired direction, which rays, if coming across a metallic object, such as another steamer or ship, would be reflected back to a receiver screened from the local transmitter on the sending ship, and thereby immediately reveal the presence and bearing of the other ship in fog or thick weather. One further great advantage of such an arrangement presence and bearing of ships, even should these ships be unprovided with any kind of radio" (Marconi, 1922).

2.5.4 *Re-inventing radar before WWII*

The concept of radar was clearly in the air. However, as Süsskind points out, four major milestones needed to be reached before radar could become a practical reality (Süskind, 1985). One was the development of directional antennas for both transmission and sensing. The work done in direction-finding was crucial; goniometers, like the Bellini–Tosi direction finder, had been employed as marine navigational aids already prior to the outbreak of WWI, helping ships locate where they were in relation to pairs of transmitters broadcasting from shore. In the Battle of Jutland in 1916 the British Navy garnered an advantage by using goniometers to locate the German fleet. Another milestone was the development of generators that could be used as the basis of a pulsed-radar system. An early type of pulse generator was invented in 1919, but several years would pass for the technology to be sufficient for radar. Thirdly, it wasn't until the incorporation of electronic displays that an adequate visual representation of location and movement could be produced; listening to sonic echoes left too much room for interpretation. While Ferdinand Braun invented the oscilloscope using cathode rays already in 1897, it would remain an obscure laboratory tool for four decades until the television came around in the late 1920s. Finally, to be able to detect signal reflections radar applications required ultra-short wave generators with enough power. That part of the spectrum was still mostly left to amateurs, and J. C. Bose's pioneering work in millimeter waves would remain forgotten for decades. Even after all these conditions were met, radar did not become useful until it could be *"incorporated into a man-machine system that could process the incoming data and act upon them"* (Ibid, 93).

Several technological developments in the 1920s would eventually become relevant for radar, such as the use of radio travel times to measure distances instance in aircraft altimeters or ionospheric probing experiments (Sarkar et al., 2016). Furthermore, in the beginning of the 1930s various countries - particularly France and the US – began researching phenomena that would eventually lead to radar, such as static waves, obstacle interference, and refraction from aircrafts. Consequently, radar was simultaneously and independently re-invented in several countries in the mid 1930s. A brief overview of how that occurred follows (based primarily on Sarkar et al. (2016)), Süsskind (1985), Guarneri (2010), Kostenko et al. (2001) and James (1989)).

In September 1922, two Americans working for the US Naval Aircraft Laboratory - Dr. Albert Hoyt Taylor and his assistant Leo Clifford Young - where experimenting with VHF transmission at 60MHz when they noticed that steel buildings reflected their signals. They conducted further experiments with a mobile receiver mounted on a car which revealed that radio signals also bounced off trees, a wooden boat, and other objects. In an ensuing memorandum, they proposed using radio waves around that frequency to detect ships regardless of visibility conditions. Their idea was not picked up, but they were both moved to the newly founded Naval Research Laboratory (NRL) in 1923, with Taylor leading its Radio Division. Seven years later, in 1930, another radio engineer from NRL - Lawrence A. Hyland - detected an aircraft using similar instrumentation. Hyland submitted his own proposal for a ship- and aircraft-detection system based on continuous wave transmission and received a patent for it. Like the *Telemobiloscope*, it could not deduce location/distance or velocity, only presence. Young suggested employing a pulse-based transmitter to deduce distance, such as the one he and Hyland had developed in 1924 to measure the ionosphere's height; Taylor appointed Robert Morris Page to implement such a system. In December 1934, the trace of an aircraft from 1.6km away appeared in the oscilloscope of his 60MHz pulse-modulated system. This system developed by Page, Taylor and Young is considered by many to be the first true radar. Page followed up with developing a *duplexer*, which allowed the same antenna system to be used for both transmission and detection, as well as the *monopulse radar*, which enabled precision tracking and over-the-horizon localization. He also patented the *Plan Position Indicator (PPI)*, the most common radar visualization method that displays moving targets over a circular map-like display. Page received a substantial grant and in June 1936 he presented an improved prototype to government officials. This radar operated at a lower frequency (28.6 MHz) and had a range of up to 40km; however, its large antennas made it only useful on the ground. *XAF*, a subsequent and improved long-range system at 200MHz was first installed on a battleship in 1938 as a navigational and gunnery aid (figure 2.41c). NRL's success and the outbreak of WWII led to the establishment of a Radiation Laboratory at MIT in 1940 to perform research on microwaves, which produced a slew of important radar innovations.

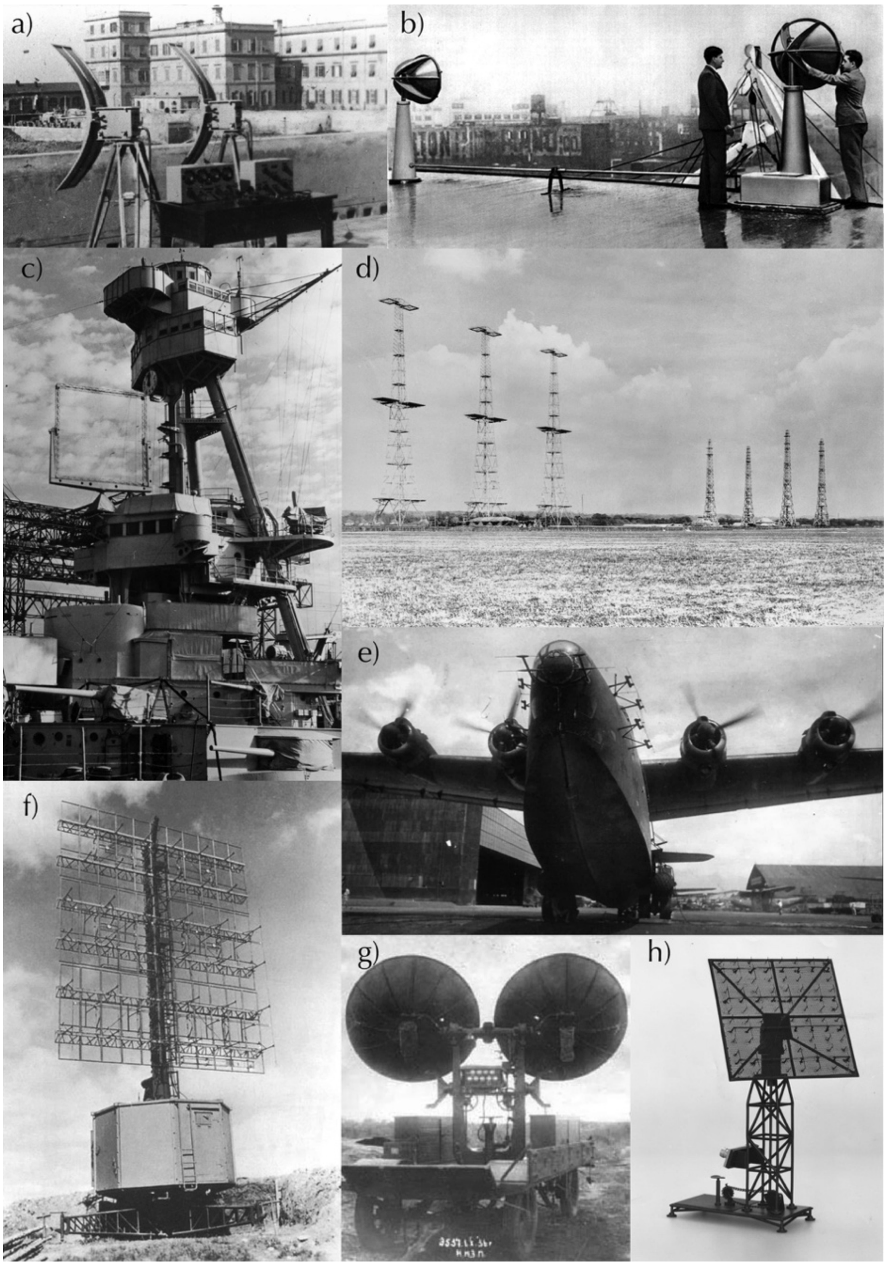

Figure 2.41. Photos of various early radar systems invented in the 1930s-40s in different countries: (a) Italy: *Radio Detector Telemetro* being tested on a terrace in Livorno in 1936 (Galati 2014); (b) France: Maurice Ponte and Henri Gutton testing their radar on board an ocean-liner in New York in 1935 (Blanchard 2010); (c) US: a battleship with the *XAF* radar antenna visible from late 1938/early 1939 (National Museum of the U.S. Navy, Wikimedia Commons); (d) Great Britain: *Chain Home* radar installation in Sussex in 1945, with a line of three remaining transmitter towers on the left (originally four) and a transmitter building in front of them, and a rhombus of four receiving towers in the right, with the receiving building between (Royal Air Force photographer, Wikimedia Commons); (e) Japan: *H-6* radar system (in service since 1942) installed on a Kawanishi H8K2 aircraft, with two frontal Yagi antennas and a pair of dipoles on each side of its nose (date of photo unknown, www.worldwarphotos.info); (f) Germany: *Freya* radar (date of photo unknown, U.S. National Archives and Records Administration, Wikimedia Commons); (g) USSR: *Burya,* a mobile aircraft detection unit with dual parabolic antennas (date of photo unknown, Yanovsky 2016); (h) Netherlands: scale model of von Weiler's *'electric listening device'* (Museum Waalsdorp).

In France, Pierre David suggested detecting aircraft from the electromagnetic radiation of their alternators in 1925. This was a concept relating to direction-finding (and TEMPEST) that had already been investigated by US Signal Corps Major E.H. Armstrong during WWI. In 1928 David conceived of a system for detecting aircraft through the reflection of high-frequency radio beams. Five years later, in 1933, he successfully demonstrated this concept with a 75MHz bistatic radar system in which transmitter and receiver were placed 5km apart. After 1934, David's research on continuous waves for the military was paralleled by commercial efforts led by Maurice Ponte, who eventually turned to pulsed radar. That same year, a radar system by Émile Girardeau's was installed on a cargo ship and an ocean-liner (figure 2.41b). An early warning system that borrowed elements from both David and Ponte was installed in cities and ports in 1939. Later that year, France and Britain began sharing their work on radar technology. However this stopped after Germany occupied France, with some French radars even making it on board German ships.

In the USSR, Professor V.L. Granovskii began experimenting with infrared as a means to detect aircraft in 1932, but turned to radio within the next year. Soviet radar research focused on gunnery guidance and air surveillance. In 1934, a 64MHz bistatic continuous wave radar was completed. It was followed by *BURYA* (*Storm*) in 1935, a search-and-tracking radar with parabolic antennas for transmission and detection (figure 2.41g). A pulse radar system was completed in 1936. Even though, starting in 1937, research in the USSR became hindered by internal politics and Stalin's conspiracy paranoias, the more accurate *ZENIT* pulsed radar appeared in 1938. The switch from bistatic to single-antenna systems started in 1941 and was completed in 1943 with *RUBIN*.

In Italy, Marconi was ready to realize his ideas on radar by 1933. He began experimenting with a bistatic system and invented a technique for sensing objects with parabolic antennas. In 1934-35 he demonstrated his new radar to Benito Mussolini and the Italian military seeking financial support. Among the impressed witnesses was General Professor Luigi Sacco - knowledgeable in direction-finding, antenna design, and radio propagation. Sacco hired a young radio scientist, Ugo Tiberio, to systematically research the subject. The first tests were made in 1936 using a frequency-modulated continuous wave system at 200-MHz, called the *Radio Detector Telemetro* (figure 2.41a). The first Italian pulsed radars were developed in 1939-41.

In Germany, the Airforce focused on offensive direction-finding systems to guide its bombers, while the most likely potential targets of such aggression, Britain and France (but also the US), emphasized on defensive aerial sensing. The naval situation was different, with the German Navy investigating any possible technological advantage that could minimize British superiority. Underwater sonar research provided the impetus for radar, leading to the development of some of the best radar systems developed prior to WWII. The principle of radar was (re)discovered by Dr. Rudolph Kühnold, head of signal research, who at the time used sound waves to detect objects underwater. In 1933 Kühnold realized that a similar concept could potentially work in the air with radio waves. Thus, a continuous wave prototype was built and successfully demonstrated in 1934 to naval officials. Its potential was immediately acknowledged and a new company, *Gema,* was formed securing funds for further research. By 1936, aircraft could also be detected and the Luftwaffe joined the Navy in supporting the project. A pulsed-radar named *Freya* - after the Norse goddess of love, fertility, gold, war and death - was complete by 1938 (figure 2.41f). It initially operated at 600MHz and then 250MHz. Its transmitting antenna system was composed of an array of 10 dipole pairs reflected with a mesh and its receiver used 3 switchable dipole antenna pairs, incorporating Braun's cathode-ray tube as a visualizer. Gema also developed *Seetakt*, a radar for guiding ship guns (at 600MHz, 500MHz, and 390 MHz). Seeing Gema's success, Telefunken decided to enter this lucrative field and by 1938 had developed *Würzburg*, a small and mobile pulse radar (553–566 MHz) that excelled at intercepting aircraft.

By mid-1930s, the British government had become alarmed by the idea that German scientists might develop Nikola Tesla's concept of a death ray and asked scientists to conduct research on the subject. Among them Robert Watson-Watt was tasked to find out if a powerful enough radio beam could disable an aircraft or its pilot. While his answer was negative, it was accompanied by a suggestion for another experiment: finding out if such a radio beam could be sensed after it was reflected off a metal target, such as an aircraft. Watson-Watt was familiar with a 'fading effect' caused by aircrafts flying over communication links, as it had been observed in the 1920s by his younger colleague Arnold Frederic Wilkins. After successfully detecting such a reflection, on 12 February 1935 Watson-Watt drafted a secret memorandum titled *Detection and Location of Aircraft by Radio Methods*.[85] The memorandum spoke about *"illuminating"* crafts via waves projected from the ground - light, heat, sound, or radio, with the latter being *"the most attractive scheme"* for many reasons (Watson-Watt, 1935). Two weeks later, a successful test was performed using BBC's powerful Daventry radio transmitter and a separate receiver

[85] According to Süsskind this is *"the most influential single publication in this field"* (Süsskind, 1985, 92).

connected to an oscilloscope. Soon thereafter the British military machine set its wheels in motion: On June 11 1935, an aircraft was located at 46km away. On December 19th a plan was approved for the construction of the first five *Chain Home* (CH) stations, an early warning radar network. By 1939, CH consisted of 20 stations that would soon become crucial for defending the island in the Battle of Britain (figure 2.41d). The 20-30MHz British systems had longer range but were less advanced and simpler than their German counterparts. While this meant they were less accurate, it also made building them easier; his allowed Britain to create a larger network. Further research led to the development of the 'beamed' radar in 1937, operating at 1/10 of the wavelength (1.5m) and equipped with a rotatable antenna and a visualizer. This radar had a slightly increased range over the CH system (at 160km) and was mounted on aircraft or used on the ground for coastal defense (hence its name CD, or CH Low). The British shared their findings with other members of the Commonwealth, Canada, Australia, New Zealand and South Africa, helping them develop their own radar technologies.

In the Netherlands, radar was discovered independently thanks to a UHF telecommunication system developed by Jacob Lambert Wilhelm Carl von Weiler for the Dutch army in 1934. During propagation tests undertaken a year later, in 1935, it was found that signal strength fluctuated when birds flew between transmitter and receiver, and when planes flew above them. Von Weiler and his team thus begun designing a pulse radar system operating at 425MHz. In a very Dutch manner, the radar used bicycle pedals to rotate its antenna array and mesh reflector (figure 2.41h). Following the German invasion of the Netherlands in 1940, von Weiler fled to Britain with his assistant and two of the four built prototypes, sharing his research with the British who readily incorporated it (Kasper, 1972).

Japanese radar research begun in the 1930s. In 1937, the Japanese Navy conducted experiments with a frequency-modulated continuous wave radar system; an aircraft-mounted radar was shared with their German allies (figure 2.41e shows a later version of such a radar). Starting in 1941 the Army and the Navy intensified their radar research, developing continuous wave, doppler, and pulse systems with the capture of British radars providing a technological boost. Prof. Kinjiro Okabe, an electrical engineer who performed significant research on magnetron technology since 1920, devised a pulsed system in 1941 that was deployed in ships a year later.

Finally, Hungary also decided to research radar technology after entering WWII on the Nazi side in 1941. By 1944, a team under Dr. Zóltan Lajos Bay had developed a 600MHz prototype with a parabolic antenna. Their work was paused with the German occupation in 1944 but was restarted by the Soviets in 1945. Between 1945-46 Zóltan Bay's team conducted experiments in which they managed to detect radar echoes from the moon, thus helping jumpstart the field of radar astronomy (Kovács, 1998).

By the end of WWII, several countries (US, USSR, Britain, Germany, Japan) had installed radars on the ground, on ships and on aircrafts, and also used countermeasures to jam transmitters and locate receivers. The technological leap achieved during this period in this field was immense, leading to further unforeseen advances in tangentially related fields (e.g. radio and radar astronomy, microwave oven, mobile communication networks). Once the war ended, radar applications started being used in numerous areas such as aviation, navigation, policing and surveillance, meteorology, medicine, and more.

2.6 Wi-Fi, a contemporary radio network

As an epilogue to the broader media-archeological overview of the Hertzian medium given in this chapter, I will briefly present the context and inner workings of the specific Hertzian technology and medium that I use in the *Hertzian Field* series and in some of my earlier works, WiFi. This introduction will be particularly useful to more fully comprehend the subjects discussed in chapters 5 and 6.

2.6.1 *From ALOHAnet to Wi-Fi*

The foundations of contemporary radio-based communication networks like WiFi can be traced back to 1970-71 and ALOHAnet, a project led by Norman Abramson at the University of Hawai'i. Like in the late 19th century, the problems that open seas posed on communication were once again the reason for developing a new wireless system, with ALOHAnet aiming to connect the university's seven campuses on four different islands (figure 2.42). Initially, the network used telephone links to connect terminals, a solution that was both slow and inconsistent (Van Beijnum & Barcelo, 2011). Abramson proposed to use a radio link instead, operating at 400MHz. He also suggested a new way of sharing bandwidth. At the time it was common for a communication channel shared by many nodes to be split either in frequency bands or in time slots to avoid simultaneous transmissions; this slowed down communication significantly. ALOHAnet introduced a different type of network architecture connecting all other stations through the main one in Honolulu via two channels: an upload link and a download link. Furthermore, a protocol was introduced to optimize communication and make sure all messages were being received.

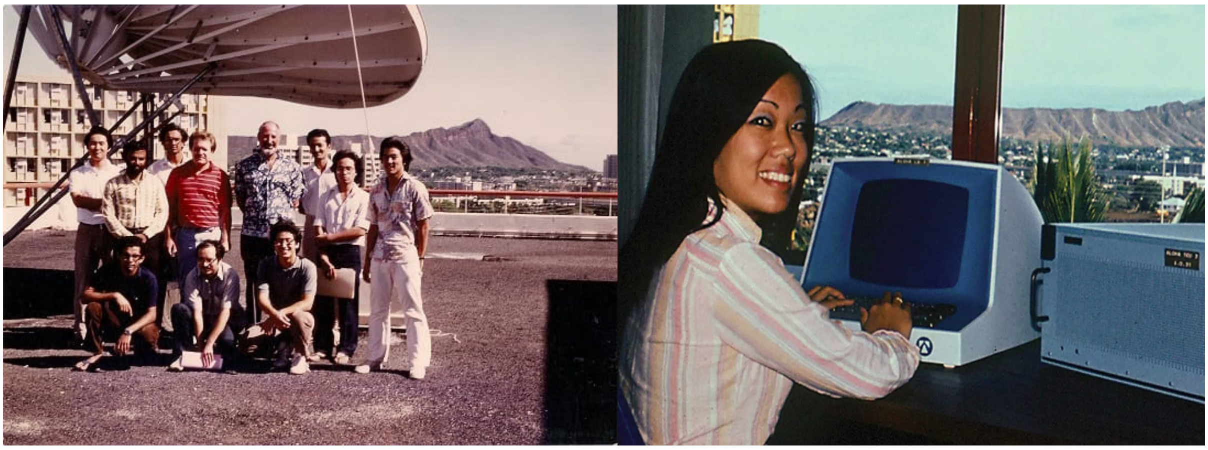

Figure 2.42. ALOHAnet in Honolulu. Left: Photo of some of the system's founders in front of one of its satellite dishes installed on the roof of a building at the University of Hawai'i, Mānoa (photo by Ram Chandran). Right: Woman in front of an ALOHAnet computer on the same campus in 1971 (photo by Norman Abramson).

What is of particular importance with the ALOHAnet approach is that it marked the passage from a voice-based network to a data-based one. Thus, the first packet switched wireless network was created (Ibid). Acknowledging the potential of the system, DARPA - the *Defense Advanced Research Projects Agency* and creator of ARPANET, the precursor of the Internet - invested significantly in ALOHAnet and the further development of data packet radio broadcasting technology. The success of the model inspired Xerox to develop Ethernet in 1973-74, a fundamental technology for creating wired Local Area Networks.

With digital technology advancing, the use of computers spreading, and the invention of the World Wide Web by Tim Berners-Lee at CERN in 1989, the 1990s saw an explosion in the proliferation of wired networks (Berners-Lee et al., 1992). Packet radio networks entered the commercial world in 1990 with the introduction of AT&T's WaveLAN in 1990 ("Demystifying IEEE 802.11 myths", 2005) but were soon replaced by cellular networks such as the GSM protocol (initially Groupe Spécial Mobile) which was introduced in 1991 (Seymour & Saheen, 2011). The chipset that made Wireless Local Area Networks (WLANs) possible was commercially introduced in 1996 ("History of Wireless LANs", 2005). A year later, the Institute of Electrical and Electronics Engineers (IEEE), an American standardization authority, introduced 802.11, the WLAN standard still in use today. 802.11 was not the only option at the time but was competing against other systems, such as HomeRF (1998) and HiperLAN (2000) from the European Telecommunications Standards Institute (ETSI) ("Demystifying IEEE 802.11 myths", 2005). While the ETSI standards were more sophisticated, 802.11 was chosen by the industry for its simplicity and ease of implementation.[86]

In 1999, industry members of IEEE founded the Wi-Fi Alliance to provide hardware compliance certifications (McKenzie, 2010). 802.11 technology was branded *Wi-Fi,* a catchier name that aimed to bring the term *Hi-Fi* in mind (which is the reason it has been suggested Wi-Fi stands for *Wireless Fidelity)* (Berghel, 2004). The name tactically implies that, just like a home stereo, the technology is of *"high quality but for domestic use"* - easy, fun, reliable, and of no poorer quality than wired networks (McKenzie, 2010, 102). Early advertisements introducing the technology between 2001-04 promoted this concept of *"fun and reliable"* by emphasizing the notion of freedom for consumers - free of wires, free to roam and connect from anywhere (Ibid, 103). At the same time, they were also touting that Wi-Fi was dependable for conducting business, often depicting professionals - typically men, unsurprisingly – working from their office, from remote locations, or while in transit.

2.6.2 *The air interface as a stochastic medium: The problems of physical space and sharing a common resource*

Parallel to the efforts in increasing the operational range of WLANs, the main problem for the development of a commercially viable technology was WiFi's inherent unpredictability as a medium. Some of the noise problems were (and still are) caused because the 2.4GHz frequency band it operates in is so crowded.[87] This band was opened in 1985 for public use by the US Federal Communications Commission (FCC), together with other Industrial, Scientific, and Medical (ISM) frequencies.[88] This made it possible to develop radio applications, such as wireless communication, that can be used by companies and individuals

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[86] 802.11 is generally an open protocol, although proprietary standards have also been introduced. Some of its specifications have particular applications in mind, e.g. 802.11e was made for better quality of service and 802.11i for better security.

[87] To at least alleviate the problem of having too many WiFi transmissions operate in the same frequency, the protocol has divided this band (ranging between 2.4-2.495GHz) into 14 discrete channels, 25MHz apart from each other. In principle this should create complete separation between WiFi networks broadcasting in different channels, however consumer WiFi transmitters and receivers are not that precise in reality. Therefore, there is still considerable bleed, with WiFi signals typically spreading across 5 channels. This can be a problem, and in fact WiFi networks are better equipped in filtering data from other Access Points on the same channel than to deal with this type of interference (van Beijnum, 2011). Nonetheless, there are numerous other radio applications and systems making use of that same band, further complicating the issue.

[88] The FCC first allocated three *"harmonically related frequencies"* for ISM use in 1945: 13.66MHz, 27.32MHz, and 40.98MHz (Osepchuk, 1984, 1203). Today, the principal ISM bands that can be used without a license are: 900MHz, 2.4GHz and 5.8GHz (Seymour & Saheen, 2011). The 5GHz band has become available to WiFi since 1999, two years after being sanctioned by the FCC as *Unlicensed National Information Infrastructure* (UNII).

without the need for obtaining operational licenses, which has contributed greatly in their adaptation. The downside is that many other applications share this band, which has led to a constant struggle against interference.

Figure 2.43. Promotional image of Raytheon's new *Radarange* microwave oven from 1947 captioned: *"Microwaves cooked this steak dinner in just 35 seconds"* (Zeluff, 1947).

The history of the open 2.4GHz frequency band is both intriguing and illuminating, and begins with microwave ovens. The technology of *microwave heating* or *Radio-Frequency heating* came out of WWII research in wireless communication and radar systems (Osepchuk, 1984). After the war two American companies, General Electric (GE) and Raytheon - the main radar supplier of the US military - were developing such applications. In the end of 1946, they each received rights to an unused frequency around their preferred range: GE at 915MHZ and Raytheon at (or around) 2.45GHz, where its new *Radarange* oven would operate (O'Brien, 2013 and Zeluff, 1947) (figure 2.43).[89] As radiation from a microwave oven can cause some interference to adjacent frequencies - which is why WiFi networks may suffer when they share the same space as a microwave oven - it was decided to

[89] A 1947 article on the *Radarange* mentions that it operates at 3GHz (Zeluff 1947). It is unclear if that was the original operating frequency of the device prior to a 2.45GHz license, or if the author chose to simply round the numbers (he mentions a frequency of 3 billion cycles and a wavelength of 0.1m).

give some more space to these two bands (±25MHz and ±50MHz respectively).[90] The companies had chosen these frequencies because of their efficiency to dielectrically heat water and fat. Because of this effect, WiFi waves make a good candidate for short-range radar-type applications for tracking human bodies, like the *Wireless Information Retrieval* system used in the *Hertzian Field* series (chapter 6). Interestingly, this brings WiFi microwave sensing technology full-circle: from radar, to ovens, to communication, to radar sensing of human bodies.

Another factor contributing to the unpredictability of WiFi is that while wires are deterministic radio is stochastic. This is especially true when line-of-sight connection is lost. Signals radiate from the antenna of the transmitter to the antenna of the receiver. The space in-between, called the *air interface,* is an active part of the communication system. A number of factors can distort a radio signal as it travels through this interface. For example, multipath propagation caused by signals bouncing around walls, furniture, and other obstacles inside buildings has the effect that multiple delayed echoes of the transmitted signal arrive at the receiver – a kind of radio reverberation. The resulting transformations of the original signal are practically impossible to calculate, even more so when one adds the effects of humidity, human bodies, and the presence of other networks and microwave sources. For these reasons, radio propagation can only be calculated with statistical probabilities. As such, functionally and in the context of the 802.11 communication protocol, the air interface should be thought of as a hybrid medium combining physical and algorithmic properties. The nature of this interface emerges from the encounter of: a) the material interaction of radio waves with the physical space within which they propagate, with b) a set of computational strategies implemented to tame the physical unpredictability of this interaction.

These computational strategies form another testament of the inter-connectedness and inter-operability of wireless research. An innovative algorithm used to counteract the intrinsic noisiness of the domestic environment was borrowed from an unexpected source: radio astronomy. In the late 1970s, John O' Sullivan was working on detecting black hole radiation (*Hawking radiation*) at the Netherlands Foundation for Radio Astronomy. He developed a hardware based on the Fast Fourier Transform (FFT) to unscramble the weak radio signals by separating them from cosmic radiation. In 1983, O'Sullivan joined Australia's science agency (CSIRO, the Commonwealth Scientific and Industrial Research Organization) and was asked

[90] Contemporary microwave ovens operate at 2.495GHz to minimize interference to communication technologies in the 2.4-2.495GHz band.

to find potential commercial application for his research. He assembled an interdisciplinary team who in 1990, following several years of investigations in different fields, decided to focus on wireless communication. The goal was to create a WLAN whose speed would be on par with wired solutions - something unthinkable at the time. The solution was to break up the signal and transmit it through several frequencies simultaneously using FFT; then to invert the process in the receiver and reassemble the original message (O'Sullivan, 1996) (figure 2.44). In 2012, the team was awarded the European Inventor Award by the European Patent Office (EPO) for their achievement.[91] The statement of the EPO states: *"The technology developed to screen out galactic noise in radio astronomy was just what was needed to help make sense of WLAN signals here on earth"* ("High-speed wireless networking", 2012).

Figure 2.44. Photo of the main components used to prototype Wi-Fi at CSIRO in the 1990s, with the transmitter stack on the left and receiver stack on the right. Equipment includes: analog-to-digital and digital-to-analog converters developed at CSIRO (bottom); 40GHz transmitter and receiver units also developed in-house (middle); laptops (top), and spectrum analyzer for received signals (right, under the laptop); a dedicated Austek/CSIRO Fast Fourier Transform chip originally developed for radio astronomy is not visible ("CSIRO WLAN Collection", 2012).

[91] CSIRO applied for its first of a series of patents in 1992 and fought legally to get WLAN product manufacturers to pay licensing rights. While many settled out of court, there is some controversy regarding whether CSIRO's claims are valid (Mullin, 2012).

The CSIRO technique is a spread spectrum algorithm, i.e. a type of message encoding that breaks the signal in different frequency bands. Spread spectrum encoding is necessary for broadcasting at ISM frequencies to allow for many users and different radio-based systems to share the same air interface with minimal interference. The simplest and earliest such technique is frequency hopping – i.e. sequentially jumping between different frequencies to transmit a message. This concept was first introduced by Tesla in 1903 (Emek & Wattenhofer, 2013). The technique was re-invented by many others in the following decades, most notably in the 1940s by an actress/inventor and a composer/inventor: Hedy Lamarr and her husband George Antheil. Lamarr developed a frequency hopping system for torpedo-guidance to avoid jamming and enemy detection. Antheil provided the necessary mechanism to synchronize transmitter and receiver using a system he had developed for his Ballet Mécanique from 1923 (van Beijnum, 2011). The different versions of 802.11 have introduced a number of complex spread spectrum algorithms that use FFT to simultaneously transmit parts of the signal in different sub-bands. The original 1997 specification used both Frequency-Hopping (FHSS) and Direct-Sequence Spread Spectrum (DSSS) modulations. The 802.11a variant, also from 1997, introduced Orthogonal Frequency Division Multiplexing (OFDM), spreading the signal into 48 subcarrier channels, to achieve faster data rates and minimize interference.[92] 802.11a operates at 5GHz to attenuate the effects of multipath echoes, as this smaller wavelength is more easily absorbed by the environment, and to evade the more crowded 2.4GHz band. In 2003, OFDM entered the 2.4GHz range with 802.11g.

The need for yet more speed brought 802.11n in 2009.[93] Its most important innovation was the multiple-input/multiple-output (MIMO) concept. MIMO uses multiple antennas to send and receive multiple channels of information in parallel - to give an audio analogy, this is like having several 'radio microphones' and several 'radio speakers' in the same WiFi station. The comparison with microphones is useful to understand how the system works: MIMO antennas are pairs or arrays of electromagnetic sensors, each placed at a different location in the electromagnetic field. By combining the signals from the different antennas and digitally processing them it is possible to recover a more accurate version of the original signal,

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[92] These subcarrier channels are contained within the range of a single WiFi transmission channel.

[93] It is important to note that the 802.11 protocol is designed for backward compatibility and fair access to all nodes sharing the same air interface. This has the side-effect that the node operating under the slowest protocol will set the transmission speed for the entire network. Moreover, 802.11b consider OFDM signals as noise, so faster networks have to pad the handshakes between devices in the network with more information on their transmissions to avoid confusing older protocol nodes (van Beijnum, 2011).

filtering out echoes and interference. Essentially, MIMO allows to more accurately split the original signal from the interfering noise. Given that in the original conception of the 802.11 protocol the key focus is communication, this typically means that the noise is discarded and the signal is kept. However, the same system also permits focusing instead on the noise rather than the signal, which allows to make the passage from communication to radar. Having multiple points of electromagnetic listening in space is ideal for localization and activity recognition applications, as will be discussed in chapters 5 and 6.

Additional algorithms have been developed to counteract the unpredictability of the air interface, such as the *Viterbi* error-correction algorithm which is implemented into the hardware of many types of wireless communication chips besides WiFi (e.g. Bluetooth, cellular and satellite). Originally designed by telecommunications engineer Andrew Viterbi in 1967 to counteract noise in digital communication systems, this algorithm allows re-ordering messages that have been jumbled during transmission by obstacles and multipath interference (Mackenzie, 2010). The algorithm involves infusing additional data into the signal prior to transmission (a process called *convolution encoding*). Upon reception, the Viterbi decoder uses a decision-making process to deduce the most likely original order of the received signals.

2.6.3 *The layers of WiFi networking*

According to the Open System Interconnection (OSI) model of the International Organization for Standardization (ISO), the air interface and the algorithmic strategies used to tame its stochastic nature are part of the *Physical layer* (PHY) of wireless communication. The OSI model, whose development began towards the end of the 1970s, is an open and modular conceptualization of networking that aims to describe communication in abstract terms (Russel, 2013).[94] The overall model consists of 7 layers. Data flows down along these layers from the last (the *Application* layer) to the first (the *Physical* layer) within the transmitter. As it does, layer-specific headers (metadata) are added to the data to guide it further down the chain - a process of encapsulation that creates the so-called *Payload Data Unit* (PDU). The encapsulated data and metadata are then broadcast through a physical link that connects transmitter and receiver – such as wires in case of Ethernet or the air interface in the case of WiFi. After being captured by the receiver, it travels back up through a reversed sequence of these layers (from layer 1 to 7). Through a process of unpacking and de-encapsulation, each

[94] For a brief historical overview of OSI and its relationship to TCP/IP see (Russel, 2013).

layer strips the appropriate metadata and guides the PDU upwards. The layers described by the OSI model are:

1. The *Physical* layer *(PHY)* is responsible for the physical connection between transmitter and receiver via a communication medium or interface (e.g. by wire or radio). This layer describes the signals, circuits, and algorithms used (such as the spread spectrum techniques mentioned above). This layer is not concerned with protocols but with the physicality of communication and the digital representation of physical signals. It implements functions such as synchronization, detecting errors, filtering noise and avoiding the collision of messages.

2. The *Data Link* layer connects the physical to the logical, i.e. the real world to the network. It is responsible for transferring data between neighboring nodes (e.g. computers in the same network) and managing its flow.[95] In this layer, communication protocols are defined and data is formatted according to the desired protocol. For example, IEEE802 protocols convert the logical IP addresses to physical MAC addresses via the Address Resolution Protocol (ARP). Communication happens through *Frames* that include a header, a payload and a trailer part. Errors that may have been introduced in the *Physical* layer can be further filtered here.

3. The *Network* layer operates I"n the logical (non-physical) space of the network. It provides routing services between nodes co-existing in the same network and transfers data packets between them, but does not verify whether such data has been received. The Internet Protocol (IP) of TCP/IP corresponds to this layer. Additional error correction can be implemented in this layer as well.

4. The *Transport* layer is not concerned with the network mechanism itself - which is taken care of in the lower layers - but with the rules that establish successful data transfer between nodes. This layer handles important details such as the appropriate size, sequence, and segmentation of data, as well as the re-transmission of data that failed to be

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[95] This includes the main implementation of collision avoidance. Given that many devices can potentially be transmitting at the same time, the 802.11 protocol contains strategies to coordinate and avoid message collisions. That includes waiting until another transmission has stopped - i.e. the Carrier-sense multiple access (CSMA) Medium Access Control (MAC) protocol - and using randomness to avoid simultaneous transmissions. It also includes a complex *handshake,* which is established using four types of short messages: The transmitting node sends a request-to-send (RTS) message. The receiver (i.e. the access point) sends back a clear-to-send (CTS) message; this also contains the time duration the transmission channel is reserved for thus notifying other nodes they should remain silent during that time. The node is then clear to send its data. Upon successful reception, the receiver sends back an acknowledgement message (ACK).

received.[96] Multiple transport connections can be active simultaneously involving the same computer. The transmission unit is comprised of a header and payload.

5. The *Session* Layer handles the connection details between nodes - starting, maintaining and terminating node-to-node links. It also checks if a data packet has been received or if it needs to be sent again. TCP segments and UDP datagrams correspond to the transport and the session layers.

6. The *Presentation* layer handles the proper representation of digital data - encoding, encryption, syntax semantics - so that it is compatible with upward or downward layers.

7. Finally, the *Application* layer interfaces between software and protocol. It is responsible for formatting data in the appropriate way as they are received by applications or delivered to them within a computer. HTTP, FTP, SMTP, POP3, IMAP and DNS are application protocols residing in this layer.

The OSI model provides a useful map for understanding specific protocols, how they operate, and how they relate to each other. The family of IEEE802 specifications - which includes wired Ethernet and wireless technologies like WiFi, Bluetooth, e.a. – is concerned with the physical aspects of networking and thus only implements the two lowest layers: *Physical* (PHY) and *Data Link*. Connecting to the Internet brings TCP/IP and higher layers into play, and is not part of the IEEE802 specification itself.

In IEEE802, the *Data Link* layer is broken down in two sub-layers, the *Logical Link Control* layer (LCC) and the *Media Access Control* layer (MAC). LCC is the highest level; it identifies and encapsulates network layer protocols (such as IP addresses), performs error-checking, and synchronizes frames. This layer is specified by the 802.2 standard, which is shared by both wired (802.3, i.e. Ethernet) and wireless applications (e.g. 802.11 and 802.15, i.e. WiFi and Bluetooth). The MAC layer deals with connecting and disconnecting devices to the network, manages when they can transmit data and how to avoid collisions with other transmitting devices. The wireless MAC layer is considerably more complex than the wired one to account for the effects of the mobility of connected devices.

The *Physical* layer of wireless protocols like 802.11 is also much more intricate than that of wired networks. It consists of two components: The *Physical Layer Convergence Procedure* (PLCP), which prepares MAC frames for transmission, and the *Physical Medium Dependent*

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[96] In 802.11 the transmitter waits for a message from the receiver acknowledging the transmission; if it does not receive such a message it will send the data again.

(PMD) system, responsible for the transmission of bits over the air interface. Various versions of these layers exist, using different types of signal encoding - HFSS, DSSS, OFDM, etc (see Gast, 2005).[97]

[97] Besides these radio wave encodings, the protocol was also designed to work with infrared when it was introduced, however that was never implemented.

Chapter 3. RADAR AND DIRECTION-FINDING IN SONIC ART (AND BEYOND)

3.1 LEV TERMEN / LEON THEREMIN: MUSIC AND SURVEILLANCE ENTANGLED THROUGH WIRELESS TECHNOLOGY

3.1.1 *Harnessing bodily interference: From the 'radio watchman' to the 'etherophone'*

The first musical instrument designed to be performed by interacting with radio space, the *Etherophone*, was invented almost by accident, most likely in the autumn of 1920. Its maker was Lev Sergeyevich Termen (1896-1993), or Leon Theremin as he became known in the West.[98] Theremin brings together music and surveillance through his electromagnetic inventions, but also his life. At the moment of this invention, Termen was heading a new laboratory for radio research in Petrograd, USSR, under Abram Fedorovich Ioffe, a very knowledgeable and influential scientist. Back in 1912, a lecture by Ioffe on electromagnetism greatly inspired a 16-old Termen to seek the hidden language of the Universe by investigating the laws of its vibrations (Smirnov, 2008a). In 1914 he entered the University to study Astronomy and Physics alongside his cello studies at the Conservatory. In 1916 he was drafted but because of his skills he was sent to the Military Engineering School, with a further specialization in radio engineering. The 1917 revolution found Termen teaching at the same school, overseeing communication projects for the military, graduating from the University, and obtaining a 'freelance artist' diploma from the conservatory (Glinsky, 2000). After the regime change, Termen continued with what he later described as mundane radio work, this time on behalf of the Red Army.

In 1919, Termen returned to Petrograd and reconnected with Ioffe, who brought him at the Physico-Technical Institute and in contact with the Soviet inner circle. After some brief work with X-rays and observing objects under different wavelengths, Termen was put in charge of setting up and leading a radio research laboratory. His military training in tackling radio engineering problems had provided him with valuable knowledge and experience in the subject, but had also raised some interesting questions. The first project he set to investigate was a peculiar effect that he had observed during his time in the military and which had

[98] In these pages I will refer to him as Termen when he was in Russia and the USSR and as Theremin when in the West as those were the names he was known with at each place.

fascinated him: human bodies interfered with circuits when in proximity because of their electrical capacitance.

Termen embarked on a series of indoor experiments, echoing Hertz’s early investigations of the body as a dielectric in the Karlsruhe lecture hall, but with a much more practical goal. His first invention was a simple apparatus that harnessed this bodily interference for a practical application: wireless surveillance. His so-called ‘radio watchman’ was a device that overlaid an electromagnetic field upon an area and sounded an alarm when it sensed the presence of a human body. The transceiver was based on the audion tube, a tool that would be at the center of many of Termen’s later inventions. Termen was familiar with the work of De Forest, Armstrong, and Fessenden from his military days. He used the audion as an oscillator coupled to an antenna to radiate electromagnetic waves at a fixed wavelength and with a low power so that the field could be confined within the limited space of a room (4-5 meters). An approaching human body within this protected area would change the capacity of the circuit and consequently the frequency of the audion's oscillation; this change activated a sound-making circuit that alerted of the intrusion. Termen was back on the forgotten path that Popov and Hülsmeyer had first marked, coming up with a kind of primitive radar but for indoor use, one that was built to track the presence of bodies rather than thunderstorms or boats. Termen had more success than his predecessors. Recognizing the device’s potential, Ioffe suggested to Military Affairs Commissar Leon Trotsky that he could reduce the number of guards at the Kremlin by employing such an ‘electric security system’ (Smirnov, 2008b). In 1924, Termen was asked to install his ‘radio watchman’ in the central bank, the Hermitage Museum, and state vaults containing treasures expropriated from the church (Glinsky, 2000).

Back around 1920, a following experiment, after Ioffe’s request, required creating an instrument to measure the dielectric properties of gases. Termen designed a sensitive apparatus that revealed two intriguing phenomena: variations in temperature caused the circuit’s capacity to change, as did air fluctuations caused by minuscule motions of his hand. Both phenomena were made visible through the movements of his meter’s needle. Termen quickly added an audion-based circuit to sonify changes in the system. Wearing a pair of headphones he could move around in space and listen in real-time to the apparatus’ response. To magnify the effect, he added a frequency dial that allowed tuning his circuit to the properties of particular gases (Glinsky, 2000, 24). The ‘parasitic’ effect of his body to the circuit was audible: the static whine of the oscillator would change in pitch according to movement, rising when he approached the circuit and falling when he pulled back (Theremin

& Petrishev, 1996).[99] The antenna and his body acted as the two plates of a capacitor, increasing and decreasing capacitance depending on the distance between them. Shaking his hand as if holding an invisible bow caused a vibrato like it would on a cello - an instrument Termen used to play (figure 3.1). This must have certainly felt like a magical moment to him, listening in his ears a siren-like song he could produce by simply moving his body inside a radio field! Termen shared this amazing discovery with an astounded Ioffe, and began exploring the radio space around the antenna with his hands, using his ears to guide him and trying to replicate melodies he loved and used to play - Saint-Saëns and Gluck. News that *"Theremin plays Gluck on a Voltmeter"* spread quickly, and by next day his experiments had an audience curious to see and listen this touch-less performance with an invisible instrument made of electrons (Glinsky, 2000, 24).

Figure 3.1. Lev Termen performing his *Etherophone*, or *Thereminvox*, in the Paris Opera, December 1927 (photo by Corbis Bettman, Wikimedia Commons).

In accordance with musicology jargon, the instrument was initially called the *Etherophone*,

[99] Termen uses the term 'parasitic oscillations' to describe the effect of the moving hand (Theremin & Petrishev, 1996, 50).

as the medium with which it created sound was the ether.[100] As Termen wrote, musical instruments produce tones by creating periodic oscillations in a solid body (string, membrane, bell, etc), or in a gas contained in a receptacle (tube, resonant box).[101] Instead, his instrument was *"purely electrical"*, using *ether waves* to create music (Theremin & Petrishev, 1996, 50). Later on, the instrument would be renamed the *Thereminvox* (i.e. Theremin's voice), or simply the *Theremin*.

The instrument was monophonic with an initial range of 3 to 4 octaves - expanded in later versions to 7 octaves or more (Glinsky, 2000). It sounded like a cello in the bottom range and like a violin or a soprano's voice in the top. To make sound audible to an audience, Termen replaced the headphones with a large earpiece coupled to a paper horn. The sound-generating section of the system was initially quite rudimentary. Termen soon implemented Fessenden's heterodyne principle in his circuit, through which he managed to increase both the range of the instrument as well as its sensitivity. This involved adding another oscillator to the system that operated at a fixed frequency - the same as that of the transmitter's variable oscillator when there was no interference. Multiplying these two signals created a third signal from the difference of their frequencies; the frequency of this difference signal was in the range of human hearing and was sonified by a detector circuit. At first, volume was controlled with a foot pedal. Termen soon replaced this with another radio-sensing circuit, adding a loop antenna at a right angle to the pitch-controlling vertical antenna. This volume control was played with the left hand, allowing the performer to stand upright in front of the instrument, completely untethered from its housing. The dual electric fields surrounding the instrument were extremely sensitive, producing a faster and more delicate response than a piano or violin according to an enthusiastic contemporary reviewer (Kaempffert, 1928). Termen maintained that the instrument offered a *"psychic freedom"* to the player, similar to that enjoyed by singers, as materiality and physical force were completely removed from its performance (Ibid). Free from the pains - and visual connotations - of Newtonian instrument mechanics, the performer could interact with Hertzian space to conjure notes out of thin air, gesturing like a conductor - or magician - and suggesting to his audience a telepathic connection

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[100] While the ether's existence had been disproven by that time, the word was often used much like we use 'radio' today. Apart from scientific and engineering connotations, it also carried with it many 19th century ideas, speculations, and fantasies about the substance – from radio and telegraphy, to telepathy and mind control.

[101] For more details see Theremin & Petrishev (1996), an abridged article from a 1921 lecture by Termen. In this lecture the inventor looked into "*modern engineering*" to tackle the following design goals: the instrument had to allow a) controlling multiple parts at the same time; b) varying timbre and sound character *"as desired";* and c) playing sustaining sounds without change. It should also d) have a wide dynamic range, and e) enable virtuosic performance.

between man and machine. As Theremin said many years later, *"I conceived of an instrument that would create sound without using any mechanical energy, like the conductor of an orchestra. The orchestra plays mechanically, using mechanical energy; the conductor just moves his hands, and his movements have an effect on the music artistry"* (Mattis & Theremin, 1989).

3.1.2 *Ether-wave music*

In November 1920 Termen gave the first 'Ether-wave music' concert, playing cello repertoire for an audience of *"spellbound"* Mechanical Engineering students of the institute (Glinsky, 2000, 26-27). The following year he applied for a patent for a 'Musical Instrument with Cathode Tubes' (granted 3 years later) and made his first official appearance at the Electro-Technical Congress in Moscow's Polytechnic Museum, a very high profile event meant to jumpstart Soviet electrical innovation. By then, the etherophone was equipped with another technological marvel, the loudspeaker, which gave it better sound quality and more volume, thus allowing performing for large audiences (figure 3.2). In this event, Termen briefly presented his instrument and underlying technology and went on to play Russian folk songs and pieces by Tchaikovsky and Saint-Sans. As a Soviet journalist wrote,*"a strange music, unlike anything yet heard, floated over the quiet audience"* (Gleb Anflivov quoted in Glinsky, 2000, 27). Another performance followed, this time for the general public, and Termen the performer began to grow next to Termen the inventor.

News of this extraordinary instrument soon reached Vladimir Ilyich Lenin. In March 1922, Termen entered the Kremlin to demonstrate his instrument side by side to his surveillance device. A short performance ended with Termen holding the hands of an enthusiastic Lenin, teaching him how to play the instrument. Lenin announced that this incredible invention should be promoted around the country as an example of soviet scientific achievement. This was, after all, a time and place *"when everyone was interested in new things, in particular all the new uses of electricity*", as the inventor reminisced years later (Mattis, Moog & Theremin, 1992). Subsequently, Termen received a free railroad pass to tour the country with his instrument. He performed for massive audiences in Moscow and gave numerous concerts around the country while making waves in the press. He was dubbed the 'Soviet Edison' and the etherophone was touted by newspapers as *"the ideal instrument"*, an important invention that is like "*a musical tractor coming to replace the wooden plough"* and which is doing for music "*almost what the automobile has done for transportation"* (Galeyev, 1991, 575). By the following year, the instrument's first clone had already been produced.[102]

Figure 3.2. Lev Termen in 1922 with his Etherophone and three rhombic loudspeakers in the background (unknown photographer).

Like Nikola Tesla and many inventors of the time, Termen's preferred format in this tour was the lecture-performance. Explanations on his instrument and its principles were followed by a proto-multimedia show that, according to a poster for his Petrograd premiere (in December 19, 1922) combined *"sound operation with free spatial hand movements, light, and radio and*

[102] The clone was made by Konstantin Kovalsky, a student of Termen who also performed with him on several occasions (Glinsky, 2000).

could be possibly combined with dance" (quoted in Glinsky, 2000, 32). The etherophone was the centerpiece but not the only invention presented. Perhaps inspired by Alexandr Scriabin's synaesthetic work, Termen had also developed the *illumovox*, an instrument projecting light through a rotating color-wheel (Ibid). This could be connected directly to the etherophone's antenna so that hand movements could produce shifting color hues to accompany the sounds. Termen also experimented with scents. Aiming to evoke further synaesthetic effects, he would ask his audience *"to imagine dancers moving their bodies in an electromagnetic field to materialize a new sort of spontaneous music."* (Ibid, 32).

Lenin's death in 1924 and Stalin's rise to power pushed Termen further away from his research work at the institute and into his career as a performer. In May 1924, accompanied by the Leningrad Philharmonic, he played the first piece ever composed for the instrument: Andrey Filippovich Pashchenko's *Symphonia Mysteria* for Termenvox and orchestra (1923) (Nesturkh, 2012). The concert featured an improved iteration of the etherophone with better and more powerful loudspeakers as well as with the addition of twelve switches for controlling the instrument's timbre like the stops of a church organ (Glinsky, 2000).

While the instrument was radical, Termen's aesthetics were decidedly not. He performed romantic classical music from the previous century – pieces by Schubert, Offenbach, Saint-Saëns and Scriabin - often accompanied by piano or other instruments. Beyond an aesthetic choice, this might had also been a tactical move by Termen (Wilson, 2017). His instrument was based on bodily interference and the principle of radio feedback. Interference was an undesirable effect for broadcast radio and feedback was a rather hated effect at the time, being responsible for the howling artifacts of wireless communication – an obnoxious noise that was increasingly creeping into everyday life, as we saw in the previous chapter. Both of these facts had not gone unnoticed by the experts. In his New York Times article on the instrument, Waldemar Kaempffert wrote how Theremin tamed the squeals of radio feedback with a touchless instrument that not only functioned like a radio set but also looked like one: a wooden box with an antenna coming out of it and *"a maze of glowing radio tubes, coils and condensers"* inside it (Kaempffert, 1928) (figure 3.3). Technically speaking, Termen had already managed to contain radio oscillation within the same circuit so it did not interfere with other receivers (Wilson, 2017). Nonetheless, as Wilson notes, it was perhaps more important to the instrument's acceptance that, by playing pieces from an established canon, Termen was associating his instrument with high art rather than with the world of weird sound effects and descriptive music that belonged in lowbrow music halls.

Figure 3.3. Leon Theremin demonstrating the electronics inside his latest Thereminvox version circa 1928 (photo from the archive of Thom L. Rhea).

It is worth diverging for a moment to consider what exactly Termen was setting himself apart from, especially as it is quite interesting in terms of sonic history. Already since the 1860s, Johann Baptist Schalkenbach had introduced electro-mechanical instruments in vaudeville theater, performing for magician John Nevil Maskelyne among others (father of Nevil Maskelyne of the *Maskelyne affair*). With the aid of an electrical keyboard he would control whole orchestras of mechanical instruments and sound effects to support a narrative. Schalkenbach would mesh classical and popular music with imitations of sounds from the real world – thunder, lightning, explosions, etc. Later on, he even went as far as mounting electrical contacts on the audience's seats to produce accompanying electrical shocks (Wilson, 2017). Schalkenbach's performances were very popular, and by the 1880s many others were performing similar acts, often combined with light effects and optical illusions. Some shows created whole worlds full of surprises and reversals. For example, *Electricity* by Sandor Rosner, aka Edwin Rousby, featured an interactive break of the fourth wall: *"[E]very visitor will be a performer. All that is required is to press buttons, turn handles, pull levers, and at once you will be able to produce the most marvellous electrical effects"* (Rousby from

1890, quoted in Wilson, 2017, 156). The genre spread as a popular novelty. Nonetheless, saturation from many acts, technological advances, and the increasing familiarization of audiences with electricity – resulting in it having less of a magical effect - led to its rapid decline in the beginning of the 20th century. Such 'programme music' was by then widely derided as cheap, vulgar, and uncultured by musicologists and taste-makers - even by the radical-thinking Futurists who called for crafting and composing with noise rather than performing an impressionist reproduction of modern sound environments. This attitude did not change much in the decades after the invention of the Thereminvox. The instrument's most famous virtuoso, Clara Rockmore, had often expressed her aversion to using the instrument for cheap 'sound effects', like in Hollywood sci-fi films, and insisted on only played classical and romantic repertoire (Ibid).

Considering this context, personal aesthetics was likely not the only reason for Termen to be musically conservative. Still, his musical taste seemed to have remained unaltered even after many avant-garde composers wrote for his instrument. The fact that he could neither remember his collaboration with Edgard Varèse and Henry Cowell, nor offer any comments on Joseph Schillinger's work with his instrument is another indication that he was not very invested in contemporary aesthetics.[103] When asked much later in life about the repertoire he and Rockmore chose to play, he said he had created the instrument with the idea that composers would write new pieces for it, an idea also supported in a 1928 interview in which he spoke about making *"a new kind of music based on unheard-of scales"* (Mattis & Theremin, 1989 and Theremin quoted in Kaempffert, 1928). However, he claimed that since he could not find *"well-written"* music for the instrument he chose to mainly perform existing works of music (Mattis & Theremin, 1989). For him the work of modern composers was *"not popular"* enough, neither did it *"fully exploit the instrument"* but instead would *"imitate old instruments, such as the violin, the voice, etc."* (Ibid).

Perhaps unavoidably, the techniques Termen developed for playing the instrument where tied to the type of music he played. As Kaempffert wrote in his 1928 review, Theremin *"gestures back and forth, slipping his hand hither and thither as if on an invisible string, and picks his melody out of the air. The familiar vibrato of the violinist he produces by shaking his hand. (...) When he brings his hand very low he can quench a tone just as if it were the flame of candle. When he lifts his hand the effect is the same as when an organist swells a note"*

[103] In later interviews Theremin said he could not remember these composers as he had simply met too many people during his time in New York, many times not even being introduced by name (see Mattis & Theremin, 1989 and Mattis, Moog & Theremin, 1992).

(Kaempffert, 1928). To play fixed notes rather than glissandi players had to move their hand quickly and rest it at specific distances from the antenna that corresponded to the correct pitch and tuning - a rather hard feat for the uninitiated. The beginner was guided by the ear but, similarly to other instruments, to become a virtuoso one had to develop a kinesthetic muscle memory through practice, a memory that – unlike in other instruments - had to be built purely on the performers internal sensation of their body, without the help of the instrument's physical resistance or friction. The instrument, thus, became notorious for being hard to master.

3.1.3 *Leon Theremin the luthier: The Terpsitone and other Thereminvox variants*

After his successful soviet tour, Termen was allowed to perform internationally and showcase this marvel of soviet musical engineering abroad. He went to Germany, Britain, and France, captivating large audiences that came to witness his futuristic instrument at prestigious venues like the Royal Albert Hall in London and the Paris Opera House (Smirnov, 2008c) (figure 3.1).[104] Termen arrived in New York in 1927; he stayed there for 10 years, mingling with the rich and famous. Both the American public and reviewers found Theremin's instrument fascinating. His performances filled huge spaces, such as a stadium for 12000 people, and captivated audiences ("Radio Corporation to Sell 'Ether Music' Device", 1929). Equipped with *"huge loud-speakers"* the instrument's sound was described as rich and full, but also versatile as it could mix harmonics to sound like a cello, tuba, clarinet, flagolet, or organ (Kaempffert, 1928). It had extensive pitch and dynamic range; tuning was not necessary since any frequency could be produced with the right placing of the hand. Kaempffert imagined how large theremin orchestras might be the future of music: *"A hundred men"* producing sounds simply by waving their hands, grasping music out of thin air (Ibid).[105] Indeed, in April 1930 a 10-piece Theremin ensemble accompanied by a Theremin cello, piano and harp made its premiere in Carnegie Hall ("Theremin Presents 'Ether-Wave' Recital", 1930). Two years later, the *Theremin Electric Symphony Orchestra* featuring keyboard and fingerboard variants made its debut in the same venue ("Theremin's Electric Symphony," 1932) (see figure 3.4). Emulating a classical ensemble, each instrument produced a different timbre; alongside the standard thereminvox, the ensemble featured

[104] In Paris tickets sold out in a mere three days. Non-ticket holders tried to force themselves in and the police had to step in (Smirnov, 2008c).

[105] This was likely after Theremin had spoken about his plans of creating a 40-piece theremin orchestra - see (Glinsky, 2000, 116). It is worth noting that, while Kaempffert imagined an orchestra of men, the most accomplished thereminists have generally been women.

fingerboard and keyboard versions of the instrument as well. The concert was a major event, regarded as a milestone for the music of the future.

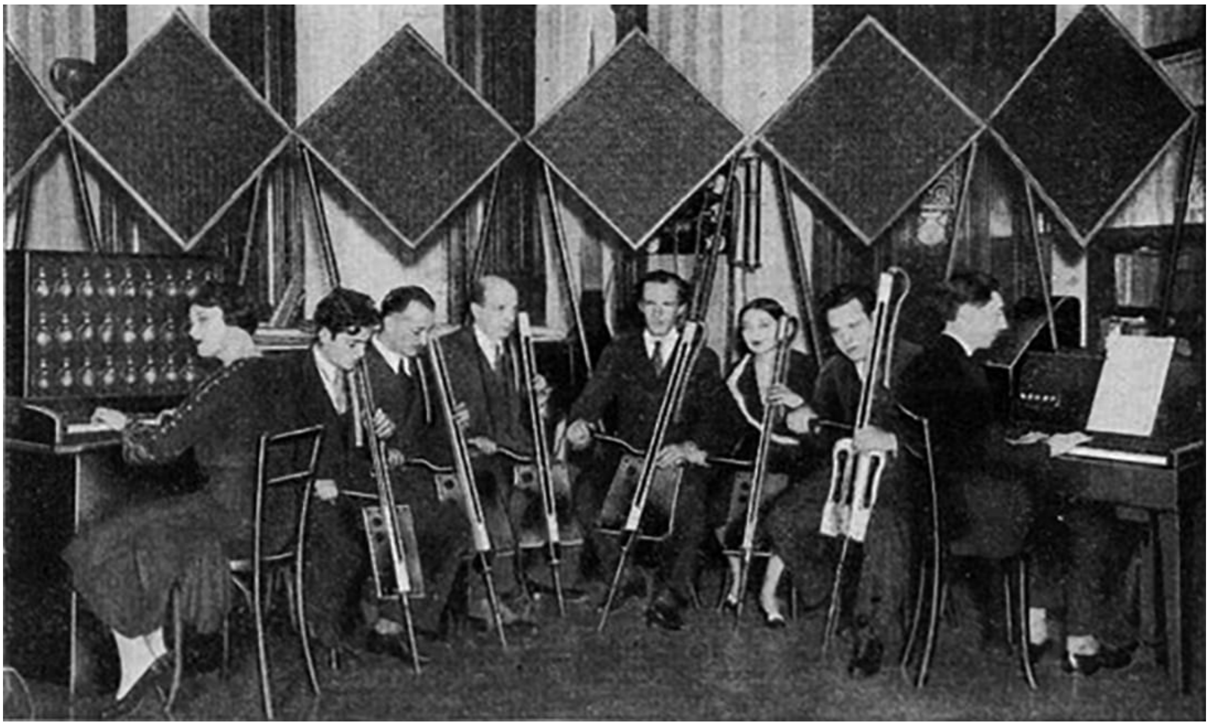

Figure 3.4. A photo from the debut of the *Theremin Electric Symphony Orchestra* at Carnegie Hall in New York, April 1932 (from "Theremin Cellos Win Music Public in “Electric Concert””, 1932).

Theremin made a number of Thereminvox variants as well as other instruments. In the late 1920s he built a ‘music stand’ thereminvox, and, between 1930-32, a keyboard thereminvox with timbral controls (Glinsky 2000). One of the more successful versions, also called *Thereminvox* or *Theremin Cello*, was a string-less electronic cello. Similarly to the keyboard thereminvox, its interface was emulating an existing instrument (Mattis, Moog & Theremin, 1992). To select different pitches, players put their fingers on a fingerboard, which made the instrument easier to play and to master, since familiar playing techniques could be applied. The conductor Stokowski asked Theremin to build 10 such instruments to replace double-basses and cellos, and avant-guard composer Edgard Varèse also had him build one for his work *Ecuatorial*.

The most pertinent variant to this thesis, and the one pushing the envelope of instrument design the furthest, was the *Terpsitone*. Developed in the early 1930s, this instrument was a radical manifestation of Theremin’s ideas on gestural sound attempting to fuse music and dance. It was named after Terpsichorè, the ancient Greek muse of dance. Later on, it also became known under a more technical name: *ether wave dance stage*.[106] The Terpsitone was meant to be for the dancer what the Theremin was for the musician. It is worth noting that Theremin was not alone in wishing to explore his technology's potential for dance. In 1931 dancer Sophia Delza and composer Gertrude Karlan used the original Thereminvox in a dance performance. A New York Times reviewer of that performance found that the instrument had *"undeniable possibilities for dancing"* and included a critique of strategies for mapping movement to sound that he deemed successful (such as the *"legato of physical movement"* producing a *"musical legato"*) or unsuccessful, such as deeming the association between rising and falling movement to an ascending and descending scale *"rather literal"* (Martin, 1931).[107]

The Terpsitone was played with full-body motion rather than hand gestures. The performer stood on a wooden platform which contained a large metal plate antenna. The platform dimensions of a rather standard Terpsitone from 1966 were measured at 2m x 1.8m x 0.2m (Gimazutdinov, 1996). Vertical movements changed the pitch. Initially, volume was controlled by an operator backstage but later versions featured a second antenna behind the performer through which horizontal movement could be used to control volume (Glinsky, 2000).

The instrument, schematics included, was presented in a 1936 article in the Radio Craft magazine (Mason, 1936) (figure 3.5). The article read: "*By means of Prof. Theremin's latest device, a dancer may create music by the movements of her body. A capacity device in the floor is mainly responsible. (...)"*. It added that, with the Terpsitone, *"it is possible for a dancer to dance in tune as well in time (...) The motions of the danseuse are concerted into tones varying in exact synchronism with her pose. (...) We have thus a new instrumentality of the terpsichorean art, as well as the lyric, combining the best features of both; and permitting even greater expression of individuality, as well as demanding even more refined technique. And all from another extension of the principle of 'hand capacity,' which used to be such a nuisance to the seeker after DX."* (Ibid). Over half a century later, Theremin offered a few more insight on how the instrument operated and how sound was controlled: *"When the dancer's body is low, you hear the lowest pitch. When the dancer raises her body, the pitch*

[106] The alternative name is mentioned in Glinsky (Glinsky, 2000, 143).

[107] Glinsky (2000) mentions a couple more cases in which the thereminvox was used in dance performance in New York at the time. This includes one of Theremin's students, Henry Solomonoff aka Eugene Henry, playing the instrument to accompany dance on stage, and a choreographed solo by Harald Kreutzberg on a piece for theremin and piano by Friedrich Wilckens.

also goes up. It's also possible to dance without changing the sound. For instance, if the dancer raises one arm and lowers the other there will be no change in pitch. But if the dancer raises both arms, then the pitch will go up. (...) If the dancer goes more forward, it gets louder. When she steps back, the sound gets quieter." (Mattis, Moog & Theremin, 1992).

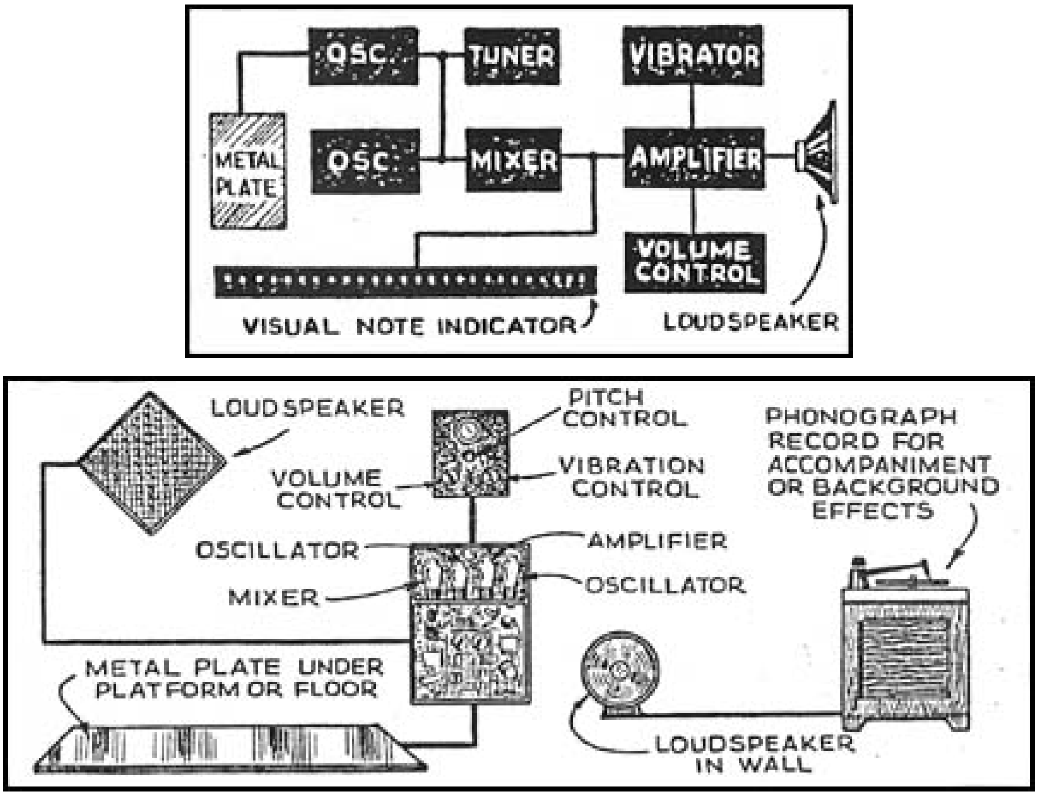

Figure 3.5. The Terpsitone: system schematics (left) and system components (right) (from Mason, 1936).

The Terpsitone was first presented during Theremin's 1932 Carnegie Hall concert, alongside his *Electric Symphony Orchestra*.[108] The performer was virtuoso thereminist Clara Rockmore who had to step in because Theremin had found no dancers that *"could carry the tune*" (Clara Rockmore, quoted in Glinsky 2000, 144) (figure 3.6). Rockmore was fascinated by how much more dynamic and expressive this full-body control was. She said that in the standard Thereminvox *"you have no choice - you go up the scale, down the scale, and God forbid that you move one pinhead too much, you're in the wrong place - such small intervals. You can't* dance *that way… how could you possibly do it? Here you had the whole body instead of the whole hand. In other words, you could do* this, *and you didn't have to do* that. *You could move your head, rather than your hand… You could raise your shoulder. Your whole body was in the musical field; you had a* choice.*"* (Clara Rockmore, quoted in Glinsky, 2000, 144).

[108] This was Theremin's last concert before fleeing back to the USSR in 1938.

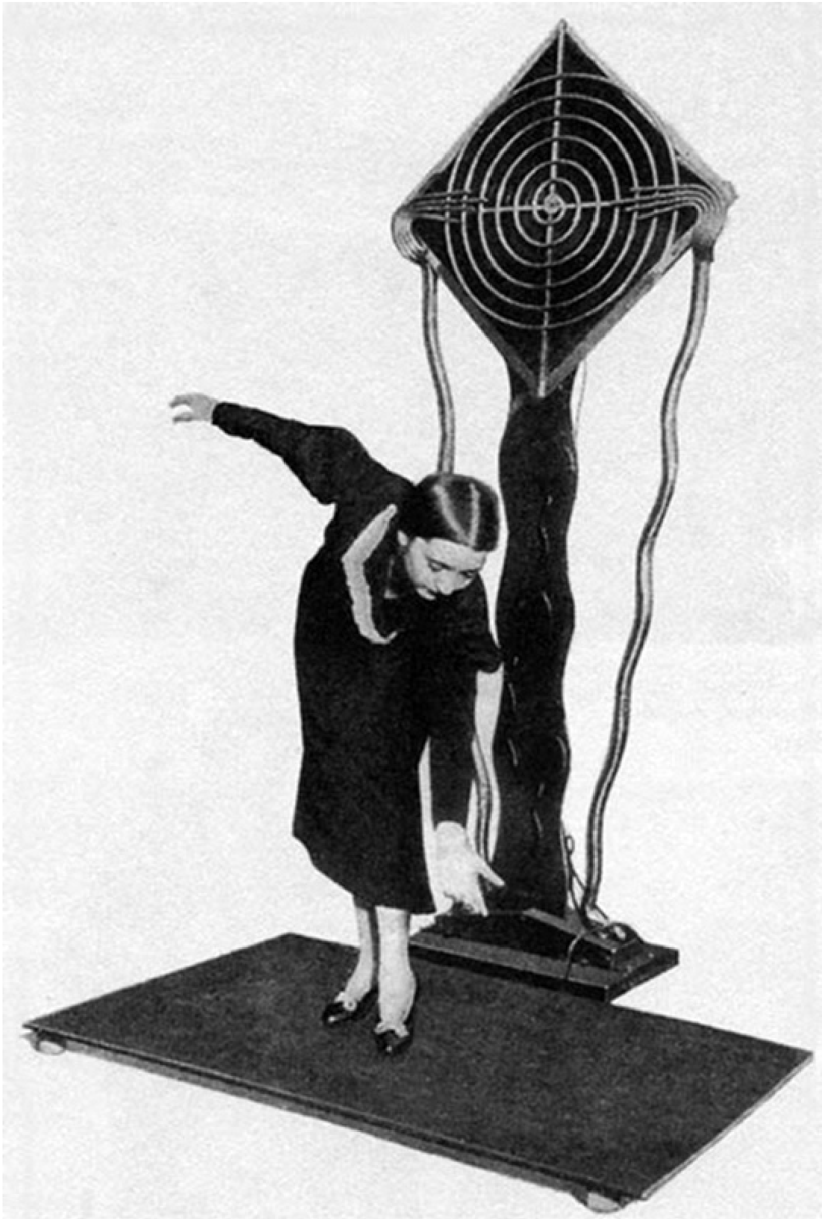

Figure 3.6. Clara Rockmore premiering the Terpsitone at Carnegie Hall in April 1932 (from "Radio squeals turned to music", 1932).

Besides Rockmore, Theremin taught many more musicians and dancers how to play the Terpsitone. He also performed many studies with it and constructed a number of different variants throughout his life in the US and USSR (Mattis & Theremin, 1989). Some of these instruments contained additional features, such as a tuning circuit to limit the output to the 12-tone scale (i.e. playing only semitones and no glissandi), or a sound-playback device to accompany the soloist. Other instruments were constructed as a self-contained version of his early multi-modal shows, featuring the 'visual tone indicator' - an electro-mechanical apparatus that projected light, mapping different color hues to each note (Nesturkh, 1996). Some instruments were built to size for a specific performer, as was the case for the last surviving instrument, made for Termen's grandniece Lydia Kavina. This fact is particularly interesting, revealing the close relationship between body and field, particularly as it coincides: a) with my own personal experience in designing the sensing area for Hertzian Field #2 according to my own body size, as I am the performer (section 7.2), and b) with Gottfried Willem Raes's discussion of tuning his doppler-radar sensing systems to the bodies of his performers (see section 4.7).

3.1.4 *Leon Theremin the wireless entrepreneur*

While in the US, Theremin attempted to commercialize several of his inventions. In 1928, a year after his arrival, he received a US patent for the Thereminvox, which RCA subsequently bought. General Electric and Westinghouse would collaborate to produce commercial RCA Theremins on a large scale. The plan was to distribute the instrument widely, marketing it as an easy to play instrument for unskilled amateurs. As the RCA vice president said, *"any one who is able to hum a tune, sing or whistle is likely to play the RCA Theremin as well as a trained musician"* ("Radio Corporation to Sell 'Ether Music' Device", 1929). [109] Interestingly, this was a strategy that would be repeated ad infinitum by music technology marketing teams throughout the 20th century. Nevertheless, given how difficult mastering an instrument so foreign to anything else at the time must have been, amateurs were most likely not the best target group. Timing was also far from optimal, as the instrument was released right after the 1929 financial crash. Despite a successful promotional campaign with many full-house concerts, only about 500 instruments were produced and sold (Nikitin, 2012).

In his New York studio, Theremin created many other tools besides musical instruments. Like many of the electromagnetic pioneers of the 19th century we saw in the previous chapter, Theremin worked on a slew of different projects. Around 1931, he began increasingly shifting his entepreneurial focus away from musical applications and returning to the ideas behind his 'radio watchman'. He thus soon entered the security market (Booth, 2013). In 1932, the *Teletouch Corporation* was formed to produce and sell a variety of different inventions of his.[110] Potential products included (Glinsky, 2000):

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[109] Not everyone shared the same positive outlook on making such an instrument available to the public. A French critic wrote in 1927: *"With the ethereal piano – and the apparatus will be put on the market quickly – the most musically stupid will be able to practice. What will happen when every office apprentice, at the end of his day, plucks the strings of the ethereal harp and gives expression to his emotions at the open window?"* (Andreas Lunus quoted in Booth, 2013, 27)

[110] An introduction of Theremin and his corporation in *Fortune* magazine gave a colorful description of the company and its technology: *"The Teletouch office-factory-laboratory in the brownstone house is a crazy place.*

- Alarm systems: *“New Burglar Alarm”*, *“Fire Alarms”*, a *“Device for detecting metal or guns when concealed in a person's clothing”*
- A capacitative *“Automatic Door Opening and Closing Device”* (figure 3.7).
- Signaling systems*: “Railroad Signaling’, “Signals for Vessels”,* and a *“Device for Broadcasting in an extremely narrow band”.*
- Recording devices: *“Photoelectric Recording and Reproducing Device”*, *“Sound Recording and Reproducing Apparatus”*, and *“Wireless Microphone”*.
- An altimeter for aircrafts.
- A *“Method for Preventing Corrosion*”.
- The “*Teletouch”*, or “*Magic Mirror”* an advertising screen activated by human presence.
- The *“teletouch glove”,* a product combining haptic and telematic technologies to allow its wearer to touch objects from afar.
- Finally, many musical instruments: *“Electric Fingerboard”*, *“Electric Keyboard”, “Electric Organ”* and *“Polyphonic Keyboard Musical Instrument:”,* and a *“Dance Platform*”, i.e. the Terpsitone.

Figure 3.7. Theremin demonstrating a capacitative sensing system designed for opening doors with a wave of the hand, based on the same technology as his instruments (from “Electrons in new industrial miracles”, 1932).

Walk through a door and a shrieking alarm goes off. Touch a filing cabinet and another alarm goes off. Go to a mirror to set your tie and a light flashes behind the mirror so that you see, not your tie, but an advertisement. Mr. Morgenstern is full of the future of Theremin and Teletouch as protection for any number of things—although some electrical engineers say that the device is sensitive to weather changes and therefore may not be altogether reliable. Vice-President Theremin spends most of his time at a long laboratory table on the second floor. He is so busy disturbing electromagnetic fields that he scarcely has time to play the Theremin.” (“Theremin”, 1935).

The company had some initial success. Following the Lindbergh kidnapping in 1932, Theremin released an electronic crib alarm to the market. In 1934, he was commissioned to build and install a metal detector system for the Alcatraz prison (Booth, 2013). However after some time it became apparent that the system occasionally failed, thus the contract was retracted and another contract for the Sing Sing prison was also annulled (Nikitin, 2012). The device was also deployed by the Cuban government, and had been purchased by Macy's who did not end up using it, as it required someone to constantly monitor it ("Theremin", 1935). Theremin also tried to commercialize a device he had developed in Petrograd: an early television system that allowed seeing from afar by wirelessly transmitting moving images rather than static photographs. Termen had been inspired by Ioffe's 'distance vision' concept and by 1926 had completed *"the system of Dalnovidenie",* which was based on the cathode ray and a mechanical mirror drum (Smirnov, 2008a and Nikitin, 2012). This first Soviet television was much more advanced than its competitors, broadcasting moving images at a 1.5m square screen with a resolution of 64 lines (Smirnov, 2008a and Smirnov, 2008b). Theremin tried to market this apparatus in the US, even forming the *Theremin Television Corporation* for this purpose, but did not succeed. By 1933, his TV technology had become obsolete.

A decade after Theremin's arrival to the US, neither his musical nor his non-musical inventions had proven to be successful business endeavors. His financial situation was aggravated in 1938 after marrying Lavinia Williams, a black dancer and Terpsitone performer (Smirnov, 2008b).[111] This interracial relationship was a big scandal for the segregated American society costing him the support of several bankers and patrons. To escape a large debt and problems with the Immigration Service, Theremin fled the US alone on that same year with the help of the soviet military intelligence (GRU).[112]

3.1.5 *Lev Termen the spy, and the top-secret lives of the Thereminvox's spawns*

Unbeknownst to everyone, during the entire time of his stay in the US Theremin was living a double life. As far as the Soviets were concerned, the man known in the west as Leon Theremin – inventor, performer, and entrepreneur - was merely a cover for Lev Termen the

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[111] Williams was a dancer for the *American Negro Ballet*, a modern dance company ran by a German anti-Nazi dancer and choreographer. Theremin built the sound system for their performances. For a more detailed account, see Glinsky (2000, 174-176).

[112] Theremin did not tell anyone that he was fleeing, not even his wife, which is likely part of the reason why many believed that he had been kidnapped by Soviet spies (Fischer, 1970/2010).

spy, although this may not have necessarily been how Theremin/Termen felt himself about the situation (Nikitin, 2012). It is not clear what his missions entailed while in the US as he only talked about his double life in later years, responding with care to not get in trouble (Fischer, 1970/2010). Understandably, he also gave conflicting responses to his American and Soviet audiences. As a secret and redacted CIA report writes, his role was likely more important than he admitted (Ibid).

Theremin returned to a much changed Petrograd (renamed Leningrad) towards the end of the Great Purge repression campaign, bringing with him 2 tons of electronic components with hopes of setting up his own lab (Smirnov, 2008b). Upon his arrival everything was confiscated and soon thereafter he was also arrested, condemned as a spy, and sent to the Siberian Far East in the arctic gold-mining Gulag of Magadan, in Kolyma. Nine months later he was spared from these dreadful conditions with a transfer to a 'Sharashka' in Moscow by Lavrenty Beria, chief of secret police. Sharashkas were minimum-security prison-laboratories that had become central to Soviet innovation. Many scientists, technicians and engineers found a similar fate to Termen, performing the tasks dictated to them as cogs of the Soviet R&D machine.[113] The conditions in the Sharashka were much better than at the Gulag, and Termen had access to a lab, equipment, information, and assistants, which kept his spirits up.[114] His main quip was that his time was consumed *"with different nonsense"* (Theremin quoted in Smirnov, 2008b, 91). Nonetheless, the fact of the matter is that he worked in top-secret Soviet research centers for decades and was involved in numerous top-secret projects, a number of which seem to have been technically related to the Thereminvox. After a stint in aviation, he was transferred to a facility developing radio and radar technologies as well as measuring instruments. Projects included a radio beacon for locating submarines, aircraft that had gone missing, or supplies dropped behind enemy lines. Theremin also worked in speech encryption, leading the development of the M-803 vocoder (Fischer, 1970/2010).[115] As one of his assistants recounted, projects were developed *"mainly for intelligence and investigation purposes* (...) *We made radio-detonators for acts of terrorism in rear of the enemy. We also developed a detonator for an aviation bomb which provided explosion at*

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[113] In the Sharashka, Theremin worked together with several eminent imprisoned scientists like Andrei Tupolev (the aircraft designer) and Sergei Korolev (developer of the Sputnik rocket) (Nikitin, 2012).

[114] An assistant of Termen reminisced: "*Nobody could recognize him as a condemned person without knowledge that after the working day he wouldn't be getting out of this place*" (Rem Merkulov, quoted in Smirnov, 2008b).

[115] Aleksandr Solzhenitsyn included a character modeled after Theremin in his novel *The First Circle* by the name Pryanchikov, "*an engineer ordered to build a sophisticated voice encryption system*" (Fischer, 1970/2010, 29).

height about two meters above surface of the ground. The destruction ability of the bomb essentially increased. We used a Theremin principle for this system." (Rem Merkulov, quoted in Smirnov, 2008b, 91-92).[116]

Termen's most successful espionage project was the *Great Seal bug*, a revolutionary eavesdropping device placed inside a large carving of the Great Seal of the United States of America. The object was gifted by the Soviets to the American ambassador during the Yalta Conference in 1945 and hung in his office from 1945 to 1952. Hidden behind the eagle's beak was a pencil-like device containing no wires, no typical microphone, no circuitry, and no power source (Smirnov, 2008b). Because of this, the device was invisible to the many scans for surveillance devices that were performed throughout the years. Its design was both ingeniously simple and never before encountered, operating in a similar principle as today's passive RFID tags (Nikitin, 2012). A resonant cavity was closed off with a diaphragm and was connected to an antenna. Sound waves excited the surface of the diaphragm thus altering the size of the chamber and, consequently, its resonant frequency and the electromagnetic load of the antenna. A 330MHz transmitter in a nearby van sent out a high power microwave beam which activated the device. The backscattered beam was modulated by the sound in the room, thus encoding it with that sound. As it was revealed years later, this microwave bombardment presented serious health risks for embassy employees (Smirnov, 2008a).[117] The discovery of the device, dubbed 'The Thing', was officially announced in 1960 in front of the UN as a response to Soviet claims of US espionage (figure 3.8). [118] This caused growing concerns that Soviet surveillance technologies were far ahead than those of the West, at a *"level previously thought to be impossible"* according to an intelligence expert (quoted in Fischer, 2010, 32). As CIA historian Benjamin Fischer remarks, *"[i]n the demimonde of the CIA-KGB spy war, the psychological impact was akin to the launching of Sputnik a few months later"* (Ibid, 32). President Harry Truman himself voiced strong concerns, urging intelligence services to find ways to counter the device and its

[116] In his 1989 interview Theremin discussed that work as being related to the development of non-lethal technologies, such as "*[e]lectronics and other things that were mostly associated with military matters: television and other types of communication."* (Mattis & Theremin, 1989). Interestingly, his lab was using American components to hide the provenance of their devices in case they fell into the hands of the enemy (Smirnov, 2008b). Even more interestingly, because of this reason Termen was reunited with some of the components he brought with him from the US when he returned to the USSR.

[117] Smirnov (2008a) comments that Termen did not seem to have ever investigated or addressed the potential health risks of his devices.

[118] The discovery had already been leaked by a US newspaper years earlier, in 1953.

technology.[119]

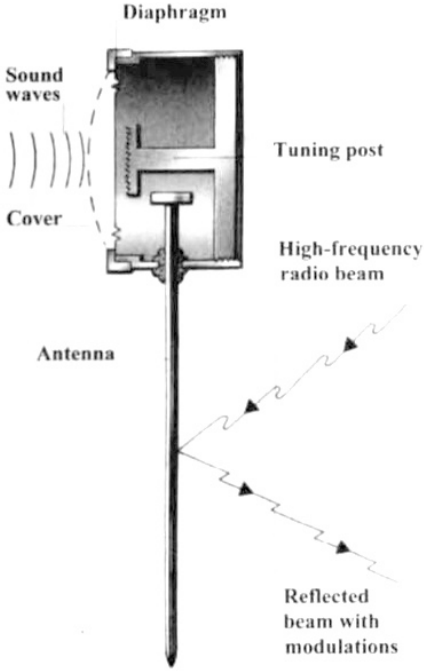

Figure 3.8. Termen's *Great Seal bug*. Left: a replica demonstrated in front of the UN Security Council by the US Ambassador to the United Nations, Henry Cabot Lodge Jr, in May 26th, 1960. Smiling behind him is the Soviet Minister of Foreign Affairs, Andrey Gromyko (Photo by John Rooney, AP). Right: a schematic of the mechanism and the basis of its operation (from Melton, 1996).

Another eavesdropping system developed by Termen was the *Buran* ('Snowstorm'), a project supervised personally by Stalin and Beria that became operational by 1947. The Buran was a type of radar microphone that operated like a microwave thereminvox (Smirnov, 2008a). It could record conversations from afar by reflecting microwave or infrared beams on the surfaces of objects such as glass windows. Vibrations caused by sound on these surfaces created microwave fluctuations of the original signal and could be converted back to sound on the receiver, thus rendering all sounds that hit the surface audible. This is essentially the principle used today in laser microphones. The Buran used a low power microwave beam, a light-detector, and an interferometer to convert electromagnetic vibration to light, then voltage, then sound. Such devices were undetectable and could not be jammed or interfered with. Beria used the device to spy on the US, French, and British in Moscow, but also on Stalin himself once the General Secretary’s mental stability had come to be questioned

[119] Smirnov (2008a) mentions another embassy-related espionage incident involving Termen. In 1946, the US counter-intelligence was invited to survey several embassies for bugs. The Soviets managed to quickly remove their bugs from all embassies except from that of New Zealand. Termen provided a successful solution to avoid getting caught: blasting the embassy with high-powered microwaves to jam detecting instruments.

(Fischer, 1970/2010). Theremin, deeply embedded in the surveillance mechanism of MVD (KGB's internal affairs predecessor), reported being part of this operation assigned with cleaning up clandestine recordings from Stalin's apartment and office – he even kept some tapes for his archive (Smirnov, 2008b). Ironically, Stalin awarded Termen for this invention soon after his release from prison, in 1947. After earning his freedom, Termen decided to stay in the Sharashka; thus he joined the MGB (KGB's state security predecessor) becoming the lab's director. From that moment on his life and actions became a protected state secret.[120] In the West, he was believed to have died in 1945.

3.1.6 *From espionage to music research*

Around 1962, after being assigned to work on unengaging research involving UFOs, telepathy, and psychic phenomena, Termen retired from the KGB to dedicate his time to music (Smirnov, 2008a). He first joined the USSR Sound Recording Institute, and after it was disbanded in 1965, the Moscow State Conservatory as a professor of acoustic research.

At the Conservatory, Termen continued his research on instruments and cutting edge interfaces. For example, in a 1966 article he wrote about controlling a Theremin's timbre with eye tracking. He also envisioned using electricity from the body to control sound parameters such as loudness (Glinsky, 2000). His main field of research involved the capture and analysis of performance data – a rather revolutionary method for understanding musical expression at the time. He created various tools, including an electronic tuner for organs, an apparatus to *"photograph sounds"* (essentially a spectrogram with 70 frequency bands), a spectrograph for measuring *"tone colors"*, and a device for changing the speed of recorded sounds while retaining their pitch (Smirnov, 2008b, 131-132). One of the sensing devices he built is of particular interest, as it may be the first radio-based tool for music expression analysis. Theremin described it as follows: *"Here is some work I have been doing on the pedals of the piano. With this you can see by colored lines the pianist's pedaling. Very important. We have compared and graphed the pedaling of many great pianists in the same piece. Very interesting. (...) Richter uses more left pedal than most pianists."* (Termen quoted in Smirnov, 2008a, 93).

Because of this change of career, Theremin the instrument inventor was rediscovered in the

[120] Termen was followed by bodyguards and not allowed to write to friends or family (Fischer, 1970/2010). He later claimed he was allowed to write and converse after 1947; however, his daughter says that was not the case until the 1960s (Mattis & Theremin, 1989).

West. An article about him was published in the New York Times in 1967, authored by a music critic who visited his Moscow lab. The great response from his American colleagues and the international community - and in particular the focus on the music and dance instruments Termen was building at the conservatory - had an unfortunate effect, however. Termen was fired and his equipment was trashed after the article reached the hands of the director's assistant who, realizing the nature of Termen's work for the first time, declared: *"Electricity is not good for music. Electricity is to be used for electrocution"* (Mattis, Moog & Theremin, 1992). While there are possibly political reasons also involved in this decision, the argument largely reflected mainstream Soviet attitudes of the time towards electricity and music (Glinsky, 2000). From the 1930s until the 1980s, electronic music was generally frowned upon in the USSR as a Western influence. Composers like Alfred Schnittke and Sofia Gubaidulina who wrote for the Theremin in the '60s-'70s were the exception – and definitely not part of the inner circle of Soviet culture.

In 1972, Termen moved to the Physics department of the Moscow State University where he worked as a simple radio technician until his death. There, and in his own time, he made more new Theremins. This included a version *"that could articulate words",* and a polyphonic version that could accompany a melody with chords (Nesturkh, 1996, 58; see also Glinsky, 2000). This variant added a second antenna for the left hand, perpendicular to the volume control, that allowed selecting different chords thus employing 3 radio fields for interaction. Theremin explained: *"A person could regulate one voice, or at the same time could add two or three more voices which would be in some sort of correct intervallic, I mean chordal, relationship in some natural pitch system. You change the pitch with the right hand just as it was with my other instruments, and the amplitude with the left hand. But then if you move the left hand from left to right, you can select 12 or 13 different intervals in exact relation to the melody - 3:4, 5:7, and so on."* (Mattis & Theremin, 1989). Termen had finished a 'radio lamp' version of the instrument while at the University, but its components were being slowly picked apart. He nearly completed a semi-conductor version in the late 1970s, but had to stop when he lost his lab space as *"[t]he chairman of the physics department considered music not to be a science"* (Ibid).

While Theremin would had thrived in today's interdisciplinary world, his work was deemed both too scientific to be art and too artistic to be science in his time and context. Still, during that time Termen taught countless students how to play his instruments and helped engineers develop and obtain patents for their own variants, such as the *Tonica* for children (Nesturkh, 1996).[121] While he received many invitations from around the world, he was only allowed to exit the Soviet Union starting in 1989 when he attended a new music festival in Bourges, France (Fischer, 1970/2010). A final international tour included a performance at the Electronic Music Festival in Stockholm in 1990 and a visit to Stanford and New York the next year. In 1992, the Moscow Conservatory inaugurated the Theremin Center for Electronic Music following a decade-long effort from many Thereminists. A year later, Theremin/Termen died at the age of 97.

3.1.7 *The Thereminvox as a liberating music machine for compositional imagination in the 1930s*

A handful of avant-garde composers were inspired by the Thereminvox and its merging of music, science and engineering. Joseph Schillinger (1895-1943), another Russian émigré in New York, composed the *First Airphonic Suite* for Theremin and orchestra in 1929 using the RCA instrument (figure 3.9). Schillinger was a practitioner of many art forms and a trained conductor and composer. He had deep philosophical and scientific interests and believed that cutting-edge scientific tools and ideas should be used for the creation of art. As Glinsky writes, *“[h]is theory of the arts was based on a conviction that natural laws and mathematical formulas operate on the molecular level in every artistic work. By discovering those formulas and reapplying them, talent, he believed, could take a back seat to knowledge.”* (Glinsky, 2000, 131-132). In many ways, these ideas predated - and perhaps helped seed - groundbreaking music movements that would not be established until several decades later. One can readily see that they share similarities to ideas expressed by both John Cage and Iannis Xenakis, for example, two composers with very different practices but equally large influence in music and art since the second half of the 20th century. Schillinger’s acquaintance with Theremin and his instrument in Leningrad in 1922 had been an ‘overwhelming’ futuristic experience*, “for the distance from the bowstring and calfskin to the theremin really must be measured in millennia”* (Schillinger, quoted in Glinsky, 2000, 134). Like Theremin, Schillinger’s ideas incorporated all human senses: light, sound, but also smell, flavor and haptic texture could be composed in time and space. Schillinger proposed that new art forms combining multiple disciplines and media could be produced by devices yet to be invented - and which could even create ‘semi-automatic’ entertainment! *"The men who will be responsible for the music of radio and television of 1950 will be neither*

[121] Termen collaborated with several inventors and musicians from the Scriabin Museum, in particular, including the inventor of the famous optical synthesizer *ANS*, Eugene Murzin.

composers nor performers, but a new kind of 'music engineer' who will operate the machines that compose and perform music" (Schillinger, quoted in Glinsky, 2000, 135).

Figure 3.9. Leon Theremin in his New York studio with Joseph Schillinger and Nikolai Sokoloff around 1929 (from "Presents Etherwave Music", 1929).

Another composer who embraced the Theremin was Percy Grainger from Australia (1882-1961). For Grainger, this instrument provided a way to realize his vision of a new kind of music - *"the only music logically suitable to a scientific age"* - free from the tyranny of scales, rhythmic pulse and tonality (Grainger, 1938/1996, 109). Grainger was attracted to the instrument because it allowed composing *"tonal glides and curves"* thus liberating music from the reduced resolution of the harmonic grid and bringing it closer to sound as a natural phenomenon, which he saw as a natural step in the evolution of music (Ibid). In 1935 he rearranged a string quartet piece, *Free Music 1*, for four Theremins, and composed *Free Music 2* for six Theremins. These two works were characteristic of his approach. The Thereminvox was not the perfect instrument for Grainger, however; merely the first step away from the limitations of acoustic instruments. The next step would be to remove the performer altogether, composing directly for a machine (Grainger, 1938/1996). In the late 1940s-1950s he would design a number of such 'Free Music Machines' together with Burnett Cross. As he wrote, *"Too long music has been subject to the limitations of the human hand,*

and subject to the interfering interpretations of a middle-man; the performer. A composer wants to speak to his public direct. Machines are capable of niceties of emotional expression impossible to a human performer. That is why I write my Free Music for Theremins – the most perfect tonal instrument I know" (Ibid).

Edgard Varèse, a French composer who, like Grainger, studied with Ferruccio Busoni was also drawn to the instrument.[122] Varèse spent a great deal of his life yearning for tools that are very standard today but which at the time seemed outlandish. In 1917 he had declared: "*I dream of instruments obedient to my thought and which with their contribution of a whole new world of unsuspected sounds, will lend themselves to the exigencies of my inner rhythm"* (Varèse & Wen-Chung, 1966, 11). By the 1930s he had moved beyond traditional concepts of harmony and melody to composing textures, sound masse and shifting planes, and was interested in the types of phenomena that occur when these elements meet. The Thereminvox, with its idiosyncratic sound and behavior and its freedom from mechanics and acoustics, was a promising tool for achieving these goals. In 1932, Varèse had Theremin build two high-pitched fingerboard Theremins operating at the range of the violin to use in *Ecuatorial*, an ensemble piece that premiered two years later.[123] Had Theremin stayed in the US the collaboration would had most likely continued. Varèse expressed his wish to compose for Theremin's instruments in a letter he sent him in 1941: "*I don't want to write any more for the old Man-power instruments and am handicapped by the lack of adequate electrical instruments for which I now conceive my music"* (Varèse quoted in Smirnov, 2008b). Unfortunately, Theremin never received this letter, as by then he was back in the USSR and a prisoner (Mattis & Theremin, 1989). Varèse was envisaging a *"new musical apparatus",* a machine that could produce sounds of any frequency and overtone combination according to a graphic score, allowing him to find *"an entirely new magic of sound"* (Varèse & Wen-Chung 1966, 12). In a 1939 lecture titled 'Music as an art-science', Varèse proclaimed what he was looking from such an instrument in very specific terms: *"And here are the advantages I anticipate from such a machine: liberation from the arbitrary, paralyzing tempered system; the possibility of obtaining any number of cycles or if still desired, subdivisions of the octave, consequently the formation of any desired scale; unsuspected range in low and high registers; new harmonic splendors obtainable from the use of sub-harmonic combinations*

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[122] Kahn suggests that Busoni's influence is likely the reason why Varèse and Grainger shared some ideas on the future of music (Kahn, 1996).
[123] In later performances, the instrument was replaced by the *Ondes Martenot*, another early electric instrument that Varèse was fond of.

now impossible; the possibility of obtaining any differentiation of timbre, of sound-combinations; new dynamics far beyond the present human-powered orchestra; a sense of sound-projection in space by means of the emission of sound in any part or in many parts of the hall as may be required by the score; cross rhythms unrelated to each other, treated simultaneously, or to use the old word, "contrapuntally" (since the machine would be able to beat any number of desired notes, any subdivision of them, omission or fraction of them) - all these in a given unit of measure or time which is humanly impossible to attain" (Ibid, 12-14).

Another avant-garde composer whose imagination was excited by Theremin was the American Henry Cowell. Cowell approached Theremin in 1930 with the concept for a photoelectric instrument: the world's first electric rhythm-machine. The *Rhythmicon* or *Polyrythmophone* was completed by Theremin by the end of 1931 and used lamps, rotating discs and photocells. Similarly to how the Theremin gave composers like Grainger and Varèse the possibility to navigate a free pitch-space, the Rhythmicon allowed Cowell to explore a complex rhythm-space. Cowell had reached the limits of the rhythmic complexity human musicians could perform with his *Concerto for Piano and Orchestra* in 1929. He came to Theremin with the concept, design, and some raw technical ideas about a new instrument that would allow him to play *"multiple rhythmic patterns simultaneously"* (Mattis, Moog & Theremin, 1992). Cowell wrote: *"My part in the invention was to invent the idea that such a rhythmic instrument was a necessity to further rhythmic development, which had more or less reached the limit of performance by hand, and needed the application of mechanical aid"* (Cowell in a 1932 letter to his stepmother, quoted in Smirnov, 2008d). The purpose of the instrument was twofold: acting as a compositional tool and musical instrument, but also useful *"for the carrying on of numerous scientific physical and psychological experiments with rhythm"* (Ibid). The instrument had 16 keys tuned to the harmonic series. The ratio of each key in relation to the fundamental determined both the pitch height and the speed of note repetition. Cowell wrote several works for this instrument, such as *Rhythmicana* for rhythmicon and orchestra (1931), and *Music for Violin and Rhythmicon* (1932). However the Rhythmicon never became as successful as the Thereminvox, with only Cowell and Schillinger writing for it. Perhaps its specificity to the vision of a single composer operating ahead of his time had something to do with that. Perhaps the flaws of the instrument were also to blame: sounds were short and without many harmonics, so the low registers did not carry; furthermore, the performer did not have precise control over when a note would actually play, as the pattern was controlled mechanically.

The Thereminvox became particularly famous due its use in cinema after WWII. While it had appeared in Soviet films already before then, its use greatly increased after Miklós Rósza included it in his Oscar-winning score for Hitchcock's *Spellbound* in 1945 (Booth, 2013). From that moment on, the instrument became the cinematic voice of unbalanced mental and psychological states, of mystery, horror, and the unknown. In the 1950s it featured prominently in many sci-fi films to demarcate 'the Other' (such as, *The Day the Earth Stood Still*). From the mid 1950s and for about a decade it also featured in exotica music. In the 1960s it made its passage to Pop/Rock, used by bands such as the Beach Boys, Led Zeppelin and Pere Ubu. The Theremin was rediscovered in the 1990s, appearing in several albums and productions of bands like The Pixies, Jon Spencer Blues Explosion and others (Sauer, 1996).

3.2 Direction-Finding Instruments

3.2.1 *Pupitre d'Espace: an electromagnetic spatialization interface*

Apart from the influence on composers due to its sound, the futuristic Thereminvox and its touchless radio interface opened another pandora's box, paving the way for radio frequency sensing as well as a variation of the concept of Direction-Finding to seep into the world of contemporary music. In 1951, Jacques Poullin, an engineer at Radiodiffusion-Télévision Française, developed the *Pupitre d'Espace* ('Space console') for avant-garde composer Pierre Schaeffer (Valiquet, 2012).[124] This would be the first of many interactive custom-built spatialization interfaces to follow as a response to the desires of specific composers (Pysiewicz & Weinzierl, 2017). The *Pupitre d'Espace* was an electromagnetic control interface for spatial diffusion of prerecorded sound, allowing a performer to intuitively position monophonic audio in space and to control its volume (Teruggi, 2007). It was one of the very first spatialization instruments and was designed for use in concert, rather than in the studio. The concept of *playing* music - 'jouer' - was very important for Schaeffer and easily lost in the nascent medium of electroacoustic music; this instrument provided a solution, offering a new way to play (or better, to spatially diffuse) electronic music in front of an audience (Emmerson, 2007).

The *Pupitre d'Espace* took a page off of Theremin's book, re-imagining a military technology (Direction-Finding in this case) for an artistic application. It consisted of 4 induction coil loops, each about a meter in diameter, acting as receivers and placed around

[124] It was originally named *Pupitre de relief spatial* or *potentiometre d'espace* (i.e. 'Spatial relief desk', or 'spatial potentiometer').

the performer (Pysiewicz & Weinzierl, 2017). A smaller coil, which the performer held in their hand, acted as the transmitter of an oscillating signal (figure 3.10). Each receiver coil captured a different voltage depending on the transmitter's proximity to it. By moving the device in the area between the four loops, the performer determined how much sound was sent to four speakers arranged around the audience in a configuration that mirrored the coils around the performer: two speakers in front of the audience, left and right, and two behind them in the center, with one of them positioned high above and facing down (Teruggi, 2007).[125] The four-speaker layout allowed positioning virtual sources in 3-dimensional space and the *Pupitre d'Espace* allowed moving them, an idea that was quite revolutionary at the time (Poullin, 1954).

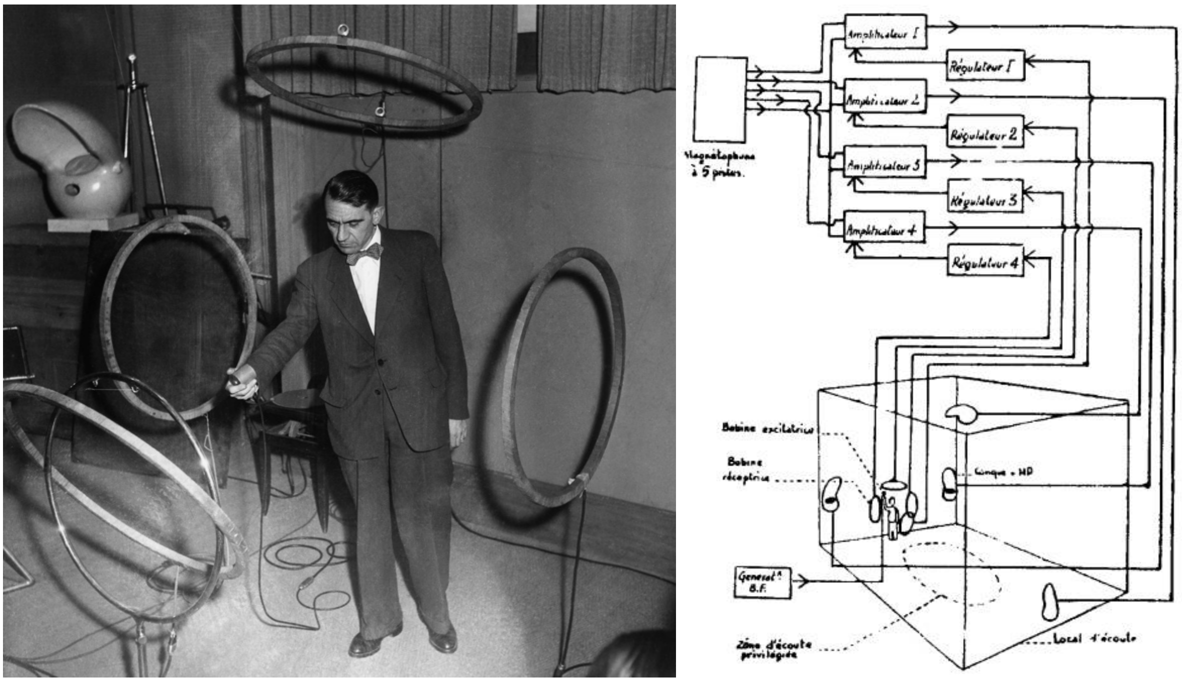

Figure 3.10. The *Pupitre d'Espace.* Left: Pierre Schaeffer playing the instrument in 1955 (photo by Maurice Lecardent / Ina). Right: the interface and sound diffusion schematics (from Poullin, 1954).

The instrument made its debut on July 6 1951 in a performance of *Symphonie pour un homme seul*, a tape piece by Schaeffer and Pierre Henry (Emmerson, 2007). Three months later, Schaeffer established the first studio designed for the creation of electroacoustic music, the *Groupe de Recherche de Musique Concrete* (GRMC).[126] This interface became an important part of the studio's arsenal together with a *"morphophone"*, a tape-loop based

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[125] Poullin notes that the speakers had been customized with focusing baffles to concentrate their projection beam to 60° to avoid spatial distortion (Poullin, 1954)

[126] GRMC was established in the same month as the NWDR studio in Cologne.

device for creating artificial reverberation, and two *"phonogenes"*, instruments for controlling tape players with adjustable-speed (Cross, 1968).

Schaeffer's studio was hosted in the radio and it mostly produced single-track compositions, as that was the appropriate format for radio broadcast at the moment (Valiquet, 2012). Still, concerts were the principle platform for showing these works to the public. They were also fundamental in helping establish this new electronically produced music as part of the contemporary classical music tradition and canon. One of the challenges was that, given that the same fixed medium work could be heard on the radio, composers and concert organizers needed to find ways to make the performance of tape music more exciting for the audience. This was primarily done by providing exceptionally different conditions and experiences, not only in terms of presentation and context but also technically, such as by using better speakers and experimenting with speaker orchestras and various multichannel layouts (Chadabe, 1997).

For Schaeffer, space could become a compositional parameter in itself, and 'sound objects' could also be composed and developed spatially (Valiquet, 2012). Furthermore, addressing the paradox of performing fixed medium work, Schaeffer pioneered the idea of spatialization as a parameter for live performance, introducing with it the sound projectionist as performer (Chadabe, 1997).[127] The *Pupitre d'Espace* was in part designed to take focus away from the machines required to reproduce the work (tape players, mixers, amplifiers, and speakers) by bringing back the human performer on stage (Valiquet, 2012). This performer is there not to create sound and music from scratch, like a musician playing an instrument, rather to shape, control and direct it, inscribing spatial trajectories with conductor-like gestures in front of an audience.

In performances involving the *Pupitre d'Espace*, only part of the music was diffused live. The system played back five tape tracks; four of them were sent directly to the different speakers while the fifth was spatialized live by the performer. This was enough to establish a convincing link between performative action and sound (Poullin, 1954). Making a more complex system would had likely been too challenging technically, and would also perhaps give the performer too much control for what was, in the end, fixed medium tape music. In its somewhat limited mode of control, the *Pupitre d'Espace* was both intuitive to play as well as effective in providing a new type of concert experience that engaged listeners visually while

[127] Spatialization as performance is an established practice in the field of electroacoustic music today, especially important in the French acousmatic music tradition.

immersing them in (modulable) surround sound (Valiquet, 2012).

As Joel Chadabe (1997) notes, spatial diffusion became a significant element of tape music concerts following Schaeffer's success. For experimental composers, this approach opened avenues much more interesting than sonic emulation and realism, which was for instance what cinema sound aimed at. Multichannel performance and diffusion techniques and technologies were an important emerging subject in the early days of electronic music, with many composers and new-found electroacoustic music studios starting to actively explore the field in the 1950s. The *Pupitre d'Espace* was demonstrated to audiences and journalists and was used in performance by GRMC composers, but also by French cultural linchpins Olivier Messiaen and Pierre Boulez (Valiquet, 2012). Karlheinz Stockhausen had visited Scheffer's studio in 1952 and had likely seen the interface in action before developing his own spatialization system a few years later (Emmerson, 2007). John Cage was also very interested in spatial diffusion as a strategy for more immediate and immersive listening of his tape works of the time (Valiquet, 2012). Many decades since its appearance, the *Pupitre d'Espace* is still an inspiration for contemporary systems like the *NAISA Spatialization System,* introduced by composer Darren Copeland in 2006, which uses an electromagnetic sensor with 6 degrees-of-freedom to spatialize sound in 3D (Copeland, 2014).[128]

3.2.2 *Radio Baton and Radio Drum*

The *Radio Baton*, invented in the late 1980s, was another musical instrument employing direction-finding techniques and building on the legacy of the Theremin. It shared a similar starting point with the *Pupitre d'Espace*: seeking to identify what the role of an electronic music performer could be, and finding ways to add expressive control and nuances to the performance of electronic music, and specifically computer music (Mathews, 1991). The latter was not a simple feat, given the limitations of digital technology of the time. The former, remained a very open question as electronically produced music was still by and large presented in the form of fixed medium works, i.e. 'tape music', rather than as real-time performance.

The *Radio Baton* was the brainchild of Max Mathews - a pioneer often regarded as 'the father of computer music', in part because in 1957 he developed the first computer music software. Mathews, working within a strictly Western paradigm, looked at classical music to

[128] The system uses the Patriot electromagnetic sensor, see: https://www.vrealities.com/products/magnetic/patriot-2. Last retrieved 31 March 2022.

distinguish between the compositionally predetermined part of a work delivered through its score - commonly defining pitches and relative note durations at the very least - and the expressive part open to the performer's interpretation, such as tempo, dynamics, and timbre (Mathews, 1991). As technology advances, he wondered, what does it mean to play music if one does not have to think about playing the right notes any more - arguably the hardest part of learning an instrument?

Mathews aimed to improve on existing motion and positioning systems by reducing latency, which would make it possible to perform music requiring tight synchronization (Mathews, 1990). Thinking of the computer as a complex orchestra, he regarded conductors as the best paradigm for computer music performance, as their duties involve controlling tempo and its micromodulations, as well as the dynamics, balance, and volume of the ensemble - but not the notes and their duration (Dodge & Jerse, 1997). In particular, Mathews looked at Pierre Boulez's conducting gestures as a model for the type of gestures and precision that a musical control interface should be able to capture. His idea was to design a system that could sense such gestures and use this motion data to control musical expressively (Park & Mathews, 2009). He developed an early prototype at the Center for Computer Research in Music and Acoustics (CCRMA) in Stanford in the mid 1980s, called the *Radio Drum* (figure 3.12, left). This instrument contained a contact microphone and two wire grids that would come in contact when the drum's surface was hit with a mechanical baton (the *daton*). According to Mathews, the instrument was not particularly successful, as it was easy to break and only transmitted information when hit (Ibid). A later version, created in 1988, included a joystick for additional 2-dimensional control, and 10 knobs. It also featured the 'Conductor', a computer-aided performance system that enabled 'conducting' pieces of pre-composed music (Mathews & Barr, 1988).

Unsatisfied by the limitations of his prototype, Mathews approached one of his associates at Bell Labs, Bob Boie, a robotics engineer and expert in capacitative sensing. Boie developed an innovative system that allowed tracking an object in 3D space via radio (Turi, 2014). This became the basis of a system that kept Mathews busy during the rest of his tenure at Stanford (Park & Matthews, 2009). In a 1990 patent application, Mathews described *"a radio signal actuated electronic drum"* with two or more batons (Mathews, 1990). The system used capacitative sensing of electromagnetic radiation (figure 3.11). Each baton contained a low-frequency transmitter coupled to an antenna at its end. Each of the batons transmitted at a different frequency around 50kHz to avoid interference. Embedded in the drum were two pairs of antennas - shaped to correspond to the X and Y axes - that captured the transmitted signals as the batons moved above the drum. In later versions, a fifth antenna was introduced to better capture motion in the Z axis (Boulanger & Mathews, 1997). In this configuration, the strength of a received radio signal corresponded to the amount of capacitative coupling between each transmitter and the four receivers. Using these signals and a lookup table, a CPU computed the position of each baton in three axes. It could also predict when the baton hit the drum's surface outputting a trigger signal, and later on it could estimate the velocity of the strike (Mathews, 1990). The system was most accurate in X and Y when the baton was close to the plane. When moving away, accuracy in X and Y decreased, though Z indications remained precise (Mathews, 1991). Overall, the instrument had enough precision to control all parameters but pitch. Mathews called his system a *"two-and-a-half-dimensional sensor"* (Park & Mathews, 2009, 14).

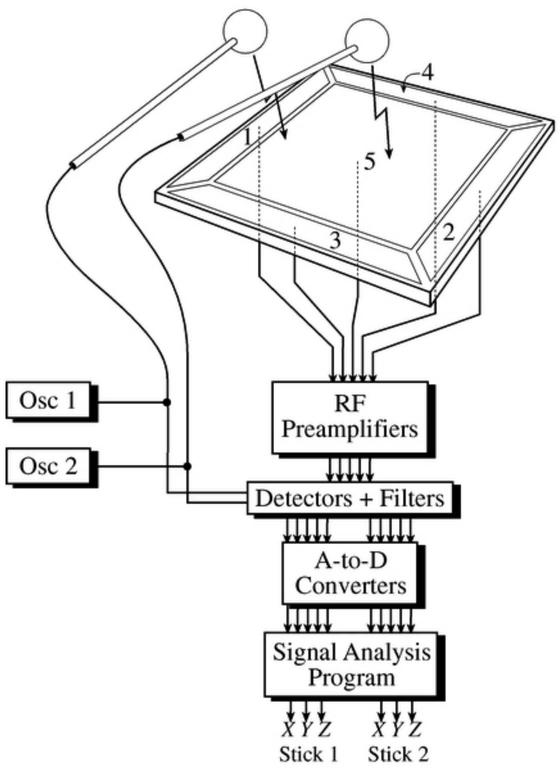

Figure 3.11. Capacitative elements and block diagram of Mathews' *Radio Baton* (from Putnam & Knapp, 1996).

Unlike the *Thereminvox*, and similar to the *Pupitre d'Espace*, the instrument did not produce any sound. Instead, the microprocessor packaged the resulting data as MIDI information, which allowed connecting the interface to synthesizers or software implementing the protocol (Mathews & Schloss, 1989) (figure 3.12, right). This enabled the exploration of many different mappings and sonorities. The instrument was used widely by performers and composers and many new works were written for it - over 40 by 2003 - in a variety of settings (Miranda & Wanderley, 2006 and Bresin et al., 2003). When coupled to the Conductor program the instrument was dubbed the *Radio Baton*, and was used to control music playback and sequencing (Turi, 2014). It could also be used as a percussive interface (*Radio Drum*) "*as an electronic drum, much like an electronic keyboard is used with a musical synthesizer",* or as a gestural controller (Mathews, 1990). For these uses the Conductor did not fair well, therefore the 1997 software implemented a second mode, 'Improv', which was used for improvising or interacting with algorithmic processes by providing triggers and continuous gestural control (Park, 2009; Boulanger & Mathews, 1997 and Mathews, 1991) . The *Radio Drum / Radio Baton* became a commercial project with a price tag of $1200 in 1997 that included both hardware (made by Tom Oberheim) and accompanying software (Boulanger & Mathews, 1997).[129]

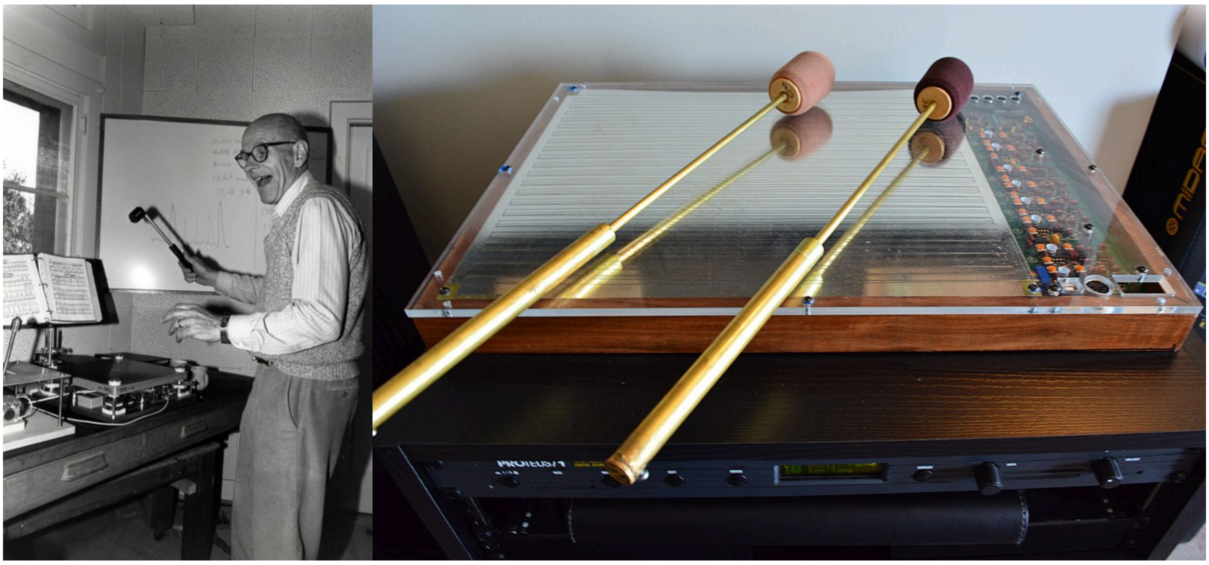

Figure 3.12. *Radio Drum* and *Radio Baton.* Right: Max Mathews playing an early version of the *Radio Drum* around 1984 (Park & Mathews 2009). Left: A recent version of the *Radio Baton* connected to an E-Mu Proteus 1 MIDI-controlled sound module below it (photo by Daniel Hartwig, Wikimedia Commons).

MIDI opened up many possibilities but these came at the expense of resolution (especially when compared to previous analog methods of controlling electronic sound, such as control voltage), as the protocol comes with a set of limitations. While the hardware allowed for a temporal resolution of up to 100kHz, it was crippled to about 1% of that because of MIDI (Mathews & Schloss, 1989). Throughout the years, a number of efforts have been made to

[129] For a video presentation of the instrument and interviews of Max Mathews and CCRMA researchers/composers Andrew Schloss, Joanne Carey, David Jaffe, and Julius Smith, see (UVicMISTIC, 2008).

extend the *Radio Baton*'s capabilities. For example, in 2001, Andrew Schloss and Peter Driessen bypassed the MIDI protocol using the raw signals for increased responsiveness and resolution (Miranda & Wanderley, 2006). In 2003, Roberto Bresin, Kjetil Falkenberg Hansen and Sofia Dahl explored new applications of the underlying technology, replacing the batons with a thimble-embedded transmitter (Bresin et al., 2003). This allowed them to model DJ scratching, playing the bodhran (an Irish drum) with two thimbles at each end of the double beater (which they called *radio bodhran*), or moving a sound-making virtual ball over an elastic surface - an application that included sonic, visual, and haptic feedback modalities. Another high resolution variant, called the *radiodrum*, was developed in 2011 with the collaboration of Boie, putting MIDI aside to achieve better continuous positioning resolution (Ness et al., 2011). This variant also introduced a new interaction modality based on gesture recognition to allow for the use of a richer vocabulary of gestures, matching incoming 3D motion data to a library of predefined gestures.[130] The instrument can identify simple gestures such as sweeping across the drum's surface, or more complex ones that a composer or performer inputs in the system's library. Gestures can be mapped to specific actions, such as triggering a new set of processes or a new section in a piece, or they can be used to control sound generators directly - the mapping is entirely up to the composer.

3.2.3 *Near-field RFID instruments*

Mathews' instrument inspired many others to create baton-style controllers. Donald Buchla presented the *Buchla Lighting* in 1991, an interface consisting of two infrared-enabled wands, which were optically tracked to transform direction, velocity and acceleration into MIDI messages. The instrument had presets such as *conducting* and *percussion*. Five years later, the interface was coupled to a dedicated 32-voice synthesizer (*Lighting II*).

Another Buchla instrument using Direction-Finding principles is the *Marimba Lumina* (2000). This instrument is a Marimba-like control surface that implements nearfield radio frequency sensing (figure 3.13). With this mechanism, it can sense objects with a passive electronic tag within a couple of centimeters from the reader (Paradiso et al., 2003). The instrument uses an array of antennas shaped like the instrument's bars to detect the position of four programmable mallets (Goldstein, 2000). Each mallet contains a passive Radio-Frequency Identification (RFID) tag, consisting of a coiled wire and a capacitor (resonant LC

[130] To achieve this it implements two gesture recognition techniques tested in many non-electromagnetic sensing systems: feature classification using Support Vector Machines and Dynamic Time Warping.

tag) (Patten et al., 2000). When a mallet is within 1cm away from a bar, the system outputs its location in 3-axes: over which bar it is, how high above it, and its longitudinal position along that bar. It can distinguish between downstrokes and upstrokes and provides velocity, position, and contact information (Goldstein, 2000).

Marimba Lumina's design took into account the particularities of marimba performance. The above features were meant to replicate and electronically extend traditional mallet keyboard technique, offering more than note and velocity information without adding foreign interfaces for continuous control, such as knobs. For example, marimba players often use various types of mallets simultaneously for different effects; therefore it was deemed important for the instrument to be able to distinguish between different mallets so it can produce different types of sounds (Ibid). The location where a bar is stricken in a marimba is important for the quality of sound, hence the longitudinal tracking in the *Marimba Lumina*. Moreover, different types of strokes - upstroke, downstroke, damping and dead strokes – produce different sounds on a marimba, which is why tracking on the Z axis was implemented. The performer can choose between different playing presets or configure the instrument with their own mappings. The instrument, sold by 'Nearfiled Systems', included a built-in synthesizer and was rather expensive ($3,500) (Buchla, 2005).

Figure 3.13. Don Buchla with his Marimba Lumina in 1999 (Photo by Susanne Kaspar, from Pareles, 2016).

The increasing ubiquity of RFID technology towards the end of the millennium – mostly in commercial security applications, such as to prevent shoplifting - together with the inexpensiveness and embedability of the technology led to a number of other RFID-based interaction systems being developed. The technology allows detecting the position and orientation, motion, and pressure applied on many tags simultaneously. The tracking range of systems using passive tags is limited, as the reader must not only read, but also power the tag. Optimizing range usually requires compromises in speed that are not ideal for musical applications (Paradiso et al., 2003). Using more expensive active tags with longer range is a possibility, but a power source is needed in that case.

Figure 3.14. Early RFID musical environments from the MIT Lab: *Musical Trinkets* from 1998 (left) and *Musical Navigatrics* from 2002 (right) (photos from the project websites).

Around the same time as the *Marimba Lumina* was introduced MIT lab researchers embedded passive resonant tags in objects, combining radio technology with tangible interfaces as a strategy to make contactless performance easier given that it was *"notoriously difficult to virtuosically master"* (Paradiso et al., 2003, 395). They produced two *"musical environments"* inspired by *"acoustic improvisers who perform using a table strewn with soundmaking paraphernalia"* (Ibid, 407). The first, *Musical Trinkets* (1998), was controlled via 16 tagged toy-like objects that could be freely position on a reader surface (figure 3.14, left). By placing three tags at right corners on an object, the system could estimate range and inclination independently. Mechanical pressure could also be used to alter the resonance of the tag circuit, turning it thus into a tactile sensor. The second, *Musical Navigatrics* (2002), used a less simplistic approach aiming to enable more virtuosic playing (figure 3.14, right).

Technically, this involved upgrading the reader hardware, designing a system that could respond in three axes, and developing more complex mapping strategies. The system was a control interface that was paired with commercial software to produce sound. Using twelve fuzzy objects, the performer could control musical parameters such as arpeggiation, filters, effects, and tempo (the meter was limited to 4/4). The system could also record and play back gestures.

3.3 Direction-Finding Systems in Sound Art

3.3.1 *Max Neuhaus' Drive In Music*

Direction-Finding principles have also been used by a number of sound artists outside the concert hall. Typically, the range of the systems used in these works is larger. The reach of their radio field extends beyond the confined area surrounding the body of a performer – as is the case for the instruments in the previous section - to larger spaces. This may be a wall, a room or a building, such as in the case of Christina Kubisch's *Electrical Drawings*, a street, such as in Max Neuhaus' *Drive In Music No. 1,* a square or block like in Mark Shepard's *Hertzian Rain*, or an entire neighborhood or city, such as in Edwin van der Hide's *Radioscape* and Kubisch's *Electrical Walks*.

The first sound art piece using such principles is Max Neuhaus's *Drive In Music No. 1*. This work has been widely regarded to be the first sound installation or sound art piece - although the veracity of this belief has been disputed (see Gál, 2017).[131] What is particularly interesting is that radio waves were used as the means for the piece to develop sonically by enabling the audience, rather than a performer, to interact with the installation. Furthermore, this development was tied to a spatial exploration rather than a temporal progression of events. This connection between sound and space is crucial for much of Neuhaus' work. As LaBelle remarks on the maker's oeuvre, *"Neuhaus aims for a tuning of sound and place as an expanded instrument"* (LaBelle, 2006/2015, 151). Before discussing the work, it is interesting to consider how this approach came about.

Neuhaus's music career started at a young age, as a brilliant virtuoso percussionist specializing in new music, performing works of renowned avant-garde composers

[131] Neuhaus himself called this his first sound installation for years which prompted many others to declare it the first sound installation ever. However, as composer and musicologist Bernhard Gál writes, this cannot be true as *Drive In Music* followed another sound installation by Neuhaus, *Fan Music*, which has been misdated as created in 1968, a year later. For more details, and for an interesting and thorough look on the history of the terms *sound installation* and *sound art*, see (Gál 2017).

internationally. After spending ten years as a concert musician, and frustrated by what he saw as the flaws of the musical context - such as *"the onus of entertainment"* and Western art music's audience becoming more and more niche - he turned towards a sonic practice that was primarily concerned with space rather than with time (Neuhaus, 1980/1994, 18).[132] As he wrote, *"Traditionally composers have located the elements of a composition in time. One idea which I am interested in is locating them, instead, in space, and letting the listener place them in his own time. I am not interested in making music exclusively for musicians or musically initiated audiences. I am interested in making music for people."* (Neuhaus, 1994a, 34).

In 1967 Neuhaus was invited to participate in an experimental art event organized by composer and sound artist Maryane Amacher at the Albright-Knox Gallery in Buffalo (Cianciusi, 2013). There, he presented one of his very first works as a maker, *Drive In Music No. 1*. Rather than waiting for an audience to come to the gallery to experience the work, Neuhaus sought to find the audience himself by grafting sound into physical public space (Neuhaus, 1980/1994). His idea was to place the work where people could encounter and inhabit it as part of their daily activities, experiencing it as they go about with their lives. This would become a common strategy for Neuhaus later on, as many of his works have been embedded in public spaces - physical, radiophonic, or virtual - turning the passerby, the listener, or the internet user into an audience. As people in Buffalo rarely walked but drove everywhere, their cars were an ideal venue for such an encounter - especially given that people were already used to listen to sound through their radios.

Without being knowledgeable on radio technologies at the time, but familiar with the existence of wireless microphones that could transmit to a nearby radio, Neuhaus looked into ways to realize his idea (Ibid). In the end, he mounted 20 low power radio transmitters on the trees lining Lincoln Parkway, starting from the gallery and ending half a mile down, towards a residential neighborhood (Föllmer, 1996 and Duckworth and Neuhaus, 1994). The transmitters were coupled with antenna wires and placed in the center of the area where Neuhaus wanted sound to emanate from. All of them broadcasted on the same frequency; they were connected in groups of seven circuits, each producing a different sonic layer consisting of a mixture of sine tones (Duckworth & Neuhaus, 1994) (figure 3.15). The piece

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[132] For Christoph Cox this is somewhat of a red herring, as he believes Neuhaus's approach just involves a different concept of time (Cox, 2009). Nonetheless, this concept does often involve space or revolves around space, as is the case for *Drive in Music.*

was *“invisible”* and *“silent”* until listeners passed through it with their receivers tuned in (Ibid). Residents were informed about the piece by newspaper ads, and could also take a map from the gallery to find the location. Sound appeared unexpectedly, as a surprise, and evolved as one drove through the street, passing from one transmitter’s reach to another’s as if crossing a radiophonic tunnel. Drivers created their own individualized variation of the soundscape, dictated by the car’s location, trajectory, and speed. As Neuhaus reports, the circuits were also sensitive to weather, producing different sonorities according to environmental conditions (Ibid). Recounting his creative process, he wrote: *“I began gradually, setting up one transmitter, broadcasting different sounds, driving through them, listening to them over the radio, getting a feel for how they arrived and departed as I drove through them. Then using two transmitters I tried different antenna configurations, listening to how they interacted and mixed with each other on the car radio, gradually building the piece south.”* (Neuhaus, 1980/1994). As he said in a 1995 interview, *“at the start of it I thought of it as music – that in fact the car going along the road in either direction 'played' the piece, the driver played the piece, a succession of sounds for each car according to its direction of passage and speed”* (Neuhaus & des Jardins, 1995).

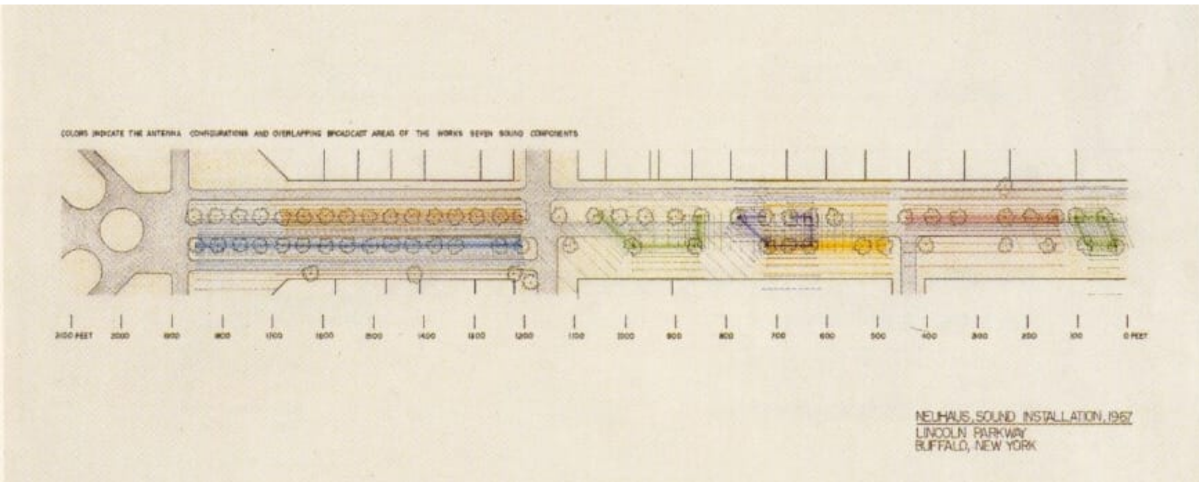

Figure 3.15. Max Neuhaus *Drive In Music*: Neuhaus’ graph showing the broadcast area and spatial configuration of antennas transmitting the seven sonic layers of the work in its 1967 iteration (from Neuhaus & des Jardins, 1994).

Regrettably, as with many works of the time there is no documentation or much information on the exhibited work, except from words, drawings, and the memories of ear-witnesses (Gál, 2017). The work remained installed for half a year, during which Neuhaus *“was taken into custody several times”* - likely because he did not have a transmission license (Neuhaus, 1980/1994). A second presentation of the work in 1975 at the Artpartk in Lewiston was not functional during the opening; according to the engineer working with Neuhaus it was never quite completed due to its technical complexity (Gál, 2017).

Neuhaus's concept of time was largely influenced by John Cage, his work being part of a wave of contemporary composers that wanted to redefine the time as a compositional parameter (Cox, 2009). Composers were fighting against the supposed objectivity of the clock, exploring time without pulse, rhythm or narrative, or using sound to shrink or stretch time - as evidenced, for example, by Karlheinz Stockhausen seminal article titled *Structure and experiential time* from a few years prior (Stockhausen 1958). In Neuhaus's compositional thinking, temporal progression was reconceived as a spatio-temporal duality, giving the audience the freedom to freeze the work or make it flow simply by moving in space. By treating space-time as a compositional parameter, Neuhaus stepped closer to visual arts, breaking from the confines of music and becoming one of the first sound practitioners to successfully enter the world of visual arts (Cianciusi, 2013). In his practice, sound, rather than being the end work itself, is a material employed to transform spaces and transit areas into places referencing their social, physical, architectural and acoustic contexts (Ibid). This is particularly true for *Drive In Music* and other of his *passage works* – i.e. works "*situated in spaces where the physical movement of the listener through the space to reach a destination is inherent"* (Neuhaus quoted in Kotz 2009, 109).[133]

3.3.2 *Edwin van der Heide's Radioscape and Mark Shepard's Hertzian Rain*

Radioscape (2004), an immersive radio-sonic environment by Dutch composer and sound artist Edwin van der Heide, is another work that strongly relates to Direction-Finding (van der Heide, 2009a and van der Heide 2009b).[134] This is true not only in terms of the technology involved but also in terms of audience experience. The work operates in a rather extended spatial range, treating the public space of a city (or rather, a neighborhood) as a navigable, interactive score. In this work, Van der Heide approaches radio as a spatial phenomenon with an implied question: is it possible to perceive and interact with radio waves in the environment in a similar way as we do with sound waves?

The work deploys 15 custom-built radio transmitters with ranges between 50-200 meters,

[133] In the 1990s Neuhaus felt that the term *sound installation* had become meaningless, so he began defining some of his pieces as *place works* and others as *passage works* as a way to narrow down and further define what the different pieces where about (Neuhaus & Des Jardins, 1995).

[134] The piece was realized with the help of Paul Morus, and Alexei Blinov from Raylab, a design studio specializing in electromagnetic technologies.
See: https://web.archive.org/web/20200223182340/http://www.raylab.com/.

spread throughout the city with some overlap so that one can hear between 2-5 signals mixed together at any given location. Each transmitter broadcasts a different monophonic audio signal that forms a single layer of a 'meta-composition' - a parallel sound world that van der Heide embeds in the urban space through electromagnetic radiation (van der Heide, 2013). These layers last between 4-10 minutes and are played in a loop. They consist of very gradually changing electronic textures - blips, drones and repeating sonorities that are reminiscent of various types of electromagnetic noises and encoded messages.

The transmitted soundscape is reconstructed via special, custom-made handheld receivers with which visitors explore the radio-sonic field as they walk through the city. The design of the receivers themselves resembles early Direction-Finding technology (figure 3.16). The devices combine two antennas with different reception patterns to create a stereo image of the radio sound field: an omnidirectional vertical antenna and a directional loop antenna that is only sensitive to its sides. The signals are mixed and relayed through a pair of stereo headphones much like one would do with the stereo microphone technique that inspired this configuration (called *Mid-Side*), in which an omnidirectional and a directional figure-eight microphone are combined. The effect is that changing the orientation of the receiver changes the soundscape's orientation, thus revealing the direction and distance of the broadcast layers. Similarly to *Drive In Music,* the content and pacing of the composition depends on how the listener navigates space. For van der Heide, the piece works best in a dense urban environment with many streets and forking paths so that visitors have to decide which way to go depending on what they hear, instead of passively following a map.

Figure 3.16. Edwin van der Heide's *Radioscape*. Left: Visitors exploring the work with handheld receivers during the *Urban Explorers Festival* in Amsterdam 2004. Right: A transmitting antenna installed in Rotterdam for the *Electromagnetic Bodies* exhibition in 2006 (Photos from van der Heide, 2009a).

Like in early Direction-Finding, walking and rotating the receiver become the two principal ways in which sonic change is introduced in the work. Loudness is tied to distance, with nearby transmissions sounding louder than faraway ones as electromagnetic energy dissipates with distance. Changes in orientation of the receiver antennas also change the signal strength, and therefore a layer's volume. To achieve this, van der Heide's transmission returns to the medium's past, eschewing the technological advancement of modulation techniques implemented in radio broadcast to avoid such effects. Amplitude Modulation (AM) involves a gain control circuit on the radio receiver to compensate for changes in received electromagnetic energy, and Frequency Modulation (FM) completely decouples loudness from distance. Furthermore, modulation-based receivers can only tune to a single transmission at a time. When two AM or FM transmitters broadcast on the same frequency and in the same area, their signals interfere with each other producing distortion rather than additively mixing together. Instead, *Radioscape* transmits unmodulated audio so that the signals from different transmitters can be mixed together in space just as if they were acoustic sources. Sound is simply shifted to a higher register before transmission (from the audio range to the radio range) and then shifted back down by the receiver's circuitry. In this manner, the signal retains a fairly high quality, closer to the fidelity of FM than AM.

Radioscape transmits at a low frequency, slightly higher than the AM range, at about 1.7MHz (1700KHz) and a wavelength of 175 meters. The frequency was chosen to avoid the creation of standing waves by buildings as at this wavelength they only partially reflect waves but also act as conductors and resonators, meaning that approaching a building may affect the content of the radioscape and the system's response (van der Heide, 2013). In terms of content, besides the composed layers a listener may also encounter distortion and interference in certain places caused by EM-generating sources in the urban environment, such as neon lights, street lights and security systems. These noises are quite localized and do not travel far from their source because they are not coupled with antennas.

Another broadcast radio work from the 2000s is *Hertzian Rain* (2009), a piece by American artist and media architect Mark Shepard (figure 3.17).[135] The work uses more conventional radio technology than van der Heide's, which it combines with special material to blocks transmitted waves. Shepard's starting point was not sonic art but Dunne and Raby's concept of hertzian space. *Hertzian Rain* was designed as a platform or system – or a *"variable event structure"* as Shepard describes it (Shepard, 2009) - with loosely specified content that was

[135] The work was created by Shepard in collaboration with Heamchand Subryan and Nick Bruscia.

meant to change in every showing of the work.[136] It involved a variable number of audio transmitters installed around an urban area, like a square, each broadcasting live sound produced by an invited collaborator either on site or from a remote location. This could include soundscapes created by sound artists, music played by DJs, or spoken word performances. All transmitters operated on the same UHF frequency around 900MHz (most likely using FM modulation), creating zones where their signals interfered with each other. Visitors explored the area with wireless headphone receivers and special umbrellas made out of electromagnetic shielding material. By walking and moving the umbrellas around them they could focus on the signal of a particular transmitter, blocking interferences from the rest of the transmitters. As a secondary layer of interaction, the umbrellas also contained embedded electronics: accelerometers captured movement data which they transmitted wirelessly back to the sound-making stations via WiFi. The data could be used by sound artists to manipulate the sonic content, creating a control feedback loop. Through this system, the piece aimed to make visitors aware of the spatiality of wireless and to create a playground in which issues relating to the electromagnetic landscape of urban spaces become apparent. Shepard was particularly interested in highlighting how different transmissions fight for signal dominance, and how this fight pertains to the concept of 'Tragedy of the Commons'. [137]

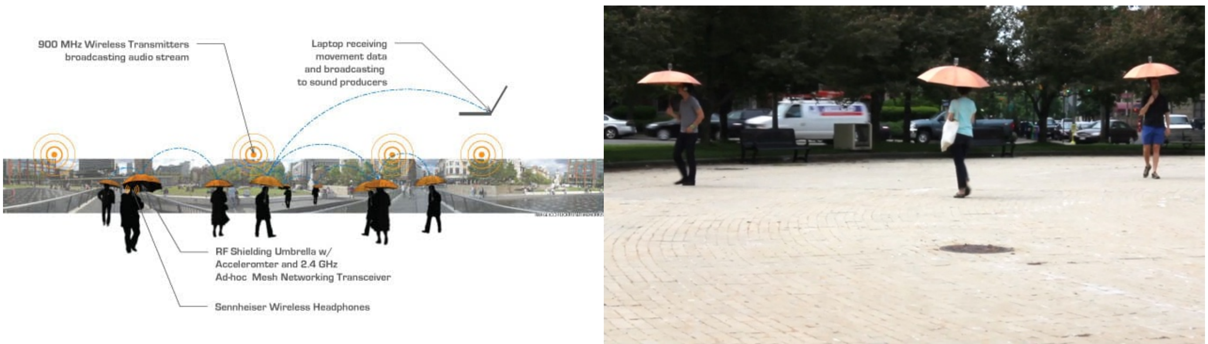

Figure 3.17. Mark Shepard's *Hertzian Rain.* Left: schematics of the work's operation. Right: documentation from a presentation of the work (photos from the artist's website).

3.3.3 *Christina Kubisch's electrical drawings*

Another artist that has worked extensively with hertzian technologies is Christina Kubisch (1948), a German composer and sound art pioneer with a background in classical flute and painting. Kubisch studied music in the end of the 1960s, and started as a composer but her

[136] The piece was presented in New York City in 2009 (during Eyebeam's *MIXER:EXPO* event) and at the Birchfield Penney Art Center in Buffalo NY in 2011 (during the exhibition *Eyes of the Skin*).
[137] Proposed in 1968 by Garrett Hardin, the notion of the 'Tragedy of the Commons' refers to situations in which the selfish use of a limited shared resource results in its depletion or destruction.

work did not receive much recognition initially - as she recalls, for a woman at a time the options were to become a performer or a teacher, but not a composer (Sonic Acts Academy, 2018). In the 1970s, she focused on staged concert performances that combined music with elements of the growing movements of performance art and conceptual art, questioning what it means to perform music and what it means to play her instrument, the flute. At a time when visual artist Rebecca Horn was creating a number of works extending the body with various prostheses, Kubisch started playing the flute on stage with thimbles, boxing gloves, while getting wrapped up in tape, or wearing a gas mask connected to the instrument, breathing and vocalizing through her flute (Ibid). She extended this approach to other instruments, for example playing string instruments with phallic-shaped vibrators rather than bows. Continuing her move from music *"to a more open form"* she created a number of performances using video in collaboration with artist Fabrizio Plessi (Metzger & Kubisch, 2000). Around the end of the 1970s, however, she decided to stop performing as she did not enjoy the pressure of being on stage anymore (Sonic Acts Academy, 2018).

Largely influenced by John Cage's ideas, Kubisch found herself in a similar place as Neuhaus, *"unhappy with the predetermined or limited time for the audience to take advantage of the works"* (Milani & Kubisch, 2009). She began looking into ways for moving from performance to installation, seeking an experience more open to audience exploration and creating a context that would give listeners the freedom to move around and engage with the work in more active ways and at their own pace. In 1980, after finishing her studies at the Conservatory in Milan, she enrolled in a nightly electronic studies program at the Technical Institute where she had an accidental but life-changing breakthrough. At the time, she would buy various electronics to tweak and experiment with. Once, she arrived in class with an induction cube in her handbag - a device originally designed as a telephone amplifier and which was used to transduce the voltage from telephone wires into audible sound for hearing-impaired people. The device had accidentally switched on inside her bag and began making strange noises in class. Curious about the source of the sound, she asked the professor about it and he explained how electromagnetic induction worked (Sonic Acts Academy, 2018). This set her to a path that she is still exploring over 40 years later, having produced many groundbreaking works.[138] As she recounts, *"[t]hat was a kind of key experience, because I*

[138] It is unclear when exactly Kubisch started to work with electromagnetic induction. She frequently recounts this story from 1980 as the beginning of this type of work, but also often mentions that she started working with induction in the late 1970s. It is possible this just means that she was experimenting with induction and these cubes for a while before knowing what the principle of operation behind them was.

had discovered a technique with which I could transport sounds and leave the audience the freedom to put the musical sequences together themselves, to move freely in the room" (Metzger & Kubisch 2000, 87). With this interface, she could create fixed medium works that need not be experienced in concert, but which come into being through *the "individuality of listening and of movement"* of each visitor's actions (Ibid).

Kubisch first began exploring the technology as a way to wirelessly transmit audio. She found that she could feed her sounds through loops of cable, then use electromagnetic induction to retrieve them wirelessly. This was essentially a reappropriation of audio induction loop systems, an assistive listening technology originally developed for delivering noise-free signals to hearing aid users. Such systems are often used in courtrooms, banks, conference rooms, and other public spaces. They work by laying a copper wire in a loop to form an antenna, connecting this loop to a microphone through an amplifier, and thus feeding it a fluctuating voltage corresponding to the audio signal captured by the microphone. The ensuing magnetic field emanating from the wire is captured by the coils in hearing aids, which can thus clearly relay the microphone-captured sound without any background noise ("Audio Induction Loop", 2021).

Kubisch worked on this system throughout 1980 and had 50 such boxes built. Her first installation to use them, *Il Respiro del Mare* ('The Breath of the Sea'), was shown a year later (figure 3.18). The description reads: *"A labyrinthine drawing made of round electric wire is mounted with small nail clamps on each of two facing walls. The resulting wire reliefs each transmit a single sound that is not heard through loudspeakers but can be received through small 'listening cubes'. The visitor can hold the cubes up to his ear and hear the sound quietly by himself, or he can move through the room, making audible the sounds stored in induction loops in the room. Several persons can perform sound improvisations with each other. The regular sound of ocean waves is stored in the blue labyrinth, while the red labyrinth contains the sounds of calm breathing. If one stands in the room between the two cable fields, the acoustic sequences mix and overlay each other. One hears the sounds more softly or more loudly in accordance with one's distance from the wires"* (Kubisch, 2000, 102).

Figure 3.18. Audience member moving speaker cubes in front of Christina Kubisch's *Il Respiro del Mare* (originally from 1981), exhibited in 2021 at Galerie Mario Mazzoli in Berlin (Photo by Frank Paul, from the artist's website).

With this system, the cube-equipped visitor became a performer. Fittingly, the first electromagnetic induction work Kubisch showed in Germany *(Untitled* from 1981) was exhibited during a performance festival. The work was an electrical cable drawing installed on the outer walls Heidelberger Kunstverein's Garden Hall. Visitors would walk among the rich vegetation with their loudspeaker boxes, pointing attentive ears to discover "*delicate, mysterious, strange and yet seemingly familiar sounds triggering a variety of associations emanated from the drawings"* (Gercke, 2000, 42).

Another piece from the same year, *Listen through the walls*, features a similar drawing to *Il Respiro del Mare* (figure 3.19). Installed on a rooftop in Apulia, Italy, the sound consisted of whispered syllables seemingly coming from the wall, often audibly cut up and at times supported by electronic layers. In many ways this work approaches sound poetry, creating a texture of language at the threshold of making sense. Kubisch released the composition used in this piece without any intervening interaction in a cassette tape in 1984.[139] *Murmures en*

[139] The title of the LP is *On Air*. The composition for *Listen Through the Walls* can be heard here: http://web.archive.org/web/20170326113125/https://www.youtube.com/watch?v=WY0nz1qsB9o

sous-sol, from a year later, was a 12-channel composition with an electric wire drawing taking over two adjacent walls. Another work featured four triangles inside one other on a wall, each emanating a different sonic layer. *On Air*, a work shown in Langenfeld, Austria in 1984 and *Magnetic Air*, a 14-channel piece shown in Vercelli a year later, featured vertical and diagonal grids of wires resembling powerlines.

Figure 3.19. Christina Kubisch's *Listen through the walls,* installed on a rooftop in Martina Franca, Puglia, in 1981 (photo from Kiefer, 2010).

Electrical cable became Kubisch's medium of choice. It was a functional tool but also an important visual element for the staging of her architectural interventions and a clear marker of her work. Wires presented themselves in various configurations to the visitor, forming two-dimensional patterns on walls, hanging from the ceiling, wrapped around pillars, stretching across rooms. They were simultaneously sculptural objects and antennas overlaying complex electromagnetic fields in a space to transmit her pre-composed sounds.

Through this system, Kubisch invented a particularly innovative and intuitive way of turning a fixed medium work into a continuous, dynamic, and infinite interactive environment. Her strategy in these works involved breaking a soundscape into layers and transmitting each of them separately via a different wire loop laid through the exhibition space. Visitors generate the work by navigating the different paths suggested by these fields of cables. As they scan the drawings and surrounding space with their boxes, the capture sound changes, revealing the composition's different strata and mixing them together. This action has an effect on one's own experience, but also on the experience of others. The content but also the density of the soundscape depends on how many visitors explore the piece at a time, and how they discover the work together. As Hans Gercke write, the viewer-and-listener becomes *"a participant in a relational system that the artist has staged and into which he brings his own specific preconditions - his own specific way of moving and of perceiving, his own experiences, and the associations that result from them - just as this also happens to the space. For this space is not abstract, general, arbitrary, or interchangable, but rather always specific. Its individuality, history, and unmistakability is not only the medium, but also the message"* (Gercke 2000, 42).

At the time, Kubisch preferred to exhibit these works outside museums and gallery spaces, following a site-specific, non-narrative approach. She presented *"countless induction works"*, presented as temporary interventions in various sites or outdoors - in "*gardens, cellars, parks, churches, old factories, abandoned buildings, etc"* (Kubisch quoted in Gercke, 2000, 43).[140] In these interventions, she sought ways to integrate the visual with the acoustic, exploring each particular site to find relationships and points of contact between the two. The sonic content was always informed by the context of the space, its architecture and its history; it was tied to the site, its environment, and the movement within. In this regard, Kubisch was very much in tune with contemporary developments in visual art.

Embedding sound in space was an important part of her compositional process. It combined planning with improvisation, intuitively responding to what the site offered once she was in it; for that reason she chose to install large parts of these works herself. Compositionally, she often started with precise structures, layering them together to produce seemingly random

[140] Museums and galleries began to approach her to exhibit her work there around 1985.

results. She worked with density and emptiness, often with quiet sounds as she is not a fan of being *"bathed in music"* (Metzger & Kubisch, 2000, 87).[141] In these works from the 1980s she often used processed recordings of natural sounds, causing the listener to wonder what was real and what not, if what they heard was from the site or the work.

By 1984 Kubisch had become tired of the limitations of the handheld interface. Realizing she could have the circuitry built into headphones, she asked a headphone company in Italy to produce a new interface for her (which she reportedly paid for by giving many flute lessons (Cox & Kubisch, 2006)). The result was a pair of large, closed, cordless headphones, containing coils to capture electromagnetic fields, an amplifier, speakers, and *"some little secrets"* (Sonic Acts Academy, 2018). She kept tweaking and improving this instrument through the years and in 1991, with the support of a sponsor, produced a new version with improved sound quality. The headphone interface was more mobile and encouraged a more natural interaction than the boxes, allowing one to walk and listen without having to hold anything. This binaural sound reproduction submerged listeners into their own, personal aural environment. As the sensor coils were placed directly in front of the ear, the soundscape would intuitively change following the motion, orientation, and proximity of the listener's head to the electrical wires of her work. At the same time, the closed headphones attenuated environmental sound, further contributing to the production of a fully immersive personalized space somewhat removed from the real space one found themselves in.

Nonetheless, I feel it is important to also note that, by becoming more solipsistic and insulated, the new system left some things behind. Sonically, the emergence of polyphonic, spatially-distributed soundscapes emanating from the cubes of many visitors became no longer possible. Furthermore, by enclosing every person in their own personal sound-world, interaction between visitors is no longer part of the work's experience, and the relationships between various visitors exploring and discovering the work together has been set aside. Visitors still perform the work but only for themselves, not with - or for - the group they share the space with. Instead, from an outsider's perspective, the headphone wearer's performative actions do not produce audible sounds but are reduced to a silent choreography. The elements lost in this change of interfaces seem to not have been particularly important for Kubisch, as she has been using the headphones ever since in a multitude of different works.

[141] This seems somewhat contradictory with her choice to swap her loudspeaker boxes with headphones later on - an immersive interface that can easily enclose the listener in a personal sonic bubble fully 'bathing' them in the sound of her work.

Figure 3.20. Christina Kubisch's *Der Vogelbaum* from 1987 (photo by Roman Mensing, from Kubisch, 2000).

This shift is evident in Kubisch's description of her work *Der Vogelbaum* from 1987 ('The Bird Tree'): "*The wireless headphones permit even more free movement in the room. Individual sound choreographies arise in dependence on the visitor's kind of movement, speed, and distance from the fields of cables.*" (Kubisch, 2000, 104). *Der Vogelbaum* was a 12-channel composition played through a large tree-like drawing, about 12 meters long and 3 meters wide, made out of yellow-green grounding cable (figure 3.20). Every cable contained the sound of a different bird – "*Nightingales and parrots, gulls and hummingbirds, thrushes and Australian huias encounter each other, producing a complex interweaving of singing voices and languages of birds that are now rarely heard in nature*" (Kubisch, 2000, 104).[142] The *Klanglabyrinth* ('Sound labyrinth'), another piece from 1987, was yet larger - 13 by 16,5 meters (de la Motte-Haber et al., 2008). Electric wire was stretched over the top section of 66 wooden stakes, about 1,70 meter tall, to form a labyrinth (figure 3.21). Visitors walked through it, mixing the different layers of a 12-channel composition along their way while -

[142] Interestingly, Kubisch reports that many listeners were unsure whether the sounds were real or synthesized.

judging from the documentation - others could watch them from a vantage point. The piece was exhibited in open space outside the Ars Electronica center in Linz, Austria. *Die Konferenz der Baume* (“The Conference of the Trees’) from 1988/89, was a subsequent indoor piece using the same system. Five pots with bonsai trees of various sizes were placed on a wooden conference table in an empty room, with yellow-green grounding wires wound around their trunks. As the description informs us, this is how bonsais are shaped in nurseries. The wires were flowing over the table ‘like roots’, and out the door. Each tree transmitted its own sound based on processed field recordings, which visitors could discover by circling around the table with special headphones (Kubisch, 2000). In a later iteration of the work the cables were painted fluorescent green, and the room was dark. A piece from 10 years later, *Klang Fluss Licht Quelle* (1999)**,** features some similar motives. The work was exhibited in an underground garage whose columns were wrapped with spiraling fluorescent cable, each playing back different types of water sounds (Kubisch, 2015). In a 2003 work, *Marine remix*, visitors walked with galoshes in an inundated pool of water with cables embedded in its bottom and stretching out of it, relaying 12-channels of water-related disaster reports (Goethe-Institut Russland, 2017).

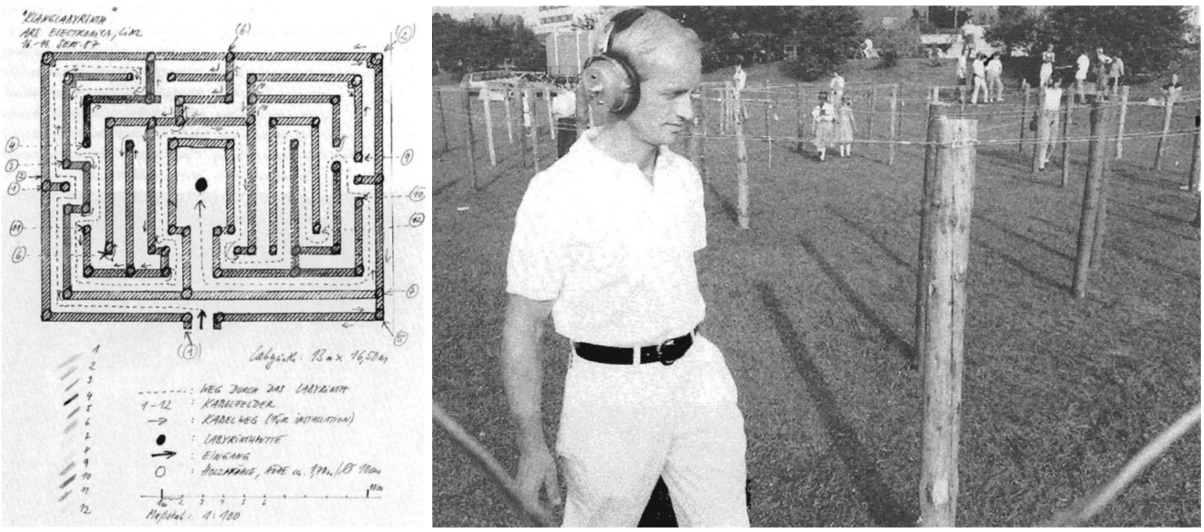

Figure 3.21. Christina Kubisch’s *Klanglabyrinth*: A graph of the work's configuration at Ars Electronica in 1987 (left), and a photo from the event (right) (from Kubisch, 2000).

Oase 2000, also from 1999, is another work in which Kubisch altered the environment through the use of sound recorded from a different site – a tactic frequently employed by sound artists, such as Bill Fontana, but also by film directors, such as Jacques Tatti. The piece was first shown inside the garden of the Heidelberg Kunstverein. While the landscape was idyllic - promoted to tourists as an oasis in the middle of the city - the site was sonically overtaken by the surrounding urban noise. Kubisch embedded a 16-channel composition in loops of yellow wire hanging down from the trees with the implied, yet missing, sound of the site: babbling brooks, birds from around the world, unprocessed field recordings from rainforests in Brazil, and sounds of forests at night (Gercke, 2000). The following year, a subsequent iteration of the work was exhibited on the balcony of Hayward Gallery, overlooking the urban horizon of South London (figure 3.22). Acknowledging the difference between the sites, the piece was given a subtitle - *Oasis 2000: Music for a Concrete Jungle*. Kubisch also adapted the layout of the cables to the new environment. Rather than falling down organically, they were taut diagonally across the balcony like power lines. The content of the 14-channel composition was very similar to the one in Heidelberg, but overall the piece produced a very different feeling. Listeners felt lifted away from London's 'concrete jungle' and transported to nature through sound which, for Kubisch, raised questions on the reality of our experience of space (Sonic Acts Academy, 2018). This would become a topic that Kubisch soon began tackling head on - although from the opposite starting point - with another series of works, her *Electrical Walks*: by tapping into the existing electromagnetic energies found on a site, and by using a process of 'audification' to directly transduce these non-sonic energy fluctuations into sound, she created environments that seemed artificially synthesized, but were actually produced by the site itself.

Figure 3.22. Christina Kubisch's *Oasis (2000): Music for a Concrete Jungle* at the Hayward Gallery in London 2000 (photo by Nicola Levinsky, from https://www.whitechapelgallery.org/events/david-toop-exhibition-histories/).

3.3.4 *Christina Kubisch's Electrical Walks*

The advent of various new technologies in the 1990s caused a rapid increase of electromagnetic radiation in urban spaces. These signals interfered with Kubisch's electrical drawings and, unable to filter out their sounds, she stopped working with induction and shifted her focus to solar energy and UV light as materials (Sonic Acts Academy, 2018). However this would soon change. In 1999, a new headphone system developed for a large commission revealed to her a completely unknown sound world, full of interesting noises and interferences: *"When I put on the headphones again after all these years, I heard so many strange sounds: humming sounds, rhythms, and all kinds of things that, of course, disturbed me, because I didn't want them"* (Cox & Kubisch, 2006) Her attitude towards these sounds shifted after a walk around Tokyo, wearing a pair of headphones with filtering circuitry removed (Sonic Acts Academy, 2018). Through this interface, the city revealed itself as a dynamic score, creating an ever-changing concert for her ears as she navigated it. This inspired a new approach and a new series of works, titled *Electrical Walks*: *"Eventually, I realized that I no longer needed to put my sounds in cables because they were already out there. So I built a new generation of headphones that are especially sensitive to electricity and that don't suppress or ignore all these electromagnetic fields but, instead, amplify them"* (Cox & Kubisch, 2006).

Her first *Electrical Walk* was presented in Cologne in 2004 as a test. Following positive responses she continued, producing a new headphone design the following year (Goethe-Institut Russland, 2007). Between 2004-2021 Kubisch has presented 84 *Electrical Walks* in numerous cities around the world (figure 3.23).[143] In these works, each audience member receives a pair of headphones and a map suggesting paths and places where they can encounter interesting electromagnetic emissions. *"The map for me is like a composition"*, says Kubisch (Sonic Acts Academy, 2018). With her headphones and maps, she provides a type of augmented reality experience that completely immerses the listener into a layer of the

[143] Cities in which Kubisch's *Electrical Walks* have been exhibited include: Cologne, Oxford, Berlin, Karlsruhe, Bremen, London, Haarlem, Birmingham, Riga, New York, Oldenburg, Kortrijk, Chicago, Krakow, Huddersfield, Mexico City, Montreal, Quebec, Poitiers, Darmstadt, Mailand, Copenhagen, Leeds, Recklinghausen, Gelsenkirchen, Dorsten, Marl, Oberhausen, Linz, Porto, Utrecht, Tallinn, Turku, Nancy, Dortmund, Krems an der Donau, Hong Kong, Basel, Kosice, Aarhus, Athens, Moscow, Brussels, Montpellier, Danzig, Vienna, Hamburg, Reykjavik, Aix-en-Provence, Bangkok, Lagos, Ystad, Vancouver, Manchester, Bordeaux, San Francisco, Ekaterinengurg. Münster, Lausanne, Brno, Rome, Shanghai, Saarbrücken, Amsterdam, Frankfurt, Oslo, Paris, Potsdam, Graz, Bonn, Gera, Zagreb. The work has been shown more than once in a few of these cities. For a list, see https://christinakubisch.de/electrical-walks/list-of-walks. For a long video with various explorations of different locations, see (Skulpturenmuseum Glaskasten Marl, 2010).

world that is always there, but to which we are oblivious without the headphones. Audiences realize that *“[n]othing looks the way it sounds. And nothing sounds the way it looks”* (Kubisch 2021). Cities are full of rich textures filling the entire audible spectrum, from very low to very high frequencies. Many of these sounds are surprisingly musical and even reminiscent of specific genres - as Kubisch says, some sound like chords, others remind her of LaMonte Young, or 1970s electronic music (Cox & Kubisch, 2006). She also notes that, while some sounds can be found across the globe - usually those emanating from security systems - there are also a lot of special sounds that give each city its own sonic character (Goethe-Institut Russland, 2007).

Figure 3.23. Experiencing Christina Kubisch’s *Electrical Walks* in Birmingham 2006: Audience member (left) and the artist holding a map of the work’s proposed trajectory (right) (photo by Ikon gallery).

The experience strongly relates to the growing genre of sound walks or audio walks, practiced by artists such as Janet Cardiff and George Bures Miller, Yolande Harris, Francisco López and many others. The biggest difference however, is that rather than using pre-composed material, Kubisch’s special headphones tap into signals already present. The sonic experience is created by the site itself, usually the urban environment of the city - although Kubisch has also created some walks indoors, such as in the ZKM museum in Karlsruhe.[144] The headphone interface allows discovering electromagnetic fields as found sound objects (which draws connections to the works of Alvin Lucier, John Cage, and Marcel Duchamp).

When composing a new walk, Kubisch starts with listening. For 2-3 days, she roams around the city exploring with her headphones, often at night and usually starting from a shopping district where she is bound to encounter many machines creating a dense layer of interesting sounds. She takes notes, writes down interesting places, and then creates a map with possible routes and specific places of interest (Cox & Kubisch, 2006). Some of the sound sources she finds most fascinating include (mentioned in Sonic Acts Academy, 2018, unless otherwise noted):

- Bank ATMs, a source of rich sounds that are often the same across the world as these machines are manufactured by a few large multinational companies. Kubisch recently noticed that there are less and less of these devices around, as plastic money has started taking over.[145]
- The sound of advertising equipment, and in particular light screens and LED screens, is another interesting source. Light screens tend to produce drone-like harmonic textures with many timbral components, reminiscent of analog synthesizer 'pad' sounds. Large light screens found in Asia are particularly rich and melodic, producing textural and harmonic changes as one walks around them. Newer LED screens, especially the larger ones, produce a characteristic sound very different than neon, with many high-pitched components in constant fluctuation generated by individual pixels changing color.
- Some of the most interesting sources she has encountered are anti-theft alarms used in store exits. These security gates produce pulsing rhythms, from simple beats to sophisticated textures, like at the Centre Pompidou, in Paris (Cox & Kubisch, 2006). In larger malls, where many of them line up, one can experience an orchestra of percussive sound generators.
- The sounds of wireless communication (WiFi, Bluetooth, GPS, and the familiar GSM chirping of mobile phones) are also ever-present, producing very digital sonorities - noisy, crunchy, granular and in constant motion, with rhythmical elements and irregular sounds.

[144] Kubisch mentions that the soundscape of the ZKM museum in Karlsruhe was particularly surprising as it involved listening to the sounds generated by the electronics of new media artworks from past decades, such as by Nam Jun Paik (Goethe-Institut Russland, 2007).

[145] ATMs have become even more scarce after the COVID-19 pandemic, particularly in Europe.

Sometimes the headphones will even capture broadcast radio stations. They also receive speech leaking from churches or other public buildings that are equipped with induction systems to accommodate hearing-impaired people, bringing in a vocal layer into the soundscape (Cox & Kubisch, 2006).

- Transportation is another interesting source, with train stations in particular brimming a variety of sounds, often with a local twist. Kubisch notes that French stations, for example, use a different electricity system which produces a techno-like pulsing beat not heard elsewhere. Subways and trams, particularly old ones from Eastern Europe, or old buses - like in Rig - have their own particularly musical character. Harbors also produce a variety of sounds with their security gates and ongoing wireless communication with ships.

Typically, Kubisch directs her audience to where money is located – shops and banks in the center of town – and to nexus points of transportation - train stations, subways, traffic lights (Goethe-Institut Russland, 2007). People usually experience the work on their own, walking around the city wearing her headphones and with a map of suggested paths. Nonetheless, Kubisch also likes to offer guided walks, leading small groups (of about 8 people) to explore together places beyond what her maps suggest (Sonic Acts Academy, 2018). As she notes, people often run around together when they see a potential source, investigating it with their own personal choreography. Observing video documentation of the work in various cities, one can easily notice that this choreography entails some behaviours that likely give pause to unsuspecting bystanders: people with large headphones walking inquisitively, approaching various electronic infrastructures with their ears to aurally scan them, moving their heads slowly, rocking back and forth, flocking together, etc.

One of Kubisch's goals with this series is to map out cities and continents, their electromagnetic fields and their sonorities (Cox & Kubisch, 2006). She has been recording her own walks since 2003 and has thus produced a large and still growing archive. There is an implied political and a - somewhat more explicit - ecological underlayer to the *Electrical Walks*, as Kubisch aims to point attention to the hidden noise of our infrastructure and the increasing electromagnetic smog generated by our technologies. Similarly to Murray Schaffer's *World Soundscape Project* – see (Truax, 2002) - her walks perform an ongoing investigation and registration of the electromagnetic soundscape of various cities, following its evolution through the years. As she comments, many of the sounds she heard early on have now disappeared, because old – mostly analog – equipment has been taken out of commission. Re-visiting a city years later invariably reveals a different soundscape due to updates in infrastructure and the establishment of new wireless communication technologies (Sonic Acts Academy, 2018).

Seth Kim-Cohen (2009) offers an interesting critique on Kubisch's *Electrical Walks* and how they are discussed, which I think provides a perspective that is worthwhile to consider. His critique is true to the spirit of his book (*In the blink of an ear: Toward a non-cochlear sonic art*), in which he brazenly highlights the importance of non-sonic components in shaping the experience of sonic artworks, and points out how often these components are completely ignored. First, he notes that *"[t]he service provided by Kubisch is not the one typically assigned to composers, painters, and poets, but rather that of scientists, educators, and whistle-blowers: to alert us to the presence of previously undisclosed facts"* (Kim-Cohen, 2009, 110). At the same time, he objects to the notion that the city can be revealed in its essence and as a complete body - its secret life laying bare in front of the audience - simply by translating its inaudible signals into sound. He believes this to be a fantasy that falls short because of an *"encoding problem"*: the work cannot offer insights on the message of the signals it captures, as *"the key that encodes these messages, first turning electrical/mechanical processes into voltage signals, is not the same as the key used to decode them as sound. The output of the process is in a different language, indeed a different informational paradigm, than the input."* (Ibid, 111). While he acknowledges that the *Electric Walks* do shed some light on the by-products of the city's inner working through their sonification of electromagnetic fields, he also questions what the use of the work's sounds actually is and what aesthetic values they can deliver. He posits that simply revealing the presence of a phenomenon and translating it to a different medium is not enough to provide an artistic experience. Moreover, he considers that presenting or discussing the work in a way that suggest this is where its value lays is problematic, particularly because *"these sounds, and the way they are presented, decline to engage the rich cultural, technical, social, ontological implications of their origins. It makes no sense to ignore the text of which they are part; to reject their inherent discursivity in favor of their blunt materiality"* (Ibid, 115). One can deduce that Kim-Cohen feels that the work only touches on the true meaning, function, and context of these signals in a superficial manner. Instead, he points to a number of seemingly ancillary elements of the work that, in his opinion, do more to reveal the real life of the city than its sound. This includes how sending an audience into an urban exploration highlights the dual private and public character of the city; how wearing Kubisch's large headphones unavoidably turns this audience into public space performers;

how the same headphones create an immersive sensation of isolation in that space; how the need to move in rather peculiar ways to interact with that immersive world of the work makes this audience self-aware about how they act. For Kim-Cohen this is where the aesthetic value of the work can be found, as these elements greatly connect with how we interface with the urban environment, how we behave in it, how we create our identities in it, and how we relate to others inhabiting it and to their own peculiar ways of being.

Apart from her installation works and her walks, Kubisch has also been using her recordings of electromagnetic landscapes for many years in fixed media compositions. Typically, she stitches these recordings together in a Digital Audio Workstation (Pro Tools) with minimal processing, such as pitch shifting and FFT filtering (Milani & Kubisch, 2009(. Recently, she also began using these sounds in mixed performance works, such as in a new piece in development for string quartet and electromagnetic recordings. She has also explored other installation formats. For instance, *The electromagnetic City*, a work exhibited in Tallinn gallery in 2011, is an archived version of her own walks in the city of Talin. Visitors are presented with many photographs from various locations mounted on a wall and a set of 'audio guide' devices like those found in museums. They can enter the number corresponding to a photo to listen to the sounds collected at a specific location (Goethe-Institut Russland, 2007). Since 2003 she has also returned to performing on stage, collaborating with musicians and dancers using her headphones and other electromagnetic transducers (such as a pair of devices shaped like toy tennis-rackets). When performing she scans induction cables, various types of electronic equipment and computers on stage, or she explores a building's hidden infrastructure as an instrument, often followed by a video camera recording her actions (Sonic Acts Academy, 2018).

In 2011 Kubisch initiated *Cloud*, a new series of installations whose title refers to *cloud computing*, and in which she brings together elements from her *Electrical Walks* and her *Electrical Drawings* (Ibid). The installations feature an imposing 3-dimensional cloud-like formation made from many meters of red or black cable hanging in the middle of an indoor space (figure 3.24).[146] Visitors can walk around this sculpture wearing Kubisch's signature headphones to listen to a multi-channel composition (consisting of 12 to 16 channels), with

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[146] A 2017 iteration in Berlin used 1500 meters of cable (Ars Electronica, 2017). Building up the installation first involves Kubisch shaping 12-14 smaller cloud modules with electrical wire, a process which takes her about 2-3 days. Then these clouds are mounted on a supporting structure that can withhold the weight of all the wiring. Once the piece is mounted, the cables are connected to media players, each playing back a layer of the composition (Sonic Acts Academy, 2018).

each channel containing different electromagnetic recordings from server farms and other sites where electricity is produced and data is processed. With the many iterations of this work, Kubisch aims to focus on the physical infrastructures behind online data storage, streaming services, and 'the Cloud' – huge server farms consuming massive amounts of electricity - all services that marketing-speak has promoted extensively as virtual and immaterial.

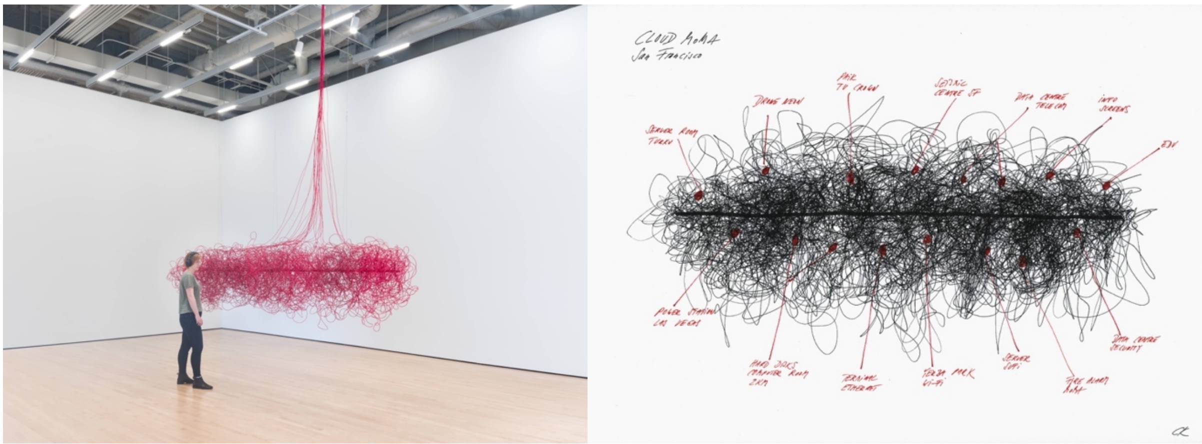

Figure 3.24. Christina Kubisch's *Cloud* at San Francisco MOMA: exhibition image (left) and schematic of where each of the 14 sound sources emanate from (right) (photo and graph by Christina Kubisch).

3.4 From the Theremin's Gestural Echoes to Electric Field Sensing

3.4.1 *Variations V: Multimodal sensing fields and intermedia networks*

In the second half of the 20th century, a handful of artists and engineers turned to the *Thereminvox* as a means to explore the concept behind Theremin's *Terpsitone*, i.e. using capacitative sensing to perform sound with full-body movement. This included John Cage who took a much more experimental approach than the inventor would had ever imagined. Cage had been a critic of the unoriginality with which the Theremin was being used already since his 1937 manifesto, titled *The Future of Music: Credo*. He wrote: *"Most inventors of electrical instruments have attempted to imitate eighteenth- and nineteenth-century instruments, just as early automobile designers copied the carriage (...) When Theremin provided an instrument with genuinely new possibilities, Thereministes did their utmost to make the instrument sound like some old instrument, giving it a sickeningly sweet vibrato, and performing on it, with difficulty, masterpieces from the past. Although the instrument is capable of a wide variety of sound qualities, obtained by the turning of a dial, Thereministes* *act as censors, giving the public those sounds they think the public will like. We are shielded from new sound experiences"* (Cage, 1973, 3-4).

In 1965, nearly three decades after that statement, Cage spearheaded *Variations V*, a groundbreaking work that deserves looking at closely particularly for its integration of radio-frequency sensing, movement and live electronics in an artistically adventurous setting that foreshadowed later developments. In many ways, this work forms part of the ancestral roots of my own *Hertzian Field* series, even though its influence is indirect. *Variations V* was a collaborative intermedia performance seeking to create a new type of immersive multisensory experience through the collision of several artforms, various media, and a copious amount of electronic equipment and new technologies - including an array of modified *Thereminvoxes*. This performance formed a further evolution of Cage's work in *intermedia* since the 1940s, such as his performances/happenings at Black Mountain College (1948 and 1952) in which different disciplines were combined without any of them being the centre; instead, each performer and artform constituted their own center. The concept of *intermedia* forms a counterpoint to that of the *Gesamtkunstwerk,* in that it is not concerned with creating a totality that combines all involved media together under a single plan, but instead in establishing a network of media in discussion with one another (Lista, 2000).

The work was influenced by Marshal McLuhan's media theory, in which he posited that electronic media are an extension of the human nervous system. Cage had read McLuhan's work and often spoken about his influence on him; they had also met in person (Ibid). With *Variations V*, Cage and his collaborators were particularly interested in exploring processes of translation between media. The goal was to create a network of relationships between sound, movement, image, as well as electromagnetic energies, with each medium depending on something beyond itself to produce content. At the center of this was a multi-modal sensing system that translated the actions of dancers into voltage and then sound; this was achieved through the use of light waves, radio waves, and sound waves. It is worth pointing out that electromagnetism in particular is a medium whose importance is generally underrepresented in discussions on *Variations V*. This is possibly because the work fell somewhat short of Cage's original planning in that regard (particularly in relation to its visual aspect, as will be demonstrated below), but more importantly because discussions on the artistic use of the hertzian/electromagnetic medium in general are much more limited than those of sound, video, or dance.

Variations V was initiated as an equal partnership between long-time collaborators John Cage and choreographer Merce Cunningham. The performance was commissioned by the French-American Festival in New York, who invited the two makers to produce something different than their usual collaborations (Miller, 2001). Cage and Cunningham, in their turn, invited a number of other collaborators to help them realize this work, each contributing with their own expertise and aesthetics. The team consisted of seven dancers (including Cunningham), five musicians manipulating electronics live on stage (including Cage and David Tudor), a light designer (Beverly Emmons), two video artists (Stan VanDerBeek and Nam Jun Paik) and several technology developers and technicians.[147] Led by Cage and Cunningham, the team worked together forming *"an intricate web of relations"* (Hoover, 2010, 66). Thematically, the content of the performance - its sounds, choreography and imagery - related to topics of everyday life in the US of the 1960s.[148] As a contemporary reviewer wrote, *“[i]n a sense, it was a monumental symphony of the visual and aural banalities of our age and as such was highly successful”* (Hughes, 1965a).

According to Cunningham, the piece came about when "*Cage decided to find out if there might not be ways that the sound could be affected by movement, and he and David Tudor proceeded to discover that there were”* (Cunningham quoted in Büscher, 2012, 9). Creating live sound in response to the choreography was the complete opposite approach of how Cage and Cunningham had collaborated until that moment. Having initially explored many possible relationships between music and dance, the two artists had decided in their past collaborations to completely separate the two media in the creation process to the point that, in their most recent work prior to *Variations V*, the dancers would not even hear the music until the premiere (Miller, 2001). Taking a complete turn, the connection of movement to sound through technology was at the center of *Variations V*.

The idea was to create a real-time interactive system that could sense the movement of dancers, using the resulting motion capture data to trigger, generate and modulate sound. Cage asked two brilliant engineers to help with this task. First, he invited Billy Klüver from Bell Labs.[149] Klüver and his assistants designed an optical system employing an array of ten

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147 The dancers of that performance were: Merce Cunningham, Carolyn Brown, Barbara Lloyd, Sandra Neels, Albert Reid, Peter Saul, and Gus Solomons. Cage was credited with the music with the musicians credited for ‘sound’ (the musicians’ names will be mentioned further below as the line-up changed in different performances). VanDerBeek was credited with the video.

148 Hoover argues that this also includes comments on environmental and ecological concerns of the time (Hoover 2010).

149 Billy Klüver’s role in connecting arts and technology in that period has been very significant. Five years earlier, he had helped Jean Tinguely build a machine that destroyed itself for the artist’s piece *Homage to New York.* Soon after *Variations V*, he would initiate *Experiments in Art and Technology* (E.A.T), a platform for

photocells that could be used to sense movement. A light beam was pointed at each of them so that whenever a dancer's body blocked it a trigger would be produced that was used to control tape players and short-wave radio receivers. After Tudor's suggestion, synthesizer designer Robert Moog was then invited to develop another sensing system based on radio waves (Lista, 2000). Moog had been building his own Theremin variant for over a decade and thus developed a system based on modified Theremins to create a large sensing field. In the work's premiere, twelve 1.5m tall antennas were dispersed on stage - *"a sparse forest of electronic spears that could be activated by the movement of dancers"* (Hughes 1965b).[150] Each of the antennas generated a sensing sphere with a diameter of almost 2.5m (Glinsky, 2000 and Miller, 2001). Given that the dancers needed to be free to move on stage and only at times had to orbit around specific sensing antennas, this design was much closer to the *Theremin* than the *Terpsitone*, on whose platform the dancer was confined (it is also plausible that neither Moog nor Cage were aware of the existence of the rather obscure *Terpsitone*). Unlike the original *Theremin*, these twelve instruments did not produce sound directly but generated voltages that could be further mixed, manipulated, and used to control a variety of sonic parameters beyond simply the pitch and volume of an oscillator. This was a decision made by Cage and Tudor so as to avoid making the connection between sound and movement too direct (Lista, 2000). Essentially, the *Theremin* antennas were control interfaces rather than synthesizers. This allowed for much more flexibility, and created a system that could be performed collectively by the dancers and musicians.

Accompanying these radio- and light-based sensing systems for capturing the dancers' actions and connecting them to sonic events, the work also deployed sound as a third sensing modality. This was achieved by using a number of contact microphones - a type of device that Cage was very fond of and which he used in numerous of his works. The choreography made it impossible to attach such mics to the dancers, so those were instead fixed to various objects on stage with which the dancers interacted throughout the work – such as a plant and pots, a table, two chairs, and a towel.

Despite this intricate multi-modal interactive system, the dancers had no real agency in the actual sound produced in the work. As Cunningham remarked, the dancers' role was not to

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bringing together artists and scientists. E.A.T. was initiated following the landmark event *9 Evenings: Theatre and Engineering,* which took place in October 1966 and which was initiated by Klüver and Robert Rauschenberg.

150 While performances in the US used twelve such antennas, only six were used in the subsequent European tour of the work (Hoover, 2010).

make sounds audible to the audience, but to make them available to the musicians (Lista, 2000). In his own words: *"The general principle as far as I was concerned was like the doors automatically opening when you enter a supermarket. The dancers triggered some of the sound possibilities, but the kind of sound, how long it might last, the possible repetition or delaying of it, was controlled by the musicians and technicians who were at the numerous machines on a platform behind and above the dance space"* (Cunningham quoted in Chadabe, 1997, 82).

In *Variations V* music was the result of a complex and collaborative system in motion. This made the connection between movement and sound rather opaque for performers and spectators alike. Moreover, there were so many sonic layers that any cause-and-effect connections between the two were drowned (Lista, 2000). Each performer could influence sound but no one could truly control it, a statement true not only for the dancers but also for the musicians. The musicians sat on one edge of the stage before a long table that featured an overflow of cables and an abundance of audio equipment.[151] This included an array of magnetic tape players and shortwave radios, oscillators and electronic percussion designed by Moog, and a special 50-channel mixer built by Max Mathews and Phil Giordano at Bell Labs for a recent piece by Cage.[152]

The magnetic tapes contained material prepared by Cage in advance with many of the recordings featuring sounds from nature, such as birds, insects, animals (Hoover, 2010). These tapes formed a sonic parallel to nature-based imagery of the video, and to actions related to nature present in the choreography. On the other hand, the sound of short-wave receivers opened a sonic window to everyday pop-culture, which formed another thematic pillar of the work. Cage was very fond of broadcast radio for a number of reasons and had included it in many of his works (14 in total).[153] In one of his most famous such pieces, *Imaginary Landscape No. 4* from 1951*,* he had used radio as a tool for removing his personal stamp of authorship, handling authorship of the work's content to the collective hands of humanity that are responsible for creating mass culture (Pagnutti, 2013). Essentially, through

[151] Cunningham mentions that they were seated on a platform behind and above the stage, although in the filmed version of the work the musician's table is on the stage floor in front of the dancers.

[152] The use of oscillators is mentioned by Cunningham (Chadabe, 1997, 82) and the use of electronic percussion by Lista (Lista, 2000). A number of devices that look like oscillators - and possibly filters – are also visible in the film of the performance. In regard to the mixer, Mathews reported to Miller that he gifted it following the performance of that previous work to Cage *"in the hope that I would never see it again"* (Mathews, quoted in Miller, 2001, 551).

[153] The first work of his to use radio was C*redo in US* from 1942, originally composed to accompany a dance performance by Merce Cunningham and Jean Erdman.

broadcast radio, Cage was opening the artistic process to a collaboration with the world at large (although one could argue that he was also handing over part of the creative result to those who control what the radio stations are broadcasting). Moreover, by tapping into the radioscape as a sound source, each performance of such works became time- and site-specific – *specificity* being a concept explored by many artists at the time. Cage also used radio as a generator of sonic unpredictability, that interjected – and interfered – with musical content that was outside of the control of the composer and the performers. Nonetheless, his interest in the medium was not limited to such conceptually heavy ideas but extended to the rich universe of noises present in the short-wave band and to the radio's potential as an instrument. His fascination with the sound of radio had already been documented in his 1937 manifesto, where he commented that the *"[s]tatic between the stations"* is an integral part of the noise that surrounds us, suggesting it is not disturbing but actually fascinating if we listen to it carefully (Cage, 1937/1973, 3). He had also proposed that, with the right technology these sounds can be used *"not as sound effects but as musical instruments"* in their own right (ibid). Lastly – in what is likely a significant reason for the inclusion of both broadcast radio and a radio-based sensing system in this work - Cage was also captivated by the fact that radio waves are constantly surrounding around us, even though they remain unnoticed. For Cage, electromagnetism was another form of energy that artists could tap into in their exploration of our universe. This is evident from a widely quoted response to fellow composer Morton Feldman in a radio conversation from the following year: *"but all that radio is, Morty, is making audible to your ears what was already in the air and available to your ears, but you couldn't hear it. (...) In other words, all it is which you're already in. You are bathed in radio"* (John Cage 1966, quoted in Kahn, 2013, 117).[154]

During the premiere, composer-performers James Tenney, Malcolm Goldstein, and Fredric Lieberman mixed multiple sources to produce up to 50 separate channels of sound material by improvising.[155] [156] As Tenney recollects, *"Cage had come to terms with free improvisation (though he didn't like that word) as long as it was done by people sympathetic*

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[154] The idea of exploring these energies that surround us became central to a following work by Cage from 1966, *Variations VII,* which was concerned with *"catching sounds from air as though with nets, not throwing out however the unlistenable ones . . . making audible what is otherwise silence therefore no interposition of intention. Just facilitating reception."* (John Cage from his notes on the work, quoted in Kahn, 2013, 116).

[155] Lista mentions that there were 96 sound sources, likely following Cage's references to that number (Lista, 2000). However, Miller confidently suggests this is erroneous and there were only 50 sound sources (Miller, 2001).

[156] Tenney's and Goldstein's instrumentarium was limited to tape players, while Lieberman had 12 tape players and 12 radios at his disposal. He performed the radios using his own precomposed, chance-based score that was similar in concept to Cage's score for *Imaginary Landscape No. 4.* (Miller, 2001).

to his aesthetic aims" (quoted in Miller, 2001, 553). In the role of cybernetic pilots, John Cage and David Tudor manned Mathews' mixer, selecting, amplifying, transforming, mixing and diffusing sounds in real time.

The result was an immersive soundscape projected through six loudspeakers that surrounded the hall and the audience.[157] Lista describes it as *"[a] kind of collage-like effect between music and voices, between 'abstract' and 'concrete' sounds"* (Lista, 2000, 109). To my ears, the sound of the filmed performance feels very familiar, reminding me of many of the improvised experimental electronic music shows that I have attended throughout the years (for the complete film, see Chloe, 2020). Naturally, *Variations V* predated those shows by decades, undoubtedly contributing indirectly to their aesthetics either through the influence of the work itself or, more decisively, the influence of the oeuvre of Cage, Tudor, and Mumma who were the musicians on that performance to generations of future musicians. The soundworld combines many different types of sonorities: from noisy textures (often filtered) that are present throughout the performance, to frequently appearing oscillator sounds (high-pitched tones, bleeps, bloops, buzzes and glissandi), to brief drones and the whines of what may be feedback-generated Larsen tones. Field recordings from both urban environments (e.g. what sounds like a jackhammer) and nature (e.g. cicadas or bird song) are audible in the soundscape a number of times. There are several appearances of monophonic rhythmic percussion throughout the work (sometimes with a distinctly 'woody' sound) whose unexpectedly straight-forward rhythmicality makes them pop out from the rest of the music. It is worth noting that the dancers do not synchronize to these rhythms, which is of course on character for a Cage-Cunningham collaboration. There are also the occasional sounds of acoustic instruments (such as piano, strings, and maybe brass) - mostly cut-up, abstracted, or processed.[158] In one occasion there's a surprisingly present tonal snippet of 19th century piano music; less audible snippets of tonal music are interspersed throughout the work. Spoken and sung voices also sporadically emerge. Although it is very hard to notice any direct connection between movement and sound, at times one can nearly distinguish sounds produced by the actions of dancers picked up by the contact mics. Overall, the music consists of rather thick textures and is devoid of any fast or dramatic changes in density or sonority. Nonetheless, the texture does thin out at times, especially in the last 3rd of the work, and the sonorities are in a

[157] Only 4 loudspeakers were used in the European tour of the work (Miller, 2001).

[158] This material most likely came from recordings of New York Philharmonic musicians for an earlier work (Miller, 2001). Attaching contact mics to the string instruments was a contentious process that was exacerbated by Leonard Bernstein's initial *"dismissive attitude"* (Ibid, 550).

state of constant flux. The many different qualities of sound are generally interspersed throughout the performance without giving the sense of a deliberate progression from one type of texture to another. The music feels largely improvised and I can imagine that every performance must have sounded quite different on a microscopic level, but at the same time rather similar from a birds-eye-view. The piece did not have a fixed duration; the premiere lasted around 45 minutes and the film version around 40.

As opposed to his previous works, Cage only wrote the score for the work after its premiere – but before most other shows - between September-October 1965.[159] Cage's score does not contain any standard notation. Subtitled *Thirty-Seven Remarks*, it instead consists of annotations regarding particular elements, from technical aspects to aesthetic intentions. This includes specifying the type of media to use in particular sections (e.g. film, certain configurations of radios and tapes), ways to generate sound (e.g. from the dancers' movement), how to scan the radio spectrum (e.g. asking operators to be selective and favour non-referential sounds), or what the state of mind of the performer should be (e.g. "*irrelevance," "adapt to circumstances," "non-focused"*) (quoted in Miller, 2001, 554). In the score, Cage also attempted to free the performers' minds from the anxiety of uncertainty and potential equipment failure, instructing them to: *"Accept leakage, feedback, etc (...) Adapt to physical circumstances; procrastination, mistakes"* (Ibid).

Sound was accompanied by large video projections acting as the background or sometimes foreground for the dancers (Electronic Arts Intermix, n.d.). The New York premiere featured one large screen whereas the European tour of the work also included multiple smaller screens of different sizes distributed on stage (Hoover 2010) (figure 3.25). In the documented performance of the work (filmed in Germany) there are several projections with their images moving in and out of the various screens. The lighting also makes it so that the dancers occasionally cast shadows on these screens, creating a form of negative projection (see Chloe, 2020). Similarly to the music, the video produced the effect of *a "gigantic collage in motion"* (Lista, 2000, 106).

Variations V was Cage's first work to include a cinematographic component. Originally, the idea was to have multiple camera operators circulating the stage to capture fragments of the choreography in real time. This footage would then be processed, mixed, and projected on

[159] Cage initially thought he should produce a score in advance, but after trying some ideas out with Tenney they decided there was no need for that (Miller, 2001).

multiple screens (Ibid).[160] Placing multiple projections around the stage paralleled the principle of an immersive sonic environment enveloping both stage and audience that Cage was interested in creating with this work. These ideas also related to the new experimental form of *expanded cinema* which was being developed by several other artists at the time. VanDerBeek was particularly interested in this field and in the process of instantaneous mediation of reality, finding it to be *"a unique theatrical tool for dance-drama-ritual - opening the walls of the stage-space with virtual-images, new visions of scale - and transparencies"* (VanDerBeek, 1967, 30). For VanDerBeek the dialogue between body and new technologies was based more on the idea of a reality multiplied and transfigured live by the medium. (Lista, 2000). He wrote that *"cinema and dance-theatre are diagrams for reality / life-magic-theatre, a means to take the pieces of experience…and assemble them into resemblances of life / life…looking…at life"*. (VanDerBeek, 1967, 30).[161]

Figure 3.25. Photo from a performance of *Variations V* in Hamburg, August 1966. In the foreground operating the electronics from left to right are John Cage, David Tudor and Gordon Mumma. In the background, Barbara Lloyd and Merce Cunningham can be seen dancing in front of a theremin antenna (photo by Hervé Gloaguen, from Lista, 2000).

[160] Cage only achieved including such live cinematography in another piece in collaboration with Cunningham a few years later, *TV Rerun* (1972), which involved live video (by Jaspers Jones) and data capture of dancers' movement with accelerometers (by Gordon Mumma).

[161] With his approach to video VanDerBeek aimed to bypass logical comprehension and reach the layers of the unconscious and the non-verbal denominator of what makes us human (Lista, 2000).

Overall, the team started with the ambition to create a symmetry of sorts in regard to the relationship between different media: for instance, just like the dancers influenced sound, sound could be used to alter the live video of the choreography (Lista, 2000). Or, video could be used to affect sound: in the score for the work, Cage introduces the idea of placing photocells on the screen, thus making it possible for the image to influence the music. Nonetheless, this was never realized in any of the work's performances.

The electromagnetic medium was meant to have a similar role in this network of media, establishing complex relationships between sound, image, and movement. In this spirit, Nam Jun Paik's involvement in the work was related to the electromagnetic techniques for processing TV signals that he was developing at the time. In several pioneering works from 1963 that contributed to launching video art as a discipline, Paik had experimented with various methods of producing and modulating analog television signals, including using audio signal generators or radio signals (Kang, 1988 and Daniels, 2004b). More pertinently, he had also discovered that he could distort TV images in radical ways by using a strong magnet. This was a profoundly innovative effect for art, even though it was not unknown to technicians. As Paik noted, *"many millions of engineers knew that you could distort TV signals with a magnet; millions knew it, but no one did it. They were trained never to question the source material"* (Paik quoted in Davis, 1973, 152). One of Paik's works featuring this technique was the iconic *Magnet TV,* from 1965*:* a black and white receiver with a heavy industrial horseshoe magnet on it (borrowed from Klüver and Bell Labs) that produced a complex blue-colored geometric form on the screen.[162] This form was the result of the magnet's interference on the receiver's electromagnetic field, with the external force bending the geometry of the receiver's scan lines. The resulting geometry could be changed interactively by moving the magnet. Interestingly, Paik had initially placed the magnet in front of the TV, and it was one of the visitors that first put it on top of it (Kang, 1988). In Paik's own words, *"my most famous work was not done by myself; somebody in the crowd did it."* (quoted in Davis, 1973, 149).

The plan was for Paik to use this type of processing during the performance. In a letter to Cage he proposed using a specific projector model for *Variations V* with which he had successfully experimented (Lista, 200). This electromagnetic modulation system for video would provide a form of interaction between the hertzian medium and the image that echoed

[162] An image of the work can be accessed here: https://whitney.org/collection/works/6139. Last accessed 7 April 2022.

the relationship between sound and the hertzian established through the use of radio receivers and, more importantly, through the use of the *Theremin*-based sensing system. Unfortunately, however, budget considerations prevented including this projector in the production (Ibid). Paik's role was thus limited to using his electromagnetic video processing methods to prepare fixed video material for the work.

In the end, there was no live camera work, no live electromagnetic processing of video, nor any form of sensor-based or other technological interaction between the video and other elements of the performance.[163] Any connections were established purely through the iconography. The video consisted of static and moving images from a variety of sources provided by VanDerBeek. It combined urban shots and imagery from nature (such as landscapes, trees, animals, rocks, etc, most often without any humans in it), maps, drawings and animation, imagery from pop culture and everyday life with snippets taken from American TV and Hollywood films (including shots of fishing, cooking, factory work, construction work, and dance passages from a musical comedy), and abstracted footage from the dancers' rehearsals. Overall, VanDerBeek's material aimed to contextualize the work's choreographic language "*outside of its kinetic immediacy as an image of movement among many"* (Electronic Arts Intermix, n.d.)

This collage of figurative footage by VanDerBeek formed a counterpoint with the abstracted and distorted images produced by Nam June Paik. Their mix produced an *"intersection of multiple semantic codes"* that *"result[ed] in a destabilizing telescoping of still and moving images"* (Lista, 2000, 109).[164] VanDerBeek selected the order of the images prior to the performance. Nonetheless, this did not necessarily mean that the video played from beginning to end like a film. The film documentation of the performance shows someone (possibly the light designer) operating a film projector, which suggests there might be some control over what happens and when (Hoover, 2010).

Just like the visual and sonic components, the choreography also involved several layers that enabled Cunningham to play with densities that ranged from one dancer occupying the stage alone to a multiplicity of actions happening simultaneously. The dancers formed solos, duos, trios or larger ensembles, which at times operated independently and often shared a

[163] It is interesting to note that the film version of *Variations V* makes use of some of the ideas that did not make it into the performance. For example, it often superimposes one or more layers from Paik and VanDerBeek's images, or even from the performance itself to the camera footage of the performance. Towards the end there is also some processing applied to those shots.
[164] Quote translated from French.

movement vocabulary, at times acted contrapuntally, and at times seemed unrelated to one another. The movement language varied, occupying a wide spectrum of contemporary dance that ranged from more ballet-influenced movement, to various forms of pure contemporary dance, to warm-up exercises dancers perform when they train, to yoga-influenced sequences, to more pedestrian everyday actions that would feel at home in a happening – all filtered through Cunningham's aesthetics. This included several of what the choreographer called "'*non-dance' activities",* many of which established relationships to everyday life and nature or environmentalism (quoted in Electronic Arts Intermix, n.d.).[165] For example, the piece began with a 'prosaic' action of Cunningham entering while carrying a plastic plant, removing its leaves (all of which were mic'ed), then putting them back on, potting the plant in a pot that another dancer later smashed before repotting it again, and then having other dancers manipulate it (most of this while other actions were also happening on stage). The relationship to the quotidian and the sense of multiplicity was also echoed in the costume design, with dancers changing frequently between rehearsal attire and normal everyday clothes.

Cunningham viewed the use of the interactive sound-producing system not as much as a comment on technology being an extension of man, as an extension of theater into the direction towards which society was heading (Lista 2000). This is perhaps evidenced by the fact that the relationship between choreography and its surroundings was for the most part ambiguous. Throughout most of the performance the dancers seemed to not particularly acknowledge the sensors on stage. There were however some exceptions, such as a canon-like ensemble sequence in which the dancers lined up and went to perform the same routine one after the other, deliberately slaloming around the antennas. This was followed by a duo between Cunningham and Barbara Lloyd in which they wrapped their arms around an antenna. In the closing sequence, Cunningham biked across the whole stage slaloming around the antennas, as if to give the audience a sense of how this trajectory impacted the soundscape.[166] Nonetheless, the various sensors and mic'ed objects were taken seriously into

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[165] For the relationships of Variations V to environmentalism see (Hoover, 2010).

[166] There were a few other instances of direct integrations of technology to choreography, such as a duo in which a dancer appears to perform a combination between auscultation and clothes-fitting on another dancer using a contact mic connected to the system, or a dancer performing a headstand on a mic'ed up towel. Lista (2000) also considers a reference to technology a section in which dancers stretch between them what she identifies as cables or a strip of magnetic tape. Nonetheless, this material does not appear to be connected to any electronics. According to Electronic Arts Intermix (n.d) the dancers were actually pulling out a spool of white thread, a gesture which *"cites Duchamp's 1942 installation, Mile of String, in which he made an unwieldy web of string throughout a Surrealist painting exhibition restricting the movement of exhibition-goers."* Another

consideration in Cunningham's choreography, with the dancers' actions and the placement of these actions centered not only on movement but also on the production of sound. This included handling various objects equipped with contact mics, or moving near or around the sensing antennas. As one of the dancers said, the idea was that *"movement was stimulated by factors outside the body"*, following Cunningham's *"appetite for exploring the reasons why movement arises"*. (Barbara Dilley quoted in Miller, 2001, 555).

The sensitivity of Moog's electrical fields matched well with Cunningham's attention to precision, detail, and total control of the body that was concerned with even the tiniest of movements.[167] The choreography was simultaneously fairly open but quite detailed and specific; Cunningham had a particular vision on the movement language, which he wanted the dancers to execute with precision and clarity (Hoover, 2010). Even though the dancer's movements could appear to consist of random events to the viewer, their vocabulary was tightly composed. In the end sequence, for instance (titled 'Aerial Sweeps' and lasting about 2 minutes), Cunningham *"outlined a specific order in which the dancers gathered together, dispersed in movements, regrouped, and moved across the stage in repetition"* (Ibid, 67). As is evidenced by his notes and accompanying diagrams, he notated specific trajectories in space for each dancer to follow, together with a simple set of movements that everyone was to execute in sequence and repeat four times (see Hoover, 2010, 68-69 for diagrams).

Variations V premiered in New York, at the Lincoln Center for the Performing Arts on July 23rd 1965. It then went on European and US tours where it was performed 30 times in total between 1965-1968 (Miller, 2001).[168] The piece was a major technological undertaking for the time, and was produced with less funds, preparation, and setup time than it required. Klüver's photocells, for example, demanded a last-minute change of placement during the premiere. While the initial plan was to install them on the sides of the stage, there was not enough light there because the light designer had not been informed about their placement.

Duchampian reference may be found in the final scene, Cunningham riding a bicycle - this time to Duchamp's first readymade, the bicycle wheel. For Lista, this may also be a somewhat ironic or post-dadaist reference on McLuhan's discussion of the wheel as a simple technological extension of the body.

[167] Miller mentions two interesting anecdotes: Gus Solomons being frustrated at his inability to execute a *"tiny hip movement the way Cunningham wanted it done"* and that *"[a]t one point [Cunningham] merely wiggled Carolyn Brown's toes in and out of the field of one of Moog's antennas"* (Miller, 2001, 555-556).

[168] The European tour featured a somewhat smaller setup, but there were still many challenges with traveling with all that equipment as the piece was not initially conceived for touring. For the most part, Cage and Tudor were the only music performers in the tour. Gordon Mumma was invited for the piece's filming by the Norddeutscher Rundfunk.

They thus had to be eventually attached to the base of the *theremin* antennas.[169] Moog also spent part of the dress rehearsal troubleshooting and re-soldering failing circuits. While he claimed that everything functioned correctly during the performance, some of the performers were unsure of that (Miller, 2001). This was possibly because the system was in fact so complex that identifying clear relationships between sound and movement with so few rehearsals was near impossible.

The response in the US was ranged from enthusiastic, to perplexed, to downright hostile. A Sunday Times reviewer wrote: *"Mr. Cage has discovered a new way for dancers to obtain original music to accompany their works. They can compose it themselves while performing. (...) When Merce Cunningham, or one of the members of his company, danced past a spear, a sound source (or, perhaps, a group of sound sources) began to hum, buzz, beep, scratch, whistle or whir in one of several speakers distributed around Philharmonic Hall.(...) Mr. Cage and Mr. Cunningham may have given us a fascinating, if extremely primitive, glimpse into an extraordinary theater of the future. This would be a theater in which dance (possibly drama), music, scenery and, certainly lighting, could be created simultaneously in the process of performance"* (Hughes, 1965b). Outside of New York, reviewers were not as positive: the piece was judged to be *"an assault and battery to the senses"*, though with *"some interesting bruises"*; a demonstration of how *"eight people can baffle, confuse and annoy 800 others"* by using the noises of everyday (meaningless sounds, images, and gestures); and a work with which Cunningham and Cage were*"not only breaking fresh ground but breaking fresh eardrums"* (Miller, 2001, 557-558). Nevertheless, as another reviewer pointed out about the work, *"[t]here may have been some few who did not like it, but they will never forget it",* likening it to a "*drugless (...) [p]sychedelic experience"* that was impossible to be bored from (Ibid, 561-562). Regardless of the contemporary responses, and the many technical setbacks and imperfections of the performances, the conceptual and technological innovation of *Variations V*, combined with the undoubtable prominence of its makers, placed this work firmly within the cannon of contemporary performance and multimedia. It also opened up the path for the use of motion sensing as a creative strategy for connecting dance/movement to other media. All in all, *Variations V* should be considered a

[169] Cunningham's lighting designer commented: *"That a project in which technical equipment was so central to the concept of the work and yet so untried should be left to the day of the piece to be put together was wildly naive".* (Miller, 2001, 555)

landmark work for a number of different niches of the contemporary arts. [170]

3.4.2 *Re-inventing the Terpsitone in Australia: Philippa Cullen*

In 1969, the publication of a theremin circuit in *Electronics Australia* led to some interesting, though fairly unknown, artistic experiments that continued on the path of the intermedial *Variations V* and Leon Theremin's multimodal 'radio vision'. That same year, *The Optronic Kinetics* trio (David Smith, Jim McDonnell, Kaz Kondziolka) built an interactive installation at the Sydney University Fine Arts workshop using a theremin with a modified antenna - a long wire strung around the walls of a shed (Jones, 2004a and Jones, 2004b). The antenna created a radio field surrounding the room, rendering its entire area reactive. The theremin's sinusoidal signal was used to create Lissajous patterns on a TV screen, as well as to control the speed of a spinning color-wheel in front of the screen. The sound and visual patterns thus changed with movement, and different configurations and positioning of bodies within the room.

One of the visitors to the installation was Philippa Cullen (1950-1975), a young Australian dancer. Cullen was inspired by the possibilities offered by "*a device which switched the relation of movement and sound; now the dancer could create music*". (From Cullen's notebook, quoted in Jones 2004b, 67). She thus asked the group to build a long-wire antenna theremin for her. A year later, in 1970, she presented the piece *Electronic Aspects* for 9 dancers and this instrument. While she was excited about the possibilities of this technology, she found the instrument's simple sonorities rather uninteresting. As a result, in her two following works (created in 1971-1972) she turned to voice as the medium with which the dancer generates sound. During that time, Cullen deepened her relationship to music. She began working with avant-guard music improvisers, became familiar with works by John Cage and others contemporary composers - but also with the intricacies of music technologies.

In the beginning of 1972, *Philippa's Electronic Dance Ensemble* was founded by Cullen, several dancers, a composer, and an engineer. The goal was to discover *"a new medium in which dance is inseparable with technology, music and lighting"* (quoted in Jones 2004b,

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[170] After this piece, Cage led more multimedia productions operating a similar vein in the second half of the 1960s. This includes *Variations VII* (1966), in which he used TVs, radios, telephones and contact mics probing the bodies of performers (not dancers). In *TV Dinner* (1967), a piece also featuring Cunningham, VanDerBeek, and Billy Klüver together with poet Robert Creely and filmmaker Len Lye, was a happening that culminated in a dinner being served on stage, with amplified tables and dishes, in which the goal was to also incorporate the senses of taste and smell as part of the audience's multimedia experience.

66).[171] It had been suggested to Cullen that, in order to improve the theremin's 'musical capacity', she should convert its output to voltage so that it could control external synthesizers. The ensemble got access to two EMS VCS3 synthesizers and set off to explore the relationships between sound and movement afforded by the Theremin principle. Each synthesizer was connected to two theremins, one controlling pitch and the other a different parameter. An architecture student designed various types of large antennas to experiment with: vertical and horizontal loops, at times with highly complex - and hard to interact with – fields, an upright S-shaped surface, and other shapes. A more successful design was discovered by accident: a circular pedestal, resembling very much the Terpsitone's square platform (figure 3.26). Using this system, the ensemble performed a new piece at Sydney University in July of the same year (figure 3.27).

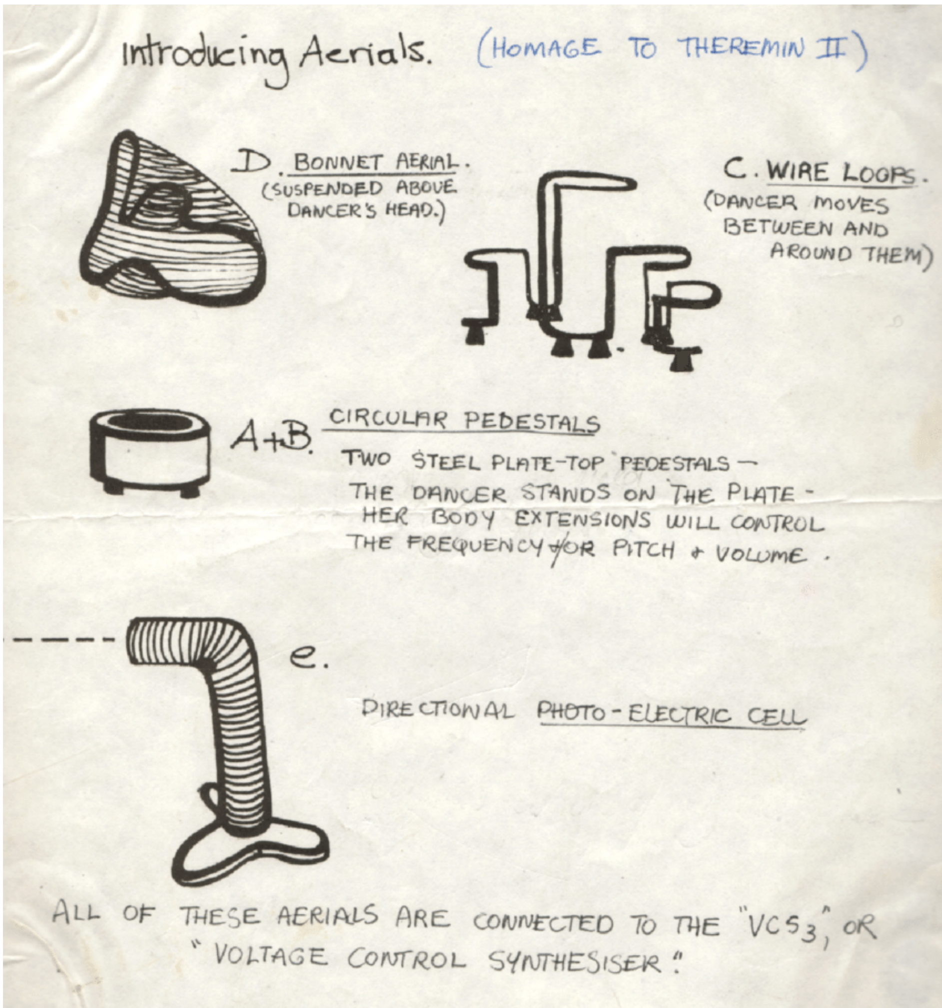

Figure 3.26. Drawings of four different antennas and a photoelectric sensor for Philippa Cullen's work *Homage to Theremin II* by architecture student Manuel Nobleza (from Jones, 2004b).

[171] Original text from a 1971 funding bid to the Australian Council for the Arts to form the company.

Figure 3.27. Philippa Cullen rehearsing the work *Homage to Theremin II* in 1972, featuring theremin antennas designed by Nobleza (left photo by Alex Osonis, right photo by Lillian Kristall; from Galasch, 2016).

However, as Cullen remarked, the 3-month rehearsal period was not long enough for dancers to familiarize themselves with the system and its intricate, but invisible, radio spaces. I find this reflection by her, a dancer, particularly interesting. It certainly aligned with my own observation of the dancers I workshopped with being at the same time very intrigued and somewhat alienated and out of their comfort zone when interacting with the radio-sonic space of *Hertzian Field #1,* as it altered the intricate relationship to physical space that they have worked painstakingly to develop through years of dance training. Granted, they had much shorter periods to experiment with my sensing system than Cullen's team - a few hours or a few days. Returning to Cullen, in 1973 she reflected on the matter: *"Now there has been discovered a number of electronic devices which can transform human movement into different forms of energy. The detection is through radar, light intensity or a change in the electro-magnetic field around the dancer. The energy released can be converted into sound. Thus, the dancer can make his own music. But whether this discovery is taken up by the dance world depends on our readiness for this reversal of the elements and whether dancers are skilled enough to make music and whether they should be producing recognisable musical structures. (...) I have for the last three years worked with these new electronic media which I have developed into body instruments. Just as the use of new material of prefabricated concrete changed the shape of the building and the life of the people inside, so I found that the use of electronics changed my concept of dance and my values for dancers."*

(quoted in Jones, 2004b). *172*

Cullen moved to Europe to continue her studies in 1972. Initially she could not find anyone combining dance with electronic sensing but eventually she met David Tudor and Gordon Mumma in London who understood her work. Soon thereafter she went to the Netherlands to study at the Sonology Institute, then in Utrecht. She also became involved with the Studio for Electro Instrumental Music in Amsterdam (STEIM). After completing the Sonology Course she went to Germany to work with Stockhausen, whom she had met in Australia in 1970. She returned to Australia in 1974, giving workshops, seminars, and demonstrations. In Cullen's short career, she pioneered interactive dance and in particular composing relationships between sound and movement. Besides Theremin-based systems, she employed photocells, biofeedback sensors, and pressure-sensitive floors to generate audio and video.[173] Unfortunately, her work was cut short by an untimely death in 1975.

3.4.3 *Re-inventing the Terpsitone then creating an interactive sound art practice: Liz Phillips*

Around the same time in the US, another young artist, Liz Phillips, started exploring the potential of capacitative fields for translating movement into sound. Phillips was trained as a sculptor, but her interest had quickly moved beyond objects to the empty *negative space* surrounding them, and to how audiences navigate that space to experience sculpture (Phillips & Rabinowitz, 2006). Around 1970, she began creating systems for 'sculpting' that empty space, turning to sound as *"a way to describe activity"*. (Eppley & Phillips, 2016). This resulted in her practice shifting to interactive sound art and interactive multimedia installations. Phillips is a pioneer of these established art practices, but more pertinently also a trailblazer in the development of a modality of hertzian art exploring the spatiality of radio and its physical interaction with the human body. Her work extends over decades and includes numerous interactive works using capacitative sensing to control sound, as well as many works using other sensing technologies, such as ultrasound and infrared.

In 1970, as a 19-year old college student in Vermont, Phillips created her first work with radio-field capacitative sensing, titled *Sound structures,* with which she aimed to explore *"how space becomes tangible for the audience"* (Phillips, 2009). She had long been intrigued

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[172] Original text from: Philippa Cullen, "Towards a Philosophy of Dance," privately published in June 1973.

[173] In 1975, Cullen showcased her last performance system, developed in collaboration with engineers. It deployed a pressure sensitive floor connected to a PDP-11/40 computer to generate live video from the dancer's movements. The music in the piece she presented was pre-composed (Jones 2004b).

by the mechanism with which her body interfered with the signals of her family's analog television, as well as by the thereminvox's principle of operation (Eppley & Phillips, 2016). She had also become knowledgeable on electronics and radio technology through years of tinkering. Her capacity to build her own circuits enabled her to experiment in an innovative manner. This was aided by a few productive residencies and collaborations that helped further her practice. In 1970 she had an artist assistantship at MIT Center for Advanced Visual Studies, and the following year she was artist in residence at the Riverside Research Institute (NY) which was involved in defense contracts. The engineers there helped her considerably, sharing knowledge and components (Eppley & Phillips 2016). She also did a 3-month residency at Calarts after an invitation by Allan Kaprow and Nam June Paik who advised her, and another 3-month artist residency at Bell Labs, where she further experimented with capacitance fields. Interestingly - as she later noted - even though today capacitative technology is behind numerous technologies (e.g. touchscreens) Bell Labs engineers were not interested in it at the time because capacitative fields were unstable. In contrast, it was this dynamic and unstable property of fields - with different spaces, different environmental conditions, and different bodies producing different conductivities - that particularly interested Phillips, as she saw great potential in it for creating open systems that brought together technology and audience.

This early piece, *Sound structures,* was an interactive sound installation that operated in a rather straightforward manner as a capacitative circuit. It was based on a metal rectangle hidden under a carpet which radiated an electromagnetic field, much like a theremin - or, more precisely a Terpsitone, even though Phillips was probably not aware of this instrument as she does not mention it. The signal emanating from the capacitative circuit formed between the plate and the body was received by several AM radios distributed in the room, and subsequently transduced to audible sound through the heterodyning effect. The installation was quiet until someone stepped on the mat thus grounding the field. Standing on the edge of the mat generated a low tone that became higher in pitch as the interactor moved towards the center. Being a sculptor, Phillips conceptualized this work as an invisible space to be explored, not as an instrument. She aimed to create *"a new kind of environmental space"* with a field that *"takes a three-dimensional form which can be found only through physical involvement with the space"* (Philips, 1970). Structure emerged through interaction – one could say, by the touch of the audience's entire body - and became "*perceived as changes in audio tones"* (Ibid). Furthermore, she was interested in the work's potential to be interacted with collaboratively, as each person *"could act as individual systems within a larger system"* (Ibid).[174] In this manner, the generated tones related both to the actions of participants as well as the relationships between them.

Sound structures was not a one-off experiment by Phillips that year. A brief video documentation includes footage of another unnamed piece with similar sound and operation (Phillips, 2016c).[175] The video shows dancers moving under what appears to be a ceiling-mounted plastic structure connected to a wire from which a capacitative field appears to emanate. The sound of both these works is simple, as is the mapping to movement. As Phillips states, the technology she used was essentially *"just a Theremin"* (Eppley & Phillips, 2016). This encouraged people to attempt to play tunes with her installation – something that was very far from what she wanted to achieve.[176] As a consequence, Phillips replaced her simple oscillators with a synthesizer as soon as she could, and began exploring more complex mappings and sonorities.

Until 1974 she was experimenting with capacitative fields primarily in gallery settings, aiming to explore the relationship between body and space in smaller, closed spaces. This changed in 1974, when she was commissioned to make an outdoor public installation at the Lewiston Artpark, near Niagara Falls (Phillips, 2009).[177] For this work, she moved away from synthesized sound to environmental recordings, capturing the sound of the river at different locations before and after the waterfall. The piece was installed in a pathway of the park, with multiple speakers and capacitative sensors along it. These sensors captured the movement of visitors down that path, with Phillips using their output to control filters applied on the pre-recorded sound.[178]

That same year, Phillips also had a brief collaboration with American composer Richard Teitelbaum for one of his performances, building a sensing system for him.[179] Teitelbaum

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[174] Technically speaking, multiple people touching each other become a single, large circuit that produces even stronger conductivity.

[175] The video is titled *Two of My interactive sound Installations at Bennington College 1970* which clearly implies there were more such works – perhaps different types or spatial configurations of *Sound Structures*?

[176] She in fact calls this *"a disaster",* especially because *"the Theremin is a pretty bad instrument - and it is not about space, it's about playing"* (Eppley & Phillips, 2016).

[177] It is interesting to note that a year later, in 1975, the Artpark presented another radio-frequency sensing piece: a new iteration of Max Neuhaus' *Drive-In Music*.

[178] In 2010, the piece was reprised for another exhibition at the Artpark with its technology updated (Foran, 2010). Neither Phillips nor the Artpark archives provide a name for it.

[179] It is worth noting that this collaboration was quite rare as Phillips rejected many collaboration proposals by other famous artists. La Monte Young and Allan Kaprow were both interested in her sensing system and had asked her to work with them, but she didn't accept as she felt *"they just wanted my technology".* (Eppley &

had been exploring the potential of biosignals and biofeedback for performance, having created and performed a number of works based on EEG and ECG devices between 1967-1974. In 1974, he started a new cycle of experiments taking EEG measurements of the moving body, specifically while practicing T'ai Chi - most likely because his performing collaborator, Barbara Mayfield, was a T'ai Chi practitioner. To solve the practical problem of wires getting in the way, Teitelbaum coupled his EEG device with an FM radio transmitter - thus forecasting the development of contemporary wireless EEG headsets. He also asked Phillips to create a capacitative sensing system with which Mayfield's movement could be traced. The system transduced the speed and size of her gestures into control voltage which was mapped to control hardware synthesizers. This resulted in a new work by Teitelbaum, performed by Barbara Mayfield and called *T'ai Chi Brain Wave* (1974). In this work, the sounds created by the alpha waves and those created by the gestural control system formed a correlated 'duet' *"between the slow external movements and the internal EEG rhythms"* (Teitelbaum, 1976, 49).

Returning to the gallery space the following year, Phillips created a new capacitative sensing work for The Kitchen, titled *Broken/Unbroken Terracotta* (1975). This installation had a more sculptural format, an approach she has increasingly moved towards over time, with her later works typically centered around objects with a compelling visual presence, often made out of metal because of its conductivity. This installation featured two radio fields emanating from a shiny donut-shaped mylar sheet placed on the ground that visitors could walk on and touch, and a copper-coated metal sheet suspended from the ceiling a couple of meters above it, which they could walk under and also touch (Phillips, 2020a) (figure 3.28). There were two omnidirectional loudspeakers, painstakingly tuned by Phillips so that sounds move between these objects and become balanced when someone is in the center of the mylar sheet (Eppley & Phillips, 2016). The sound was rather minimal, with four layers of sinewave oscillators creating moving pitched drones and beating patterns; approaching a field created a rippling effect via amplitude modulation. Overall, judging from the video documentation, the mapping of movement to sound appears to be less direct than in her previous works, though the connection of the two is still clear - particularly when transversing the edges of the mylar sheet, moving towards the copper sheet, or touching the objects. Touching other visitors while interacting produces changes in sound as well.

Phillips, 2016). John Cage had also been very interested in the sound of her work, especially the rich low end, and had asked her to work with him. She refused, however, because she did not want to decontextualize the sounds from the movement-based system that produced them by putting them on a tape.

Figure 3.28. Liz Phillips' *Broken/Unbroken Terracotta* (1975). Left: Nam Jun Paik interacting with the circular radio field emanating from the floor (left). Right: visitor interacting with the field emanating from the flag-like metal sheet hanging from the ceiling (photos from Eppley & Phillips, 2016).

Beyond returning back towards sculpture with this work, Phillips was also developing her technical toolkit. She built the electronics for this work herself - sine oscillators, voltage controls and modulators – casing them in a cigar box. This system was sensitive to both speed and direction, generating control voltage in response. To achieve more complex relationships between sound, space and movement, she used an array of large capacitors that stored the electrical energy generated by movement. The resulting charge was slowly released by the capacitors to form continuous or stepwise voltage release curves (the latter using a sample-and-hold circuit). This meant that sound continued to be modulated as an after-effect of movement. Using this method - in this work but also many subsequent ones - Phillips created fluid soundscapes consisting of multiple layers operating at various timeframes and tuned to react differently to the various states recognized by the system - absence, presence, stillness, activity. As she reflects, *"[t]he integrating and proportioning of stored potential energy based on activity in time and space is a key element"*, enabling visitors to *"stretch and manipulate and store potential energy (...) so that their current movement takes on an altered significance that manifests itself through sound events in multiple time periods."* (Phillips 2009, 59). I find this introduction of *hysteresis* to her system, the multiplicity of this response in several tempi, and the reasoning for it all particularly intriguing, because it is a strategy I have also used in my own *Hertzian Field* works, long before I knew of her work. The fact that she was likely the first to implement this somewhat advanced mapping already in 1975 is a testament to how pioneering and in-depth her work with capacitative sensing was. In any case, owing to this strategy she managed to make visitors stop trying to play notes by moving in space in her works (Eppley & Phillips, 2016).

Her next sensing piece, *City Flow* from 1977, was a return to public space - a high-traffic area in a New York shopping mall. Phillips installed an array of copper plates at specific spots to capture the flow of passers-by and used their movement to modulate, filter, and segment pre-recorded sounds with an analog synthesizer she built (Singer, 1977 and Eppley & Phillips, 2016). According to a contemporary reviewer, the soundscape included sounds such as *"rushing water, voices under water, trains in tunnels, muffled drums, the shriek of a pterodactyl, and plain old radio static"*, as well as a live feed from a nearby microphone on 42nd street. (Singer, 1977).[180] While the piece was running, Phillips also received permission to connect to the traffic light monitoring system of the city. She decided to transduce this data into audio and use that as an additional layer of motion-based sound in the work, so that one could hear at the same time the movement of people within the mall combined with the movement of cars in the city (Singer, 1977 and Eppley & Phillips, 2016).

Figure 3.29. Visitor interacting with Liz Phillips' *Sunspot I* (left) and *Sunspot II* (right) at Neuberger museum in 1981. Phillips and her modular synthesizer are visible in the background on the right image (video stills from Phillips 2016c).

This work was followed by a more sculptural series of works, called *Sunspots,* presented in several occasions between 1979-1984 (figure 3.29). Phillips calls these works site-specific, as they involve meticulously tuning them to the room they are shown in – tuning being a process on which Phillips spends much time for all her capacitative works (Eppley & Phillips, 2016). *Sunspots* consisted of two objects presented in an empty room and of their respective electromagnetic fields (*Sunspots I & II)*. On one side, *Sunspot I* was suspended from the ceiling. It consisted of a semi-transparent brass mesh screen with a copper strip attached to it, sealed in plexiglas. A few meters away was *Sunspot II* in the form of a coiled

[180] Singer reports that a security guard he spoke to complained about this *"weird noise"* driving him crazy. The same guard also informed him that the humidity of a rainy day made the work create a different, denser soundscape (Singer, 1977).

arch resembling a narrow doorway; it was made of gleaming copper tube fabricated from plumbing pipe that the artist shaped by hand (Rabinowitz, 2002).[181] The position, direction, speed, and touch of visitors had a clear audible effect, modulating the volume, pitch, rhythm and timbre of the sounds coming from two speakers placed at different sides of the room. Sound was created by Phillips' modular analog synthesizer combined with a digital synthesizer (Phillips, 2020b). All necessary equipment was placed in a roped off area in the same room, visible to the public - technology is typically exposed in Phillips' work as *"a visible reminder of the physicality of sound"* (Rabinowitz, 2002, 37). The system's response was tuned so that visitors could recognize specific sound events happening in certain spots or with certain movements – although, as a reviewer noted, this relationship became nebulous with many people in the space (Ahlstrom, 1982). The same reviewer described the soundscape as consisting of *"tinkly sounds, like Chinese wind chimes, percussive little points of sound, cascades of sound that spill like water, and bundles of pointed sound like a million tiny Christmas tree lights flickering on and off as though at a great distance. Intricate rhythms alternate and follow each other, passing from speaker to speaker. To create stationary sounds (long notes) or a settled, even pattern of sound, a participant has to leave the room, because the static side of Sunspots is brought into being only when the participant leaves a threshold space."* (Ahlstrom, 1982, 82). Phillips described this work as a composition to explore rather than to listen to. Rather than looking for beautiful sounds, she approached sound as a material, as a *"a way to describe something that is taking place in time and space",* acknowledging at the same time that working with sound meant she had to also consider music as a context (Phillips, 2016a).[182] Discussing her process in making the work, she commented that *"[t]he visual forms evolve as the sounds evolve"* and "*none of the decisions are made independently"* (Ibid), which is why she preferred materials easy to cut and fast to manipulate while thinking and trying things out.

While *Sunspots* was presented as an installation, it should be noted that in its earlier iteration in 1979 it was part of a performative video collaboration between Phillips and Nam Jun Paik. The *State of the Arts* TV program had commissioned them to create a video piece together to

[181] Dancer Robert Kovich mentioned that the coil emitted two fields – at least in its 1979 iteration (Phillips, 2020b). A description of the work also mentioned that it uses light sensors and solar panels, though that is not discussed or referenced in other sources (Wooster, 1982).

[182] Phillips makes an interesting remark on the relationship of installation sound to music: *"If [sounds] just function as music, then everyone sits still. That happened sometimes - John Cage came into my studio and just sat still. He sat on the floor under a field and move the slightest bit to see what happened. He really didn't want to be called on to move because he thought of it as performance. It wasn't, but coming from his [musical] background, it felt like it if he had to move."* (Eppley & Phillips, 2016).

be broadcast on television (McShea, 2015; Phillips, 2015; and Phillips, 2020b). The process involved Robert Kovich, a dancer from the Merce Cunningham company, exploring a roughly fabricated asymmetric prototype of the *Sunspot* coil and a prototype of the *Sunspot* bronze screen, both suspended from the ceiling of Phillips' studio. Kovich's improvisation and the resulting sound were documented on video tape which Paik later processed with his video synthesizer. Being the program's first commission, the video work was titled *State of the Arts, Étude No. 1.*

Phillips' next work with this technology, *Graphite Ground* from 1987, was a larger scale indoor installation reminiscent of Japanese rock gardens. Following a visit to Japan to install *Sunspots* at IBM's showroom, Phillips became inspired by the rock gardens in Kyoto, with the waves drawn into the sand around the rocks reminding her of the invisible capacitative fields enveloping objects in her work (Phillips, 2016b). In *Graphite Ground*, sand and pebbles were replaced with uncombed lamb's wool, and rocks replaced with large shards of naturally conductive copper ore that looked like abstract sculptures and functioned as antennas (Phillips, 1988) (figure 3.30). At the center of the work was a structure housing all electronics behind a milky white screen. A wooden walkway, similar to those found in parks, formed a path around this structure. To further approach and interact with the copper shards, visitors could step and sit on sandstone flags dispersed through this 'garden'. Similarly to her other works, the proximity of visitors' bodies – as well as shifts in humidity and temperature - affected parameters such as pitch, timbre and volume of the soundscape. The relationship between the rocks and visitors' bodies created a dynamic sound environment that juxtaposed the physical stillness of the garden. The brain of the piece was an Apple II computer running software written by composer John Bishop. This was used to control a Serge modular analog synthesizer whose sound emanated out of four speakers placed in the corners of the space, thus creating an immersive environment (Revaux, 1987). The sounds seemingly followed visitors in their path through this space, *"as if the curious creatures of the airwaves had come to investigate your actions"* according to a reviewer – an effect that became much more pronounced when touching the stones (Ibid). The reviewer added: *"As if this were some ethereal tropical rain forest, the clicks, hoots, hums, chirps, drips, and splashes swell and wane, never repeating themselves as they shift and drift around the room",* creating a constantly evolving soundscape with *"restless unpredictability".* (Ibid). With more people present, the soundscape became denser and more complex. Another reviewer noted that *"[t]he smallest motion by anyone in the space could stimulate an acoustic response",* nonetheless there was *"no apparent pattern of cause and effect"* which made the piece produce a *"sense of disorientation"* that *"incited curiosity"* (Phillips, 1988).

Figure 3.30. Liz Phillips' *Graphite Ground* at the Whitney Museum of American Art, NY, in 1988 (from the artist's website).

In the following decades, Phillips created a few more sculptural works with capacitative sensing, moving from analog electronics to digital platforms. *Garden* (1996) was an interactive installation centered around three objects selected for their capacity to conduct and radiate electromagnetic fields: an agave cactus, an anchor, and a copper shard. Phillips generated the sound material by making these and other objects (e.g. a wine glass, a Tibetan bowl, a rainstick) resonate and creating sonic loops with them (for example by rubbing a wire brush around the shard's perimeter). Through digital processing, she produced a pool of different textures, durations and pitches. The work was performed by a computer running real-time software to create a dynamic soundscape with the sensing data, as well as to adapt this data to changing conditions such as weather, number of visitors, etc (Phillips, 1996). *Intermingling,* from 2002, was another sculptural installation that combined capacitative and ultrasonic sensing to react to the movement of visitors. Sounds emanated from directional self-made speakers – such as a bowl, a vase and speaker horns mounted inside boxes and on the ceiling.

A more recent work, *Waterfall* (2004) is an interactive sculpture: A slate of natural copper ore, about 1.5 meters tall, is mounted on the wall creating a capacitative field around it (figure 3.31). The soundscape consists of field recordings of a small waterfall with birdsong, and metallic wave sounds (probably processed recordings) (Phillips, 2014). These are accompanied by synthesized metallic sounds with a water-drop quality whose pitch, rate of repetition - and probably other qualities - change depending on the proximity of viewers.

Figure 3.31. Visitor interacting with Liz Phillips' *Waterfall* at Frederieke Taylor Gallery, NY, in 2004 (video still from Phillips, 2014, video by Kevin Kay).

A later work, *Elastic Space* from 2008, consists of four covered objects on pedestals, all wrapped in brass textiles/screens to emanate and receive capacitative fields. Philips used armature wire to sew them closed, creating simple 3D forms that function as antennas (figure 3.32). Depending on their shape and size, these wrapped objects create an assortment of *"fragile human-scale fields"* for visitors to interact with. (Phillips, 2009, 62). The work uses software programmed to track changes in activity between the objects, and to measure the accumulation of that activity; it can also calibrate itself. This data is processed and sent as MIDI control information to a sound module. Phillips also presented a variant of this work in which volunteers become performers by having a wire attached on them, thus making their body part of the transmitter/receiver's antenna. As their posture and position changes, so does the form - and hence the sound - of the radiated fields they are connected to. Other visitors can also interact with them. Finally, *Plant Fields* from 2012 combines wind-power (which Phillips has used in a number of works) with capacitative sensing. The work consists of an anemometer mourned on the roof of the exhibition building, a silver bowl on a pedestal, four pots with plants on pedestals and on the floor in a cluster - with wires connecting them - and two fabric sheets suspended from the ceiling and from the wall on opposite sides of the work. The soundscape is dominated by woody and metallic grains of sound - at times reminiscent of Iannis Xenakis' *Concrete PH* and at times closer to wind-chimes - accompanied by more sinusoidal glissandoing grains. Various sonic parameters respond to the movement and touch of visitors in a clear in an indirect manner (Phillips, 2012).

Figure 3.32. A participant connected to Liz Phillips' performative sculpture *Elastic Space*

at the University of California at Santa Barbara in 2008 (photo by Jodi Chang, from Phillips 2009).

3.4.4 *MIT Lab's Electric Field Sensing*

In the 1990s, Joe Paradiso and several collaborators at the MIT Lab began investigating Theremin-related sensing techniques (Zimmerman et al., 1995; Paradiso et al., 1997; Miranda & Wanderley, 2006). This resulted in a handful of interesting human-computer interaction projects.

At the time, the proliferation of surveillance and security systems had firmly established the need for reliable contactless sensing. The commercial availability of inexpensive components made it possible to create systems based on a type of technique called *Electric Field Sensing*. Interestingly, this research grew out of music performance and the development of a *Hypercello* instrument for Todd Machover's 1991 composition *Begin Again Again* .... The instrument, played by cellist virtuoso Yo Yo Ma, employed a number of sensors; however measuring bow movements proved to be a considerable challenge. To solve this problem, a system inspired by Max Mathews' *Radio Baton* was developed, in which a transmitter was attached to the instrument's body and a receiving electrode to the bow. Experiments with a violin bow revealed that the performer's hand produced different interference patterns depending on its position relative to the transmitter/receiver pair. The team tested various configurations and proposed a typology of *Electric Field Sensing* with 3 different modes, depending on the relationship between the radio circuit and the human interactor/performer (figure 3.33).

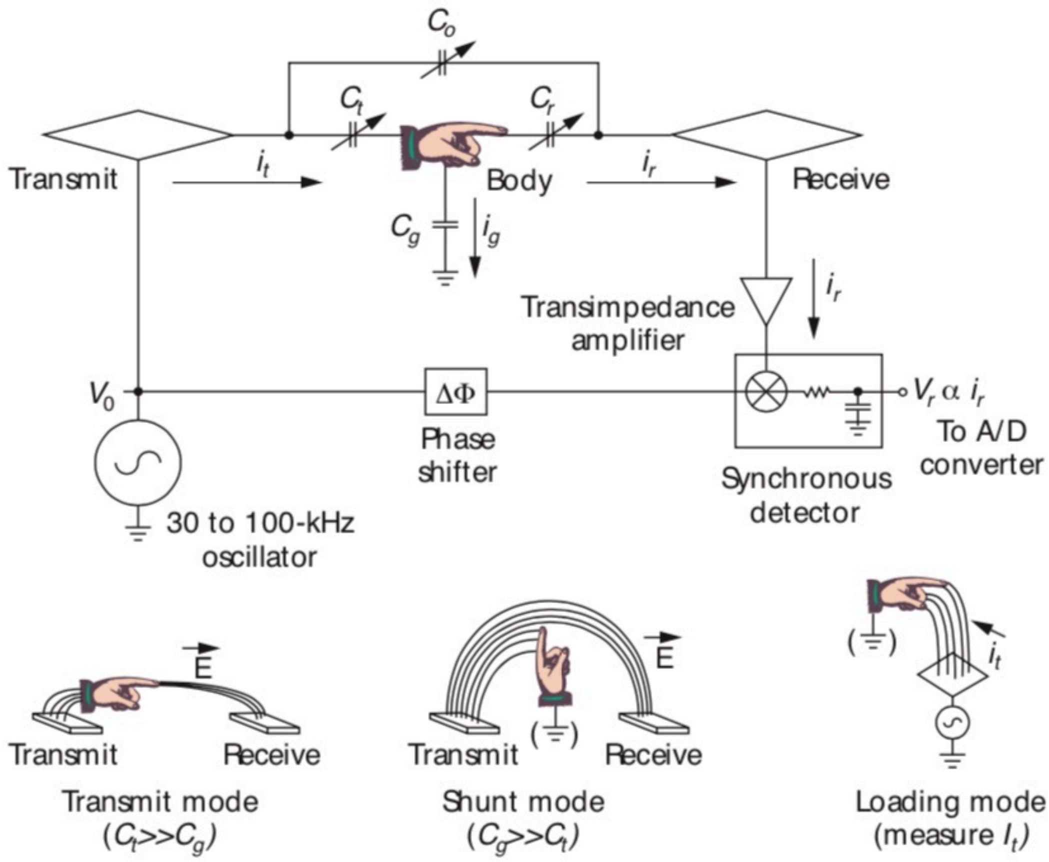

Figure 3.33. A graph of the general implementation of Electric Field Sensing (top) and of its three principal modes (bottom) (from Smith et al. 1998).

- The *load* mode is the one used by the Theremin instrument. It measures the distance between a single electrode and an object, such as a performer's body, through the change in capacitance between an electrode and ground.
- In *shunt* mode, an electric field is formed between two or more electrodes and is partially interfered with by an object, such as a human body, placed within this field. The field's strength at the receiver is dependent on the position of the interfering body.
- The *transmit* mode similarly involves at least one transmitter and a receiver electrode pair. Rather than simply interfering with the field, the performer stands, sits, touches, or completely blocks one of the electrodes so that the electric field passes in its entirety through their body. When the performer moves so close to the electrode the body becomes an extension of the transmitter – effectively, an antenna – pushing a *shunt* system into *transmit* mode. Other bodies in direct contact will also become part of the system. As the researchers remarked, in such configurations it is possible to distinguish between different individuals by analyzing the transmitted signal.

The team designed special hardware consisting of one transmitter and four receivers initially, with the goal being to locate body parts, such as a hand, in 3-D space (each dimension requires at least one receiver electrode). Their research discovered that measurements are not proportional to distance, but depend on the geometry of the electric field. They also noticed that body parts outside of the electric field interfere with it as well - the closer, the more they affect the system, a phenomenon well known and utilized by Theremin performers. Thus, to achieve better results they used a training phase through which they created a database of positions and corresponding electric field values. This is a similar principle to the fingerprinting technique used in Device-based Localization (section 5.3.2).

Comparing the technique to vision-based systems, the authors mention that reflectivity and surface texture are non-factors in this sensing system (Zimmerman et al., 1995). Moreover, sensors can be hidden from sight as their medium can pass through non-conducting materials. Furthermore, much fewer data and thus less computation is required (only three channels, rather than a matrix of pixels) which also makes this system smaller, more light-weight, and requiring less power. Because of its detailed spatial resolution - owed to its small wavelength as it operates in the millimeter range - and because of its fast temporal temporal resolution, with the signal being sampled at several kilohertz per second, the system was particularly suited for music, outclassing the various MIDI-based systems of the time.

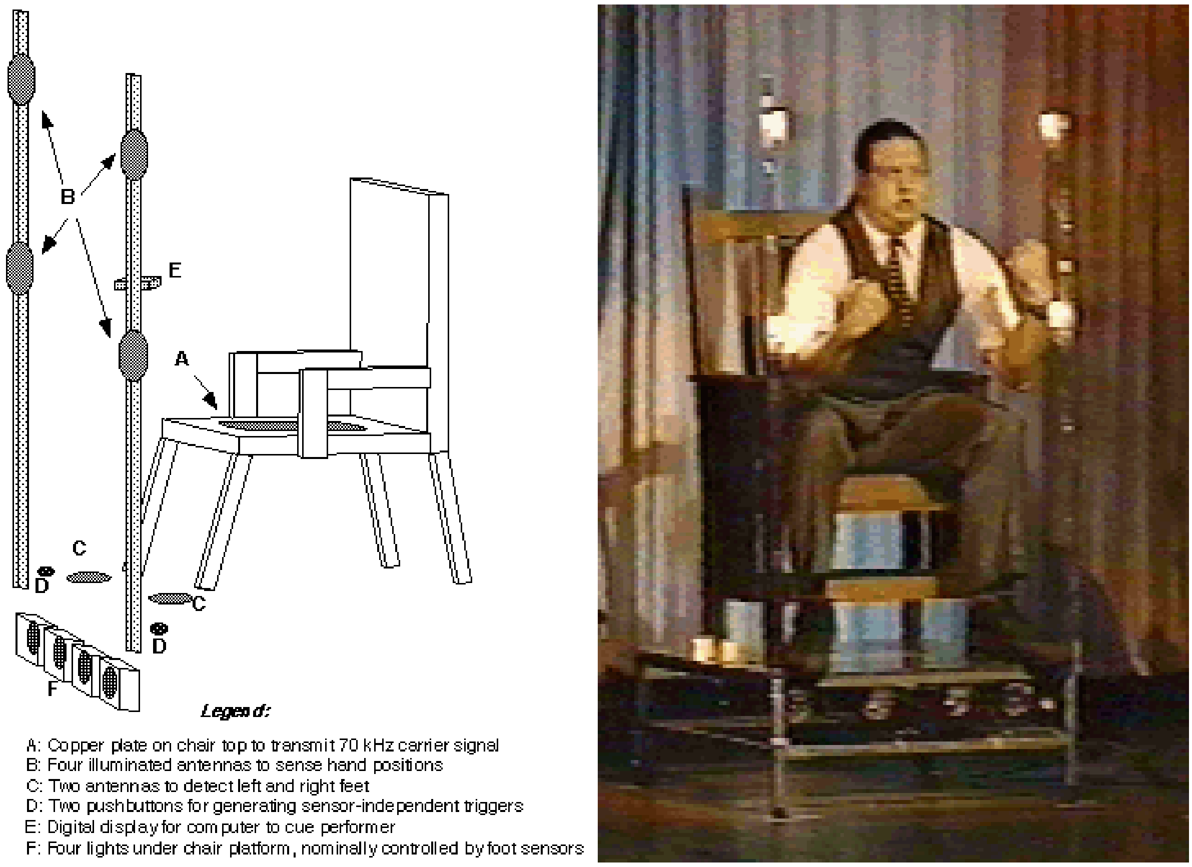

Figure 3.34. The *Spirit Chair* (a.k.a. *Sensor Chair*): Schematics (left) and a photo of Penn – of magician duo Penn and Teller - performing on the *Spirit Chair* during the Digital Expression Conference in MIT in 1994 (right) (from Paradiso, 2018).

A number of utilitarian Human-Computer Interaction prototypes were designed with this hardware, such as a touchless *2-D Finger-Pointing Mouse* and a *Smart table* which monitored gestures to control the display of an electronic newspaper. More creative-oriented implementations included a planar structure using shunt mode for use by conductors, a cube for sensing hand movements by two performers, and the more evolved *Gesture frame*, which deployed 2 transmitters and 4 receivers to sense hand motion above a plane. Another project was the *Person-Sensing Room*, in which a transmit electrode covered the entire floor with 4 receivers placed on the walls. Similarly to the previous interfaces, comparison of Received Signal Strengths indicated the person's location and was used to create dynamic soundscapes. Yet another project, the *Smart chair* embedded a transmitter into a seat, two receivers in each armrest, and two more in the headrest so that head and arm placement could be tracked for controlling audio. A variant of this design, the *Spirit chair*, created for stage magicians Penn & Teller, embedded a transmitter in a seat and included a gestural frame with 4 receivers, two receivers by the chair's feet, as well as lights and switches (see Paradiso, (n.d.) for 3 short video clips of the *Spirit Chair* in action) (figure 3.34). It was used as a musical interface for the duo's performances enabling them to create and control sound 'as if by magic'; it was also used by MIT composer Todd Machover. It is worth noting that because of the different body sizes of Penn and Teller, the chair was calibrated separately for each performer. Finally, another system was developed for the artist formerly known as Prince, featuring a nude mannequin with electrodes embedded in different parts of the body (2 transmitters and 6 receivers) that responded to nearby gestures.

3.4.5 *Sonia Cillari and the body as interface*

Over a decade later, Sonia Cillari - an Italian architect turned media artist, based in the Netherlands at the time – was inspired by the artistic potential of MIT Lab's work on *Electric Field Sensing*. Between 2006-2011 she created two interactive performative installations based on the *transmit* mode, with the sensing interface being the body of a live performer. In these works, Cillari started from the notion that the body is an interface, a *"generator of perceptions"* that puts us in contact with the outside world (STEIM, 2010); that it re-creates this world internally and then interacts with it through this internal model. For her, *Electric Field Sensing* was a way to investigate the relationship between active performer and passive spectator blurring the line between the two and turning the human body simultaneously into object and subject. The technology enabled her to *"measure human encounters"* and help participants realize that *"the boundaries of the self extend beyond their skins"* (Cillari in MediaArtTube, 2008).

The first of these works, *Se Mi Sei Vicino* ('If you are close to me') from 2006-07, was conceived as practical research into the interaction between body and environment and into ways of turning the body into an interface (Cillari, 2007 and LIMA, 2007).[183] Visitors enter a faintly lit quiet room and see a female performer standing in the middle, immobile and silent, almost like a sculpture (figure 3.35). She is positioned over a small square marked with white tape in the center of a larger (about 2x2m) slightly lifted black platform. This platform contains four capacitative plates with the marked square acting as the transmitter, thus turning the performer's body into an antenna. Two of the room's walls are filled with abstract video projections, displaying a gently waving grid-like 3D form, generated algorithmically. The same algorithm is used to control the work's immersive soundscape, which emanates from four speakers in the corners of the room. The space surrounding the platform is not

[183] The work was created in collaboration with Steven Pickles (software programming) and Tobias Grewenig (sound design).

reactive, therefore nothing happens when visitors enter. As soon as they join the performer on the platform however they become part of the circuit, their movements creating a fluctuation of the electromagnetic field surrounding the performer due to a change in the circuit's capacitance. This sets a sonic texture with rumbling low noise accompanied by metallic granular sounds in motion. The visuals are also affected, moving faster and becoming denser and more colourful the longer people interact. Visitors investigate various manners to approach and touch the performer, even moving her arms or touching other visitors on the platform, observing the effect of their actions in the audiovisual environment. The response appears intricate and rather complex and indecipherable; however, the system is actually quite simple, being able to distinguish between four different states: no visitors present, visitors present but further away, visitors closer, and visitors touching the performer (Kwastek, 2013). Additionally, it also tracks how long visitors interact with the performer, a parameter used to increase complexity and to add a temporal aspect to the development of sound and video over time.

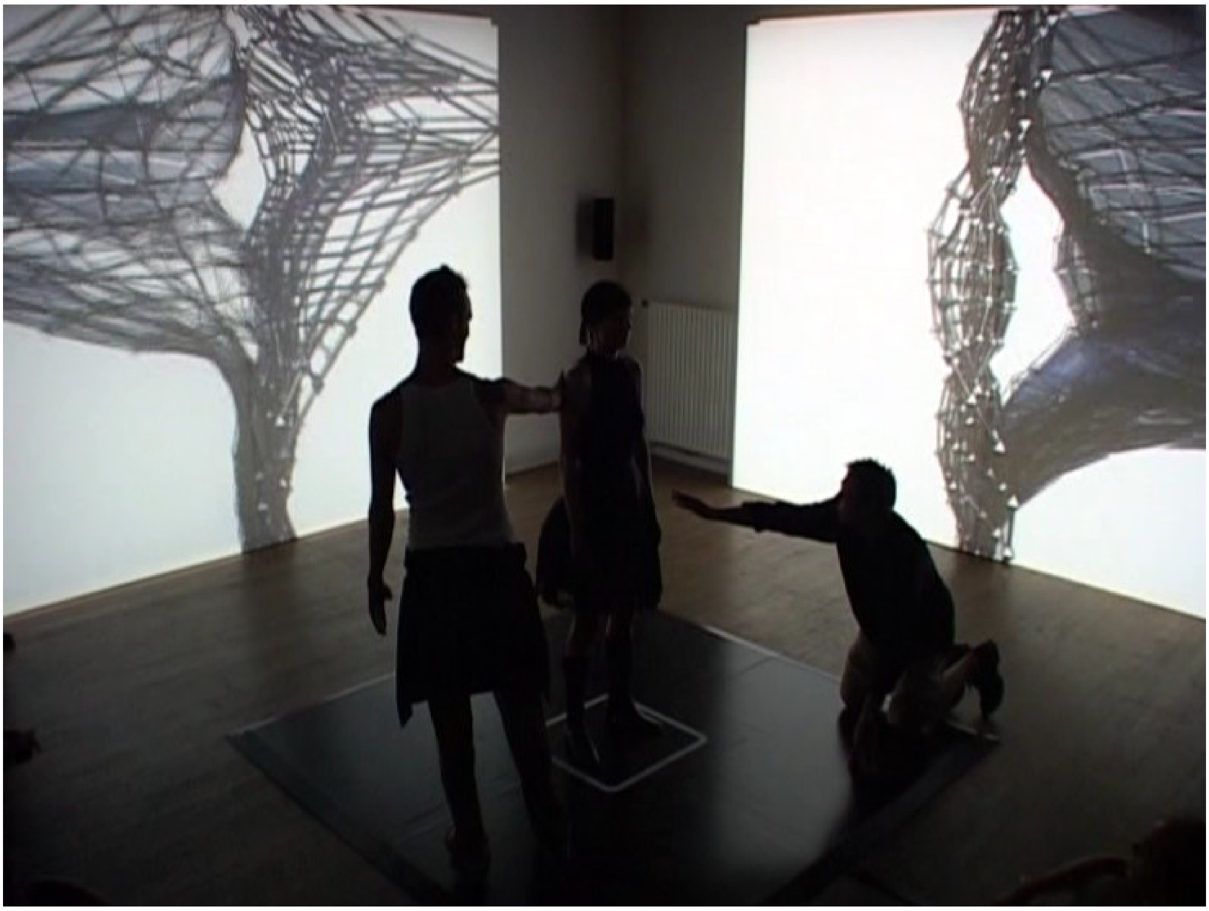

Figure 3.35. Sonia Cillari's *Se Mi Sei Vicino* at the Netherlands Media Art Institute 2006 (photo from LIMA, 2007).

Cillari built on this first experiment with her following work, with which she pushed the envelope of interaction much more forcefully to create a more developed, more poetic, and much more confrontational work. *Sensitive to Pleasure* (2010-11) is a multimodal performative installation lasting about 2 hours (Cillari, 2014; Cillari, 2015; Cillari, 2018; and STEIM, 2010). The piece was conceived as a metaphor for the *"controversial relationship"* between maker and artwork, paying homage to the myth of Pygmalion, the sculptor who fell in love with a statue he created (Cillari, 2015, 91). As the audience approaches the installation, they see Cillari standing still in front of a 2.5m cubic room (figure 3.36, left). Metal strips are stretched around her waist and arms, and wires tether her to the cube. She is the doorkeeper, allowing one audience member at a time to enter and explore the 'creature' she keeps inside. As visitors enter the dimly lit cube they are confronted with a naked female performer standing in the middle, completely still, like a statue (figure 3.36, right).

Figure 3.36. Photos from Sonia Cillari's *Sensitive to Pleasure* (2010-11) (from Cillari, 2014). Left: The outside of the performing cube, showing the light path leading to the entrance and Cillari as gatekeeper (photo by Sandra Dollo). Right: The naked performer inside the cube acting as antenna, together with an interacting audience member (photo by Sara Tirelli).

The floor of the room contains a grid of 5 electrode plates (figure 3.37). The performer stands in the middle, on top of the transmitting plate, with her body becoming an antenna radiating an electromagnetic field. As the visitor approaches or touches her body, changes in the field's properties occur. The signal strength of each receiver plate is analyzed by a computer and used in three different manners:

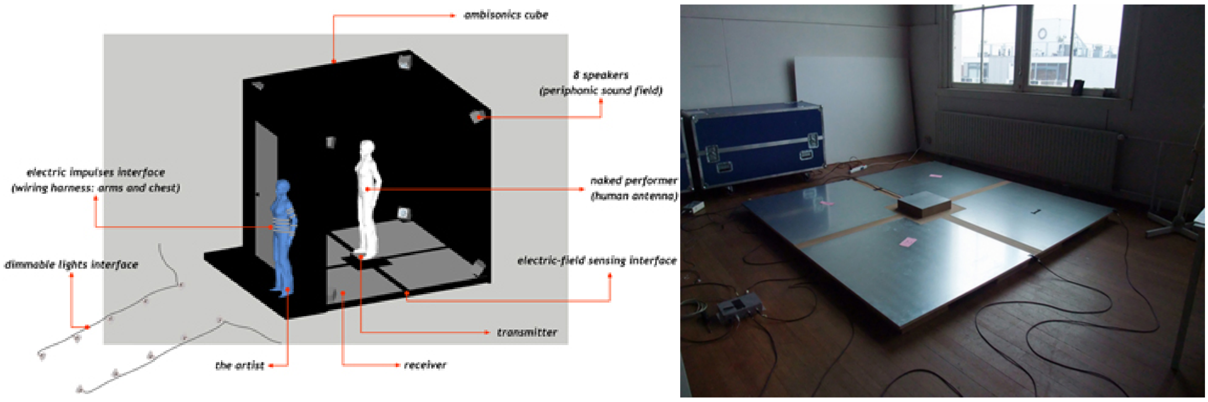

Figure 3.37. Sonia Cillari's *Sensitive to Pleasure,* behind the scenes. Left: Drawing of the installation setup (2010-11). Right: The *Electric Field Sensing* interface inside the cube (from Cillari, 2014).

a) The distance between the two bodies controls the immersive soundscape inside the cube. This turns the performer's body into an instrument to be explored in an intimate and fragile, but very confrontational and uneasy one-on-one setting by visitors. Sound is projected from 8 speakers hidden in the cube's corners, filling the space with a 3D ambisonic soundfield designed and composed by interdisciplinary artist TeZ (Mauricio Martinucci);[184]

b) Visitor behavior also affects the environment outside the cube, changing the patterns of a path of lights leading to the entrance.

c) More importantly, it affects the gatekeeper herself: Before entering, visitors are informed that depending on their behavior inside, electric impulses will be sent to the metal strips on Cillari's body, giving her electric shocks. The shocks will be stronger the closer they come to the performer and the longer they remain close to her or touch her body. As Cillari comments, whether this is a painful experience or a pleasurable one is up for the audience outside the cube to decide while they watch her reactions.

Cillari's capacitative works seek to rediscover interaction as a fundamental human experience in its different modalities, from intimate, to personal, to social. In doing so, they create a contradicting feeling, with visitors having to contend on the one hand with their desire to explore and interact, and on the other with established social norms about not coming too close to strangers, and especially not touching them (particularly when naked). Nonetheless, the gallery setting – where one is expected to interact with such works - the heavy mediation of the relationship between the bodies of visitors and performer through sound and video, and

184 The rest of the team behind the work included Byungjun Kwon, Stock, Ulrich Berthold, and Valentina Sanna.

the attitude of the performers – motionless, expressionless, and detached - encourages visitors to treat them as an inanimate object, a *human interface*. It is worth noting that interviewed performers of the first work reported that, while most visitors remained respectful while interacting with them, some *“tried to violate the setting created by the artist, either through aggressive or careless behavior toward the performers or by means of provocation such as concerted efforts to make eye contact"* (Kwastek, 2013, 246). The performers interpreted this as coming from visitors objectifying them or trying to push them to break character. As a final note, is also worth pointing out an interesting technical detail mentioned by Cillari (STEIM, 2010): Before calibrating the system, performers were instructed to drink a certain amount of water and to urinate a certain amount of times so that their body is better tuned for the system. Cillari also noted that, during the 2-hour performance, the system becomes slowly de-calibrated as the performer’s body loses water.

3.5 From Broadcast Radio to Embodied Instrument

3.5.1 *Redefining radio beyond broadcasting*

While broadcast radio established itself as an engaging and popular medium for composers in the 20th century, making work for the medium today feels radically different. Radio’s socioeconomic importance has been steadily declining, as has its number of listeners. The passage from analog to digital is also rendering it technologically obsolete and, to add insult to injury, some of its functions have been cannibalized by newer forms, such as internet radio, podcasts, audio and video streaming services, etc. Nevertheless, the medium’s supposed obsolescence is merely a result of the way it is most often looked at, described, and used, rather than because of its actual nature. Many artists have been redefining what it means to work with radio, imagining new creative uses for this aging medium that move beyond the idea of broadcasting messages and programming content. Imbued by a strong DIY ethos, these experimental approaches to radio art propose new ways of looking at the medium, rediscovering its physicality and calling for an escape from the strict confines of what societal and technological conventions have reduced radio into. Most pertinent to this thesis are the ideas of two artists focusing on the medium's spatiality and potential for embodied interaction.

For Tetsuo Kogawa, a Japanese performance artist and media theorist, to regard radio as a communication medium is to be entrapped by an outdated modernist idea (Kogawa, 1990).

He posits that while the concept of sending and receiving is convenient it also becomes an obstacle for understanding radio's nature. Broadcasting is not radio's natural state, but merely the realization of a particular industrial ideology (Meusault, 2013). Long-range transmission is not only *"wasteful and not ecological"* but will also soon be replaced by Internet-based applications as communication technology advances (Kogawa, 2006). Radio's decline makes it easier to expand its possibilities and find more extreme, but also more pertinent, applications. Kogawa thus proposes using wireless media in a qualitatively different way so that they become something other than message machines (Kogawa, 2007). By redefining and identifying radio's potential in a contemporary context the medium can be emancipated (Kogawa, 2008b).

For Kogawa, there is a distinct separation between *art radio* and *radioart* (Kogawa, 2008a). With the former, he describes works made for broadcasting, focusing on content and using radio simply as a distribution medium. He identifies the beginning of this approach with the Futurists in the 1930s, noting that even Cage merely "*used radio as at tool for music and sound art"* (Ibid, 129). Instead, Kogawa defines *radioart* as a new and advanced genre of electronic art that goes beyond merely considering radio as a distributor of content, focusing on the inherent raw materiality of the medium. *Radioart* is thus preoccupied with the nature of radio: the electromagnetic waves endlessly oscillating around us regardless of whether we encode messages on them or not; their radiation, their oscillation, and the resonant relationship between transmitter and receiver. *Radioart* immerses us in this world, making us aware of the electromagnetic vibrations around us and giving us a way to interact with them.

For Anna Friz, a Canadian sound artist and media scholar influenced by Kogawa, radio is an environment that allows the unexpected to happen. It can become an instrument in different ways: as a sound source, as a subject, as a transmission medium, or - what is more relevant here - as a performative medium (Friz, 2009). Working with radio does not mean one has to be concerned with the *message*. The focus may instead shift towards the phenomenology of radio and electromagnetism, the medium's invisible materiality, and the role of the human body - not as an incidental interferer but as the producer of a different kind of message. By coupling the body to a circuit through electromagnetic radiation the performer *becomes radio*, activating radiophonic space with their body. *Radio as instrument* can be conceived as an assemblage of circuits, antennas, and bodies; the particular configuration of that instrument is the framework through which the parts form relationships with each other (that can often be rather unpredictable or unintuitive). *Radio as instrument* explores these relationships through proximity, distance, interference and feedback in electromagnetic space. Setting aside broadcasting and the context of the radio play genre, radio is then about exploring the electromagnetic medium, its materiality and its interaction with the environment in which it radiates (Friz, 2011).

A serendipitous example of this idiosyncratic approach to broadcast radio from around 1971-72, predating Kogawa's and Friz's writings by many years, has been documented by microcomputer pioneer Jim Horton. He recounts an episode involving himself and Tom Zahuranec, a fellow experimental musician who, at the time, was using plant micro-currents to make music and who attempted to discover the response of plants *"to emotional stimuli, including telepathic transmissions"* (Horton, 1996). As Horton writes, *"Tom was a genius at getting extreme music out of anything. Once I saw Tom, on peyote, walk by a radio and it just slightly changed frequency. He noticed it immediately and began moving back and forth exploring the effect and an hour or so later he was running in patterns around the room changing the radio from one station to another."*(Ibid). Both composers were familiar with the work of Cage and Cunningham, so it is possible that *Variations V* influenced Zahuranec's intuitive play with electromagnetic flows. For broadcast radio to become a truly embodied instrument, however, the ability to also transmit had to first come into the hands of artists, and its range had to be shrunk into the size of domestic spaces and the human body.

3.5.2 *Tetsuo Kogawa's Mini-FM*

The roots of Kogawa's radio practice start with the movement of *free radio* in the early 1980s, and with the idea that radiospace should be regarded as a public resource instead of a state monopoly (Kogawa, 1990). Inspired by radio activists from Europe and in particular Italy, Kogawa pioneered the *Mini-FM* movement in Japan after finding a legal loophole that allowed unlicensed low-power transmission - a loophole initially meant for wireless microphones and remote-controlled toys.[185] He started building his own low-power/short-range micro-transmitters and sharing designs, which quickly spread through the DIY community. This reappropriation of radio technology established alternative, localized, channels of communication outside the centralized, long-range state and commercial networks. By reducing the range of transmission to a city block or a building, new uses for

[185] The term *Mini-FM* was introduced in 1982. As Kogawa writes in his manifesto, the FCC created a special Low-power FM license in 2000, institutionalizing and taking control of this *"early dream of micro radio paradise"* (Kogawa, 1990).

the technology were being discovered such as throwing ‘radio parties’ in Tokyo apartment buildings (Kogawa, 2008a) (figure 3.38). For Kogawa, these grassroots events could be thought of as a new kind of *micro radio theater* or performance art (Kogawa, 2006). Narrowcasting allowed altering spaces qualitatively through transmission. *Mini-FM* became a way to re-imagine communication and coming together in an urban context, linking people, creating communities, and giving voice to many subcultures (Kogawa, 1990). As such, these 'radio parties' could also be described as manifestations of *relational art*, a concept that will be discussed in section 7.4.3.

Figure 3.38. Photo of one of Kogawa’s Mini-FM ‘radio parties’ in Tokyo, 1984 (from Meusault, 2013).

Mini-FM suggested to Kogawa that the most important element of radio is not its content, but its range (Kogawa, 2008a). In broadcast radio, the received and demodulated signal within a station’s operating range remains the same regardless of distance. Contrary to this, Kogawa’s *Mini-FM* can turn radio into radar: By reducing radio's transmission power and range, it becomes more sensitive to its environment; the human body can intervene, interfere, and become part of the circuit, and thus radio can re-materialize in our perception as a phenomenon of radiation rather than an act of broadcasting.

As a result, Kogawa's radio art practice is concerned with proximity and the gradation of space between body and circuit (Friz, 2011). He radically opposes the modernist idea of radio as an immaterial, disembodied medium that collapses space and distance; the only immaterial, disembodied, and spaceless part of radio is its message. Communication technologies should instead be regarded as body prostheses, and radioart should become a form that enables true experimentation on the relationship between body, gesture and technology – especially as increased digitalization is making experimental music *"forget its hands"*, as Kogawa writes (Kogawa, 2008a). For him to make radioart is to *"play with airwaves"* (Ibid). Sound is used to reveal this relationship, and to guide playful exploration. Radioart is thus a process rather than an object, often producing unpredictable results because of the nature of the electromagnetic medium. It therefore involves intuition more than it does mental planning and decision-making. The body is not directed by the mind but rather develops a mind of its own as it learns how to interact with the radio field (Meusault, 2013).

An early iteration of Kogawa's embodied electronic performance is documented in a video from a 1987 performance at an outdoors performance art festival in Japan (snbnsx, 2012). His instrument, a tangle of wires and circuits, is initially contained inside a suitcase. Kogawa, bare-chested and standing on his knees, gestures above it to produce a kind of distorted theremin sound, with frequency modulated oscillations glissandoing up and down. Later, he tapes parts of the instruments to his arms and back, tethering himself to the suitcase while walking away from it. His posture, orientation and distance effect the pitch of the instrument as he moves around, crawls, lights fires and finally a sparkler whose radiant electromagnetic energy destabilizes the system causing wider pitch fluctuations.

Kogawa quickly became interested in identifying the smallest meaningful radio range for embodied radio performance (Kogawa, 2008a).[186] He found this to be a sphere with a 1-meter radius. This was a space that could be manipulated by one's hands, which he thought of as the smallest unit of the (performing) human body (figure 3.39). This type of mini-FM fields feature in many of Kogawa's performances, such as his *Hand waving play with airwaves* (justing 2008). This piece involves up to six 50mW FM transmitters placed close to each other on a table to create a dense radio field, and a couple of receivers to sonify this

[186] Kogawa wanted to minimize the radio field to the smallest possible unit that could enable change, as an exploration of the notion of 'molecular politics and aesthetics', building on philosopher Felix Guattari's concepts of 'molecular revolution' and 'micro politics' (Friz, 2011). He writes: "*Let's start with your own familiar space. Change in a tiny space could resonate to larger space but without microscopic change no radical change would be possible"* (Kogawa, 2006).

field (Friz, 2009 and Friz, 2011). He often moves and repositions these elements around during his performances. The transmitters are tuned to the same or nearby frequencies, or in sympathetic ratios (i.e. in frequencies that share some harmonics), so as to maximize interference between them. This invisible performative field allows Kogawa to create sound by manipulating radio interference. Similar to the Thereminvox, Kogawa's body becomes part of the circuit through the principle of feedback. Without transmitting any sound, he conjures electronic sonorities with a large dynamic range and rich textural variety, moving his hands and body to probe the radio-sonic space, blocking and reflecting the radiation paths between transmitters. Kogawa acknowledges the *Etherophone* as a predecessor of his practice: *"Leon Theremin showed the minimum example of micro radio. His invention is not only a musical instrument but also a micro radio"* (Kogawa, 2006). Nonetheless, he operates under a very different set of aesthetics, political ideas, and context. This is evident in the kind of music Kogawa performs (noise), the venues he plays (intimate and underground), as well as his instruments' appearance: His hand-made circuitry is always unboxed and visible, designed on purpose to be easy to understand and reproduce; he even at times fabricates it on stage as part of the performance (Friz, 2011).

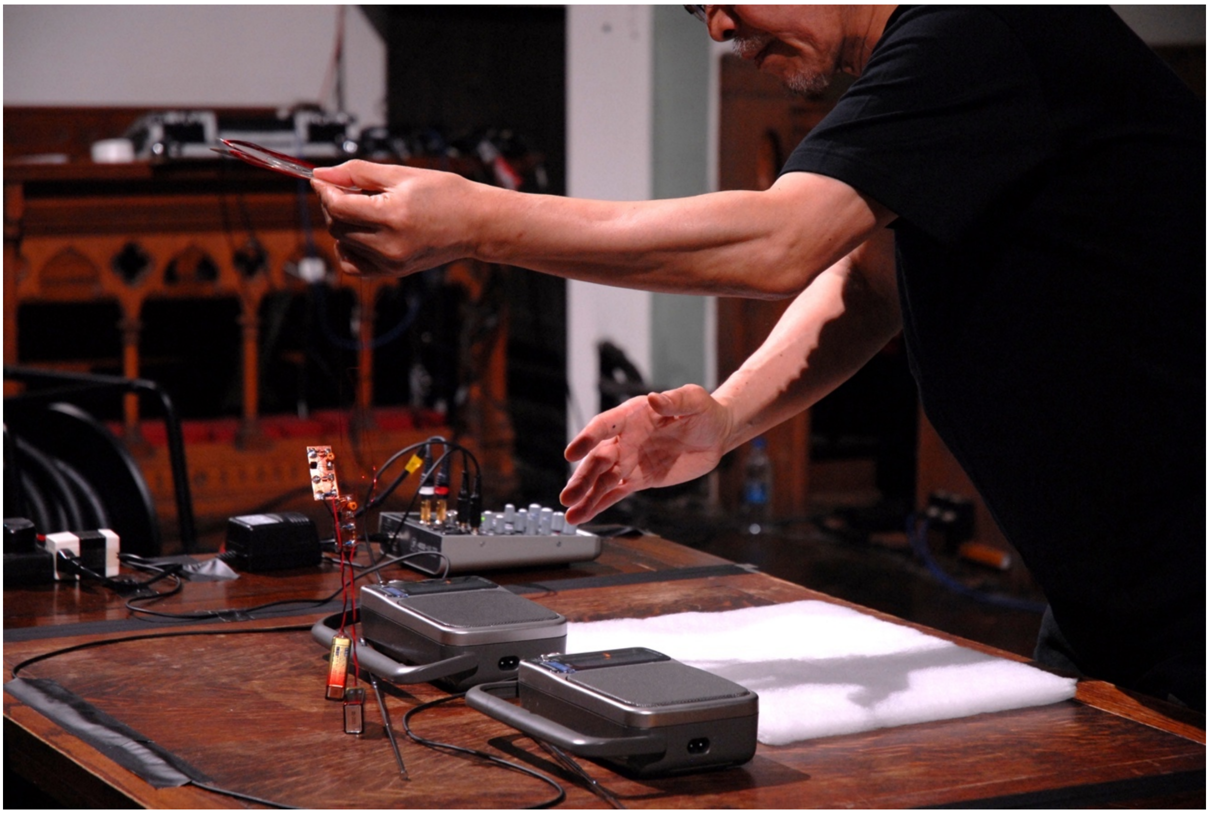

Figure 3.39. Tetsuo Kogawa performing live at *Full of Noises* festival, in Barrow-in-Furness, UK, in 2011 (from the artist's website).

3.5.3 *Anna Friz's radio arrays*

Anna Friz's practice also often involves the embodied performativity of broadcast radio. Friz grew up immersed into the world of Canadian experimental radio and states being an avid radio listener her whole life (Friz, 2008b). Her radio-related creative practice started with recording electromagnetic fields and improvising with them, which helped her better understand the medium. Since 1998 she has been working extensively with Kogawa-style low-watt FM transmitters, creating performances, installations and 'pirate interventions' that reflect on radio as a source, subject, and medium.[187] She has developed a critically informed radio practice, aiming to challenge preconceived notions about the medium, its practice and its experience. Her perspective is simultaneously historical and futuristic, *"exploring the (radio) future as imagined by the past, and proposing histories of the radio of the future"* (Friz, 2011, 5). To this extent, she proposes *"an expanded phenomenology and ontology of wirelessness that offers alternate ways to theorize transmission, communication, and media culture"* (Ibid, 6).

Visually, her installations are characterized by assemblages of portable radio receivers, counting from a couple to hundreds. Friz is particularly interested in what transpires when many radio receivers coexist in space, which is something that does not typically happen. She selects devices based on technical factors - their receiving capabilities, sound quality and sensitivity to interference - as well as for their appearance and the historical context and cultural references that implies. For example, she utilizes old radios for their nostalgic look, or generic-looking modern devices when she wants them to visually fade into the background (Ibid). While explorations of radio's physicality were initially not part of her compositional process, she has slowly began to focus more and more on that aspect, increasingly adding more instability in her work as a means to facilitate this investigation. Outside of her numerous other works using broadcast radio, Friz has composed several pieces in which radio is treated as an embodied instrument, such as *You are far from us* (2006-2008) and *Respire* (2008-09). Both of these works seek the poetics of radio outside communication. They have been presented in several iterations as performances and installations and are both better suited to explore specific sites rather than to be exhibited in a gallery or theater. They combine composed and improvised layers in a dynamic interplay with sounds generated by the receivers' response to the radioscape of the site. The noise of the system forms an integral

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[187] Friz learned how to build low-power transmitters in a workshop using an adaptation of Kogawa's design (Friz, 2011).

element of these works and is a way for the medium's physicality to enter the listener's imagination. As the artist writes, *"[t]he resulting works transport 'noise' from the status of surplus or discard to that of potential: the potential to further pry open the radio imaginary. With my multi-channel radio arrays, sound serves as representation, but importantly sound is also an index of the complex, changeable, embodied relationships between devices, bodies, radio waves, and electricity."* (Friz, 2011, 111).

Figure 3.40. Photo from an exhibition of Anna Friz' *You are far from us* showing hanging radio receivers and audience (from the artist's website).

You are far from us was Friz's first exploratory piece seeking to identify the role of the body in radio. She was particularly interested in playing with the radiophonic paradox of intimacy at a distance. As she writes, in an effort to oppose the established notion of the disembodied radio voice, she focused on the body and its sounds as a strategy for creating empathy (Ibid). Breathing features as a prominent sound source, with samples collected from baby monitors, citizen band radios (CBs) and phone calls from broadcast radio programs. Sounds that are incidental to normal radio broadcast are also strongly featured - extra-linguistic vocalizations, microphone noise, creaking chairs, and other unintentional noises produced in the studio (Friz, 2009). Types of voices common in news radio appear as well, such as eyewitness reports from various types of events (Friz notes these often produce a more sensationalistic feeling rather than the empathetic one she aimed towards). These sounds are mixed with composed or improvised layers of electromagnetic sounds, for example recordings of theremin and VLF sounds. The piece consists of 5 movements (*inhale, suspend, witness, nocturne, exhale*), focusing on these unintentional sounds to create an intimate soundscape (Friz, 2008b). The first iteration of the work used 4 low-power FM transmitters, transmitting in 2 to 4 different frequencies, depending on what the site and conditions allowed.[188] Sixty handheld receivers were suspended over the heads of visitors in an 'X' formation (sometimes formed a bit more irregularly). One third of the receivers had LED lights shining to the floor to create a dimly lit environment in an otherwise dark space (figure 3.40). The receivers are small, silver, generic contemporary devices, all of the same type. These small radios limit the volume and kind of material that can be used, as they cannot produce sound lower than the mid frequency range, but are good for sounds in the vocal range. In performance settings they are sometimes accompanied by larger radios and speakers.

Figure 3.41. Anna Friz' *Respire* exhibited at Scotiabank Nuit Blanche in Toronto as a large-scale installation, 2009 (photo from the artist's website).

Respire (2008-2009) is a follow up work that focuses on breathing. It uses a denser array of

[188] Friz uses commercial FM transmitters (generally between 50mW to 6W) as they are generally more stable than homebrew designs. Her equipment is unlicensed, but she considers it more 'squatting' than piracy - looking for a slice in the spectrum to temporary transmit her signals (Friz, 2011).

receivers (up to 250) to more directly explore the idea of radio as instrument in a way that is *"operational as well as representational"* (Friz, 2011, 112) (figure 3.41). In this piece, Friz investigated attentively the configuration of the hertzian field. Like Kogawa, she tuned FM transmitters into sympathetic frequencies so that they overlap and interfere with one another. Thus, the system produces sound even when no signal is transmitted, with receivers crackling, twittering and oscillating on their own. This denser electromagnetic field is also more sensitive to bodily interference and can be destabilized by visitors' bodies. The work is not explicitly interactive, but was made to respond to audience presence and movement. Visitor bodies blocking the line-of-sight path between transmitter and receiver interrupt signals causing bursts of sound in the 'blinded' receivers, and they reveal weaker transmissions buried by the more powerful local signal that is blocked. Often, local transmissions are overpowered by commercial stations (Friz, 2009).

Figure 3.42. Photo from the dance performance *Heart as Arena* (2011-13) by choreographer Dana Gingras and dance company *Animals of Distinction*, featuring a radio installation and sound composition by Anna Friz (from the artist's website).

More recently, Friz began collaborating with choreographers to create performative spaces where her FM systems become sound diffusers, part of the scenography, and non-human performers. *Heart as Arena* (2011-13, is a performance for 5 dancers exploring distant intimacy, love, longing, and the desire to communicate (Friz, 2013). The piece was developed during workshop sessions with choreographer Dana Gingras and her company. It involved a ring of suspended retro-looking radios, and a collection of mid-century receivers placed on the floor and handled by the dancers (figure 3.42). *Endless Love: All Transistor Model* (2015) is a durational performance-installation exploring similar themes in collaboration with dancers/choreographers Karine Denault and Dana Gingras (Friz, 2015). The piece involves 30 mid-20th century radio receivers placed on the floor and 4 speaker drivers attached to heating radiators in the room. Low-power FM transmitters overlay a responsive radio field, playing *"a drunken, time-stretched version of a love ballad, static, textures, heterodyne hums and signals"* that are broken by the interferences caused by moving bodies. Two performers scan through the radio spectrum in search of love songs, and dance with audience members and each other. Throughout the performance, Friz reconfigures the radio system into different sculptural sets, further processing inputs and outputs and interjecting feedback into the system.

Low-watt FM systems are highly unpredictable, which is part of their charm. Friz's strategy has evolved to harness this unpredictability, composing with it in mind rather than trying to combat it. She regards radio as a dynamic, animate system that consists of diverse elements: arrays of transmitters and receivers, the found radioscape of the site, the bodies of performers and visitors. This system can be tuned to become more sensitive to errors, such as human motion, distortion, interference, static, bursts of noise. In her PhD dissertation, she offers a handful of tips and observations coming from her experience with *micro-casting* systems that employ multiple transmitters and receivers (Friz, 2011):

- It is important to consider the physics of electromagnetic transmission, and recognize how it is different than, for example, the transmission of sound waves.
- It is also important to consider the particular radioscape of a site, as the same system will behave differently depending on the 'transmission ecology' around it. This depends, for example, on the presence of high-power commercial transmitters and other sources of electromagnetic radiation (e.g. power generators, lights, etc.), the architecture of the site, environmental conditions, time of day, and so forth.
- Cheap digital devices used for playback, such as CD and mp3 players, may interject loud electric humming noise due to poor shielding when they are plugged into the electrical grid; therefore, she suggests powering such devices with batteries.
- FM radio primarily travels through line-of-sight, which means that when blocking the signal of a weak transmission (e.g. a faraway commercial station or a local mini

transmitter) unknown signals may appear *"most often either a lamentable pop hit from the nearest big radio station signal or aggressive static"* (Friz, 2011, 147).

- Receivers respond in different - and somewhat unexpected - manners when placed too close to a transmitter. This includes distortion, overmodulation, and signal leakage in adjacent frequencies; digital receivers may start automatically scanning frequencies, while older ones may *"emit fluttery oscillations from receiver desensitization interference, which sounds something like an electronic pepper grinder"* (Ibid).
- Clustering many receivers together brings their antennas into resonance, which causes interferences that pass from one radio to another - high-frequency feedback oscillations resembling the chirping of birds or insects (plausibly the same phenomenon to the one mentioned in section 2.3.5 that gave the 1920s the nickname 'roaring '20s').
- Throughout the years, the radio industry has been increasingly shifting to a model were high quality radio transmitters are paired with cheap, and lesser quality, radio receivers. As a result, low-power transmitters work best with mid-20th century receivers and with more advanced contemporary models that allow tuning into less standard bands like shortwaves.
- To maximize control over the system, the transmitter and all antennas need to be tuned to the specific frequency used and coupled to high quality analog receivers. Alternatively, the transmitter has to be more powerful and its antenna installed high above, where there is less chance for obstruction of line-of-sight transmission.

3.6 DOPPLER-RADAR IN ART: EARLY SYSTEMS

3.6.1 *The Senster*

Doppler radar sensing technology was most likely first introduced in the artworld by Polish sculptor and autodidact engineer Edward Ihnatowicz. Fascinated by movement, and after struggling to find his personal voice as an artist, Ihnatowicz turned to robotics and cybernetics in his 40s aiming to create life-like sculptures with the aid of sensors and actuators. He readily embraced the techno-scientific revolution of the 1960s in order to *"enhance his understanding of the world"* following a belief that art's principal value is *"its ability to open our eyes to some aspect of reality, some view of life hitherto unappreciated"* (Ihnatowicz, 1986, 4).

Ihnatowicz's first cybernetic work, *Sound Activated Mobile (SAM)*, was presented during the groundbreaking 1968 *Cybernetic Serendipity* exhibition at the Institute of Contemporary Art in London. *SAM* was a creature-like kinetic sculpture that resembled a spine with an ear or radar dish on top. It used an array of 4 microphones to localize sound and responded by moving its spine and rotating its 'head' towards the source. The sensing system was not perfect, making *SAM* appear temperamental and thus more lifelike to the audience.

That same year, Ihnatowicz was commissioned by Philips to create a more advanced work for the company's Evoluon, a permanent exhibition of technology in Eindhoven, the Netherlands. *The Senster* was an ambitious project: an autonomous cybernetic sculpture that reacted to its environment by responding to sound and movement around it. It was a 5m long and 2.4m tall mechanical creature made of welded steel tubing with all its joints and hydraulic actuators exposed. Its form and mechanics were inspired by the lobster claw but instead of a pincer it had an insect-like head. A microphone array, similar in concept and operation to SAM's, stuck out from the head's center, looking like alien eyes; two gold plated horn antennas were on either side of the head, like alien ears (figure 3.43). These antennas were coupled to Doppler radar modules and functioned as its radio eyes. The radar system operated at 9.6GHz and had a range of about 8m, sensing radial motion towards or away from the creature's head; the optimal angle of the antennas was determined experimentally. The system only tracked direction and speed of motion, given by the Doppler shift in frequency, and ignored the size of the moving person (which influences the amplitude of the Doppler signal). Still, this was a radical technology for an art piece at the time. The visible serial number on one of *Senster's* radar units is a testament to how obscure this technology was, as it shows it to be just the 251st such device fabricated (Stravers, 2004).[189]

The Senster was developed with the help of Philips engineers and the support of the University College London's Mechanical Engineering department; it took over two years to be completed. It was controlled via a hybrid analog-digital system using a digital computer made by Philips, making it most probably the first computer-controlled sculpture. The computer processed sensor inputs and controlled the hydraulic actuators via a 'predictor' circuit. This was used to translate the digital commands to smooth accelerating and decelerating gestures that passed through the different joints of the creature, causing it to appear life-like. When the 'creature' heard something, it would first move its head and then the rest of the body would follow - the louder the sound, the faster it would move towards its

[189] The doppler radar was a Hewlett-Packard 35200B/001 unit (Stravers, 2004). For more information on the mechanics, electronics, and software of *The Senster* see (Zivanovic 2005b).

source. To make the behavior more complex, Ihnatowicz programmed it to back away from the loudest sounds, seemingly 'afraid'. Its response to motion was similar, being drawn to gentle movements bur recoiling away from more sudden ones. The unpredictable behavior of the public, compounded by the acoustics of the exhibition space, gave *The Senster* a behavior much more intricate than the simple rules it operated with would suggest.

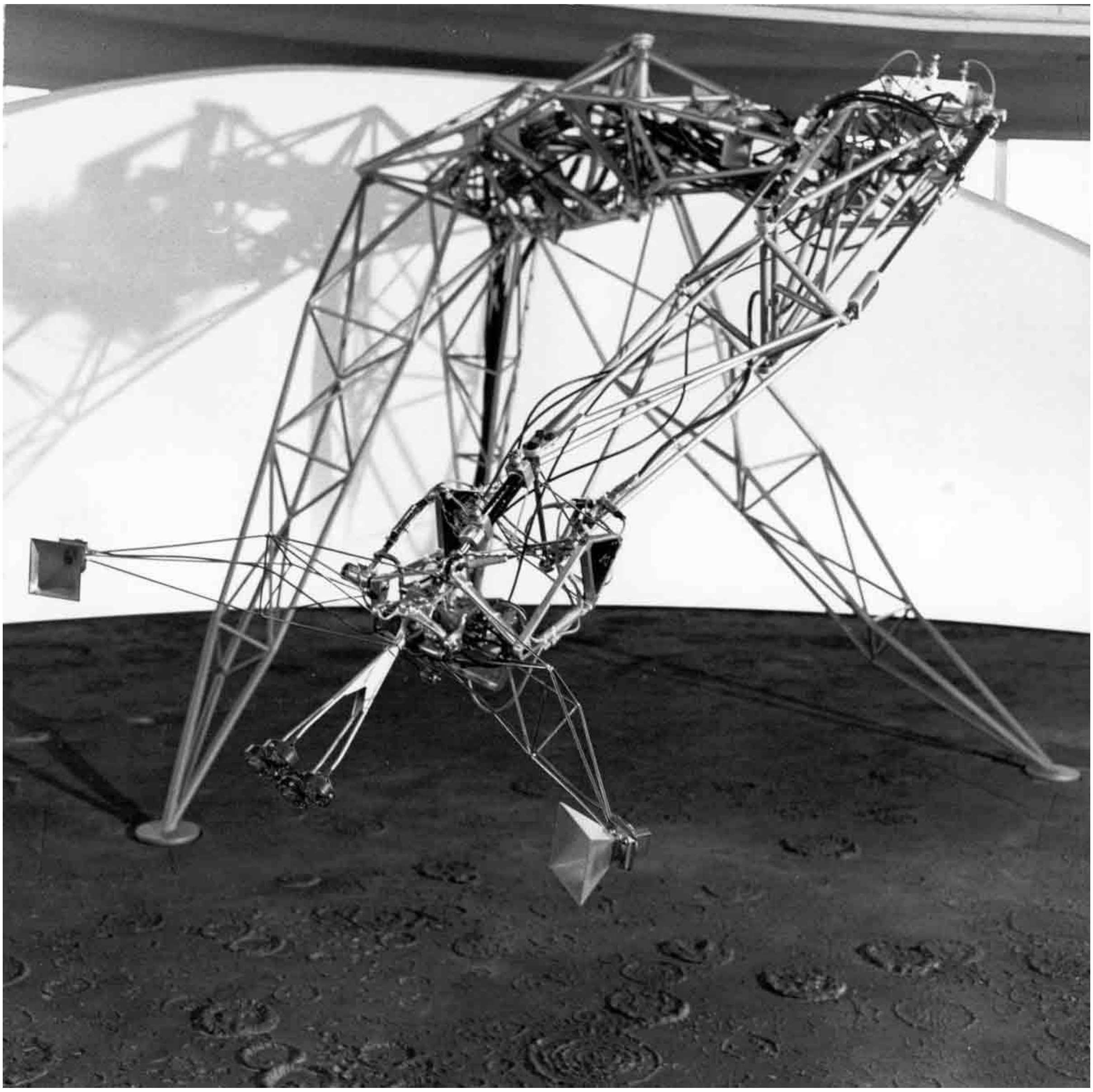

Figure 3.43. Edward Ihnatowicz' *Senster* at Philips' Evoluon in 1971, with two horn antennas visible on the left and right of the sculpture's 'head' (photo from the Philips archive, in Zivanovic 2005b).

The exhibition opened in September 1970 with *The Senster* confined inside a circular area, like a mechanical animal in a zoo (figure 3.44, see also a video in Zivanovic, 2005c). Its behavior was *"more like a large, curious but distracted, herbivore rather than a dangerous* *carnivore"*, making it less threatening and more inviting for interaction (Zivanovic & Davis, 2011, 59). Ihnatowicz remained in Eindhoven for a few months after the opening to observe the interactions between visitors and the sculpture, tweaking the program accordingly. While this was his first contact with software programming, he considered it to be the future and hoped that more programs could be developed to give his creature different characters. He soon turned to Artificial Intelligence as a potential way forward.[190] Somewhat ironically to his desire for new programs, however, the piece was taken down and dismantled in the end of 1973 due to *"bad publicity",* which Ihnatowicz attributes to Philips engineers altering his program *"in order not to cause too much excitement and noise"* (Ihnatowicz quoted in Zivanovic, 2005a, 106).

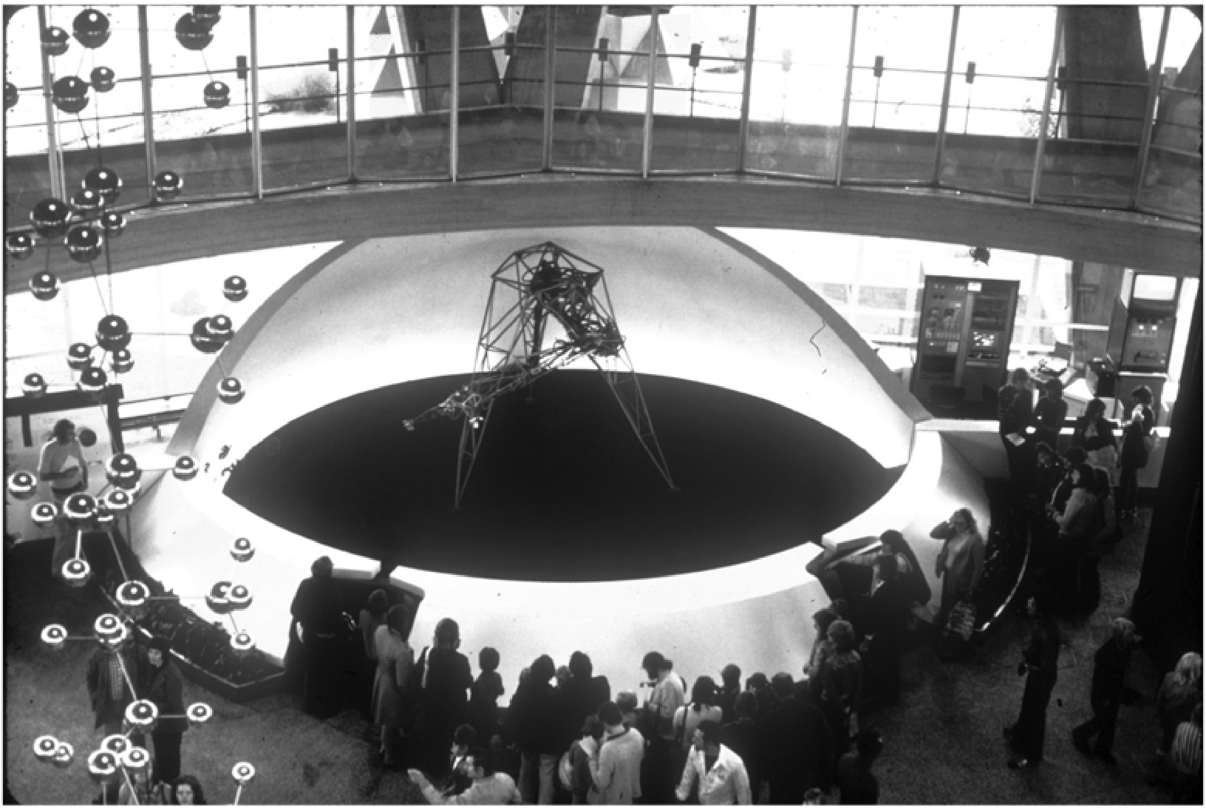

Figure 3.44. A wider view of Edward Ihnatowicz' *Senster* at Philips Evoluon, showing the sculpture's zoo-like enclosure and audience around it. The cabinet on the right of the enclosure housed a 16-bit Philips P9201 computer running the software and the hydraulics controlling the sculpture (Stravers 2004) (Photo by unknown photographer).

For Jasia Reichardt, curator of *Cybernetic Serendipity*, *The Senster* was a predecessor of the ultimate machine: a sculpture that has desires and needs, that moves and responds to the environment, that can dialogue with others and can restore its own energy. While the piece

[190] For more on Ihnatowicz approach of artificial systems and AI see (Ihnatowicz, 1976).

did not achieve all that, it came close enough, appearing to have its own mechanical agency and managing to *"provoke the kind of reactions which one might expect from people who are trying to communicate with a person or an animal"* (Reichardt, 1972). Nevertheless, Ihnatowicz's work - *SAM, The Senster*, and *The Bandit*, his next and last piece - remained somewhat of an oddity to the art world for a couple of decades. One of the reasons, as acknowledged by Ihnatowicz himself, was the very high cost of producing such works which was aggravated by the complexity of the combined mechanical, electrical, and software engineering involved. This resulting in Ihnatowicz's works influencing researchers in the fields of robotics and Artificial Intelligence research much more than they did other artists (Zivanovic & Davis, 2011).

3.6.2 *Steve Mann's Doppler gadgets*

With Doppler technology becoming commercially available at a lower price in the early 1990s, a handful of art-oriented projects using it as a new form of motion sensing appeared. While most of these results are rather naïve artistically, they are worth mentioning briefly as the early steps of a type of radio-based interaction that is founded on dynamic movement rather than static positioning.

In 1991, Canadian inventor and researcher Steve Mann - most famous for his sousveillance wearables - reported in Leonardo Journal on a new project he was developing, called *DopplerDen* (Mann, 1991). His goal was for it to become an interactive environment that used the psychological effect of Doppler-affected light and sound to produce the sensation of being in *"a time warp"* (Ibid). A computer monitor, a number of backlit windows and other light sources, together with a clock and a radio set playing a song, all responded to the speed of a person's movement: lights changed from red to blue, a song played faster or slower, the clock ticked faster or even stopped when one stood still. All this was meant to create the illusion of time slowing down or speeding up according to one's movement. Mann reported having several such devices at hand with the idea being to juxtapose *"the modern-looking computer and traditional decor ... to set the mood for the anachronisms that enhance the twisted sense of time"* (Ibid). At the time of the article, he was *"still looking for the ideal place to set them all up"* (Ibid).

A year later, having just joined the MIT Media Lab, Mann reported on a related project under development, called *DopplerDanse*, and gave some details on the underlying technology (Mann, 1992). The project aimed to allow dancers to control sound through radio fields but in a manner different than the Theremin-based systems we have seen in the previous sections because his system captured dynamic movement rather than position in space. Mann used a number of X-Band doppler radar modules (operating at 10.525 GHz) that were commercially deployed as motion-detectors "*for burglar alarms, automatic doors and automatic lights*" (Ibid). The voltage output of these modules was directly transduced to sound with the intervention of a low-pass filter. Mann included a more detailed schematic of that system in a 2017 report (Mann, 2017).[191] As he initially wrote, *"[w]ith DopplerDanse, when a dancer moves quickly, a comparatively high-pitched squeal of sound is produced; a dancer's slow movements result in a deep growl. Acceleration produces chirps. The whole Doppler sound spectrum is produced in a dancer's walk toward one of the radar units: the dancer's body creates a deep growling sound, yet over that sound can be heard a periodic chirping caused by arms swinging back and forth"* (Mann, 1992). He added that one could produce more intricate sounds by further processing the signals, for example by quantizing them in a musical scale, or using them to trigger a drum machine; one could even spatially arrange several directional modules to allow grabbing different notes in space. Mann described how this - rather facile - mapping was used: *"In one performance, seven dancers with pale skin and white clothing created an octave by representing white piano keys, while the remaining five dancers with dark skin and black clothing represented black piano keys. Each dancer's movement sounded a different note. Simultaneous movements by the appropriate dancers produced chords"* (Ibid). He also described a few different configurations with *"very interesting spatial effects"* (Ibid): One involved 3-radars whose output was routed to speakers around the room - one in front, one on the side and one above the performer. Another one he installed in his car, placing 4-radar modules in its corners and connecting them to 4 speakers so that he would know when other cars approached.

3.6.3 *MIT's Magic Carpet*

Another MIT project that used Doppler radar was the *Magic Carpet* from 1997, led by Joe Paradiso (see Paradiso et al., 1997, 1999 and 2000; Miranda & Wanderley 2006). Originally

[191] In this more recent report, Mann (2017) referred to an interesting problem of the *DopplerDanse* system, that its low-frequency sound caused certain objects to vibrate, such as drywall, cardboard boxes, and furniture. When these objects were within the radar range, their vibrations would be picked up by the doppler system, then amplified by the sound system, which would in turn cause more vibrations, thus causing a feedback loop. He suggested that this type of artifact can be harnessed to perform a form of acoustic imaging to reveal areas where objects are most responsive to sound, and thus less stiff or solid and more vulnerable to external forces. This would, for example, allow police officers to scan a wall or a door to find its weakest points and easily force themselves in, as he wrote.

developed for Todd Machover's interactive *Brain Opera* from 1996, the *Magic Carpet* was an interactive audio environment employing a combination of sensors: A piezoelectric grid under a carpet tracked foot position and pressure, while a pair of Doppler-radar transceiver modules where placed on stands to sense upper-body movement (figure 3.45). These were simple and inexpensive modules operating at 2.4GHz. They were coupled to directional micropatch antennas focusing microwave energy to a 20º frontal beam (with sidelobes). They had a range of about 2.5m and radiated energy at about 10mW - much lower than regulation limits, and therefore considered safe for interaction. Bodies moving within the radar beams reflected microwave energy back to the receiver antenna, shifting the signal's frequency up when moving towards it, and down when moving away; the faster the movement, the larger the shift. The range of the frequency shifts the system could detect was tuned to human motion, and was thus limited between 0.1-100Hz. The Doppler signal was amplified and preprocessed through an analog circuit to produce three different signals (Paradiso et al., 1999):

- Full-wave rectifying and low-pass filtering it produced a voltage corresponding to the amount of motion.
- High-pass filtering and full-wave rectifying it corresponded to velocity of motion. Peak detecting this signal produced fast-attacking triggers when quick movement occurred.
- A more complex differential correlation of the signals from the two modules was used to reveal the direction of motion.

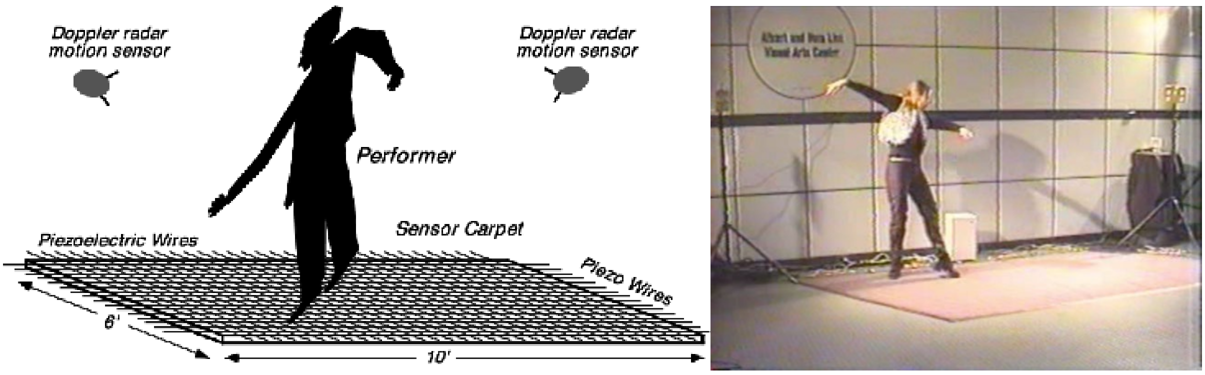

Figure 3.45. MIT's *Magic Carpet*. Left: Installation diagram (from Paradiso, 1999). Right: Video still from a performance by MIT researcher and dancer Mia Keinanen at Media Lab Atrium circa 1999 (from Paradiso, 2018b).

These signals were digitized at a sampling rate of 50Hz with an 8-bit resolution, and were sent to a computer for further processing. While the sensing system was fairly sophisticated, the mapping was rather banal. The computer output MIDI values, originally mapped to a 3-

voice polyphony. The piezo sensors controlled a low pedal note and a middle harmonizing voice, as well as the overall timbre and musical structure. The radars controlled the high melodic voice - with speed, pitch and spatial position mapped to motion – and the type of chord to harmonize with (defined by the direction of movement). The authors described the output as a *“relaxing, ‘new age’ soundscape”,* intuitive and responsive to subtle movements (Paradiso et al., 1999, 145). Another mapping used environmental sounds. In that case, radar-detected motion controlled wind and rain sounds, with fast gestures sounding like thunder and stepping on the carpet creating percussive and crunching noises. The artistic naivety of these mappings was reportedly a conscious strategy from the makers to engage with a general audience that was unfamiliar with contemporary, experimental, or electronic music. This radar system was also used in the *LaserWall* project from 1998. In that configuration, two Doppler modules were placed behind a video projection wall to control interaction with the projection, complementing a scanning laser rangefinder.

3.6.4 *Arthur Elsenaar’s Body Convention*

In 1993, around the same time as Mann’s experiments, Arthur Elsenaar - a young Dutch artist of the same age as Mann - presented *Body Convention*, a performance combining muscle stimulation with Doppler radar sensing.[192] Elsenaar had started tinkering with radio while still at school, becoming a *“well known supplier of home-made radio and television transmitters”* in the Dutch pirate scene of the 1980s (Elsenaar, 2010, iii). Following a stint as Stelarc’s assistant in 1990, and enthralled by the way the human body responds to electricity, he began working with muscle stimulation with a similar experimental DIY ethos. He would later become well known for his pioneering ‘Face hacking’ techniques and his lecture-performances in which, with the aid of electrodes and software, he explores the human face as a ‘computer-controlled display’.[193]

Body Convention was Elsenaar’s first work using electrodes and the only one utilizing radio as an interaction interface. Like many of his later performances, the piece was very much tongue-in-cheek while being technologically robust and innovative. The artist stood motionless in a white suit in a crowded exhibition holding a metal plate with a framed picture

[192] This was Elsenaar’s graduation piece in digital arts, first presented at the Art Academy Minerva in Groningen, and subsequently exhibited in Amsterdam at the Fons Welters Gallery and the Doors of Perception conference.

[193] For Elsenaar, *“[h]acking is a practice based activity that is situated in between the disciplines of art, science and technology”* (Elsenaar, 2010, 1). It draws from and contributes to these disciplines but is not part of any of them.

of a sausage (Elsenaar, 2011).[194] The prop covered a Gunnplexer, a Doppler radar sensor similar to those used in police radar guns, and some circuitry. This created a sensing zone around his body, *"like an aura, or an extension of my skin into space, into which people can walk"* (Elsenaar quoted in Marshall, 1993). When an audience member entered this zone, the amplified Doppler signal was sent to four electrodes attached on his body, two on the jaw muscles, and two on the shoulder muscles. The current stimulated these muscles causing them to twitch and convulse. The faster someone moved towards him, the greater the shock.[195] The electrodes on Elsenaar's face, very raw versions of his later systems, made all facial muscles contract to an expression of pain while the shoulder electrodes made it look like his body was shrugging the pain off (figure 3.46).

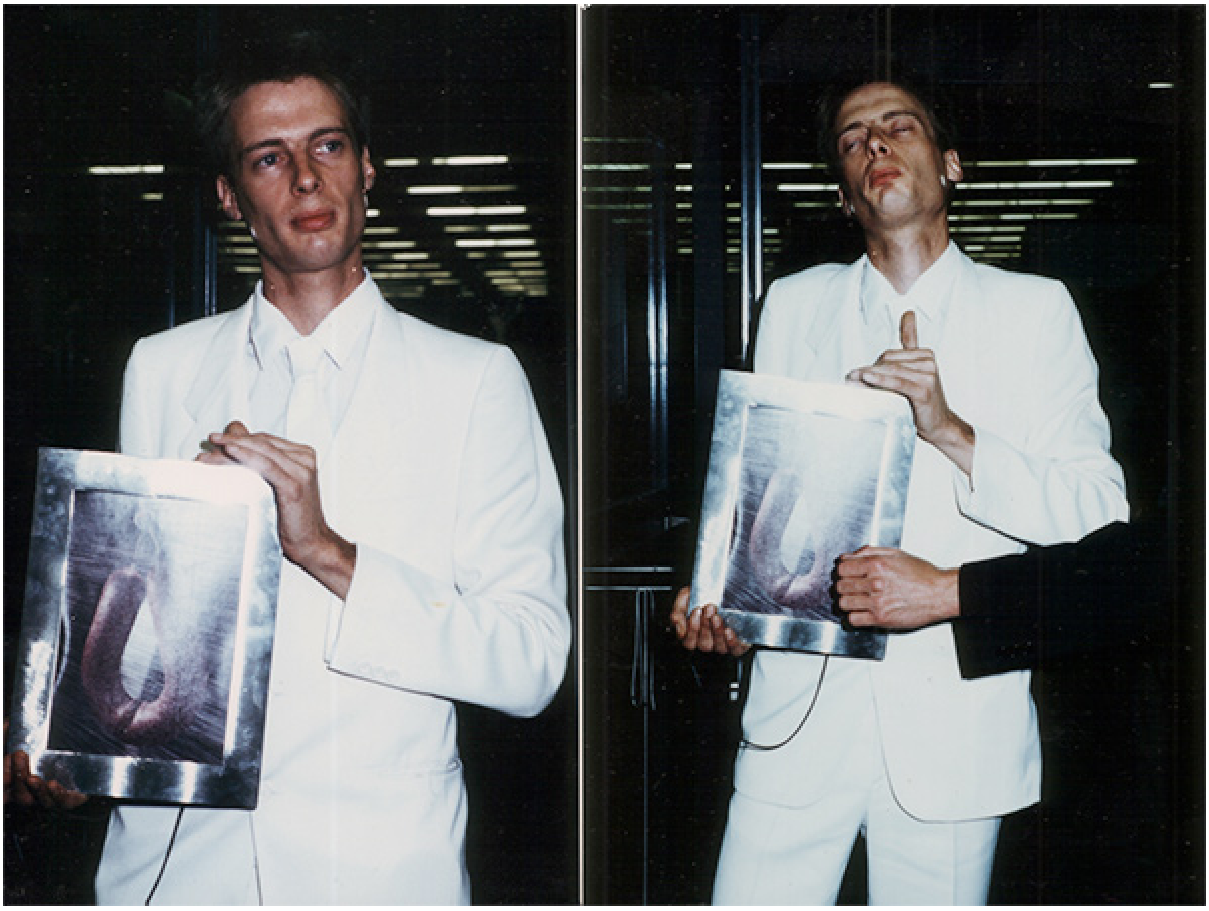

Figure 3.46. Photos of Arthur Elsenaar performing *Body Convention* in 1993. Left: without stimulation. Right: with muscles triggered by doppler-controlled electric shock (photos by Josephine Jasperse, from Elsenaar 2020).

[194] This *"manipulated meat",* as he called it, was meant to reference the manipulation of the body by the electrodes (Marshall, 1993).
[195] While the artist mentions that the system reacted to proximity (Elsenaar, 2010), watching the video and judging from the circuitry description – a few transistors, an amplifier, and a square wave generator - it is likely that in reality it tracked the speed of movement when in proximity,

Elsenaar was particularly inspired by 19th century amateur research of *"gentlemen scholar-types just running current through their bodies or brains and recording the results"* (quoted in Marshall 1993).[196] In a way, *Body Convention* is a reversal of Georg Mathias Bose's *Venus Electrificata* from the 1740s. Also called the *Electric Kiss*, this *"interactive salon performance"* featured a statically charged, attractive female 'performer' (Elsenaar & Schaa, 2002). Any guests trying to touch her – or invited to kiss her – received an electric shock, the goal being to illustrate science in a tantalizing and playful way. Instead of shocking the audience, however, Elsenaar rewarded their interaction with the knowledge that it causes the performer pain - much like Cillari did almost twenty years later (as explained in section 3.4.5).

With this piece, Elsenaar attempted to make a statement against a prevalent notion in media arts of the time: that the body was becoming irrelevant. The emergence of a new communication medium in particular, the Internet, was seen as a challenge to the relevance of the body's physicality, and brought forth many claims that human contact would no longer be necessary in an increasingly virtualized world. This was an absurd idea for Elsenaar, which he decided to oppose with works that focus on the body and that use technology not to negate, but to enhance physical experience. The piece also meant to tap into our fear and mystification of electricity. Elsenaar, despite being a seasoned practitioner of the electrical arts, admits about himself that, *"besides the knowledge to work* with *electricity, I never gained a full understanding* of *electricity as a natural phenomenon"* (Elsenaar, 2010, iv).

3.7 Godfried-Willem Raes's Doppler Radar Instruments

3.7.1 *From ultrasonic sonar to microwave radar and from electronic sound to musical robots*

Around the same time as Elsenaar, and about 100 miles away at Logos Foundation in Ghent, Godfried-Willem Raes was developing the first of a series of instruments based on Doppler radar. Raes, Belgian composer, performer, instrument maker and co-founding director of Logos, a musical research and production center, had been experimenting with translating movement to sound since the early 1970s, fashioning his own microphones and transducers to make up for the unavailability of off-the-shelf components (Raes, 1997a/2019). For over

[196] A notable influence on Elsenaar's subsequent work is Galvani follower Guillaume Benjamin Armand Duchenne de Boulogne and his mid 19th century ideas and techniques for electrotherapy via muscle stimulation.

10 years he had been developing his own real-time sonar-based motion sensing techniques seeking to create invisible and contactless gestural instruments with configurable mappings. His first such performative piece, the music theater performance *Holosound* from 1980-83, analyzed ultrasonic Doppler shifts to trace movement in 3 dimensions. It featured 1 ultrasound transmitter and 3 receivers placed on the corners of an imaginary tetrahedron – a layout Raes chose for technical, practical, and aesthetic/philosophical reasons (Raes, 1999/2019). The dimensions of the tetrahedron were derived from the performer's height. His ensuing work, *Book of Moves* from 1992, was a large scale composition featuring a series of invisible instruments, samplers and synthesizers, in which he mapped specific gestures to musical parameters with a variety of strategies, from very simple to more complex ones. In a later piece, *Songbook* (1995), he used gestures to process the performer's voice through dedicated DSP hardware (with pitch shifting, harmonizers, filters and other effects) (Raes, 2012).

Raes started using microwave radar with his piece *Virtual Jewsharp* from 1993, which he developed during his doctoral research as a natural continuation of his sonar-based work (Raes, 1997/b2016). That instrument used Doppler radar modules operating between 10-20GHz to detect the velocity, acceleration, and mass of a moving body (figure 3.47). Although few details are available on that instrument, the way to play it is described as somewhat reminiscent of or inspired by playing a jaw harp (or 'jew's harp'), hence the name.[197] Sound was generated electrically, passing the module's output through a simple analog pitch converter (Logos Foundation, 2021f). Raes's note that "*acceleration is used for the melodic aspect of the sounds and body mass for the global sound volume"* supports this theory (Ibid). The work was first shown in the summer of 1993 as an interactive installation with its modules placed at the medieval gates of the Austrian town of Krems. It premiered in concert as an instrument 3 weeks later, played by four performers each with their own module tuned at a different frequency. In the next few years it was shown in various occasions in these two formats.

[197] Raes (2016) writes: "*The project is an implementation of a virtual jewsharp, since the movements needed to truly play it closely resemble those required to play the acoustic jewsharp. Of course, since no real and physical object is involved, the cavity resonance of the mouth is not used here as a means for timbral and harmonic control of the instrument. Instead, acceleration is used for the melodic aspect of the sounds and body mass for the global sound volume."*

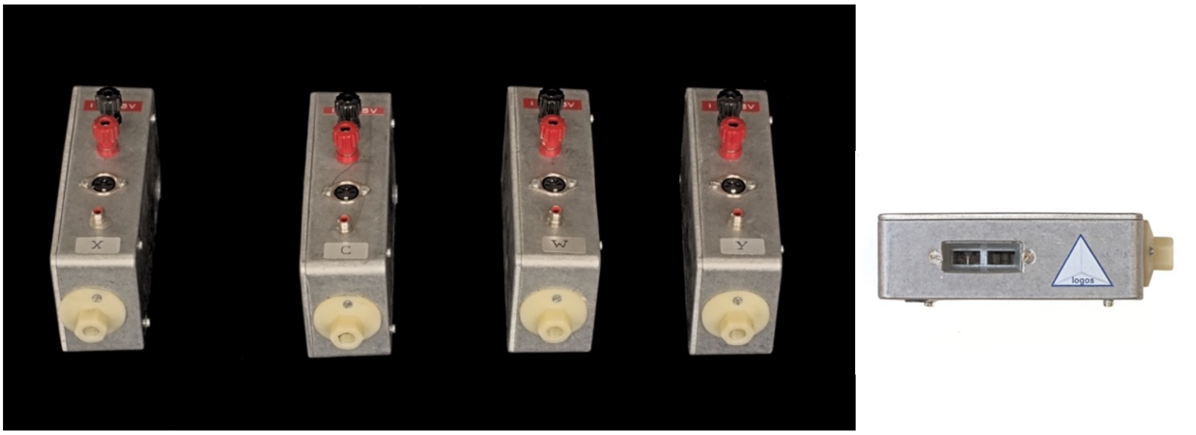

Figure 3.47. Godfried-Willem Raes's *Virtual Jewsharps* doppler radar system. Left: Rear view of four identical radar modules built in 1993, showing banana connectors for battery power, screw connector for tripod mounting, RCA connector for audio, and alternative DIN connector for power and audio. Right: Front view with the transmitter and receiver antennas visible (photos from Logos Foundation, 2021f).

By the turn of the millennium Raes had moved away from electrically produced sound, taking an intentional stance against loudspeaker-based electronic music – which he believes to be a mere virtualization of acoustic reality - and positioning himself within the aesthetics of a long tradition of mechanical music automata (Raes, 2012).[198] Since 1990 he has been developing an impressive robotic instrumentarium at Logos Foundation called the *Man and Machine Robot Orchestra* (M&M in short). As of spring 2022, this growing collection of musical robots consists of 81 instruments: 25 automated percussion instruments, 21 pipe and reed organs, 15 monophonic wind instruments, 8 string instruments, and 12 uncategorized (figure 3.48).[199] Raes calls them 'naked robots' because - like *The Senster* - the mechanism of these instruments is made entirely visible to reveal their inner workings. The instruments use MIDI-controlled actuators to produce sound by purely acoustic means. Starting with the sonar-based *Gestrobo* series in 2001, the M&M orchestra has been the exclusive sonifier of Raes's motion sensing systems, with gestural input being analyzed by a computer and used to control the orchestra via MIDI.

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[198] For an informative brief history of mechanical automata and their relationship to electronic music see (Wilson, 2017).

[199] For a complete list of the instruments, including links for more information, see (Logos Foundation, 2022). The orchestra is made available for composers to write works for it and present them at Logos, with 67 composers having written at least one work for it by 2011. Most of these compositions use a fixed MIDI score, while some are algorithmically generated or interactive using, for example, sonar or radar sensing, or audio analysis. For an overview of this work, see (Maes et al., 2011).

Figure 3.48. Photo of a collection of instruments from the *Man and Machine Robot Orchestra* at Logos Tetrahedron, taken circa 2011 (from Maes et al., 2011).

3.7.2 *Raes' many doppler radar systems*

Raes is undoubtedly the most prolific, inventive, and diligent artist working with radio-sensing for embodied sound performance. For about 20 years, he and the Logos lab have been experimenting with a variety of Doppler radar modules operating at different frequencies – 1.2GHz, 2.45GHz, 9.35GHz, 10.5GHz, 12GHz, 22GHz, 24GHz. This has resulted in the development of a number of technically impressive complete systems for far-field radio-frequency sensing.

In a report first published in 1999 (and updated every few years since), Raes made an early presentation of the sensing technologies developed at Logos (Raes, 1999/2019). The report involved details on how to create invisible instruments with sonar and radar, as well as on the software used to derive information from movement data generated by these interfaces. It introduced a microwave radar system based on three 12GHz Gunn diode transceivers in an equilateral triangle configuration (somewhat resembling my own isosceles setup for *Hertzian Field #2*). This geometry was preferred to the tetrahedral one used by Raes' sonar system because the particular radar modules had a narrower transmission beam than his ultrasound transducers (Ibid). They were also noisier and less stable. These modules produced the Doppler signal internally, outputting a low frequency voltage corresponding to the Doppler shift. In early implementations, Raes sonified the Doppler signal directly, like in the *Virtual Jewsharp*. In later works he used a gesture recognition software developed initially for the sonar system, aiming to make a more versatile instrument that would be more than *“a magical 3-dimensional super thundersheet”* (Ibid).

As Raes wrote in that report, microwave radars present both advantages and disadvantages in comparison to his sonar systems: Firstly, they respond much faster (about 880.000 times) because radio propagates at the speed of light and ultrasound at the speed of sound. Microwave radar is also immune - or at least less sensitive - to some of the interferers of sonar, such as differences in temperature within a space, leaking gasses, airflow caused by wind, fans, air conditioning, and moving audiences, as well as noises with ultrasonic components in them like breaking glass. On the other hand, new challenges are also introduced, as bodies outside the sensing triangle or tetrahedron can interfere with the system. This was due to the significant sidelobes of his directional antennas, and because radiation is not dampened much in free space but can even passes through walls. Radar modules can also interfere with each other, so it is necessary to tune each one at a slightly different frequency, just above the maximum of the expected Doppler shift.[200] Depending on their frequency, these systems are also sensitive to interference from ionizing sources such as electroluminescent and gas discharge lights, CRTs and various types of transmitters.[201] Finally, one may need a license to use these microwave instruments, depending on their frequency and national legal framework. For the above reasons, but also because his sonar

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[200] Elsewhere, Raes suggests spacing modules at least about 20kHz apart to avoid any audio-rate artifacts (Raes, 2003/2017). Modules can be manually tuned with the help of a high-frequency oscilloscope which may be a challenge to obtain. Otherwise one must hope that the modules remain tuned apart, or use power supplies with slightly different voltages, to take advantage of the fact that power can effect transmission frequency (Raes, 2004/2021).

[201] Raes has been mentioning a list of equipment to avoid placing near his microwave instruments since the *Virtual Jewsharp*, stating that “*the technology can only be used at locations free of ionising sources. So places with permanent electroluminiscent tubes of any kind (including sodium vapour), CRT's, X-ray equipment, particle accelerators, satelite communication and TV emitters/repeaters are not to be considered for performances nor installations of these devices.”* (Raes, 1997b/2016). Such devices, as well as gas discharge lights, were also problematic for his later, more sophisticated instruments operating in the X-band (8-10.5Ghz) or higher, between 10-30GHz (Raes, 2009c and Raes, 2003/2017). These interferents were less of a problem around 2.45GHz, nonetheless, Raes still suggests that *“TL-light, mercury vapor bulbs (...) welding equipment, sodium vapor bulbs within a range of 10 meters around the setup should be discouraged.”* (Raes, 2003/207). There is no mention of interference by other wireless technologies operating in the 2.45GHz band (e.g. WiFi and Bluetooth).

system was smaller and more portable, Raes initially deemed sonar to be a more practical solution than Doppler radar.

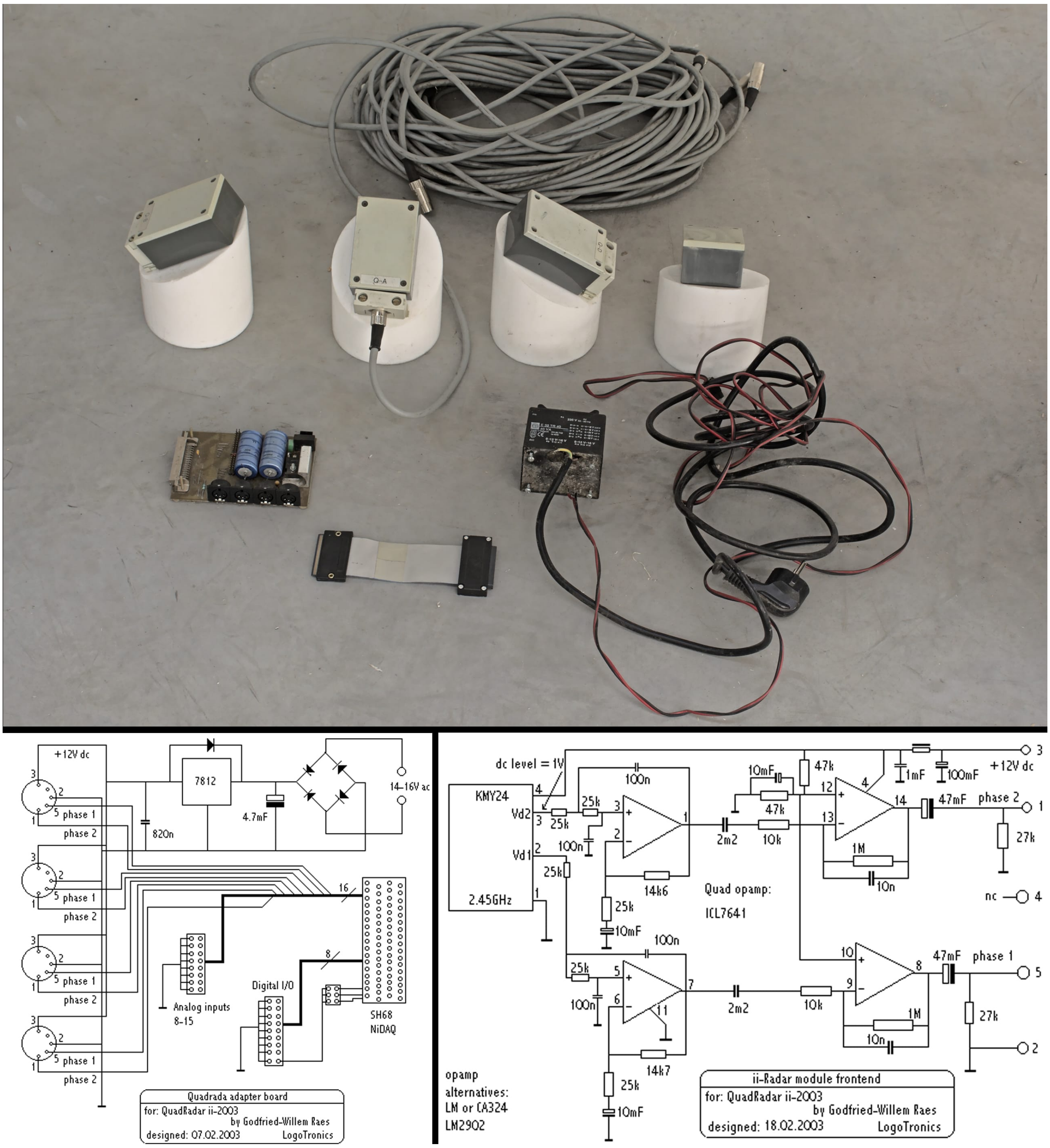

Figure 3.49. Godfried-Willem Raes' *Quadrada* doppler radar system. Top: Photo of the 4 radar modules, on 12cm plastic mounts used for placing them angled on the floor (on a square formation around the performer). The DIN cables connect them to the *Quadrada* adapter board, which provides power and connects to a computer running special software developed by Raes. Bottom left: Schematics of the adapter board. Bottom right: Schematics of the electronics for each radar module (all images from Logos Foundation, 2021d).

Further research produced more refined microwave systems, with *Quadrada* from 2003 being the first major version (Raes, 2003/2017) (figure 3.49). This system operated at 2.45GHz and was an improvement over both Raes' original radar implementation and sonar sensing system.[202] The modules had a range of up to 5-8 meters, with motion farther away masked by the device's internal noise. They were equipped with patch antennas, with a primary frontal radiation beam of 120° and some sensitivity on the rear side. As the name suggests, *Quadrada*'s standard configuration involved four transceivers in a square formation - or more precisely a cross - with diagonally opposing modules facing each other (see figure 3.53). Because of this layout, *Quadrada* could estimate the absolute position of the performer within the square, in addition to implementing the capabilities of its predecessor – tracking velocity, acceleration, body mass and certain predefined gestures.

PicRadar was a variant developed in 2004 (figure 3.50). It was based on four low-power Doppler radar modules operating at 9.35GHz with a power rating below 1mW (Raes, 2004/2021).[203] This system operated at a higher frequency than *Quadrada* (making its interaction with the body slightly different), its active range was slightly smaller (up to 5-7m), and the on-board patch antennas had a narrower frontal beam of about 60° with weak sidelobes; a strong lobe in the back was still present.[204] Furthermore, the signal-to-noise ratio was slightly improved, at 42dB. The performative layout for *PicRadar* was the same as for *Quadrada*, although Raes mentions potentially developing a cubic configuration with 8 transceivers.

Yet another variant was the *BumbleBee* from 2009, operating at 5.86GHz (Raes, 2009b/2010). This system was based on a commercial pulsed Doppler radar board by the same name.[205] It was considerably cheaper than the other systems with each module costing about $100 at the time.[206] On the other hand it was also less precise, featuring a signal-to-noise ratio of 30dB. Nonetheless, its lower frequency made it less susceptible to interference from lights and other ionizing sources than *PicRadar*. The antenna was integrated on each

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[202] The Doppler modules used in *Quadrada* are: Siemens KMY24 or HFMD24.

[203] The *PicRadar* instrument was based on the Waldmann HFMD10 doppler module. Its power rating is about 1/30th of a WiFi transmitter, which makes it safe for use.

[204] It is worth reminding the reader that radars operating at different frequencies have slightly different responses, as waves in different parts of the spectrum are affected differently by objects in their path. Modules operating at different bands are thus not interchangeable and cannot be combined without software modifications in a system like *Quadrada*, as they will skew results. On the other hand, as has been discussed in section 5.4.4, a layered system where modules of different frequencies cover the same area can give better results with increased resolution. This is in essence the principle behind Raes' latest *Holosound* system which combines sonar and microwave radar.

[205] For more information on the *BumbleBee* doppler radar module see (Samraksh Company, 2015).

[206] As a comparison, *Quadrada* and *PicRadar* were available on sale from Raes and Logos Foundation at much higher prices - *Quadrada* between €4,000-10,000 and *PicRadar* at €350 for a single transducer and about €1,500 for the complete system.

board producing a frontal radiation angle of 60°. The operational far-field range of the system was between 1-10 meters (like all other Logos systems, the near field range (0.2-1m) was not utilized). Raes noted that the boards had to be placed a wavelength or more apart from grounded objects (5.2cm), as these objects absorb radiated energy.

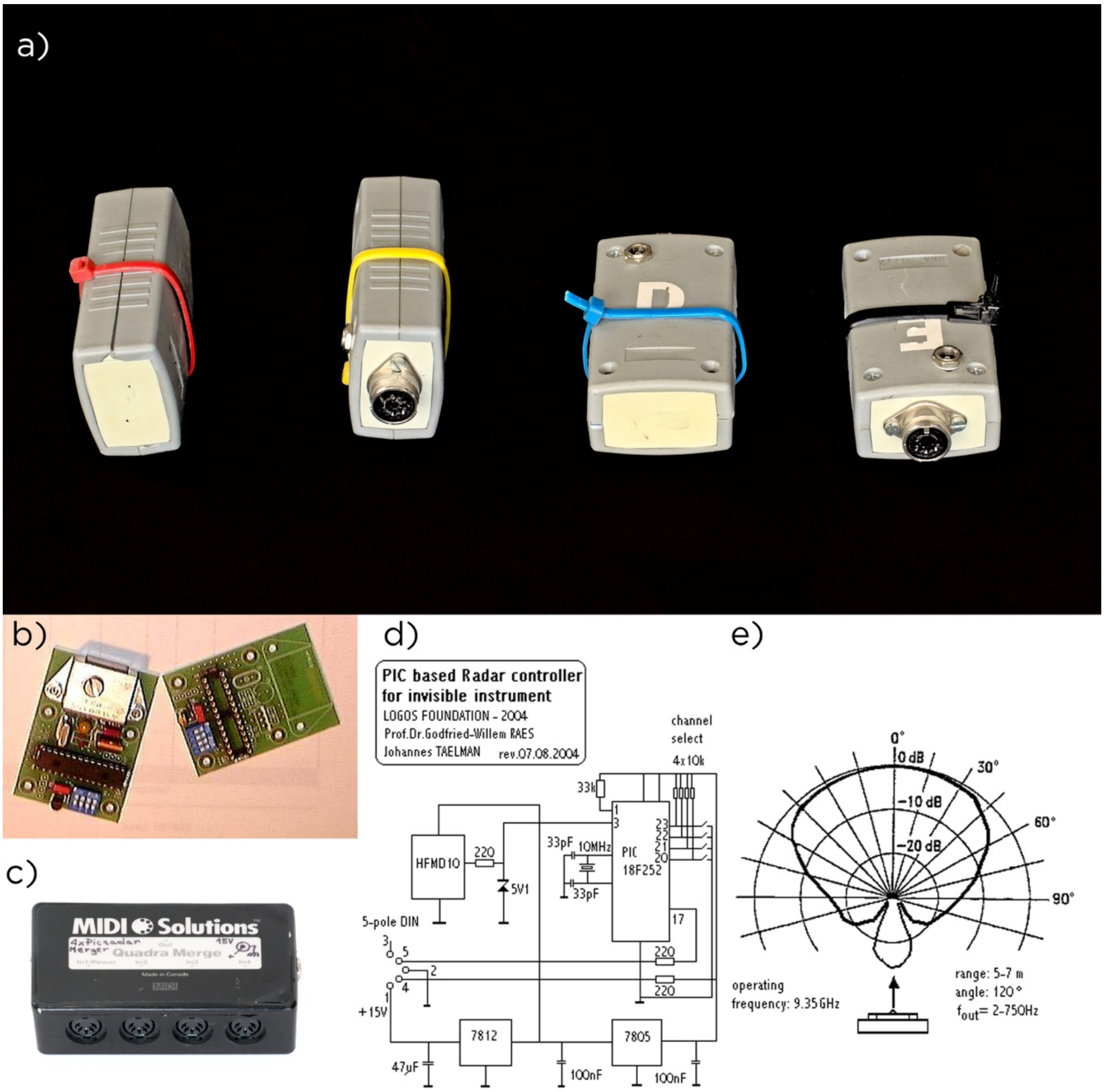

Figure 3.50. Godfried-Willem Raes' *PicRadar*: a) Photos of the 4 modules of the second generation of that sensing system, meant to be placed in a square formation around the performer like *Quadrada*. Each module consists of a microwave doppler radar, a circuit, and a PIC microcontroller that converts data to MIDI. The PCB can be seen in (b) and the circuit schematics in (d). The modules are connected to a computer via a 'MIDI merge' box visible in (c). The sensitivity pattern of the doppler module used can be seen in (e) (photos and graphs from Logos Foundation, 2021c and Raes, 2004/2021).

More experiments were performed with various doppler modules in the X-band (10.587GHz) and K-band (around 24GHz), with frontal beams of about 70° degrees and a range of up to about 10m (Raes, 2009c).[207] The system developed with these modules is sometimes referred to as *Tetrada*. A significant improvement of this system compared to previous ones is that its modules allowed frequency-modulating the microwave signal, thus making it possible to implement a more advanced *Frequency-Modulated Continuous Wave* (FMCW) radar system. While that introduces some low amplitude noise in the signal (around -54dB), it enables tracking absolute movement speed as well as position, which in an FM radar can be deduced by comparing the phases of transmitted and received signals. *Tetrada* uses sinusoidal rather than triangular modulation to avoid the presence of sidebands in the spectrum. This system was designed with a tetrahedral setup in mind and has been incorporated in Raes' latest experimental *Holosound* system (also referred to as *Invisible Instrument*, see figure 3.51). This is a hybrid interface, combining ultrasound sonar with microwave Doppler radar at 24GHz (Raes, 2010a).[208] Ultrasound and microwave sensors are meant to work complementary to each other; the audio and radio Doppler signals are compared to deduce absolute distance of the moving body by leveraging the differences in velocity between sound and electromagnetic waves.[209] According to recent documentation, this is not a finished product but requires further research and evaluation (Logos Foundation, 2021b).

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[207] The devices Raes and his team experimented with include: Microwave Solutions *MDU1100, an* X-band Doppler radar module at 10.587GHz with a 72° horizontal and 36° vertical beam; Microwave Solution MDU2400, a K-band module at 24.2GHz with a 72° horizontal and 18° vertical beam; Conrad RSM1700, Microsense IPM170, and Allsat Amiwima DRM-24, around 24.15GHz, with a 70° conical beam. These types of K-band devices are commonly used in cars for cruise control.

[208] The doppler modules used in *Holosound* are the Conrad RSM1700 and Microsense IPM170.

[209] More specifically, the software looks for local maxima in the two signals (ultrasound and microwave) to trace the start of a gesture, which has the downside of introducing latency. This technique was preferred over correlation, which would work better but is more computationally intensive.

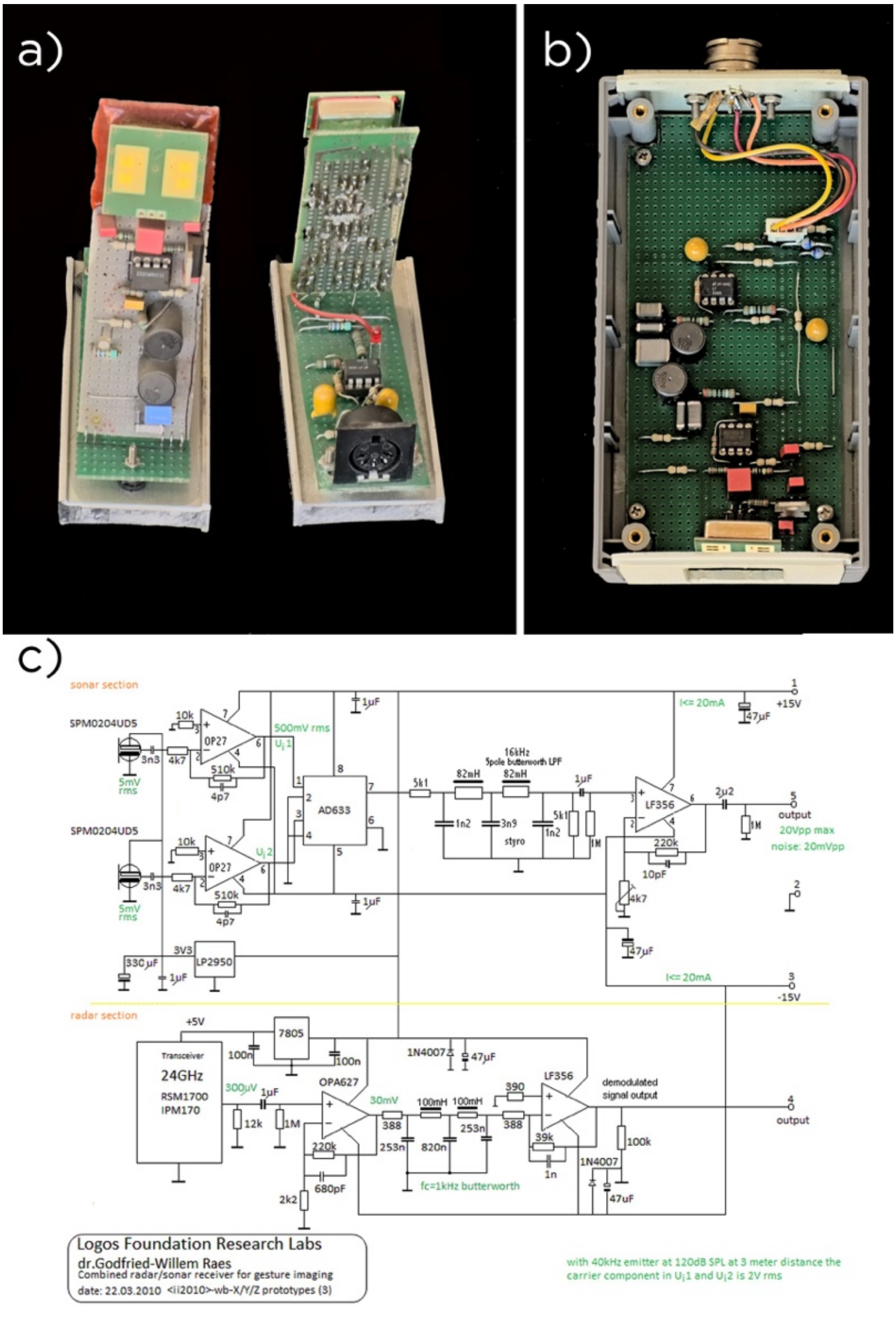

Figure 3.51. Godfried-Willem Raes' *Holosound,* a hybrid ultrasound/microwave doppler sensing system whose development began in 2010. The bottom graph (c) shows the schematics of the electronics for both sonar and radar modules, although in practice these have always been separated. Sensors are placed in a tetrahedral formation, i.e. a triangle surrounding the performer with additional sensors hanging above the center of the triangle. Figure (a) shows two of the radar modules placed on the triangle: a PCB with electronics and a DIN plug for power and signal transmission are mounted on a metal slat, with a second PCB mounted at a 90° angle, containing the radar sensor (its transmit and receive plate antennas are visible); (b) shows the radar module placed above the performer (photos and graph from Logos, 2021d).

Beyond these complete sensing systems, Raes also fitted two M&M robots with microwave sensors and self-made microcontroller boards in 2017, so as to allow presenting these instruments as autonomous interactive sound installations (figure 3.52). Their radars operate at 10.587 GHz; they have a 120° radiation angle and a range of up to 10m. *Aeio* is an aeolian cello robot (constructed in 2010); it performs gesture recognition on the sensor input to modulate elements of five compositions playing in sequence (Raes, 2018).[210] *Rodo* (constructed in 2014) is an extended toy piano of sorts made from bronze rods and activated by beaters or ebows; it features two radars, one on either side of the instrument (Raes, 2017). *RadaRodo* is an embedded interactive composition by Raes for the instrument, in which pitch is controlled by the speed of movement of visitors or performers around it, and the rate of note repetition is controlled by their acceleration.

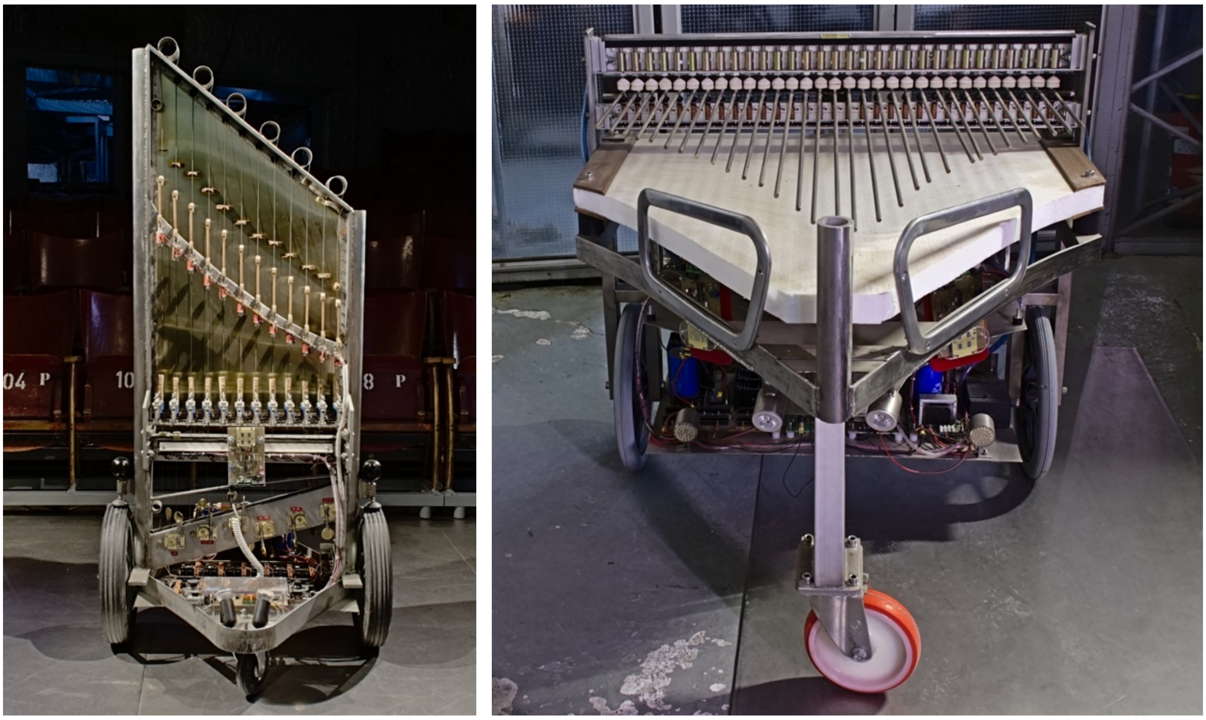

Figure 3.52. Front views of two robot instruments from the *Man & Machine Orchestra* controlled via embedded doppler radar. Left: *Aeio* (2010); the PCB on which the radar module is mounted is located on the crossbar under the strings. Right: *Rodo* (2014); its two radar modules are visible above the large blue capacitors on either side of the instrument (from Logos Foundation, 2021a and 2021e respectively).

3.7.3 *From doppler signals to motion data: technical details*

It is worth looking at Raes' sensing technology in some detail, as it is by far the most advanced radio-frequency sensing system for performance - at least before my own *Wireless*

[210] These five pieces are composed by Godfried-Willem Raes and Kristof Lauwers.

Information Retrieval. It also remains the most advanced doppler radar system in the field. Thus, summarizing Raes's prolific, though somewhat convoluted, writing will be beneficial to other artists inspired to use such a technology.

All of Raes' systems feature: a) an array of Doppler radar modules (usually 4); b) custom-made electronics to preprocess the analog signal before sampling; c) Analog-Digital Converters (ADCs); and d) two layers of software analysis for extracting useful data from the sensor input (Raes, 2003/2017). These systems were designed for real-time performance, therefore their primary goal was low latency. This means that a compromise was made in regards to precision and to the amount of features that the software extracts from the signal (Raes, 2010b).[211]

The systems generally function as follows: Prior to sampling, incoming doppler signals are low-pass filtered to the Nyquist frequency of the desired sampling rate and then amplified. They are usually sampled with a 12-bit resolution, although as Raes (2003/2017) remarks the operating precision does not exceed 10 bits because the internal noise of these systems (about 4-bits) makes the last 2 bits unusable. Mathematically, the minimum usable sampling rate depends on the operational frequency of the radar and the speed of the fastest motion the system needs to capture. The sampling period can be derived from the Doppler formula:

$$f_d = \frac{2vf_0}{c}$$

where f_d is the Doppler frequency, v is the speed of motion towards the antenna (in m/s), f_0 is the frequency of the radar module, and c is the speed of propagation of radio waves (299,792,458 m/s).

The first system used dedicated ADCs to sample the signal at 1024Hz (Raes, 1999/2019). *Quadrada*'s ADCs pre-sample at 500Hz, then pass the digitized signal to software which resamples at 128Hz (with an option for 256Hz sampling) for an optimized maximum tracking speed of 4m/s. This speed was deemed sufficient as human motion on a confined stage does not exceed 5m/s (Raes, 2003/2017).[212] *PicRadar* runs at a higher microwave frequency, therefore signals are sampled at 620Hz to allow capturing motion as fast as 5m/s (which corresponds to a Nyquist frequency of 311Hz at 9.35GHz) (Raes, 2004/2021). *BumbleBee* is

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[211] As Raes (2010b) commented, the 2010 version of his gesture-tracking system utilized about half the available processing power of a quad core Pentium processor, with the majority of that required for spectral analysis. This made it possible to achieve a latency of less than 10ms.

[212] Raes (2010a) points out that, while Usain Bolt's 100m world record at 9.58 seconds corresponds to an average speed of 10.52 m/s, this speed is far beyond what can be achieved on stage in a performance.

optimized for somewhat slower speeds - between 0.026-2.6m/s with a maximum of 3.2m/s – and thus samples signals at 256Hz (Raes, 2009b/2010). Finally, *Tetrada* uses dedicated ADCs at a much higher sampling rate which can be replaced by an audio interface. The software then resamples the signal at the minimum required rate - 1024Hz for 10GHz, and 2048Hz for 24GHz – to track motion speeds between 0.026-2.6m/s (Raes, 2009c).

It is informative to take a bit of time to delve into Raes' strategies for extracting meaningful data out of the many different types of Doppler radar modules he has worked with. Some systems include specific pre-processing circuitry. For example, *BumbleBee* is a pulsed radar; therefore a simple circuit is required to first filter out the pulsing of the Doppler signal from the output (Raes, 2009b/2010). Furthermore, analog conditioning is used in some systems to offload processing from the computer. The 1999 system, for example, introduced true Root-Mean-Square rectification and signal integration to electrically deduce moving body mass and motion velocity (Raes, 1999/2019). Once the doppler signal is sampled, the software first analyzes it to arrive at 2-3 key features that can be used for gesture tracking or as direct controls. These features are typically: a) the Doppler frequency or period, used to estimate motion speed, and b) the Doppler amplitude which is inversely proportional to the square of the distance between transmitter and receiver, and directly dependent on the size of the moving body's surface. With a square configuration setup, the software can also derive information on a moving body's position in 2 dimensions, on its size and orientation, as well as its absolute velocity and acceleration (Raes, 2009b/2010). Position, surface size, and orientation can be estimated independently of velocity.

Some of the modules used in these systems output a single Doppler signal. *PicRadar* transceivers mix the transmitted and received signals internally to produce the differential Doppler signal within the unit. Instead of employing a dedicated ADC, they are coupled to PIC microcontrollers that preprocess and encode data to MIDI directly, yielding two control streams: i) The Doppler period, corresponding to frequencies between 2-320Hz and formatted as 14-bit unsigned pitch bend data, and ii) the logarithmic RMS amplitude of the received signal, formatted as a 7-bit continuous control message. *Tetrada* also outputs one signal, but because this can be a frequency-modulated wave, distance can also be reliably measured given that it is encoded in the phase difference between the transmitted FM signal and the received modulated carrier. The data made available by the *Tetrada* system includes: i) Doppler frequency (between 0.2-350Hz), ii) Doppler amplitude, and iii) distance of the target body. The latest *Holosound* system calculates vectorial acceleration by differentiating vectorial frequency data. It also uses high-pass filtering to remove DC offset and artifacts caused by slow movements, as these are considered involuntary (this is because of the movement language used in Raes's performances, which will be discussed further below).

On the other hand, *Quadrada* and *BumbleBee* radars output two signals. The transmitted and received signals are combined in two internal mixers, producing two distinct Doppler signals with a phase difference. In *Quadrada*, the phase difference reportedly fluctuates between 40°-120°. A phase comparator circuit can be used to derive a voltage proportional to the phase difference between the two signals. When the body is receding from the radar it is positive and when approaching negative. The software produces the following 5 parameters: i-ii) Doppler frequencies of the two signals (between 0.5-63Hz, with a 0.5Hz resolution), iii-iv) amplitudes of the strongest spectral component of the two signals using logarithmic frequency analysis, and v) phase angle between the two signals. *Bumblebee* outputs two signals in quadrature whose phase relationship similarly reveals when bodies approach or recede from the antenna. The system treats these voltages as the real and imaginary parts of a complex signal, and derives the overall amplitude – and thus the size of the moving surface - by taking the sum of the two squared signals. The data available are: i-ii) Doppler frequencies of the two signals (0.5-100Hz with a resolution of 0.5Hz), iii) the amplitude of the two combined signals, and iv) the phase difference between the two signals.

To derive motion capture data from these signals, Raes and his team have experimented with a number of algorithms.

• *Frequency*: Frequency of movement can be estimated with a Discrete Fourier Transform (DFT), or by finding *"the nearest complete almost periodic wave"* (Raes, 2003/2017). Raes notes that both solutions are somewhat problematic as human motion is rarely periodic, thus the analyzed signals contain a lot of noise. Two other algorithms sidestep this issue: One estimates frequency by adding positive half-waves to negative ones and treating the result as one period. The preferred technique, used in the most recent system, converts the incoming signal to a square wave with hysteresis using a Schmitt trigger ("Schmitt trigger", 2022). This circuit starts a positive wave when the input signal exceeds the 'on' threshold and brings it back to zero when it is smaller than the 'off' threshold. A zero-crossing counter is used to deduce frequency (Raes, 2010b).

• *Spectral Density*: A more musically expressive feature is given by calculating the spectral density of the Doppler signal (for more information on spectral density see section 6.2.9). This is calculated by counting the number of sign inversions within a small timeframe.

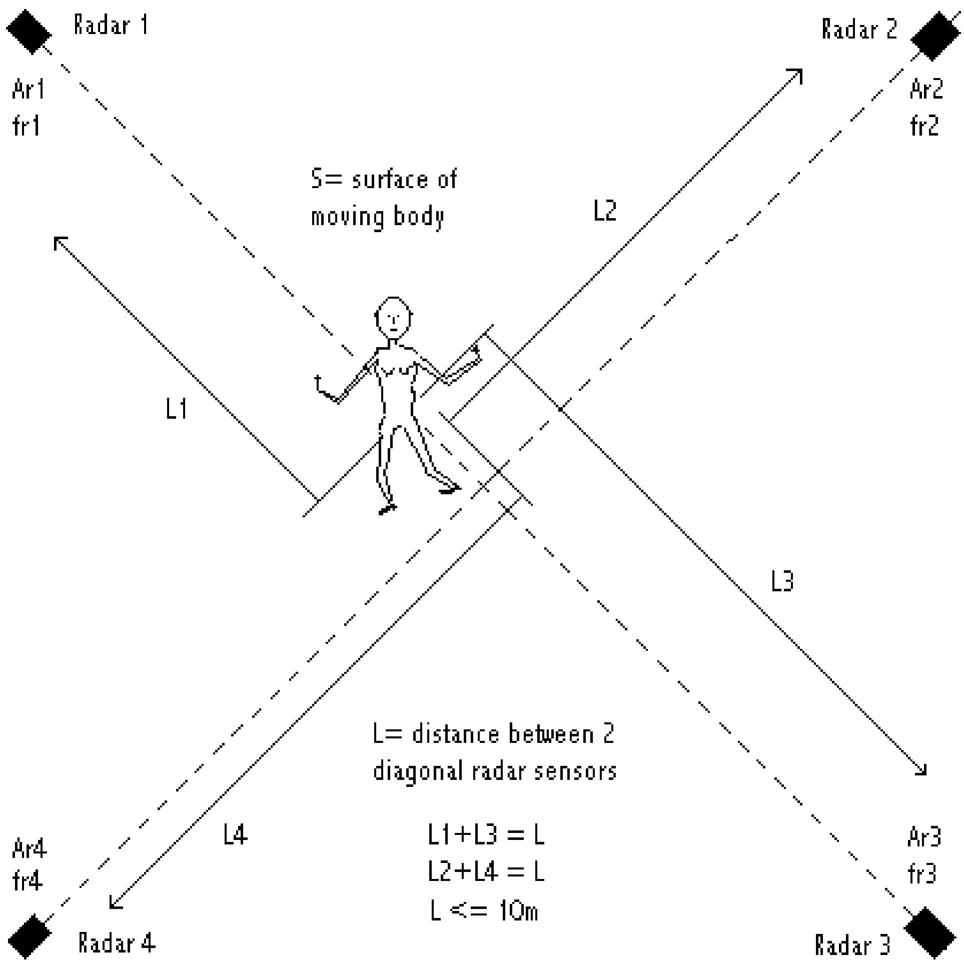

Figure 3.53. Spatial configuration for Raes' *Quadrada* system (Raes, 2003/2017). The symbols *Ar* and *fr* in the graph are simplified into *A* and *f* respectively in the equations below.

• *Position*: The position of the moving body can be easily derived in the diagonal cross setup introduced with *Quadrada* (figure 3.53) using the following equation, where A is the amplitude of each transceiver's Doppler signal, f its frequency, k a scaling factor, S the surface of the moving body (calculated as a sphere), and L the distance of the body to the antenna (Raes, 2003/2017):

$$A_n = \frac{kS}{(L_n + 1)^2}$$

For positioning purposes, surface can be ignored, and thus the equations can be simplified to:

$$\frac{A_1}{A_3} = \frac{(L_3+1)^2}{(L_1+1)^2} \quad \text{and} \quad \frac{A_2}{A_4} = \frac{(L_4+1)^2}{(L_2+1)^2}$$

To simplify even further, the distance between diagonally opposing sensors can be normalized, and a new variable, *Q,* can be defined as the square root of the ratio of their signal amplitudes, i.e.:

$$Q = \sqrt{\frac{A_1}{A_3}}$$

This produces:

$$L_1 = \frac{2-Q}{Q+1} \quad \text{and} \quad L_3 = \frac{2Q-1}{Q+1}$$

The faster the sampling rate, the higher the spatial resolution of the system. *Holosound*, for example, allows sampling with a standard audio interface at a rate of 44,1kHz, which provides a theoretical spatial resolution of 7.6mm (Raes, 2010a).

• *Speed, angle, vector magnitude*: Positional information can be used to calculate the overall speed of movement within the field; this calculation concerns the body's center of gravity. Having deduced the distance of the moving body to each of the four transceivers (L1 to L4), position in X and Y can be calculated with the following equations, which treat the center of the field as the starting point (0, 0):

$$X = \frac{(2L_1-1)+(1-2L_3)}{2} \quad \text{and} \quad Y = \frac{(2L_2-1)+(1-2L_4)}{2}$$

This Cartesian representation can be converted to polar coordinates to produce the angle and vector magnitude of motion. The trajectory of movement can then be easily calculated by comparing the current position (at time *dt*) to the previous (at time *dt-1*). To get the absolute speed, the frequency of the vector signal is divided by the angle's *sine*, for radars 1 and 3, and its *cosine*, for radars 2 and 4.

$$\overrightarrow{L_{1,3}} = \frac{f_{1,3}}{|\cos(a)|} \quad \text{and} \quad \overrightarrow{L_{2,4}} = \frac{f_{1,3}}{|\sin(a)|}$$

Then all four values can be averaged to reduce noise and uncertainty:

$$V = \frac{\overrightarrow{L_1} + \overrightarrow{L_2} + \overrightarrow{L_3} + \overrightarrow{L_4}}{4}$$

Raes and his team have developed a radar-like polar display to facilitate testing, evaluating and tuning their setups. Calculations for the tetrahedral configuration are similar to the above, though a bit more complex. Positional information in 3 dimensions can be derived with more certainty, as all angles are smaller by one third.

• *Surface size*: To calculate the size of the surface of the moving body per transceiver, the software takes the logarithm of the Root-Mean-Square (RMS) of the last 0.5 seconds, and then scales it to produce a 7-bit MIDI-compatible value. To deduce the overall surface movement in the field, the values of all 4 transceivers are considered. For the diagonal of radars 1 and 3, this is calculated by the equation:

$$S_{1,3} = Ar_1(L_1 + 1)^2 = Ar_3(L_3 + 1)^2$$

In reality, the values of these two transceivers will not be the same but will be affected by the distance of the body to the transducer and the signal's reflections and multi-path propagation in space (see the discussion on *link asymmetry* in section 6.1.2). For simplicity's sake, the software combines the two measurements to calculate an average value per diagonal. For example, for radars 1 and 3 this is expressed as:

$$S_{1,3} = \frac{Ar_1(L_1 + 1)^2 + Ar_3(L_3 + 1)^2}{2}$$

• *Orientation*: Because the front and back of the human body have a larger surface than its sides, the values between the two diagonals may differ depending on the body's orientation within the field. Orientation within the square can thus be estimated with the equation:

$$\frac{S_{1,3}}{S_{2,4}} = \frac{Ar_1(L_1 + 1)^2 + Ar_3(L_3 + 1)^2}{Ar_2(L_2 + 1)^2 + Ar_4(L_4 + 1)^2}$$

• *Velocity*: Absolute velocity estimation poses another problem, as angular motion in relation to the transceiver produces different results than linear motion. In that case, velocity is a function of the cosine of the angle of movement in relation to the transducer. This is tackled by employing a layout with a known geometry, using multiple transceivers to trace movement in different vectors which can be combined to measure movement speed in 2 or 3 dimensions (Raes, 2010b). As such, rather than separately calculating velocity per transducer the software uses the position measurement to derive absolute velocity within the field by tracking the change of position in time. This is a measurement well suited to slow movements. Faster movement is estimated by a more complex method based on spectral analysis with a cosine correction, and by additional gesture-specific spectral characteristics (Raes, 2003/2017).

The software allows mapping these features to control sonic parameters directly. Raes offers an overview of what he judges to be the 'most intuitive' mappings for the robot orchestra, acknowledging that other mappings may be better suited for different uses (Raes, 2012):

- Moving body surface mapped to control volume or density
- Motion speed mapped to control pitch
- Spectral shape of the motion mapped to control harmony
- Acceleration mapped to produce percussive triggers (presumably when exceeding a threshold)

3.7.4 *Gesture recognition*

While direct mappings of features to sonic parameters can be implemented in these systems, Raes' main focus has been to enable performing with a vocabulary of predefined gestures. This is a very fundamental difference between his *Virtual Jewsharp* and the systems he has been developing since 1999. It is also a radically different approach to that of *Hertzian Fields*.

Gesture recognition in Raes' systems was made possible through the implementation of a circular buffer (a memory of 4-5 seconds) for storing sampled Doppler signals. In the first iteration, this memory was used to analyze data in two variable timeframes, a short one between 20-100ms and a longer one between 125-1000ms. The short timeframe was used for spectral analysis with some very simple windowing, and for pattern recognition. The longer memory, or *"context buffer",* was used to derive periodic gestural information, like tempo and rhythm (Raes, 1999/2019). Even longer memory was not initially implemented as it was not considered particularly useful for real-time performance. However, it was added in later systems, which implement 3 circular buffers with progressively longer durations and coarser sampling rates. This includes: A short-term memory lasting 250ms and sampled at 1024Hz; a medium-term memory lasting 1 second and sampled at 512Hz; and a long-term memory lasting 4 seconds and sampled at 128Hz (Raes, 2009c). Spectral analysis is performed on all three timeframes with a spectral resolution of 128 bins. The short memory tracks movement in frequencies between 4-512Hz with a refresh rate of 25Hz, the medium between 1-128Hz every 5Hz, and the long between 0.25-32Hz every 1.25Hz (Raes, 2010b).

The system analyzes the data in these memory slots and uses simple fuzzy logic to identify if a gesture from a pool of gesture prototypes is occurring. The output is a 'strength' or 'confidence' coefficient per dimension that denotes closeness to the prototype gesture, plus an additional coefficient averaging the coefficients of all dimensions. The most recent *Holosound* system is using a gestural corpus that Raes calls *Namuda gesture prototypes*. This is a set of 13 gesture types developed after *“thousands of experiments with more than 20 different human bodies”* – including musicians and dancers (Raes, 2010b).[213] These gestures last between 0.1-1 second, with a few of them being mutually exclusive opposites. The movement vocabulary includes:

- *Speeding up* vs *Slowing down*, where the speed of movement increases or decreases in a timeframe of 0.5 seconds. These two gestures replaced earlier prototypes that were harder to identify, *Pushed* vs *Inhibited motion* from (Raes, 1999/2019, which involved an increase or decrease in velocity while the surface of the moving body remained constant.
- *Growing* vs *Shrinking* (or *Expansion* vs *Implosion*), where the surface of the moving body increases or decreases within 1 second.

The above 4 gesture types are recognized using a Finite Impulse Response (FIR) filter whose coefficients are set to the type of gesture to be tracked. This is a simple linear function, although it is suggested that it could be further refined to include other curves, such as quart sine, cosine, exponential, etc (Raes, 2010b). The system traces motion in all vectors - x, y, z when using a tetrahedral setup – and identifies how strong the correlation is between the model gesture and the real time doppler signals.

- *Fluency*, or *fluent motion* is a movement in which velocity and moving body surface remain constant within a defined timeframe. *Fixspeed* is a variant of this gesture that only considers speed. This feature is tracked by measuring the standard deviation of the performer’s speed; the smaller the deviation, the more confidently the system will recognize a gesture as *fluent* or having a *fixed speed*. Motion can be circular or straight from the point of view of the doppler sensor.
- *Collision* and *Theatrical collision* are another duo of gestures recognized by looking at acceleration data. In the first case, acceleration increases until it suddenly comes to a standstill - the collision. In the second case, movement decelerates, stops and then accelerates again. The algorithm used to trace this gesture requires setting a sensitivity threshold on the acceleration data; values that exceed this threshold pass through a leaky integrator and values below the negative of that threshold pass through another integrator. The temporal window for this gesture is between 0.1-0.39 seconds – the smaller the window, the more responsive the tracking.

[213] These ‘Namuda gestures’ are a somewhat simplified subset of a typology of performative gestures Raes proposed in (1999/2019), in which the parameters of body surface and speed were taken simultaneously in account.

- *Roundness* vs *Edginess* (or *Smooth* vs *Jagged*) involves spectral analysis of the Doppler signals in a short time window to distinguish between 'round' (harmonic) and 'edgy' (noisy) gestures. The first type describes smooth and continuous movement whereas the second describes gestures with abrupt changes and discontinuities. The distribution of spectral power is analyzed using an FFT with a Hanning window of 0.25 seconds and 25% overlap; the value of the lowest bin (i.e. the DC offset) is discarded.
- *Airborness* is a gesture that revealed itself during experiments involving throwing balls within the reactive field (Raes, 2010b). It was observed that flying objects produce a discontinuous spectrum with no energy on the low end. This is because, unlike what commonly happens with a moving human body, there are no parts of the object that remain static. The size of the gaps in the spectrum is an indication of the kind of airborne object, for example if it is a human performing an acrobatic jump, a ball being thrown, etc. Raes points out that, while this feature is not very relevant for musicians, it can be explored by dancers, acrobats and jugglers. For it to be recognized, the analysis window has to be very short. Because of the slow refresh rate of the calculation (8Hz), this feature was initially unusable in real time. A faster variant was developed in which the spectrum was first reduced to octave bands, and then the power of the lowest two bands was compared to the sum of all higher bands. The gesture is identified if the overall spectral energy exceeds the noise-floor and the proportion between lower and higher values is higher by a predefined threshold. Raes reports a 90% success rate for this method. As he points out, it is important to filter out background noise in order to be able to properly work with this feature in particular, but also to optimize other spectrum-based gesture recognition. The best way to achieve this is through a tuning phase in which the background microwave noise of the empty field without any moving bodies can be captured, spectrally analyzed, and converted into an FIR filter. However, a simpler solution was preferred for practical reasons, in which an approximate filter curve is added by hand.
- *Periodicity*, and by extension *tempo*, are the most complicated features to extract. Raes and his team have used a number of different algorithms, each with its advantages and disadvantages. An early implementation did not allow reliable deduction of meter but could track accelerandi and ritardandi (Raes, 1999/2019). *Quadrada* attempted to derive tempo and musical meter with the following process: the incoming signal was low-pass filtered at 4Hz and stored in an 8-second buffer. A DFT of that buffer could reveal

gestural periodicities and their frequency *"pretty well"* (Raes, 2003/2017). In more recent implementations, the fastest option measures the time between consecutive periods of gestures - for example by finding the frequency of successive 'collisions' - and calculates the standard deviation of each repetition (Raes, 2010b). This method incurs a latency of about 100ms and works for specific slow gestures, such as clear collision slower than 4Hz. Tempo-tracking for conductor-like gestures however is not reliable. While it is possible to synchronize sound production to gestural tempo, there will always be some latency and sudden tempo jumps are unavoidable. Another option mentioned is to perform an FFT and attempt to estimate tempo by interpolating between the strongest frequency bins. This works better than the first option for gestures that are not very clear, however it results in a latency of several seconds making real-time synchronization impossible. Finally, a technique mentioned by Raes as theoretically promising involves analyzing the logarithmic spectrum of the power spectrum (i.e. the *cepstrum*). This analysis occurs over 4 seconds, with the inverse DFT of the cepstrum revealing time-domain periodicities (*quefrencies*). This technique produced considerable latency and did not allow for syncing. Moreover, Raes and his team achieved unsatisfactory results, possibly because their method was not yet refined enough.

- Finally, *freeze* is a feature that reveals the absence of motion within a timeframe. A body within the field will usually cause some fluctuation above the noise floor, even when at rest, therefore the *freeze* property usually only requires one vector to be identified, rather than all 3 dimensions.

3.7.5 *Practicing and mapping*

Performing with Raes' systems requires a twofold learning process (Raes, 2012): first, the performer practices to learn the instrument using the default mappings. Then, once gestural control has been mastered, the gesture recognition modules are fine-tuned to the specific performer. This second step helps account for variations between different bodies and movement styles of performers, as well as filtering out noise and software errors (Raes, 1999/2019). The only general-purpose classifications that need no tuning involve identifying lack of motion (i.e. the *freeze* gesture), and when a body enters or leaves the interactive area.

Raes stresses the importance of learning how to perform with the system and practicing with it to develop the necessary motor skills and gestural control (Raes, 2012). Performers rehearse specific gestures, one at a time, with a series of musical studies. The sonic output of

M&M robots is the principal mode of feedback, with each gesture mapped to different robots:

- *Speedup* is practiced with 3 musical robots, each responding to movement in a different vector - x, y, z. The pitch of these robots is controlled by the strength coefficient for each vector (meaning how confident the system is that the *speedup* gesture is occurring). Their volume is controlled by the speed of movement. When the *speedup* motion is recognized in all three dimensions, a 4th robot begins sounding.
- *Slowdown* is practiced with 2 pipe organ robots, mapping their pitch to movement speed rather than to the strength coefficient. When the *slowdown* gesture is recognized on all three vectors, the lights on one of the robots flash.
- *Fixspeed* (i.e. keeping motion at the same pace for 0.5 sec) is studied by mapping speed in all three vectors to a toy piano robot's pitch; when the gesture is recognized in all three vectors, the robot's lights are switched on.
- *Expanding* is practiced with 3 robots: 2 percussion robots for x and y, with the strength coefficients controlling pitch and body surface size controlling volume. The z axis is mapped to a third robot, with the duration of the gesture in that axis controlling which of its sound-making elements will be used.
- *Shrinking* uses another set of three robots, mapping strength coefficient to pitch, surface size to volume, and flashing the lights of the x-vector robot when the gesture is recognized in all 3 axes.
- *Steady* triggers when the moving body surface remains the same within a defined timeframe. The value denoting surface size is mapped to a quarter-tone organ's pitch, whereas the strength coefficient is more subtly mapped to control the velocity of attack. The robot's lights turn on when the gesture is recognized in all 3 axes.
- *Smooth* and *edgy* are practiced together, with the *smoothness* strength coefficient mapped to the pitches of the same organ robot as above, and the *edgy* strength coefficient mapped to the pitches of a player piano. Attack velocity is controlled by the size of body surface whereas the organ's volume is controlled by the energy of the lowest bins of the power spectrum of movement (i.e. by the slowest moving body parts).
- *Freeze* is practiced with an inverse mapping, in which a robot produces sound until there is no motion in the field.
- *Jump* - the most physically demanding gesture to practice - uses the *airborness* feature; it is triggered when all body parts are in motion, although false positives are sometimes produced with *"large stepping movements"* (Raes, 2012). Three robots are used to

practice this gesture, one per vector; a fourth robot is triggered when the property is recognized in all axes. Higher or longer jumps produce a stronger confidence coefficient - a parameter that is mapped to pitch. Volume is controlled by body surface size. In order to produce a trigger in the z vector, performers have to land on a different position than where they jumped from.

- *Collision* is mapped to a set of percussion robots. The x-vector controls a snare and another robot with 7 drums, y controls a cowbell, and z a set of woodblocks and a metal sheet. Simultaneous triggers in all 3 vectors cause a cymbal to play. 'Softer' collisions – i.e. gestures detected below a threshold - will make the robots flash their lights. The study should be performed with all body parts and it is suggested that performers avoid *"rebounding movements"* as it makes the system produce false double triggers (Ibid).
- *Theatrical collision* is mapped to a percussive microtonal organ robot.
- *Periodic* is the worst functioning feature of the system, as it produces false positives and has a high latency. It is practiced with a multi-drum robot and can *"even be got to work"* with simple rhythmical motion on a stable tempo (Ibid).

The timescale for most of these gestures is small - from 7ms to no longer than 2 seconds, especially for airborness and collision. *Freeze, periodic, smooth/edgy, fluent* and *fixspeed* can also be tracked over longer windows.

3.7.6 *Artistic output and results*

Raes is a prolific composer having written many interactive works for his microwave radar sensing systems, often for specific performers. Between 2003-2009 he composed 20 pieces just for *Quadrada*, his first microwave radar system, including 18 *Studies*. These works last between 2-15 minutes and are scored for the complete M&M robot orchestra, small ensembles, or specific robot instruments. Most pieces call for a solo performer - defined as a *dancer* or *butoh dancer*, *performer*, or *player* – that is often Raes himself. There is also a duet, a piece for 1 to 2 performers, and another for 1 to 4. A *laptop player* is often also present (with a further undefined role). Performers are also occasionally asked to use their voice or play an acoustic instrument besides moving in the field. The *Quadrada Studies* feature various field configurations. The simpler *Studies #1*, *#6*, and *#7* use a single transceiver, whereas *Study #2* deploys two in a line. *Study #16* can be performed with the standard square format or with a tetrahedral configuration. The tetrahedral format is used in *Study #18*: Three sensors are placed on the floor in an equilateral triangle formation, angled upwards at about 25° and with an approximate distance of 4m from each other; a fourth transceiver is suspended above the triangle's center. Typically, the dancer/performer is in the center, surrounded by the robot orchestra. Other microwave systems – beyond the hybrid sonar/radar *Holosound* system from 2010 - have been used less extensively than *Quadrada*. *PicRadar* features in three solos and two duets, composed between 2006-2007; an earlier version with 2 radars was composed in 2004. For a video of Raes performing solo with the *PicRadar* system, see (Raes, 2006). There seem to be no completed works for *BumbleBee*. Raes has also used doppler radar systems in two large scale music theater pieces. *TechnoFaustus*, which he describes as his 'magnum opus', features most of his inventions. This piece has been in development since 1998 with several of its sections having been performed throughout the years. *Hanaretemo* (2009) is another work employing both radar and sonar gesture-sensing technologies, scored for two Butoh dancers.

Since 2010 Raes has been composing a growing suite of works for the hybrid ultrasound/microwave-based *Holosound* system, titled *Namuda Studies* (Raes, 2020). So far there are 80 such studies of varying lengths (from a couple of minutes to over an hour), sometimes created collaboratively with other Logos composers. Most of these pieces are solos written for specific performers with the exception of a few works, such as *Namuda: Black and White* (2012) for 6 dancers. These works can be performed autonomously or together as a large-scale suite – Raes in fact presents a new hour-long *Namuda production* at Logos once a year consisting of multiple shorter pieces. Almost all of the studies use the M&M orchestra with the exception of *Namuda Impossible* (2015) which also involves radar-controlled airplane propellers. A few pieces involve acoustic instruments and a traditionally notated score for their parts, but there is no musical score for the robots as the system's response is embedded in the software. On the other hand, the choreography is described using verbal scores and 'descriptive plots'.

The various *Namuda Studies* focus on specific gestures or gesture combinations to control the M&M robots; a few of them utilize all gestures. They commonly combine pre-composed parts with interactive elements, sometimes playing them by directly mapping analysis features to sound (e.g. body size to pitch), most often mapping different gestures to control different instruments, and at times simply using gestures to start and stop precomposed sections. In this regard, *Namuda Study #43: "High Order Derivatives"* (2014) and *Namuda Study #51: Seduction* (2015) stand out, being the only works completely based on direct mapping rather than gesture recognition (figure 3.54). Specifically, they investigate using first, second and third derivatives of surface and speed in different vectors which results in *"extreme sensitivity for dynamic gesture properties and very high responsiveness"* (Raes, 2020). In my opinion, the fact that smaller motions, ignored in other studies, have an effect on the sound creates a much stronger and more engaging connection between sound and movement, and clearly instigates the performer to move differently (see video in Raes, 2019). Nonetheless, these studies were primarily meant as research, being "*much more an implementation of an invisible instrument* (…) *rather than a composition"* (Raes, 2020). They were principally devised *"to test extentions and further possibilities"* of the gesture tracking system rather than to radically alter the ways in which movement is mapped to sound (Ibid).

Figure 3.54. Video still from a performance of *Namuda Studies #43* by Dominica Eyckmans in 2014. Godfried-Willem Raes can be seen in the background operating the computer (from Raes, 2019).

In musical terms, Raes's compositions are overall much more informed by the aesthetics of mechanical music than those of contemporary instrumental or electronic music. As such, they are concerned with sound events (notes) in a somewhat traditional manner and appear not too interested in the more adventurous sonic idioms developed in contemporary music during the last 70 years. Overall, Raes' music is about notes, pitches, harmonies, and rhythms, with timbral variations and timbral development limited to differences between the sound colors of instruments.

With his invisible instrument, Raes aims to create a less mediated and more *"honest"* way of performing (Raes, 2009a/2010). Unimpeded by the presence of physical objects behind which performers can hide on stage - like instruments or microphones – he believes even the musically unskilled can become musically expressive.[214] Nevertheless, performing with Raes' systems is still a highly mediated process, owing to the abstractions of gesture recognition as well as the reductionist mapping of these gestures to notes played by the robot orchestra's instruments (as opposed to using movement to control sound in more complex and intricate manners). Generally, and to my own eyes, the performers' movement language looks often rather awkward, a feeling that is exacerbated by the system's latency and the often unclear relationship between motion and sound. This latency is most likely due to heavy reliance on gesture analysis and the fact that a gesture can only be identified once it is completed. Beyond introducing latency, this also means that the analysis system performs a drastic temporal reduction of the sensing data – and thus the performer's expressive motion – by grouping series of movements into single gestures. Moreover, any movement that is not recognized by the system is ignored, which means that a lot of what a performer does on stage produces no result, instead becoming visual noise from an audience's perspective. This is especially true for smaller movements which with other radio-frequency sensing instruments can provide very nuanced expression. The low 7-bit resolution of MIDI does not help promote expressivity either, nor the fact that there cannot be any cross mapping connecting different movement features to create a network of interconnected sound parameters – something that, to my experience, goes a long way in making a system feel expressive, as will be discussed in chapter 7. Part of this is because it is by definition impossible to modulate the sound of one M&M robot with that of another acoustically. This inherent weakness in Raes' sonification system is possibly one of the reasons why he does not use direct mappings that much. While it would make the system more responsive it could also easily result in a very literal and dull one-to-one connection between motion and sound, with one movement feature (e.g. moving towards X) directly affecting one sonic parameter (e.g. the pitch of a robot's notes). In total, while Raes' hardware engineering is impressive, and while the software technology developed for gesture tracking is quite ingenious and

[214] As Raes observes in his essay, 'Naked', a musical instrument functions both as a sound-making object, as well as a 'psychological screen' that can be put between performer and audience. As a result, many musicians hide behind their instrument when performing - perhaps with the exception of vocalists, though, as he notes, even they often need to hold a microphone to feel safer, or a handkerchief, like Pavarotti. An invisible instrument however, "*exposes the performing musician"* and requires a certain quality of *"psychological exhibitionism"* (Raes, 2009a/2010).

affords some higher level control, a great deal of resolution is lost by the system's reduction of motion into a set of specific gestures. The implementation of the system's *confidence coefficient* in the recognition of a gesture as a musical control may also be the cause of some of the seemingly arbitrary results observed.

3.7.7 *Naked Music Dance performance (Namuda)*

Namuda is a compound word that stands for 'naked music dance'. Raes uses it to describe the latest iteration of his system, referencing both his dance-oriented (or, perhaps better, movement oriented) approach to making music, and his requirement for performers to be nude.

In regard to the first point, Raes sought to define the performative space between dance and music already in 1993. He writes the following to describe his multimedia music theater work *A Book of Moves*: *"Although the piece might appear to people as having a lot to do with dance, it was neither conceived as a dance piece nor is it actually very appropriate to be used as a dance piece. First of all, it really is and behaves like a real musical instrument and should be played as such. Moves that are too "elegant," for instance, do not lead at all to musically interesting results. Furthermore there is the fact that dancers are trained to follow the music as it goes, whereas here things only work the other way round. The movement has to be performed as a rhetoric sound producing behaviour and not as a gesture of mainly visual nature"* (Raes, 1997a/2019). These remarks feel particularly relevant, as they are valid not only for Raes' own instruments, but virtually for any and all instruments based on full-body sensing, from the *Terpsitone* to my own *Hertzian Field* systems.

As the composer notes, his performers need a cultivated ear, but also some physical awareness and full-body motor control. Musicians excel in the former but the later is not at all a given; with dancers it is the other way around. This is, in many ways, the performative conundrum that such full-body gestural instruments or interfaces pose - as has already been discussed, for example, with the Terpsitone (section 3.1.3), and as has been my own experience with *Hertzian Fields* (see section 7.2.4 in particular). Throughout many years, Raes has tried to discover which danceforms are more appropriate for his systems. Early on, he invited dancers trained in classical ballet and modern dance, but both forms were deemed unsuitable (Raes, 2012). Other failed experiments involved pole dancing (using a special set of sensors mounted on top of the pole, see Raes, 2007b), flamenco, and breakdance (Raes, 2012). He reports that all these dance forms were unsuccessful, some due due to incompatibilities with his experimental aesthetics, others due to the lack of connection to performers from a younger age-group. A somewhat strange fit was found with tango and milonga, not as much owed to an artistic connection but because Raes is an aficionado of these dances. Unsurprisingly, his system works best with forms and dancers focusing on improvisation. Butoh has been the best option for Raes, owing to its non-narrative expressionism that involves the entire body, its twisted character, roughness and nakedness (Raes 2009a/2010). Thus, many of his works have been created for and performed by Butoh dancers. He found contact improvisation also relevant, but not a good fit for a technology that cannot distinguish between different bodies. Martial arts, such as judo and in particular karate, have been mentioned as another field where potentially interested and capable performers could be found.

Overall, Raes works with performers that are invested to learn the system, eager to perform experimental music, and happy to do this while naked. His insistence on compulsory nudity - the other fundamental performative requirement of the *Namuda* cycle - may perhaps be one of the reasons behind his difficulty in finding a larger pool of willing performers, especially musicians. Raes' scores very explicitly require naked performance and he advises other composers to require the same from their performers when using both his microwave radar and ultrasound sonar systems in order to produce better body surface measurements (Raes, 2007a/2010). His reasoning is twofold, technical and philosophical, but not entirely water-tight in either case.

The technical claim is that the naked skin is the most radio reflective surface - with the exception of *"wet or smoothly oiled naked skin"* (Raes, 2009a/2010) - all of which is true at face value. As proof, Raes states that a pullover reduces resolution to *"at least 12dB"* in Quadrada (Raes, 2003/2017), *"at least 15dB"* in PicRadar (Raes, 2004/2021), and even more in other systems. It is evident that clothes incur some damping, with the mentioned variation between these systems easily explained by their different operational wavelengths and circuitry. However, Raes unfortunately provides no graphs, no detailed measurements, nor any precise explanation or experiments on this claim than an often-repeated statement involving the interference of a pullover. The mentioned numbers are indeed quite significant, and reduce the dynamic range of these systems by almost a third. Still, these systems are primarily based on gesture recognition rather than direct mapping of motion capture data, which means that this dynamic range is not used to produce sound in itself. Any reduction in resolution will possibly make it harder for the system to recognize a gesture, but should not produce different sonic results if the gesture is successfully recognized. One should also keep in mind that the system, once analysis and gesture recognition is performed, typically reduces data resolution to a 7-bit MIDI value when mapping movement to sound. This all raises a question whether the software should just be able to successfully identify gestures if the input signal has reduced resolution. Moreover, the reported large reduction happens with a pullover, which is a rather bulky piece of clothing and certainly not a particularly common or necessary item to wear on stage - especially if it inhibits the sensing system. This makes the argument over lost dynamic range seem like willful exaggeration and somewhat of a rhetoric device. As a testament to that sentiment, Raes mentions that *PicRadar* performed much better with a *“a shiny T-shirt”,* reducing “*the amplitude of the reflections with 6dB”* (Raes, 2004/2021). Although he mentions this number as a significant impediment, it is much better than a loss of 12 or 15db, and should be a figure much easier to work with. This mention also begs more questions: What if the T-shirt is not 'shiny'? Or, what will be the resolution loss if, for instance, performers were wearing underwear instead of being completely naked, something that is very much commonplace in contemporary dance? One would imagine that this garment choice would have a negligible effect on the sensing system. Given that no measurements are given for any other type of clothing, one cannot help but wonder how hard Raes has tried to find a workable non-nude option for his performers. The answer on this is given in his essay ‘Naked’, where he writes that, *“the instrument (...) works best when the musician literally plays it naked. It did not take us much research to realise this on the basis of comparative measurements and auditory evaluations”* (Raes, 2009a/2010). All in all, in technical terms the need for performing in the nude feels much more tenuous than Raes makes it seem, if not a bit gratuitous, even though he most often mentions it as the main reason.[215]

Indeed, it seems that the most fundamental motivations behind this compulsory nudity are not as much technical as they are philosophical, political – but also *“aesthetical”* (for the latter, see Raes 2013). In the above-mentioned essay, Raes (2009a/2010) – a child of the late ‘60s and ‘70s - presents the reader with a historical review of nudity as a taboo, from the ancient Greek gymnastics to today. He regards nakedness as liberation from social and religious repression, and connects the growing use of nudity in non-music performance since the 1970s

[215] See for example his explanation in an interview in Dutch where he focuses on these *“technological reasons”* before adding that he also has *“a number of aesthetical reasons”* (Raes, 2013).

to the growing movements of naturism and nudism, which he personally supports.[216] In terms of on-stage nudity he finds the approach of dance more relevant to his practice, being closer to music than theater and performance art where the naked body often becomes a symbol. Instead, in dance it is a way to explore form, locomotion, and the transfer of energy in a pure, unconcealed manner. Reflecting back on performing his music theater piece *A Book of Moves* with costumes from metallic fabric, he comments that while these costumes worked well enough as spacesuit-looking props, *"in fact they really were a despicable form of self-censure."* (Ibid). Through naked performance, *"[a]ll concessions to prudishness are thus done away with, with both technological superiority (maximum sensitivity and sensor precision) and a radical consistency in artistic honesty as the result."* (Ibid). He believes this to be particularly true when performing with the M&M robot orchestra. As he states, unlike commercial robots his machines are also 'naked', exposing their inner workings with no attempt for concealment or decorations. On one hand all their actuators, sensors, wires and electronics are visible; on the other hand, their circuitry and software are also made available – which is rather admirable - making them entirely 'readable' to anyone with enough knowledge. For Raes, it thus follows that the performers also need to be naked to reveal "*the simple fact that humans, too, are actually machines"* (Ibid).

While I appreciate and sympathize with Raes' politico-philosophical reasoning – especially in a time when society feels to be regressing to more conservative morals in many areas in comparison to recent decades, particularly to when Raes came of age - and while I do not believe that on-stage nudity is anything controversial, or strange, or something to fret about in this day and age, researching his work gave me a feeling of unease: the reason was that nearly all of the (nude) performers of his radar-based works besides himself are female. There is no mention of the performers *needing* to be female, nonetheless this seems to be the norm when Raes is not on stage himself. One could surmise that this perhaps relates to his *"aesthetical"* reasons; while he does not elaborate on what these are, it is probably not far-fetched to suspect they relate to old-fashioned ideas about the use of the naked female form in the arts, shared by many people of previous generations, particularly men. In any case, despite thorough searches and scraping the Logos Foundation site for any evidence to the contrary, I found a dearth of works by Raes featuring other male performers. There are references to just two performances - exceptions that seem to prove the rule while bringing

[216] Nudity/nudism as liberation has long been a political stance for Raes, resulting in him and his partner being convicted of public indecency in the past when participating in a nudist action/happening.

forth additional questions. The first is an hour-long sextet from 2012 mentioned earlier - written by Raes with *“musical and code contributions by Kristof Lauwers and Sebastian Bradt”* (Raes, 2020) - which features the complete robot orchestra. It is titled *Study #25: Black and White,* presumably because it is performed by 3 black male performers, and 3 white performers, Raes and two of his frequent female dancers.[217] The *Namuda Studies* webpage includes a rather puzzling mention: that the performance incorporates a version of *Study #5: RoboGo,* initially a solo piece written for Raes, *“slightly adapted such that it could be performed by three black dancers*: *Zam Martino Ebale, Flavio Marques and Ousmane Gansor”* (Ibid). Unlike computer vision systems, microwave and ultrasound sensing are both indifferent to skin color, so it is unclear why the composer chose to add such a statement. The only other instance I found of a man performing Raes’ work is *Study #30: Force,* a solo 5-minute work with movement language derived from Tai Chi, which was performed thrice in an evening in 2013 by 3 different dancers, two women (Emilie De Vlam and Dominica Eyckmans) and a man (Zam Martino Ebalé).

[217] The female dancers are Emilie De Vlam and Dominica Eyckmans. The other male dancers, besides Raes, are Zam Martino Ebalé, Flavio Marques and Ousmane Ganso.

Chapter 4. FIRST HERTZIAN EXPLORATIONS: FROM THE NETWORK TO THE BODY, FROM WIFI TO RADAR

4.1 FIRST GLIMPSES: OBSERVE, RECOUNT, DISTORT!

The seed of my interest in the hertzian medium was planted in Spring 2010 with *Observe, Recount, Distort!,* a project created for a class on Telematic Art at DXArts led by Dr. James Coupe. While this was merely an experiment and by no means a finished artwork, it gave birth to many interesting questions and produced some intriguing results that motivated me to investigate further, seeding ideas at the core of my following works with the hertzian medium. For this reason, I will briefly discuss it here.

My initial goal for this project was to make a networked sound art installation. Conceptually, I was driven by a desire to investigate the agency of the networked person and explore, in a rather abstract manner, the effects that the structures of social networks have on the dissemination of information. In particular, with this project I wished to comment on the observer effect, which states that by observing a situation one inevitably changes its outcome. My focus was on creating a sonic metaphor for the distortion of information that occurs when a fact is iteratively re-stated by different members of a social group - hence the name *Observe, Recount, Distort!*. Sound was meant to suggest and portray the constant transmutations this networked context causes to the original message.

I started off with research on the subjects of collaborative instruments, network music and network acoustics. I became very interested in the idea of the network as a space and began to imagine what the 'acoustics' of such a space could be and how it could be explored. Inspired by works investigating the acoustics of radio - such as Max Neuhaus's *Public Supply* series from 1966-1973 (see Neuhaus, 1994b) - and the acoustics of the Internet - such as Chris Chafe's *Ping* from 2001 (see Chafe et al., 2002), and Juan Pampin and Nicolás Varchausky's *Catch 22 goes online* from 2006 (see Pampin, 2010 and Varchausky, 2018) - I set out to create a system through which a Wireless Local Area Network (WLAN) could become a feedback-based generative idiophone, i.e. a system that could generate sound on its own using audio feedback driven by network data. I imagined this as a kind of reverberant space in which the computers of connected users acted as resonators. An idea that would be closer to the modus operandi of the above-mentioned works by Neuhaus, Chafe, Pampin and Varchausky would be to transmit audio signals through the WiFi network and aggregate the many versions of the original source, thus exposing the delays inherent to the network. While this could produce a potentially interesting sonic effect of echoes and reverberations, I wanted to create a system that could provide more possibilities for sculpting and controlling sound. Therefore, I decided to focus on the network-specific domain of data packets, using the time these packets take to travel from one node to another as an indicator of the distance between them. The data was obtained with the *traceroute* command, a network diagnostic tool commonly used to identify the path (or 'route') which data packets follow when traveling within a computer network. [218]

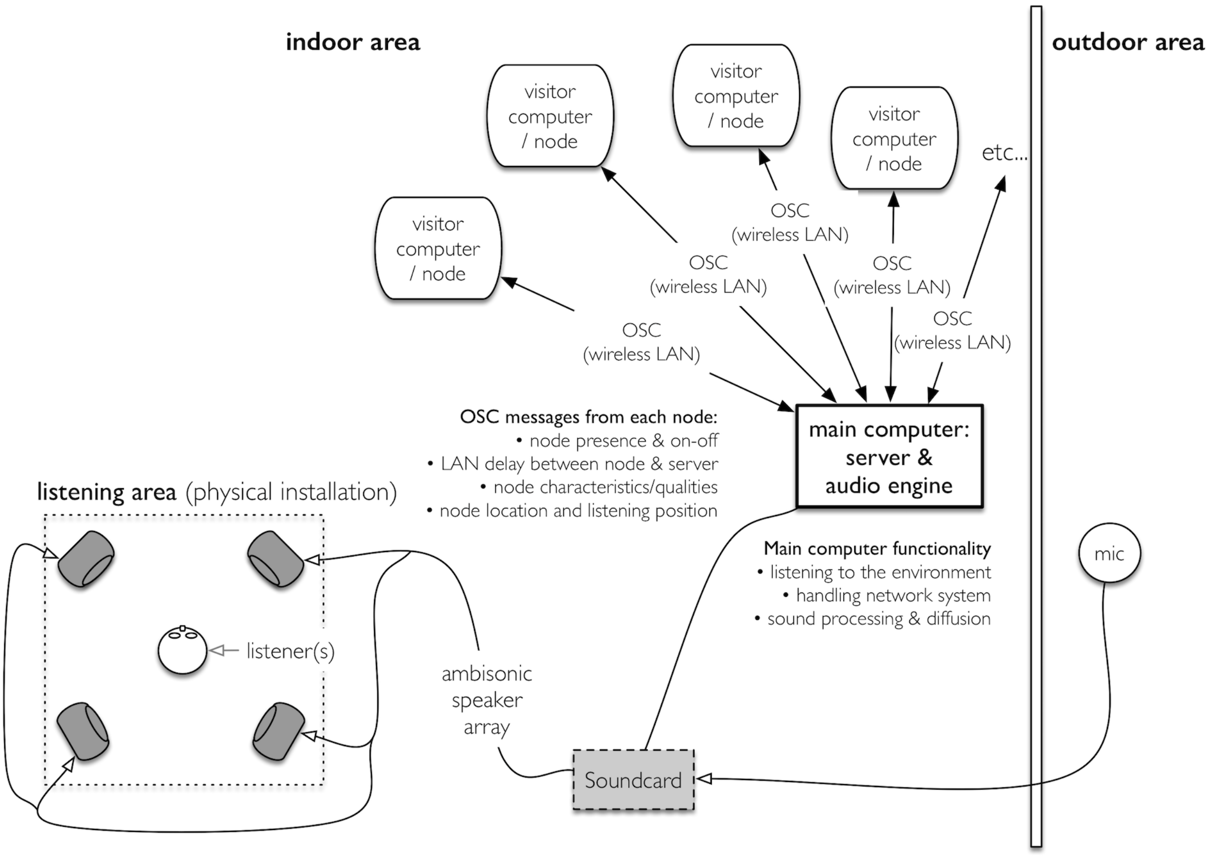

Figure 4.1. Basic diagram of the system structure and spatial configuration for the installation *Observe, Recount, Distort!*

To briefly describe how the system operated, at the center of the system was a computer transmitting a WLAN and acting as the central server, number-crunching 'brain', and sound engine (figure 4.1). To participate, visitors could connect with their laptops and install an application with which they could send control data to the server. Each connected device

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[218] Traceroute is a *nix system command; its Windows equivalent is the *tracert* command. Using traceroute instead of ping, another common networking utility, was a suggestion by friend and colleague Nicolás Varchausky, who kindly shared his preliminary experiments and implementations in SuperCollider with me.

inserted itself as an agent in the network, filtering the original audio information through its own 'sonic lens'. The original sound source was a live feed from a microphone installed outside the exhibition space. In terms of sound design, each node was configured as a dynamic waveshaper – i.e. a continuously modified lookup table used to map the signal's input values into a different set of output values (figure 4.2). The lookup table of the waveshaper was created algorithmically in real time, using a variation of waveterrain synthesis (see Bischoff, Gold & Horton, 1978 and Roads, 1996).[219] These waveshaper processes had the ability to produce feedback internally within themselves, as well as with other nodes in the network.[220] Broadly speaking, the more visitors connected the noisier and less intelligible the original source became, as one node was fed another node's modified re-statement of the original signal, thus perpetuating distortion ad infinitum.

Visitors could interactively configure the 'persona' of their node via controls in their application screen to change its agency within the system. This persona was defined by 5 'personality traits' ('egocentric', 'receptive', 'opinionated', '(un)stable', 'inventive', 'misinforming') that were mapped to particular synthesis parameters.[221] Visitors could set the amount for each, as well as influence how sonic information travelled from one node to another.[222] While reliance on a Graphical User Interface and a computer screen was far from ideal, some of the ideas related to mapping different behaviors/'personas' to sound proved quite useful, informing how I mapped the results of statistical analyses of time delays in my next work, *The Network Is A Blind Space.*

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[219] *Waveterrain synthesis* is an extension of *wavetable synthesis* that generates sound by scanning through a series of lookup tables, instead of just one table.

[220] This was inspired by Agostino DiScipio's extensive work with feedback systems (see his website at https://agostinodiscipio.xoom.it/adiscipi/index.html) and followed up on my own work with digital feedback (see in particular Manousakis, 2009a, 2010, 2011, 2019b and 2020, but also *Hertzian Field #2* and *The Water Within* (Hertzian Field #3.1)).

[221] The more 'egocentric' a node was, the more it would feedback with itself, whereas the more 'receptive' the more it would be fed input from other nodes. 'Opinionated' nodes were louder, while the 'inventive' parameter defined the amount of timbral richness, controlling the number of distinct waveform segments within a waveterrain. 'Misinforming' nodes contributed more noise by adding more segments. Finally, the stability parameter ('(un)stable'), controlled the rate with which a waveshaping table was created from a waveterrain surface.

[222] Each node generated sound in a specific spot of a virtual circle, which was reproduced sonically through a two-dimensional ambisonic speaker setup. A node's signal could be captured by other nodes whose listening point was set in the same vicinity. Visitors could define where their node's 'voice' (sound output) and 'ears' (sound input) were located via the software interface.

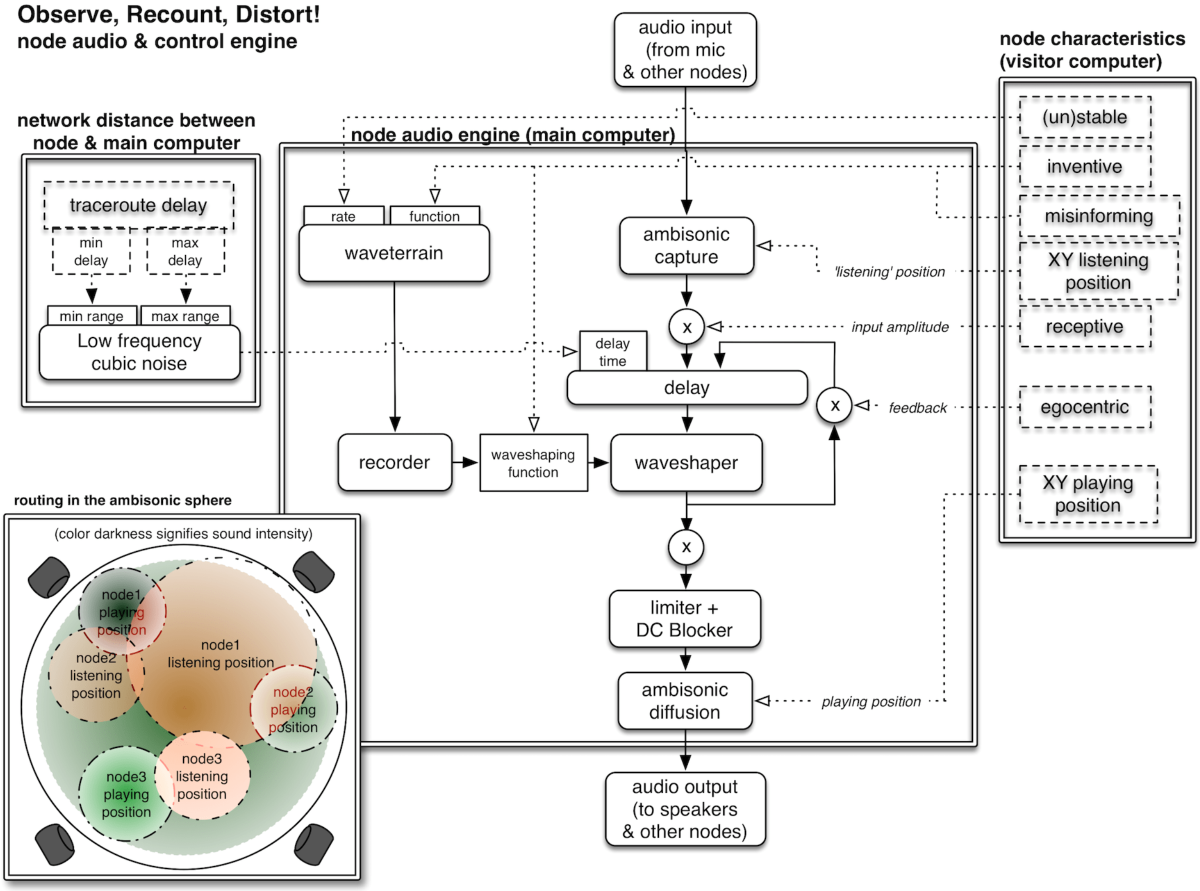

Figure 4.2. *Observe, Recount, Distort!:* Schematics of the audio engine and how it was controlled using tracerouting data (top left) and user-defined parameters set via a GUI (top right). On the bottom left, a graph displays how input and output was routed for both feedback processing and sound diffusion from and to the ambisonic sphere.

4.2 Exploring Hybrid Acoustics: The Network Is A Blind Space

4.2.1 *About the piece*

Following this first experiment, I became particularly interested in the gap between the typical understanding that most of us have of WiFi networks – thinking about them as something virtual or immaterial – and their actual characteristics: the fact that they are true amalgams combining the digital word (which is dependent on software and hardware), with the electromagnetic (as digital information radiates in space as electromagnetic energy) and the tangible (as these waves interact with physical space and objects that we can see and touch). Consequently, a few months later (September 2011), I began working on *The Network Is a Blind Space*, a distributed, 'micro-telematic', interactive sound-art installation. With this piece, I wanted to explore the hybrid nature of hertzian spaces created by WiFi networks; my strategy was to use sound as a kind of 'network echolocation' medium, guiding visitors in their navigation of this compound digital/electromagnetic/tangible space.[223] I developed most of the piece during an artist residency at the New Media Gallery of the *Jack Straw Cultural Center* in Seattle, where it was presented between December 9, 2011 – February 3, 2012 (figure 4.3).

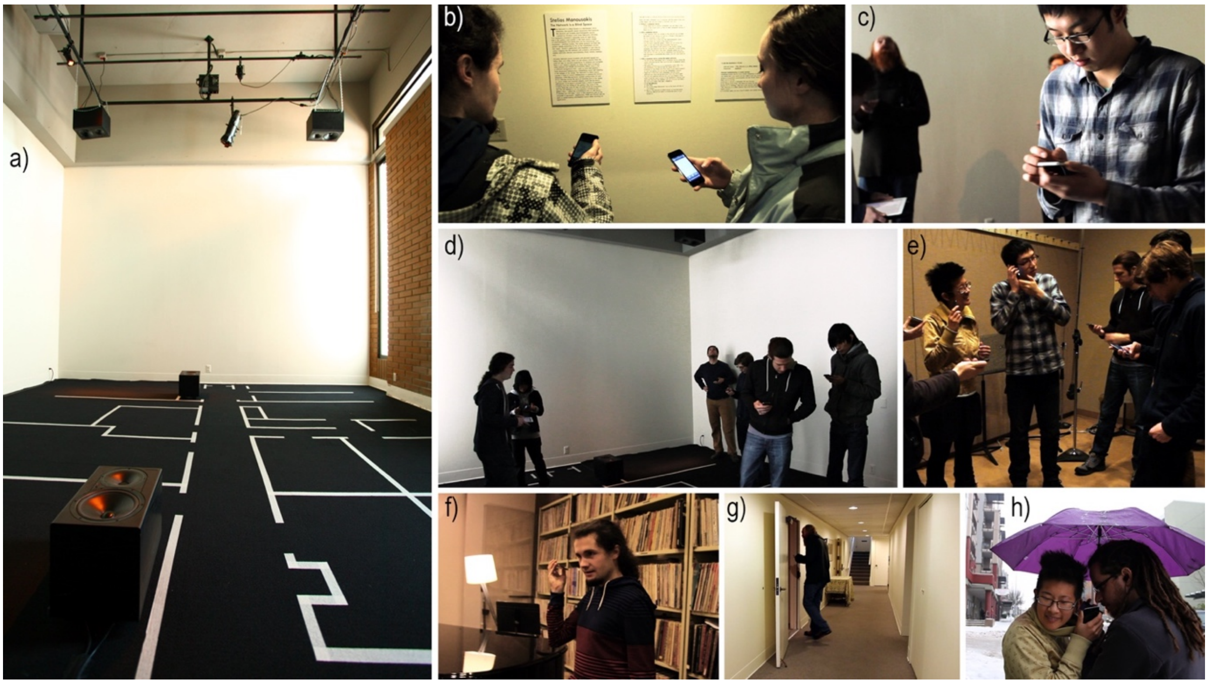

Figure 4.3. Photos from the exhibition of *The Network Is A Blind Space* at *Jack Straw Cultural Center* in 2011-12, taken in different rooms (for an architectural plan of the space see figure 4.4). Images (a), (c) and (d) are taken inside the main installation area, the *New Media Gallery*; (b) shows two visitors connecting to the work's network just outside the door of that room; (e) shows a group inside *Studio 2*; (f) is taken inside *Studio 1*; (g) shows a visitor in the corridor; (h) is taken outside the building while still within the reach of the work (photos by Stelios Manousakis, Martin Jarmick and Vincent Hill).

The text describing the work and its concept follows (Manousakis, 2012a):

"The Network Is a Blind Space *is a distributed, micro-telematic, interactive sound installation that explores the physical yet invisible electromagnetic spaces created by WiFi networks.*

We make wide use of electromagnetic radiation in our daily lives and depend on it increasingly to wirelessly transmit and receive information of all sorts, for all sorts of uses. However, despite relying on this radio space that engulfs us, it can be difficult to truly understand its nature or even acknowledge its very physical presence in a manner that involves our bodies directly. Moreover, while wireless network spaces co-exist and interact with physical ones, they follow their own rules, which are not always intuitive from the point

223 The term 'micro-telematic' was suggested by colleague James Hughes, owing to the piece's exploration of ideas related to telematics, but in a smaller range.

of view of every-day experience. To explore and navigate these spaces a new sense is needed, as vision falls short. In nature, many animals that inhabit environments where vision is not a sufficient navigational tool – such as bats and dolphins – have developed echolocation, transmitting sound and listening to the echoes of a space. The Network Is a Blind Space *creates an electromagnetic musical echolocation system in which visitors can use WiFi-enabled mobile electronic devices (smartphones, iPods, tablets, laptops) to poetically and viscerally explore this hidden Hertzian dimension, as it exists within the particular space the piece is installed in.*

The piece addresses the physicality of WiFi waves together with the deeply social nature of computer networks. It explores how such a network behaves inside a space, how it modulates the psychogeography of that space affecting visitor behaviors and interactions, but also how it reacts itself to visitor presence. To this extent, The Network Is a Blind Space *reveals the network as a dynamic, navigable space, as an open score spread in that space, and as a large, invisible, collective idiophone – a collaborative distributed instrument which devices of connected visitors excite into resonance."*

The work aimed to convey an immersive artistic experience, rather than to directly sonify network data. My goal was to enable visitors to experience the invisible and intangible world of WiFi communication that engulfs us in a poetic and playful way through sound, helping grasp its nature and its very physical presence simply by walking through the exhibition building while listening.

4.2.2 *Technology basics*

The physical distance between two devices/nodes in a WLAN corresponds to the actual path radio signals take to arrive from one node to another. In closed spaces without Line-of-Sight communication this path is next to impossible to measure, as a transmitted signal will bounce around inside a building many times before being received. Instead, however, we can use the time it takes for a data packet to travel from one device to another and back as an indicator of the distance between these two devices. This measurement is called the *Round Trip Time* (RTT), or the network's latency or 'echo'. One can think of such a data packet as akin to the pulse of a sonar except rather than measuring, for example, how far the ocean bed is from the hull of a ship, it measures how far one device is from another in the network.

RTTs form the basis of the 'WiFi echolocation' mechanism in *The Network Is A Blind Space.* The system uses two methods:

- *Time of Arrival* (TOA) measures the absolute time it takes for a message to travel from one device to another.

- *Time Difference of Arrival* (TDOA) calculates the difference in TOA between two or more devices in the network. TDOA can be used to deduce the relative position of a device between two, three or several other devices, meaning which device it is closest to.

In this work, these two methods were used to perform a *ranging* process similar to triangulation, called *trilateration* – the difference being that instead of using angle measurements to calculate position this process uses distance measurements (for more see section 5.7.2). Though the term *trilateration* is generally used in the bibliography to describe such systems, a more precise term can be used, depending on the number of nodes involved in the ranging operation: *bilateration* involves two nodes, *trilateration* involves three, and *multilateration* multiple nodes. *The Network Is A Blind Space* implemented an extension of TOA and TDOA *bilateration*, which was based on performing various types of statistical analysis on the RTT data.

Statistical analysis is a fundamental aspect of the system I developed for this work. On one hand, it allowed compressing the stream of *traceroute RTT* data into a more manageable set of numbers by *extracting* a set of *features* that represent it. On the other hand, and more importantly, these features could be used to derive meaningful information about the state of the network and the devices within it. *Feature extraction* is a commonly used technique in pattern recognition, machine learning, and audio analysis, among other fields. Besides reducing the dimensionality of the input data, it also helps reduce noise in the data and makes patterns clearer to identify. The subject of feature extraction will be discussed in more detail in the following chapters, as it is also a foundational element of the technology developed for the *Hertzian Field* series.

An important fact to keep in mind is that network distance is not only related to physical space. Instead, this measurement is a result of the interaction between all the components of the WiFi ecosystem, being influenced by the specific software and hardware used, the devices' transmission and reception capabilities, as well as physical space, architecture, and environmental factors such as humidity. The network space is a true hybrid whose properties are affected by all these factors in rather intricate ways, as I discovered in practice. For example, the effects of software and hardware became evident during my experiments, as different types of devices produced vastly different results at the same physical distance. My observations revealed a tendency of specific device models to be located 'further away' than others in network terms. Operating systems also played a significant role, with devices running Android appearing much further than their iOS counterparts (that was the case around 2011-12, things may be different now). In general, the WiFi hardware of handheld devices was demonstrably inferior to that of laptops or desktops, not only appearing orders of magnitude further than those devices (between 10 to 500 times further), but also exhibiting stochastic behaviors and fluctuating measurements somewhat independent of the network's properties (my educated guess is that some of these fluctuations may have been caused by battery-saving optimizations implemented by these mobile devices). Furthermore, as will be discussed in section 4.2.6, at times the system also clearly revealed the influence of environmental factors such as humidity and network congestion.

This all means that spatial localization based on straightforward TOA and TDOA measurements is rather imprecise, especially without cleaning up the data, which is where statistical analysis really came into play. Nevertheless, while these discoveries would be problematic if I were developing a commercial localization application (it's not by accident that TOA and TDOA of WiFi data packets are not the main methods for such purposes) they produced results that were very interesting in an artistic context and particularly when mapped to sound. In *The Network Is A Blind Space* stochastic behavior became a form of musical counterpoint, which was especially effective when there were multiple devices in the same general area, as they all tended to give similarly fluctuating results but at different times. It was a moment of revelation during the development of this project when the 'inferior' noisy data from tracking mobile devices (compared to laptops) suddenly produced a musically superior sonic behavior. Given that the goal of this project was not to create a robust localization algorithm but to listen to the network as it exists in a space, at a particular time, and with a particular set of devices connected, this was not a problem but a defining quality of the network's components - and by extension of the artwork - to be welcomed and explored.

4.2.3 *Configuration, experience, interaction*

The piece was designed with the specific architecture of the *Jack Straw Cultural Center* in mind, but in an open-ended way that allows adjusting it for other multi-room exhibition spaces. Its configuration responded to the site's most characteristic architectural feature: a long corridor with various rooms on its left and right (recordings studios and offices) (figure 4.4). There was a main area for experiencing the work (the *New Media Gallery*), acting as a kind of 'control room' and central listening area for the entire piece. Beyond this room, the work extended as far as the its WLAN could reach; visitors could interact with and experience it by exploring all the different spaces inside the building as well as outside with their devices.

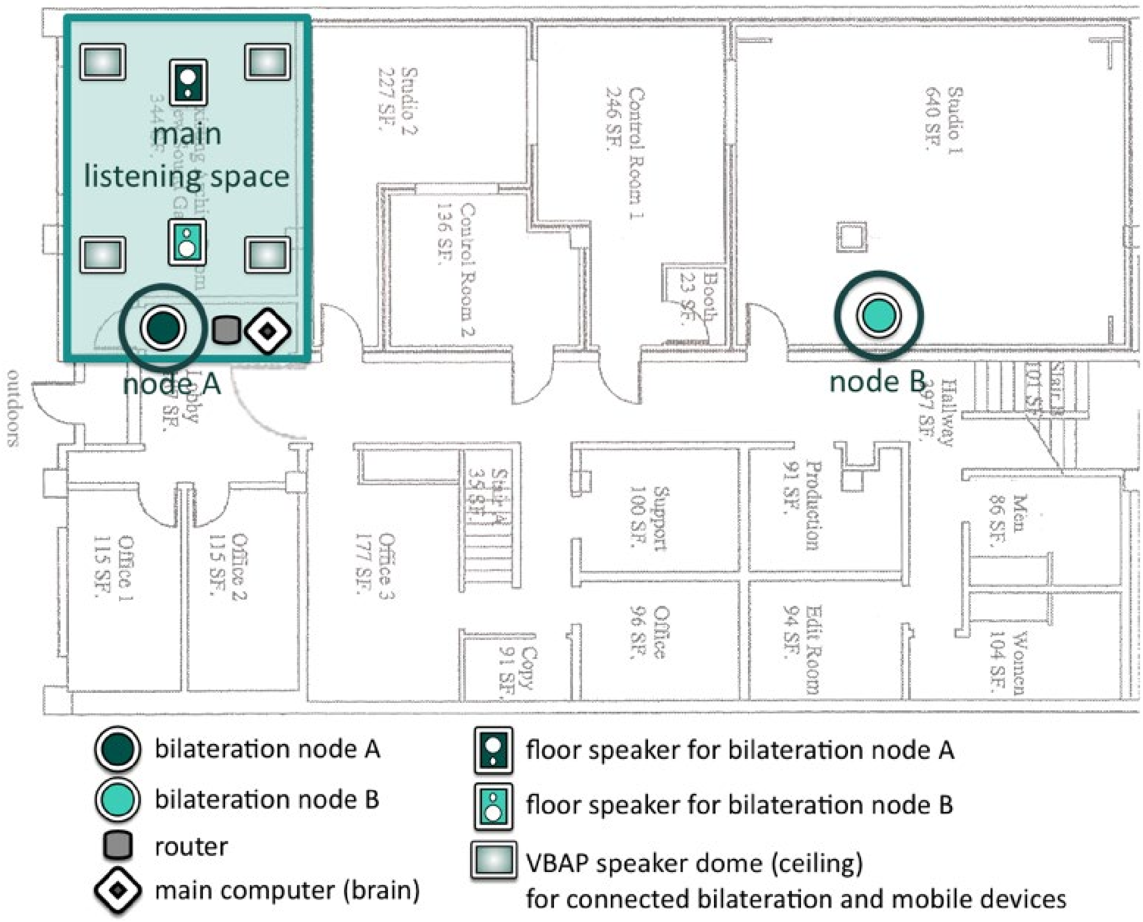

Figure 4.4. Spatial configuration of the *The Network Is A Blind Space* at the *Jack Straw Cultural Center.* Visitors could explore the work through the entire building; the *New Media Gallery* room was the main listening space containing visible speakers (as well as a bilateration node, a WiFi router, and the main computer running the work hidden inside a crawl space and out of sight). The second node was hidden in *Studio 1* at the other side of the building.

The *network echolocation* system consisted of the following hardware components:

a) A router creating and managing the WLAN of the piece.

b) Two computers acting as trilateration nodes. These were installed at two opposite ends of the building to create an electromagnetic line that could be transversed and explored by visitors.

c) Another computer acting as the main 'brain' of the installation. This machine did most of the number-crunching and was in charge of the interaction, mapping, sound synthesis and spatial diffusion; it also made a number of compositional decisions. Its sonic output could be heard from a dome of speakers in the main listening space (see figures 4.3, 4.4).

c) A handful of iPod Touch devices available to visitors which ran a special software I developed that turned them into mobile sound-producing *network echolocation sonars* (figure 4.5).[224]

d) A variable and unknown number of ordinary WiFi-enabled mobile devices that visitors brought with them and with which they could connect to the installation's WLAN (smartphones, iPods, tablets, laptops, etc.). Visitors with iOS devices (iPhones, iPods, iPads) could also download and install the special application, turning their devices into network sonars.

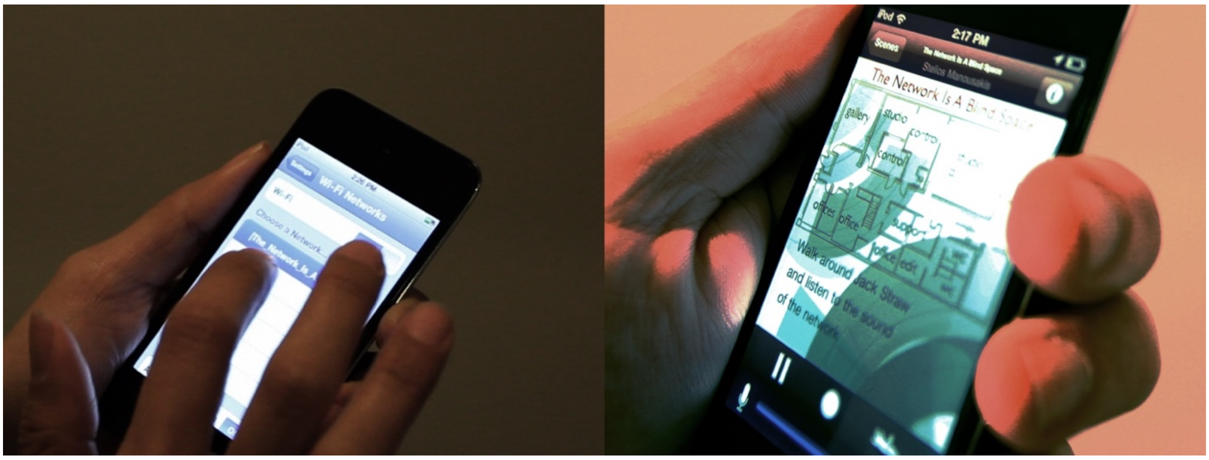

Figure 4.5. Engaging with *The Network Is A Blind Space* using mobile devices. Left: Visitor connecting to the WiFi network of the work. Right: Visitor holding an iPod Touch running special sound-generating software developed for the work (photos by Martin Jarmick and Vincent Hill).

Each device logging into the WiFi network, including the two trilateration nodes, became part of the network topology, meaning that it increased the dimensions of the *network space* as each new node added a new distance to be measured and echolocated by the system (i.e. a new *echo*). The three computers of the system ran software that I developed in the *SuperCollider* real-time audio programming language.[225] This software was used to produce sound, compute all control data, and interface with various command line tools that formed the project's networking backbone. The mobile device application ran on *RjDj*, a free port of the *Pure Data* audio programming environment.[226]

[224] These devices were kindly made available courtesy of DXARTS.

[225] http://supercollider.sourceforge.net/. Last retrieved 29 December 2022.

[226] *PureData* is a graphic audio programming environment by Miller Puckette (see http://puredata.info, last retrieved 29 December 2022). *Rjdj* was a short-lived mobile port of *PureData*, active between 2008-2013 ("Rjdj", 2022).

The rules of engagement were kept deliberately simple and intuitive. Visitors interacted with the piece simply by moving in space, typically while carrying a handheld device with its WiFi interface connected to the work's WLAN. They judged where and how to move purely according to the sounds they heard. There were a few different principal modes of participation:

- Without any mobile devices connected to the network, one could listen to the sound of the system itself, which revealed the continuous stretching and shrinking of the *microwave line* connecting the two trilateration nodes. The state of the network from the point of view of each of its two computers/nodes, was projected by two speakers placed on the gallery floor. The floor depicted the architectural plan of the building marked with tape as a somewhat cryptic navigational roadmap; these two speakers were placed on the respective spot of the computer they represented. Interaction was still possible though minimal in this manner, for example by opening and closing the doors of the different rooms and of the corridor to add or remove obstacles in the path of the WiFi microwave signals.
- Equipped with a WiFi-enabled device, visitors could more directly change the properties of the network space, and as a consequence affect the soundscape of the work. By simply connecting to the piece's WLAN, the network topology was augmented with the addition of a new path through which information travelled, thus altering the system's balance. This changed the properties of the network and consequently modulated the sound of the trilateration nodes. Furthermore, each connected device became an active 'agent' in the software system. Once connected, the system created a new 'instrument': a sound generator creating and modifying sound in real time, that represented the particular mobile device. The synthesized sound corresponding to each individual device could be heard from a dome of speakers hanging from the ceiling of the main space.
- The modes of interaction with a device running the special *RjDj* application were similar, except the sound character and – to a smaller extent – the mapping of data to sound in the gallery were different. Most importantly, these devices also generated sound through their own speakers, allowing visitors to directly expose the electromagnetic and acoustic properties of the space while moving in it, with their device acting like a portable sound-making network sonar.

Overall, visitors could experience the piece by standing still to listen how the network space changed in time, by moving around the central gallery room, walking outside that room to the rest of the building – or even outside - actively changing their device's distance from the two trilateration computers, or by looking for particular spots with interesting electromagnetic properties (such as spaces where architectural features caused microwave ‘shadows’, partially or completely obscuring the network, or resonances that amplified its signals). As a more direct way of interacting, turning on and off a WiFi interface or disconnecting and reconnecting had a clear audible effect: it destabilized the system but also removed and recreated the device-specific instrument in the software, assigning it a slightly different sound every time it appeared in the system because the synthesis algorithms involved some randomness upon initialization to provide greater sonic variety.

4.2.4 *Networking echolocation toolbox*

Diving a bit deeper into the technical aspects, my implementation of TOA and TDOA was based on the *traceroute* command, building on past work from *Observe, Recount, Distort!*. *Traceroute* is typically used with devices not directly connected to each other, mostly to trace the path of information flow on the internet. Unlike *ping,* however - another network utility that is commonly used to find how long it takes for messages to travel between two nodes in a network - a single *traceroute* command can send multiple Round-Trip data-probes nearly simultaneously. This makes it a very convenient tool for tracking the network distance in networks where devices are connected together directly, like WLANs.

The data in a traceroute reply contains information on:

- the presence of an IP address, i.e. if a device with that IP was found in the network or not;
- the number of hops, i.e. how many nodes a message has to be routed through in the network to go from the tracerouting device to the target device; in a WLAN there is just one hop;
- temporal distance, i.e. how long was the RTT between each hop (in milliseconds).

A *traceroute* response of a probe that was successfully delivered to looks like this:

1 10.0.2.5 76.363 ms 3.394 ms 6.008 ms

The first number is the *hop index* (i.e. how many routers away from the original device this message was sent to); it is followed by the *hop IP address* (i.e. the IP of that router/node), and a series of *RTT times.* These RTT times represent how long it took the data-probes sent by a single traceroute command to return to the sender.

Data probes are transmitted in sequence, following each other within a few hundred μs. The temporal gap between separate probes within a single traceroute can be adjusted. In a WLAN scenario, like in *The Network Is A Blind Space,* statistical analysis of the RTT differences between probes of the same traceroute can help deduce connection quality and physical distance between two devices. This could be called a ‘micro-time’ analysis, in analogy to Curtis Roads’ categorization of different time scales in music (Roads, 2001). Differences between the RTTs of consecutive traceroutes (what could be called ‘event-time’), or between the average RTTs between sequences of traceroutes (‘meso-time’) can help indicate movement of a device in physical space or reveal general motion patterns. As a result, tracerouting devices in a WLAN can help reveal a variety of information, from giving insights on their distance, to the movement of mobile devices, connection stability, overall network congestion, or even humidity. Moreover, when applied in a space with known obstacles to the transmission of WiFi signals, such as walls, these data can also give insights about the possible areas a device may be located. This is related to the fundamental idea behind network fingerprinting, a technique that will be explained in a following section (5.3.2).

For this project, I developed a number of SuperCollider classes to interface with *traceroute* and other auxiliary command-line networking tools and to parse, analyze, and use the data generated by them (figure 4.6). These classes allowed automatically setting and querying network settings and retrieving data about the network’s topology. They handled all tracerouting and micro-time statistics and they received, processed and stored incoming data from remote trilateration computers. They retrieved various types of stored trilateration data, and they parsed, cleaned-up, shaped and mapped this data, converting it into control streams for sound synthesis algorithms. These streams were used locally by the system’s sound-generating computer, as well as remotely (via Open Sound Control) by connected mobile device clients.[227]

The two bilateration nodes ran a standalone application written in SuperCollider. They were responsible for finding devices that joined the network. Once a new device was found, the bilateration nodes began sending traceroute probes to it for as long as it remained connected. RTT data within each traceroute was statistically analyzed and sent to the main computer via the Open Sound Control protocol (OSC) (figure 4.7).

[227] OSC is a protocol for communication between computers. See: http://opensoundcontrol.org/

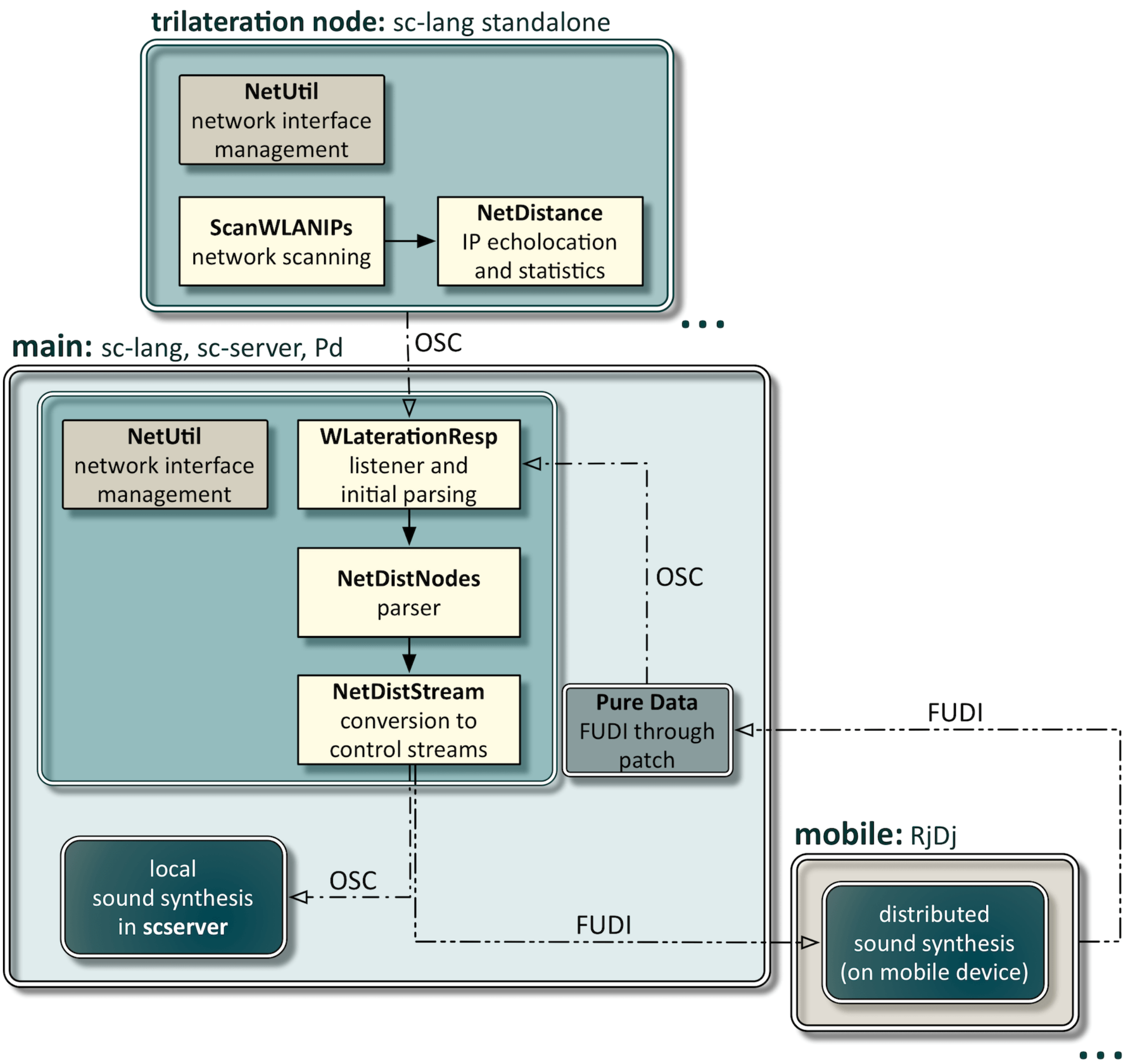

Figure 4.6. A graph providing an overview of the *network echolocation* toolbox developed for *The Network Is A Blind Space,* and showing how information is shared between the system's different modules across devices in a WiFi network.

This analysis involved performing a number of time-domain statistical operations on the incoming stream of RTT data. Features extraction was performed over three different windows of time:

- the ‘micro-time’ of the data probes within a traceroute,
- the ‘event-time’ between a short temporal window successive traceroutes,
- and the ‘meso-time’ of a longer window of traceroutes.

Extracted features included: the *minimum*, *maximum*, *sum*, *integral* and *median* RTT; the *arithmetic*, *harmonic* and *geometric mean* and two separate *running average* counts, each with a different low-pass filter coefficient; the *standard deviation*, *skewness*, *kurtosis* and *variance*.

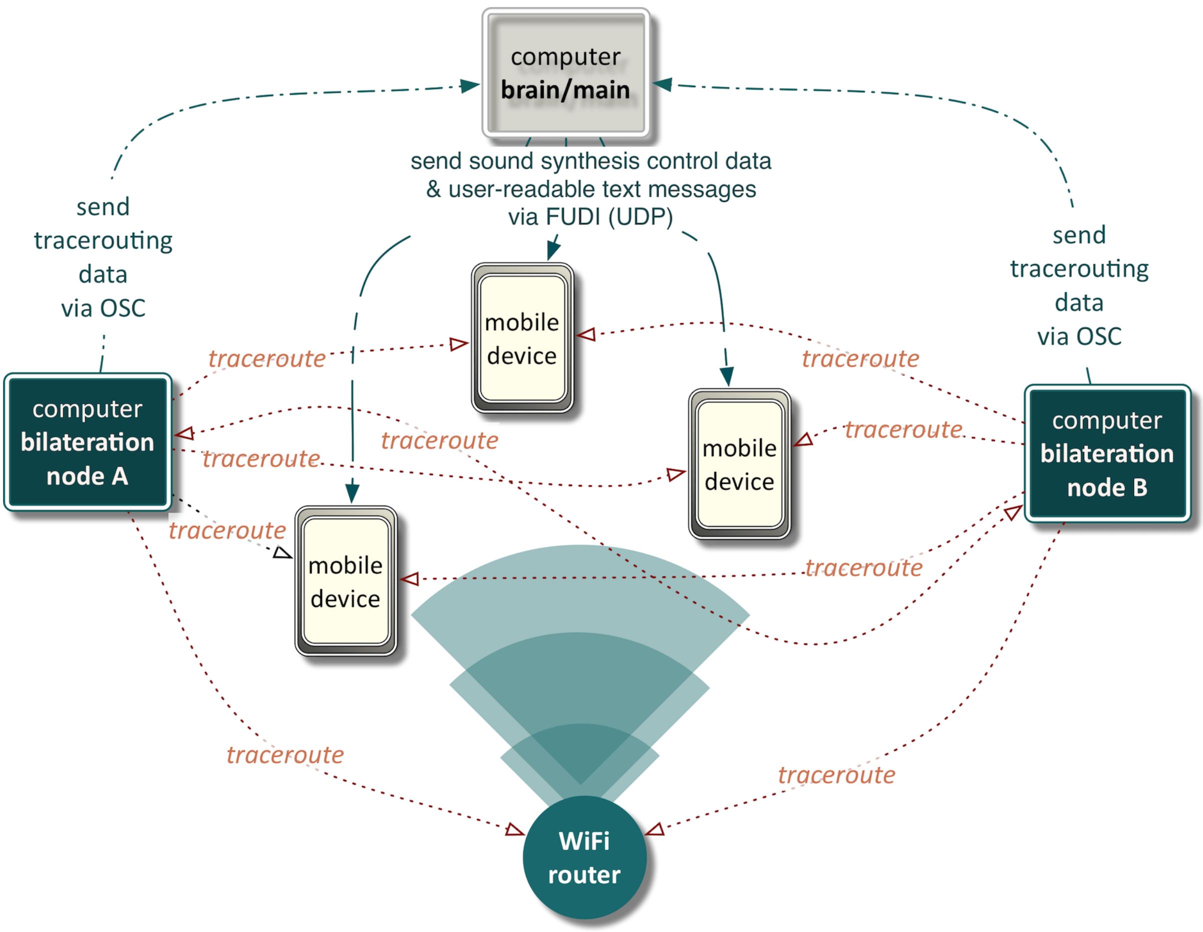

Figure 4.7. *The Network Is A Blind Space*: A simple graph displaying the computational hardware involved, the network distance capture system (via tracerouting), and the communication between devices through the network.

The main computer registered all extracted information and parsed it in different ways, giving access to all traceroute statistics/features as well as extracting additional useful data. The latter included: how many and which devices were connected to the system or to a specific trilateration node (devices were identified by their IP address, although the MAC address would be a better identifier); when was the last time a device was seen; if a specific IP was connected; if it was still active; and various combinations of the above. This functionality permitted looking at the network's topology from three different points of view:

a) The global, i.e. the network topology in its entirety.

b) The local/nodal, i.e. the network and the distance between its nodes as perceived by a specific bilateration node.

c) The mobile, i.e. the network as perceived by each mobile device connected to the system.

All data could be converted on demand into real-time control streams which could be subsequently mapped to sound synthesis parameters. A special module was developed for this purpose to convert the data in the most flexible way (figure 4.8). This operation involved:

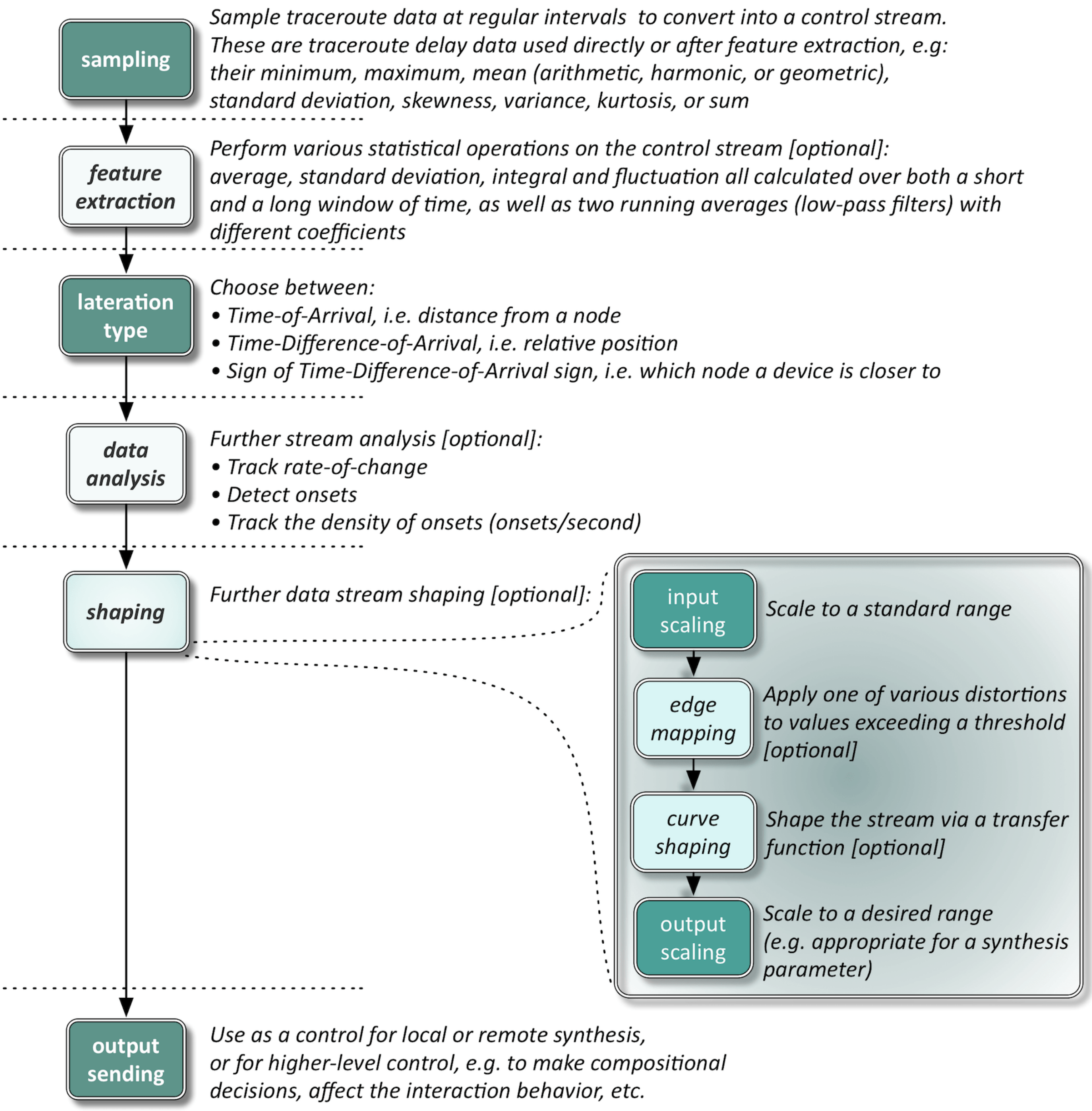

Figure 4.8. *The Network Is A Blind Space:* The multi-stage process of converting *traceroute* information to control streams involves sampling, feature extraction (optional), choosing lateration type, performing additional analysis (such as detecting onsets, optional), shaping the data to conform to a particular range (also optional), and using them to control sound parameters directly or to make higher level decisions.

a) Sampling the incoming traceroute data at regular intervals. This was crucial because, by definition, traceroute information arrives at irregular moments.

b) Extracting specific features from the data.

c) Choosing between one of the following trilateration methods to generate the control stream:

- a TOA value, i.e. the network distance of a device to a particular node
- a TDOA value, representing the relative position of a device in space
- the sign of the TDOA value, showing which trilateration node a device was closer to.

d) Optionally, tracking *rate-of-change* (i.e. *slope*) on the stream resulting from (c) - e.g. calculating the *rate-of-change* of the *standard deviation* of a TDOA stream. Such features could be used as a control stream in themselves, or as a way to detect '*onsets'*, i.e. sudden changes, and to calculate the density of these onsets (*onsets-per-second*).

e) Prior to mapping to a synthesis parameter, the resulting data stream could be further scaled and shaped by a series of mathematical operations that includes: i) scaling the input data to a specified range, ii) applying various clipping or distortion methods on values that exceed a threshold, thus defining specific sonic behaviors when surpassing both low and high boundaries,[228] iii) using transfer functions to further shape the data stream's range; and iv) scaling the result to a range appropriate for a specific synthesis parameter. This shaping functionality was a fundamental compositional tool, allowing transforming streams in ways most appropriate to the incoming data, to the synthesis parameters they were called to control, and to the compositional plan of the piece. It was also key to fine-tuning the *traceroute* data to the specificities of the exhibition space.

f) The shaped streams could be mapped to sound synthesis algorithms locally on the installation's main computer, or remotely by sending them to the mobile devices via the User Datagram Protocol (UDP).[229] They could also be used by the system to take compositional decisions or affect its interaction behavior rather than to control sound.

Different features were used to deduce various useful states and relationships of a device with the network and the space. For example, various types of *TOA RTT* values (e.g. *minimum, mean, maximum*) were the standard method for revealing distance from a node. The *standard deviation* of RTTs was also extremely useful; for instance, small values revealed a good connection – therefore closeness. This made the *TDOA* of the *standard deviation* a practical

[228] The system provides over a dozen different algorithms that make sure the value of a stream does not exceed a low or high threshold, such as *clipping*, *soft-clipping*, '*overdriving'* like an analog circuit, *folding*, *wrapping* over the other edge, calculating the *sine*, *cosine*, *tangent* or *arc-tangent*, as well as using '*reflecting'* from the threshold using a number of stochastic operators. This is all similar to the *waveshaping 'edge' function* described in more detail in section 6.5.4.

[229] As mentioned, the mobile devices ran a mobile port of *Pure Data* (RjDj). Pure Data did not implement OSC messages at the time, using instead its own networking protocol, the 'Fast Universal Digital Interface' (FUDI).

tool for finding relative position in the actual physical space. A *low-pass filtered* version of the *sign* of the *TDOA,* in its turn, was translated to probability of closeness. On the other hand, tracking *slope* or using *onset detection* on a *mean* or *standard deviation* stream helped identify, in most cases, when a device moved from one room to another. This was used in the piece to create an audible response when a visitor passed through a door.

Beyond this work, my experimentation and close investigation of feature extraction of this network distance data, and my development of strategies for mapping them to sound, proved to be of great value later on, during the development process of the *Wireless Information Retrieval* system and the composition process of the *Hertzian Field* series.

4.2.5 *Composition and sound*

The piece was meant to be experienced as a semi-autonomous, complex 'world', in which visitors could passively or actively immerse themselves, shifting between different levels of engagement - exploring, interfering or destabilizing this world with their actions. Compositionally, I approached it as an *open work* as defined by Umberto Eco: that is a work in which *"[e]very performance* explains *the composition, but does not* exhaust *it"* (Eco, 1959). Naturally, there are some fundamental differences from Eco's original concept of the open work, as the piece was an interactive installation not a music composition. Most importantly, there was no absolute beginning, middle and end, but visitors created for themselves a somewhat linear temporal flow as they explored the space and the system within it. In this manner, the roles of performer and audience were fused. As a result, the system needed to be able to simultaneously communicate an experience and give insights on how to engage with the work. To achieve this, the computational backbone of the piece functioned in multiple layers: as a compositional framework, a field of possibilities, an interaction platform, a score and a collective instrument. Thus, it embedded aesthetic decisions and time-based compositional development in its treatment of the hybrid physical/digital/electromagnetic space, and in its treatment of the actions of visitors within it.

The experience was very much dependent on the characteristics and behavior of the network when a visitor joined it. Among other elements, this was influenced by the interaction of the WLAN with the specific site of the installation, by the specific devices connected to the network and their location, and by the behavior of the people in control of those devices. It was also influenced by extraneous environmental factors, such as network saturation and humidity. The piece aimed to heighten the sonic sensibility of participants, thus listening was the primary mode of feedback and guidance. While this is a rather *Cagean* idea in its essence, the approach and aesthetics of the work were very different than those in John Cage's work, particularly as they involved a purely synthetic sonic environment instead of pointing an ear to sounds that were already present.

Sound was responsive to visitor interaction, and its behavior and variations were designed to help reveal properties of the network. The various control streams were interconnected in the synthesis engine using cross-coupled, 'many-to-many' mappings to create a dynamic, organically behaving sonic environment (for an explanation of 'many-to-many' and other mapping strategies see section 7.1.4 and Hunt & Wanderley, 2002). My goal was to create a soundscape that visitors experienced in its totality as a unified evolving world, rather than to turn their attention to the sound of specific network features (which would turn the piece into a sonification project that might be informative, but not poetic). To this extent, I made extensive use of feedback-based synthesis models. This, combined with the above mapping strategy, made the various 'instruments' within the network's 'orchestra' more expressive and fun for visitors to interact with.

An important orchestration decision was to assign different sonic and behavioral qualities to each of the system's components, thus enabling visitors to easily distinguish between the 'voices' of the trilateration nodes, the 'voices' of devices simply connected to the network, the 'voices' of devices running the special application, and the sound emanating from the devices themselves - while ensuring it all sounded well together. At the same time, conceptual ideas strongly influenced the sound design. As such, the sound of the bilateration nodes was highly localized and emanated from the ground, as it was meant to highlight the computers that were always connected to the network. Their synthesis engine was based on a single-oscillator feedback FM instrument, with an FFT-based filter generating harmonics embedded in the feedback loop for additional timbral control. This produced a continuous sound with a kind of 'natural element' effect, and a flow reminiscent of waves in the ocean. When the bilateration nodes perceived the network to be stable (i.e. with no external devices connected, or no external devices moving), they droned calmly, soothingly and harmoniously, with an almost vocal timbre that contained many formants. When the network was more active, their sound also became active and louder, more sinusoidal and melodic, and moderately unstable. High entropy made them turbulent and tumultuous, emitting broadband and noisy sonorities.

The sounds corresponding to connected visitor devices emanated from speakers mounted on the ceiling. They enveloped visitors inside the main exhibition room so as to convey the illusion of data packets moving around them. Sounds moved depending on where the system perceived a connected device to be located in the overall space, and how robust its connection was. The sound engine for these nodes was based on either a filtered feedback FM network incorporating various types of distortion, or a more complex algorithm, implementing a wavetable variant of the *Voltage Triggerable Function Generator* ('VT-FUG') – essentially a 'tone-burst' variant of the *VOSIM* oscillator (Tazelaar, 2005) that produces a variable number of oscillation periods every time it is triggered (for more, see section 7.3.5) .

The sound of passive nodes, i.e. devices that did not run the special application, was continuous and less pronounced, as those nodes were portrayed as having less agency in the system. The individual 'voices' of such devices were relatively similar to each other and remained in the background where they tended to fuse together, at least to a certain extent. The 'emotional bandwidth' or 'dramatic capabilities' of their sound was fairly neutral and restrained. Their sound engine used a special wavetable-feedback synthesis model I designed, and their timbres ranged from harmonically rich but strongly pitched to noisier ones, depending on the state of the device they represented within the network (i.e. its distance from a trilateration node, connection stability, etc.). Radical changes, such as moving from one space to another, caused pronounced but brief bursts of melodic patterns.

In contrast, active nodes - i.e. ones that were running the RjDj application - had much more striking characters, generating discrete percussive events in rhythmic successions. Similarly to their passive counterparts, their sound was dependent on the network behavior of the device they were linked to. At times they were slow and smooth, other times fast and polyrhythmic or - when a device moved further away from the main space, when it crossed spatial barriers such as moving between rooms, or when it explored an electromagnetically shadowed area - they were more broadband, distorted and aggressive.

As opposed to this more dominant sound in the main space, the sound that active nodes produced locally on a device was much more intimate and smaller, even fragile. Conceptually, this aimed to convey a duality between the nodes' inner voices and 'personas', and between their public voice in a social context. Despite their different sonic characters, it was easy to correlate the two sounds due to the control data being the same, which resulted in similar behaviors. The RjDj application run a 'pulsar synthesis' patch (see Roads, 2001) giving the devices an almost insect-like or bird-like quality, but with a truly digital voice that paired well with the limited capabilities of the smartphone speakers. At the same time, this percussive and pulsing sound activated the acoustic resonances of the spaces in which devices were located, helping convey the notion of echolocation. Active nodes thus emitted high-frequency, percussive pulsaret chirps, whose timbral, temporal and frequency characteristics changed according to the device's state inside the network. A swarm of these devices sounded compellingly biological, yet entirely digital and synthesized.

4.2.6 *Conclusions*

The system made it possible to interactively navigate WLAN networks as spaces through sound, exploring their inherent properties, their relationship to physical spaces, and their response to actions of connected visitors. It provided a large variety of user-generated control data through multi-layered feature extraction of network distance data. For optimal response, it had to be fine-tuned to the specific site. The final system was robust and versatile, to the point of permitting live-coding instruments, behaviors, and mappings during the compositional process - which was particularly useful for fine-tuning and putting the last touches.

Developing the framework presented many challenges, both artistic and technical. The least pleasant of the latter involved long hours of troubleshooting networking hardware while grappling with the network's response to extraneous and unpredictable factors such as humidity and network congestion. This also led to some rather interesting observations: For example, I noticed that practically every Friday afternoon the system sounded different and mobile devices had a hard time connecting to the main router. My interpretation of the phenomenon was that many people in nearby offices likely spent the last working hours of the week browsing the Internet, which caused noticeable network congestion. Another interesting observation had to do with the effect of weather and humidity on the system. This became most obvious during the last days of the work's exhibition in Seattle and particularly the day when I was documenting the work. After a few days of snow fall, the weather had warmed up and the snow was beginning to rapidly melt. To my surprise, humidity made those 'Friday afternoon problems' reappear to an even more extreme degree (years later, I explored the effects of humidity with the installation *The Water Within / Hertzian Field #3*). Yet another observation was that when there were small groups of people blocking the corridor, the distance between nodes would significantly lengthen, almost as if a new wall was temporarily added. This clearly hinted to some type of signal absorption by the human body, which I was fascinated by and on which I ended up focusing on a few years later with the *Hertzian Field* series and the development of the *Wireless Information Retrieval* sensing technique.

Overall, during a 7-week gallery exhibition of *The Network Is A Blind Space* the system proved very successful, intriguing visitors, who listened attentively and engaged with the work for extended periods of time, with many coming back to explore and experience it under different circumstances, on their own or bringing friends. I finished the piece with the idea of further developing this framework to use it in a family of related works. Some ideas involved investigating different found spaces or architectures specifically sculpted for the system, expanding to multiple sites and on the Internet, but also incorporating performative elements where visitors and trained performers could engage together through the network. A few of these ideas have been realized; for instance, my 2015 piece *Music for Browsing* features a similar echolocation system that operates on the virtual space of the internet (Manousakis, 2015). Some other ideas eventually let me to discover a more fruitful path, that led to the system employed in the *Hertzian Field* series.

4.3 Closing in on Hertzian Physicality: 'Act so that there is no use in a centre'

4.3.1 *Background, and about the work*

In the beginning of 2014, I spent 3 months in Vienna for an artist residency.[230] As part of the residency, I was offered the opportunity to present a new work in a group exhibition with a visual arts focus. Being in Vienna, one of the historical centers for the development of radio drama and radio art in general, I was inspired to broaden my artistic research on wirelessness and investigate how I could use broadcast radio as an artistic medium for a work that could be exhibited in such a context. Consequently, I decided to create a sound installation that made allusions to the varied history of creative radio practices. In particular, I wanted to work with text and the voice as a reference to the genres of *Hörspiel* (German-language radio drama) and the ghostly poetics of the disembodied radio voice. My idea was to create abstract fragments of narrative that came close to making sense – but never quite did. I also wanted

[230] The residency was hosted by *KulturKontakt Austria*, a non-profit visual arts organization with rich history, and by the Austrian Federal Chancellery.

the piece to be informed by pioneering avant-garde compositions involving the radio, such as John Cage's *Imaginary Landscapes No 4* and *No 5*, and Karlheinz Stockhausen's radio works from 1968-70 (*Kurzwellen*, *Spiral*, *Expo*, *Pole*). Furthermore, I wanted to explore the – typically ignored - spatial qualities of wireless transmission and the physicality of hertzian spaces, which I felt I had only began touching upon with *The Network Is A Blind Space*. In terms of form, my desire was to make a work that did not repeat, that was dynamic, exhibited some sort of agency and could be interactively experienced – all without using a computer.[231]

Figure 4.9. Photos of *'Act so that there is no use in a centre'* from its inaugural exhibition at the gallery of the Austrian Ministry of Culture in Vienna, in 2014.

The original description of the work follows (Manousakis, 2014a):

"'Act so that there is no use in a centre' i*s an abstracted and deconstructed spatial radio play. It sets 'Rooms', from Gertrude Stein's seminal language-art book 'Tender Buttons' (1914), as a distributed, radio-transmitted, sound installation, meant to be explored interactively. The work takes its name from the first sentence of the text, which also sets the tone for the visitor experience.*

The piece deals with fragmentation, interference, and distortion of memory, place, and meaning. Emanating out of 6 storage boxes, the combined memories of the writer (text) and the artist (sound) haunt the exhibition's hertzian space with imaginary landscapes, wordscapes, and fleeting soundscapes, waiting to be discovered using 7 small portable radios. Each box contains fragments from a particular type of space implied in Stein's text and transmits them to the nearby airwaves: studio, living room, bedroom, kitchen, outdoors, and transitional spaces. Original material, together with sounds from the maker's audio archive composed and recorded in various locations in the span of 10 years, support and

[231] Simplifying the technology for this work was first and foremost a practical limitation. There was not enough budget to rent a computer, and I could not dedicate my laptop to run the piece during the exhibition as during that period I had to give a workshop, a lecture, and several concerts around Austria. While these circumstances were limiting, they helped me discover creative and effective solutions outside of my usual arsenal - which is one of the things one hopes to achieve during a residency.

expand on the text. The work lasts 35 minutes.

Experiencing:

Visitors can experience the piece using the handheld FM radios found in the exhibition space. The piece is interactive and visitors are encouraged to shape their experience as they see fit: please feel free to move the radios, walk around the space with them, adjust their volumes, and switch them on or off. If you get lost in the airwaves, you can find the piece at 87.9 FM."

Figure 4.10. *'Act so that there is no use in a centre'*: visitors experiencing the work at the Faulconer Gallery in Grinnell, Iowa, in 2015.

The work has been exhibited three times so far: in Vienna, Austria in 2014 (figure 4.9); in Grinell, USA in 2015 (figure 4.10); and in The Hague, the Netherlands in 2019 (figure 4.11).

Figure 4.11. *'Act so that there is no use in a centre'* at the *Musical Utopias* festival / *Sensing Sound* exhibition in Korzo theater, The Hague, 2019. Top: layout of the work. Bottom: photos of interacting visitors (Left: video still by Alina Ozerova; right: photo by Lam Lai).

4.3.2 *Text as system*

After considering many different possible paths about this work, the installation started to take flesh once I decided which text I would base it on. I was familiar with Stein's *Tender*

Buttons, a three-part book written in 1912 and published in 1914 (Stein 1914/1997), as I had already composed a work based on a collection of prose-poems from its first section, *Objects.*[232] That work, *'What is the current that makes machinery',* is a cycle of short compositions for female voice and surround live electronics that I began composing in 2012 for my duo with voice artist Stephanie Pan (who is also the voice for *'Act so that there is no use in a centre'*). Seven of those short works premiered in a performance at the new music festival *Dag in de Branding* in The Hague, a year later. After a closer reading of *Rooms*, the second section of Stein's book, I was greatly inspired and realized it was an extraordinary fit for my initial vision; I thus proceeded to plan the installation with that text in mind.

When composing a musical work that involves a text, I regard this text as a system, or perhaps even as a kind of metaphorical oracle. First, I try to understand, reveal and abstract its inner logic, its form, its meaning, its syntactic and phonetic rhythm, and use my findings as the foundation for the rest of the work. This is an important part of my process, as it helps me make choices by asking the text, as it were, on how to proceed when I am faced with creative questions.[233] This approach is very suitable for Stein, who used the term *word-system* herself to describe her work and whose work is definitely highly systematic, even though at first glance it may seem almost random (see Pitchford, 1999). My approach involves closely analyzing the text in its different layers, accompanying my findings by reading critical and philological texts about it. This is somewhat similar to what I perceive as the fundamental function of a director staging a play: revealing the hidden qualities of the work to support and complement it with what is implied but not written.[234] After analyzing the text, I proceeded by looking into how I can incorporate its deeper ideas to the different layers of my work: its structure, sound, layout, type of concentration or mode of interaction with the reader, and overall feel. My goal is to integrate concept, form, content, and experience in a powerful and coherent work that is artistically adventurous while being respectful to the text, offering a new perspective for understanding it rather than merely using it as a starting point or backdrop for furthering my own agenda.

Tender Buttons is a very idiosyncratic, dense and evocative modernist book. Its language is

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[232] The text can be found here: http://www.bartleby.com/140/index.html, last retrieved December 29, 2022.

[233] This is a welcome influence from my past studies as a philologist and linguist.

[234] The approach of using the author's own writing as the most authentic interpreter of their own work has been engrained to me since my school days in Greece, influenced by centuries of philological research that is best summarized by the motto of Alexandrian scholar Aristarchos from the 2nd century BCE, *"explain Homer through Homer"* (*Ὅμηρον ἐξ Ὁμήρου σαφηνίζειν'*).

very 'noisy' and has been characterized as 'verbal cubism' or 'language art'.[235] Stein is a master of using language for all it has to give. She liberates it from the tyranny of having to reference the real world and redefines it as a material for art rather than as a mere communication medium. Language becomes *"an arrangement in a system to pointing",* as she declares in the beginning of the book (Stein 1914/1997). Rather than aiming to simply represent the world outside it, she composes her text by sculpting the raw materials of language - signs, sounds, rhythm, syntax and semantic fragments – and reconfiguring them to produce a multitude of possible new worlds, all simultaneously coexisting. She does not necessarily aim towards absurdity nor does she strip language from meaning, like some of her contemporary poets did. Instead, she deconstructs it to rediscover it as an abstract aesthetic object in a state of constant flux, giving it the power to fabricate inexplicably complex 'realities' in the listener's mind. Stein's language flows endlessly, making it impossible to firmly grasp her sentences or solidify them into one sole concrete meaning. As such, *Tender Buttons* opens itself to many possible interpretations, none less likely than the other. In this manner, the text points to the gap between language and the world it is meant to represent, and in doing so it makes this gap even deeper. The reader/listener can decide to interpret it in a particular way, however attaching any specific meaning to the text can only give a partial view of the whole. While reading or listening to the text, the mind constantly jumps from one possible meaning to another in an attempt to decode and understand, never quite sure if it is right or not. These multiplicities and unresolved tensions are a fundamental element of Stein's writing.

Tender Buttons often hints to Stein's public life, the dinners and conversations in her famous salon, picnics, excursions and trips.[236] She writes about philosophy and religion, music, the weather, and the past. The focus, however, is more often revolving around her private, domestic life. In *Rooms*, in particular, she often uses language as an interface for retrieving thoughts and memories from her past. Language echoes memories that have faded, memories that have fused together and interfere with one another. During this process of 'mining' the past, language also causes more interference through its inner mechanics - phonetics, syntax,

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235 Stein was personally close to Picasso and other cubists, and was inspired by their work, not necessarily in terms of technique but in how far they could take their medium, in their vision about what their artform was, and how it could portray a different reality that does not need to correspond to the real world, For more on the comparisons between cubist painting and Stein's writing, and the relationship of her writing to that of other modernists, see DeKoven (1981), Perloff (1979), and Pitchford (1999). A more biographical interpretation of *Tender Buttons* is offered by Hadas (1978).

236 Her salon in Paris was frequented by many influential artists such as Pablo Picasso, Ernest Hemingway, F. Scott Fitzgerald, Ezra Pound, Francis Picabia and Henri Matisse.

and semantics – and the associations they create guiding the remembering mind to wander. Stein creates a textual field in which her thoughts and memories are laid out as a network, or some kind of multi-dimensional map. Connections and interferences in this field actualize through language, for example when phonetics take over – with certain sounds bringing to the foreground other sounds through similarity and repetition, regardless of their meaning - or when syntax is broken, or when semantics bifurcate like a fractal in a multitude of possible meanings. Through these paths, Stein jumps between these mental processes, creating an almost dreamlike environment where everything is true but nothing is real.

While at first glance the text may often seem like a product of stream-of-consciousness writing, its construction is often discernibly mathematical.[237] Semantics, syntax, phonetics and the overall morphology develop independently, following their own trajectories as Stein makes them orbit around each other and cross each other's paths, temporarily meeting until they *almost* produce meaningful language, before shifting them back to their individual planes. We could say that in *Tender Buttons* Stein performs the linguistic equivalent of splitting the atom, foreboding Bohr's quantum model of the atom (from the following year, 1913), and Ernest Rutherford's physical split via nuclear reaction (from 1917).

Kucharewski (2004) elaborates on the correlations between Stein's writing and quantum physics theories of the time: Stein was trained in science and medicine and was also a student of philosopher and psychologist William James, influences of whose *Principles of Psychology* (1890) Kucharewski traces in both Stein's writings and Bohr's theory. In both, the observer influences the outcome of the observed. The instrument of perceiving, whether it is language or scientific equipment, stands in the way of understanding the truth and of forming truly objective thoughts. As he writes, *"[i]n a way that is similar to the assumption that quantum entities can have properties of waves and particles without actually being either of the two, Stein's aesthetics and linguistic practice move beyond mere dichotomies towards a state in which the conditions of a word as a phonetic particle and a semantic wave exist at the same time"* (Ibid, 501). Words "*become vessels for a multitude of possibilities and probabilities. Or to put it in the terminology of quantum physics: they become pure potentials that collapse into momentary concreteness according to their respective contexts"* (Ibid, 508) - and I would also add, according to what the observer/reader/listener is looking to find in these words.

[237] For an interesting read on Stein's linguistic strategies as fractal-like constructions, see (de la Torre, 1995).

4.3.3 *Axioms and compositional strategies: texture, space, and the poetics of interference*

The first axiom that was suggested to me by the text is to treat language as sound rather than image. Phonetic texture, intonation and rhythm are fundamental elements of Stein's writing in general. *Tender Button*s is primarily meant to be read aloud and listened to, rather than read from a book in silence.[238] This is evident by her patented use of repetition, homophones, and similarly sounding words. Stein loops through words and phrases, altering their meaning through a mere change of context (even simply by adding a coma), sometimes repeatedly within the same sentence. Bringing to mind Steve Reich's tape loop experiments from a few decades later (such as in his influential work *It's Gonna Rain* from 1965), Stein uses repetition as a strategy for shifting focus away from semantics and into the inner world of language.[239] Because of its strange syntax, style and repetitions, the text creates a very characteristic sonic environment. The brain attempts to follow and make sense, which requires intense concentration. Any lapse, any drift of the mind, quickly turns language into a texture; fragments of meaning peak out like rocks by the seashore, only to rapidly transmute and disappear behind the incoming waves of text. Consequently, it seemed to me most meaningful to use the entire section of *Rooms* as a kind of language-based sonic tapestry, narrated by a female voice in a fairly flat, non-dramatic manner, reminiscent of Stein's own delivery but without copying it. The text was voiced by the vocalist of *'What is the current that makes machinery'*, Stephanie Pan, who also contributed a number of extra-textual vocal and foley sounds (such as sighing, flipping pages, etc). Stephanie has been my collaborating partner in a number of projects throughout the years, therefore her voice is also present in a number of sounds and musical snippets from my audio archive that I used to create the overall soundworld of the work.

A subsequent fundamental decision, also inspired by the text, involved laying Stein's textual field in physical space, as a way to create a spatial map of her memories. These memories are personal and portray a strong link with the spaces of domestic architecture, with many of them created in or retrieved within the lived space of her home. This is why I believe Stein titled this section *Rooms*. Further analysis suggested that the memories and thoughts in the

[238] Stein was widely known to recite her own texts to her contemporaries. You can listen to some recordings of her reading her works in http://www.ubu.com/sound/stein.html, last retrieved May 2, 2018.

[239] Unlike in Reich, Stein's loops never truly repeat, instead they are more like spirals. As she noted herself, one repeats words to insist, to emphasize (Kucharewski, 2004). Every repetition is informed by the previous one, its sound and intonation is changed – even ever so slightly – making it impossible to completely replicate the sound. In this respect, the human voice is quite different than an inscription medium like the magnetic tape used by Reich.

text come from six different points of view or states of mind, connected to six types of spaces, most of them domestic. These are: the place of social gatherings (salon, living room, dining room); the place of mental work and philosophical questioning (the study); the bedroom; the kitchen; transitional spaces (windows, doors and in-betweens); and, finally, the outdoors. Stein’s text weaves through these different 'rooms' changing points of view every few paragraphs through this section of *Tender Buttons*.[240] To make this evident, I broke up the continuous text into six ‘voices’ or 'threads', assigning each of them to its corresponding room. This produced a clear structural breakdown of the work, but also suggested a spatial layout: The memories of each room could be transmitted from a different location in the exhibition space, forming a number of overlapping radio zones that act as invisible representations of the rooms in hertzian space.

The notion of transmitting a message is as integral to communication media as is the notion of interference. While this is somewhat evident for radio (as broadcast radio technology uses these exact terms), Stein’s text poetically demonstrates how that also rings true for language. By applying syntactic, semantic, and phonetic interference in her text, she conveys the notion of forgetting and the blurring of memories. Stein uses the inherent nature of her medium (language) to filter and distort the content it conveys, and abuses it until the medium ‘glitches out’ to produce new content. This fundamental character of her writing greatly inspired the design of my piece, as well as its format and experience. Radio, with its stochastic nature, felt like an incredibly appropriate medium for a text that is decidedly non-linear and non-deterministic. Like in the text, the noise of the radiophonic system became a crucial and integral part of the installation, juxtaposing Stein’s linguistic interferences with the interferences inherent built into radio.[241]

Having broken the text into six different rooms allowed me to regard ‘tuning-in’ as a spatial phenomenon that could take place through physical interaction, i.e. not by scanning a dial but by physically entering the hertzian aura of each ‘room’. As a result, the overall radio field of the installation is composed of 6 low-power FM radio transmitters, each corresponding to a different room and all transmitting on the same frequency, thus forming overlapping zones. When a radio receiver is closer to a particular transmitter, the content (i.e. the transmitted

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[240] The word count for each of these rooms resulting from my analysis is: study: 904, bedroom: 890, salon: 836, in-betweens: 649, outdoors: 646, kitchen: 532.

[241] Radio also felt like a good match for the text’s focus on memories because of its implied nostalgia. Analog broadcast radio is an old medium that, like many others my age or older, I have fond recollections of. In a way, it is a medium with one foot in the present and one in the past – much like memories themselves.

thought or memory) rings clear, ignoring the other transmissions. This is due to a long-known phenomenon called the *capture effect,* which describes the ability of many receivers to identify the strongest transmission reaching their antenna and correctly demodulate it, while disregarding any and all other captured signals on the same frequency as long as they are weaker (see Leentvaar & Flint, 1976). The spaces in between, however, are full of radio interference, FM-demodulation glitches, and static, as the receiver attempts to make sense of the conflicting signals and figure out which one is strongest. In these areas, small movements of the receiver’s antenna and changes in orientation and angle may boost one transmission while attenuating others. All this creates a dynamic and intuitive interactive space, where tuning into a memory means finding the location and antenna placement where that memory best resonates with the receiver. Environmental conditions, such as the bodies of visitors within the field and humidity, also affect the signals.

4.3.4 *Composition, sound material, and playback system*

The fixed part of the work – its *deep structure* to use a linguistics metaphor - is a sound composition that consists of 6 stereo channels (“Deep structure and surface structure”, 2021). It lasts about 35 minutes and repeats in a loop. This deep structure, however, can only be partially experienced; the work’s actual sound, i.e. its *surface structure*, materializes through the interaction of visitors with the work’s radiophonic system. Just like the text, it continuously evolves and never repeats in the same way.

In terms of the composition, I combined Stein's textual field with my own archive of sonic thoughts, memories, and creations - sounds I have recorded, performed, or composed over the span of 10 years and in several locations. This field of sonic memories responds and dialogues with the text, it supports and expands upon it. It forms a sonic environment that binds words with worlds real and imagined, contextualizing them. Stein's textual multi-verse is very open and thus gives – or even demands - great freedom in creating various types of relationships between sound and text.

The sonic content of each of the 6 rooms consists of several sections of text and sound separated by extended pauses (see figure 4.12). This produces a soundscape that varies in density and moves in space over time, thus driving visitors to also move with it. The transmission of silence is one of the principal elements of the work in conceptual, sonic, and experiential terms: As the sound of memories (textual and sonic) fades away, all that remains is silence and static. Visitors listening to a particular transmission thus inevitably will have to move with their receiver at hand, bringing their antennas closer to a different box in an attempt to locate another active transmission peeking through the static.

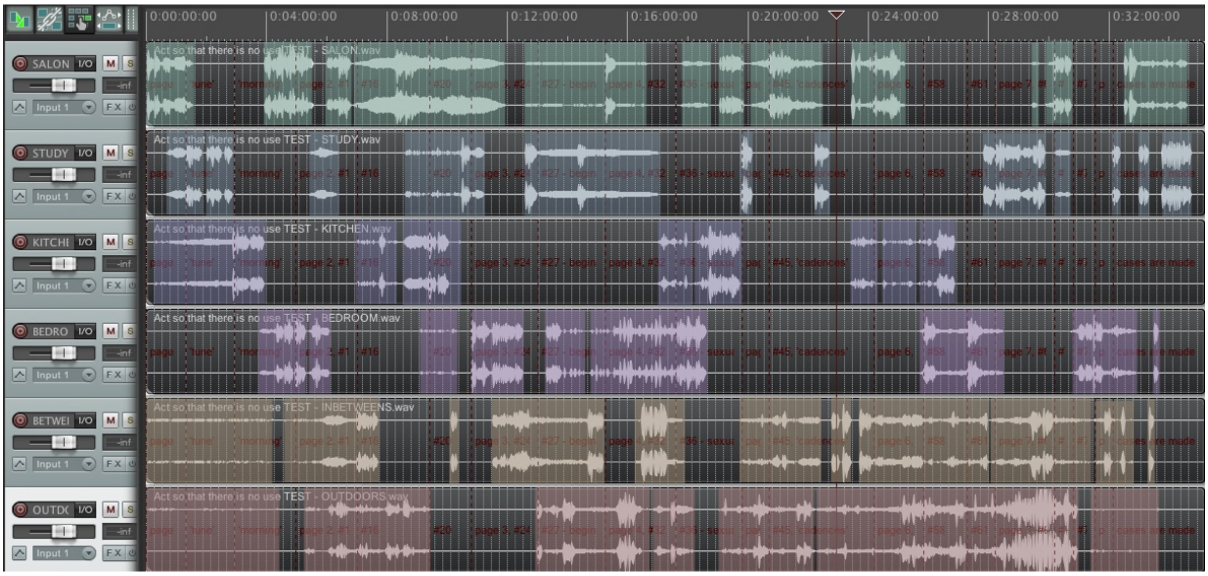

Figure 4.12. Timeline of *'Act so that there is no use in a centre'*: a screenshot of the Digital Audio Workstation multichannel project showing when sound is transmitted from different 'rooms'/boxes throughout the work's duration.

Overall, the audio environment is composed of various kinds of sounds, some commonly encountered in broadcast radio shows (such as music and voice), some rarely (such as field recordings), and others never (such as silence, static, and noise which are typically forbidden in broadcast radio, as they may cause the radio listener - or the silicon brains of contemporary digital receivers responsible for tuning - to think they are not tuned to a station). The following types of sounds can be heard in the work: voice and sounds of the body (by Stephanie Pan); various acoustic instruments: cello (played by Jelte van Andel), viola (by Garth Knox), zither, and wineglasses (by Stephanie Pan), chamber organ and harpsichord (played by myself); electric instruments, and synthesized sounds that I performed and recorded through the years, such as electric organs, recordings of electromagnetic fields, digital electronics and analog electronics (mainly from the Institute of Sonology's voltage controlled studio). Another large category involves field recordings, with various locations setting the tone for different sections of the piece.[242] In many of these recordings, my physical presence and actions while recording are made evident through sound, hinting to a

[242] I made these field recordings in the following locations: In the USA: Mount Rainier, WA; Redwood national forest, CA; San Fransisco, CA; Seattle, WA. In the Netherlands: Amsterdam; Ijmuiden bunkers; Scheveningen; The Hague. In Greece: Chania, Crete; Kedrodasos, Crete. In Austria: Kramsach; Vienna. In Slovakia: Bratislava. In Spain/Cataluña: Montseny mountain.

‘first person’ perspective and pointing to a lived experience rather than an ‘objective’ recording.[243] The piece also includes a number of Foley sounds specifically made for the work, such as cooking, walking, opening doors, and more. An additional layer involves digitally processing some sounds from all the above families. A final but important sonic layer is added into the piece in real time: the glitch of badly-decoded FM signals caused by the receiver attempting to decode transmissions fighting each other in close proximity, as well as the sounds of interference, static, radio feedback, and various other radiophonic noises. These sounds are not pre-composed, but emerge through the interaction between the visitors’ actions, the system’s components, the site’s architecture, and environmental conditions.

The playback system used in this work has gone through different iterations. In its premiere, I used 6 portable CD players to play back the content in a loop; each player was enclosed inside the corresponding room’s box relaying the sound of that layer. I composed the layers having in mind the limitations of that technological solution (the only playback technology I had available in that occasion), giving each layer some affordance for slight temporal variations to account for the fact that CD players would slowly go off sync, as there was no way to synchronize them. I devised a mechanical system to make sure that all of them could at least be switched on together, however the system drifted considerably towards the end of each day as each player took a slightly different amount of time to re-read and repeat its CDR disc after each loop. For the second presentation of the work, I replaced that clumsy system with a Raspberry Pi microcomputer relaying all 12 channels of audio. The microcomputer was hidden in the center-most box, with audio cables fanning out to all other boxes to connect to the FM transmitters inside them. The third presentation featured an even more elegant solution; each box contained a much more advanced short-range FM transmitter with the capability to play back audio from an SD card. Due to the lack of mechanical parts (like CD discs) these player-transmitter devices would remain in sync with each other even after hours of play.

While developing the work, I discovered an interesting – and very welcome for this work! - side effect, especially pronounced when using rechargeable batteries to power the transmitters. As batteries begin to slowly drain, the range of each transmitter becomes smaller, with the signals losing some clarity as one moves away from the transmitting box.

[243] This is a strategy inspired by the work of electroacoustic music composers Jonty Harrison (https://web.archive.org/web/20120223134750/http://artsweb.bham.ac.uk/harrison/) and Joseph Anderson (https://joseph-anderson.org/).

Towards the end of each day, and after running for several hours, the system becomes noticeably more 'tired', adding increasingly more interference to the transmission of memories - almost like a real human remembering things after a long day.

4.3.5 *Visual aspect: Containers and spatial configuration*

Figure 4.13. White IKEA box marked ‘bedroom’, containing an FM transmitter and paired with an FM radio receiver and a stool for audience members to sit on (photo by Lam Lai).

Each room’s FM transmitter is contained within a white storage box by IKEA, radiating memories around it (figure 4.13). I chose these specific cardboard boxes after much thought because of their visual connotations and familiarity, as they are ubiquitous for storing papers, photographs, and mementos in European households. Six of these white boxes are installed on the floor of the gallery space, spread across an overall area of about 10 x 15 meters. The boxes are about 4.5-6 meters apart from each other to give enough space for each box's FM transmission, as well as to allow the sound from the receivers to blend together in space. The boxes are connected with straight white gaffer tape lines, forming what looks like the outlines of an architectural drawing on the floor, as a reference to the architectural spaces implied in the text. The tape has a practical function as well: hiding cables (power cables for the CD players in the first iteration, or audio cables carrying the signal to each transmitter in the second; the player-transmitters of the third iteration do not require cables coming out of the boxes). Six minimal-looking, lightweight stools are placed by the boxes for visitors to sit. This is an important element of the work's setting, as seats are very effective cues for suggesting to visitors that they should take their time to listen on one hand, and that they can experience the work from several perspectives on the other.

The specific layout, position and distances of the boxes, as well as the frequency used by the transmitters, all depend on the characteristics of the exhibition space, its acoustics and the properties of the radioscape formed within. Frequency-wise, it is important to find a part of the spectrum that is not used – the wider this empty band is, the better - so the piece does not have to compete against more powerful commercial transmissions. All transmitters are tuned to the same frequency. The minimum distance between each transmitter depends on the power of the transmitters and the size of the space; I have worked this out experimentally to be about 4.5m. When the distance is smaller, there can be more distortion that makes it harder for receivers to decide which signal is more powerful, and thus to which transmitter they should tune into. I found this out in practice, while developing the piece in a smaller studio space. The room where the piece was first exhibited, at the gallery space of the Austrian Ministry of Culture, was larger but still a bit narrow - just under 6 meters wide. The piece worked much better in its following presentations. This included the open space of the Faulconer Gallery in Grinnell, Iowa, US where it was exhibited in 2015, and a small theater space at Korzo Theater, The Hague, the Netherlands, where it was shown in 2019. In both cases visitors were able to move around the piece as well listen to it from further away, rather than just from within. Like *The Network Is A Blind Space,* the piece can be experienced from as far as its FM transmissions reach, which may extend outside the confines of the gallery. So far, I have managed to tune into the 'outdoors' room outside every location where the piece has been installed.

4.3.6 *Visitor experience*

Visitors experience the piece using seven handheld FM radios placed in the space of the installation. While they can also use their own devices (portable radios – which hardly anyone carries any more – or smartphones with an FM chip) people rarely take that initiative. The provided receivers are neutral looking and quite minimal, with a small but somewhat decent speaker. They are well suited to reproduce frequencies in the range of the voice but are fairly limited otherwise, particularly in the low end. The radios are meant to sound together in the actual space of the gallery, thus creating a polyphonic, immersive, and dynamic soundscape, rather than a solitary sonic line heard through headphones. The sound of the piece changes depending on how many radios are turned on, how loud they are, which transmission they are tuned to, how many of them are moving, etc.

Visitors are encouraged (by attendants and/or the work's text description) to walk around, sit, turn on/off and reposition however many of the receivers they like to create their own personal realization of the work. Usually, however, most hold onto a receiver and begin exploring, adjusting volume to taste.[244] Interestingly, the two times the work was exhibited in the context of visual arts rather than new media or interactive art, visitors tended to not touch the radios unless they either saw someone else doing that, read the description of the work, or were told by staff that the radios were meant to be handled. This happened regardless of the placement of the devices or whether they were making any sound or not. My assumption is that, given the context, visitors likely thought that this must be how the artist's hand placed them, and thus how the work is meant to be. This was not the case in the work's third exhibition in the Netherlands, as the audience was familiar with interactive work and sound art.

When exploring, visitors tend to saunter around the space with receiver at hand, orienting their antenna to find the direction of a transmitted sound. While walking between boxes, they encounter a sea of static and interference. As they come closer to a box, their receiver tunes to its transmission and the static transforms into a signal, acoustically materializing memories from that location. Commonly, they will sit in front of an active transmission, closely listening to their receiver until the transmission fades back to silence or static. They will then stand up and start exploring again or approach another visitor that has tapped into an active field. With more people present - or more radios tuned in - the sonic experience is richer and more immersive, creating a collectively produced soundscape that is diffused around the space and that is in constant motion.

Due to the analog nature of the interface, this FM-based system is very sensitive to the placement of antennas and bodies in space. Minimal changes of the spatial relationship between receiver and transmitter can cause perceivable (and repeatable) changes. Interaction is very intuitive and directly connects sound to space as visitors seek FM transmissions by physically scanning the ether with their device. In comparison, the network echolocation

[244] The tuning knob is deactivated to prevent visitors from accidentally detuning their receivers.

system of *The Network Is A Blind Space* is slower and more indirect. While both works feature, in a way, Direction/Finding systems, the latter operates in a hybrid physical/network space and is influenced by software, hardware, and the delays incurred by converting analog signals to the digital world. All this adds a layer of stochastic variation caused by invisible, non-physical factors, which makes for a different type of experience. Furthermore, the operational size of WiFi fields is considerably larger than that of low-power FM radio. Spatial sensing in the case of TOA/TDOA systems is thus more useful in a larger architectural setting, where a system can react to things like being in a specific room, crossing or closing a door, etc. The immediacy and intuitiveness of the response of the FM-radio system in *'Act so that there is no use in a centre'* became a significant inspiration and motivation for me to develop the WiFi-based sensing system used in the *Hertzian Field* series.

4.4 FAILURE AS INSPIRATION

4.4.1 *Jumping from the Network layer to the Physical layer, and ending deep into hertzian space*

Upon my return to the Netherlands following the residency that produced *'Act so that there is no use in a centre'*, and in preparation for another residency at ZKM Karlsruhe in Germany, I began developing a more advanced iteration of the system from *The Network Is A Blind Space*. This had felt to me as an area of research with significant artistic potential, and a number of exciting ideas for future works employing this system had been brewing in my mind. My plan was to further explore the acoustics of the network with a more advanced implementation, but also a more portable and affordable one that would replace the Mac mini computers I used in that piece with Raspberry Pi B single-board computers. Although I eventually put this project aside (at least so far), it greatly contributed to deepening my knowledge about Linux/UNIX and networking; this proved fundamental, as it slowly led me to a breakthrough: the development of the sensing technology behind the *Hertzian Field* series.

The new toolkit I developed for the ZKM residency involved a complete refactoring of the codebase from *The Network Is A Blind Space* with numerous improvements, extensions and additions of new capabilities which resulted in a new set of classes for the SuperCollider language. The new library featured a much more thought-out structural model that later informed my design of the WiFi sensing system. Most pertinently, I had implemented a new Linux-specific class that opened the door to the *Wireless Information Retrieval* system by reading the *Received Signal Strength Indication (RSSI)* of the WLAN that a device is connected to. The fluctuation of these RSSI values intrigued me immediately as a potential source of interesting control data, however I did not press further as I was more focused on exploring the artistic potential of network echolocation via trilateration/multilateration.

I arrived at ZKM with this system near technical completion, very happy about the codebase and having achieved some promising early results in my studio. I had several potential applications in mind for this system that I hoped could result in interesting artworks. While I began the residency full of ideas and eagerness to explore them, things did not go as planned, however. The network landscape in my studio was radically different than that at ZKM. A few days in, and once I had finally completed the system and tested it on location, it became apparent that the Raspberry Pi models of the time were far too weak for doing any of the things I had in mind. These machines could only handle extracting features for a handful of connected devices, which rendered them practically useless for this task at the busy ZKM Center. After a few days of refactoring and optimizing my code I realized that it would be impossible to proceed with this equipment, which made all the ideas I came with practically unrealizable. I thus found myself without a project about a week in the residency.

Facing a disappointing dead-end, I gave myself two days to imagine an alternative project on which to concentrate for the remaining time. I decided to pursue an idea that had already been circulating in my mind for a few years: figuring out a way to detect the presence of wireless devices in a space (mostly smartphones) without them having logged into a network. This was something I thought should be possible in one way or another but had yet to figure out the nuts and bolts of how it could possibly be implemented. The research and development I performed before the residency had given me a deeper knowledge on the inner workings of networks, and I realized I needed to abandon the *Network Layer* of communication and instead tap into the *Physical Layer*. Moreover, I remembered having come across some very interesting research on *ubiquitous sensing*, most of it tangentially related to the idea of network acoustics I had been exploring at the time. I turned to these papers with renewed interest, and within two days I had a project far more exciting than the ideas I came to ZKM with; a project that felt almost like magic when I first made it work: sensing the movement of my body and of objects using plain old WiFi signals.

Before diving into the details of the system I implemented to achieve this, however, (chapter 6) I will first present the context, theory and some state-of-the-art experiments in the field of Ubiquitous Sensing using radio and microwaves in the following chapter. My focus will be on papers and research that inspired and influenced this second phase of my own work with the hertzian medium that led to the development of the *Hertzian Field* series. Hence, I will not emphasize as much on more recent developments dating after the realization of the *Wireless Information Retrieval* sensing system. The chapter will conclude with a discussion on factors relating to physics and human anatomy to get a more intricate understanding of how and why such sensing systems actually work (sections 5.5-5.6).

Chapter 5. UBIQUITOUS SENSING WITH RADIO WAVES AND MICROWAVES

5.1 TECHNOLOGICAL CONTEXT

5.1.1 *Wirelessness, localization, sensing*

In the last couple of decades, wirelessness has become a fundamental part of everyday life in a manner radically different than it was in the 20th century. The model has shifted away from the centrally authored, one-sided communication of broadcast media like radio and TV. Today, we carry laptops, smartphones and an increasing number of other mobile devices full of sensors and radio antennas to connect us to a variety of networks covering a variety of ranges: cellular interfaces to connect to telephone towers in a neighborhood, WiFi to access WLANs and the Internet by connecting to routers (typically inside a building), Bluetooth for connecting to accessories and devices in the same room, Near-Field-Communication chips (NFC) for contact-less payments and other interactions at ultra-short range. Furthermore, the Internet-of-Things is promising smart homes, smart offices, smart cars, smart fridges, smart clothing, smart everything, which will produce an even denser radioscape in our living and working spaces.

This, in its turn, has created a commercial need for tracking and localization technologies, both of which have become important features of our contemporary 'wireless living'. Context-aware services like navigation, emergency response systems, patient monitoring and robotics are relying on localization. Similarly, localization is crucial for Wireless Sensor Networks (WSN) in an era that pushes towards more and more automation. WSNs are collections of distributed sensing devices connected to each other via radio or microwaves. These may not have a fixed or known position, but still require being able to reliably associate physical context to sensor measurements so as to perform various tasks, such as intrusion detection, managing a supply chain or maintaining an inventory, among other things.

At first, wireless tracking was primarily concerned with space, and was synonymous to localization. However, researchers soon moved beyond localization to *activity recognition*, and the market followed this shift with an attentive eye. The goal became to identify not merely *where* one is, but what one *does,* or how one *behaves*. This began with identifying simple physical activities such as walking, standing, sitting, etc, and moved to higher-level activities, *"like car repair, furniture assembly and Kung Fu exercises"* (Sigg et al., 2015, 3). The smartphone revolution and the wide proliferation of cheap motion sensing in the new millennium - from the Wiimote to the Kinect to DIY Arduino-based solutions and their successors - had a considerable effect in taking this research out of the labs and into real-life applications.

5.1.2 *Ubiquitous sensing and Big-Data everywhere*

During the first years of the new millennium and in its early days as a field, *ubiquitous sensing* emphasized on the development of personalized and autonomous sensor-enabled devices gathering data for a single user/consumer and aiming to offer a variety of personalized services. It should be noted that this form of data-gathering and analytics frenzy has not been limited to tracking the presence and motion of our bodies in space, or of the devices we carry as a surrogate/proxy of our bodies. It has also extended inwards, aiming to measure the effects of various activities on the body, such as sleeping, eating, exercise, sporting, and more. The tools and ideologies are similar regardless of application: *Big Data* epistemology, so prevalent throughout the rest of society, has been transposed to the scale of the self and the individual, promising to find a *"new kind of truth"* that is inaccessible with our senses (Schüll, 2016, 9). According to this narrative, the self is best represented through data-points and databases, and the body is merely another subject to be data-mined. Surveillance tactics become a tool for *sousveillance*, tracking patterns rather than events, and looking at correlation rather than causation.

The 'Quantified Self' community, founded in 2007, believes in *"self-knowledge through numbers"* – a phrase it uses as its motto.[245] This type of lifestyle management aims at measuring and quantifying everyday choices, gathering data to understand how these choices affect one's personal health and well-being. While people have used analog means to measure, record and control bodily states and processes for a long time, in the last few years we are witnessing an explosion in self-tracking technologies and analytics that promise to optimize how we live. Wearable monitoring technology is rapidly developing into a huge market and a slew of gadgets and algorithms are available for observing, predicting, and regulating the performance of our bodies in real-time. These systems promise to function as a *"sixth sense"* of sorts based on data (a *"datasense"*), predicting things that we ourselves are

[245] See: https://quantifiedself.com/. Last retrieved 29 December 2022.

too close to perceive on our own (Kang & Cuff, 2005, 110). Sensors and algorithms promise to externalize and de-subjectify knowledge of the body's state. In this context, data and analytics are promoted as the best way to govern one's own life, implying that individuals are not equipped to properly understand or manage their own bodies (Schüll, 2016).

The continuous monitoring of biological functions provides a numerical and 'objective' view as the first step; the ultimate goal of the technology is to recognize and inform the user how their body is performing and offer motivation and directions for the future. To quote cultural anthropologist Natasha Schüll, health "*has been recast as a perpetually insecure state that depends on constant vigilance, assessment and intervention. (...) Digital tracking products and applications promise to help fill in the blind spots and take the guesswork out of everyday living by supplementing the myopic vantage of real-time experience with a continuous, informatic mode of perception*" (Ibid, 2 & 9). As she points out, the underlying subtext of self-tracking is that the responsibility of health planning passes from the state to the individual, and from the doctor to the sensor and the algorithm.

We can trace the roots of this movement already a few centuries earlier, particularly in the 1800s, with the development of several media-based approaches for measuring and understanding the body. In 1761, Viennese physician Leopold Auenbrugger proposed that doctors use the ancient diagnostic method of *percussion*: putting an ear on the patient's chest and tapping it to listen to its sound. This type of 'immediate auscultation' was unfavored by western doctors and patients alike for many reasons, including the perceived indecency involved in physicians touching female patients in that manner. René-Théophile-Hyacinthe Laennec revived this forgotten art of auscultation with the invention of the stethoscope in 1816. Mediated auscultation gave doctors the right distance, but also an instrument that could act as a gateway to the inner sound-world of the body. By attentively listening to sonic features such as the amplitude, dynamics, and timbre of bodily processes they could recognize pathologies via the inner noise of the body (Schwartz, 2011, 201-221 and Donnarumma, 2016, 18-22). About a quarter of a century later, in 1842, it was found that the heart produced electrical currents. Those signals were first recorded in 1869-70 by Alexander Moorhead. The first electrocardiogram was produced by Augustus Waller in London in 1886-87, the same time that Hertz was conducting his breakthrough experiments on electromagnetism (see figure 5.1). Fifteen years later, after the turn of the century, an apparatus designed by Wille Einthoven allowed him to identify six different waves that propagate through the heart tissue and make the heart contract. Various other instruments were invented to transduce and register bodily vibration into visual recordings using the motion of the body, such as the *sphygmograph* (recording blood pressure), the *myograph* (recording muscle movements), and the *pneumograph* (recording force and patterns of respiration). As Hiller Schwartz observes, *“[a]ll of this new instrumentation appeared to escape the pitfalls of the personal equation. Self-observing and self-recording, the body could surely be truer to itself”* (Schwartz, 2011, 424).

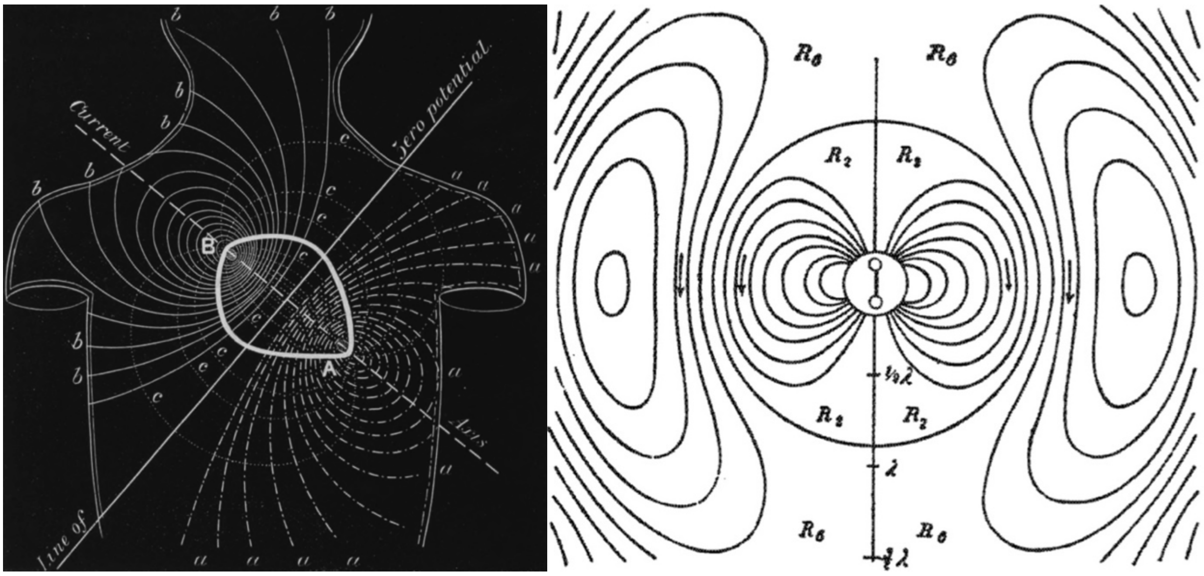

Figure 5.1. Two visualizations of electric fields, both published in 1889: Augustus Waller’s mapping of the electrical fields of the human heart (left, from Waller 1889), juxtaposed with Heinrich Hertz’ mapping of electric fields around his dipole antenna (right, from his 1889 paper, *The forces of electric oscillations treated according to Maxwell’s theory* -Hertz 1893).

Today, ubiquitous sensing has gradually moved from a simple surveillance paradigm - an alarm goes off when an intruder enters a protected space - to one of crowd control and advertisement = How are people behaving? In front of which products are they spending more time? And so forth - and then to one that closer resembles contemporary medical practice. The next frontier is moving yet inwards to studying the brain and its functions, aiming to understand and identify mental states and cognitive processes. This is called *sentiment sensing,* an area of research in which the focus has shifted from physical and outer sensing to psychological and inner sensing that can reveal emotions, intention, attention, mental states (Sigg et al., 2015). The goal of this approach is to deduce such inner states by observing the body’s functions - its eye-gaze, breathing, movement patterns, etc.. Sentiment sensing is concerned with finding correlations between movement patterns, physiological data and mental states. While it is still primarily based on wearable devices - such as eyeglasses and biosensors - there is growing research investigating the use of radio-frequencies for that purpose (Raja and Sigg, 2016). Inferring emotion from gestures and poses is thought to be as accurate as inferring them from a subject's face. At this point, the goal is not to arrive at nuanced conclusions but to judge a person's mindset within certain predefined dipoles, such as how interested or how bored someone is, or if they agree or disagree with something. Deducing attention is becoming another area of research with the goal being to enhance recall and focus by identifying "*the best times for the user to relax, learn, study or engage in spare-time activities, depending on their current cognitive state"* (Sigg et al., 2015, 14).[246]

5.1.3 *From sensor-packed devices to parasitic radio sensing*

After an enthusiastic start in the beginning of the new millennium, the promise of ubiquitous sensing begun to stall as adding sensors to everything proved to be not as simple or cost-effective as people initially thought (Patwari, 2015). In the last decade or so there has been a shift towards more global and interconnected paradigms, as is evident in the examples of *opportunistic sensing* - distributed sensing networks that can provide information to any nearby mobile device, and *participatory sensing* - a variant that aims to address some privacy concerns.[247] According to Sigg et al.'s review mentioned earlier (2015), these models and their successor, *parasitic sensing*, demonstrate a clear tendency to offload sensing from personal devices - with their assemblages of different sensors - to the environment, creating sensing possibilities by tapping into existing infrastructures. Parasitic sensing uses environmental and ubiquitously available sources instead of specialized sensors (see figure 5.2). It takes advantage of the noise of existing systems, typically analyzing interference patterns in them to deduce activities outside of the original scope of that infrastructure. This includes harnessing media already present in the environment for the purposes of sensing, such as audio and radio. Parasitic sensing is thus much cheaper and administratively simpler to implement than its predecessors.

Wireless communication infrastructure is a particularly strong candidate for this type of sensing, leading to an increasing amount of research on the field in the last decade. Having the possibility to use radio interfaces as sensors means that it is possible to exploit the dense radio fields created by smartphones and Internet-of-Things devices without the need for installing any additional infrastructure. Moreover, another major benefit of using radio

[246] For a more extensive overview of the growing research in this field, see the thorough literature review by Sigg et al., 2015 and Raja and Sigg, 2016.
[247] For more on opportunistic sensing see: www.opportunity-project.eu. Last retrieved on 29 December 2022.

frequency sensing (RF-sensing in short) is that it does not need an optical link to the monitored object or space, unlike a camera. Radio waves can penetrate darkness and smoke, they can be hidden behind walls and objects, and they can masquerade as something innocuous, like a WiFi access point. As such, RF-sensing systems can easily operate unbeknownst to the public. They also raise less privacy concerns than audio or video surveillance and are so far largely unregulated - there are no laws, for example, controlling how one reads and interprets unencrypted WiFi data captured by their device.

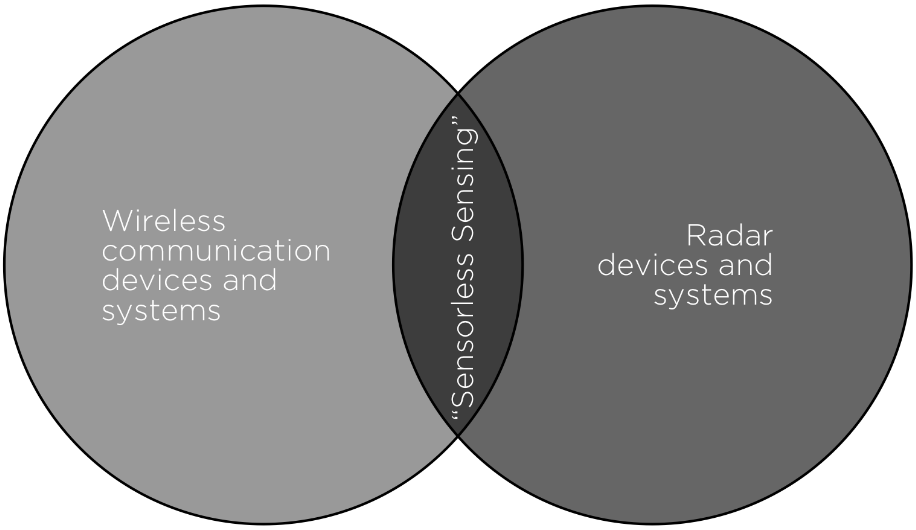

Figure 5.2. 'Sensorless sensing': a form of 'parasitic sensing' in which wireless communications devices and systems meet radar devices and systems (graph adapted from Patwari, 2015).

Sigg et al.'s (2015, 2) prediction about the future of this field is that *"[a]ctivity recognition in Ubicomp is going towards Big Data with systems developing capabilities to monitor virtually everybody, everywhere and without specifically installing system components at any particular physical location"*. As opposed to the Quantified Self movement, this approach extends from the consenting individual to random passers-by, shoppers, etc. Big Data strategies, after all, are most useful when they tap into massive collections of data, with Machine-Learning in fact requiring such collections to produce useful results. Nowadays, there are a number of such tools publicly available to researchers and companies; as connectivity becomes more widespread, faster, and reliable, it also becomes easier to capture data on the field and send it to the lab to mine it.

5.2 RADIO FREQUENCY SENSING MODALITIES

5.2.1 *Device-bound versus device-free sensing*

In general, sensing systems can be implemented in two principal modalities: *Device-bound* and *device-free*.

Figure 5.3. Device-bound tracking has entered daily life. Left: A sign in a central shopping street in Amsterdam notifying passers-by about the use of WiFi tracking technology by the city. Right: A sign in Amsterdam Airport Schiphol notifying arriving passengers about the use of both Wi-Fi and Bluetooth tracking (photos taken in 2018).

Device-bound sensing uses instruments with various types of built-in sensors. Those can be, among other, specialized inertial sensors (accelerometers), magnetometers (compass), biosensors measuring heart rate, blood pressure or the electrical activity of muscles (Electromyography, or EMG), the heart (Electrocardiography, or ECG), or even the brain (Electroencephalography, or EEG). There are also many experimental and commercial projects using on-board cameras and microphones in non-standard manners - for example, as biosensors, for gestural interaction, or in localization systems. The same rings true for the various radio interfaces one commonly finds on a device like the smartphone - WiFi, Bluetooth, Cellular, GPS, FM radio. Overall, such non-standard methods can be quite accurate, especially when using dedicated hardware. The obvious complication with those systems is that the person whose actions are monitored needs to carry a device to monitor them with. This has become much easier today in comparison to just a couple decades ago, as most people carry smartphones, which allow device-bound radio-sensing to bypass explicit consent. For a few years now, department stores, super-markets, museums and airports, among other businesses, have been using device-bound radio-frequency tracking based on GSM, WiFi, or Bluetooth signals (see figure 5.3). Typically, the only way for citizens to opt-out is to turn off the radio interfaces of their device when in such an area.

On the other hand, *device-free* sensing does not track devices as proxies of the human body, but instead tracks the body itself. In their overview of ubiquitous sensing literature, Sigg et al. (2015) posited that there are three main types of device-free approaches:[248]

a) Installation-based sensing, employing specially installed hardware. This includes:

- *Video and computer vision*, often complemented by Machine Learning and statistical modeling. This is the most common modality. While excellent for many tasks, vision systems need Line-of-Sight contact, they have limited range, and need light to properly work. They can also be costly and require some effort in installing them. Moreover, they raise privacy concerns and usually have to abide by an established legal framework for commercial use.
- *Depth cameras*, (e.g. Kinect) have similar pros and cons but can see in three dimensions, which makes them better for spatially oriented applications.
- *Infrared sensing* detects objects through their infrared radiation. The technique is similar to video, but is immune to lighting conditions and color variations.
- *Pressure sensing* is another technique, using for example floor-mounted sensors to track footsteps, or touch screens to interact with users.
- *Ultrasound* is another type of technique that can be very precise. It uses Time-of-Flight information and trilateration to localize targets.

b) Infrastructure-mediated approaches that take advantage of already existing infrastructure, measuring energy flows to deduce what is happening in a space. This can be through:

- *Changes in resistance* or *inductive load* in a building can reveal human interaction (Patel et. a. 2007).
- *Electromagnetic interference*, for example interference from ‘switched mode’ power supplies, may reveal human interaction with appliances, or the proximity of human bodies

[248] For references to specific papers and research with the various sensing systems mentioned below see Sigg et al. (2015).

to fluorescent lamps.

- *Water pressure fluctuations* can reveal certain water-related activities (e.g. washing hands, showering, flushing toilet), thus allowing to make deductions on a resident's behavioral patterns.

- *Audio analysis of gas flow* through pipes has been used to identify the type of device that consumes gas (e.g. heater, furnace, fireplace).

- *Electromagnetic noise* has also been used to detect whether a surface has been touched by the human body (this happens by tracking potential electrostatic discharge caused by touch).

c) Environmental or parasitic sensing approaches, harnessing audio or radio waves already existing in the environment.

- *Audio* has been used to locate a phone in a room or on the body. Audio-fingerprinting has also been used to deduce the proximity of a device to a sensor.[249]

- *Radio frequencie*s: Passive radar uses ambient radio-frequency signals that 'illuminate' an environment with radio waves to detect and track objects and bodies – their location, gestures and activities, attention levels, breathing rate, and more.

Speaking of RF-sensing in particular, which is what this thesis is concerned with, device-bound radio tracking systems are primarily used for localization and can be thought of as an evolved *Direction-Finding* technique. On the other hand, device-free RF-sensing systems can be thought of as a domestic-scale extension of the *RADAR* principle. They target human bodies, using radio waves and microwaves to sense space and deduce the activities of humans therein. This area of research is receiving increasingly more attention, with a noticeable tendency to use 'parasitic' tactics, partly because device-free sensing can be stealth and clandestine. Device-free RF-sensing poses different technical challenges to device-bound RF-sensing as, instead of tracking the presence of a signal from a device, such systems work by analyzing interference patterns on ambient signals caused by the target body. To put in a simplified manner, rather than looking at how strong the signal coming from a device is - like device-bound systems do - they look instead at how much a transmitted signal is attenuated as it propagates in its environment.

[249] While analyzing audio signals is an obvious application of device-free sensing, these examples mentioned by Sigg et al. (2015) in this regard involve devices and thus should be regarded as device-based.

5.2.2 *Device-bound radio-frequency localization, outdoors and indoors*

Beyond the differences between device-bound and device-free localization methods, there are also significant differences between outdoor and indoor localization systems. Outdoor range-based systems include GPS and positioning via cellular tower information. Such systems can be quite accurate, especially when combining multiple interfaces.[250]

Figure 5.4. A graphic depiction of the GPS constellation of satellites surrounding the Earth. There are at least 4 satellites visible from any point on the planet (Public Domain image by NOAA, https://commons.wikimedia.org/w/index.php?curid=4118967).

GPS has been a very successful and widespread technology for outdoor localization. It is a satellite-based system owned by the US government, initially developed for military use. GPS satellites transmit radio signals which are captured by receivers equipped with a special chip that connects to a "*quartertrillion-dollar constellation of GPS satellites in their orbits twenty million meters above the Earth* (Greenfield, 2017). The receivers calculate the distance to each satellite whose signals they have received, and perform triangulation to find their own location on Earth. GPS was first launched in 1973; a less accurate version, featuring a resolution of about 100 meters, became available for public use a decade later (McDuffie, 2017). After another ten years, in 1993, the infrastructure of the system was solidified. Since then, GPS deploys 24 satellites orbiting the earth and communicating with a network of ground stations (figure 5.4). In 2000, a new US law gave the public version more accuracy, resulting in the development of many new devices with GPS chips and the rapid

[250] Smartphones commonly use a combination of GPS, Cellular and WiFi information to increase localization precision (Golestanian et al., 2017).

spread of commercial location-aware applications. GPS technology made interactive real-time navigation possible for the first time, introducing maps that can follow our paths and instruct us on where to go next. As Greenfield notes, the infrastructure involved in this is immense and complex: "*It fuses globally dispersed infrastructures of vertiginous scale and expense—the original constellation of American NAVSTAR Global Positioning System satellites, and its Russian, European and Chinese equivalents; fleets of camera- and Lidar-equipped cars, sent to chart every navigable path on the planet; map servers racked in their thousands, in data centers on three continents; and the wired and wireless network that yokes them all together—to a scatter of minuscule sensors on the handset itself, and all of this is mobilized every time the familiar blue dot appears on the screen"* (Greenfield, 2017).

Owing to its success, GPS technology has functioned as the paradigm after which the majority of indoor tracking systems have been developed. Nevertheless, the translation from outdoor to indoor is not seamless. First of all, GPS navigation and its real-time maps are designed for the large scale of the outdoors – being on the road, navigating a city or a neighborhood. The spatial resolution available for civilian use does not allow for the finer grained localization that is necessary for indoor use - indoor localization systems aim to provide accuracy with a margin of error below 30cm (Brown & Dunn, 2011). GPS is also designed to operate in open spaces that are relatively free of obstacles. The technology encounters problems when tracking devices surrounded by mountains, dense foliage, or the so-called 'urban canyons' formed between tall buildings (Ibid). As such, GPS does not work indoors. The accelerometers and magnetometers that smartphones are usually equipped with can be used to develop 'dead-reckoning' localization by tracking inertia and movement direction. However, these types of systems easily drift and lose their accuracy over time.

More localized radio signals that do not require connecting to orbiting satellites, like GPS, are a good alternative for this type of localization. Nevertheless, indoor environments still pose many challenges. For instance, the logistics of mapping indoor spaces by organized large-scale endeavors like Google Street View are too complex. Furthermore, each space has different 'radio acoustics', making signals bounce around in different manners, which can be challenging to calculate.

Different types of radio/microwave interfaces and networking protocols are being used for RF-based indoor localization**.** WiFi (IEEE 802.11 at 2.4 and 5GHz) has emerged as one of the most prominent technologies for this purpose, and many commercial and experimental systems have been introduced (for an early review and classification of some of these systems, see Brown & Dunn 2011). As WLANs have become ubiquitous, WLAN-based localization can be implemented as a parasitic system that taps into existing infrastructure. This is a major advantage, because it essentially makes WLAN indoor localization a 'software-only' solution. Bluetooth (IEEE 802.15.1 at 2.4GHz) is another common radio-frequency protocol that can be used for indoor localization. Bluetooth Low Energy (BLE) is a variant of the protocol with reduced power consumption used by devices that require low-power usage, such as Bluetooth beacons employed in context-aware applications. Short-range Wireless Personal Area Networks devices (IEEE802.15 at 2.4GHz) have also been used, in particular IEEE802.15.4, for local low data rate communication, such as in sensor networks (XBee and other), the Internet-of-Things devices, and home automation. All these protocols operate in the same frequency bands (mostly at 2.4GHz, sometimes also at 5GHz, and in the near future also at 6GHz), so the physics between all these systems and their response to environmental factors is similar.

Before delving deeper into the technical nitty-gritty of indoor localization however, it is worth zooming out to see the context within which this technology has been developing.

5.2.3 *The indoor localization business*

Indoor localization is a growing field of research in academia and the industry, with several commercial applications making their appearance in the past few years. Location-based analytics, in particular, combine tracking with Big Data into a lucrative mix. In the commercial sector localization services can be used, for instance, to track the paths and behaviors of visitors by annotating and monitoring the physical space of a store - commonly using WiFi beacons that communicate with shoppers' devices. The promise is to provide brick-and-mortar stores with a data-rich equivalent of website cookies and other trackers, i.e. *"the kind of information that e-commerce sites like Amazon have in spades*" (Clifford & Hardy, 2013). Such systems can give insights to many questions, such as: how many visitors are in a store at any given time, and how much staff is needed to assist them? How many people walk by and how many enter the store? Did they walk in immediately, or did they first have a look at the storefront and then decide to enter? Which sections of the store did they visit, and in what order? Where did the spend more time? Where is the best place to put a specific product, and which products should be put next to each other? How have customer's paths changed since a new layout was made or since new marketing banners were installed? Beyond such more general matters, tracking systems can also register first-time and repeat customers, record their paths and habits, how often they visit and how long they stay in a store (figure 5.5).

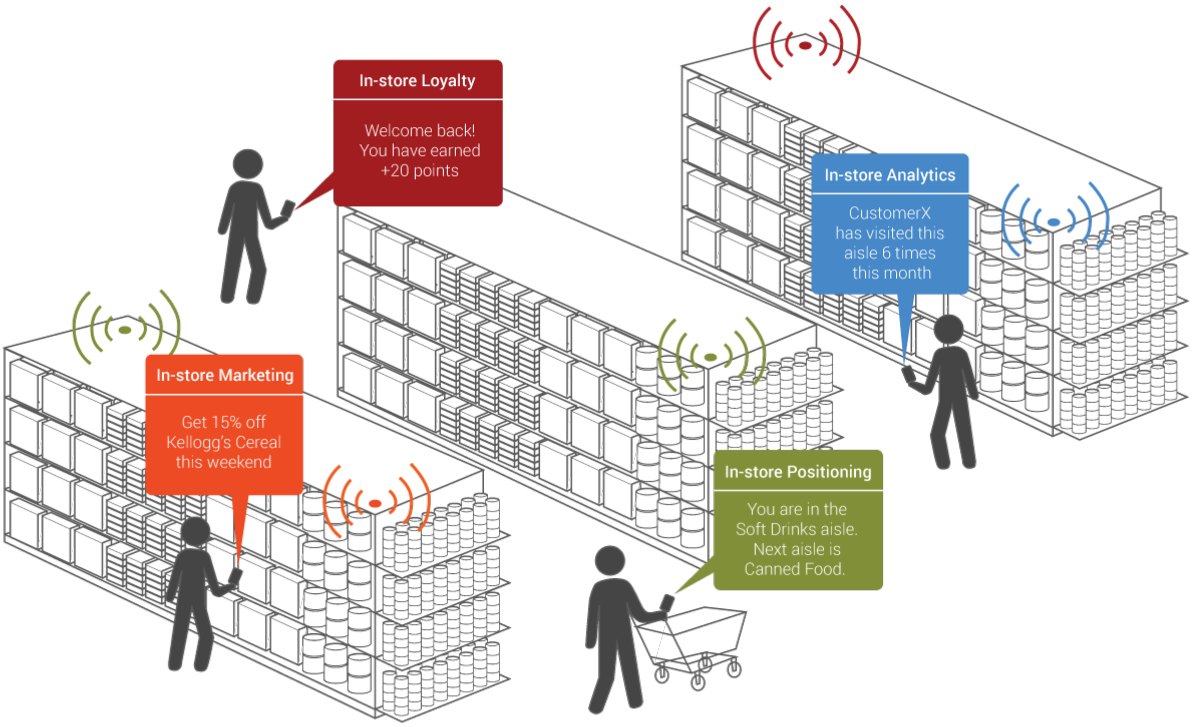

Figure 5.5. A graphic by *B'wireless*, a company specializing in *"Smart Cities and Free WIFI around the globe"*, used to advertise their 'Proximity Marketing' service. (from https://bwireless.eu/proximity-marketing/index.php, last accessed 19 Nov. 2022).

Video surveillance coupled with camera vision and machine learning has been used extensively for this kind of information gathering, but radio-frequency localization can easily bypass any privacy concerns - not to mention it is also much cheaper to install. WiFi is the preferred medium over Bluetooth, as less customers have the latter enabled on their devices when they visit a store (Schellevis, 2014). To incentivize shoppers to keep their WiFi interface switched on, many stores, cafés, airports, and other business that use analytics offer free WiFi as a kind of Trojan horse. It is not even necessary for a device to be connected to a network in order for it to be tracked because an active WiFi interface continuously broadcasts its MAC address (a unique hardware identifier) to all nearby Access Points. Unbeknownst to most users, in parallel to the more familiar layer of data traffic in a network there is a constant radio chatter of devices identifying themselves and their services to each other (see 6.2.3). This chatter can be exploited for localization purposes simply by installing arrays of Access Points or Beacons in an area, and then use them to triangulate the location of shoppers in the store. The only way to 'opt-out' of such systems is to turn off the WiFi of one's device.

An article from the New York Times gives an idea of how the technology was regarded in its very early days, just a handful of years ago in 2013 (Clifford & Hardy, 2013). The Nordstrom chain had just began testing a technology that tracked customers' movement in stores through their phone's WiFi. When they posted signs notifying about it, customers began complaining and Nordstrom soon ended the experiment. While people were not too bothered about cookies and other tools that interfere with online privacy, localization in physical space raised many more privacy concerns in that occasion.[251] For some, *"being stalked in a store"* can become particularly *"creepy"* when radio-frequency localization is connected to other data, allowing companies to infer much more about a shopper than cookies (Ibid). This combination of multiple data sources, online and offline, has become widespread nowadays. For instance, as the NYT article reported, the New York-based company Nomi matched phone identities to individuals and to data they had voluntarily provided by downloading an app or registering their email to access a store's free WiFi. Nomi could provide retailers with data profiling a shopper, such as the number of times they visited a store, what products they were looking for on the Web, and their purchase history. Proponents from the commercial sector defend this data collection claiming that its focus is the analysis of mass behavior rather than the surveillance of individuals, and that through this type of technique they can tailor their products and marketing strategies better. NYT reports: *"'I walk into Macy's, Macy's knows that I just entered the store, and they're able to give me a personalized recommendation through my phone the moment I enter the store,' said Corey Capasso, Nomi's president. 'It's literally bringing the Amazon experience into the store.'"* (Ibid). Nomi can shadow the customer through the store constantly making deductions and offering deals: *"'If I'm going and spending 20 minutes in the shoe section, that means I'm highly interested in buying a pair of shoes,' Mr. Capasso said, and the store might send a coupon for sneakers.'"* (Ibid). While to some citizens this may feel intrusive, others are happy to get deals in exchange for their personal data and privacy.

Since that article, the technology has become increasingly more mainstream with a multitude of companies around the world embracing its potential. An Economist article from December 2016 estimated that 200,000 shops around the world employed systems tracking mobile phones at the time, opening up a data goldmine ("In-store detecting: A new industry has

[251] The overall attitude on online privacy showed some considerable shift a few months after I first wrote these lines in 2018 due to the Facebook/Cambridge Analytica scandal and the discussions around it ("Facebook–Cambridge Analytica data scandal," 2022). It will be interesting to see if this wave of concerns continues in the future, and how it could potentially influence physical location tracking and activity recognition.

sprung up selling "indoor-location" services to retailers", 2016). Beyond retail, tracking technologies have been used for years now in numerous other sectors - airports, commercial centers (see figure 5.6), festivals (e.g. South by Southwest), hotels, the Major League Baseball, museums, public transport, even dating apps (Reddy, 2014). For example, Gizmodo UK reported in 2017 that Transport for London (TfL) ran a similar pilot system in the London Underground (Malley, 2017a). Passengers were informed that WiFi data was being collected so they had the option to turn their WiFi off (assuming that they knew how this tracking technology worked and how to opt out). About one third of passengers were tracked. The collected data provided information on train routes taken, passenger paths and travel times within stations rather than just between the entry and exit stations, which is the information registered on an electronic ticket or card. This data was on one hand aimed at improving the service, but it also provided useful information to advertisers and the market – helping for example determine the pricing of ads or rent depending on how many people passed from a location. TfL's aim was to use this data to generate additional revenue of £322m (Cheshire, 2017). The Natural History Museum and National Railway Museum in London are also using radio-tracking software to track their visitors, revealing how long they visit and how long they spend in each room, whether they are passing through or dwelling in front of specific works and for how much time, and what return visitors do (apparently they spend more time at the museum's café) (Malley, 2017b). It is worth noting that while entities employing this type of tracking claim to anonymize the data, cybersecurity experts raise concerns that too few steps are taken to sufficiently protect citizen's privacy (Malley, 2017a).

A growing number of companies have been offering 'Big Data for retail' solutions across the globe (see Datoo, 2014 and "8 Startups Following You with Beacon Technology", 2017). The 2010-founded company Euclid Analytics, for example, was one of the key early players in this field.[252] In 2012 they made their radio tracking services available to stores for free, aiming to create a ubiquitously present tool. While each retailer had free access to their in-store data, Euclid 's database assembled data collected from all its customers together, which meant they could track a person across stores, cities, and even countries by using the MAC address of their mobile phone. Besides software-only solutions, there is a move towards specialized hardware, commonly referred to as *beacon technology*. These devices are similar to normal Access Points but are specifically engineered for device-tracking and localization

[252] The company was acquired in 2019 by WeWork: https://www.wework.com/newsroom/wework-acquires-spatial-analytics-leader-euclid. Last accessed 29 December 2022.

services rather than data distribution. Several companies offer such products such as Google, Apple, Estimote, Qualcomm, Kontakt, Sensorberg, and many more, with their ranks growing every year.[253]

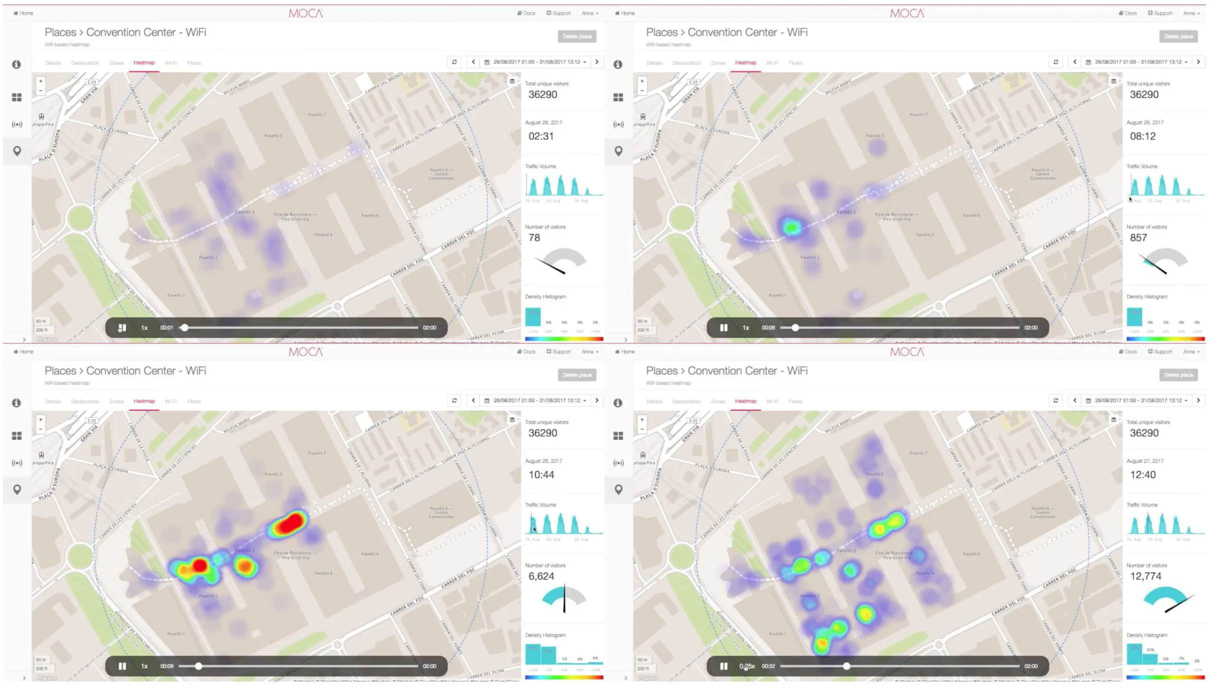

Figure 5.6. Four snapshots from the *Dynamic Heatmap* generated by location tracking platform MOCA Wi-Fi Analytics, one of many emerging companies focusing on indoor localization analytics. The images display the presence, movement, and behavior of visitors at Fira Barcelona Gran Via Convention Centre in real-time by tracking their phones via WiFi (video stills from MOCA Platform, 2017).

5.2.4 *COVID-19 and contact-tracing*

While I was writing this dissertation a new kind of localization service emerged with intense urgency: contact tracing to combat the spread of the COVID-19 virus. This involved utilizing varied mixtures of data, algorithms, systems, and manual labor. There were many diverse approaches, with different countries - even different states in the US - implementing their own toolkits; so much so, that the MIT Technology Review built a special *Covid Tracing Tracker* database to keep track of them all (see O'Neill et al., 2021). Most of these contact tracing systems were smartphone-based. A few made use of devices' cameras, e.g. requiring citizens to scan QR codes in order to enter specific areas (such as in China and in New Zealand during the early days of the pandemic) or deploying facial recognition combined with AI (such as in China, Russia and Poland, see Stanely & Granick (2020) and Colaner

[253] For a list of the first wave of such products see (Groot, 2014).

(2020)). In most cases, however, tracking technologies based on radio and microwave interfaces were the ones preferred.

Some countries chose to implement contact tracing smartphone apps using GPS location data. This included Israel - who infamously put its internal security agency, Shin Bet, in charge of contact tracing thus raising severe concerns (Amnesty International, 2020) – as well as Ecuador, Iceland, Saudi Arabia, Ghana, Bulgaria, Kuwait, and Cyprus (O'Neill et al., 2021). Others used GPS to enforce quarantining, with Kenyan authorities for instance requiring that anyone entering the country share their location to ensure they stayed put (Colaner, 2020). There were even proposals to use special GPS wearables like ankle bracelets, such as by US judges in West Virginia and Louisville, KY who authorized law enforcement to impose such devices on infected citizens (Ibid).

Many other countries decided that GPS lacked the fine-grained capacity necessary to control the spread of the virus effectively. Some thus opted to combine GPS with other data. South Korea almost immediately rolled out an intricate contact tracing system based on the combination of various data points - from cellphone location to CCTV and transaction records – that quickly made the news around the world (Thompson, 2020). When someone got infected, authorities broadcast a text alert to the population that allowed them to cross-check their potential exposure. However, these messages included links to poorly anonymized location data which inevitably led to some unwanted and harmful results, instigating incidents of public shaming and social stigmatization, as was reported in early March 2020 (see Kim, 2020). In China, beyond QR code scanning, citizens in numerous cities were required to install software that harnessed and combined a variety of location data – such as geo-tracking, travel bookings, and possibly other information. This enabled authorities to assign each person a color code according to estimated infection risk (green, yellow, red), banning some from entering certain locations (Thompson, 2020). The – also poorly anonymized – locations of infected and suspected cases were overlaid in real-time on a map so that citizens could avoid risky areas (Stanley & Granick, 2020).

Beyond the cases of Israel, China and South Korea mentioned, numerous other countries launched contact tracing apps during the pandemic that raised various types of concerns, particularly in regard to privacy and the use and abuse of data. This included apps that aggregated data on centralized servers with little transparency or oversight – e.g. in Saudi Arabia, Mexico, Australia, and over a dozen other countries. Other apps needlessly collected a plethora of data from citizens' phones that were unnecessary for contact tracing, like in

Ghana, Vietnam, Qatar (whose app also had a major security breach), and Kuwait, whose app was described by Amnesty International as *"one of the most invasive in the world"* (O'Neill et. al,. 2020). In some cases, like in Norway and Poland, popular protests about lack of privacy resulted in apps being adapted or discontinued.

Already in the first few weeks of the pandemic, the emergence of several questionable app implementations around the world led many to ring the alarm, cautioning that new paradigms of surveillance were emerging, taking advantage of people's very legitimate distress to camouflage authoritarian desires behind contact tracing. I will briefly mention a few publications from early April 2020, as they were not only informative and successful in painting a clear picture of the situation while it was unfolding, but also because they did so with a sense of urgency uncommon to discussions on the use of localization in the past. One of these voices was Amnesty International (2020) who, on April 3rd, published an article acknowledging the need for technology to play a role but warning that governments across the world *"are rushing to expand their use of surveillance technologies to track individuals and even entire populations",* using the pandemic as a pretext and working on their own or with the help of *"controversial surveillance vendors"* infamous for their spyware, like Clearview AI, Palantir, and NSO Group (who 1.5 years later got blacklisted by the US government for its dubious practices, see Sanger et al. (2021)). The article advised taking a long-term view on the subject, reminding the world that any measures taken during that stressful time may outlast the fight against the virus and become permanent, much like the global surveillance apparatus continued expanding following the events of 9/11/2001. A few days later, an article on The Atlantic proposed some steps to prevent totalitarian dystopias from taking a foothold: open-sourcing the code of contact tracing apps, making sure that governments and tech companies do not become the exclusive controllers of info-rich databases, and limiting the amount of information gathered in those databases (Thompson, 2020). The following day (April 8) the American Civil Liberties Union (ACLU) published a White Paper echoing similar thoughts and including both a detailed analysis of the problems and offering solutions. While recognizing that a combination of measures and contact tracing was very much needed to overcome the virus, the authors stressed that *"[t]he potential for invasions of privacy, abuse, and stigmatization is enormous"* because *"location data contains an enormously invasive and personal set of information about each of us, with the potential to reveal such things as people's social, sexual, religious, and political associations"* (Stanley & Granick, 2020, 1). The paper proposed a series of questions to take into account when considering how such data is used, including: what the goals of a system are and how data is used (e.g. to identify trends, for contact tracing, or quarantine enforcement?); how data are collected (are they individualized, complete enough to allow identifying people, or anonymized, and do they under- or mis-represent certain communities?); who is given access to it (e.g. governments, public health entities, or private, often *"shady, privacy-invading companies"* (Ibid, 4)?); and what is the data's lifecycle before it gets destroyed. The authors also advised that citizens should retain some healthy skepticism in regard to the accuracy of any technological implementation, mentioning some failed examples, such as when a woman in Israel was identified as a contact and forced to quarantine *"simply because she waved at her infected boyfriend from outside his apartment building"* – a scenario too subtle for Israel's GPS-based system (Ibid, 4).

As a positive alternative to location-based systems worth of further exploration, the ACLU paper referred to Singapore's approach. Its *TraceTogether* app was the first to use Bluetooth to implement a system based on proximity between people instead of tracking their physical location. Singapore's system was quickly borrowed by Google and Apple who, on April 10th and within a month since the World Health Organization declared COVID-19 a pandemic (Cucinotta & Vanelli, 2020), announced a partnership rather rare for Big-Tech giants. The goal of their coming together was to develop a cross-platform, inter-operable infrastructure for *"Privacy-safe contact tracing using Bluetooth Low Energy"* (Google, 2020 and Apple, 2020). Figure 5.7 shows a graphic accompanying this announcement and explaining how this technology was expected to work. Essentially, Google and Apple proposed that phones running such a contact tracing app and with their Bluetooth interface switched on continuously broadcast anonymous identifier beacon keys that any other device within range and that software can register and store for a number of days. Once a user is diagnosed with COVID-19, they voluntarily notify the app, which in its turn notifies any users with that person's key stored on their phone that they have been exposed to the illness. To ensure privacy is maintained, cryptographic operations take place locally on the phones rather than on centralized servers (Brandom and Robertson, 2020). This constituted a significant modification to the Singaporean model, in which everyone registered to a central database with their phone number to enable authorities to directly impose quarantine measures (Thompson, 2020). Bluetooth-based proximity tracing soon became the most popular approach to contact tracing across the world, with many countries adopting the Google/Apple model directly (such as Austria, Belgium, Canada, Denmark, Finland, Germany, Italy, Ireland, the Netherlands, South Africa, UK) or rolling their own centralized (e.g. Australia, France, Hungary, Tunisia and Mexico) or decentralized versions (e.g. Czech Republic, Fiji, Gibraltar, Malaysia, North Macedonia, Philippines, UAE, Vietnam).

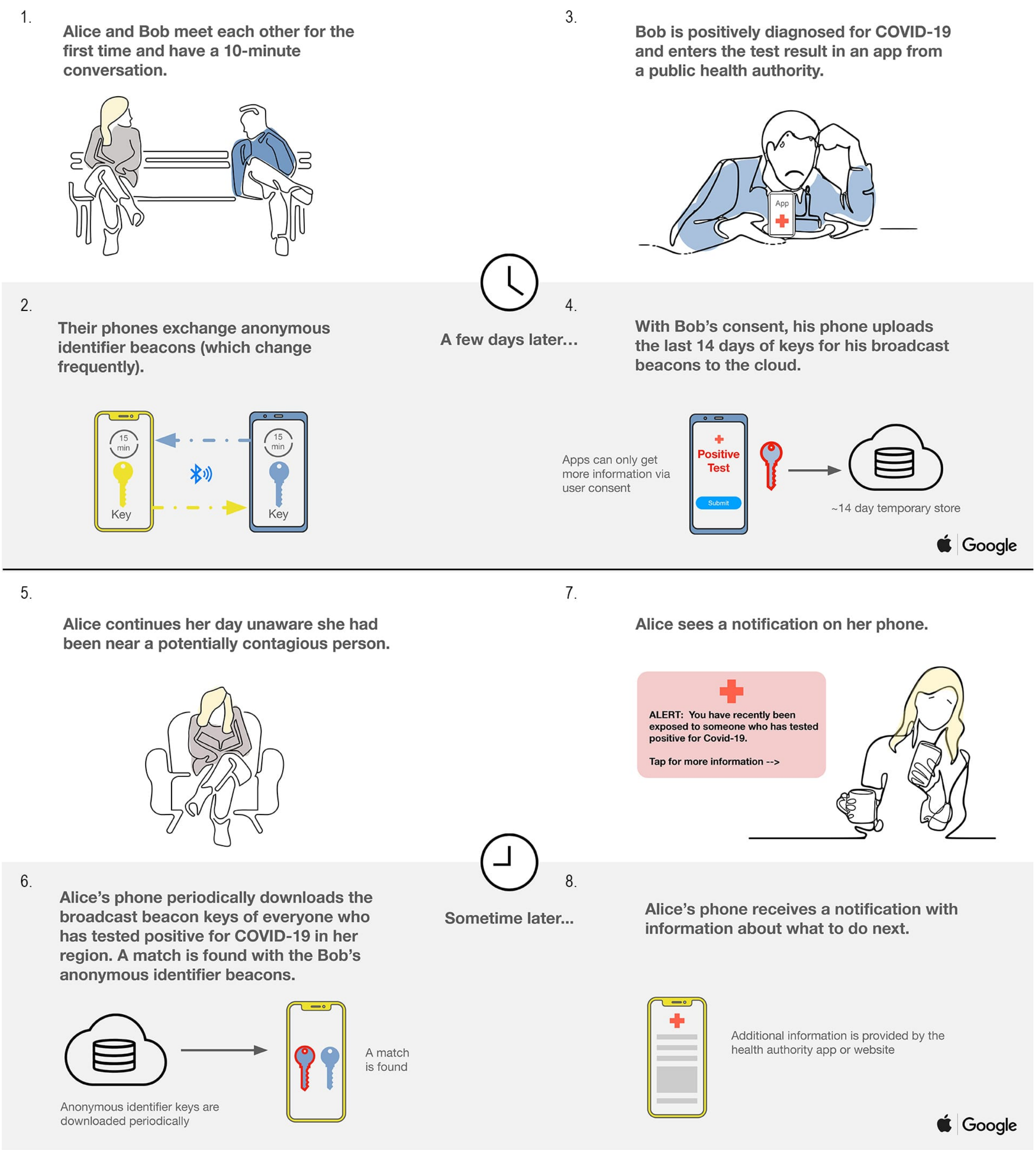

Figure 5.7. Graphic by Google and Apple explaining how their proposed COVID-19 contact tracing platform would work (from Google 2020, with added indices on each figure for clarity).

While innovative and an improvement over other location-based methods, contact tracing via *proximity tracking* and Bluetooth is not devoid of its own set of problems. On one hand, there is always the possibility that captured data is used for nefarious purposes, particularly when keys are stored in centralized servers owned by governments or companies.[254] While this technology does not readily allow mapping users' paths in space – hence ensuring some privacy - it can be mined to provide a different type of fertile information: who people's (physical) social contacts are and how much time they spend near them. This type of information could be a goldmine when used, for example, to map out the relationship networks of dissidents by an authoritarian regime, or of journalists investigating touchy subjects. Combining it with location data (like the apps in India, Indonesia, Turkey, Thailand, Qatar and Bahrain did) could give even more insights.

Furthermore, there are technical issues that should caution both health authorities and the population against using such a system as a contact tracing panacea. For one, microwaves are not transmitted in space in the same way as aerosolized viral particles. For instance, while aerosols cannot pass through glass or the walls between two houses, microwaves can, resulting in false positives – as was in fact reported in several cases (e.g. concerning the official National Health Service app *Test and Trace* in the UK, see Duncan, 2021). This is a problem inherent to the medium, and as such any contact tracing effort based on microwaves is bound to suffer from it. Similarly, it is impossible for any such app to take the effects of wearing a mask into account.

In addition, there are numerous subtler technical issues relating to discrepancies between equipment, with precision and range differing between devices depending on their hardware (the particular antennas, chips, even the batteries they use). This is especially relevant as Bluetooth proximity tracing apps utilize the Received Signal Strength Indication (RSSI) to deduce how close to one another people are and how long they spend together to thus estimate the risk of viral transmission. As is evident, contact tracing assumes that people's respiratory system and their phones are at the exact same place. Even discounting the fact that one's phone may be meters away from their head (e.g. placed on a table or in another room), there are additional elements to consider. As Sven Mattison, one of the inventors of Bluetooth, commented on an article researching the technical limitations of this solution published about a month after Google/Apple's announcement, RSSI in Bluetooth devices *"can be rather crude and not well calibrated"*, minimizing the accuracy of these apps (quoted in Biddle, 2020). Furthermore, RSSI brings environmental and architectural factors into play and can be affected by the human body absorbing microwaves, which makes the

[254] It should be noted, that due to the nature of the technology, emitted beacons can also be captured by anyone nearby which opens up some possibilities of foul play.

system useless in certain conditions like crowded places. This was proven in a study of proximity measurements of Italian, Swiss and German Bluetooth-based contact tracing apps inside trams that showed their accuracy to be essentially as effective as a coin-toss (Leith & Farrell, 2020). Accurate contact tracing with radio or microwaves would require dedicated hardware, or multiple devices operating together to create a radar-like system, something that is impossible *"with vanilla point-to-point Bluetooth links"* (Mattison quoted in Biddle, 2020). The co-inventor of Bluetooth, Jaap Haartsen, voiced similar concerns regarding the technology's accuracy while recognizing that using it is still better than the alternative of sensitive location data. At the same time, he also highlighted that any contact tracing app is only helpful if many people use it. This is an exceptionally important point, as such apps can provide a false sense of safety to their users; even if they are around infected people, the app will not notify them if these people are not users as well.[255] For all these reasons, as well as because it was unclear how to measure the efficiency and accuracy of contact tracing apps, reports published a few months into the pandemic found little evidence in favor of them, even though privacy concerns regarding their use still remained well founded (Klosowksi, 2020).

5.3 Device-Bound Indoor Localization with Radio-Frequencies

5.3.1 *RF ranging techniques based on time, angle, or signal strength measurements*

Device-bound RF localization systems can be categorized by the type of localization strategy they use into *range-based* or *range-free*.

The first indoor localization systems were *range-based*, implementing various ranging techniques modeled after GPS**.** *Ranging* is a term used to describe a family of common localization methods based on triangulation or trilateration. This may entail determining the *distance*, *angle*, or *signal loss* between a transmitting device and a target device and requires a set of two or more reference points with a known location. While triangulation and trilateration work fairly well outdoors, they are more error-prone indoors because of multipath propagation, shadowing, reflections and interference by other networks (Brown & Dunn, 2011).

Time-based ranging techniques are most similar to GPS. They measure the *Time-of-Arrival*

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[255] Without probing deeply into the reasons why people refrain from adopting them, lack of trust seems to be a fundamental inhibiting factor. As an example, according to an Axios poll from May 2020, about 2/3rds of Americans would not use a contact tracing app developed by a large company (Klosowksi, 2020).

(ToA) of signals from a target device to several system nodes acting as the equivalent of GPS satellites. In WLAN, these are typically Access Points. Distance is computed as follows: a ToA measurement is first converted to *Time-of-Flight* (ToF), meaning how long it took a signal to travel from one device to another. In its turn, ToF is multiplied with the speed of transmission (which equals the speed of light for radio and microwave signals) to convert it to the distance traveled between the target device and each Access Point. For this to work, it is important that all nodes/Access Points in the system are synchronized to the same clock so that the distances at any given moment can be compared to localize the target.

At this point, a number of different localization algorithms can be applied over the collected ToF data (see Golestanian et al., 2017). Most typically, each distance measurement is treated as the radius of a circle starting from the point of reference (i.e. the known location of the Access Point). The area contained in the cross-section of all circles generated in this manner discloses the estimated location of the target (see figure 5.8).[256] The accuracy of such systems falls typically within a few meters (Ibid). Alternatively, the *min-max* method uses an intersection of squares rather than circles. The known location of a reference point in the system (such as an Access Point) is placed at the center of a square, whose sides are twice as long as the measured distance between reference and target. A more advanced - and less common - range-based localization technique involves comparing the *Time Difference of Arrival* (TDoA) between two signals that propagate at different speeds, for example radio and audio signals.

The most significant problem encountered with time-based ranging systems is that there is an inevitable processing delay introduced between when a signal arrives at the antenna and when it is ready to be used at the *Application layer*. This is because various hardware and software components are involved. The delay can be significant and, more importantly, can also be time-variable thus adding noise to the actual ToF measurement.

Two-Way Ranging (TWR) or *Roundtrip Time of Flight* (RToF) simplifies the process by measuring the time a signal takes to return to a transmitter. This technique can be further refined by using *Symmetric Double-Sided Two-Way Ranging* (SDS-TWR). In that case, both nodes transmit a signal and measure its RToF; then an average value is calculated to give a more robust measurement of the actual distance. This is related to the network echolocation technique I developed for *The Network Is A Blind Space*. Like in ToA systems, more

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[256] Trilateration creates a cross-section of three circles and multilateration a cross-section of multiple circles.

advanced methods may involve transmitting signals through multiple radio channels and frequencies to get a better average ToF between two nodes.

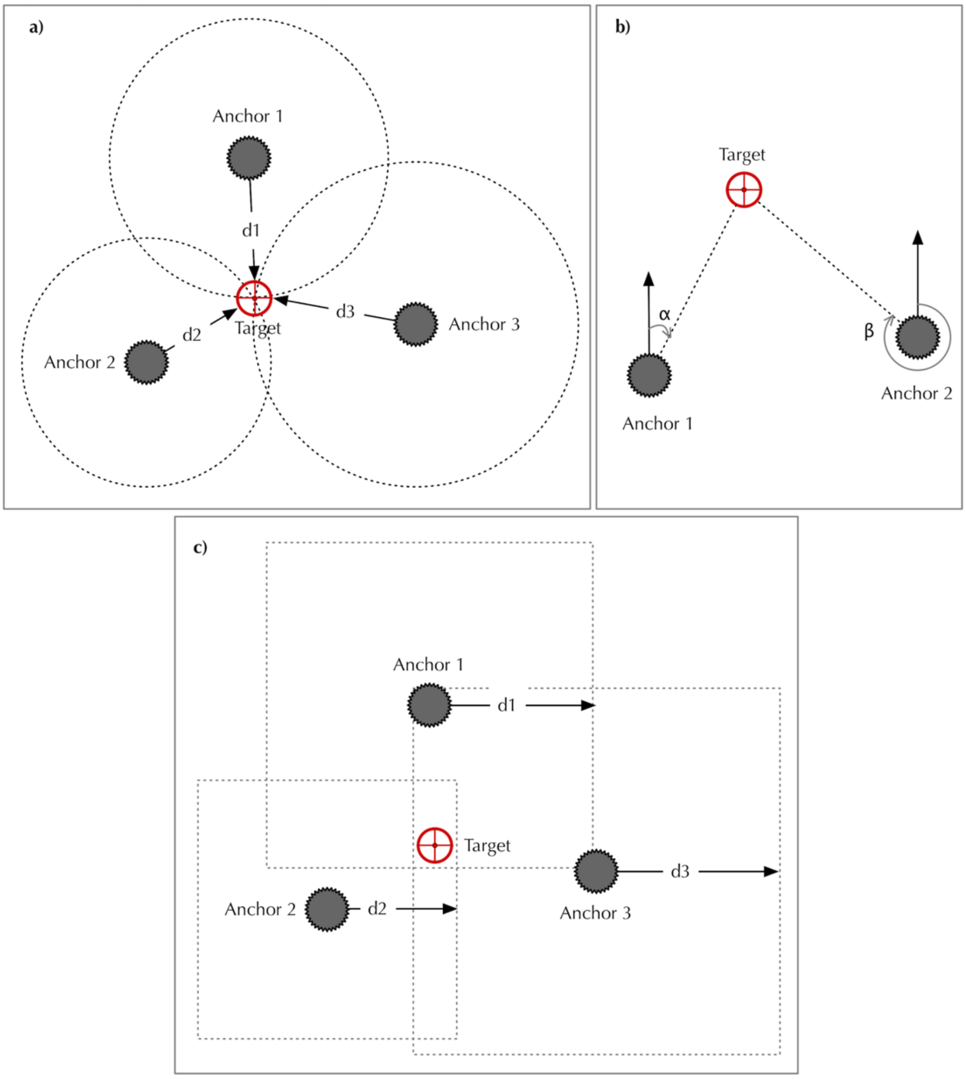

Figure 5.8. Localization estimation using different ranging techniques: a) trilateration with 3 anchor/reference nodes and distance information; b) triangulation with 2 anchor/reference nodes, angle information, and a common reference direction; c) 'min-max' localization with three anchor/reference nodes and distance estimation.

Angle-based ranging systems work in a similar manner to time-based ones but instead of calculating distances they measure the angle between a reference node and the target. *Angle-of-Arrival* techniques (AoA) involve deploying multiple antennas at different locations. These can either be antenna arrays or a single antenna moving at a fixed rate and direction, like in the case of Synthetic Aperture Radar (SAR) systems. In that case, the *Time Difference of Arrival* (TDoA) between the different antennas (or between the different points in the SAR antenna's path) is used to deduce the AoA of the target signal. By combining these measurements, the target's location can be calculated through triangulation. The *Phase-of-*

Arrival (PoA, sometimes referred to as *Received Signal Phase*) can also be used to produce an angle measurement.

In the indoor localization field, there has been a noticeable shift from techniques using time and angle measurements to techniques based on the *Received Signal Strength Indication* (RSSI) of a transmitted signal. These methods derive distance by measuring the attenuation of a signal as it travels from a device in a known location to a target device in an unknown location. [257] It should be noted that RSSI is not an absolute measurement of signal strength but a nominal one. Even though the term *decibel* is often used when discussing RSSI, this is a device-specific measurement that does not correspond directly to the actual strength of a radio/microwave signal, and thus does not directly correlate to measurable distance. To make matters worse, the implementation for each device is rarely specified in detail to the public. Furthermore, discrepancies may even be observed between individual devices of the same design, especially with cheap equipment. Regardless, RSSI can still be accurate enough for many indoor localization applications.

RSSI localization systems work as follows: Anchor or reference nodes (such as APs) establish wireless contact with a target device and compare the signal strength of packets when they were received to when they were transmitted to calculate path loss. These measurements are combined together with the known locations of all anchor nodes to estimate a target's position via triangulation. In such systems, calibration is necessary to fine-tune them to the specific characteristics of the space as well as to the specific hardware they use. Any changes in the equipment or in the space - even minimal adjustments like repositioning furniture - require a new calibration.

In many protocols, like WLAN, RSSI represents signal strength as an 8-bit integer. In practice, however, the measurement's usable bandwidth is a fraction of that, which makes it a somewhat coarse tool when used without further processing. Straight-forward RSSI-based

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[257] The mathematical relationship between RSSI and distance (D) for WiFi transmissions depends on transmission frequency (f) and the Received Signal Strength as expressed in the following equation (Golenstanian et al., 2017, 127):

$$D = 10\left(\frac{27.55 - (20\log(f)) + RSSI}{20}\right)$$

For Bluetooth Low Energy and XBee, this relationship can be expressed as a function of: i) transmission power (A) - i.e. the expected RSSI at a distance of 1 meter; ii) distance (D); and iii) a path loss exponent (n):

$$RSSI = -\left(10n\log(D) - (A)\right)$$

However, experiments show a discrepancy between theoretical and measured values. This is caused by a combination of environmental factors (multipath reflections), transmission power, antenna orientation, receiver sensitivity, and possibly interference from other transmissions on the same frequency band.

localization is also not that fine-grained because signal decay (path loss calculation) is not a full-proof measurement. RSSI-based systems make two simplifying assumptions: that radio/microwave signals decay in a predictable way, and that antennas are perfectly isotropic – meaning that they radiate electromagnetic energy in a perfect sphere and with equal strength in all directions. When these two assumptions are correct – or close enough to being correct - the decay of a signal should reveal the distance from the transmitting reference point through simple or somewhat more complex path-loss models. Estimation can be improved by using filtering and prediction algorithms, e.g. Kalman filters and maximum-likelihood estimation (Golestanian et al., 2017).

A final note is that RSSI values may still fluctuate even when transmitter and target remain static. This may occur due to a number of factors including imprecise hardware, the effects of multipath propagation, or changes in the environment between the two devices, such as the movement of human bodies or furniture (for example, I have noticed RSSI being affected by opening/closing doors or by slightly angling a chair). Fluctuation also increases with distance: the further a transmitter and a receiver/target are from each other, the more fluctuation will be observed (Golestanian et al., 2017). In this regard, WiFi is generally more stable than XBee and even more than Bluetooth Low Energy (Ibid, 124 & 129).

5.3.2 *Range-free RF localization*

Range-free methods estimate location utilizing prior knowledge of the characteristics and geometry of the network and of the space in which it propagates. These approaches are generally less computationally demanding than ranging, but also tend to be less precise (Golestanian et al., 2017). There are a few different approaches to range-free localization:

Proximity-based systems use a coarse-grain assumption, defining the position of the target as that of the anchor node it is connected to. This anchor node will always be the one with the strongest signal - though not necessarily the closest in terms of physical distance, as spatial layout, architecture and other environmental factors may come into play. This type of crude localization is implemented in cellular networks: *Cell IDs*, a unique number associated with a specific Base Transceiver Station, are utilized to identify which Cell tower a user is connected to, and can thus deduce their approximate location. Access Point proximity is a similar concept for WLANs. In this case, the location of a device is thought to correspond to that of the AP it is connected to. This technique can be used, for example, to find the room in which a user is located in a building. To increase resolution of a proximity-based system a finer grid of Cells or APs is required.

In a more advanced scenario, many anchor nodes may be deployed to detect one target device. A simple *centroid algorithm* can then be used to estimate the center point between these nodes and thus deduce the general area where the target device is expected to be located. For example, the position of a target that is connected to three nodes (cells or APs) with known locations can be estimated by finding the centroid of a triangle created by these three reference points.[258]

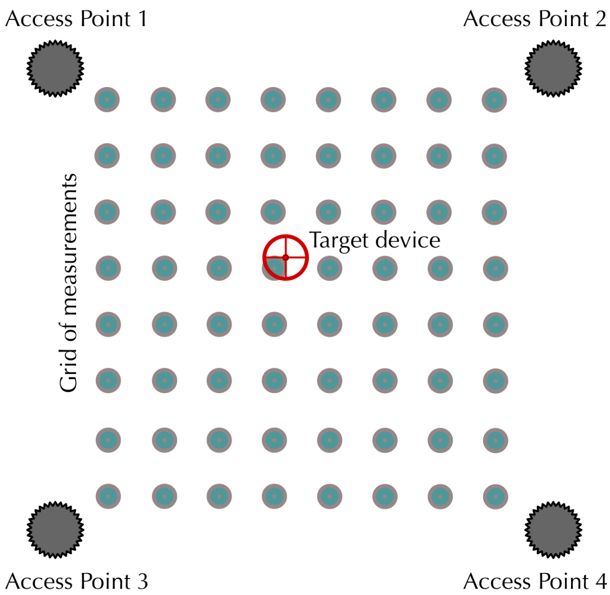

Figure 5.9. A graph demonstrating the principle of localization estimation using the range-free technique of *fingerprinting*. This involves deploying a number of access points/transmitters and taking an array of measurements of their signal strengths received at different points, typically configured in a grid to facilitate localization calculations.

Fingerprinting is another oft-used advanced range-free method that can achieve very good results (see figure 5.9). It was introduced by Microsoft in 2000 with the pioneering *RADAR* system (Padmanabhan and Bahl, 2000), and has since been implemented for WiFi, GSM, and FM radio signals (Sigg, Shi et al., 2013). Fingerprinting is site-specific and requires an offline training or mapping phase. This phase typically involves taking measurements of the Received Signal Strength (RSS) and Signal-to-Noise-Ratio (SNR) of a set of transmitters or Access Points in a grid (e.g. 1x1 foot, for *RADAR*). This grid of measurements is then collected in a database to create the RF 'fingerprint' of a space; the finer the grid, the higher the spatial accuracy of the system. The second phase is real-time and involves estimating a

[258] There are numerous centroid implementations to accommodate different geometries (see Golenstanian et al., 2017).

target device’s location by trying to match the incoming RSS and SNR values with the values stored in the database. This can be calculated using various methods, such as k-nearest-neighbors (KNN), probabilistic estimation algorithms or estimation techniques based on simulation (such as Bayesian particle filters). The RADAR system has an accuracy of around 3 meters, reaching 1.5m with better calibration – results that were considered exceptionally good even a decade after the tool’s release (Brown & Dunn, 2011). The downside of fingerprinting is that it requires many nodes/APs, hours of calibration, and tightly controlled conditions as any changes in the environment require recalibration. It can also be quite slow in producing results. Therefore in the 2010s the focus shifted towards other type of real-time systems that can produce sub-meter accuracy (Sigg, Shi et al., 2013).

Given that there are many different possible approaches to localization, the type of usage typically dictates the hardware and the method that will work best in a particular situation. For example, in a scenario where all nodes are moving and there are no fixed reference points, the algorithm cannot be based on anchor nodes (i.e. it has to be *anchor-free*). The network topology - meaning how nodes are connected to each other - is another important factor in choosing a localization algorithm as it dictates how information is shared between nodes. For example, a *star network* - in which a main node connects to all other nodes - prevents direct communication between peer nodes and thus suggests using a system in which a *master/main node* collects all information and handles computation. Instead, a mesh network encourages distributed computation and data-sharing or other forms of collaboration between peer nodes.

5.4 DEVICE-FREE SENSING

5.4.1 *‘Sensor-less sensing’: ubiquitous sensing research reinvents the wheel – or the rediscovery of the Thereminvox principle as a domestic radar*

In 2006, a paper by Woyach et al. (2006) introduced a new concept to the Ubiquitous Sensing community: *sensor-less sensing*, or Device-Free Radio-Frequency sensing. Suggested applications included motion detection, velocity estimation, and recognizing different configurations of the environment (e.g. open versus closed doors, moved furniture, etc). The paper came out of research on Wireless Sensor Networks (WSNs) at a time when the promise of ubiquitous sensing had begun to stall, as adding sensors to everything was proving too expensive and complicated. WSN applications had increased researchers' interest in optimizing wireless connectivity, while simultaneously offering a platform for observing and troubleshooting connectivity problems that plague RF systems. In that paper, the authors suggested *"adopting a completely different stance"* in regard to the effects that hinder radio communication (Ibid, 1): By analyzing signal fluctuation, multipath fading and shadowing could be transformed from a nuisance to a medium for sensing motion and changes in spatial configuration! *Sensorless sensing* was the key to exploiting physical phenomena "*traditionally regarded as negative"* while also providing *"a deeper understanding of wireless links"* (Ibid, 7).

To me, it is rather fascinating to realize that an emergent multimillion-dollar industry would discover, almost by accident, something that had been common knowledge in music for almost 90 years by then. The *Thereminvox*, Lev Termen's 1920 invention, had made it evident that radio waves can sense the human body. For many musicians that followed – such as John Cage, Tetsuo Kogawa, Gottfried-Willem Raes and many other composers and performers beyond those mentioned in the previous chapter - radio and microwaves were one more tool for expressive embodied performance. Apparently, however, the barriers between distinct fields are not as permeable as one would think. In the context of ubiquitous sensing research Woyach et al.'s paper presented a groundbreakingly different perspective. I believe this to be a perfect example of how our context and tools construct the ways we see the world and define the limits of our imagination.

The authors performed a number of experiments at 433MHz and 2.4GHz. The devices they experimented with were also equipped with accelerometers, which they used to compare motion registered by RF signal strength to motion registered by inertial sensors. In this manner they verified that it was possible to: a) detect the motion of a connected node, and b) detect objects moving between or near a stationary transmitter-receiver pair, an effect called *slow fading*. Another interesting finding was that radio sensing was able to detect very slow movement better than accelerometers because, as the authors stated, the moving object changes the configuration and radio acoustics of the environment regardless of its speed (ibid).

The paper made several very interesting remarks and experimental observations on radio sensing, setting off a wave of investigations from other researchers. A number of implementations followed it, first aiming to localize people and objects, and later to recognize various activities. Today, over 15 years later, several RF-sensing sensing systems have been developed for use in smart buildings and factories, health care, monitoring older people at home, evacuations, but also for surveillance and law enforcement (an application fantasized way before it became possible, see figure 5.10). A variety of frequencies, protocols and interfaces have been used. Implementations can be categorized according to the type of signals they use as *continuous* (when using continuous signals) or *discrete* (when they are based on data packets). They can also be categorized as *active* or *passive*, depending on the system's configuration: *active* implementations use both transmitter and receiver nodes whereas *passive* systems only receive; instead of using a transmitter, they leverage ambient signals and measure the interference of the environment on them. Conceptually, active systems are similar to radar applications whereas passive one are more akin to radio astronomy in that regard. Most systems in the ubiquitous sensing literature are active, as this method gives more control, is more accurate and more robust. Passive systems are still in earlier stages, but are developing rapidly.

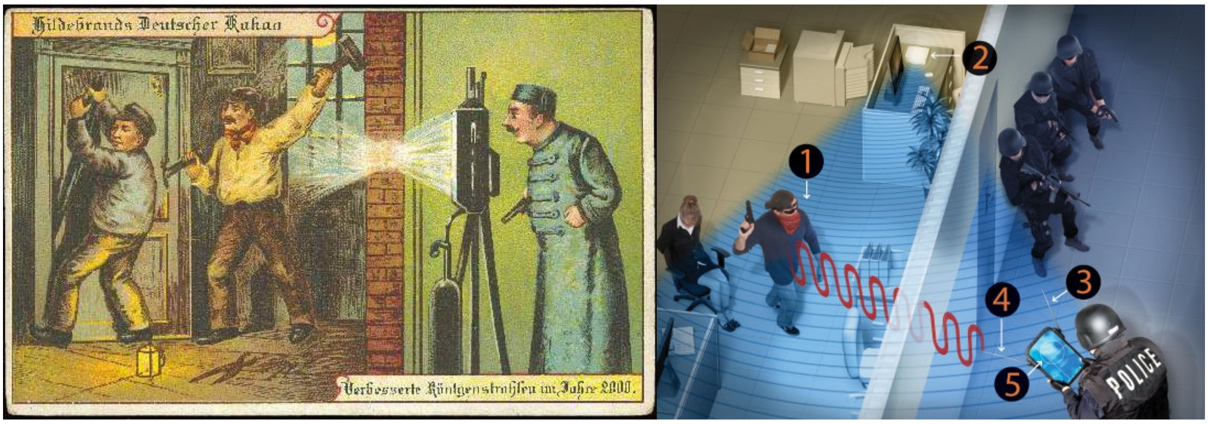

Figure 5.10. Two images portraying how electromagnetic waves may allow law enforcement to see through walls - a fantasy with a long history. Left: A collectible trading card from around 1900 (advertising a German confectionary company) speculating how the police will be able to see criminals behind walls using X-rays in the year 2000. (Public Domain image, https://de.wikipedia.org/wiki/Theodor_Hildebrand_%26_Sohn). Right: A contemporary speculative image on the same theme, published on the *Popular Science* website in 2012 to describe a technology introduced in a paper that allows to detect people behind walls with WiFi (from Hambling 2012, discussing Chetty et al., 2012)

Most early research on device-free sensing was based on active, continuous systems implemented with *Software Defined Radio* equipment (SDR), a relatively new technology in which most of the functionality of a radio system is implemented in software rather than hardware (Ulversoy, 2010). SDR hardware, such as the Ettus Universal Software Radio Peripheral (USRP N200 and N210), is generally very accurate and very flexible, having the ability to transmit and receive continuous and discrete signals in a variety of frequencies and protocols. These devices can also operate on high sampling rates, which greatly facilitates the implementation of frequency domain analysis. However, this equipment is still rather expensive (Ettus devices cost about $2000 per unit at the time of writing), although recently there is a new wave of cheaper equipment geared towards amateurs and hobbyists, such as the HackRF One.[259] This makes SDR systems harder to take out of the lab and into the real-world, and means that implementing multi-node modular applications can be financially prohibitive. Because of this, various alternatives to SDR systems have been investigated in the literature, most of which implement active and discrete techniques using off-the-shelf devices and based on the analysis of the RSSI of data packets. This approach is feasible with a variety of devices, interfaces and protocols such as WiFi, Bluetooth, Xbee and WSN devices, even passive RFID tags. GSM telephony and FM radio signals have also been harnessed for activity recognition. Furthermore, Doppler-based continuous sensing implementations have been on the rise lately due to the recent availability of inexpensive doppler radar modules.

In their 2015 overview, Sigg et al. (2015) identified what has been achieved in each category by various implementations up to that point. All types of systems (continuous and discrete, active and passive) had been used to effectively track presence, location, movement speed and specific activities. However, only active, continuous systems had been successful in tracking specific gestures. In terms of how many subjects these systems could track simultaneously, passive and continuous systems were limited to a single subject whereas the rest demonstrated the ability to detect the presence of crowds as well. Furthermore, active systems had been used to simultaneously track multiple subjects, and active discrete systems had demonstrated the ability to identify specific subjects within a crowd.

5.4.2 *Device-Free Localization (DFL)*

There are two major trends in device-free sensing: *Device-Free Localization* (DFL), which was the first implemented application of the technology, and *Device-Free Activity Recognition* (DFAR).

The goal of DFL systems is to track bodies in space even if they are not carrying a radio-enabled device. A DFL implementation may use one of several approaches:

- *Feature extraction* through statistical analysis of continuous (SDR) or discrete (RSSI) signals can be used to detect presence and movement. An early implementation a year after

[259] For a list of commercial SDR devices see (“List of Software Defined Radios”, 2022).

Woyach et al.'s paper extracted the moving variance and moving average of the RSS to recognize presence between a transmitter and a receiver (Youssef et al., 2007). Similarly, a 2010 'sensorless-sensing' system used RSSI for intrusion detection by looking at fluctuations in mean and standard deviation (Lee et al., 2010). Another system from 2012 used standard WiFi hardware to detect presence, although it could not estimate location because its sensing nodes were not placed on a fixed grid (Kosba et al., 2012). This implementation included a short training phase, without any subjects standing or moving in the target area, to produce a set of baseline RSS values. The system then used 'anomaly detection' to track any changes. The authors tested the mean and variance of measured RSSI, and found the latter performing better. This type of calibration is similar to what I implemented in the *Wireless Information Retrieval* system for *Hertzian Field #2* and *#3*.

- *Geometric models* and *estimation techniques* can be used when the location of the transmitter and receiver nodes are known, such as when they are installed in a grid formation. For example, a 2007 system featured an array of ceiling-mounted sensors transmitting at 870MHz; it implemented various algorithms and required a short training phase to calibrate the system without anyone's presence (Zhang et al., 2007). Statistical analysis and feature extraction can also be valuable with such geometric configurations, as was demonstrated a few years later by another grid-based system which deployed a statistical model correlating RSSI variance to the location of a single body (Patwari & Wilson, 2011). Gridded systems can also be used to effectively track multiple bodies, for example by isolating the line-of-sight path and extracting phase information from the RSSI differences at various frequencies (Zhang et al., 2012).
- *Physical modeling* is another algorithm that can be used to complement estimation techniques. This was demonstrated in a 2009 paper, which involved creating a physical model of the effects that the human body has on RFID signal strength when placed in different positions relatively to transmitter and receiver (Lieckfeldt et al., 2009). The authors used algorithmic estimation to combine that model with the geometry of the tracking system. While the method is promising it is rather complex and computationally demanding.
- *Radio tomographic imaging* techniques (RTI) 'illuminate' a space with bursts of radio waves (or microwaves) to capture radio/microwave 'images' of objects inside it. Obstacles are located by analyzing received waves for the effects of reflections (for a detailed description of RTI see Mostofi & Sen, 2011 and Mostofi, 2012). RTI systems typically operate at a much slower rate than other localization algorithms and are commonly used to produce image-

based snapshots of spaces. The concept is akin to an X-ray in 'burst photography' mode (i.e. taking a continuous sequence of photos by keeping the shutter pressed), but with microwaves. These systems are often developed with security and rescue applications in mind, such as allowing a SWAT team to visually investigate the inside a building before a raid without the need for actual visual contact or allowing first responders to locate survivors trapped under rubble after an earthquake (Maas, 2014 and Hillyard et al., 2017). Beyond its slow rate, another downside of RTI is that it requires many nodes. A proposed solution for minimizing the number of nodes involves deploying mobile receiver and transmitter nodes in conjunction with a technique called *compressed sensing*, which focuses on gathering a limited subset of useful data (see Donoho, 2006; Candès et al., 2006; Needell and Vershynin, 2010; and Patwari and Wilson, 2010). This is conceptually similar to *Photogrammetry*, a photography technique that creates 3D models using a single camera rather than an array of cameras. In the case of RTI, one can readily assume that by decreasing the number of nodes, the time it takes to capture a radio tomographic image is increased. Several researchers have investigated RTI as a method for locating a human body through walls, such as Wilson and Patwari (Wilson & Patwari, 2010). Their experiment involved circling a room with 34 transceiver nodes and investigating the RSSI variance between each node. The nodes were synchronized to all transmit a signal at the same time, with a prediction algorithm (Kalman filters) used to clean up the data. The authors could differentiate between when the space was empty, when there was someone standing, or someone moving. Moreover, they could pinpoint the location and trajectory of movement when it was slow. The system produced one image every 10 seconds with a localization accuracy of 0.5 meters. RFID nodes have also been explored as a cheap alternative for RTI with promising results, although the technology is less flexible to control than WiFi (Wagner, Patwari, et al., 2012).

- *Machine Learning* is an alternative to time-consuming RTI methods. For example, researchers have used RFID nodes and a triple-layer neural network to produce localization accuracy below 0.5m within a 3x3m sensing area (Wagner, Timmerman, et al., 2012).
- *Fingerprinting* has also made its way into device-free sensing and can be useful for systems that are concerned with static situations. When used for device-bound analysis, fingerprinting involves registering the RSSI between a node and a device at different points in a grid. The concept is similar for device-free systems, except that the map of the space is instead created by registering the *interference* of a body to the RSSI between two nodes. Once the map is complete, real-time RSSI interference can be compared to this database

using a similar set of strategies as in device-bound tracking. It is important to note once again that the database degrades as objects move or conditions change. Popleteev (2013) reported encountering this issue with his passive system, which used an SDR device to capture ambient FM radio signals. His implementation included a training phase and employed a k-nearest neighbors algorithm to locate presence. The system had to be trained every day, so that conditions between training and sensing phases remained as similar as possible – from the location of objects in the room, to humidity and overall radio traffic. Popleteev also suggested using multiple radio frequencies to improve accuracy. Making such a map - especially on a daily basis - is a time-consuming process. Seifeldin et al. (2012) proposed an automated method to expedite fingerprinting, noting as well that, in their case, night was a better time to create maps and evaluate the system as there was less overall traffic in the building where their lab was located – suggesting that movement outside the room of their experiment had an influence.

5.4.3 *Device-Free Activity Recognition (DFAR)*

While DFL is essentially concerned with static situations – where someone is located at a given moment in time, or in a sequence of such moments – *Device-Free Activity Recognition* (DFAR) deals with change, seeking to identify activities, gestures, or situations that unfold over time. Sigg, Shi et al. (2013, 48) summarized some applications that early DFAR research had in mind: *"For instance, we might detect presence of non-cooperating intruders, activities conducted by persons in emergency situations or the status of indoor environments for maintenance or surveillance. (...) In some scenarios, for instance in surveillance cases or for property maintenance, a localisation of activities conducted is anticipated."*

Because of its time-based nature, DFAR requires a higher sampling rate than DFL. How high this needs to be is contingent on the particular application, with sampling rates of DFAR systems varying between 4-70Hz (Sigg et al., 2015). This requirement of temporal precision makes many techniques used for localization not applicable for activity recognition - for instance, standard Radio Tomographic Imaging is generally too slow. Furthermore, other algorithms that are strictly concerned with finding a target's location, such as geometric models and fingerprinting, are also ineffective for activity recognition. Instead, DFAR systems are primarily based on statistical analysis and feature extraction, which allow mining useful information from real-time data streams. The extracted data are often fed into a variety of other algorithms that are used to make sense out of them and consequently train DFAR systems to identify specific situations. This includes estimation and Machine Learning algorithms, tree-based approaches (e.g. decision tree) and classification algorithms (e.g. k-nearest neighbor, support vector machines, Bayes).

The potential of using radio-frequency signals for activity recognition was hinted at in a pioneering DFL paper by Patwari and Wilson in 2010 (Patwari & Wilson, 2010). A year later, their research team submitted a technical report with the following experiment (Patwari et al., 2011): A hospital bed was surrounded with 20 Telos B nodes (IEEE 802.15.4) forming a dense web of Line-of-Sight paths (figure 5.11). The nodes transmitted a 2.48GHz signal every 240ms (i.e. a sampling rate of 4.17Hz) which was interfered by the breathing body laying between them. This configuration is essentially a high-speed variation on the concept of Radio Tomography. By analyzing the RSSI variation and using a Maximum Likelihood Estimation algorithm, the authors were able to calculate the subject's breathing rate. The more nodes employed, the higher the accuracy. This technique was granted a US patent five years later (Patwari & Wilson, 2016).

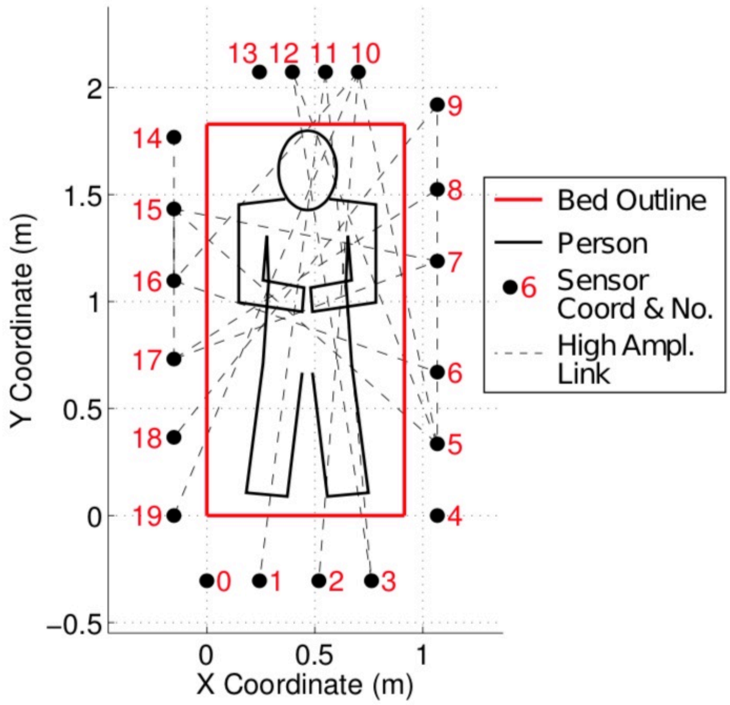

Figure 5.11. Configuration of an experiment for monitoring the breathing rate of a sleeping patient in a hospital bed. The graph shows the wireless nodes surrounding bed and patient, as well as the high-amplitude Line-of-Sight links used to track breathing (image from Patwari et al. 2011).

Another experiment by Scholz, Sigg et al. (2011) used radio-frequency sensing for *"context recognition"*. The experiment was based on two USRP SDR devices - the weapon of choice for most DFAR research: one transmitted a continuous signal at 900MHz (the GSM frequency) and another received it, sampling it at a rate of 40Hz. Both devices were equipped with directional antennas and were placed inside a room on either side of the entrance. By analyzing the received signal within a defined window of time, the system was able to track 3 different situations: Firstly, whether the door was closed or open (in the latter case, the Line-of-Sight was broken); this was achieved by feeding the amplitude of the signal and the number of peaks to a k-nearest neighbors algorithm. Secondly, the presence of a moving body within the room was detected by investigating whether the number of large deltas between consecutive peaks exceeded a threshold. Finally, the system could identify when a (GSM) phone call was taking place by looking at strong peaks in the captured signal. Subsequent additional experiments at the 2.4GHz range further refined the system, adding the extraction of more time-domain features from the received signal, such as signal amplitude, Root Mean Square amplitude (RMS), Average Magnitude Squared (AMS) and Signal-to-Noise Ratio (SNR) (Sigg et al., 2015). Variance was also reported to be a feature that could reliably detect dynamic activities regardless of any static changes in the environment (e.g. repositioning furniture).

In another paper, Sigg, Shi et al. (2013) benchmarked a number of features extracted from continuous signals (using SDR) or from discrete RSSI data (for the layout of this experiment, see top image of figure 5.12). These were primarily time domain features of the analyzed signal/data and included the mean, median, standard deviation, variance, minima and maxima, skewness, zero-crossings, spectral energy, and a few other features. These features were combined in pairs and these pairs were subsequently evaluated for their success in activity classification. The experiment was designed with rescue applications in mind and aimed to distinguish between five states: an empty space or an occupied space with four different activities taking place in it: walking, crawling, lying, or standing. The authors employed passive and active configurations, testing SDR and IEEE 802.15.4 sensor nodes at different frequencies.[260] The latter involved a cruder implementation than the former, as sensor nodes and similar off-the-shelf devices only provide access to the packet level, not the raw continuous radio signal like SDR does. In the case of these sensor nodes, the researchers

[260] Active SDR involved transmitting a 2kHz sine wave sampled at a high rate over 900MHz. The passive implementation involved listening to FM radio signals. Finally, the IEEE802.15.4 method involved a number of wireless sensor nodes (Inexpensive Node for General Applications, INGA - see: https://www.ibr.cs.tu-bs.de/projects/inga/, last retrieved 29 December 2022).

only used signal strength (RSSI) to extract sensing information.[261] For the classification step, they fed pairs of analysis features into a number of different algorithms - Classification tree, Naive Bayes and k-nearest neighbors. The lower resolution and sampling rate of the RSSI system (about 100 packets/second) rendered some of the features unusable and produced inferior classification accuracy than SDR, which allowed estimating the location of these activities as well as walking speed. A following paper by Sigg, Scholz et al. (2014) presented experiments with 2 SDR nodes at 90MHz, sampled at a rate of 70Hz on the receiver. It implemented a slightly different set of time- and frequency-domain RSS features that produced increased accuracy in classifying between these same 5 states (for the layout, see bottom image of figure 5.12).[262]

The papers mentioned above greatly inspired me to create the system for *Hertzian Field #1*. While I was not interested in activity classification myself (as I found the model of producing a trigger when a particular gesture of activity is recognized to be a very reductionist approach to performance) this research made it clear to me that sensing with radio waves was possible. Moreover, the use of statistical analyses and feature extraction demonstrated clear parallels with the type of analysis I had used in *The Network Is A Blind Space*. In addition, and perhaps more importantly, such strategies felt very familiar being similar to an audio-related field that I had been well acquainted with, *Music Information Retrieval* (MIR), and which had in fact inspired me to use feature extraction on traceroute data in that earlier work of mine. Audio analysis, feature extraction and other MIR approaches are tools I had been using already for years in my practice. This made my imagining potential uses for RF-sensing and implementing them much faster and easier. Furthermore, the above papers provided an extensive list of potential analysis features that I could begin testing in the lab, on my way to implementing a proof-of-concept sensing prototype based on WiFi signals. What made me particularly curious was the inclusion of a couple of frequency-domain features (spectral energy and spectral entropy in particular). Overall, these papers clearly pointed to me that there *had to be* some similarities between analyzing audio and radio signals, which suggested I could apply my knowledge of the former to the latter.

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261 It is worth noting that, Signal-to-Noise Ratio (SNR) and Link Quality Indicator (LQI) can potentially also be useful. However, these measurements are neither as reliable as RSSI, nor are they always made available by the driver implementation or the hardware.

262 Classification was achieved in one or two steps: Estimating directly which one of the 5 activities is occurring, or first deciding if a static or dynamic activity occurs (an empty space, standing, lying, or walking, crawling), before narrowing it down on the specific one.

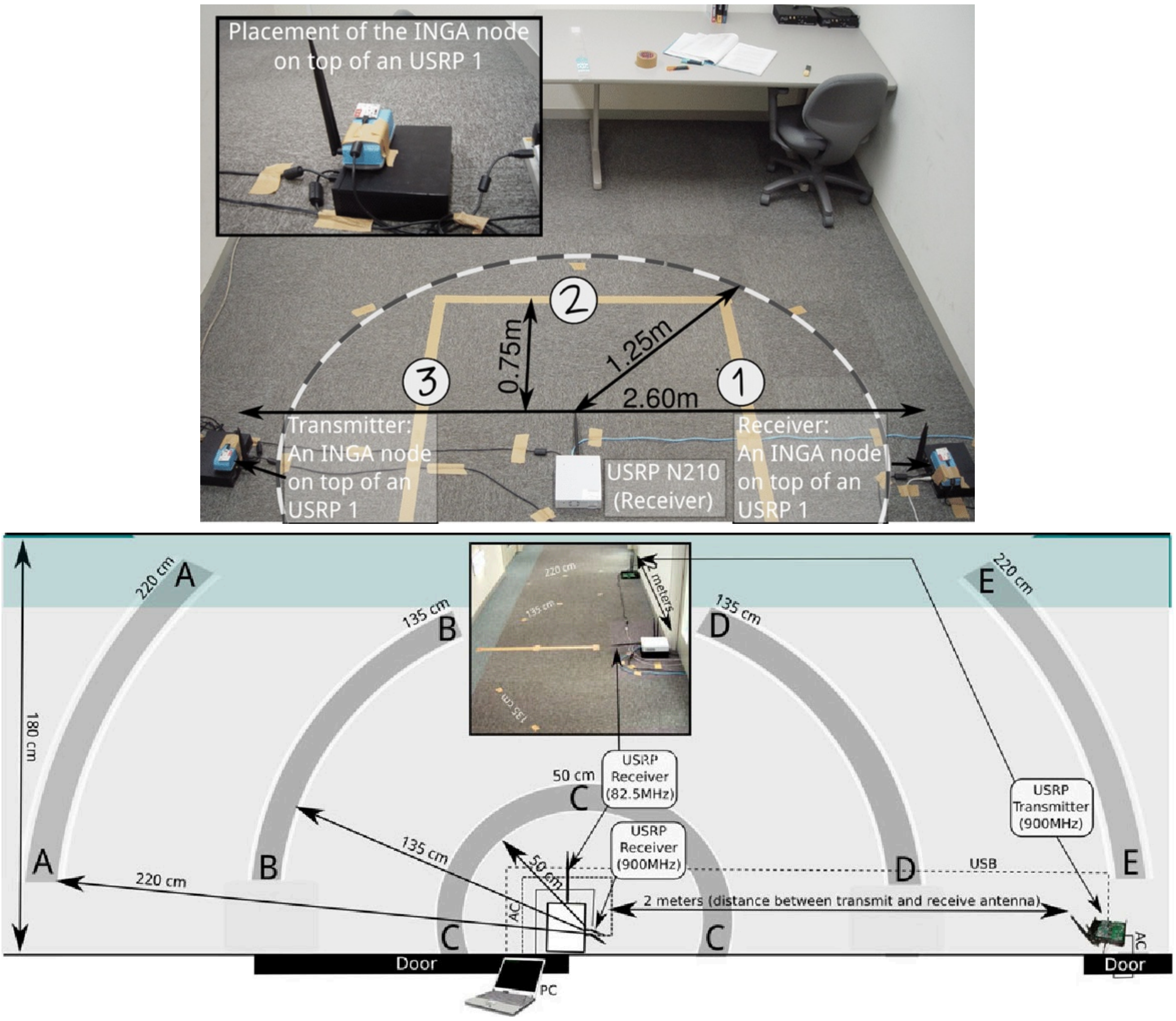

Figure 5.12. Configuration of two indoor experiments using feature extraction for Device-Free Activity Recognition with both active and passive systems. Top: Setup for benchmarking the effectiveness of different features and systems in identifying 5 activities in a 3x5m room. The equipment consisted of two transmit and receive pairs at opposite sides (a pair of SDR devices operating at 900MHz and a pair of IEEE802.15.4 nodes at the 2.4GHz band), and an SDR device in the center of the room capturing ambient FM radio signals; activities were performed at the areas marked by the circled numbers (from Sigg, Shi et al., 2013). Bottom: A similar experiment in a 1.8m wide corridor using an SDR transmit-receive pair at 900MHz and another SDR receiver capturing ambient FM signals. The same activities as above were performed in 5 different zones, their features analyzed and evaluated (Sigg, Scholz et al. 2014).

DFAR research has also been done with passive systems that capture and analyze existing ambient signals (e.g. those transmitted by Internet Access Points). Sigg and his team experimented with using a smartphone to capture transmitted RSSI packets (typically about 10 such packets per second) in a variety of urban spaces (Sigg, Hock et al., 2013 and Sigg, Blanke et al., 2014).[263] They were able to identify simple situations and localize hand

[263] These experiments took place in a University building, a dormitory, a café, a train station, and an apartment.

gestures in these spaces, although at a lower accuracy than when using active systems. Frequency domain analysis can be particularly useful in those cases to help increase accuracy. Around the same time, a passive experiment by Shi et al. (2013) involved capturing signals of a neighboring FM radio station via SDR, extracting frequency-domain features, and classifying the input using Machine Learning. Despite the very low sampling rate of this system (2Hz), frequency-domain analysis enabled it to achieve a level of accuracy similar to active sensing systems.

Finally, another family of DFAR techniques harnesses the doppler shifts that moving bodies and body parts produce on microwave signals. Ordinary WiFi equipment cannot capture these minute shifts because they are an order of magnitude below the resolution of such equipment.[264] Thus, such approaches typically involve tracking and analyzing continuous signals and are therefore based on the use of special continuous wave doppler modules or advanced SDR devices. The availability of doppler radar modules since the early 1990s (see section 3.6), and the fact that doppler analysis has long been a mainstay in radar technologies, contributed to doppler research having a longer history as a microwave sensing technique, although that concerns more obscure and secretive fields, mostly within or adjacent to the military and law enforcement. This includes, for example, an early and rudimentary portable alarm system that, according to its inventor *“adds a new dimension to surveillance",* enabling law enforcement to detect movement behind walls and closed doors (Frazier 1997, 23). In the new millennium, several researchers experimented with specialized microwave doppler devices to gather detailed information on certain types of motion, in particular walking. Geisheimer et al.’s DARPA-funded research analyzed gait patterns and created a simulated model of gait (Geisheimer et al., 2001 and 2002). Considering *"security, medicine, animation, military and other applications that are interested in human behaviour"*, Van Dorp and Groen (2003, 365) used a more intricate model of the human body (consisting of 12 basic moving parts, 14 rotation trajectories and 3 translation trajectories) to develop parameterized tracking and to animate a 3D model of a walking human. Having *"security and perimeter protection applications"* in mind, such as border crossings, Otero (2005, 538) presented a prototype that could detect and classify walking patterns, potentially distinguishing humans from animals. A few years later, as a response to an *"increasing demand for physical security and surveillance",* and aiming to address *“the more difficult yet*

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[264] The speed of a relatively human gesture is around 0.5m/sec, and will produce shift of 8.33Hz on a 2.45GHz transmission or a 17Hz shift on a 5GHz transmission (see Pu et al., 2013). With each WiFi sub-band spreading across 20 or 40MHz, this shift is unnoticeable unless some complex signal processing comes to the rescue

important question of determining human intent" (particularly in applications relating to "*physical security, law enforcement, and urban military operations"*)*,* Kim and Ling (2009, 1328) used feature extraction and a trained support vector machine to investigate the *"micro-Doppler signatures"* produced by the moving human body. Their experimental system identified between 7 different types of activities characteristic of their use scenarios: *"running, walking, walking while holding a stick, crawling, boxing while moving forward, boxing while standing in place, and sitting still"* (Ibid) (see figure 5.13).

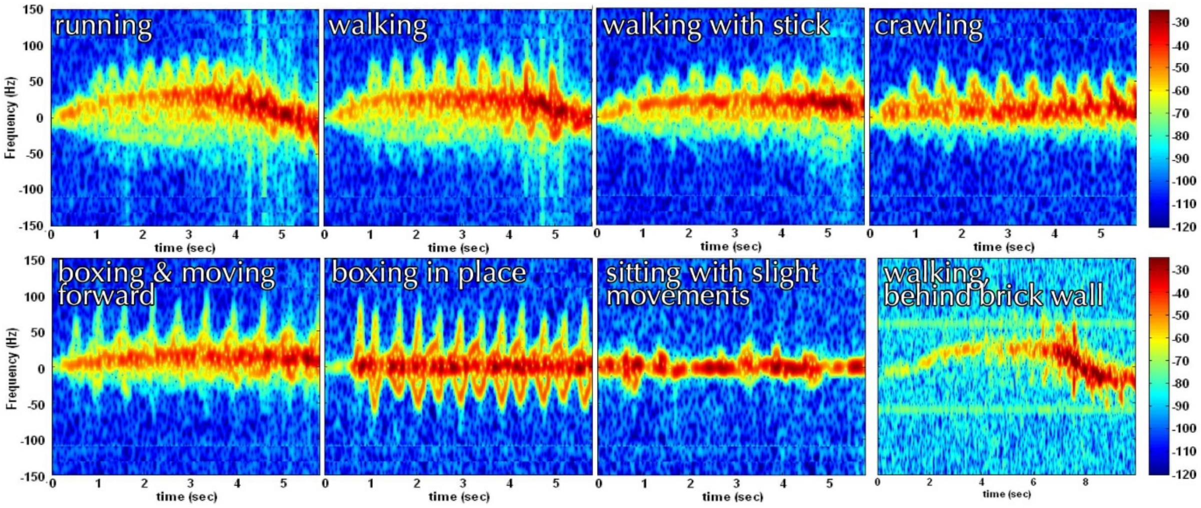

Figure 5.13. Spectrograms of microwave micro-doppler signatures resulting from seven different activities, plus an activity (walking) performed behind a brick wall (images compiled from Kim and Ling, 2009).

More recently, and just before I developed my *Wireless Information Retrieval* system, a new wave of microwave doppler research emerged, bringing together the more security-focused intentions of past research with the more commercially oriented perspective of Ubiquitous Sensing. It involved using SDR to extract and analyze doppler signatures from telecommunication signals, such as WiFi. The following three prototypes use the same tools (the USRP-N210 and WiFi) but illustrate three distinct approaches. *WiSee*, a proof-of-concept developed at the University of Washington by Pu et al. (2013) having applications in home automation, elderly care, and gaming in mind, can identify 9 gestures performed by up to 5 stationary users within indoor spaces and even through walls.[265] The system involves one or more single-antenna SDR transmitters and a receiver combining multiple SDR devices and up to 5 antennas. It operates on the OFDM sub-bands of WiFi transmission and utilizes the Fourier transform, signal segmentation, and a classification algorithm. A related system from

[265] *WiSee* only works with stationary targets because a moving body produces 'louder' shifts than those from a gesturing arm or hand.

the same year, *Wi-Vi,* was developed to sense moving bodies, identify the number and approximate locations of people in a room, and combine sequences of basic full-body gestures into simple messages - all behind walls and closed doors (Adib & Katabi, 2013). Proposed applications include law enforcement, alarm systems and personal security on-the-go, monitoring of children and elderly, emergency response and gaming. Like *WiSee, Wi-Vi* also operates on the OFDM sub-channel of WiFi communication; it deploys 3 small directional MIMO antennas (two to transmit and one to receive) using them in conjunction to eliminate strong reflections produced by static objects, like walls. *Wi-Vi* implements an analog processing technique borrowed from inverse synthetic aperture radar (ISAR); it takes consecutive measurements over time to track the moving microwave beam reflected off of a moving body and to thus treat it as if it were an antenna array. Finally, Tan et. el. (2014) use two SDR devices to implement a passive radar meant to leverage ambient WiFi signals. Their technique is an extension of a form of cross-correlation commonly used in radar systems (cross ambiguity function). Their system detects small full-body movements and hand gestures, with potential applications in Human-Machine interaction, healthcare, and fields interested in *"high accuracy indoor target tracking"* (Ibid, 1).

5.4.4 *Advanced approaches and new trends: Calibration, adaptive beaconing, Channel State Information and more*

Technically, the main challenge for radio-frequency sensing is the complex nature of indoor spaces. The effects of multipath propagation, shadowing, noise from other sources, Non-Line-of-Sight (NLoS) conditions, and moving obstacles are extremely difficult to calculate. Adjustments that account for parameters such as the size of the space, the number of transmitting nodes and their transmission power can help find a computational formula with which, for example, to linearly convert RSSI to distance, thus tackling one of the goals of DFL systems. To achieve this, Golestanian proposes measuring the RSSI between two different beacon pairs at *"sufficiently dissimilar"* distances, and interpolating between the two with a curve that can be used to adjust incoming RSSI measurements (Golestanian 2017, 130). This method reduces overall errors, although it also introduces a few large error peaks.

All in all, *calibration* in its various forms – i.e. tuning a system to the particular characteristics of a space at a given time - is a very useful strategy for improving accuracy. Manual calibration is most common in the literature, partly because it is more straightforward to implement. More complex *adaptive calibration* mechanisms, however, maintain accuracy with much less time and effort spent as the system can recalibrate itself when it detects a change in environmental conditions. In principle, calibration for DFL and DFAR systems could be extended and developed into a more intricate and precise mechanism through the inclusion of more advanced algorithms that model the interactions between electromagnetic waves, space/architecture, and the body. This could include variables that are unpredictable or difficult to calculate, and which most DFL and DFAR systems thus ignore. For instance, fingerprinting typically ignores the interference effects caused by the body of the person carrying a target device, as will be briefly discussed in section 5.6.6.

Adaptive beaconing is another potential strategy for improving localization. This involves adjusting transmitter parameters on the fly and may involve, for instance, continuously changing the rate of transmission according to the type of gesture that the system tries to identify. Still, this is often not an option due to hardware or software limitations. Furthermore, there is another very important element to consider in this particular example: while higher transmission rates should produce better temporal resolution in theory, in practice they may cause package collisions and processing delays, thus resulting in worse and slower performance. Therefore, a balance needs to be struck to find the optimal rate. Another possible adaptive strategy for improving localization involves changing the power of transmission depending on range and frequency. This is called *adaptive transmission power*, or *multirange beaconing*; it is a method suggested by Golestanian (2017) who observed that while estimation accuracy decreases with distance (the further away the less accurate), the rate of decrease is different at different transmission powers. What is of particular interest is that, according to his experiments, low-powered transmissions produce better results in shorter ranges, whereas high power transmissions are better in longer distances (his experiments spanned up to 10 meters). Thus, it can be assumed that adjusting the power according to the distance one wants to measure should improve sensing accuracy.

As has been discussed earlier, another approach for improving RF-sensing involves combining different interfaces and radio frequencies in a hybrid system, e.g. putting together WiFi, with Bluetooth, XBee, RFID, FM, etc. Extending this concept, various researchers have combined RF with non-radio sensing techniques, such as dead-reckoning with accelerometer and gyroscopes, or with computer vision. Overall, sensing becomes more precise with more sensor modalities and more streams of data involved. This happens because by averaging the results of several systems, one can minimize the errors that a particular algorithm, hardware, or frequency introduces. In the artworld, this is the approach taken by Gottfried-Willem Raes in his most recent sensing system, *Holosound* from 2010, which combines ultrasound and microwave radio sensing (see section 3.7.2 and Raes, 2010). In some way, the combination of optical sensors with theremin antennas in Cage's *Variations V* was pointing to that direction as well 45 years earlier (see 3.4.1). Nevertheless, while being more accurate such implementations increase complexity and cost substantially.

One of the most exciting recent developments relating to DFL and DFAR research is the implementation of *Channel State Information* (CSI) on a slowly growing number of WiFi chipsets. CSI provides much more detailed and low-level insights on the Physical layer in 802.11n networks, giving access to information on the signals of separate subcarrier channels. While RSS measures the total power of a WiFi signal by averaging the strengths of all OFDM subcarriers, Channel State Information (CSI) produces separate signal strength and phase shift data for each subcarrier, or at least for a large number of subcarrier groups.[266] Furthermore, wireless cards that support CSI usually have multiple antennas and implement MIMO (Multiple In Multiple Out), giving access to that many subcarriers per antenna.[267] This provides much more granular access to the Physical layer not only in terms of frequency (as shown in figure 5.14), but also in terms of spatial placement. It thus allows comparing results from different subcarrier frequencies and antenna locations, which greatly helps minimize the effects of multipath reception. All this makes CSI particularly powerful for indoors applications, producing much more precise localization and activity recognition that greatly exceeds what simple RSS models are capable of.

Regrettably, CSI has been largely kept as a secret feature by manufacturers of wireless chips. As a result, this type of granular insight was for a long time only available on SDR hardware. Currently, there is a slowly growing number of toolkits providing access to CSI on specific wireless interfaces, significantly extending the sensing potential of low-cost, off-the-shelf WiFi-based systems. One of the first and probably most widely used such toolkit features a modified firmware and a replacement driver for the Intel WiFi Link 5300 wireless card (Halperin et al., 2011).[268] A tool for another WiFi card (Atheros 9390) was first presented a couple years later (Sen et. al, 2013). An open-source version supporting more Atheros

[266] For instance, a toolkit specific to the Intel WiFi Link 5300 wireless card bundles a total of 56 or 114 subcarriers into 30 groups.

[267] For example, it is possible to obtain measurements for 30 different bands at 20-40MHz apart for *each* of the three antennas of the above-mentioned Intel 5300 interface.

[268] For an overview, details, and code, see: https://dhalperi.github.io/linux-80211n-csitool/. Last retrieved 29 December 2022.

models, called *Atheros CSI*, was developed after another couple of years (Xie et al., 2015).[269] Until recently, CSI was limited to a handful of WiFi cards with PCI connections, which made them incompatible with many computers or required the use of a special adaptor. Inevitably, those interfaces became outdated and were replaced by newer ones that were incompatible with these toolkits.

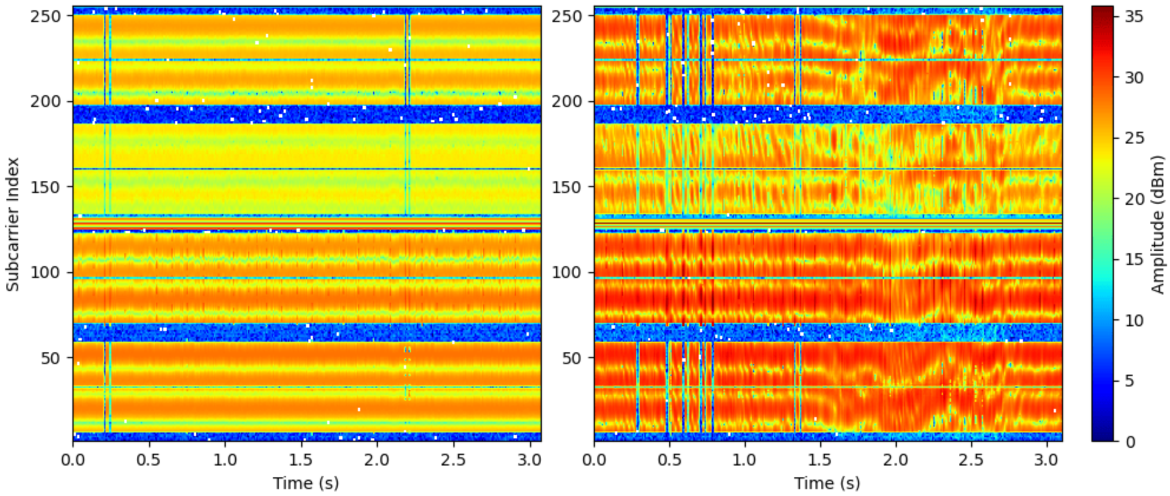

Figure 5.14. Using *Channel State Information* for DFAR: Two images comparing the effects of stillness (left) versus motion (right) on the spectra of 256 OFDM WiFi subcarriers. Note that the unaffected 'silent' subcarrier bands are empty by design to reduce interference (images from Forbes et al., 2020).

In the last few years, a new wave of CSI tools is being developed. Most notably, the Secure Mobile Networking Lab released the *Nexmon CSI Extractor Tool* in 2017*,* a more advanced and flexible toolkit for CSI research that supports a range of Broadcom and Cypress wireless chips found in devices like Nexus smartphones (Schulz et al., 2017 and Gringoli et al., 2019). Recent updates to *nexmon* have given CSI data access on many more devices, such as the Raspberry Pi 3B and 4, many public Linux kernels, and various new WiFi routers. *PicoScenes* is an even more recent software platform for WiFi sensing research that aims to solve what its authors identify as the main problems in the field (Jiang et al., 2021). [270] The platform supports a set of specific wireless interfaces; it features a layered architecture and

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[269] See: http://wands.sg/AtherosCSI/. Last retrieved 29 December 2022.

[270] See: https://ps.zpj.io/, last retrieved 29 December 2022. The 3 fundamental 'barriers' that impede CSI research according to *PicoScenes*, and which the platform addresses are: a) the influence of hardware, which has been largely unknown and thus ignored owing to the fact that hardware details are proprietary. The researchers call this 'CSI distortion'; b) the inadequacy of hardware for sensing, including lack of advanced features, low-level control, and access to additional information on the physical layer beyond CSI; c) and finally, creating measurement software that is flexible and versatile.

includes new and improved drivers, a 'middleware' application for sensing, and plugins for executing specific measurement and analysis tasks. *CSIKit* is another promising new framework developed for CSI-based sensing research that supports a variety of hardware (Forbes et al., 2020 and Forbes, 2021).

CSI has been used in the lab in a number of different experiments, e.g. to track heart rate and respiration rate, gestures, speech, keystrokes, daily activities, subjects falling, even the identity of specific target individuals by their walking patterns. For example, *WiHear* brings to mind Lev Termen's Buran system, although it is based on 'lip reading' rather than reading vibrations (Wang et al., 2014). It locates the mouth of a target and tracks how the signal reflects from the cavity to identify certain vowel and consonant combinations from the patterns of signal interference. The system has been trained to detect 14 syllables and 33 words in total, and has been tested with both USRP SDR devices and the Intel 5300 WiFi card. Another system, *WiKey* from 2015, tracks the keystrokes pressed by a laptop user by analyzing the interference of their fingers on the signal received by the computer's WiFi card (Intel 5300) (Ali et al., 2015). *WiDraw*, also from 2015, is a radio-based hand-writing system; it employs an Atheros AR9590 card with 3 antennas to track the trajectory of a hand in space (Sun et al., 2015). It allows transcribing gestures into curves, lines, and letters by using the Angle-of-Arrival information of a large number of transmitters (up to 25) and has an average margin of error of about 5cm. A system from the following year, *WiHumidity,* uses CSI to measure humidity in indoor spaces with quite promising results (Zhang et al., 2016). *Wi-fire* is an even more accurate fire-detection prototype for indoor spaces (Zhong et al., 2017). Flames that exceed a certain temperature may produce plasma through ionization, thus interacting with WiFi waves. For a 2018 overview of research using CSI for 'behavior recognition' see Wang, Guo et al. (2018). More recent examples closer to standard DFAR research include training a system to recognize between 11 domestic activities, or distinguishing between 5 different movement patterns (Forbes et al., 2020 and Forbes et al., 2021 respectively). The SDR-based doppler systems mentioned above, *WiSee* and *Wi-Vi*, could in principle also be implemented using CSI rather than expensive SDR devices.

Overall, DFL and DFAR are new fields, therefore there is a lot of room for exploration, and many paths for improvement. Wang and Zhou (2015) presented several such paths a few years ago, including: better leveraging of ambient signals; combining more than one frequencies and systems or combining radio with other sensors, as also mentioned above; obtaining a better model of the interference caused by other transmissions on the same frequency; making context-aware systems; optimizing power consumption; finding ideal system configurations – i.e. which combination of transmission power, packet rate and analysis window size is best for each application. More notably, to my opinion, they also stress that beyond solving specific engineering problems there are two other fundamental issues to address as a way forward:

a) Developing a theoretical, mathematical basis for DFAR that transcends one-off experiments. This is perhaps the single largest evolution that would take the technology out of the lab, as the real world is full of unpredictable situations that cannot be experimentally tested against one at a time.

b) Addressing issues of privacy, which I believe to also be fundamentally important. Privacy concerns are addressed much more sparsely and superficially in the ubiquitous sensing field than one would hope. In general, the attitude of the research community is the same as in many other technological fields: scientists and engineers make tools and need not waste time or effort thinking about how these tools will or should be used; that is the job of others. I believe that this attitude of voluntary blindness is irresponsible, and unfortunate for humanity at large. Although the scale is different, the example of Robert Oppenheimer - the scientist known as the father of the atomic bomb – and other scientists and inventors have shown us that science cannot and should not be divided from ethics.

5.4.5 *Real-world applications of DFAR systems*

While the technology still lives almost entirely in the lab, this is beginning to change. A 2013 article on the US Homeland Security website presented a new type of microwave radar technology for use in search-and-rescue operations, adapting a technique initially developed by NASA’s Jet Propulsion Laboratory to track satellites (“Detecting Heartbeats in Rubble”, 2013). The system, *Finding Individuals for Disaster and Emergency Response* or FINDER in short, is an easy to use, 10kg SDR-type apparatus the size of a suitcase, and one of the very first such devices to exit the laboratory (Riggs, 2013 and Rekha et al. 2017).[271] A prototype was successfully deployed in Nepal in 2015, saving 4 men buried under debris (see “DHS and NASA Technology Helps Save Four in Nepal Earthquake Disaster”, 2015 and Pearson, 2015). FINDER employs a variable frequency microwave transmitter that produces a low-power continuous wave with which it can illuminate a large volume under several meters of

[271] The system was developed by the Department of Homeland Security’s Science and Technology Directorate (S&T) and the National Aeronautics Space Administration’s Jet Propulsion Laboratory (JPL).

rubble (Ghaemi & Lux, 2015). A receiver antenna on the device captures the signal as it bounces back. The signal is processed to extract any faint fluctuations caused by breathing and heartbeat: first, it is low-pass filtered and decimated to reduced its sampling rate; it then passes through two parallel bandpass filters to split it into separate breathing and heartbeat bands, which are analyzed independently using a *non-least squares* algorithm. Those bands that satisfy detection criteria are then paired back together to identify up to 5 individual victims.

Figure 5.15. Photo from a demonstration of the *Finding Individuals for Disaster and Emergency Response* (FINDER) DFAR system, with the device and its control interface circled (public domain image, source: dhs.gov).

DFAR technology is expected to make its appearance in the market soon, and many kinds of such systems will likely become available within the next few years. One of the earliest attempts to market such a system was by the company Origin Wireless.[272] In October 2017, they presented a prototype in the Combined Exhibition of Advanced Technologies trade show in Japan, which was awarded for the its technological innovation (Lai, 2017). In May 2018, the company announced a partnership to port their system to ASUS Lyra mesh networking routers (Origin Wireless, 2018 and Lai, 2018). This technology, oddly dubbed 'Time Reversal Machine', aims to be a commercial application of various experiments in

[272] Interestingly, in 2019 the company changed its web address and the way it promotes this system stressing that it is an Artificial Intelligence solution, thus aiming to capitalize on the marketability of AI. Their website has moved from http://www.originwireless.net/ to https://www.originwirelessai.com. Last retrieved 29 December 2022.

ubiquitous sensing research. In 2018, the system was being demoed in controlled conditions and was expected to reach the market a year later - however it does not seem to have achieved this goal. At the time, the system had some latency (about 4 seconds) and produced some false triggers. It uses one transmitter (the 'origin') and multiple receivers ('bots) operating at 5GHz, and can be implemented in protocols supporting mesh networking (802.11a, 802.11n and 802.11ac). It analyzes Channel State Information with a sampling rate between 30-50Hz and uses fingerprinting and Machine Learning. The product is being developed with three applications in mind:

- Indoor positioning and tracking, with a claim for centimeter-level accuracy. This concerns tracking the receivers rather than an interfering body (i.e. device-bound rather than device-free).
- Security of homes or offices, by detecting motion.
- Monitoring residents of assisted living homes by detecting falls and estimating breathing rates of more than one person in temporal windows of one minute.

Among other things, the company's promotional material stresses the ease and low cost of installation, as well as the lack of a camera to address privacy concerns. These are arguments that will likely feature strongly in the promotional campaigns of similar products in the future.

5.4.6 *Evaluation, and some thoughts from an artist's perspective*

From an engineering perspective, radio-frequency sensing systems are typically evaluated according to the following parameters: their accuracy, their reliability, their ease of installation, ease of calibration and use, cost, and hardware availability (Golestanian, 2017).[273] Accuracy is one of the most important benchmarks. It is affected by the specific hardware used, the type of algorithms employed, the number of sensing nodes, the network topology, the environment, the quality of calibration and other such factors. Reliability, meaning how consistent the system is, is likewise largely dependent on the hardware and algorithms used and can be impacted by environmental factors and changes in the placement of nodes, objects and bodies in the sensing field. Certain applications may also have specific requirements. For instance, some applications require more accuracy and reliability than others, e.g. those concerned with safety, in which case SDR would be a preferable solution. Others require lower costs or ease of installation, and thus may use WiFi. Yet others require

[273] While Golestanian's focus is on localization, his criteria is relevant for all types of RF-sensing.

minimal power consumption and may prefer the lighter BLE protocol.

Performance, and specifically gestural sound performance like in my *Hertzian Field* series, is an application with its own set of distinct requirements. There are many differences between what I need on stage as a performer and what scientists and engineers have imagined as possible uses of this technology. While the type of system that I am after and my use scenarios are considerably different than those of DFL and DFAR research, there are still many things to learn from this field. Pouring through ubiquitous sensing literature has been a great inspiration for developing the *Wireless Information Retrieval* sensing system. First and foremost, it showed me that radio-based sensing of un-instrumented bodies was possible without the need of a wireless-enabled device to track. Furthermore, I learned that there are affordable ways for achieving that - such as developing algorithms to analyze WiFI RSSI - which do not require special instrumentation like expensive SDR devices. While it can often be quite tedious to go through the nitty-gritty of these papers, the payoff has been great. This emerging technology is a completely uncharted area in the arts, and even though the goals or usage scenarios between these two spheres (ubiquitous sensing and the arts) do not necessarily match, there is a lot to learn from DFL and DFAR. What I personally find most fascinating and pertinent from pouring through this research is:

- Learning what is physically possible and what can be practically implemented; what is established, what is cutting-edge, and what is likely to come in the near future.
- Studying and being inspired by the variety of systems, applications, and approaches especially those that do not require expensive or hard to access equipment (art-making, after all, is very often an exercise in making more with less). This can lead to discovering new methods as well as new devices. For example, while researching for this thesis, I found out that cheap Doppler radar modules have become available in the market and have been successfully used for RF-sensing (see for example Goel et al., 2015 and Rahman et al., 2015). After buying a few such modules to test, I found them to be full of potential, principally because of their very high temporal resolution that is owed to the fact that they produce a continuous analog signal.[274] While their range seems relatively short, they are very sensitive. Moreover, because of their low price, it is possible to use many of these modules as a sensor array to create a larger sensing area.

[274] This is big advantage in and of itself in audio-centric workflows, as it makes it very easy to incorporate these sensors.

- Seeing what types of features are used and for what purpose. DFL and DFAR research gave me an important head-start during my 2014 ZKM residency helping me quickly implement a few basic statistics analyses and get immediate results – e.g. using RSSI standard deviation to test for motion, and RSSI mean to test for proximity.
- It is also very interesting to read how a number of issues that I have encountered, and solutions that I have subsequently implemented, are being tackled by researchers in this field - from spatial configurations, to different types of calibration or training methods, and more. Being informed about such work by Ubiquitous Sensing research has been a very useful aid in understanding more clearly what I have done for myself, and how it can be improved or fine-tuned.
- Reading how some of these experiments are presented in the media is also rather fascinating, and it can provide useful pointers as to how this new technology is or will be viewed by a broader public. This can also prove useful in finding how to best communicate about my own work to an audience.

Nevertheless, strict DFL and DFAR applications are not what I am most interested in. Part of this is because, as mentioned, the requirements of an RF-sensing system for interactive art are different. I will thus discuss what I consider the most important points on this regard to be - from my personal point of view - and attempt a comparison to the requirements of ubiquitous sensing systems.

Accuracy is important for the type of interactive system I strive towards. Unlike DFL, however, this not in terms of measuring distance but in terms of sensitivity, both spatial and temporal. Meaning, it is essential that the system can identify and react to minuscule movements of the body – at least in certain areas within the field - and that it can do so at a high enough sampling rate and a low enough latency to feel immediate for both performer and audience. In this regard, the current iteration of my system used in *Hertzian Field #2* and *#3* is much more advanced than that used in *Hertzian Field #1* – although there is always room for further development and refinement. It is worth noting that gradation in sensitivity depending on location is a feature, not a problem as far as I am concerned. The system will inevitably be more sensitive in some areas than others, and it is up to the designer of a performance or installation to create a hertzian topology that makes sense for each particular use. While in other applications, e.g. security, this gradation might pose a problem, I believe it is a fruitful parameter to explore in an art context, as it is an inherent element of the nature of the system and of the electromagnetic fields that constitute it.

In terms of *temporal resolution,* a radio-sensing system for interactive art needs to be able to operate in real-time. This is not the case for a great deal of systems in the bibliography. DFL methods that are too slow for activity recognition, like tomographic imaging, are also far from ideal for real-time interaction. RSSI systems are usually a bit slow, however it is possible to increase the sampling rate, especially on an active system where one has access to the settings of the transmitters. Modifying these settings on the Access Points I used in *Hertzian Field #2* and *#3* made a great impact on these system's performativity. Continuous systems, such as those based on SDR or Doppler radar, should excel in this respect and I would expect them to provide superior results in terms of immediacy of response and ability to capture quick or small motions.

In terms of *spatial resolution,* DFL is not fine-grained enough for gestural control, especially when based on RSSI. Generally, reaching sub-meter accuracy is considered a good result in the literature, even in spaces smaller than the sensing area used in *Hertzian Field #2*.[275] This is far too coarse for expressive continuous control of sound – although it could be enough in different settings, for example in installations that take over a larger space or even a whole building, or for higher-level controls, such as triggering a new 'scene' or process during a piece.

In terms of *hardware*, SDR is undoubtedly the most powerful and accurate tool for RF-sensing, as it provides full access to the transmission and reception of continuous radio signals. With SDR one can emulate any communication protocol but also radar signals, or even create one's own protocol and experiment with different types of signals. As an artist, this feels like an extremely exciting and inspiring possibility! The most important problem with SDR systems is a practical one: their cost is generally prohibitive for an independent artist, especially when several nodes are required. CSI is a very promising and much more cost-effective new development. Recent research claims to have achieved sub-wavelength accuracy, which should be indicative of much increased overall performance even for non-DFL uses. Nevertheless, CSI is not as widely available yet and only works with specific hardware and platforms. Thankfully, this is beginning to change in the last years.

Reliability and *consistency* are also very important in performance. Of course, there is always a certain degree of unpredictability involved when putting a radio-sensing system on stage as the conditions of a performance are never the same as those own encounters during

[275] For example, Sigg et al. (2015) report that *"Localisation error achieved could be kept below 0.5 meters in a 3m3m square area",* which feels much too large for a performative setting.

rehearsals, setup, or even soundcheck. For instance, the presence of audience bodies changes the multipath propagation characteristics of a space (these changes can even be quite drastic, from my experience). Temperature and humidity can also change, because of factors such as the public's presence and/or the use of traditional light sources. While I have always welcomed unpredictability as a performer, there needs to be a baseline of trust that the system will behave within a bandwidth of expectations, and that if there are unforeseen changes or challenges in the environment it will respond to them in a predictable way, allowing me to 'calibrate' my own performative actions and expectations while on stage. Consistency was one of the problems that I had to struggle against with my system during its development, as I would compose something only for it to sound and feel very different the next day. After many investigations and observations, I found that this was typically due to antennas having moved slightly, or to changes in temperature or humidity. In the current state of the system (since *Hertzian Field #2*), consistency has greatly improved due to a much more reliable and fast calibration method that even allows me to tune the system just before going on stage and after the audience has taken their places.

The lack of reliability and consistency when placed in real-life spaces and dealing with real-world situations has likely been one of the bottlenecks preventing DFL and DFAR technology to come out of the lab. When getting excited about a brand-new technology in development one should never forget that there is always a gap between what the vision for a future product is, and what the technology can currently achieve. During the early stages of in-lab experimentation, conditions need to be under tight control; that seems to certainly be the case for the majority of current DFL and DFAR research. This involves choices on where and when the experiments happen, choices of personnel – i.e. who is the target subject and how do they act when they are being tracked – and convenient assumptions which may lead to downplaying or disregarding factors that the system does not properly account for. For example, most experiments happen in a University lab or an area over which the researchers have control. As mentioned earlier, some of these experiments even happen at night when nobody is around in nearby offices or corridors to avoid noise and interference. This is, of course, wise when one tries to perform an experiment, but it is far removed from real life situations, like those that an art performance system has to overcome. Such a system needs to be reliable in all sorts of spaces, large and small, warm and cold, with varying amounts of public that may be close or far, may sit or be moving, etc. Having said that, I anticipate that these issues will be soon solved in the Ubiquitous Sensing field and that systems ready for the real world will soon be available.

Being able to deal with a variety of conditions is related to another evaluation point for an artistic use of such a system: ease of installation, ease of calibration, and ease of use. More often than not, the amount of time required to setup and calibrate a DFL or DFAR system is quite long. This is typically not possible in performance, as the time available for setting up and soundchecking is limited, especially when playing in festivals where many performances are hosted in the same space or stage. Fingerprinting, for example, is a strategy whose accuracy would suffer considerably in such a setting: Besides the lack of enough time to create a detailed map, once the audience enters the environmental conditions will inevitably change, thus making the system far less reliable or even unusable.

One thing that I noticed while reading the literature, and which surprised me a little, is that in some respects many of the experiments in Ubiquitous Sensing seem to be a bit like staged performances. The main difference being that the audience is not present during the experiment, but reads about it later on.[276] Besides occurring in curated or staged conditions, there are often mentions or hints that some degree of - conscious or subconscious - *performing for the system* is involved, with the activities measured often being entirely scripted, coached, or simply subconsciously influenced by own's knowledge of the system's inner workings. When reading a paper, I often end up with several questions that remain unanswered, such as: Who are the test subjects? Do they know how the system works and what is being measured? Have they been instructed on how to behave or what to do? On the surface, these may seem like mere details, but I believe they have a significant effect on the quality of the tests and of the results reported. All these are certainly questions that, as an artist working with interactive systems, I spend a significant time thinking about in my effort to create a seamless and self-explanatory relationship between performer or interacting audiences and the systems that I develop.

In some cases, coaching is an implied part of the experiment. For example, a number of papers mention limiting the subject's speed of movement to what the system can track. In DFAR, instructions are often quite explicit, such as repeating the set of gestures that the system understands at different but specific locations to measure its accuracy and

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[276] As an outsider to the field I find this fact to be heavily understated. It is often only implied or requires one to read between the lines. Perhaps this is because most readers of these paper are the authors' peers, so some things can be left unsaid as they are shared knowledge? Meaning, something like: 'I guided my subjects to walk up straight in a manner that the system could identify them better' may be more evident to the typical reader these articles are addressed to, even if not stated..

reliability.[277] While this may be a good way to test some things, it does little to inform the reader about other important factors, such as how easy it is for false positives to be recognized when one moves in a more ordinary (i.e. non-scripted) fashion.

Furthermore, when an experiment/paper attempts to emulate how the system would perform in real life situations, it is quite important to consider who the subjects testing the system are. This is most typically not mentioned in papers, suggesting that one could readily assume that some subjects may be involved in the project, or at least are familiar with some of its aspects. This means that they may know how the system works, what it is looking for, how it performs better, what confuses it, as well as what the experiment is about – at least to a certain extent. The actions of someone who does not know how a sensing system works, and even more the actions of someone who is not even aware that they are interacting with such a system, are radically different than those of people who have that knowledge. It would be fair to presume that the most unreliable results are from experiments in which the researchers themselves are the subjects. My own personal experience as a developer of interactive systems has shown me that, even when I try to act as naturally as possible and not perform for the system, it can be extremely hard to condition my mind and body to forget the actions that they have repeatedly performed during the development process, when I try to get the system to actually work the way it is supposed to. To return to Pickering, it is unrealistic to expect that the human comes out of the 'dance of agency' of the development process without being to a certain extent incurably conditioned.

This kind of lab testing can easily lead to mistaken – or sometimes convenient - assumptions that are taken as axioms. For instance, the accuracy of Device-Based Localization is affected by the body of the user carrying the device. The amount of interference to the system is highly dependent on the body's position and orientation between transmitter (the AP) and receiver (the device). However, a common premise in the literature is that the user is holding their phone in front of them, or that they have it in a front pocket. If a system is calibrated in this manner but the assumption is not met, the incoming RSSI data will be warped, and so will the results. Li et. al. (2013), criticized fingerprinting systems in particular, like RADAR, for not accounting for such effects of the body. In their paper, they proposed an experimental method to deduce the effects of the user's orientation and position in relation to the transmitting and receiving devices, in order to estimate the expected interference and

[277] As one example, in Sigg et al. (2013) each of the tracked activities were repeated by 3 subjects for 60 seconds and at 5 locations at different distances from two sensing nodes. Experiments happened "after hours" at a corridor of their institute.

subsequently compensate for it in their localization algorithm.[278] Still, while such methods try to take into account the position of the body a bit more than usual, the representation remains rather crude. Overall, the effects of the body's orientation are rarely mentioned in DFL and DFAR, making me wonder if test subjects are generally instructed to move in specific ways. When these effects are mentioned, the systems rarely go beyond trying to find differences between placing a device in the front, the back, or the side of the body.

This brings up yet another question: beyond position and orientation what are the effects of different postures on transmission? What is the effect of putting an arm, two arms, a leg or a twisted torso close to a Line-of-Sight? The body is not homogenous, so results will differ greatly depending on the body's configuration in relation to the electromagnetic field. This, in fact, is one of the most interesting elements in interacting with the *Hertzian Field* environments in my works, as slight changes produce noticeable –sometimes even explosive – audible effects.

Naturally, building a complete computational model of all possible interactions between body, space, and field would be a massive endeavor – and it would certainly not be real-time if relying on ordinary contemporary computing equipment. Practically, one can only hope to push the boundaries of approximation and to make increasingly better models. In DFL and DFAR applications creating a simplified model of this interaction is the first step, for example through the use of feature extraction. Teaching the machine to make sense of the input is a following step. For example, in DFAR a Machine Learning or estimation algorithm is fed feature extraction data to decide which of the very few states or actions it comprehends is actually happening within the field. My approach is fundamentally different: Why have the machine try to make sense of what is happening when performer and audience are actually there in the flesh, with our eyes and ears open? My system skips this second step and instead generates a real-time audio feed from the data to model this complex interaction and transform it into immersive sound. The audience experiences this data directly as a stream of sound waves - a dynamic soundscape that envelopes them just like the radio field - while also being able to see the actions that cause it, or while performing these actions themselves in the case of my interactive installations. Having a sensory experience of the radio field makes it

[278] Li et al. (2013) deployed a hybrid system, using multiple video cameras and tracking the RSSI of a pair or more of wireless APs. When a user stood between these APs, they observed an attenuation of about 15-20dB for the AP on their back, coupled by an amplification of about 3-5dB to the AP the user faced. These measurements are about half of what I have observed in my *Hertzian Field* system for both attenuation and amplification in similar scenarios, a proportional difference likely attributed to different distances, antennas, and general configuration of the system.

almost palpable, thus enabling the brain to develop a much deeper understanding of its nature. I believe this is a much more informative and rewarding experience (at least within an art context) and it certainly makes for a more fascinating interaction with the system. The difference in resolution, subtlety and immersion achieved with this approach is immense when compared to what could be achieved with a state machine - like DFAR, or like G.W. Raes' gesture recognition systems that are rather similar to DFAR conceptually. One could say that the distance in expressivity is akin to that between Leon Theremin's Radio Watchman and his Etherophone: an alarm versus an instrument.

To summarize, localization and gesture recognition are both certainly interesting for the type of radio-sensing system for interactive art that I aim towards. However, they are not a goal in and of themselves. The most fundamental difference of my approach is conceptual. DFL and DFAR RF-sensing systems are developed as yet another sensing variant that - in most cases – could replace radio and microwaves by a different sensing mechanism. These waves are most typically treated as a proxy for vision. *'Seeing through walls'* is a very common stated goal of such systems - and a catchy phrase for attracting media in part because of its voyeuristic connotations. As we have seen earlier, other sensing modalities are also being emulated by radio: e.g. *WiHear* for hearing, *Wi-fire* for temperature, and *Wi-humidity* for humidity. All in all, it is good to keep in mind that while these systems use radio/microwaves, they are not actually *about* radio/microwaves. The hertzian is the *medium*, not the *message*. In its essence, one could maintain that the goal of ubiquitous sensing is to automate a process of tracking or recognition that an un-instrumented human could also perform – such as identifying the presence, location, or motion of a body in cartesian space, or recognizing a specific activity, gesture, or situation. These systems thus represent a desire for having a machine tell us something that a human could also observe with one's own senses if they were present. When it comes to the body's interaction with electromagnetic waves, these types of reductionist representations are much less expressive than what radio sensing technology can actually afford. To be fair, the field is in its experimental stage and still in the lab, so it makes sense that its scope is limited and focused on concrete scenarios where success or failure can be easily measured and evaluated, thus leading to stepwise progress. In addition, the unstated subtext is that most usage scenarios investigated are relevant for potential funders: the military, police, search-and-rescue organizations, or commercial entities. This has more to do with the context of contemporary scientific research than anything else.

As opposed to all this, my personal primary interest is the investigation of the *nature* of the hertzian/electromagnetic world itself, and discovering its potential for creating artistic experiences. I am interested in *interacting with* what I cannot see or sense, with a world of invisible energies that surrounds me, but to which I am completely oblivious without the help of machines. I am interested in *discovering* something I do not know through my system, rather than having it recognize something that my eyes could also verify. I am interested in exploring electromagnetic space in a *phenomenological* manner, discovering its nature and how it interacts with my body, and at the same time I am interested in transducing it to a *lived experience* for the senses. The interface for exploring this world is space and movement of the human body, and the primary medium for experiencing it is sound. Furthermore, I am particularly intrigued by the fact that this obscure kind of sensing is possible using everyday devices and by (ab)using information that is openly transmitted and available to everyone. I am also very intrigued by how few people are aware of this possibility, and by the expectation that this could be a widespread tool of control and surveillance in the future.

In terms of technique and use of data, my approach lies somewhere in between DFL and DFAR. I map multiple real-time streams of analysis features to synthesis parameters so as to create a dense web of connections between space, body, and sound. Like DFL, this requires a continuous flow of tracking data – although the use is not for localization but for gestural control. And like DFAR, my system makes extensive use of feature extraction to find patterns in the signal. However, this is not because this enables the computer to tell me how I move, where I am in space, or verify that I performed a certain action – all things that advanced computer vision and motion capture systems can in most cases do better than radio sensing at the moment. Rather, it is the interaction between body and field that I find most exciting and full of artistic potential, as it allows *imagining* how the invisible energies of radio fields are sculpting space and are sculpted by space and the body. Feature extraction is thus particularly interesting to me because it allows following the body, or more precisely because it follows the effects of the body on the radioscape around it.

What makes the *Hertzian Field* system so expressive and exciting to interact with is the complexity of the relationships between transmission, body, and space, and the ways in which these relationships can be audibly manipulated simply by moving. My system explores gentle shifts, orientations, postures, motion etc. of the body in relation to the field. The angle between transmitter, receiver and the body, the properties of those parts of the body that are within the field, how much of the signal is absorbed, how much is reflected by them, and what is the phase shift from these reflections (which results in amplifying or attenuating the signal) – these are all expressive details that become part of the exploration and the performative language that the system itself suggests through its material agency.

Nonetheless, while intuitive hands-on investigation can produce very gratifying results, it is also important to better understand the environment of transmission and the complex physical interactions that take place. Similarly to how a professional musician ought to know the mechanics and acoustics of their instrument inside-out, so should the performer of hertzian fields know about the mechanics and 'hertzian acoustics' of the elements involved. After many experiments and hands-on investigations, writing this thesis gave me the opportunity to take a deeper look into how exactly electromagnetic energy propagates in small spaces as well as its relationship with the body. To this extent, the following two sections will turn first towards understanding propagation and reflection in these spaces, and then to biology, health, and medical application research, as these fields provide a much more detailed approach on the interactions between body and electromagnetic fields than ubiquitous sensing research.

5.5 PROPAGATION AND REFLECTION REDUX

5.5.1 *Field structures of propagation*

As has been discussed (in section 1.2), electromagnetic energy radiates away from a transmitting antenna in 3-dimensions. The wavefield take the form of a constantly expanding 3-dimensional shape as it propagates in space (in the theoretical case of a purely omnidirectional antenna, this shape is a sphere). As the energy radiates away from the antenna it forms three different field structures (figure 5.16):

a) *Reactive near-field*: This region is the one closest to the antenna; its area extends from the antenna up to a distance of:

$$0.62 \times \sqrt{\frac{D^3}{\lambda}}$$

where D is the largest dimension of the antenna and λ is the radiation wavelength (Vander Vorst et al., 2006, 28). This region is characterized as *reactive* due to the predominance of *reactive power density*.[279]

[279] *Power density* measures how much power is delivered per volume. *Passive* or *complex* power does not only flow from source to load (like *active* or *actual power),* but also reciprocally from load to source.

In the *near-field,* the relationship of the electric and magnetic field is not uniform; the two fields are decoupled and their strengths rapidly decrease with distance, but at different rates (Hand, 2008). The body's interference on signals is largest here. Biological effects in this region have been widely put under scrutiny for various applications, such as to determine potential health hazards from mobile phones.

b) *Radiating near-field* or *Fresnel region*: This region typically follows the reactive near-field, unless the size of the antenna is much smaller than that of the transmitted signal's wavelength. When it exists, this region's reach ends at:

$$2\frac{D^3}{\lambda}$$

c) *Far-field,* or *Fraunhofer region*: Finally, the electromagnetic field forms the *far-field*, in which electric and magnetic fields are transverse. This is the region explained by classical electrodynamics and with which most radio and microwave applications are concerned.

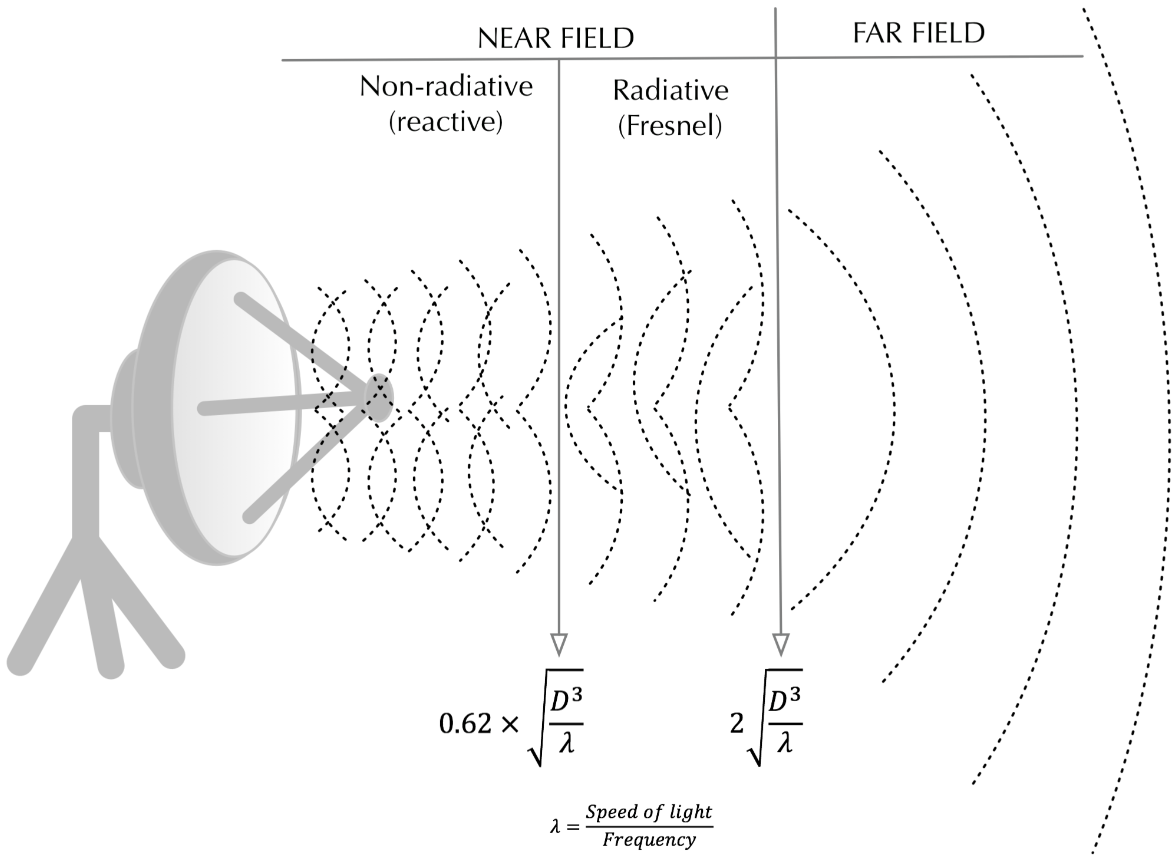

Figure 5.16. A simplified visualization of the different field structures formed by an electromagnetic field as it radiates away from an antenna.

5.5.2 *Understanding reflection through Fresnel Zones*

A transmitted radio or microwave signal will travel in the shortest possible path when there are no obstacles between the antennas of the transmitter and receiver. This direct link of radiating energy between the two nodes is called the Line-of-Sight (LoS) path. The LoS contains only a portion of the overall energy of transmission, but from the point of view of the receiver this is the path where most of the signal arrives from - provided the LoS is not blocked by an interfering object.

Keeping in mind, however, that the transmitted signal propagates as a 3-dimensional wave, a number of questions arise: How big is this 'line' of the LoS, and what exactly is its shape and volume? How far away from the LoS does an object need to be located to not block or absorb its energy? Furthermore, given that the transmission's 3-dimensional propagation produces multiple reflections in indoor spaces (*multipath propagation*), how do these reflections interfere with the reception of an LoS signal and how does a reflecting object's location influence their effect? These questions can be answered through the concept of *Fresnel Zones*, named after French physicist Augustin-Jean Fresnel who formulated it about 200 years ago while researching light defraction and interference. To understand this concept, it is necessary to first briefly discuss reflection.

When an electromagnetic signal encounters an obstacle (e.g. a human body) whose impedance is different than that of the medium it has been traveling in (e.g. air), part of it will be transmitted into the object (i.e. refracted) and another part will be reflected. Part of the reflected signal will bounce towards the antenna of the receiver appearing as a duplicate, or *echo*, of the original signal (figure 5.17). Calculating all reflections occurring in physical space would be extremely cumbersome: Every reflection becomes a new wavefront whose phase, amplitude, and vector depend on a number of factors, such as the frequency, polarization and incidence angle of the original wave, and the dielectric properties of the reflecting medium.

The phase relationship between the direct LoS signal and a coincident reflection is important, as it determines whether they will be added together - thus amplifying the signal - or whether they will cancel each other, thus attenuating it. As with all waves, maximum amplification occurs when the reflection arrives in the same phase as the original, and maximum attenuation when it arrives at 180° difference. Theoretically, the maximum amplification per reflection path is 6dB (i.e. twice the amplitude of the original signal), but in practice it is much less due to some absorption always occurring by the reflecting material. Nonetheless, total amplification at a given point in space may exceed that decibel level when more reflections contribute positively to the signal - something possible in indoor spaces.

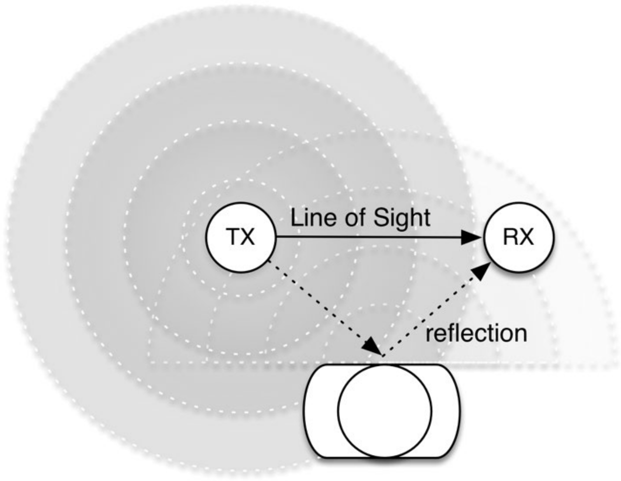

Figure 5.17. Simplified visualization demonstrating how the reflection of an electromagnetic wave radiating from a transmitter (Tx) to a receiver (Rx) produces multiple reception paths.

The angle of phase shift depends on two factors: First, phase shifts may be introduced at the reflection boundary. This is mostly a result of the relationship between the wavefront's polarization (i.e. the direction of the electric field) and the incidence angle between transmitter and reflector. The orientation of polarization depends on the orientation of the antenna, e.g. vertically placed antennas produce vertically polarized waves. Horizontally polarized waves are shifted by 180° or more, while vertically polarized waves keep their phase, provided the incidence angle is less than 30°. The second critical factor has to do with the additional distance that the reflected signal has to travel. If this distance equals a full wavelength, then the reflection will be in-phase with the original. If it equals half the wavelength it will be 180° out of phase, if a quarter wavelength it will shift 90°, and so forth.

The *Fresnel Zone* model provides a way to partition the space between a transmitter and a receiver into zones whose reflections produce alternating in-phase and out of-phase reflections. It allows estimating the influence of obstacles by calculating the amplitude and phase of a reflected signal depending on: a) its frequency, and b) the reflector's location relative to a transmitter and receiver pair.

The first zone in this model coincides with the LoS path (see figure 5.18). The LoS thus is not a literal line but a 3-dimensional cylindrical ellipsoid with the two antennas as its focal points on either end. The shape is often described as a cigar, sausage, zeppelin, or spacecraft.

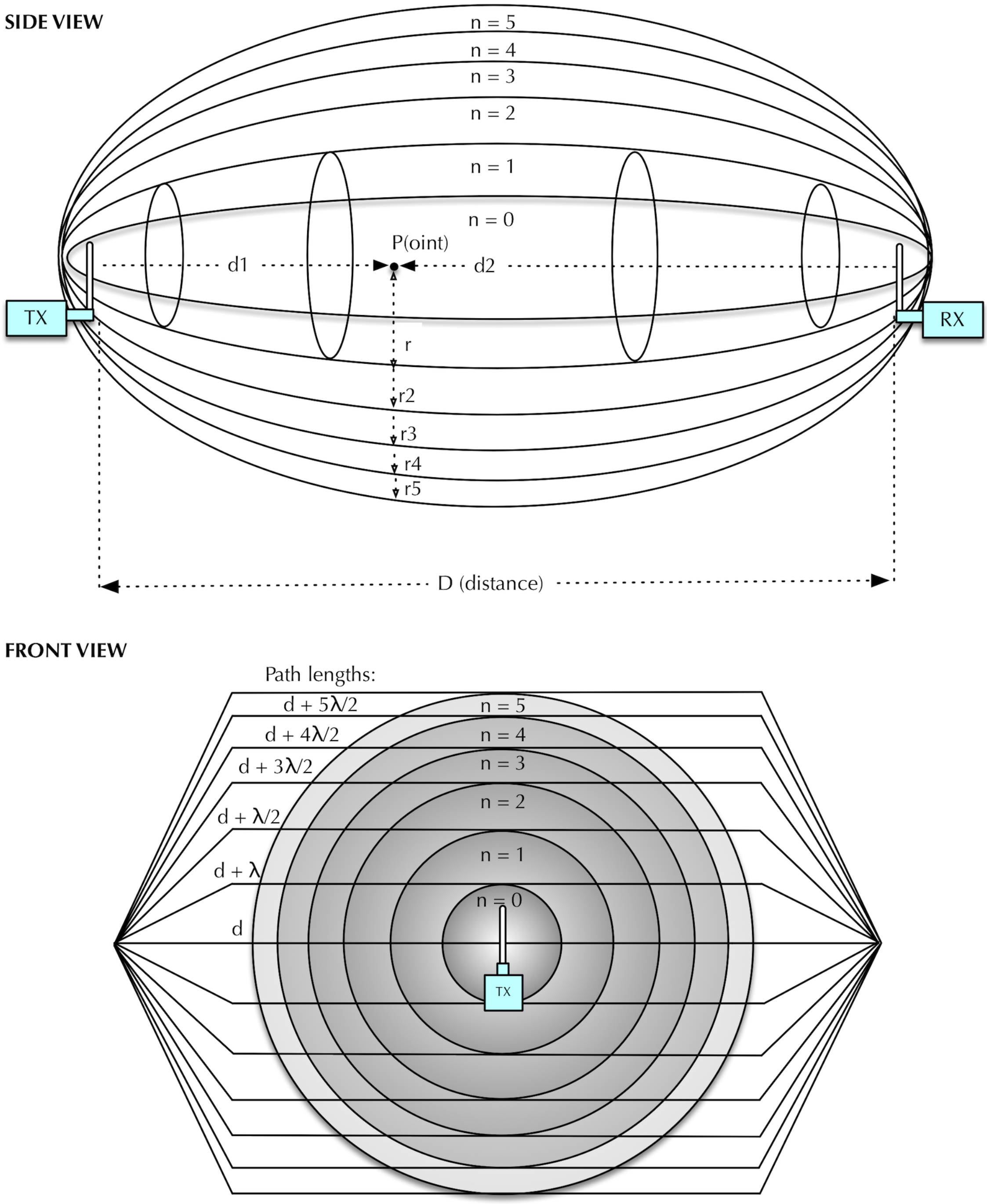

Figure 5.18. Simplified graphs showing 2-dimensional cross-sections (side and frontal view) of the first six Fresnel zones of a radiating radio/microwave signal.

The cross-section of this zone is a circle whose radius can be calculated with the equation:

$$R\ (meters) = 17.312 \times \sqrt{\frac{D\ (kilometers)}{4 \times f\ (GigaHertz)}}$$

Where *R* is the radius, *D* is the overall distance, and f is the wave frequency.

Each consecutive zone begins where the previous ends. This means that beyond the 1st zone the cross section of all other zones is a doughnut-like shape (a torus) that excludes the area of all previous zones. The equation for calculating a zone's radius at any given point between a transmitter and receiver is the following:

$$Rn = \sqrt{\frac{n\lambda d_1 d_2}{d_1 + d_2}}$$

Error! Bookmark not defined.where *Rn* is the radius of the *nth* Fresnel zone in meters, *n* is the index of that zone, *d1* and *d2* are the distances of the point from each of the two nodes respectively, and λ is the wavelength in meters.

The radius of the Fresnel zone depends on the frequency of the signal, with smaller wavelengths producing smaller zones. This means that higher frequency transmissions require less clearance from objects for an unobstructed first zone, and lower frequencies more clearance. At 900MHz, for example, it is very hard to create an obstacle-free first zone for long-range transmission, as that zone is fairly large (e.g. for a 1km transmission the radius is about 9.125m).

Theoretically, an infinite number of Fresnel zones exist. Practically, however, only the first few zones exert a considerable effect on transmission. The innermost zone (LoS) contains over 70% of the overall energy transferred between transmitter and receiver. The rest is transferred in the following 7 to 11 zones (Wang et al., 2016). This means that reflections within the inner zones have a larger effect and, consequently, that those inner zones are more sensitive to interference, making it easier to detect objects present within them than in outer ones.

The presence of an object within the first zone after the LoS will interfere with the transmission, even if the LoS remains clear. If it is near the further boundaries of this zone it will reflect the signal at an opposite phase (180° shift) because the wave has to transverse an additional half wavelength. This will be added to any phase shift introduced at the reflection point. If the reflecting objects moves towards the LoS, the additional distance that the reflection has to travel is reduced, and so is the amount of phase shift. Further outwards, in the boundary between second and third zone, the reflected signal will have to transverse yet another half wavelength, causing a shift of 360°. Therefore, in each consecutive Fresnel zone an additional phase shift between 0-180° occurs – with the exact angle of the shift depending on where in the zone the reflecting object is found. An object moving across zones will thus cause a sinusoidal pattern of amplification and attenuation of the signal.

Fresnel Zones are very frequently used in the design of long-range outdoors transmissions to estimate the quality of an LoS radio link, and to find the best position and height for the transmitter and receiver antennas.[280] Concerns most frequently involve static objects, such as mountains and buildings, though calculations may also include the more dynamic effects of traffic. Conversely, Fresnel Zones are rarely taken into account in the context of indoor transmission, as very frequently there is no LoS and multipath propagation is the norm. This is also the case for DFAR and DFL techniques. Countering this trend, Wang et al. (2016) introduced a Fresnel model for the propagation of WiFi waves in indoor spaces, aiming to understand the physical limitations of sensing with WiFi and to develop a theory and a generalization on the principles behind such systems.[281] The authors postulated how a moving object affects radio waves in the different Fresnel Zones and experimentally verified the model using RSS measurements. Furthermore, they applied the model to a CSI-based system using 30 subcarriers at different frequencies. This permitted them to significantly increase the sensing range (by harnessing the overlap of Fresnel zones at different frequencies), as well as to reach a resolution finer than the wavelength of transmission.

Reading this paper over two years after I began developing the *Hertzian Field* series was somewhat of a revelation. This model is particularly helpful in understanding the relationship between body and field in space, and matched well with my personal practical experience of how my body interacts with the system at different areas, providing an explanation of why certain *sensing hotspots* can be found in space – corresponding to nodes and antinodes - and where they can be located. I have thus found it to be a rather effective tool for mentally mapping space when performing these works.

5.6 THE BODY DIELECTRIC (OR: WHY DOES IT WORK?)

"A biological body is an inhomogeneous lossy dielectric material."
(Vander Vorst et. al, 2006, 93)

5.6.1 *The body as a dielectric space: On-body and in-body localization*

Through the years, radio-frequency sensing has been 'zooming' both outwards and inwards at

[280] The general guideline in these cases is that the first zone should ideally be 80% free, regardless of whether there is a clear LoS path, and at least 60% free to avoid considerable signal loss.
[281] The context of their research was assisted living, and in particular monitoring changes in the pattern of breathing regardless of the orientation and location of the target person (too rapid, too slow, or absent respiration being indicators of problems that may require medical assistance).

the same time. On one hand, we probe the universe with radio and microwaves, reaching further and further away from our planet into the vastness of outer space. On the other hand, we point such signals towards smaller and smaller areas in an attempt to trace increasingly more minuscule motions: Starting from the large-scale of the outdoors, such as with Radar and GPS, the hertzian medium has been transported to the smaller confines of indoor spaces, as we saw with DFL and DFAR. Yet, indoors architecture is not the smallest space in which RF-localization has been applied to: So-called *Body Area Networks* (BANs) are being deployed to investigate the inner world of the human body itself. Whenever the scale of application of such a technology changes so drastically, a new set of challenges appears that need to be solved. The passage from outdoors to indoors raised the complex problems of indoor multipath propagation. BANs brought forth questions on how to calculate the even more complex properties of the body as a radio propagation medium (Dove, 2014).

BANs are primarily used in health care and medicine, for example to monitor bodily functions of older people. Such applications utilize networks of interconnected sensing and computing devices. These networks are called *off-body* when sensor data is sent to a nearby device, *on-body* when all devices are placed on the body, and *in-body*, when a sensor is placed inside the body, as in the case of endoscopy (Ibid). Medical Wireless BANs were originally developed to operate on unlicensed bands, but because of the rapid increase of consumer devices occupying these frequencies there is increasing pressure to shift into alternative transmission modalities, such as using Ultra-Wideband (UWB) transmission (Januszkiewicz, 2014).

To achieve better results with this BANs it is important to know where exactly a device is located; this is where localization techniques come into play. Localization inside or around the body uses the same set of techniques as standard DFL: Time-of-Arrival, Angle-of-Arrival, Received Signal Strength, fingerprinting, machine learning, estimation algorithms, etc. (Dove, 2014). However, the problem is more complex than deducing the location of a device in free space, as the human body is always present, acting as a source of interference or even as the transmission interface. This requires modeling a more complicated transmission channel than the air interface: the intricately configured human body. Knowing how the body interacts with electromagnetic waves is important for the development of such EM-based systems. This is hard to measure and can change drastically depending on the technology and frequency employed, the properties of the specific body, its orientation, which parts of it interact with the EM field, and other factors (Mobashsher & Abbosh, 2015).

A widespread solution to this problem is to develop numerical models that can be used to simulate these effects of the body. This has led to an increasing number of experiments on the body's influence on wireless signals in different configurations. Modeling can be an extremely useful tool in the design of effective mobile communication systems as well as BAN, DFL and DFAR applications, helping find the right combinations of frequency, transmission power, distance and antenna types (Manfredi et al., 2015). It is also pivotal for the advancement of medical technologies such as magnetic resonance imaging, microwave radiometry, and hyperthermia (a cancer treatment that targets cancerous tissue with heat) (Hand, 2008).

5.6.2 *Understanding and modeling the interaction between body and electromagnetic fields*

One of the challenges of working with electromagnetic systems that involve the body is that measuring the body's effects on the transmission is quite a challenge (Mobashsher and Abbosh, 2015). When a living organism is exposed to an electromagnetic field, its internal fields interact with the externally supplied energy. The effects of this interaction on both organism and external field depend on the transmission frequency and power density, on the distance, incidence angle and polarization of the field, on the volume, shape, orientation and posture of the body, as well as on the properties of the dielectric fields inside it (Vander Vorst et. el., 2006). Living organisms compensate for the effects of the interaction either *physiologically,* or *pathologically* (in the latter case the interaction destabilizes the organism's healthy state). The type and extent of any biological effect is a result of numerous factors at play, such as the ways in which the electromagnetic waves penetrate the organism and propagate in it, the primary interactions between the organism's tissue and the waves, and any secondary effects caused by this interaction. This means that any effect is a result of the field's action and the living tissue's reaction to it (Ibid).

The brunt of research for determining the nature of this interaction is primarily directed towards understanding and addressing the possible health implications of various wireless technologies (Wu, 2006). The goal in this case is to find how electromagnetic fields affect an organism. Nonetheless, these findings can also be looked at from the opposite point of view, i.e. how does a body affect an electromagnetic field? This can be decidedly revealing for understanding not only how sensing systems work, like the *Wireless Information Retrieval* technique I created for the *Hertzian Field* series, but also how to perform with them.

In the literature, the relationship between electromagnetism and the body is viewed from these two main perspectives: investigating the effect of the body on radio waves / microwaves, and investigating the effect of radio waves / microwaves on the body. This relationship is complex and frequency-dependent. As it is not ethical to perform most of the required tests on living human beings, a variety of models of the body have been used to understand the interaction between electromagnetic fields outside the body and those within it. This is not an easy task, owing to the body's complex shape, its intricate tissue configuration, and the many anatomical variations in every person (Vander Vorst et al., 2006). Moreover, the dielectric properties of tissue change with temperature - particularly because heat affects the concentration of water - as well as with age, as aging has been proven to alter the organic composition of tissue and its water content (Mobashsher and Abbosh, 2015). Therefore, modeling can only establish simplified approximations with the amount of precision and detail depending on the needs of the particular application under scrutiny.

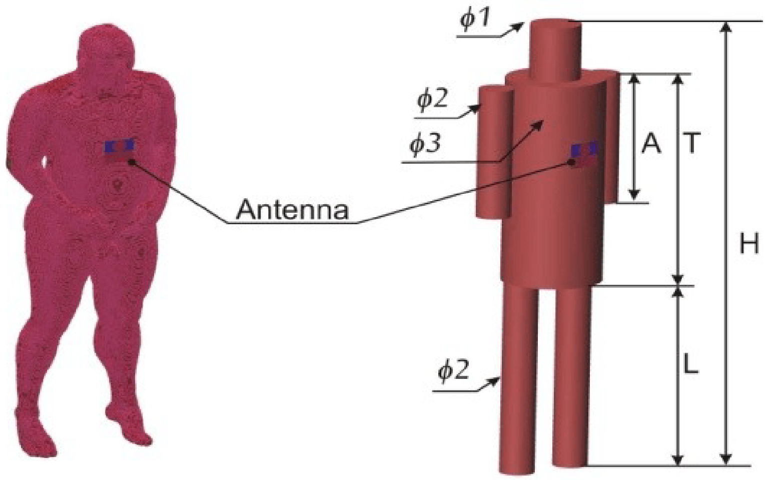

Figure 5.19. Two models used to investigate the interaction of the human body with Body Area Networks. Left: The *NMR Hershey* human body model, available with the Remcom XFdtd 3D Electromagnetic Simulation Software.[282] Right: A significantly simplified cylindrical model (both images from Januszkiewicz, 2014).

It took several decades of electromagnetic research before modeling was introduced as a practice. Starting in the 1950s, researchers began making crude geometric models to mathematically simulate the interaction between electromagnetic fields and the body. The human figure was represented with spheres, eclipses, cylinders, or aggregations of such shapes - for example, the torso, head, limbs and even specific organs can be modeled with

[282] See: https://www.remcom.com/xfdtd-3d-em-simulation-software, last retrieved 29 December 2022.

separate cylinders (see figure 5.19). These types of simple models are those most widely used in ubiquitous sensing to deduce the overall interference of a body within a field – although most often modeling does not even enter the equation (Januszkiewicz, 2014). When higher resolution is necessary, recent simulations can take advantage of developments in computer graphics and use anatomically correct models with data sets commonly obtained by MRI and CT scans (Wu, 2006).[283] In these models the body is frequently composed of a large collection of *voxels*, small cuboids between 0.5mm-1cm. A disadvantage of this technique is that the boundaries of organs becomes imprecise, having to follow the edges of such voxels. To address this issue researchers have employed anatomically correct 3D models created in Computer Aided Design (CAD) software.

Geometrical models have often been translated into physical ones to allow estimation through measurement rather than simulation. These models, called *artificial tissue emulating phantoms* (ATE phantoms), employ materials whose dielectric properties are similar to those of the body at the frequency studied (Mobashsher and Abbosh, 2015). Their anatomical precision may range from crude approximations to realistic renderings (see figures 5.20 and 5.21). Simpler models are homogenous, retaining basic features of the body without much definition - its overall shape, proportions and dimensions - and using an average of the body's properties over the entire volume, as if the body was composed of a single liquid. For instance, researchers may use cylindrical pipes filled with a liquid solution of salt and sucrose (Januszkiewicz, 2014). More complex models may consist of multiple layers to approximate the configuration of various types of tissue inside the body. Phantoms are very important for testing electromagnetic devices, such as phone antennas or MRI scanners, as they allow analyzing their performance and potential biological effects before conducting trials on living organisms. In such cases, phantoms of specific body parts are frequently employed. Head models can be particularly challenging because of the variety of tissues and their intricate distribution. (Mobashsher and Abbosh, 2015). Although not too common, age-specific phantoms have also been developed as have phantoms with regional characteristics.[284]

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[283] See for example the *Virtual Population* phantoms of the Swiss Foundation for Research on Information Technologies in Society here: https://www.itis.ethz.ch/virtual-population/virtual-population/overview/. Last retrieved 29 December 2022.

[284] Typically, results from adult models are simply scaled down to produce children models, even though results have shown that children's brains, for instance, are more sensitive to exposure than adult brains not only due to size but also because the distribution of tissue is different (Mobashsher and Abbosh, 2015). Therefore, developing age-specific phantoms is deemed quite important.

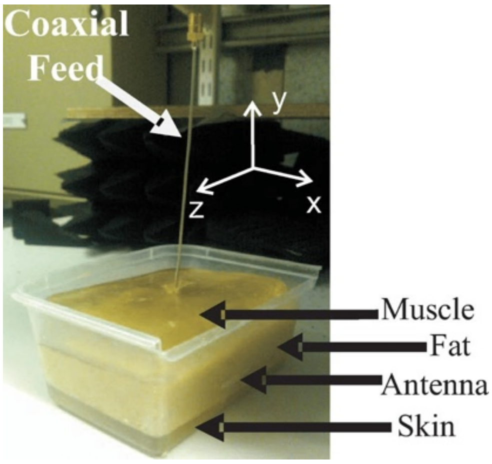

Figure 5.20. Reductionist three-layered phantom designed to study the performance of UHF RFID tag antennas implanted under the skin (from Sani et al., 2010).

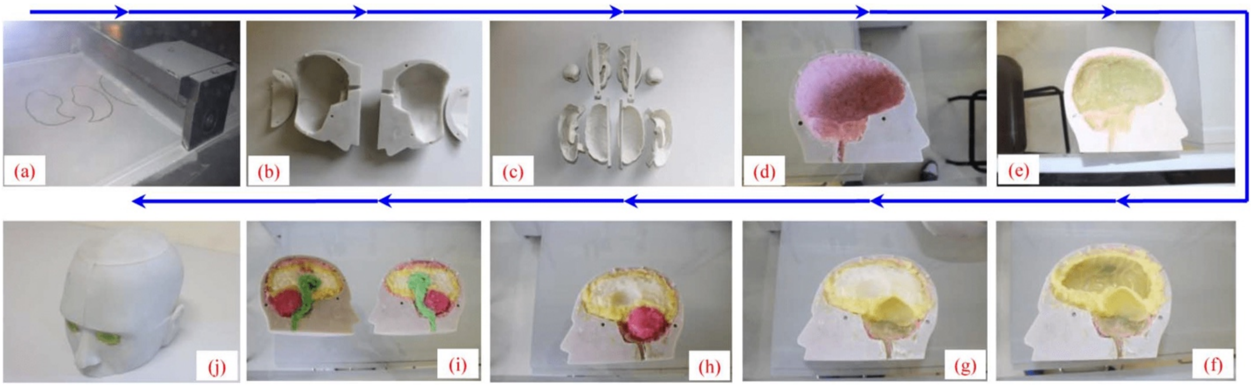

Figure 5.21. Photographs of the fabrication process of a heterogenous 3D human head phantom, designed to have realistic anatomy and electrical properties (from Mobashsher and Abbosh, 2014). Clockwise: (a) 3D printing process; (b, c): various printed parts. Head filled with: (d) dura matter; (e) cerebrospinal fluid; (f) gray matter; (g) white matter; (h) cerebellum. End result: (i) the filled head in two halves; (j) fully assembled head phantom.

A variety of materials can be used to emulate biological tissue (Mobashsher and Abbosh, 2015). Water-soluble materials are used to model high water content tissue with high dielectric properties, such as the brain and muscles. Tissue with low permittivity, like bone and fat, can also be modeled with liquids, for example by using oil or salt mixed with non-ionic surfactant materials. More solid materials, like gel, are also used, e.g. as a stand-in for muscle tissue. Semisolid or jelly materials, like gelatin, agar, and dough, can represent various types of tissue across frequencies with the added benefit that they are more stable than liquid or gel and can be layered. Finally, solid or 'dry' materials, commonly based on a combination of ceramic powders and adhesives, can also be utilized.

Beyond modeling, many types of tissue have been measured directly, thus significantly contributing to the development of better models. For instance, a widely cited study from 1996 measured the dielectric properties of over 25 types of tissue at ranges between 1MHz - 20GHz (Gabriel, 1996 and Gabriel et al., 1996). It investigated animal tissue in vitro at two different temperatures (20°C and 37°C), as well as human tissue in vivo when that was possible and safe, such as for the palm, sole, and forearm. This important study included data and graphs on the properties of various types of tissue per frequency, and compared these with findings from the literature (figure 5.22).

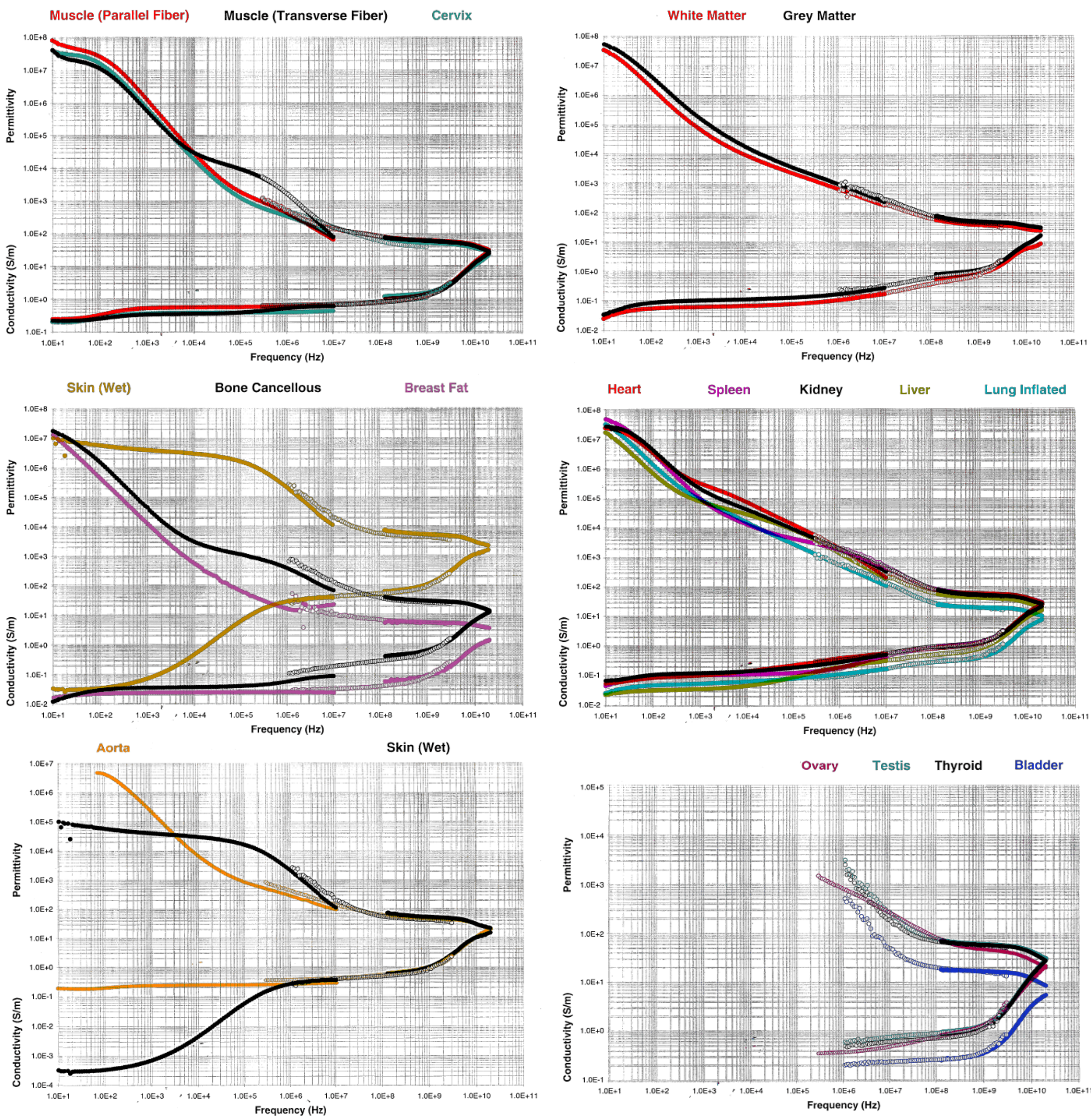

Figure 5.22. Dielectric measurements of the permittivity and conductivity of various types of human tissue calculated experimentally by Gabriel (1996) using electromagnetic sources of frequencies between 10Hz (1.0E+1) and 20GHz (2.0E+10). Note the different range of conductivity and permittivity values in the bottom row (original graphs from Gabriel (1996) grouped together and colorized for clarity and ease of comparison).

5.6.3 *The body as a propagation medium for radio and microwaves*

When electromagnetic waves come in contact with the body a number of phenomena occur. As mentioned earlier in this thesis, electromagnetic energy may be absorbed, refracted, reflected, or transmitted depending on the frequency and power of the source and on the properties of the material (the human body and its various types of tissue, in this case). Typically, part of it is reflected outside the body, and another part is absorbed.[285]

Computational models that look at the body as one single unit have revealed that the absorption of far-field radio waves is highest in the MHz range (Hand, 2008). While there is somewhat of a resonance effect happening in these frequencies, this resonance has a very low *quality factor*, often below 10. This means that the resonance slope is rather moderate and the bandwidth of resonant frequencies rather wide. This implies that, while frequency does play a role, no frequency-specific interactions should exist as far as the human body in its entirety is concerned – in simple words, there is no indication of there being some 'magic' EM frequency that makes the body resonate. The center of this resonant band is different for each person due to variations in size and anatomical configuration, all of which influence the body's dielectric properties. Resonance also changes depending on whether the body is grounded or isolated, with grounded models demonstrating resonances in lower frequencies than isolated ones (Ibid) (see figure 5.23).

Since electromagnetic waves are partially absorbed by the body, one would be correct to assume that another part of the electromagnetic energy must propagate through the body. A question thus arises: How deep do these waves reach inside the body? The depth of penetration of electromagnetic waves inside an object (biological or not) is dependent on the so-called *skin effect* - a tendency of electrical currents, charges and fields to flow on the surface of a conductor before reaching deeper (Vander Vorst et al., 2006) (see figure 5.24). The reach, or *skin depth*, of a wave depends on its frequency and the electromagnetic properties of the material – the type of tissue in the case of the human body. The skin depth is inversely proportional to the square root of the frequency, meaning that low frequencies reach deeper, and conversely that the inside of the body is more protected from higher frequency waves (Ibid). Tissue with lower conductivity and permittivity – terms on which I

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[285] In theory, an object could be a perfect, lossless absorber (called a *blackbody radiator*), or a perfect reflector (*whitebody radiator*). A *blackbody radiator* absorbs all energy transuding it into thermal energy, which in turn becomes emitted radiation. The materials lining anechoic chambers approximate this property and can be referred to as *grey bodies* (Vander Vorst et al., 2006).

will expand upon below - allow for a deeper reach. As a general rule, the more water a tissue contains, the less it will be penetrated by EM waves. The average skin depth in human tissue at 100MHz is 3cm; within 9cm inside the body, radiation power is reduced to 1%. At 1800MHz the skin depth is 0.7cm and reduces to 1% after 2cm. Waves below 10MHz have too large a wavelength thus pass through the body, and those with frequencies above 10GHz do not penetrate much under the skin layer (Hand, 2008). At the frequency of visible light, the skin depth is so small that the body becomes completely opaque.

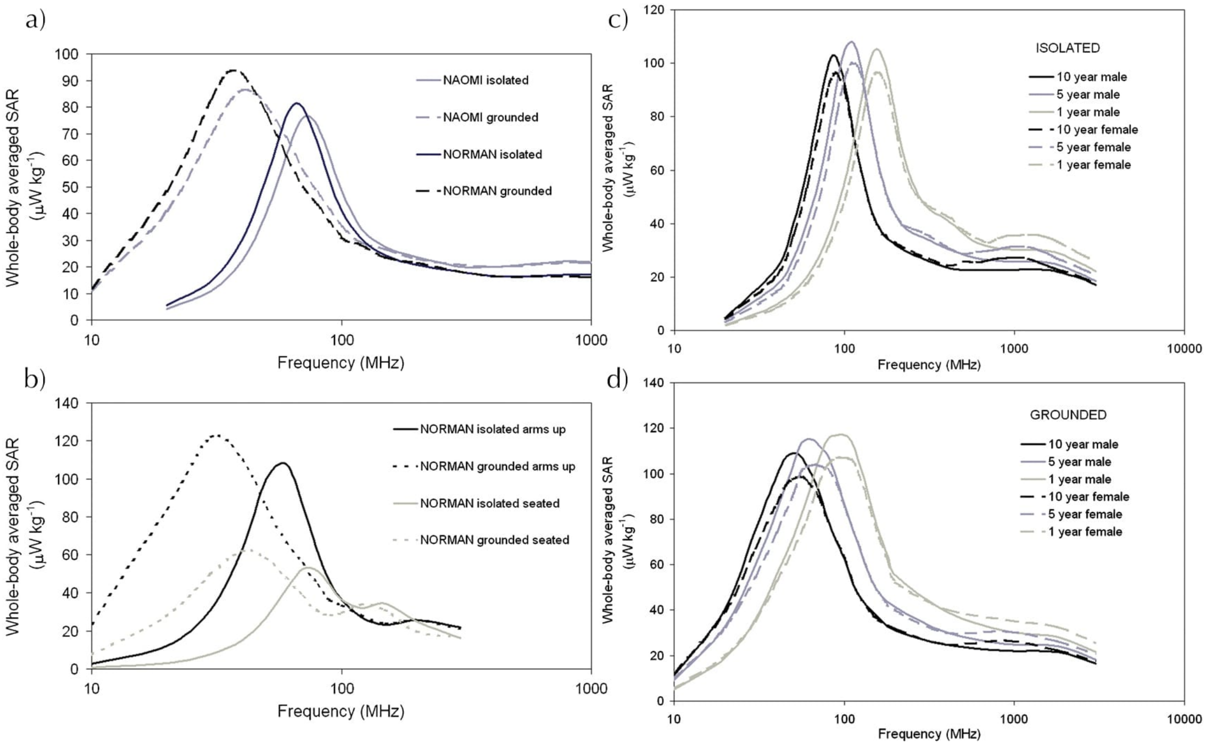

Figure 5.23. Four diagrams showing the *Specific Absorption Rate (SAR)* of different human body computational models when exposed to various plane-wave electromagnetic radiation sources, from 10MHz to 1GHz (*SAR* measures the rate of energy accumulation in the body, see section 5.6.4). Models include an adult male (NORMAN), an adult female (NAOMI), and their scaled variants representing male and female children of different ages. The diagrams display the SAR variations between different sexes and ages, between isolated and grounded models, and between models in different postures (all graphs from Hand, 2008).

As electromagnetic waves travel through the body, any materials found inside their propagating electric fields become polarized. *Dielectric polarization* is a complex phenomenon that can manifest itself differently in various materials. For example, an external electromagnetic field can induce an electric dipole where one did not previously exist. Or, it can modify an existing dipole causing it to rotate from pole to pole. This phenomenon, called *dipolar polarization*, occurs with water molecules. Water, like biological tissue, is considered a *lossy* material, as its polarization involves the *loss* or *absorption* of electromagnetic energy.

In short, when bombarded with electromagnetic energy water molecules begin to rotate (thus transducing the externally induced electromagnetic energy into kinetic energy) and then heat up (thus transducing that kinetic energy into heat). This is essentially how microwave ovens warm up our food. The process of polarization is irreversible and takes some time to fully unfold, as the system regains its equilibrium by transducing free energy into heat until it reaches a relaxation point (Vander Vorst et al., 2006). The duration of this process is measured by the *relaxation time constant*. The relaxation time of biological tissue with large water content is typically longer than that of water or bodily fluids, likely due to the interaction between the water molecules and the organic components of the tissue (Gabriel, 1996).

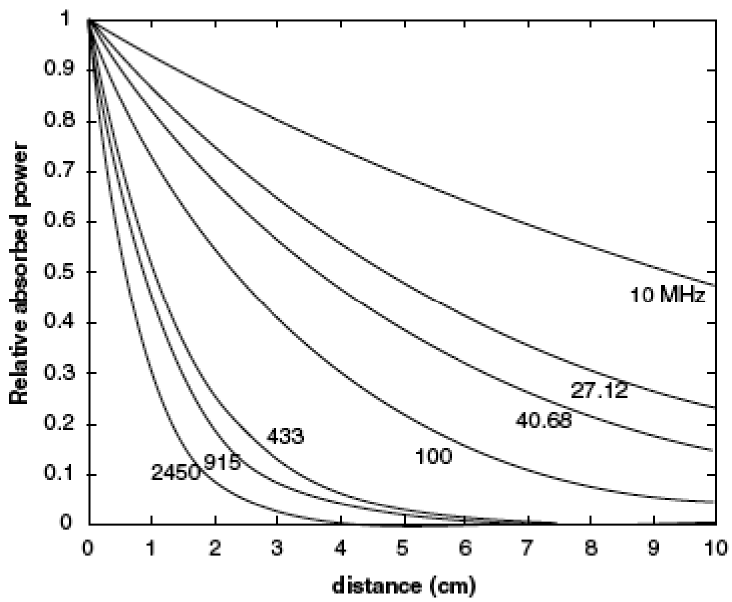

Figure 5.24. A graph showing the amount of power absorbed by the human body (y axis) depending on the depth of penetration (x axis) of electromagnetic waves in various frequencies (from Vander Vorst et al., 2006).

The ease with which a material conducts an electrical current is called its *conductivity*; this is measured in siemens per meter. Below frequencies of 100kHz, cells conduct less than the electrolyte that surrounds them, whereas from 1-100MHz their membranes are almost transparent (Vander Vorst et al., 2006). Above 100MHz cells become more conductive primarily because of three factors: a) the unevenness between the electrical properties of proteins and electrolytes, b) the difference in dipolar relaxation times between large and small molecules (with the latter relaxing at higher frequencies), and c) the dielectric relaxation of water, i.e. the time it takes for it to reach equilibrium after the introduction of electromagnetic energy. In these higher frequency ranges - where most of our telecommunication infrastructure operates - human tissue is as conductive as the fluids inside and outside of the cells. This means that the dielectric properties of many types of tissues are close to those of water. The following table presents the average conductivity values for different types of tissue and for microwave signals between 500MHz-10GHz, as extracted from Mobashsher and Abbosh's (2015) literature overview. The higher the water content, the higher the thermal conductivity and conversion to heat:

Tissue type	**Minimum**	**Maximum**
Fat	0.03	0.06
Bone	0.03	0.06
Inflated lung	0.04	4.21
Nerve	0.5	6.3
White matter	0.47	7.3
Dry skin	0.73	8
Dura matter	0.9	8.6
Gray matter	0.8	10.3
Muscle and tongue	0.8	11.1
Heart	1.02	11.8
Blood	1.38	13.1
Stomach	1.04	13.3
Vitreous humor	1.54	15.1
Cerebrospinal fluid [286]	2.3	15.4

Table 5.1: Conductivity of different types of human tissue for microwave signals between 500MHz-10GHz (data from Mobashsher & Abbosh 2015).

Another electromagnetic property of tissue is its *permittivity*. This measures the resistance of a medium to the formation of an electric field (note that it does not measure 'permissiveness', as one might expect from the name). Permittivity defines how much charge is required for an electric field to flow through a medium. In biological tissue this is largely frequency-dependent, being very high at the low end, especially below 100Hz, and diminishing exponentially as frequency rises (Vander Vorst et al., 2006). This is a general tendency, but the actual minima and maxima for different types of tissues - and different people - vary. Ordering various tissue types according to their permittivity produces a similar sequence as ordering them by conductivity, with some more overlap in observed minima and maxima. The table below is a good indication of which types of tissue are expected to produce more attenuation of radio frequencies. Typically, a relative measurement is used. This is expressed as the ratio of a particular medium's permittivity to a constant representing the lowest possible permittivity, i.e. the permittivity of vacuum:

[286] Jelly-like tissue in the eyeball behind the lens.

Tissue type	Minimum	Maximum
Fat	4.5	5.6
Bone	4.5	5.6
Inflated lung	16.2	23.2
Nerve	24.8	34.5
White matter	28.4	41
Dry skin	31.3	45
Dura matter	33	46
Gray matter	38.1	56
Muscle and tongue	41.5	57
Heart	42	64
Blood	42	64
Stomach	49	66.7
Vitreous humor	58	69

Table 5.2: Permittivity of different types of human tissue for microwave signals between 500MHz-10GHz (data from Mobashsher and Abbosh, 2015).

Permittivity, *conductivity*, and *permeability* - meaning how much a material is magnetized by an external magnetic field - are parameters that often vary with frequency, and thus are described by complex mathematical functions. A medium whose electromagnetic properties change with frequency, such as biological tissue, is called *dispersive*. *Dispersion* signifies that more energy is absorbed at certain frequencies than in others, or rather, that more electromagnetic energy is converted into heat. When dispersion is limited, the medium is considered transparent. Permittivity in the human body features 3 decreases - called *dispersion regions* - in high frequencies (Gabriel et al., 1996).

- *α dispersion* occurs in the kilohertz range and is connected to ionic diffusion in the cellular membrane;
- *β dispersion*, occurs in the hundreds of kHz; it is caused by the polarization of primarily cellular membranes preventing ionic flow between the inside and outside of the cell, but also of proteins and other macromolecules;
- *γ dispersion* is caused by the polarization of molecules of water and is found in the gigahertz range (i.e. the range in which DFL and DFAR applications typically operate).

How can we understand and model the way in which electromagnetic waves propagate inside the human body? The body as a radio channel is very different than the air interface, not only because of its different dielectric properties, but also due to its very complex structure and configuration that involves many types of tissue intricately woven together. This complexity has various effects on the transmission of electromagnetic waves, causing frequency-dependent multipath reflections inside the body. In a way, the body can be thought of as a reverberant space with a complex shape and consisting of a variety of materials. While the experimental findings mentioned earlier shed some light on how different types of these materials (i.e. different tissue types) interact with electromagnetic waves, to begin comprehending and computing the effects of the human anatomy in our transmissions we need to zoom out and put it all together in one single model.

A very useful conceptual abstraction was presented by Dove (2014) who sketched out a simplified model of the human body as a radio channel. In this model, she averaged the tissue in layers of different thicknesses and modeled propagation separately for each layer. Consequently, the torso is represented by the following concentric layers, starting from the outside and moving inward: *skin, visceral fat, muscle, subcutaneous fat,* and *small intestine* (see figure 5.25).[287] While quite reductionist, this abstraction presents an effective way for understanding the phenomena taking place when a microwave signal propagates inside the body. Dove then used both RSSI and TOA computational methods to analyze the influence of each layer on the propagating radio signal, as well as to find out what happens at the boundaries between layers. The model was tested with frequencies at the center of Medical Radio Bands: 403.5MHz (used for implants), 916.5MHz and 2.45GHz (used for BANs). Even though this investigation did not produce a formalized and accurate ranging model, its results are very informative helping decipher the processes taking place within this immensely complex and variable radio channel.

A question one may ask is, how fast does an electromagnetic wave propagate through the human body? For waves that consist of a single frequency (pure sinusoids or so called *monochromatic* signals) propagation speed coincides with the wave's phase velocity, i.e. with the rate of propagation of its phase. For more complex waves, the propagation speed for all frequency components is calculated by measuring the overall amplitude envelope. This is called the group velocity and is computed by deriving the frequency of the phase velocity (Vander Vorst et al., 2006). Overall, phase velocity is faster at higher frequencies and also varies according to the dielectric properties of the propagation material. For example, a 1GHz wave travels about 9 times slower in the human body than in vacuum. Tissue containing more water slows down the transmission more. Following Dove's model, propagation is slowest in the small intestine, then in muscle, skin, and much faster in fat. Adjusting thus for layer thickness, signals advance the fastest through the skin layer, then through visceral fat,

[287] The exact thickness of each layer varies from human to human, particularly that of visceral fat.

subcutaneous fat, muscle, and the small intestine. At 2.45GHz - the middle frequency of the band used by WiFi and Bluetooth - the total travel time for an average body type varies between 0.82-1.2nsec, depending on layer thickness. For body types with less visceral fat this number would be somewhere between 0.66-1.12nsec, and for bodies with more fat between 0.92-1.56nsec (Dove, 2014). The thickness of the skin and small intestine layers do not vary much between different body types. Instead, this variation in the total travel time of a wave through the body is mostly owed to differences in the thickness of muscle and fat layers.

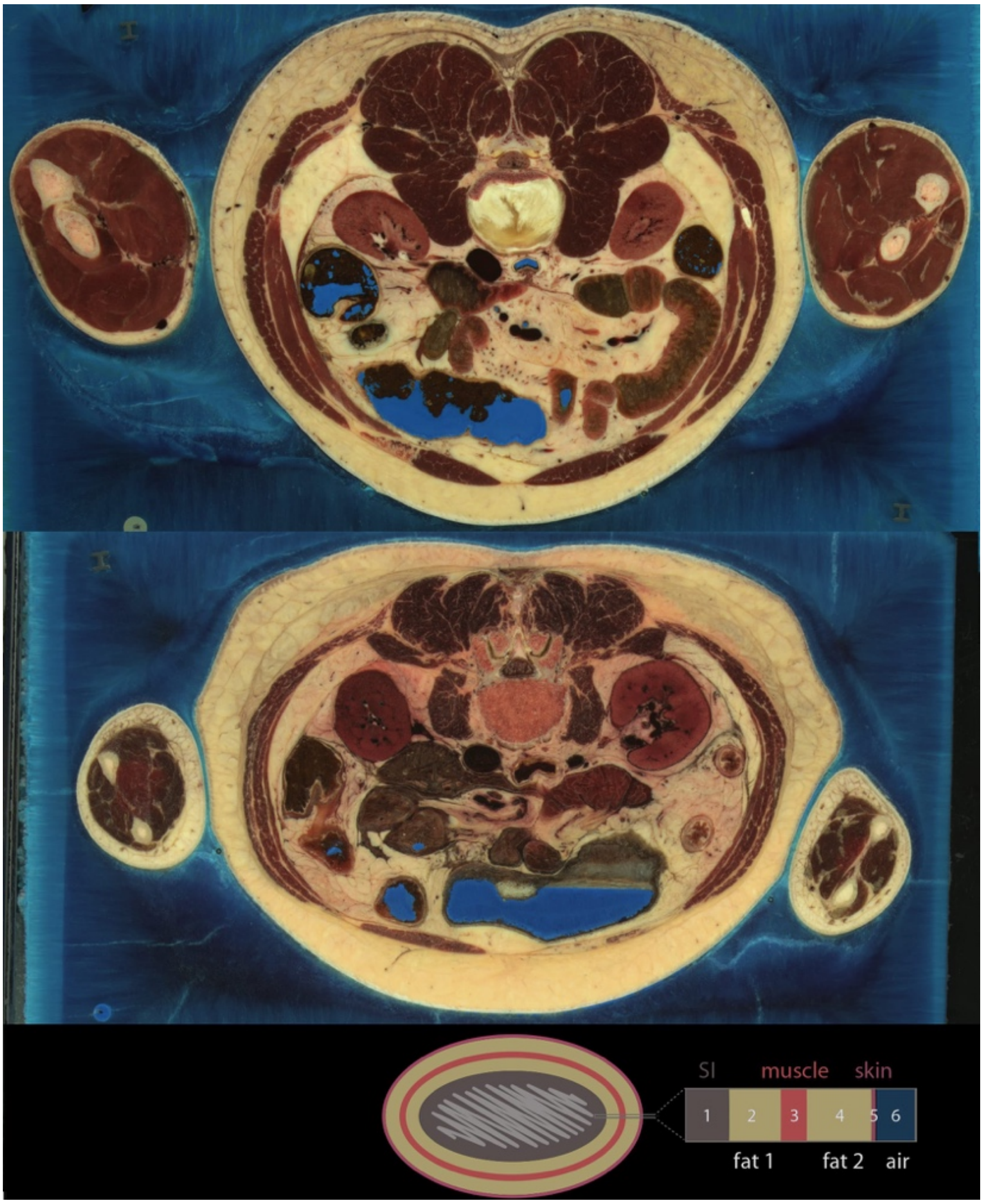

Figure 5.25. The human body in layers. Top and middle images: Photographs of frozen and dissected slices of the lower torso/upper abdomen of a male and female human body respectively (from The Visible Human Project, 1995). Bottom: Simplified cross-section model of the layers constituting the human torso (by Dove, 2014).

As a radio signal travels inside the body it is attenuated due to the following factors (Dove, 2014):

1) *Absorption by tissue*: Energy is absorbed as the wave propagates through lossy biological tissue. Overall, this increases with frequency - the smaller the wavelength the larger the absorption and thus the shallower the penetration. It also depends on the tissue's dielectric properties. At 2.45GHz, attenuation for the small intestine is nearly twice that of muscle and skin, and nearly ten times higher than that of fat. Adjusting for layer thickness, the attenuation for an average human body is:

- -0.52dB for the skin layer (3% of overall tissue absorption, and ~2% of total energy loss)
- -1.84dB for the subcutaneous fat layer (~10% and ~7-8% respectively)
- -4.67dB for the muscle layer (~27% and 17-20%)
- -3.32dB for the visceral fat layer (~19% and 12-15%)
- -6.88dB for the small intestine layer (~40% and ~25-30%).

This produces an overall attenuation of -17.23dB (between 62-76% of total attenuation).

2) *Energy loss caused by reflection*: When a wave crosses the boundary between two types of materials with different properties, part of its energy is reflected back while another part is transmitted from one medium to the next. This phenomenon is caused by differences in impedance between the two layers; it is not particularly frequency-dependent, hough in lower frequencies this reflection causes more energy loss. The energy loss for an incident wave propagating through two boundaries can be estimated by calculating the amounts of reflected and transmitted energy. The attenuation for a 2.45GHz signal when crossing layers is:

- -1.51dB when crossing from air to skin (18% of loss caused by reflection, and 5-7% of overall attenuation)
- -1.39dB crossing from skin to subcutaneous fat (16% and 5-6% respectively)
- -1.39dB crossing from subcutaneous fat to muscle (16% and 5-6%)
- -1.05dB crossing from muscle to visceral fat (12% and 4-5%)
- -3.28db crossing from visceral fat to small intestine (38% and 12-14%)

This produces an overall attenuation of -8.62dB (between 31-38% of total energy loss).

3) *Secondary reflection losses*: Similar to what occurs in free space propagation, there are also many secondary reflections and transmissions to adjacent layers besides the primary reflection mentioned above. As the reflected part of a wave travels back towards the

boundaries of the previous layer it will once more be partially reflected and partially transmitted. This happens again and again until all energy has either been transmitted out of the body or absorbed by it. Reflections and transmissions are both weaker than the boundary-crossing signal as they split and share its overall energy. In relation to each other, the transmitted signal is stronger in higher frequencies whereas the reflected signal gets stronger in the lower range. According to Dove's model, the contribution of reflections is about 12dB softer than the original wave in the microwave range. The actual figure, however, might be somewhat different as phase cancellation effects seem to not have been taken into account in this calculation.

All in all, the total absorption for an average human body was estimated by this model to be between -22.8dB to -28.0dB at 2.45GHz. Fatty layers absorb less energy so there is no significant change caused by different thickness of these layers. On the contrary, changes in thickness of the muscle layer have a larger effect, as muscle - together with the small intestine - is responsible for a large part of the overall attenuation. The boundaries between layers also produce considerable attenuation.

5.6.4 *The effects of microwave transmission on the human body*

Absorption in the body means that electromagnetic energy is transduced into heat. This may cause problems to tissue locally or even to the entire organism under certain conditions. The adversary effects of high frequency electromagnetic radiation (X-rays and Gamma rays) on biological organism are well documented. Ionization can displace the electronic orbits within an atom, changing the chemical binding of the living tissue and potentially causing irreversible damage. Owing to the exponential proliferation of wireless communication technologies, epidemiology studies are paying increasingly more attention to the potential health effects of microwaves and their electromagnetic fields using statistical analysis, modeling, and experiments on animals. While it is practically impossible to calculate the amount of electromagnetic energy coming in contact with the human body in a real world scenario due to the great number and variety of sources, such research is helping build a corpus of knowledge from which scientists can extrapolate with some confidence - at least until contradicting evidence is found.

One of the big questions surrounding wireless communication technologies – and a question which I receive after nearly every presentation of a Hertzian Field piece – is whether wireless technologies like WiFi cause cancer. The short answer is that the quantum energy of microwaves is too low to cause chemical changes at the molecular level, and no direct link between cancer and radio-frequency exposure has been established. Nevertheless, there are a number of other effects that microwaves have on living systems (Vander Vorst et al., 2006). While, for example, the *thermal effect* (conversion of electromagnetic energy to heat) is well studied and regulated by law, there is still much uncertainty and debate on the full extent of the impact of electromagnetic fields on living organisms. This is especially the case in regard to the effects of long-term exposure and the less obvious secondary effects of the interaction between body and fields. Understanding how our man-made fields impact humans, animals, insects, and plants is a massive undertaking, and is often only researched when a problem arises. For example, the effect of radio waves on bees was recently investigated as a potential culprit for the phenomenon of *colony collapse disorder* on bees ("Colony collapse disorder", 2022).

Most people are familiar with the thermal effect of microwaves from its use in a domestic appliance: the microwave oven. Like in an oven, the temperature of living tissue can increase when too much energy is absorbed by it and subsequently transferred into heat. Thermal phenomena unravel slowly enough to allow calculating the effect of electric and magnetic fields separately, making them easier to understand (Vander Vorst et al., 2006). The concept of *EMF dosimetry* – or how much is too much – was introduced in the 1950s, with much progress having been made since then to refine and measure it (Hand, 2008). National and international safety standards establish a number of limitations, such as on the amount of transmission power allowed and on the maximum permissible levels of absorption. Reference levels, on the other hand, use measurements of the electric and magnetic fields outside the body to, for example, establish the maximum acceptable power of a field and its maximum acceptable duration.

Dosimetry in the microwave range depends on the amount and duration of electromagnetic exposure (Vander Vorst et al., 2006). It is therefore concerned with the rate of energy accumulation, that is, whether energy is absorbed and converted to heat at a higher rate than what the organism can compensate for, either through simple conduction or through a regulatory counter-response of the body (Ibid). This is quantified by the *Specific Absorption Rate* (SAR), which measures how much power is absorbed by a kilogram of tissue (in watts per kilogram). In the microwave range, the SAR is the principal tool for establishing the levels of acceptable dosimetry to prevent excessively heating human tissue, measuring for instance the effects of holding a cellphone by one's ear. Dosimetry is not only affected by power; the frequency and type of waveform, such as whether it is continuous or a pulse, also play a significant role. In the case of pulsed transmission, for example, peak power may far exceed the average power over time. This can cause a number of health complications especially as non-linearities may come into play, such as neurological processes being triggered by the electromagnetic pulsing (Ibid).

The SAR of a tissue depends on its volume, its conductivity and the distribution of the electrical field inside it. For practical reasons, SAR is an average measurement over an area that usually combines several types of tissue (Wu, 2006). In many applications a single SAR measurement is used for the entire body, in which case this number represents the total energy absorbed divided by the total mass of the body. Applications concerned with the influence on specific body parts use the SAR of a more localized area, such as the hand, heart, or tongue. As one would expect, the more fine-grained the model, the more complex it is to calculate. Commonly, estimating SAR involves measuring the electric and magnetic fields and the temperature distribution inside a phantom model (Mobashsher and Abbosh, 2015). Results depend on a number of factors, such as the type of sensor and materials used, the kind of antennas, their distance and orientation; therefore, there can be discrepancies between experiments and studies (Hand, 2008).

The SAR is an extremely valuable tool but, according to Vander Vorst et al. (2006), we should not rely on it as the only safety measure, because the interaction between organisms and electromagnetic fields is not limited to the thermal effect, i.e. absorption and heat. As they point out, natural electricity is very important in living bodies for the functioning of muscle and nerve cells. External electrical currents can be used to excite these cells resulting in unwanted effects, such as interfering with how the nervous system transfers information through the body. Such effects are thus important to consider when accounting for the interactions between body and electromagnetic fields. Regrettably, non-thermal effects have not been investigated enough to produce a scientific and reliable set of numbers and rules, largely because such phenomena are more complex and harder to quantify (Ibid).[288] They commonly appear in specific frequencies and, as Vander Vorst et al. point out, they *"usually exhibit saturation at rather low intensity"* – meaning that it can only take a small amount of exposure for these effects to take place (Ibid, 125). Furthermore, they can be easily obfuscated by a simultaneous thermal response. As a result, while there are many studies on

[288] Vander Vorst et al. (2006) comment that nonthermal effects cannot be studied using classical electromagnetic theory because it does not account for them. Instead, they suggest that thermodynamics is a better tool for this.

the various effects of electromagnetic fields on the central nervous system, on the ears, eyes, and heart, on cells and membranes, even in the molecular level, there are no conclusive results.[289] Therefore, the existence of many nonthermal or microthermal effects - negative and positive ones alike - is under much debate, with various scientific, political and business agendas clashing. It is worth noting that Vander Vorst et al. (2006) point out that the controversy over the existence of such effects has more to do with politics and commercial interests than it has to do with science.

Presenting this debate is beyond the scope of this thesis, but it is worth mentioning a few of these interactions that SAR is not equipped to measure. Low frequencies, for instance, do not produce a thermal effect. Below 100kHz, the SAR is therefore replaced by measuring the *current density*, i.e. how much current is detected in an area of tissue. What is most important at this frequency ranges is that these electric fields may act as a trigger for various control mechanisms of the body. For example, nerve cells can be activated when the strength of an induced current surpasses a threshold (Vander Vorst et al., 2006 and Hand, 2008). Such interferences with non-linear biological processes can only be evaluated in vivo, which makes studying them highly problematic and very difficult. Nonetheless, this has not prevented inventors to test and develop devices for manipulating the human nervous system. For instance, Loos has been granted several patents for methods and battery-powered devices that create weak modulated electromagnetic fields to take advantage of a phenomenon he calls *sensory resonance.* This mechanism, which he admits is not entirely deciphered, works by modulating the *"firing patterns of the nerves"* at specific frequencies around 0.5Hz and 2.4Hz, thus influencing "*certain resonant neural circuits"* to obtain specific responses (Loos, 1999). This includes inducing *"relaxation, sleep, and sexual excitement, and control of tremors, seizures, and panic attack"* (Ibid). A more recent invention of his deploys weak pulsed magnetic fields to create sensory resonance with similar effects at distance of hundreds of meters (Loos, 2001). The suggested use of this battery powered device is for law enforcement or potentially for animal control.

There is another very interesting non-linear phenomenon that I find particularly intriguing because it manifests aurally: It has been shown that powerful microwave pulses transmitted at frequencies between 2.4MHz-10GHz can produce sounds inside the human head Elder and Chou 2003). This phenomenon is called *microwave hearing* or *microwave auditory phenomenon.* It was reported as early as 1947, with scientist Allan Frey being the first to

[289] For an overview of these studies, see Vander Vorst et al. (2006).

systematically investigate it in the 1960s, proposing it as a method for inducing the perception of sound on both deaf and hearing subjects (Frey, 1962). As such, the phenomenon is also known as the *Frey effect* (for a detailed overview of past research, see Lin, 2022).

The mechanism that produces this effect is called *thermoelastic expansion* and is rather fascinating: When the condensed energy of an electromagnetic pulse wave penetrates the head, the tissue inside it absorbs its energy and converts it to heat (meaning this phenomenon is caused by a more obscure incarnation of the thermal effect). This occurs very quickly (in the range of μs) causing a sudden spike in temperature and subsequent expansion of the affected tissue.[290] This expansion, in its turn, provokes a sudden change in pressure inside the head, forming a pressure wave that reaches the cochlear hair cells and is thus registered by the brain as sound (Vander Vorst et al., 2006). The fundamental frequency of sounds induced in this manner does not relate to the frequency of the transmitted waves but to the size of the subject's head (Elder and Chou, 2003). Sounds are perceived to come from within or behind one's head and have been described as a type of *"click, buzz, hiss, knock, or chirp"* (Ibid, S171). *Microwave hearing* is linked to the energy of a single pulse and not to the average energy of transmission. Somewhat surprisingly, it is assumed to not have health implications (Ibid). A similar effect has been experimentally reproduced in the heads of cats at 2.45GHz using short (2ms) square wave pulses (Vander Vorst et al., 2006 and Elder and Chou, 2003). For experimental setups involved in studying this phenomenon, see figure 5.26).

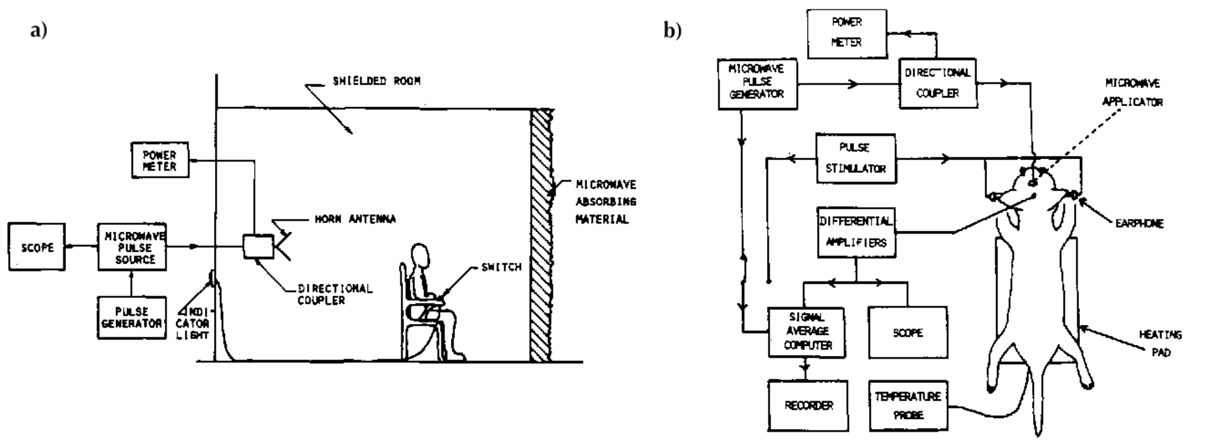

Figure 5.26. Graphs describing the configuration and equipment used to conduct experiments on microwave hearing in (a) human subjects, and (b) laboratory animals (cats and guinea pigs) (from Lin, 1980).

[290] This happens even though the rise in temperature is minuscule, 0.00001°C (Lin, 2022).

The adversary effects of strong electromagnetic pulses on living organisms were also observed in the area surrounding the Soviet-era Skrunda Radio Location Station in Latvia, whose 154-162MHz pulsed radar was operational between 1967-1998 (Šmite and Vēbere, 2008a). Although this radar did not emit ionizing radiation and was built according to soviet standards of the time for its frequency range, its power output (practically up to 3MW) exceeded today's international standards. As reported, its pulsing was picked up by electrical equipment; it could be heard on TV receivers and soundsystems, and could be picked up by other devices plugged into the electrical grid. A film crew even witnessed their camera set ablaze and other equipment become inoperative when the radar was functioning (Šmite and Vēbere, 2008a and 2008b). More importantly, extensive 10-year research tentatively linked a number of negative effects on various organisms around the radar to its operation, from slowing down the growth of trees, to interfering with bird-nesting patterns, to impacting the health of livestock (Ibid).[291] Humans were also affected. Nearby residents were reporting fatigue and their immune systems appeared inflicted – either by the radar itself or by the stress of reports on the dangers of living next to it, as one of the investigating scientists discusses (Ibid). Studies on the development of children revealed that those living in the exposure zone *"had worse memory, attention, motor skills, they were a bit slower"* (Dr. Koldynski quoted in Šmite & Vēbere 2008b, 33). At times - coinciding to when the radar was measured to operate at a higher intensity than normal - people living within kilometers from it even reported auditory hallucinations, such as waking up in the middle of the night by the rumble of an invisible tractor. These findings are supported by experiments on mice attempting to determine whether low-level microwave pulses (at 2.45GHz) can cause stress, or if drugs may provoke a more noticeable response from the body when bombarded by electromagnetic fields (Vander Vorst et al., 2006).

This type of discoveries and experiments are very relevant in regard to the "*particularly contentious issue"* of *Electromagnetic Hypersensitivity* (EHS) (Mild et al., 2006), which becomes more and more relevant as contemporary societies become increasingly enveloped by electromagnetic fields. EHS appears to only affect a few persons per million, with variable geographical spread, and with about a tenth of these people having severe afflictions (World Health Organization, 2005). Electrosensitive people typically self-attribute their symptoms to

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[291] Higher occurrence of leucosis, a disease resembling leukemia, was reported in cows inhabiting farms at a distance of about 100km from the radar (Šmite & Vēbere, 2008b). During periods of high-intensity operation, these animals also reportedly refused to graze, made noise, and their coats appeared to be electrified (Šmite & Vēbere, 2008a).

electromagnetic fields after having consulted many different specialists and conducted their own research (Bordarie et al., 2022). Symptoms differ between individuals, ranging from mild to severe, and from dermatological (most common), to neurasthenic, or symptoms severely affecting the so called *vegetative functions* necessary to continue living (World Health Organization, 2005). This includes "*headache, perspiration, emotional instability, irritability, tiredness, somnolence, sexual problems, loss of memory, concentration and decision difficulties, insomnia, and depressive hypochondriac tendencies"* (Vander Vorst et. al., 2006, 141). As the World Health Organization notes, this collection of symptoms does not correspond to a known illness, nonetheless it does approximate *Multiple Chemical Sensitivities*, a disorder linked *"with low-level environmental exposures to chemicals"* (World Health Organization, 2005). Affecting sources also differ; patients usually attribute their EHS to power lines, cellular telephony stations, WiFi, and other wireless transmissions and devices radiating at levels much below regulation. Because these effects are often subjective or take long term to manifest, it is particularly challenging to evaluate and measure them, or to confidently attribute them to man-made electromagnetic radiation as other factors (e.g. environmental or psychological) may be involved.

Hypersensitivity to electromagnetic fields has been reported and researched for years. Many studies have investigated it at different levels, including by the World Health Organization who has conducted several workshops bringing together experts to *"determine biological and health effects from exposure to EMF"* and identify knowledge gaps requiring more research (Mild et al., 2005). EHS is usually studied in so called *provocation studies*, which consist of exposing self-reported electrosensitive volunteers to electromagnetic fields in a lab so as to observe and analyze their reactions (Ledent et al., 2020). The majority of these studies do not demonstrate an increase in the perception of EMF when exposed to real versus false fields, or an increase in symptoms or physiological responses. Instead, symptoms more often match subjects' *"perceived exposure"*, suggesting a *nocebo* effect (Ibid, 426). In contrast, there are also studies providing consistent evidence that people with EHS notice adverse effects prior to suspecting the presence of electromagnetic fields, and other studies providing enough supporting evidence of the existence of EHS (for more see Ledent et al., 2020 and Bordarie et al., 2022).

Part of the controversy, as Schmiedchen et al. (2019), Ledent et al. (2020) and Bordarie et al. (2022) point out, is that the majority of provocation studies *"suffer from design and methodological limitations that might bias their findings or reduce their precision"* (Ledent et al. 2020, 425). Among others, methodological problems are connected to the duration of observation and exposure not matching the subjects' typical response, to the number of subjects studied and how results are extrapolated, and to the use insufficient protocols - e.g. in relation to blinding. In response, Ledent et al. (2020) and Bordarie et al. (2022) propose and discuss a number of research improvements for studying the phenomenon in a manner that "*does not only depend on researchers' preconceptions or technical constraints but also uses the experience of those that are afflicted"* (Ledent et al., 2020, 427). This includes the development of a scientifically robust protocol designed together with EHS people and which can be modified according to the symptoms and behaviours of specific individuals. It also includes creating less stressful test conditions to avoid muddying results, and using real instead of artificial sources of radiation.[292] Hopefully, this will lead to more conclusive results in the future.

5.6.5 *Microwaves as neuroweapons*

Regrettably, it is in our human nature that the discovery of adversary effects on our health eventually becomes weaponized. The microwave hearing effect is thus also interesting because it relates to a new set of military technologies being currently developed. These are part of an emerging type of warfare, *neurowarfare,* in which the human brain is viewed as a battlefield to be conquered or defended. As evidence to that, the US military recently adopted the concept of the *human terrain* as a sixth domain of war, distinct from the 5 already established ones of *"land, sea, air, outer space, and cyberspace*" (Krishnan, 2016, 16). As security studies professor Dr. Krishnan notes, it is only logical that militaries will try to dominate this space, hacking minds and inventing new offensive and defensive technologies to achieve the goal of forming and directing collective consciousness. As he writes, *"[u]ltimately, there is no higher valuation in war than subversion of the enemy's mind. If this can be achieved through targeting the enemy's brain directly, it would be the most powerful weapon that has ever been devised by humanity"* (Krishnan, 2016, 20).

The roots of this kind of warfare are ancient and can be traced back to Sun Tzu, who wrote that *"[t]o subdue the enemy without fighting is the acme of skill"* (quoted in Krishnan, 2014) In the US, related research has been conducted since at least the 1920s. It was greatly

[292] This approach, particularly in regard to integrating EHS patients into the design of studies, reflects a change in how science has viewed patients over the last 4 decades, increasingly recognizing them *"as informed, autonomous, and competent actors"*, exhibiting interest in the knowledge they have developed through their personal experience, and acknowledging that it can contribute to medical research (Bordarie et al., 2363).

expanded in the 1950s with the infamous MK ULTRA program by the CIA, which experimented with a number of different mind-control techniques based on drugs, sensory deprivation, electroshock, implants, and various forms of abuse and torture (Gramm and Branagan, 2021).[293] More recently, in a 1998 paper titled *The mind has no firewall* Lieutenant Colonel Timothy L. Thomas, discussed the human body as a computer and as a site for espionage and counterintelligence, examining various types of 'energy-based' or 'psychotronic' weapons. Among them, microwave weapons that can stimulate *"the peripheral nervous system"* so as to *"heat up the body, induce epileptic-like seizures, or cause cardiac arrest",* or others using *"low frequency radiation"* to influence the brain's electrical activity causing nausea and symptoms resembling flu (Thomas, 1998, 86).

Other countries have also been interested in the subject for a long time. For example, Soviet scientists concluded already in 1942 that it is possible to use electromagnetic waves to influence the human central nervous system (Gramm and Branagan, 2021). Subsequent Soviet research was based on cybernetic principles, viewing humans as complex open systems that communicate with their environment *"through information flows and communications media"* (Thomas, 1998, 85). This meant that by altering the target's environment it must be possible to affect their psychological and physiological state. More recently, Thomas reported that the Russian government has bought 'pulse wave weapons' meant *"to induce or prevent sleep, or to affect the signal from the motor cortex portion of the brain, overriding voluntary muscle movements."* (Ibid, 86).

Advances in neuroscience and related technologies are rapidly leading to a new era of neurowarfare (Gramm and Branagan, 2021). The interest of US agencies in potential applications of this knowledge for military purposes has been renewed after 9/11/2001 and supercharged during the last decade. This has been aided both by political decisions and by the development of technologies such as fMRI that allow peering into processes of the human brain.[294] Today research happens primarily in universities, in labs, and by private companies, and is largely funded by the government. As such, technology is being developed with a dual purpose in mind, civilian and military (Gramm & Branagan, 2021). The result is that there is

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[293] The public records of this research reveal no significant results of operational value, however there are many documents that remain highly classified and others that have been destroyed (Krishnan, 2014 and Gramm and Branagan, 2021).

[294] Interest has grown considerably since 2013 and President Obama's funding of the BRAIN initiative, a project aiming to map the brain modeled after *The Human Genome Project*. Oher projects aiming to map the brain have followed in Europe and Asia, with China, for example, launching its own *Brain Project* in 2016 in response.

a growing and entirely new family of weapons based on neuroscientific research that are called *neuroweapons*. These are more often non-lethal and are developed to control the minds or nervous systems of targeted individuals. Research in neuroweapons has two main goals: to enhance the performance of one's own personnel or to degrade the performance of the enemy (Krishnan, 2014). There are many different ways to achieve these goals - through the use of drugs, electromagnetic fields, light and acoustic weapons, holograms or other manners for manufacturing credible illusions – but I will only discuss those using electromagnetic fields as they are the ones that are relevant to this dissertation.

Today, there are a number of enhancement technologies that use electric of magnetic fields for brain stimulation and which can be embedded in soldier's helmets.[295] One such device is the *Direct Current Stimulation* (tDCS), which applies weak currents to the head via electrodes in order to enhance cognitive abilities and concentration. Another device, the *Transcranial Magnetic Stimulation,* creates strong electromagnetic fields to target specific regions in the brain. This device can be used to take control of one's motor cortex and hand movements, as well as to transmit Morse code into a subject's brain. It can also be used to treat mental disorders such as depression (however it is still experimental in this regard and there are safety concerns). The device is still cumbersome and it only reaches superficial layers of the brain. Nonetheless, devices like it are being tested by many US military branches as a means to *"improve shooting accuracy and decision-making speed."* (Gramm and Branagan, 2021, 26).

Another area of enhancement research includes the development of Brain-Computer Interfaces that better integrate software and hardware systems (such as remotely operated weapons) to a soldier's 'wetware'. This includes research on both implants and non-invasive devices that combine monitoring technologies, such as the Electroencephalogram (EEG) and functional Near-Infrared Spectroscopy (fNIRS), with radio, microwave or ultrasound pulsing generators that target particular areas of the brain for specific effects. One such technology developed by DARPA (the major R&D branch of the US Department of Defense) is the *Cognitive Technology Threat Warning System (CT2WS)*, which integrates cameras, Artificial

[295] Electricity has been used to stimulate the brain since at least the 19th century, with electrotherapy being very popular towards the end of that century and electroconvulsive therapy - applying currents to the brain via electrodes – popular in the 1940s-50s (Krishnan, 2016).

Intelligence and EEG to simultaneously identify threats and reduce soldiers' cognitive workload.[296]

Performance degradation technologies, on the other hand, use neuroweapons to target the enemy in a variety of manners to decrease their perceptual and cognitive abilities so as to temporary or permanently impair them, or even kill them. Degradation weapons are easier to implement than ones meant for enhancement, however they are also more challenging to develop, particularly due to difficulties in testing (Krishnan, 2016). Unsurprisingly, most such research is highly classified. Like with enhancement technologies, there are multiple different types of these technologies. The ones most pertinent here are called *Directed Energy Weapons* (DEW). These work by directing energy fields, waves, or radiation towards an enemy to affect their behaviour, mental state or mental capacity. They can also target infrastructure to incapacitate its electronics - DEW were in fact investigated already in the 1960s because of their electronic warfare capacity, e.g. to neutralize missiles (Gramm and Branagan, 2021). There exist DEWs using all types of media as their energy source: light, sound, electricity, atomic or subatomic particle beams, radio waves or microwaves.[297] Though relatively new, these technologies are currently reaching maturity and being tested outside the laboratory, even in the battlefield (Wheeler, 2017). As a result, a number of these weapons have become known to the public, including various weapons using strobing light and lasers, the *Long Range Acoustic Device* (LRAD) which uses sound, and the microwave-based *Active Denial System* (ADS).

The ADS, also known as the *heat ray*, is a DEW developed by the Department of Defense and the US Army and produced by Raytheon. Based on research conducted since 1993, it operates in the millimeter wave range, at 95GHz (LeVine, 2009). Its current incarnation is equipped with a large octagonal antenna made up of 25 reflectors that allow focusing energy into a tight directional beam and reaching a range of over 500m (see figure 5.27). The small wavelength of its beam allows it to target the top layer of human skin (1/64th of an inch) (Ibid). The effect is that it burns the nociceptors located there causing an *"intolerable heating sensation",* as a promotional video proudly states (Fogel, 2013). The ADS is advertised as a weapon designed to give US troops *"the ability to reach out and engage potential adversaries*

[296] Yet another potential application of performance enhancement technologies involves scanning the brains of personnel, which can be used to evaluate potential recruits, suggest optimal career fields within the military, perform advanced versions of polygraph tests, and more (Gramm and Branagan, 2021).

[297] This includes: *"stun weapons such as tasers, lasers, electro-magnetic pulse (EMP), high-powered microwaves (HPM), low-powered waves set at the right frequency, particle beams, and RF/acoustic weapons that impair brain function causing temporary incapacitation and/or death"* (Gramm and Branagan, 2021, 31).

at distances well beyond small arms range, and in a safe, effective, and non-lethal manner" (LeVine 2009, 1). While it is primarily meant for crowd control and similar forms of offensive or defensive operations in foreign countries, it could eventually make its way into the hands of national law enforcement for use at home (like other specialized military equipment has in the past), especially once it becomes smaller and more portable (Gramm and Branagan, 2021). ADS is operated via joystick and aimed with the help of video and infrared cameras; mobile versions are mounted on army vehicles (*Humvees*). The weapon was first presented to the media in 2007 and was later deployed in Afghanistan (Cairns, 2010). However, it was withdrawn from there, reportedly owing to practicalities but also concerns on the ramification of its use (Wheeler, 2017).

Figure 5.27. The *Active Denial System*, a microwave-based weapon promoted as a 'safe' and 'non-lethal' crowd control alternative, created by Raytheon and deployed by the US military. Left: a mockup from a promotional video (still from Fogel, 2013). Right: Photo of the operational system from a media event by the US Marines (from https://commons.wikimedia.org/w/index.php?curid=23146873.jpeg).

ADS is promoted as a safe non-lethal weapon, with claims that it does not cause injury because all humans respond to it by immediately fleeing (LeVine, 2009). In *"most instances"* of controlled experiments there were no reports of skin damage (Ibid, 7). There are also claims that its heat ray is not dangerous to the reproductive organs due to its short wavelength, and that experiments on mice revealed no danger for cancer. While the eyes are unprotected and can be potentially harmed, it is asserted that the target's reflexive response of blinking and turning away, or fleeing to avoid injury ought to be enough to protect them.

The US is not the only country in possession of such weapons. In 2014, a Chinese company demonstrated a very similar concept, the *WB-1 Anti-Riot System* (Gramm and Branagan, 2021). Six years later, the first reported use of such a weapon in action involved the Chinese Army. Chinese sources claimed that its soldiers used microwaves in a standoff with Indian soldiers in a disputed zone in the Himalayas, where explosives and firearms are banned by an international agreement. This event occurred on November 2020, a few months after Chinese and Indian soldiers were involved in a deadly fight with sticks and rocks that resulted in the death of about 20 soldiers. Chinese sources reported that their forces used this weapon to take back two disputed hilltops without using gunfire or other force, also claiming that within 15 minutes Indian soldiers were vomiting and forced to flee (Makichuk, 2020).[298]

It is believed that Russia has also developed similar technology and that is has even miniaturized it to a certain extent, allowing for more clandestine operations (Gramm and Branagan, 2021). This claim is supported by a string of events targeting US officials, which the US suspects Russia to be behind. The first of these events may have occurred in 1996, with two members of the NSA potentially having been targets of an experimental version of a microwave weapon. Twenty years later, in the end of 2016, another attack unfolded in Havana and was followed by reports of similar incidents taking place in 15 different countries between 2017-2021.[299] The people targeted were CIA, State Department, and other intelligence personnel, National Security Council members and White House staffers, diplomats and other government officials. Their reports include *"experiencing mysterious and often debilitating neurophysiological and cognitive symptoms reminiscent of a traumatic brain injury, but without any precipitating trauma"* (Gramm and Branagan, 2021, 1). This was dubbed the *Havana Syndrome*, with immediate symptoms including "*strange sensations of sound"* such as a directional *"pulsing, humming sound"* that was accompanied by *"intense pressure"* in victims' heads, "*ranging from a dull discomfort to immediately overwhelming"* (Ibid, pp. 38, 41, 1). Short-term symptoms were often very acute, leading to *"headaches, dizziness, fatigue, nausea, anxiety, vertigo, memory loss, and other cognitive difficulties"* (Ibid, 1). For some they evolved into long-term injuries, such as "*mild traumatic brain injury, hearing loss, balancing issues, and severe headaches, among other symptoms."* (Ibid, 39). Although there is no publicized proof, the fact that pain sensations seemed to be localized to specific rooms and the fact that the symptoms are consistent with the *Frey effect* suggest that the attack was likely caused by some kind of directional DEW using (probably pulsed) radio

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298 India initially claimed that this event did not happen. However, a later report from the Indian Ministry of Defence stated that China used *"unorthodox weapons"* in that area (Gramm and Branagan, 2021).

299 These incidents occurred in Uzbekistan and Moscow (2017); China (2017-18); Poland, Georgia, Australia, Taiwan, UK and Washington DC (2019); Kyrgyzstan (2020); Austria, Germany, Vietnam, India, Colombia (2021).

waves or microwaves to target victims' brains (Ibid). [300] US counterespionage has been investigating how these signals were being masked to avoid detection.

Even though several countries appear to possess and deploy such weapons that can attack the brain, there are still very few international agreements or national laws regarding their use. Apart from some specific cases (mostly chemicals and drugs regulated as biological or chemical weapons) there is a gap regarding neuroweapons like the *heat ray* (Gramm and Branagan, 2021). This lack of legal clarity enables such technologies to operate in a grey zone. Nonetheless, DEWs could very well be regulated with existing laws, *"from national civilian-use regulations and guidelines to international humanitarian law (IHL) and human rights law",* including the Geneva Convention (Wheeler, 2017, 4). These frameworks could be used to limit or forbid their use.

Despite the lack of consensus on whether the use of DEW and other such weapons is desirable or beneficial (e.g. some claim that they will make war less bloody), there have been some voices raising awareness against potential nefarious applications of neuroscientific knowledge (see Gramm and Branagan, 2021). There are also voices cautioning against the lack of research on the short- and long-term effects of these weapons on human health, particularly on persons with pre-existing conditions (for a detailed discussion, see Wheeler, 2017). The lack of transparency over these technologies raises additional concerns that these weapons may in practice be less accurate and directional than what is claimed, thus potentially endangering innocent bystanders. Furthermore, there is little available research publicized on the psychological impact of their use and how it may affect people - especially given that targeted civilians may not understand what is happening to them due to the technology being so new and unknown. This may easily lead to targeted crowds panicking, thus causing further harm. Risks on the environment and risks involving the use of electromagnetic DEWs to incapacitate infrastructure must also be taken into account, as they may trigger a chain of additional consequences (Ibid). All these concerns are augmented by the fact that experiments supporting the safety of these weapons are typically made under controlled conditions by the military and with trained soldiers as the targets. As such, better monitoring and assessing of the research and development of these weapons seems necessary, together with establishing more stringent legal frameworks for their use. The political and ethical implications of using these weapons need also be considered. All this is particularly

[300] As Gramm and Branagan (2021) write, the Soviet Union had shown interest in Alan Frey soon after his discovery of the *Frey effect,* inviting him for a lecture and a visit.

important given the risk that these weapons may soon make the passage from the military to law enforcement without further regulation. The fact that they are silent and invisible raises additional concerns about them being used stealthily and without accountability.

Chapter 6. WIRELESS INFORMATION RETRIEVAL: SENSING WITH WIFI SIGNALS

6.1 TOWARDS WIRELESS INFORMATION RETRIEVAL

6.1.1 *Introduction*

This chapter discusses the microwave-based sensing technique and system that I have been developing since my residency at ZKM in 2014. The following chapter (7) will then present three works of the *Hertzian Field* series that I have created with this system since: *Hertzian Field #1*, *Hertzian Field #2* and *The Water Within* (in its two iterations, *Hertzian Field #3 and Hertzian Field #3.1)*. These works are the first of a series with which I plan to explore relationships between body and radio fields in different configurations and settings. They present a radical shift in my approach to wireless communication as a medium for art, stripping down its layers to move from the space of the network to the physicality of waves.

6.1.2 *Discovering WiFi sensing at an arm's reach*

During the two days of my 2014 residency at ZKM when I was searching for a new project (see section 4.4.1) I realized that I had already implemented elements of radio-frequency sensing in the months prior. Most importantly, I had found a way to extract *Received Signal Strength Indication* (RSSI) - though only for packets sent by the Access Points I was connected to. While I had become intrigued by observing the signal's fluctuation at first, I had left it at that as my observations did not feel particularly relevant to the project I was developing in preparation for that residency. Mid-residency, however, with the project I had in mind having proven unrealizable, I decided to turn back to this RSSI extracting SuperCollider class and investigate if I could coax any meaningful sensing data out of it. After some experiments I quickly realized that the possibilities were wildly more exciting than I had first realized! Still, that early implementation had significant problems, mainly because it operated in a higher networking layer. As a result, RSSI data were produced at a very low sampling rate, they were noisy, and could only be captured from devices connected to an Access Point.

I quickly realized that, in order to get better results, I needed to mine a deeper layer of WiFi communication. I thus turned to another earlier find that had also intrigued me but which I had also put aside as it had felt tangential at the time: Configuring a WiFi interface to operate in a special mode allowing it to extract data from the air interface at the *Physical layer,* with no need to associate to any networks. I plunged deeper, informing myself on the ins-and-outs of this layer, and tested a number of command line tools for analyzing network traffic.

My experimental setup involved two Raspberry Pi B microcomputers, one configured as a transmitter and placed behind my chair and another configured as a *sniffer* and placed in front of me on my desk. In this manner I could block the Line of Sight just by moving my upper body. I could tell this had some influence by looking at the numbers quickly flowing on my screen but could not yet grasp what the relationship was. However, as soon as I wrote a bit of code to sonify real time RSSI data from *tcpdump*, a packet sniffing utility, what seemed merely promising to my eyes revealed itself as some form of digital sorcery to my ears: I found out that I was clearly in control of the sound simply by moving my body! Knowing that this was occurring through a simple registration of the strength of a WiFi network felt especially uncanny. A eureka moment followed suit: I got up from my swivel chair and gave it a spin. The result was a very clear *woomp … woomp … woomp* - an oscillating sound that matched the chair's rotation to a 't'.

These initial proof-of-concept experiments, controlling very simple sounds by moving my body between a single transmitter and receiver, made it apparent that there was great potential in this technology I was developing as an intuitive full-body interface for electronic music – and all that without the need to touch a single piece of gear while performing! This was an extremely exhilarating prospect, and one far more intriguing to me than developing a localization or activity recognition system, like the DFL and DFAR systems I had been reading about. From that moment, and until the end of my residency at ZKM, I spent every waking hour feverishly developing the technology, experimenting, performing sound with my body, while at the same time constantly being amazed that this technology really worked - our WiFi networks are actually radars! - my brain racing through a barrage of ideas for future works that kept it running full throttle day and night.

6.1.3 *From Ubiquitous Sensing and Music Information Retrieval to Wireless Information Retrieval*

In technical terms, the system that I have developed is heavily informed by Ubiquitous Sensing research (see chapter 5). At the same time, it is strongly guided by my knowledge of audio signal analysis, borrowing tools from the field of *Music Information Retrieval* (MIR).

MIR is a relatively new area of applied research – although still older than device-free ubiquitous sensing – that focuses on extracting information from musical signals, such as genre, instrumentation, tempo, time and key signatures, pitch, harmony, rhythm structure, performing automatic transcription, separating tracks and categorizing sounds, and more.[301] The growing scientific focus on Big Data mining has been an ideal nurturing ground for MIR, both in academia as well as in the commercial world, with MIR techniques being used for instance by streaming services such as Spotify and Pandora.

While being two very distinct fields, Ubiquitous Sensing and MIR share some common techniques. Both use statistical analyses to extract features from time-based signals: DFL and DFAR aim to understand motion via radio signals, whereas MIR aims to understand musical events through audio signals. Furthermore, both often rely on Machine Learning, estimation and clustering algorithms to categorize data and automate decisions about qualities of the analyzed content. However, the sophistication of signal processing and analysis is much higher in the field of MIR. This made me think early on that MIR could prove to be a fruitful model for developing a radio-sensing system with possibilities beyond what current DFL and DFAR systems can do.

During the development process, I first implemented all feature extraction methods (i.e. various types of statistical analyses) that I found in DFAR and DFL literature. As these were considerably fewer than those that I was familiar with from audio signal analysis, especially in regard to a signal's spectrum, I then turned to MIR looking for more algorithms that could potentially prove useful. As such, many of the feature extractors of my implementation presented below have been inspired by audio analysis and MIR research. They were sometimes ported directly and other times modified or reinterpreted in a re-imagination of MIR as a type of radar technology. This is particularly true for spectrum- and cepstrum-related analyses, which were inspired by research in the two major strands of MIR. One of these strands focuses on statistical analysis of the audio spectrum; I based my implementations off of two important software tools developed by researchers of this strand, *Timbre toolbox* and the *MIR toolbox,* both implemented in MatLab (see Peeters et al., 2011 and Lartillot, 2012 respectively). The other branch of MIR research makes wide use of the cepstrum and *Mel Frequency Cepstrum Coefficients* (MFCCs), looking into the power

[301] For more information and resources on MIR, see the webpage of the International Society for Music Information Retrieval: http://www.ismir.net/ (last accessed 29 December 2022).

spectrum of sound as a way to extract meaningful information. The cepstrum analysis tools I developed are based on this research strand.

Owing to the influence of Music Information Retrieval, I decided to call the sensing technique and system I developed *Wireless Information Retrieval* (WIR). WIR involves extracting movement-related information from the *Received Signal Strength Indication* of WiFi signals to deduce movement speed(s), speed shifts, changes in type of movement, movement patterns, position, and more (e.g. even humidity contents). The system applies extensive statistical analyses in multiple time-scales and domains (*time-domain, frequency-domain, quefrency-domain*) to effectively increase sensitivity and spatial resolution, eliminating the need for using a large number of transmitters and receivers.

As mentioned more extensively in my evaluation and thoughts on Ubiquitous Sensing from an artist's perspective (section 5.4.6), my use scenario and needs are quite different than those of DFL/DFAR projects but also of MIR. This is reflected in my approach and implementations. Briefly, in practical terms my main goal has been to create an expressive, real-time performative system that focuses on continuous control - which is primarily where musical expression resides - rather than on discrete higher-level control (which could be achieved with the types of techniques used in those disciplines). In conceptual terms, I have been interested in creating a performative/interactive system that enables discovering the nature of the invisible interaction between body and EM field, rather then superimposing an arbitrary pre-composed gestural language.

6.2 WIRELESS INFORMATION RETRIEVAL: IMPLEMENTATION

6.2.1 *System configuration, hardware and software*

Like any radar system, the minimum requirement for a *Wireless Information Retrieval* system is one transmitter and one receiver, with more complex configurations providing more complex sensing possibilities. To recap section 2.5.1, radars typically consist of at least one transmitter and one receiver - each connected to an antenna - and are coupled to a signal processing module. In *monostatic* systems, transmitter and receiver share the same antenna, and hence the same location, whereas in *bistatic* systems they are spaced apart. *Multistatic* radars incorporate more than two receiver or transceiver nodes at different locations. The WIR system can be configured in all these manners, with multistatic setups being demonstrably more versatile.

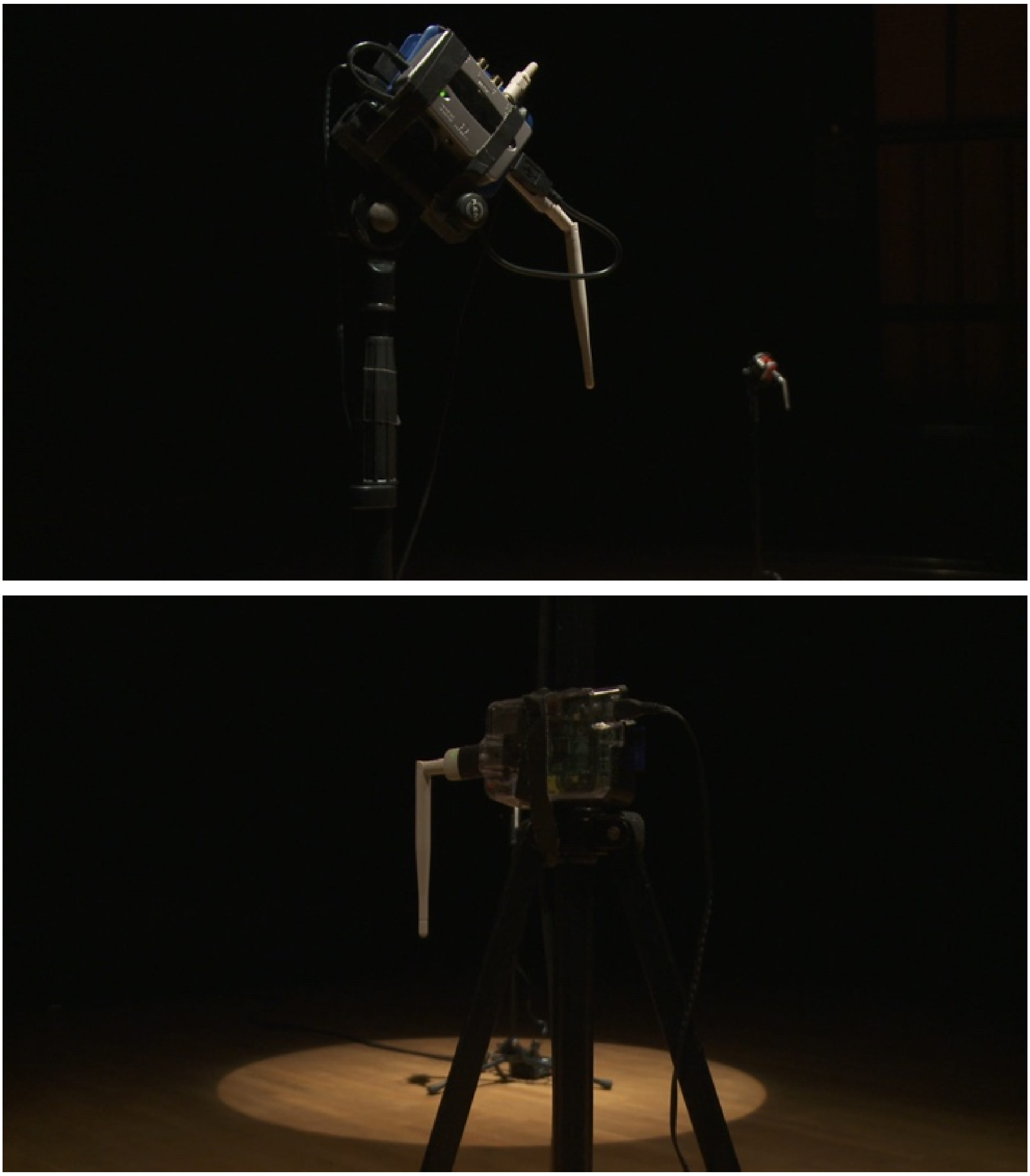

Figure 6.1. *Wireless Information Retrieval* hardware used in *Hertzian Field #1*. Top: two of the receiving Raspberry Pi B nodes (foreground and background), each equipped with a WiFi card, a dipole antenna, and an audio interface. Bottom: the transmitting Raspberry Pi node, equipped with a WiFi card and antenna (video stills by Anna-Lena Vogel).

The first WIR system implementation I developed for *Hertzian Field #1* in 2014 used separate Raspberry Pi B single board microcomputers for transmitting and receiving/scanning, each equipped with a WiFi card and antenna (see figure 6.1). The processing module and all sound generation was incorporated in the software of the receiving nodes. *Hertzian Field #1* used 5 nodes in total, one configured as the transmitter and four as autonomous WiFi scanners, processors, and audio generators.

In 2015-16 I updated the system for *Hertzian Field #2*. Since then each node acts as a *transceiver*, incorporating both transmitter and receiver functions. Furthermore, because the Raspberry Pi B hardware that I used was fairly limited, in the following works most data processing and all sound generation was moved to a separate, more powerful computer (see figure 6.2).[302]

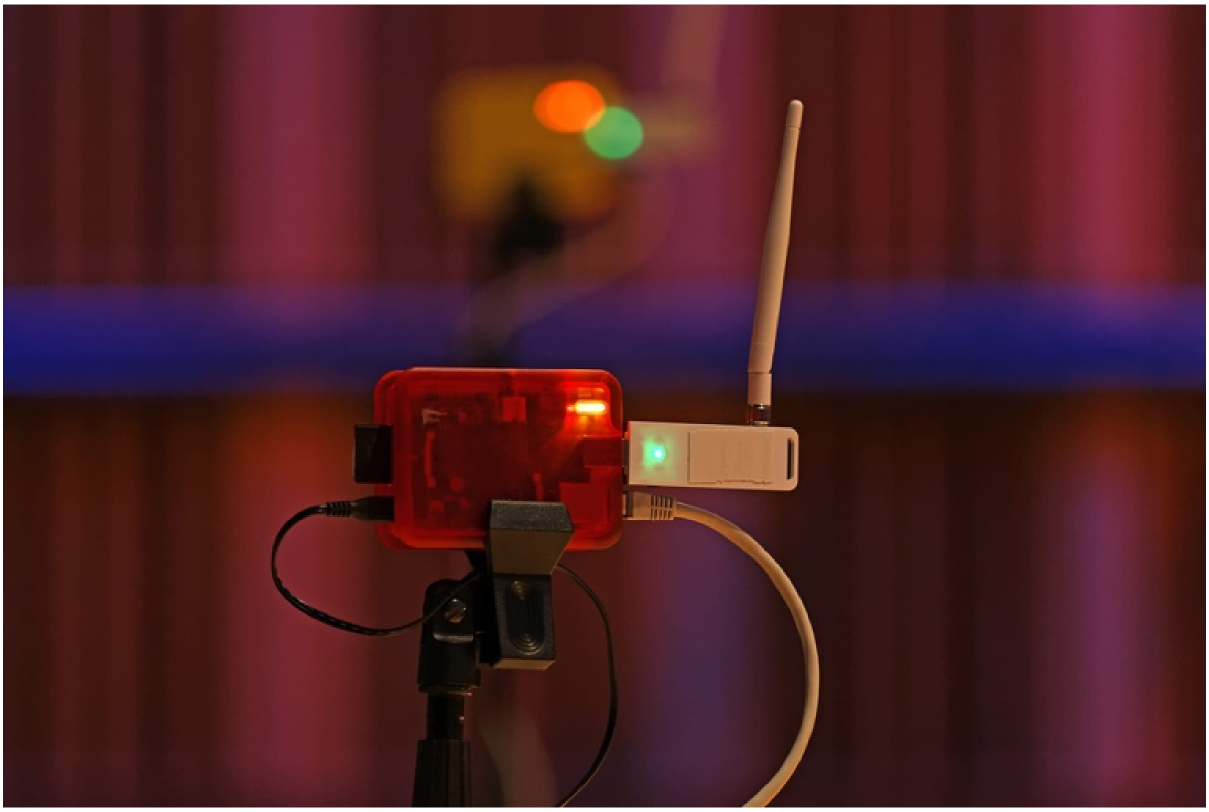

Figure 6.2. *Wireless Information Retrieval* hardware for *Hertzian Field #2*: Raspberry Pi B transceiver node using a better WiFi card and antenna; the node is connected via wired Ethernet to a main computer, sending sensing data to it for analysis and sound generation (photo by ZKM Onuk).

The most recent version of the WIR software for the Raspberry Pi sensing nodes runs on a modified version of the Raspbian operating system. Other Linux variants are also compatible.

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[302] A number of optimizations where necessary to maximize what these early Raspberry Pi B models can do and make it possible for them to run *Hertzian Field #1*. This included:
- Installing Jack audio and making many audio-specific optimizations
- Over-clocking their processor
- Allowing their GPU to only use a minimal amount of memory
- Killing the WiFi power management process
- Disabling IPv6 to make networking faster
- Removing unused utilities to lighten up the system
- Stopping a number of running services, such as *trigerhappy*, *dbus*, *polkitd*, and more.

For more relevant tips on audio optimization see (Linux Audio, 2020).

The software uses a number of UNIX command-line tools for handling all networking-related and 'sniffing' operations, a handful of Bash scripts I wrote to organize, execute, and sequence the different elements of the system, as well as a modified Perl script - originally written by Ronald MacDonald (2011) - to send sensing data to the main computer via Open Sound Control (OSC). These components will be discussed in more detail in this chapter. The entire system loads automatically upon powering the nodes and is operational within a few seconds.

In *Hertzian Field #2* and *#3,* all nodes are connected to a main computer via wired Ethernet (see figure 6.3). The main computer receives messages sent by the nodes, processes all data extracted from WiFi signals, and handles all mapping, sound synthesis, and spatialization. This computer runs a modular software environment I have developed in SuperCollider. The environment contains several functionalities, such as:

- Interfacing with the Raspberry Pi transceiver nodes via Open Sound Control (OSC)
- Parsing and analyzing incoming data from each node
- Interpreting the data and converting it to real-time sound controls
- Generating real-time audio using a spatially distributed network of custom-made processes, which are controlled by the interpreted and mapped data
- Surround spatial diffusion of audio using First-Order-Ambisonics (FOA).

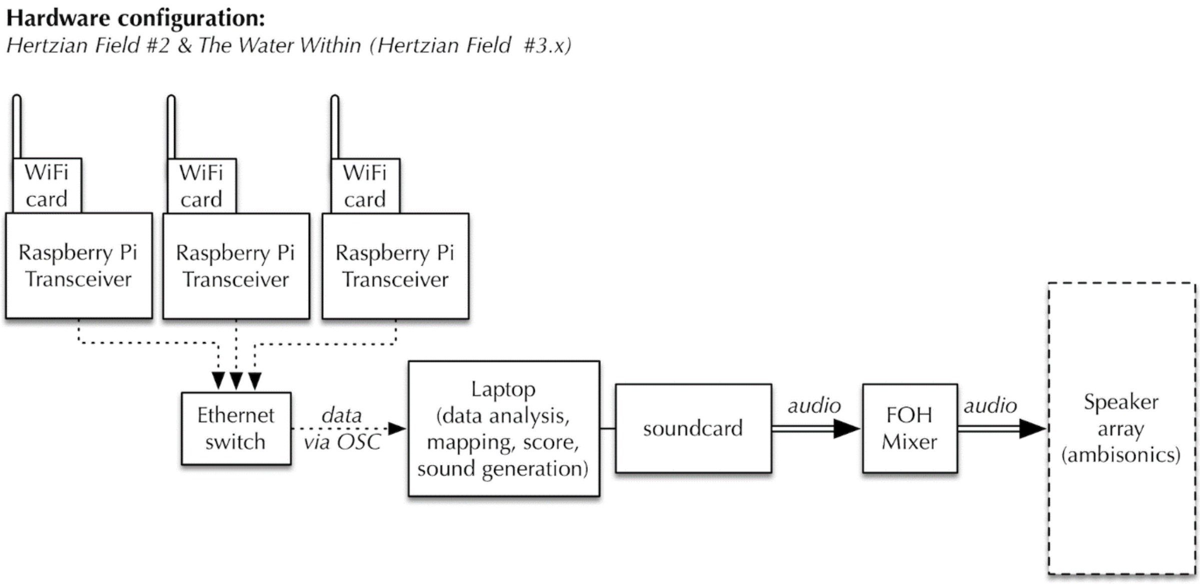

Figure 6.3. Hardware configuration schematics for *Hertzian Field #2* and *The Water Within (Hertzian Field #3).*

The implementation is entirely based on open-source tools and uses inexpensive off-the-shelf equipment as it is meant to be a low-cost solution for independent artists. The system is moldable, modular, and scalable, offering intuitive, detailed, and in-depth control. For an overview of the system structure, see figure 6.4 The following sections present how the system operates in some detail.

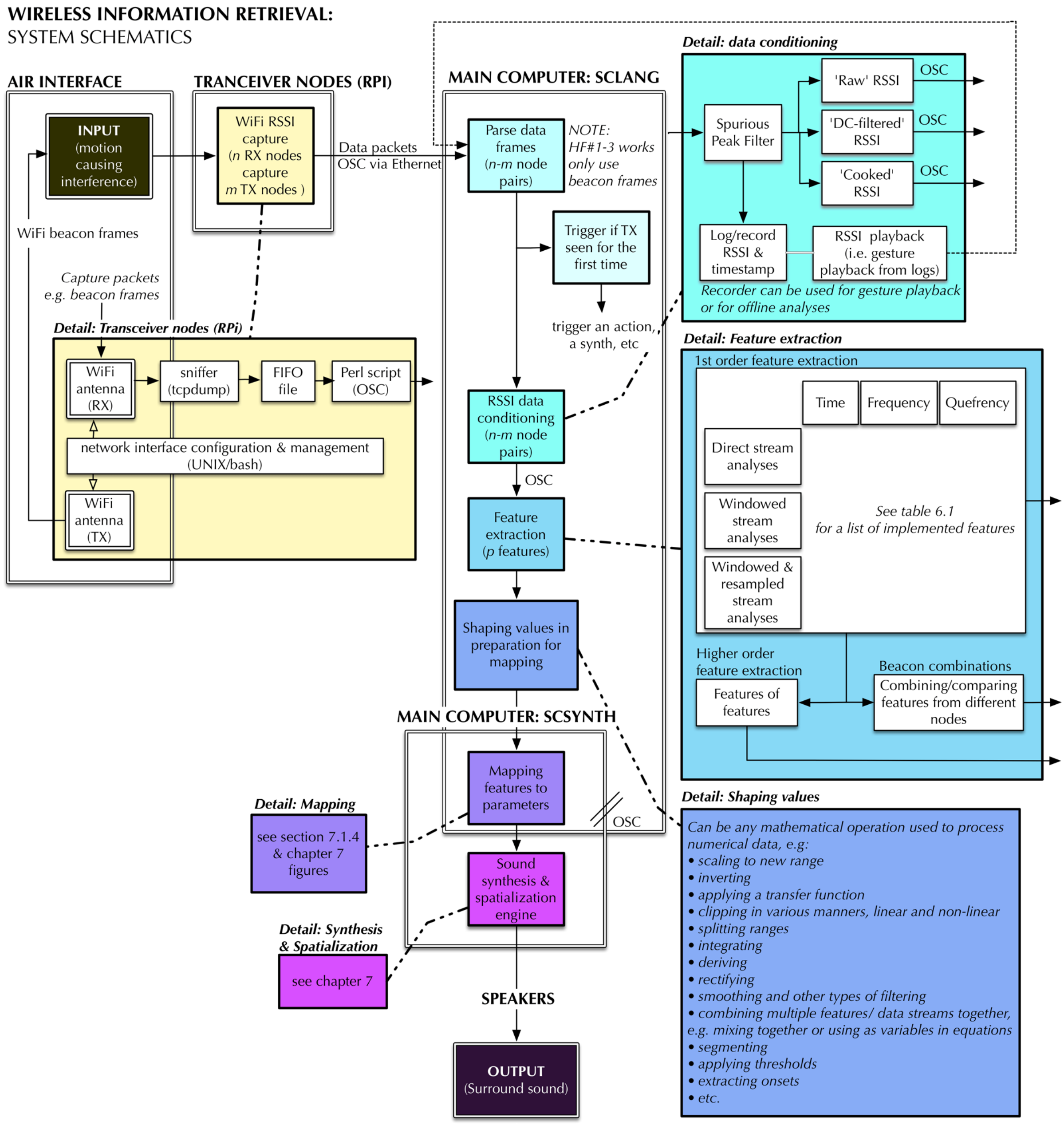

Figure 6.4. Schematic of the *Wireless Information Retrieval* system developed for the *Hertzian Field* series of works.

6.2.2 *Accessing the air interface and sniffing for data*

In WIR, sensing begins with the WiFi card and its antenna. This is the instrument through which a node can access the air interface, and subsequently capture the RSSI of WiFi microwave signals.

In IEEE802.11 communication the wireless network interface card can be configured in a number of ways, which define its role and agency in radio space. The protocol implements the following modes for communication (see IEEE Computer Society LAN Man Standards Committee, 2021 for the most recent version):

- *Master*, or infrastructure mode, in which the WiFi interface acts as an *Access Point* (AP) or router, creating a network and offering it as a service to other wireless devices. This is the mode in which a transmitter node is typically configured.
- *Managed*, in which the device becomes a client, commonly referred to as a *station* or *node*. Clients can connect to networks managed by an AP in master mode; they can only communicate with each other via with the mediation of that AP.
- *Ad-hoc*, which permits setting up a dynamic, decentralized network that does not require an AP but instead transfers data between connected peer nodes. These nodes must share the same air interface, meaning they must use the same WiFi frequency/channel and be close enough to receive each other's messages.
- *Repeater*, in which a node is used to extend the reach of a network. Repeater nodes act as intermediaries, receiving and relaying packets that are not directed to them but to the AP or connected devices.
- *Mesh* (MBSS or *Mesh Basic Service Set*), a mode similar to *Ad-hoc* in that it permits creating decentralized networks. The significant difference is that mesh nodes implement routing, meaning that they can act as a kind of repeater. Mesh mode is useful for connecting several, non-homogenous, nodes into a peer network. This allows for direct communication between them in the network without needing to first route their messages through an AP.

While IEEE802.11 supports all these modes, the firmware and driver implementation of a specific WiFi card (i.e. the software embedded in the card and the software that interfaces between card and operating system, respectively) dictate in which of these modes it can actually operate. In addition to the above five modes, some wireless interfaces implement two special configurations which are not used for communication but for packet analysis - an operation commonly referred to as *packet sniffing*.[303] These types of operation were primarily developed as an aid for troubleshooting networks. *Sniffing* comes in two flavors:

[303] Entering these modes and intercepting some specific types of packets may only be possible to users that have administrator privileges on their device.

- *Promiscuous* mode requires associating with a network and allows capturing all packets sent within that network, regardless of who sends them or to whom they are addressed.
- *Monitor* mode (*Radio Frequency Monitor*, or RFMON) is similar but more advanced. The WiFi card does not connect to a network but scans the air interface for messages transmitted by any and all nodes in the frequency channel that it is listening in, regardless of whether these nodes are associated with a network or not. This mode can thus intercept additional data on the Physical Layer transmitted by APs and nodes without connecting to any network, such as *management frames*, i.e. meta-data used by the networking infrastructure. This advanced mode can be particularly useful in a variety of applications, such as wardriving, localization, and radio sensing.

In the earlier days of WiFi, only special, expensive interfaces could enter these special modes. However nowadays it is becoming increasingly more common for WiFi cards to implement one or both.

These two modes can be used in conjunction with special network monitoring and packet sniffing software with which intercepted traffic can be decoded and analyzed. The software I have used in my implementation is *tcpdump*, a very powerful and lightweight open-source command line utility for analyzing network traffic.[304] It is an acutely seasoned tool with a long history, with many early fragmented versions gathered into one single project in 1999 (Messier, 2017). It can be used in all operating systems belonging in the UNIX family (i.e. all flavors of Linux, as well as OSX and macOS), with *Windump* being its Windows OS equivalent.

Tcpdump includes a number of filters with which one can define which types of frames should be captured (for more see Iliofotou, 2014). Filtering can significantly reduce the amount of data retrieved and analyzed, which allows tuning *tcpdump* to a specific application thus turning it into a fast and lightweight sniffer. The tool is quite flexible and the amount of information it extracts can be set to preference. It does not output raw data but decodes and parses information in a human-readable format that can easily inform the user about the type of frame received and its parameters.

Wireshark, an application which appeared under the name *Ethereal* in 1998, is another very popular and more user-friendly packet sniffer. It comes with a graphical user interface and has a number of additional capabilities for better visualization of the captured data. While it is

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[304] See: http://www.tcpdump.org/

slightly faster than *tcpdump* in capturing data and slightly more reliable – tcpdump may drop some packets with fast traffic which may be a critical flaw for forensics operations - it also requires many more resources: multiple times more memory, more processing power, and has over two orders of magnitude more energy consumption.[305] This is partly because of its graphical interface but also because, as opposed to *tcpdump, Wireshark* first receives all packets and then filters them (Goyal and Goyal, 2017). As networks become more prevalent, many more such tools have appeared. *Tshark*, for example, is a command line version of *Wireshark*, bridging the gap between it and *tcpdump*.

When in *monitor* mode, some wireless interfaces can assume a more active role than sniffing, being able to broadcast packets to all wireless devices in their vicinity, or unicast them to a specific node - even without associating to a network. This is called *packet injection* and is a technique often used to hack into networks or perform various kinds of attacks - such as man-in-the-middle, denial-of-service, flooding a network with requests or confusing it with malformed packets, cracking its encryption, and more. Common tools for this type of operations include the software *Kismet* and *Aircrack-ng*.[306] While sniffing software was initially developed to assist system and network administrators, it is also widely used by black-hat hackers to intercept traffic and attack networks and by white-hat hackers and network forensic experts to prevent, identify, and counter such attacks.[307] A few artists are also using them in their work, such as the Critical Engineering Working Group (see Oliver et al., 2011/21).

6.2.3 *Sniffing radio space for IEEE802.11 packets, frames, and radiotap headers*

To better understand how packet sniffing can be transformed into a sensing technique, as well as to get a glimpse of the many other possibilities beyond spatial sensing of human bodies afforded by the WIR technology, it is necessary to have a closer look at how networking communication operates:

Information travels through the network piecemeal, broken down into many separate packets. Apart from the transmitted content, packets also contain a number of network-specific metadata, which make communication between different devices possible. In the IEEE802.11 standard, communication packets consist of individual frames, each carrying a specific type

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[305] For a more detailed comparison of *tcpdump* and *Wireshark*, see Goyal and Goyal (2017).

[306] See: https://www.kismetwireless.net/ and https://www.aircrack-ng.org/. Last accessed 29 December 2022.

[307] For more on network forensics see Messier (2017).

of information and assigned a specific function. These frames contain details about the protocol the network uses, its encryption type, the MAC Addresses of the source and destination hardware of each transmitted message, the sequence of a series of frames (which is used by the receiver for error correction, allowing to put received frames back in their original order), as well as additional information.

A packet sniffer can capture packets in their 'raw' state, i.e. before they are converted back to human-readable information by the receiver node. This allows retrieving any and all information transmitted through the air interface at the Physical layer, even those frames containing metadata that are concealed to the user. There are three different types of frames and many subtypes, all of which can be captured with a sniffer and by the *Wireless Information Retrieval* system (see Geier, 2002a; Gast, 2005; and Darchis, 2022):

a) *Data* frames; these are the content-carriers, containing the information transmitted from one network node to another, such as, for example, the data on a web page a user visits.

b) *Control* frames; these frames assist in the successful delivery of data and help regulate how a node behaves in a network. Nodes use control frames to communicate with one another so as to avoid messaging collisions, to handle transmission priorities within the network, to perform all necessary handshakes, to confirm reception of data, etc. The IEEE802.11 standard defines several types of control frames:

- *Request-to-Send* (RTS) and *Clear-to-Send* (CTS) frames help optimize the network's throughput. A station sends an RTS frame when it needs to transmit; the receiving station will respond with a CTS message. Third-party stations in the network receiving this signal will remain silent for the time requested by this frame so that the communication between the two stations can be performed unhindered and without collisions.
- *Acknowledgement* (ACK) frames are part of an error-checking mechanism. A node that received data will check for errors and if it has not found any it will respond with an ACK frame to the transmitting station. If the sender does not receive such a frame within a certain time it will assume the data has not been received and will retransmit it.
- *Power-Save Poll* (PS-Poll) frames are transmitted by stations exiting power-saving mode to request that any buffered data that were missed be sent to them again.
- *Block Acknowledgment* (BA) and *Block Acknowledgment Request* (BAR) frames package several acknowledgments into a single frame so as to enhance efficiency.
- *Contention-Free-End* (CF-End), *Contention-Free-ACK* (CF-Ack), *and Contention-Free-*

Poll (CF-Poll) frames are part of a special mechanism, the *Point Coordination Function* (PCF). This is an optional tool, defined by the 802.11 protocol as a way to provide fair access to applications that require fast communication. In such contention-free services, the Access Point takes control as the central coordinator of the network and is responsible for notifying a station when it is allowed to transmit. All other stations remain silent at that time. CF-Poll frames are sent by an AP to permit a specific station or node to transmit a single frame. CF-Ack frames are sent by stations as an acknowledgement of having received data. CF-Poll and CF-Ack frames can be sent in a package together with data frames (e.g. Data + CF-Ack). CF-End frames are sent by the AP to signal the end of contention-free transmission and the return of the network to its regular *Distributed Coordination Function* (DCF).

c) Finally, *Management* frames have an administrative function; they are responsible for identifying networks, joining and leaving them. A number of management frame subtypes are defined by the protocol:

- *Authentication* and *Deauthentication* frames: A node that wants to connect to an Access Point sends it its identity and the AP responds with an acceptance or rejection. In protected networks, the AP first responds with an encrypted challenge (a password) that the node has to solve before accepting or rejecting the connection. Deauthentication frames are sent by a station when it wants to end secure communication in the network.
- *Association Request* and *Association Response* frames, *Re-association Request* and *Re-association Response* frames, and *Disassociation* frames: The AP needs to register every connected station and allocate resources for it to successfully operate within the network. The station transmits an Association Request with information about the device, such as the supported data rates and protocols, and the name of the network it wants to connect to. If compatible, the AP allocates all necessary resources and memory space for that station. Then, it transmits an Association Response frame to notify the station whether the request was accepted or rejected. Reassociation frames work similarly. They are used in networks where multiple APs provide access to the same network (e.g. in a network with range-extender devices), or when a previously connected node disappears and reappears in the network. This can occur, for example, when a node exits and re-enters the space covered by the AP's WiFi reach, or when its network card is rebooted. Disassociation frames are sent by a station that wishes to disconnect from the network so that the AP can free up the resources allocated to that station.

- *Announcement Traffic Indication Messages* (ATIM) are sent by nodes to notify a receiving station that information is split in multiple frame buffers and that more data follows, so the receiver should not enter power-saving mode.
- *Action* frames are special frames that can be sent to a node by connected stations or APs to trigger measurements, for example of its Quality of Service, spectrum management, or other vendor-specific operations.

Lastly, and most pertinently for radio-frequency sensing, a set of special frames are used to allow devices to search and find available networks. When a WiFi card is switched on, it starts iteratively scanning all channels of the air interface. This can occur in two ways:

- A node *actively* scans for a specific network. In that case, the station sends out a *Probe Request* frame – i.e. a query with the name of the network it wants to connect to. If the network is present, it will receive a *Probe Response* with supported rates and other connectivity information. A Probe Request can also be constructed so as to elicit a response from all APs sharing the air interface (i.e. all APs that receive such a probe, i.e. all APs in range).
- *Passive* scanning allows finding all APs sharing the same radio space / air interface with a node. This is an energy-efficient scanning method that involves simply listening for a special kind of management metadata, *Beacon frames,* instead of transmitting any requests on the air interface.

Beacon frames are at the heart of the WIR sensing system used in the *Hertzian Field* series. These frames are transmitted periodically by Access Points and are fundamental to wireless communication. They are lightweight messages (about 50 bytes) that announce an AP's availability and provide some basic information about the service it provides (Geier, 2002b). Stations sharing the same air interface use them to deduce which APs are compatible, which provide the best connection, and to which a user prefers connecting to (devices retain a memory of APs they have connected to it in the past). The information contained in Beacons frames includes: a) a timestamp used to synchronize all nodes in the network to the APs clock; b) the interval between consecutive beacons; c) the SSID of the network (i.e. its name) and the APs Mac Address (i.e. its hardware identification); d) the supported data rates, encryption, and relevant parameters of the Physical layer, such as the frequency and channel of transmission.[308]

When a receiving station captures a Beacon frame, it measures the power of the radio signal at its antenna, producing an RSSI value which it adds to the frame. This allows the receiving device to calculate how robust a connection with this particular AP is expected to be. RSSI is represented by a negative 8-bit number that measures the difference in decibels (dBm) from a nominal 1 milliWatt transmission. For frequencies in the WiFi range (below 6GHz) this number is considered to be accurate within ±5%. This is commonly displayed to the user with a significantly reduced resolution that distinguishes between four states. These states are visualized in the familiar to everyone WiFi symbol: a dot from which three curved lines appear to radiate.

Information is added to the captured frames with the use of *Radiotap* headers, the unofficial standard format for capturing and injecting packets in IEEE802.11.[309] Using Radiotap, the WiFi interface or driver of the receiving device can collate additional metadata about the captured frames and the state of the air interface that are not necessarily covered by the 802.11 protocol. Radiotap also allows adding metadata to frames before transmitting them, not only upon reception. Besides the RSSI of the received signal, Radiotap supports many metadata fields, including the dBm of noise received by the antenna, the channel used, frequency-hopping information, data rates, the *Time Synchronization Function* timer, a measurement of the attenuation of transmission power, the expected accuracy of the timestamp, and more.[310] However, only a limited number of those metadata are typically implemented in any particular interface. This is unfortunate as information on antenna noise, for instance, would be potentially very informative for sensing applications, as it would allow comparing the ratio between signal and noise. Nonetheless, none of the antennas I have experimented with so far give access to this measurement.

A practical thing of note regarding Radiotap headers is that, since different WiFi cards incorporate different types of metadata, they may format this data in their own manner. In addition, they may also use a different scale or resolution for the RSSI value. This all means that swapping interfaces/cards in a WIR system may require some adjustments in the code to

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[308] For a detailed overview of all information included in the body of a beacon frame see IEEE Computer Society LAN Man Standards Committee (2021), and in particular table 9-32 in pages 825-828.

[309] *Radiotap* was developed by David Young, originally for use with NetBSD OSs, and is especially pervasive in Linux. For more information see the project’s website, http://www.radiotap.org/ (last accessed 29 December 2022) and its manual page (Simpson and Broad, 2006). *TaZmen Sniffer Protocol* (TZSP) and *PrismAVS* are two competing frame encapsulation systems.

[310] For a list of defined fields, see http://www.radiotap.org/fields/defined. Last accessed 29 December 2022.

make them work properly.[311]

6.2.4 *Transmitter configuration and using beacon frames as radar pulses*

Theoretically, a WIR sensing system can use existing (i.e. ambient) Beacon Frames transmitted by APs in the same channel of the air interface - much like in a passive DFAR or DFL system. While this reduces the components of the system and is conceptually intriguing, ambient APs are often far away, meaning that the body's interference will produce very small changes in RSSI measurements, and thus a reduced resolution. Instead, active implementations where the transmitting AP is part of the system allow for much more control and typically produce better results in terms of sensing. In such configurations, one can choose where to place the transmitting nodes and tune their distance to the receiving node, meaning that it is possible to spatially *sculpt* the hertzian field. This is a fundamental aspect of the design of a hertzian work on which I will refer to in more detail in a following section (see 7.1.2). It is also possible to increase the field's temporal sensing resolution by increasing the transmission frequency of beacon frames.

A node/station becomes a transmitter by sending out beacon frames. To do so, it needs to be configured as an Access Point with its own *Dynamic Host Configuration Protocol* (DCHP) server activated on the same wireless interface.[312] The specific way of enabling this functionality depends on the chipset and driver of each WiFi card model. The configuration of the APs can be fine-tuned to the particular application through a number of options. This includes selecting which hardware interface and which software driver to use, the name of the network to create (i.e. its *Service Set Identifier*, or SSID), whether the network is visible or hidden, its security protocol (e.g. WEP vs WPA) and encryption key, the specific version of the 802.11 protocol to use and its parameters (e.g. 802.11ac has a number of different settings

[311] For example, here is how a single beacon frame appears with a Tenda W311U+ WiFi card and *tcpdump*:

13:15:18.978482 1.0 Mb/s 2427 MHz 11g -25dB signal antenna 1 0us BSSID:f4:f2:6d:0c:ea:c1 DA:ff:ff:ff:ff:ff:ff SA:f4:f2:6d:0c:ea:c1 Beacon (HertzianGreen) [1.0 2.0* 5.5* 11.0* 6.0 9.0 12.0 18.0 Mbit] ESS CH: 4, PRIVACY*

The TP-Link TL-WN722N card formats beacon frames slightly differently and includes two additional parameters:

19:40:30.958606 272278742us tsft 1.0 Mb/s 2427 MHz 11g -91dB signal antenna 0 0us BSSID:d4:68:4d:15:45:e8 DA:ff:ff:ff:ff:ff:ff SA:d4:68:4d:15:45:e8 Beacon (KPN) [1.0 2.0* 5.5* 11.0* Mbit] ESS CH: 4*

[312] The *Dynamic Host Configuration Protocol* (DHCP) helps manage devices on a network (see "Dynamic Host Configuration Protocol", 2022). The most important task of DHCP is to hand out IP addresses to connected devices. DHCP operates in the top layer of networking (the *Application* layer in the OSI model) and is implemented with a client-server model. It is important that it is properly configured so that the network is functional; if not, other devices and interfaces may be unable to connect.

than 802.11b), configuring power management options and various networking handshake options such as time-outs, transmission rates, accepting and blocking devices by their Mac address, and many more.

Two of those settings are particularly important for optimization: the radio transmission channel and the beacon interval.

a) *Transmission channel:* Selecting the WiFi channel to transmit on is important as it allows shifting to a more vacant part of the spectrum with less traffic. Generally speaking, it is best to use a channel with as few other APs as possible on it and on neighboring bands to prevent collisions and delays caused by congestion of the air interface. It is good practice to perform a scan of the WiFi environment on site to decide on which frequency to transmit so that the system is optimized for the location - also keeping in mind that the radioscape may be different at different times of day.[313] Typically, in a congested environment one can expect the system to be less precise in terms of temporal accuracy as messages may get delayed, retransmitted, or simply lost. An interesting though somewhat counterintuitive fact to consider is that contemporary devices are generally better equipped to ignore messages from APs transmitting on the same channel rather than from APs transmitting on adjacent ones. This is because the protocol is built to allow different networks to coexist, and thus can easily ignore a string of properly formatted messages – even when there is a lot of them. On the other hand, while messages seeping from adjacent channels will be less frequent, the unavoidable data loss of some of their frames may cause further processing delays and mix-ups, as the receiver may try to make sense of the partial data it captures. In either case, *tcpdump* and the WIR system makes it very simple to filter out beacon frames coming from other SSIDs.

b) *Beacon interval:* This is a fundamentally important setting for a sensing system like WIR, as it allows tuning the transmission rate of beacon frames to the specific application (e.g. a performance). This typically involves reducing the interval to increase the sampling rate of the overall sensing system. Beacons are transmitted at a somewhat regular rate, the *Target Beacon Transmission Time* (TBTT) (figure 6.5). This interval is measured in time units, each lasting 1024μs. By default, in IEEE802.11 each Beacon frame is transmitted once 100 of these time units have passed, i.e. every 102.4ms. This means that about 10 beacon messages are transmitted per second, producing a sampling rate of around 10Hz. The word *target* in the

[313] While scanning can be done by the WIR system, I have personally found it easiest and fastest to survey the air interface using a WiFi analyzer app on a smartphone.

TBTT name is crucial in understanding what to expect from this mechanism, as it does not constitute a precise clock. The beacon frame will be transmitted at the defined time interval *if* the air interface is available, but if it is congested, then the message will be slightly delayed. If the wireless medium remains busy for consecutive TBTTs, every second Beacon transmission will be given priority. The result is that there can be a drift from the nominal sampling rate, its amount depending on network congestion and the amount of Access Points and separate SSIDs sharing the same channel of the air interface (Carpenter, 2014). This is another reason for selecting an empty WiFi channel when possible.

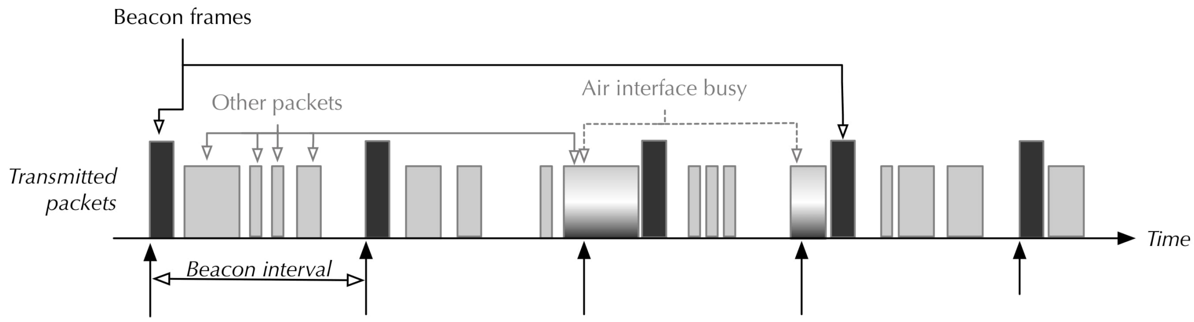

Figure 6.5. *Target Beacon Transmission Time (TBTT): Beacon frames* are not always transmitted according to the *Beacon Interval* set in the router's configurations - i.e. at a fixed sampling rate - but involve the more fluid mechanism of the *TBTT* which enables collision-free data transmissions from other devices on the same air interface.

In general networking use case scenarios, there are different benefits from using a low or high interval. The situation is somewhat complex, so experimentation may be necessary to find the right value for a given situation and location. Higher intervals (i.e. more sporadic beaconing) inject less messages in the network and require less processing from wireless-enabled devices in the area. They also require less power, which can be relevant in certain cases. Low intervals (i.e. fast beaconing) may cause congestion, and thus more fluctuation in TBTTs. At the same time, fast beaconing makes it is easier for stations to find APs and decide which one will provide the best connection; it may also prevent connected devices from going to sleep. Furthermore, it reduces the drift between timestamps and helps keep devices more tightly synchronized. The interval is yet more crucial in applications like WIR as it represents the sampling rate of the RSSI data. In this case, choosing how fast the interval should be is the result of a compromise. Higher frequencies provide higher resolution; however, one should be cautious of going too fast. There is a limit to what the air interface and its nodes can handle without creating network congestion. There is also a limit to how much real time data the hardware/software deployed can analyze and how many features it can extract. According to the sampling theorem, one does not need to go much higher than two times as fast as the frequency of motion to be tracked – which is typically not faster than 5-6Hz for motion of the human body. In *Hertzian Field #2* and *#3,* transmitters send out about 32 beacon frames per second, although there is always some fluctuation because of the TTBT mechanism (figure 6.6). This is higher than the nominal 10-12Hz sampling rate required in theory because my experiments showed that this higher rate significantly improves the temporal resolution of the sensing system, particularly the resolution of frequency-domain analysis, making the system feel much more responsive. This sampling rate of 32Hz is about as fast as the current hardware of the WIR system can comfortably manage. It will be interesting to investigate in the future if a higher rate is feasible and if it provides better results. It will also be interesting to implement an *Adaptive Beaconing* mechanism, as described in section 5.4.4.

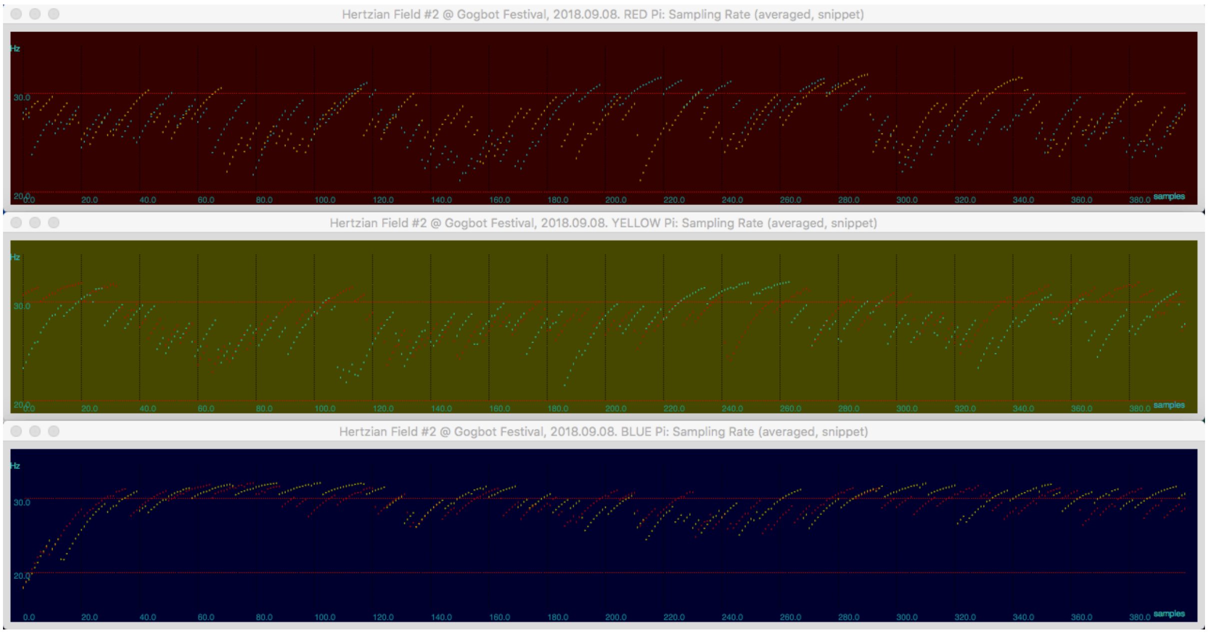

Figure 6.6. Excerpt of the sampling rate of RSSI data captured during a performance of *Hertzian Field #2* at Gogbot Festival (Enschede, 2018) with an averaging filter applied. The *Y* axis displays the rate in Hz and the *X* axis the index of each sample. Top graph: the 'red' receiver node capturing the 'yellow' and 'blue' transmitters. Middle: 'yellow' receiver capturing 'red and 'blue'. Bottom: 'blue' capturing 'red' and 'yellow'. For the geometry and transceiver layout of this configuration, see figure 7.12.

6.2.5 *Resampling non-equispaced RSSI data*

Early on, when I was not yet aware of the intricacies of beacon timing and the TBTT mechanism, drifting from the nominal rate was something I noticed in practice with the *Hertzian Field #1* system. Feature extraction accuracy was plagued by this fluctuation, particularly in the frequency domain. This was remedied in the WIR implementation for

Hertzian Field #2 with a relatively simple solution: Resampling of the non-equispaced RSSI data.

The mechanism I developed is based on the timestamps added to every captured Beacon frame upon reception by *tcpdump*. In the current implementation of WIR, these timestamps have a resolution of one microsecond (i.e. one millionth of a second) which corresponds to a sampling rate of 1MHz. The timing of these stamps is handed out by the kernel of the receiving device, therefore its accuracy depends on the accuracy of the kernel's clock. In addition, it may involve some additional (minuscule) lag because stamps do not mark the time when a packet's reception was completed at the WiFi card, but a subsequent time when the packet's reception was registered by the kernel (The Tcpdump Group et al., 2022). In any case, any clock drift or timing lag is expected to occur in a much smaller order of magnitude than the speed of human motion, thus making their influence negligible.

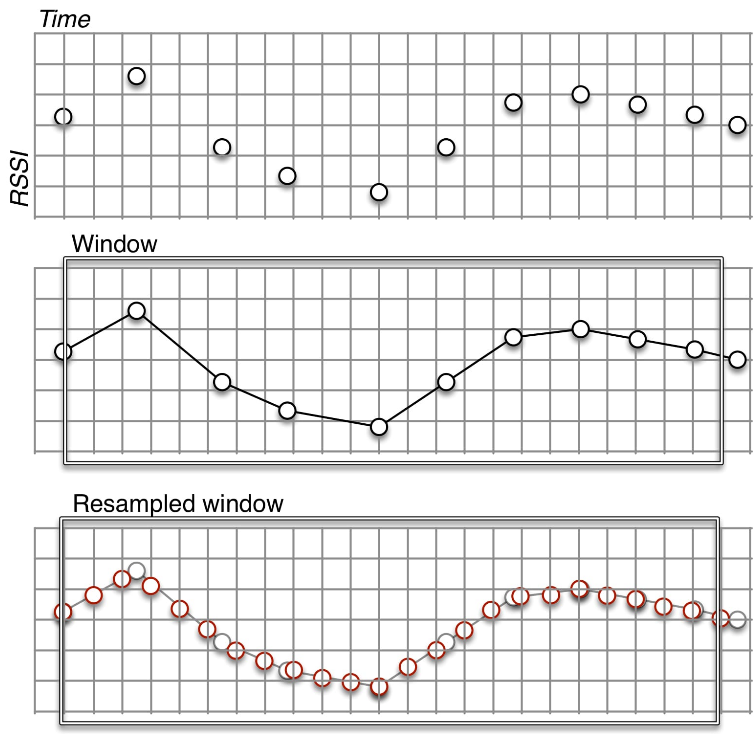

Figure 6.7. A simplified example of resampling non-equispaced RSSI data as implemented in *WIR*: The original RSSI data (top) is transmitted and received at a fluctuating rate because WiFi beacons are always broadcast using the *TBTT* mechanism. Thus, prior to being analyzed, RSSI data is first interpolated (middle) so that it can then be re-sampled at a desired – typically higher – fixed sampling rate (bottom).

The main computer responsible for all sensing calculations converts these node-specific timestamps to delta times. Instead of assuming that incoming RSSI values arrive in a fixed temporal grid defined by the beacon interval, like the *Hertzian Field #1* system did, the receiver collects frames whose timestamps are within the same rolling window of time (a circular buffer/memory). These frames are ordered according to the delta times defined by their timestamps. This results in a non-equispaced sequence of samples describing the fluctuation of RSSI within the time window. By interpolating between these non-equidistant samples (linearly, with a sinusoidal, exponential, or Welch curve), the system produces a smooth and continuous envelope as a function of the RSSI over time. This curve can then be resampled with as many points needed, and at a fixed temporal grid (see figure 6.7). This is a significant improvement and an important feature of WIR, as many feature extraction algorithms require a regular sampling rate - especially in the frequency and quefrency domains. While this approximation is expected to introduce some errors, it provides a reliable solution and significantly more accurate and robust results than simply using RSSI data when they arrive. In any case, given that the speed of human body motion is rather slow, interpolating at a rate of 28-32Hz is not too big of an issue.

As mentioned, the system used in *Hertzian Field #2* and *#3* lets all transceiver nodes operate at their own clock, and only calculates the elapsed time between beacon frames. In this manner, nodes do not need to be synchronized to each other; instead, the data itself can be synchronized by the main computer collecting them during pre-processing by consulting timestamps. Nonetheless, in certain applications such as triangulation, it can be useful to have all nodes be more tightly synchronized. This can be achieved, for example, by creating a mesh network in which all transceiver nodes operate. In this case, synchronization occurs via the *Timing Synchronization Function*, an existing mechanism in IEEE802.11 for synchronizing nodes in the same network.[314] The resolution of this mechanism is in the microsecond range, producing a drift of a couple dozen µsec. This functionality has been already implemented in WIR but was not used it in the aforementioned works. Even more precise synchronization is possible if a particular WIR application requires it. Although not utilized, the *Hertzian Field #1* system implemented the *Network Time Protocol* (NTP), a server-client model through which clients can synchronize to an external and precise reference clock ("Network Time Protocol", 2022).[315] NTP can be used both for synchronizing transceiver nodes to each other, as well as to a real-world clock. It is particularly useful for single-board computers like the Raspberry Pis, because those machines

[314] For a detailed overview on clock synchronization on IEEE802.11 and other protocols, see (Mahmood et al., 2017) and ("Timing Synchronization Function", 2019).

[315] NTP was primarily designed for operation on the Internet, but the master clock can also be hosted by a node in a local network.

do not keep an internal clock running when the hardware is not powered. This means they lose any reference to the time outside the device whenever they are switched off; when they are powered again they continue counting from the last time they were active. Applications requiring yet more precise synchronization between nodes would benefit from using the IEEE1588 *Precision Time Protocol* (PTP), which is a recent standard for *Clock Synchronization* meant for automation, communication, and entertainment applications where there is a need for synchronization in the nanosecond range (Mahmood et al., 2017). IEEE1588 implements a master-slave configuration, with the master node transmitting periodic timing information to synchronize all nodes. Still, all this requires some computational overhead that is unnecessary when nodes do not need to be synchronized.

6.2.6 *Receiver and transceiver configuration through interface cloning*

A receiver node is set up to sniff packets in the *Physical* layer, registering the signal strength of received beacon frames, which thus essentially function as *WiFi radar pulses*. To enable this functionality, the wireless network interface needs to be put in monitor mode.[316] In WIR, captured and timestamped beacon messages are either processed locally by the receiver (when an internal processing module is included in its software, like in *Hertzian Field #1*) or they are sent to another computer via Open Sound Control (OSC) for further analysis. In that case, sending OSC via a wired connection is advised for two reasons: it results in faster and more reliable data transmission, and it does not clog the air interface with additional messages, which could delay the system's Beacon frame transmissions.

Typically, a network interface can only operate in one mode. However, with some WiFi cards and driver combinations it is possible to create one or more virtual interfaces from the same physical card. This makes it possible to have a card and antenna functioning as both an AP (transmitter) and a sniffer (receiver) at the same time, i.e. as a transceiver. Technically, this

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[316] The following steps are required to achieve this in Linux (note that they require administrator privileges):
1. Turn off the *ifplugd* daemon for the wireless interface, a background process that automatically configures the networking interfaces when a cable or adaptor is connected or disconnected (For the daemon's manual, see: https://linux.die.net/man/8/ifplugd, last accessed 29 December 2022).
$ sudo ifplugd -S -i wlan0
2. Shut down the wireless interface to change its configuration:
$ sudo ifconfig wlan0 down
3. Put the interface in monitor mode:
$ sudo iwconfig wlan0 mode monitor
4. Turn the interface back on. It is now ready to capture packets with *tcpdump*:
$ sudo ifconfig wlan0 up
In WIR, these commands are bundled together in a script that automatically configures the interface when called.

happens by creating a clone or child of the physical interface which, for cards implementing the common *nl80211* driver, can be defined through the *iw* command line tool.[317] The possibility to create virtual interfaces was a significant discovery I made during the development of *Hertzian Field #2*. It brought an important improvement to the system, allowing each node and WiFi card to act as a pulsed radar and as a scanner together. Without needing to increase the amount of nodes, cards or antennas, the spatial resolution of the system can thus be increased by a manifold – thus multiplying the creative possibilities of sculpting hertzian space.

In additions, thanks to interface cloning nodes can implement a third networking functionality (beyond transmitting and sniffing) and also act as *mesh* nodes. Mesh networks are perfect for decentralized sensing systems, allowing each node to be updated on the state of each and every other node. They also allow synchronizing all devices together. It is worth noting that while mesh nodes emit beacon frames for other nodes to detect them, they do so without using an SSID. In this case, the identity of the transmitting node can be revealed through the transmitter's MAC Address. While I implemented mesh networking after *Hertzian Field #1,* the two subsequent works I created did not use this functionality. Instead, they involved a leader/follower (master/slave) architecture where all nodes are connected to a central computer that combines data and performs all processing.[318]

In the existing *Hertzian Field* works, all receiver nodes are configured to track all transmitting nodes within the system. They ignore other APs outside the system using a simple filtering mechanism. Nonetheless, WIR nodes can also be easily configured to, for example, create a passive scanning system that tracks all beacon frames transmitted through a particular WiFi channel. This brings us to a limitation of WiFi technology as radar: While WiFi interfaces can be cloned, they can only be tuned to operate on one frequency or WiFi channel at a time. In order to scan additional channels, a channel-hoping mechanism needs to be implemented. This allows to iteratively scan one channel at a time, however doing that significantly reduces the amount of time spent scanning each channel. Consequently, while

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[317] In Linux, the following command can be used to create a virtual wireless interface named 'wlan0:0' from the physical interface 'wlan0', putting it in *repeater mode* (i.e. 'wds', which stands for *Wireless Distribution System*):

$ iw dev wlan0 interface add wlan0:0 type wds

For more information on *nl80211* see (Valo, 2022) and for more information on *iw* see (Michel, 2019).

[318] A slight complication I encountered with mesh networks - at least while developing the system - was that the transmission rate of normal beacon frames was throttled significantly to about 1 per second until the *hostapd* daemon was restarted.

channel-hopping can be useful for a variety of applications, it is not a good option for a sensing system like the one used in the *Hertzian Field* series. Thus, practically, if one wishes to implement a sensing system in which nodes can operate across several WiFi channels, each node needs to be equipped with as many WiFi cards as the channels it needs to scan.

6.2.7 *Calibration strategies*

Calibration, i.e. tuning the WIR system to the characteristics of the particular configuration and its geometry, in a particular space and a particular time, is an important element that can greatly improve the system's accuracy and workability. In WIR, a separate calibration is required for each Transmitter-Receiver pairing. This means that a system consisting of 1 transmitter and 4 receivers (like *Hertzian Field #1*) requires 4 sets of calibration values, whereas a system with 3 transmitters and 3 receivers *(Hertzian Field #2),* requires 6 calibration sets.

Essentially, each calibration set involves finding the following measurements through a training phase:

- The *baseline RSSI* level of a transmission as seen by each receiver. This corresponds to the *background noisefloor* and reflects the state of the system when the space in and around the field is in a steady and motionless - i.e. typically empty - state. Tuning to this baseline value allows properly accounting for the effects of an interfering/interacting body. This value is highly dependent on the configuration of the network within a space at a given time. It is affected by the internal geometry of the system, i.e. the placement of transmitter and receiver antennas and their distance and angle in relation to each other. It is also affected by the system's interaction with the environment, i.e. the geometry and materials of the architectural space the system is installed in, the placement of furniture and people, temperature and humidity. It is worth noting that - just like in DFL and DFAR systems mentioned in chapter 5 - even when the antennas remain at the exact same place, changing any features of the environment (e.g. moving furniture, opening or closing doors, changes in weather) can affect the system, thus making re-calibration necessary. As a rule of thumb, during rehearsals I avoid moving any objects in the space without recalibrating and try to calibrate every few hours to account for environmental changes.
- The *minimum* and *maximum* RSSI values expected. These values correspond to the positive and negative peaks of deviation from the baseline RSSI value caused by

performative movement within and around field – i.e. the maximum amplification and attenuation of signal strength respectively. The minimum and maximum deviation from the baseline is expected to remain more or less the same for a given work and a particular performer, because the system's configuration and geometry is identical, the interfering body is the same, and the performative actions remain similar.

The first iteration of the WIR system from 2014 - developed for *Hertzian Field #1* in haste during my ZKM residency - was calibrated manually with a rudimentary and rather slow and imprecise process. This involved looking at large-font numbers on the screen while moving in space to deduce the RSSI baseline, minima and maxima.

In 2015-16, while developing *Hertzian Field #2,* I implemented a much-improved automatic calibration mechanism that required a short training phase – a *tuning ritual* of sorts - which usually took around a minute. It involved the performer (myself) waiting for some seconds outside the field, and then moving within the field in the places that my body would move through and occupy during the performance – focusing in particular on areas I know to produce maximum attenuation and maximum amplification of the signal. This is conceptually similar to a soundcheck before a music performance, where the musicians play their instrument soft and loud to adjust the amplification levels. To train the system I would walk inside and outside the triangle (see figure 7.15 for a photo of that configuration), walk across each line-of-sight between the nodes, and move in a circle around each node, making sure that the center of my body was brought about a wavelength away directly in front of the antenna.[319] The data was stored and processed by the system immediately after the training is completed.

That calibration process worked as follows (see figure 6.8):

- Following this *tuning ritual,* the system calculates the minimum and maximum RSS value found per transmitter by each receiving node. This corresponds to the highest amounts of attenuation and amplification respectively. These two numbers allow calculating the overall bandwidth of RSSI fluctuation.
- The system finds the baseline RSS values corresponding to an empty state. This is calculated by finding the median RSS value.
- Because of the low resolution of the RSS data, and in conjunction with the effects of

[319] This involved crouching around the lower-placed node. When developing the system and *Hertzian Field #2*, I found myself having to recalibrate many times in a day, which I could feel having an impact on my knees the day after.

multipath propagation, this baseline value often fluctuates around ±2 to ±4 dB, even when there is absolutely no motion. The system locates and registers if such jitter is present.[320]

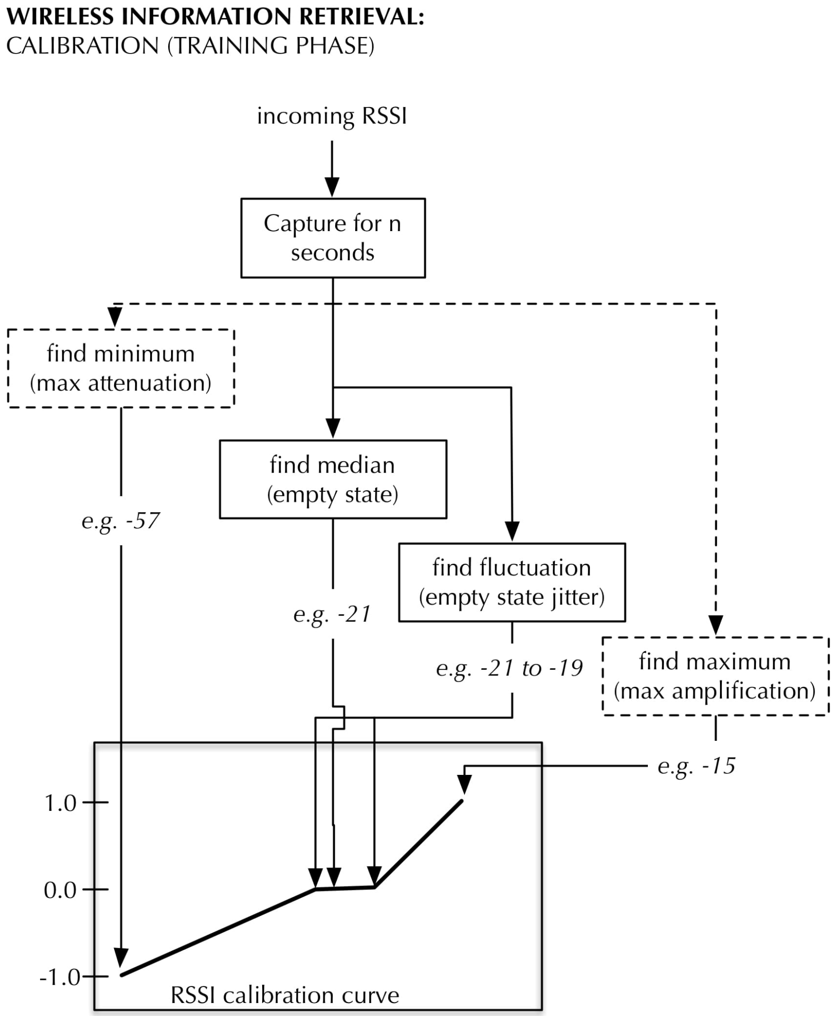

Figure 6.8. The RSSI calibration process involves establishing a calibration curve (essentially a transfer function) to apply to the incoming RSSI dBm values of a specific transmitter when captured by a specific receiver. A separate curve is generated for every transmitter-receiver pair during the calibration phase.

- Next, the calibration mechanism automatically produces a *calibration curve* from all this data. This is essentially a *transfer function* with which incoming RSS can be automatically scaled to a range where the minimum value (maximum attenuation) corresponds to -1.0 and the maximum value (maximum amplification) corresponds to 1.0. The middle point, 0, corresponds to the RSS value found when the system is empty, i.e. the background noisefloor. When baseline fluctuation is detected, this jitter is filtered

[320] This was identified by checking if the values adjacent to the median occur at least 20% as often as the median.

by collapsing the ±2 to ±4dB around the middle point to a value of 0 in the transfer function.

- Finally, the system calculates the actual sampling rate – which fluctuates over time, and is different than the nominal sampling rate, as explained in section 6.2.5 - by looking at the timestamps of beacon frames.

Currently, the system implements a third and improved calibration method. In 2018 I was able to further investigate the properties of WiFi fields by experimenting with the *Hertzian Field #2* setup for several days in a large space that approximated the conditions of a standard performance. This resulted in developing a new calibration method, similar to the one presented above but faster, simpler, more practical - and no less important, less taxing on the body.

This method involves simply finding the set of baseline RSSI values for each transmitter-receiver pair when the system is empty. The *minimum*, *maximum*, and overall *bandwidths* for each node and transmission are predefined using a set of expected amplification and attenuation values for the configuration of the specific work and performer (e.g. +6dBm amplification and 32dBm attenuation for a particular transmitter/receiver pair). These are values that have been tested, benchmarked, and fine-tuned during the rehearsal process of a work.

There two important advantages to this method: Firstly, it significantly speeds up the calibration process from a minute to around 10 seconds. Secondly, and most importantly, it removes the need for physically moving in the space to tune the system. Besides being much less laborious, this eliminates the effects of any inconsistencies between different tuning sessions, which can happen if, for example, the *tuning ritual* is done imprecisely. While tuning inconsistencies were not as important in *Hertzian Field #1,* they were much more so in *Hertzian Field #2* because of that work's use of complex feedback networks for sound generation. As such, I had noticed that when the sensing bandwidth changed (the RSS minima/maxima), the sound and response of the system would differ noticeably – at least to my own ears that were trained and tuned to the system's intricacies. As it was near impossible to repeat the same exact motions during each tuning phase and to put myself in the exact same positions and orientations in the field, the system could behave a bit too surprisingly at times. In contrast, using a predefined set of minimum/maximum/bandwidth values ensures that the system responds in a similar manner in all different spaces. Furthermore, and perhaps more importantly, this method allows calibrating right before a performance and after the audience has found its place next to the work. This makes it possible to account for the effects that the bodies of the audience have on the system, and to calibrate with the most current environmental conditions, which is a significant improvement for WIR as a performance system.

Overall, this third calibration method is most useful for performing finished works, while the second method is best for testing new configurations and during the development process of a work.

6.2.8 *Parsing and conditioning data*

In order to extract useful information from received beacon frames, the captured data needs to be parsed and cleaned up. In WIR, the module handling this functionality is implemented in SuperCollider and is quite more intricate than the transmitter and scanner functions mentioned above.

When the WIR system starts running, a parser function is activated to receive and pre-process incoming OSC messages from each scanner node. The parser can identify all type of frames – control, management, and data frames - not just beacons. WIR has many potential uses beyond sensing, which I plan to explore in future works. The spatial sensing system I have developed for the *Hertzian Field* works presented in this thesis is entirely based on beacon frames, however, therefore I will concentrate on that functionality here.

Incoming *tcpdump* data is parsed and conditioned as follows:

i) *Registering an Access Point*: The first time the system sees a beacon frame from an Access Point whose SSID is in the list of networks to track, it logs its Mac Address and sends out a trigger message. This message can be used, for example, to start a synth or any other processes that should be activated when an Access Point is found to be transmitting for the first time.

ii) *Filtering spurious values*: Incoming RSSI values from tracked APs pass through a special filter to remove outliers. This filter, which I have named *Spurious Peak Filter* (SPF), is an important two-step pre-processing function I have added to the system since *Hertzian Field #2*. The reason is that in *Hertzian Field #1* the system's accuracy was plagued by the infrequent and random appearance of spurious values with a very low RSSI – as if the connection between the antenna and the card was momentarily interrupted. To counter this, the SPF is activated when the signal strength falls below a defined threshold which is set several dB from the low end of RSS values the system expects – e.g at -80dB. Such low values are not immediately filtered out, as there is a slight chance they are in fact caused by environmental factors, slight changes in antenna orientation, someone touching the antenna, etc. Instead, these values pass through a second calculation which decides if this is in fact an outlier caused by the system's inherent noise. This works as follows: when such a low RSS value is encountered, the filter compares it to the previous RSS value and calculates the difference. If the slope is steeper than what can physically occur by human motion between two successive samples (beacon frames), i.e. if the difference is greater than a predefined threshold, the incoming value is ignored and replaced by the proceeding one. If the slope is smaller, the RSS value passes through. A difference of 25dB between successive values is a useful threshold for a sampling rate of 32Hz with the current system.[321]

The need for this filter and the specific implementation was a result of my own observations of such errors in the first iteration of the WIR system. Later on, and while diving into DFAR research for this thesis, I encountered a mention of a similar problem by Wang et al. (2016) with a similar solution proposed: a *Hampel filter* used to remove outlier RSS values. The Hampel filter is a type of decision filter; it operates within a moving time window or memory in which the sample under scrutiny is the middle value (e.g. with 3 other samples surrounding it at either side). The filter calculates the median of this window, and if the suspect sample exceeds it by a certain margin, it replaces its value with the median.[322] While my solution has greatly improved the accuracy of the WIR system, I am interested in comparing its performance against a Hampel filter. Nevertheless, Hampel filters do have one significant drawback for real-time performance compared to the *Spurious Peak Filter*: they introduce a delay because they require a number of subsequent samples to calculate each value. This number can only be reduced to a certain extent, as the less samples/beacon frames included in the window, the less precise the filter becomes. Using just 3 subsequent beacon frames with a sampling rate of 32Hz would introduce a latency of about 94ms, which is certainly not a negligible amount.

iii) *Logging values*: After filtering, the 'cleaned up' raw RSSI is logged into the SSID's history - a large running memory where all RSS values are registered - together with its timestamp. This mechanism allows playing back the data at a later stage without moving in

[321] Instead of the SPF I also tested using a high-pass filter, but that did not improve results. Furthermore, high-pass filtering affects the DC component of the signal, which can be very informative as an indication of distance of an interfering body from a node.

[322] There are many Hampel filter variants. For more in-depth information, see Pearson et al. (2016).

the field, a functionality that is extremely convenient for developing, composing, fine-tuning, and performing offline analyses.

iv) *Shaping*: Once the data is cleaned up by the SPF, it can be further shaped using calibration information obtained during the training phase. This allows shaping the RSSI in two manners to conform to the input requirements of various feature extractors. Altogether the parser outputs 3 streams of time-stamped RSS values which contain the same RSS data, but shifted and/or scaled to different ranges:

a) *'Raw' RSSI:* this is the *SPFiltered* but further unprocessed RSSI value in dBm. These values are always negative, with 0 being the maximum theoretically possible RSS – a value that would correspond to the antennas of the transmitter and receiver occupying the exact same point in space. The actual 'raw' RSSI bandwidth for a given configuration depends on the distance and angle of the antennas, the electromagnetic characteristics of the interacting body or bodies, as well as on environmental factors. Amplification happens through reflections and produces values a few dBm higher than the baseline RSSI. Attenuation occurs when the body is blocking the field and can produce significantly lower values, especially when a Line-of-Sight is interrupted. For example, a typical range in *Hertzian Field #2* is between -26dBm (when the signal is amplified by reflections) to -52dBm (when the LoS is blocked by the body), with a baseline level of -30dBm (empty space).

b) '*DC' RSSI*: in this case the 'raw' RSSI is shifted by an offset which corresponds to the background RSS level, or baseline value. This offset is calculated during the calibration phase by capturing the median RSS value when the field is empty, as mentioned in the previous section. The result is that when there is no interference in the field - i.e. no bodies or objects are within it - the system will output an RSS value of 0. Amplified signals produce positive integer dBm values and attenuated signals negative integer dBm.

c) *'Cooked' RSSI*: values are scaled to a range between -1.0 and 1.0, where -1.0 is maximum attenuation, 1.0 is maximum amplification, and 0.0 is the empty state. Mapping to these values occurs through the transfer function obtained during calibration. This is essentially a lookup table that shapes incoming values and further filters out some of the system's jitter (as explained in the previous section).

v) *Transmitting*: Finally, the parser function transmits these three streams of time-stamped RSSI values via the OSC communication protocol so that they can be further analyzed, processed, mapped and sonified. This mechanism allows performing these operations locally on the same computer that handles parsing - like in the existing works of the *Hertzian Field* series presented in this thesis - but also outsourcing computation to remote machines connected in a (wired or wireless) network and accepting OSC. This enables WIR to scale up gracefully for works requiring more nodes.

6.2.9 *Mining RSSI data: Feature extraction for radio sensing*

The WIR system analyzes *Received Signal Strength Indication* data (abbreviated henceforth as *RSSI* or *RSS*) and extracts features from it in real time, and in three different domains: *time*, *frequency*, and *quefrency*:

- *Time-domain* analysis allows deriving information on when and how interference occurs, and how this interference changes over time. Most of the time-domain extracted features are statistical operations on the RSSI data.
- *Frequency-domain* analysis allows extracting information on the speed and quality or character of motion and interference. Since many of the features implemented here are inspired by the analysis of sound, one could think of this type of analysis as an attempt to define the 'pitch', 'harmonics' and 'timbre' of the body's interference in the field. Following the same metaphor, time-domain analyses could be said to better define the occurrence of events in time (i.e. motion) and its rhythm.
- *Quefrency-domain*, or *cepstral* analysis is not quite about frequency, and not quite about time. Instead, it allows extracting information about the rate of change in specific frequency bands within a signal. Essentially, it gives an insight on how the quality or character of movement changes over time.

To the best of my knowledge there are no WiFi-based sensing implementations in DFL, DFAR, or related fields using such a large, varied and advanced pool of analysis tools.[323]

Feature extractors can operate on any of the three RSSI streams - 'raw, 'cooked', or 'DC' RSSI. Nonetheless, my experiments so far have indicated that some features work best with a particular type of input.

Some features can be extracted directly from these streams (I call these *direct features*). Others operate on an array of RSSI data collected over a user-defined window of time – e.g. a

[323] This may very well also be the case for RF-sensing systems using other protocols besides WiFi.

memory of 1.0 seconds (I call these *windowed features*). Yet others operate on a window as well, but require the RSSI values to be sampled on a fixed temporal grid (*resampled features*). In the last case, extractors use a re-sampled version of an RSSI stream, which is obtained with the method explained in section 6.2.5.

All implemented feature extractors and the type of input they require can be seen in table 6.1.

INPUT TYPE	TIME DOMAIN	FREQUENCY DOMAIN	QUEFRENCY DOMAIN
Direct features	RSSI (conditioned throughput)		
	LPF (moving average)		
	Slope		
	Slope derivative		
	Ring-buffer (circular memory)		
Windowed features	Mean		
	Median		
	Minimum		
	Maximum		
	Bandwidth		
	Standard Deviation		
	Variance		
	Fluctuation		
	Integral		
	Peak distribution		
	Mean difference between consecutive peaks		
	RMS		
	RMS slope		
	RMS slope derivative		
	Onset density		
	Low energy		
Resampled memory	Envelope		
	Resampled buffer		

Resampled features	Resampled onset density		
		Magnitude spectrum	Magnitude cepstrum
		Magnitude spectrum normalized per frame (FIR-kernel style)	
		Spectral energy	Cepstral energy
		Spectral flux	Cepstral flux
		Spectral centroid	
		Spectral brightness	
		Spectral percentile / roll-off	
		Spectral slope	
		Spectral power	
		Spectral RMS power	
		Spectral crest	
		Spectral flatness	
		Tristimulus	Cepstral tristimulus
		Spectral Density	
		Power Spectral Density	
	Autocorrelation	Spectral autocorrelation	
		Spectral entropy	
Higher-order features	i.e. features of features, e.g. the standard deviation of spectral flux		
Beacon combinations	e.g. the difference between the mean RSSI of two beacons		

Table 6.1: A table with all features that can be extracted from incoming Received Signal Strength Indication (RSSI) data in the current implementation of the *Wireless Information Retrieval* system.

i) TIME-DOMAIN FEATURES

a) *Direct feature* extraction:

The following features can be extracted directly from an RSSI stream:

- *RSSI:* a convenience function to simply pass-through RSS values (in their 'raw', 'cooked' or 'DC' states) without any further processing.
- *Low-Pass filtered RSSI:* a moving average filter with an adjustable coefficient. This is a simple and practical way to filter out high-frequency content that is deemed too fast,

such as fluctuations that are too rapid to be caused by motion of the human body and which can instead be attributed to noise from the environment or noise inherent in the system.

• *Slope:* produces the instantaneous slope between the previous RSSI sample and the current one, i.e. the rate of change, or acceleration.

• *Slope derivative:* produces the derivative of the slope, i.e. the slope between two successive slopes, which corresponds to their rate of change. This provides a good indication of sudden motion and can be used to identify the beginning of gestures. This feature produces more responsive interaction than *slope*.

• *Ringbuf:* a circular memory or moving window that contains the last *n* RSS values. The memory duration is defined in seconds (e.g. 1.5 seconds). The system automatically extrapolates how many RSSI samples that corresponds to by multiplying the memory's duration by the expected sampling rate.

b) *Windowed* extraction:

A number of other time-domain features are extracted from a sequence of RSS values obtained within a moving window. Typically, these features are statistical operations that produce a single number to characterize the distribution of the RSSI values within a given chunk of time. These operations do not require a fixed sampling grid, therefore the data is not resampled. These features are:

• *Mean:* produces the average value within the window of time. Both in the literature and to my experience, mean signal strength is a very useful feature for detecting and localizing static changes on the configuration of the space. In DFL, for instance, it is commonly used to deduce the location of a standing body. Changes in mean RSSI signify motion, therefore this feature can be further analyzed to obtain more insights – e.g. deduce the direction or speed of movement. [324]

• *Median:* outputs the median value within the window. This produces similar results to the mean but is more resistant to noise.

• *Minimum, maximum* and *bandwidth:* this analysis produces three features, the minimum and

[324] For an extensive list of features and insights on their usability from the point of view of Ubiquitous Sensing, see Sigg et al. (2015). In brief, the authors reported that, for their use-case, the best performing time-domain features were variance and standard deviation, number of peaks within 10% of maximum, median, and skewness.

maximum peak values of the RSS within a window, and the difference between them (i.e. the bandwidth). These features are indicators of motion or environmental change. The bandwidth describes the overall change within the window of time. When there is no difference, i.e. when the bandwidth is very small or 0, one can assume there is no movement in the field. A large bandwidth suggests motion from a larger object (e.g. the whole body of an interactor) and/or motion spanning from near a transceiver node to further away. The minimum and maximum values by themselves may also be indicative of the position of the interfering body. When the maximum value exceeds the baseline RSS this means that the signal is amplified through reflections, which can only occur when the body if located in certain areas in the field. When the minimum is very low, this may indicate that a body is in front of a transceiver, completely blocking the Line-of-Sight and all inner Fresnel zones. As mentioned earlier (6.2.7), besides their use for real time control, these three features are fundamental for the system's calibration as they allow discovering the expected minima and maxima of interference.

- *Standard deviation* and *variance:* standard deviation calculates the dispersion of values within a window. This feature describes the signal's variability. It is a good indicator of environmental changes between transmitter and receiver and therefore a very reliable indicator of motion. The higher the deviation, the closer to a transceiver the motion occurs, and/or the larger the moving body/body part is. Variance is the square of standard deviation. It is also a good indicator of change but typically somewhat less useful than standard deviation, as it involves squaring the original data which magnifies differences between low and high RSSI variability.
- *Fluctuation:* this feature is produced by dividing the standard deviation of a short window of time (e.g. 0.25 seconds) by that of a longer window (e.g. 2.0 seconds). It reveals how the quality of motion in the short term may have changed from that in the long-term. My experiments reveal fluctuation to be a quite noisy feature, therefore I have not used it extensively yet. More experimentation in the durations and ratio between the two windows is required to see if this noisiness is inherent to the feature, or if there is a setting that makes it more usable.
- *Integral:* calculates the integral within the window. This feature can indicate if motion or interference occurs near or far from a transceiver. To give an example, when standing right in front of a node the integral will fall to a large negative value that is impossible to obtain otherwise. This can be useful for high-level triggers, for instance triggering a new

scene when the performer stands in front of an antenna for a long enough period (e.g. a window of 5 sec). It can potentially also allow defining different zones in the sensing area, for example activating a process when the integral of the RSS falls within a certain range, and another process when it is in a different range. Then a performer can slowly move in and out of zones that have different effects.

• *Peak distribution:* This feature tracks the percentage of raw RSSI signal peaks found within 10% of the expected maximum or minimum strength within a window. It harnesses the effect of reflections to indicate activity within the field, and near-far relations – e.g. how close or how far from a node movement occurs. The feature takes advantage of the fact that reflections at nearby or remote objects impact the signal strength at a receiving antenna. When all peaks are of similar magnitude, this is an indication that movement is farther away. When they are not, this means that at least some movement occurs near a transceiver antenna. This feature can also be used to distinguish between the movements of different bodies when, for instance, one interactor moves near while another moves far from a node (Sigg, 2015). In WIR, this feature works best with the 'raw' RSSI stream compared to a pre-defined RSSI value used as the expected maximum - typically derived during calibration - rather than comparing to the maximum within the window under consideration. The latter works better when the window is very large, but that makes the feature slow and less responsive as a means of real-time control.

• *Mean difference between consecutive peaks*: The average difference between consecutive maximum peaks in a window is a useful way to distinguish between different types of activities in the field. More specifically, a low difference indicates a static environment or one without much activity or motion, whereas high differences indicate more activity.

• *RMS:* produces the Root-Mean-Square of the RSS in a time window. The concept of this feature is drawn from audio signal processing, where RMS is used to calculate the average power of a signal over time. In WIR, RMS corresponds to the average power or amount of motion. This feature can be extracted from the ‘cooked’, ‘raw’ or 'DC-filtered' RSSI.

• *RMS slope* and *RMS slope derivative:* The first feature produces the slope between consecutive RMS values, and the second the slope derivative, i.e. the slope of the RMS slope. These are excellent features for tracking movement *onsets* when the slope exceeds a threshold. The *onse*t is a concept I transposed from music to radio sensing. In audio signal analysis, an *onset* signifies the beginning of a new sonic event, such as playing a note on a piano. In WIR, an *onset* represents a new movement event, most often corresponding to a change in direction or speed of movement. These features allow recognizing when a new gesture starts and are thus very useful for triggering sonic events or changes as a response. Both 'cooked' and 'raw' RSSI can be used, with the former commonly producing more usable results.

- *Onset density:* this is another feature borrowed from music. The extraction process works as follows: First, a window of 'raw' RSSI values is split in gestural segments using an *onset-detection* process inspired by music segmentation. The system finds gestural *attacks* (i.e. the beginning of a gesture) by looking at the *peak* RSS values. Each segment is defined by: a) its peak value (the *attack* of the gesture); b) the value right before the peak (the *sample-before-attack*); and c) the last value in the gesture (its *release*, which is a sample whose value is lower than both the previous and the next value, i.e. a sample that corresponds to the lowest point of the first *trough* after the attack). For each segment, the algorithm calculates the *slope of the attack* from its beginning to its peak. If this slope exceeds a defined threshold, an onset is detected. Finally, the algorithm calculates how many such onsets are found for every second within the window, to produce an estimate of the density of onsets.
- *Low Energy:* The *Low Energy* feature is a complex analysis also borrowed from sound, and specifically from the MIR Toolbox (Lartillot, 2012 and Tzanetakis and Cook, 2002). In its original audio-based implementation, the feature combines analysis in two temporal layers: At the lower level is a sequence of short windows analyzing an input sound into segments. These windows are short enough (e.g. 20-25ms) for the magnitude spectrum and frequency characteristics to remain stable throughout their duration. Any timbral development of the sound will thus appear as a difference between consecutive windows. At a higher level, this pattern of change over successive small windows of time creates a sensation of sonic *texture* emerging through the progression of these windows. The *low energy* feature operates on this longer temporal frame which lasts just as long as a texture needs to emerge (e.g. about 1 second). This so-called *texture window* contains a sequence of metadata, corresponding to the extracted mean and variance of all shorter windows. This sequence forms a kind of energy curve over time. The *low energy* feature finds the percentage of short windows whose RMS energy is lower than the mean RMS energy across the entire *texture window*. In this manner the algorithm assesses how

energy is distributed over the larger timeframe and specifically if it remains constant or if it varies, and by how much. To give an example in the sound domain, a recording of vocal music or percussion will contain more silences than a recording of bowed strings and thus will appear more varied. This will result in a *higher low-energy* value. In terms of radio-sensing data, continuous motion produces a *lower low-energy* value than movement with abrupt starts and stops. In this manner, the *Low Energy* feature can be used to extract information on the temporal quality of movement within the field. My implementation of this feature in WIR splits a large *texture window* (a circular memory of e.g. 4 seconds long) into a number of smaller equidistant frames/windows (lasting e.g. 1/4 of a second). It performs an RMS calculation for all frames, and then finds the percentage of frames whose RMS is lower than the average. A multiplier can be used to tune this calculation to, e.g., 110% of the average RMS, which in some cases may help against noise. This feature appears to work best with ‘raw’ RSSI.

c) *Resampled* extraction:

The following features operate over a window of time in which values are (re)sampled at a fixed temporal grid. As such, these features implement the re-sampling method mentioned in 6.2.5.

The first two features simply provide access to a moving window of the re-sampled RSSI data, i.e. to a memory of a defined duration (e.g. 1 second):

• *Envelope*: this extractor converts the time-stamped RSSI into a segmented continuous function (i.e. an ‘Envelope’, in SuperCollider-speak). This is primarily a utility feature that can be used by sound or control processes that require this type of envelope function.

• *Resampled buffer*: this produces an array of RSSI values sampling the *Envelope* feature at a fixed temporal grid. This extractor essentially re-samples the input at a requested sampling rate, which can be higher or lower than the original rate of the input. This feature can be used, for example, to create a constantly changing wavetable that an oscillator reads at a low frequency as control data, or at a high frequency to produce audio. This feature formed the basis for the wavetable synthesis system used in *Hertzian Field #1*, as will be explained in section 7.2.3.

• *Resampled onset density*: this feature works in the same way as the *onset density* algorithm described earlier, but uses the re-sampled memory instead of an non-equidistantly sampled window of time. As it stands, this feature performs worse than the original *onset density* version because re-sampling and interpolation add noise, which makes tracking onsets less reliable.

• *Autocorrelation*: this is another feature inspired by audio signal analysis. WIR implements a time-domain autocorrelation algorithm as a tool for tracking periodical motion in the RSSI data, and identifying its frequency or speed. *Autocorrelation* works by comparing a temporal window of the input to a past version of itself. This allows identifying patterns that are masked by noise, such as signal periodicities. In audio, autocorrelation is used for pitch tracking - i.e. revealing high frequency periodicities - as well as for beat tracking - i.e. revealing sub-sonic periodicities which correspond to rhythm. This radio-sensing variant implemented here identifies the frequencies that appear to contain periodicities. Technically, this involves finding local peaks, i.e. samples with larger RSSI values than their neighboring samples, or samples equal to infinity. The period is calculated by determining the average time difference between successive local peaks. In WIR, autocorrelation is a higher-level feature that can be applied not only to RSSI data, but to any other extracted feature. This allows, to give an example, finding periodicities in the standard deviation of the RSSI, which can be used to identify if large movements happen with a certain rhythm. More on this type of layered - or high-order - feature extraction will be discussed later in this section.

There are also a few time-domain features in DFAR research that I have yet to implement in WIR, but which I plan to experiment with in a later iteration of the system. Sigg et al. (2015) extract the following features from a 2-second window of RSSI values:

- The amount of *zero-crossings* within a window. This is a measure of the fluctuation of the signal that indicates movement close to a receiver and which can help estimate how many bodies are within a field. In Software Defined Radio systems, where the transmitted signal is continuous and periodic, the distance between zero crossings can be used as a baseline for normalizing other features.
- The *number of changes in the signal's direction*, which points to the amount of noise or interference. This feature can be used in conjunction with the number of zero-crossings to indicate the influence of the environment (such as a moving body) on the transmitted signal. This is estimated by dividing the number of direction changes by the number of zero-crossings.
- Finally, *skewness* is a feature measuring the asymmetry or lopsidedness of the

distribution of values around the mean.

ii) FREQUENCY DOMAIN FEATURES (Analysis of the RSSI spectrum)

The WIR system uses the Fast Fourier Transform (FFT) to convert the time-domain (re-sampled) RSSI input to its frequency-domain equivalent. In this manner, the original complex time-domain signal is represented by a series of sinusoidal components representing the spectrum of the RSSI over a rolling window of time, and thus the spectrum of the interference caused by the presence and movement of a human body. The frequencies of these sinusoids are harmonics (i.e. integer multiples) of a fundamental frequency that corresponds to the lowest frequency of the analysis. The configuration of their phases and amplitudes is dependent on the signal under analysis.

In WIR, frequency-domain features are extracted after performing an FFT of the re-sampled data over a defined window of time (e.g. lasting 0.75 seconds). The spectral analysis is handled by an FFT library for the SuperCollider language (*sclang*) that I began developing at DXArts during a course on Spectral Modeling, taught by Dr. Juan Pampin and Dr. Joseph Anderson. I implemented a simple version of spectral analysis of RSSI data for *Hertzian Field #1* and significantly improved on it prior to composing *Hertzian Field #2*. The most important bottleneck for increasing the system's accuracy was negating the timing drift caused by the *Target Beacon Transmission Time* of Beacon messages, which produced non-equispaced data. To solve this issue, the current system performs a simplified type of unordered FFT**,** by using the time-reordered windows of RSSI data and resampling them with interpolation to the required rate (see 6.2.5). Thus, FFT analysis is essentially performed on the *Resampled Buffer* feature.

Overall, spectral analysis features perform better with the 'cooked' (i.e. remapped) RSSI. Spectrum extraction can be fine-tuned in many ways by defining certain parameters beyond the duration of the analysis window. This includes choosing between 5 types of interpolation to use when re-sampling (linear, sinusoidal, welch, step, and exponential interpolation), choosing between 11 types of windows to use for the FFT analysis, [325] as well as defining the lowest and highest frequencies to track, i.e. the slowest and fastest motion that the system should be able to identify. The lowest calculable frequency also produces the frequency

[325] Implemented FFT windows include: Hann, Hamming, Kaiser, Gaussian, Welch, rectangular, triangle, Blackman, Harris (-74dB), Harris (-92dB), as well as user-defined windows passed to the algorithm as an array. Some of these windows can be further shaped via a parameter.

difference between consecutive FFT partials, meaning that, if the 1st analysis bin is set at 0.25Hz, the second is at 0.5Hz, the third at 0.75Hz, and so forth.

The analysis process works as follows (see figure 6.9):

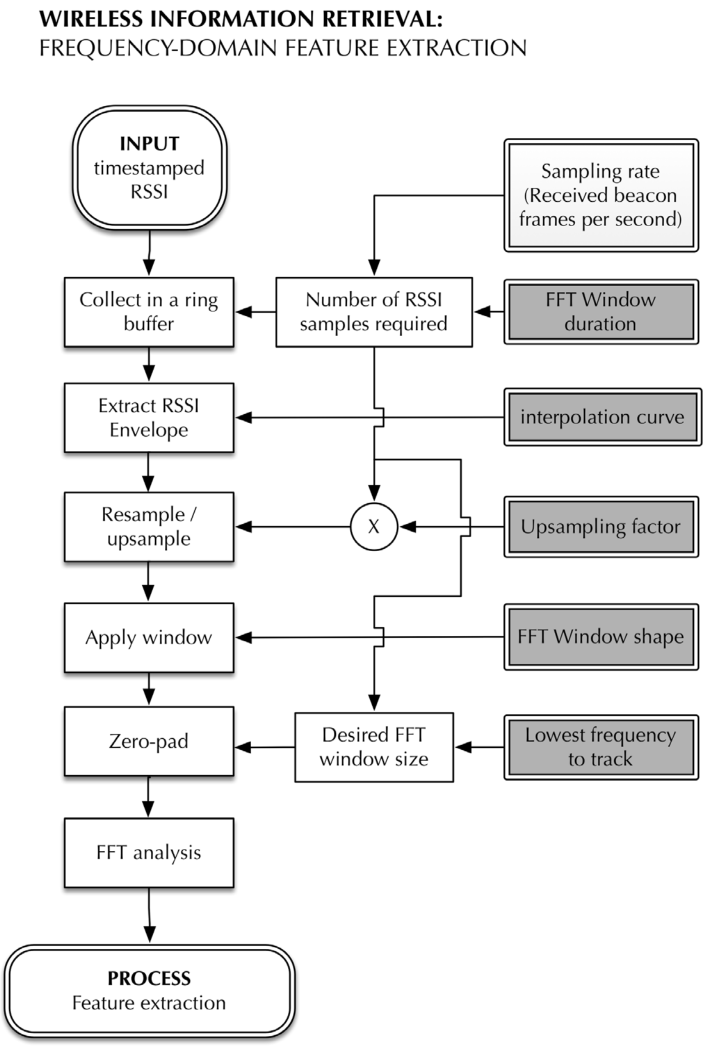

Figure 6.9. How frequency-domain features are extracted in *WIR*: On the left-hand side is the sequence of steps involved in performing FFT and extracting frequency-domain feature. On the right-hand side are fine-tuning parameters settable by the user (with the exception of the sampling rate that can be set automatically by tracking the rate of incoming RSSI values).

- First, the system calculates how many RSSI samples are required by the analysis. This is calculated by multiplying the duration of the FFT window in seconds by the amount of beacon frames received per second from the transmission under analysis.
- The algorithm then extracts the *Envelope* feature from the time-stamped RSSI data, which produces a continuous function or curve that can be re-sampled at a fixed grid.
- Then, this function is re-sampled at the desired sampling rate (*Resampled Buffer* feature). At this stage it is possible to upsample the data, i.e. to increase the sampling rate and

resolution of the incoming RSSI.

- As is standard in FFT, the resulting table of RSSI values is *enveloped* or *windowed* to prepare it for the analysis, i.e. it is multiplied by another table of values, such as a *Hann*, *Hamming*, *Kaiser* or other window.
- The enveloped window can then be *zero-padded*. Zero-padding involves adding zeroes to the end of a time-domain window of data to increase its length. This is a very useful Digital Signal Processing optimization technique used in spectral analysis to increase frequency resolution without having to use an FFT window of a longer duration, as that would produce a longer delay, thus making the system's response slower. Zero-padding is particularly convenient in WIR since the transmission rate of beacon frames is quite low. The amount of zero-padding necessary is calculated automatically by taking into account the user-defined lowest frequency to track (in Hz), and the time duration of the analysis (the duration of the FFT window in seconds).[326]
- Finally, the Fast Fourier Transform is performed on the resulting array.

Further processing of the resulting spectral data can produce a number of features. This includes:

• *Magnitude spectrum* and *Normalized magnitude spectrum*: The magnitude spectrum of the RSS produces the amplitudes of the signal in each analyzed frequency. This provides information on the speed(s) with which the interacting body is moving. The result is almost always not mono-chromatic, meaning that there is energy in several frequency bands. This is because different body parts typically move in different speeds from the point of view of a receiving antenna, which results in the presence of multiple frequencies in the spectrum. The 'harmonic content' of a particular movement is largely dependent on the position, orientation, and configuration of the body in relation to transmitter and receiver. By default, the standard FFT analysis module in WIR extracts the *unnormalized* magnitudes of each frequency bin. There is also a *normalized* variant that assigns the loudest frequency an amplitude of 1 and scales all other amplitudes accordingly. This is similar to the process for designing a *Finite Impulse Response* (FIR) filter kernel from spectral data in audio-based applications.

• *Spectral energy*: this feature calculates the sum of energy in the spectrum. The result is

[326] The size of the zero-padded window is produced by taking the next power of two of the reciprocal of the lowest frequency to track, multiplied by two times the sampling rate (so that at least two cycles of that frequency fit in the window, according to the Nyquist theorem).

normalized by dividing the magnitude of each frequency bin by that of the loudest bin. In DFAR literature, the *normalized spectral energy* has been used to detect periodic motion patterns, such as those exhibited when walking, running, cycling. This is because each different type of motion produces a unique spectral energy fluctuation pattern, making repetitions stand out. Therefore, this parameter is a very good candidate to be fed to a Machine Learning system. In practice, I have found the (normalized) spectral energy to be a very effective and responsive feature for controlling sound, because it allows to easily produce sonic repetitions by repeating movements. This feature performs better using 'raw' RSSI, as it benefits by the inclusion of a DC offset.

• *Spectral flux*: this feature calculates the amount of change between the normalized spectral energy of successive frames. The *spectral flux* excels at detecting outliers: When the type and speed of movement is similar across frames, it remains unchanged. However, when a different motion suddenly occurs, a brief sequence of outlier values will be generated, thus producing a spectral fluctuation between frames. Consequently, this feature is best used for triggering events or changing sounds, instead of constant modulation and one-to-one mapping. Like the spectral energy feature, spectral flux works better with the 'raw' RSSI, as the inclusion of the DC offset makes it less noisy. The implementation of the spectral flux algorithm in WIR uses the sum rather than the Euclidian distance suggested by some researchers (such as Peeters et al., 2011).

Inspired by MIR and audio analysis, WIR implements a number of other spectral features for radio-frequency sensing that are not found in ubiquitous sensing literature. Some of them are still in experimental stages:

• *Spectral centroid*: This algorithm finds the frequency representing the 'center of mass' in the spectrum. This allows deducing what the predominant speed of movement is. This feature works best using raw data but appears to be quite noisy. Furthermore, in the current implementation the range of its output is affected by the sampling rate, which makes using it as a control somewhat challenging. Further experimentation is required to make this feature more useable.

• *Spectral brightness*: this feature traces the amount of high-frequency energy, and thus relates to the spectral centroid. The implementation follows MIR Toolbox, which follows an implementation by Juslin (Juslin, 2000): The unnormalized spectrum is split in two bands with the cutoff frequency being user-defined. The algorithm divides the spectral energy above this frequency by the total spectral energy in the analysis frame to produce a percentage of how much energy is contained in the high part of the spectrum. In audio analysis, this indicates how bright a sound is. In WIR and movement analysis, it can indicate what percentage of the overall motion is faster than a given, predefined speed. This feature appears to work best with 'DC-filtered' RSSI. It seems to fluctuate significantly, although it has not been thoroughly tested yet.

• *Spectral percentile,* or *spectral rolloff*: This feature presents yet another way to estimate how much high frequency content is found in a signal. The algorithm extracts the frequency under which most of the overall energy is contained (e.g. 85% - this is a parameter that is user-defined). The implementation follows the MIR Toolbox (Tzanetakis and Cook, 2002) and the *SpecPcile* UGen in SuperCollider. Like the above feature, it has not been extensively tested yet.

• *Spectral slope*: similarly to the *Slope* feature, the *Spectral slope* calculates the difference in magnitude between consecutive frames. This feature has also not been extensively tested.

• *Spectral power*: This algorithm produces a measurement of the instantaneous spectral power, which is calculated by taking the sum of the squared magnitudes of the spectrum, and scaling it by the number of bins (i.e. separate frequencies) in the FFT analysis. The WIR algorithm follows the implementation of the audio analysis UGen *FFTPower* in SuperCollider. This feature is very responsive to reflections, such as those caused by the rotation of a body located in an outer Fresnel zone. Crossing Fresnel zones also produces a very clear and easily identifiable set of fluctuation curves; subsequently, crossing the LoS produces a very pronounced spike. Beyond its use as a direct control, this feature would also likely be effective for training a Machine Learning system.

• *Spectral RMS power*: Similar to the above feature, this algorithm produces a measurement of the instantaneous spectral RMS power. It is a very responsive feature that can be used for onset detection, and has potential for revealing motion across Fresnel zones and when a Line-of-Sight is blocked. While the output is rather smooth in those cases, when there is no interference in the field it fluctuates somewhat noisily.

• *Spectral crest*: The spectral crest feature indicates how ‘peaky’ the distribution of the spectral energy is. Whereas a sinusoidal signal contains one very sharp peak in its spectrum, and thus has a high spectral crest, white noise has a flat spectrum that results in a low spectral crest value. The WIR algorithm follows the implementation of the

FFTCrest SuperCollider UGen, according to which the spectral crest corresponds to the maximum value of the squared magnitude spectrum, divided by the mean value of the squared magnitude spectrum. The feature is not particularly noisy, it is responsive to movement, and produces minimum fluctuation during stasis. However, it appears to have a bit of hysteresis (continuing to fluctuate after movement has stopped) and it feels less intuitive than other features for the continuous control of sound through movement. For example, it produces a rather stable output when one moves around the outer Fresnel zones or when standing in front of a transmitter or receiver. Nonetheless, this feature has potential as a triggering mechanism as, for example, crossing an LoS produces a noticeable dip in the spectral crest value. This is a feature I have not yet used in any of my pieces, therefore more experimentation is necessary.

• *Spectral flatness*: This feature is another measure of the shape of the spectrum. It indicates how flat (noisy) or spiky (harmonic) it is, and thus it is related to spectral crest. Flatness is calculated by dividing the geometric mean of the spectrum by its arithmetic mean. The implementation follows the algorithm of the MIR Toolbox and works best with the 'DC-filtered' RSSI.

• *Tristimulus*: Another feature that WIR introduces to radio sensing by borrowing a concept from the analysis of sound, which in its turn has borrowed it from the analysis of light. Tristimulus originates in color perception as a way for measuring the red, green, and blue contents of a color. To explain it in terms of waves and frequencies, tristimulus splits and analyzes electromagnetic signals in the optical range into 3 broad bands corresponding to these three basic colors. In MIR research and audio analysis tristimulus maps out the distribution of energy in the audio spectrum by consolidating the spectrum into 3 different frequency bands: low, middle, and high. This feature reduces the spectrum to a trio of descriptive values which, typically, correspond to the spectral energy of the fundamental, the first few partials, and the higher partials (Peeters et al., 2011). In WIR I transposed this concept and technique into radio sensing to identify three ranges of movement speeds. This required some adjustments: First, the overall frequency bandwidth of movement is much narrower than that of sound, and its spectrum contains fewer ‘harmonics’. Moreover, the sampling rate for WiFi signals is significantly lower than audio, therefore the spectrum contains less peaks. Finally, the WIR system aims to analyze all types of movement, not only ‘harmonic’ ones - or whatever the movement equivalent of a harmonic sound would be - which is the types of sound tristimulus in

MIR is mainly concerned with. As a result, I have implemented two variations of the algorithm, both of which work best using the raw RSSI:

1) *Tristimulus Peaks* is a radio-frequency variant of the audio algorithm suggested by Peeters et al. (2011). It first locates the peaks of the spectrum and calculates their amplitudes; it then calculates how much of the overall energy is on the first peak, how much on the 2nd, and how much on all the rest together.

2) *Tristimulus Bins* is the better, more responsive method. The algorithm calculates how much of the overall energy is in each of three sections of the spectrum: the 0th bin (the DC offset that reveals closeness), the 1st to 3rd bins (roughly corresponding to slow or full body motion), and all the rest (higher frequency movements and movements of smaller body parts).

• *Spectral Density* and *Power Spectral Density (PSD)*: This feature operates on the spectrum of the time-domain autocorrelation function, applied on the 'cooked' RSSI. Essentially, it estimates how much of the overall power of the signal is contributed by each individual frequency, and it identifies those frequencies that appear to contain periodicity (see "Spectral Density", 2022). *Power spectral density* measurements are usually given in Watts per Hertz (W/Hz). The algorithm developed for WIR operates on a re-sampled window of data. This can be the RSSI but also a higher-level feature (e.g. the standard deviation or the spectral flux of the RSSI, etc.). The algorithm works as follows:

1. First it performs *autocorrelation* over the window of data in the time domain.
2. The resulting data is *windowed* and *zero-padded.*
3. The spectrum is *extracted* and *normalized* so that the magnitude of the loudest frequency in the analysis frame equals 1.
4. The 0^{th} frequency bin of the spectrum, i.e. the DC offset that corresponds to a static position, is *zeroed out*. This allows tracing peaks on the 1^{st} bin, which is the lowest frequency that can be represented by 2 periods in the analysis frame. The outcome is the signal's *spectral density*.
5. The frequencies that form the local peaks of the spectrum are *located* and then *sorted* by their magnitude. Local peaks are those frequencies with the highest magnitude amongst their neighbors.
6. Frequencies that are higher than a user-defined cut-off point are *filtered out*, so that motion that is considered too fast can be ignored.
7. Finally, the algorithm outputs the *frequency* and *amplitude* of the bins that mostly

contribute to periodicity in the signal. It also outputs the *spectral density* (output of step 4) for use as control data directly.

The *Power Spectral Density* feature appears to successfully reveal periodicities, but further research is required to investigate its full potential as a control mechanism in the WIR system. One potential use would be as a mechanism for synchronizing timed sonic processes to the rhythm of human motion. This feature is also slowly beginning to appear in DFAR research as a way to identify periodic behaviors. Wang et al (2016) for example, used it to track the respiration of multiple targets; through the *Power Spectral Density* of CSI subcarrier data, they were able to extract the peak frequency that corresponds to the period, or rhythm, of a subject's breathing. They could also locate a second person breathing through a second peak. Reading about this experiment was an interesting surprise, as I had already experimented with extracting breathing frequency using this feature on RSSI, which is of course a much coarser data source.

• *Spectral entropy*: this is a feature that has been only partially implemented so far in WIR. In audio, it excels in speech analysis. It is also mentioned in the context of DFAR by Sigg et al. (2015), although without any further mention of how it is used. Further development and experimentation is required.

iii) QUEFRENCY DOMAIN FEATURES (Analysis of the spectrum of the RSSI spectrum)

Quefrency-domain features involve analysis of the *cepstrum*, which is essentially the spectrum of the spectrum. Like spectral analysis, *cepstral analysis* in WIR also operates on the resampled RSSI.

The term *cepstrum* was introduced in 1963 by Bogert, Healy and Tukey to denote an approach that involved *"operating on the frequency side in ways customary on the time side and vice versa"* (quoted in Oppenheim and Schafer, 2004).[327] The name is a playful inversion of the word *spectrum*; it was originally pronounced *kepstrum*, although *sepstrum* is perhaps more common nowadays. The term was introduced together with an accompanying lexicon produced through similar inversions of existing words – *quefrency*, *liftering*, *rahmonics*, etc. The *real cepstrum*, as introduced by Bogert et al., involves calculating the inverse Fourier transform of the logarithm of a signal's magnitude spectrum.

[327] Interestingly, Bogert, Healy and Tukey's paper on the cepstrum preceded the introduction of FFT by Turkey and Cooley by 2 years.

The algorithm was invented to find periodic components in time, such as how long the decay of an echo is. It originates as a way for detecting and representing underground seismic signals caused by the echoes of earthquakes and explosions. *Quefrency-domain analysis* allows separating signals that have been combined non-additively, for example through multiplication or convolution. Essentially, it allows retrieving a source signal that has passed through a non-linear filter. In audio, the human voice represents a similar scenario: The resulting sound can be represented by a model in which the near-periodic pulse trains generated by the glottis are convolved by the impulse response of the vocal tract. A sound-specific variant of the algorithm, the *Mel-Frequency Cepstrum* (MFC) is widely used for finding similarities between audio signals - identifying voices, instruments and other sounds - owing to its efficiency and accuracy in describing the timbre of audio signals (“Mel-Frequency Cepstrum”, 2021). To account for how humans perceive sound, this algorithm first converts the spectrum into a scale of perceptually equidistant pitches, the *mel* scale, and then takes its cepstrum. This results in a number of MFCCs (*Mel-Frequency Cepstral Coefficients*) - a type of filter bank that is used as a representation of a sound’s timbral fingerprint.

Cepstrum analysis does not appear in DFAR and DFL research, however it is a very important tool for audio analysis and forms the basis for a large amount of MIR research, as mentioned earlier. Besides audio analysis and geophysics, the cepstrum is also used in a number of other fields, like medical imaging, radar signal analysis, even machine diagnostics (see Randallm 2017). While developing the system for *Hertzian Field #2*, I became curious to find if the quefrency domain would also prove useful for extracting motion information from radio signals.[328] Indeed, cepstrum analysis provides expressive and informational data, and as such has been used extensively in *Hertzian Field #2* and *#3*.

I have implemented the following cepstral features in WIR so far:

• *Cepstral Magnitude*: This feature calculates the real magnitude spectrum of the magnitude spectrum of a re-sampled window of data. Extracting the cepstral magnitude of a signal involves:

1) Calculating the magnitude spectrum of a window of ‘cooked’ RSS data.

2) Clipping the lowest magnitudes to a (pre-defined) minimum decibel value to boost

[328] As I found out while writing this thesis and after implementing cepstrum analysis in WIR, G. W. Raes also experimented with a rudimentary form of cepstrum analysis in his more recent *Holosound* ultrasound and microwave doppler system - see section 3.7.4 and Raes (2010b).

any frequencies that are too soft.

3) Calculating their logarithm

4) Performing an inverse FFT on the resulting spectrum to produce the signal's cepstral magnitude.

The cepstral magnitude is a very useful feature that provides insights over the rate of change of movement in different frequencies. It is rather expressive as a continuous controller, producing a direct link between sound and the quality of movement and how that quality changes over time.

• *Cepstral energy*: this feature is calculated by computing the spectral energy of the logarithm of the magnitude spectrum. It works best with 'raw' RSSI data.

• *Cepstral Flux*: this feature is a measure of the spectral flux of the spectrum. It also works best with 'raw' RSSI.

• *Cepstral tristimulus*: This feature is a result of personal investigation; I could not find references to it in any literature of any field.[329] I implemented it in the same way as spectral tristimulus, but instead of the spectrum the algorithm looks at the cepstrum of the 'raw' RSSI. It can be quite expressive for gestural control as my experiments have shown, for example mapping its output to the amplitudes of a trio of generators, which become more or less audible as the quality and speed of movement changes.

IV) HIGHER-ORDER FEATURES

The modular approach of the WIR codebase allows performing higher-order feature extraction, which involves extracting the feature of a feature. For example, a 2nd order feature extraction process may involve calculating the *standard deviation of the spectral flux* of the RSSI; another such feature may involve calculating *the magnitude spectrum of the fluctuation* - and so forth. Third-order and even higher-order feature extraction is also possible. However, after a certain point it can become too convoluted to understand and thus to utilize what such high-order features describe. In WIR, particularly useful combinations of high-order features can be bundled together into a 'shortcut' feature. For instance, the *Power Spectral Density* and the *Cepstral Magnitude* of RSSI data mentioned above are technically such higher order features.

329 A Google search for "cepstral tristimulus" or "cepstrum tristimulus" still produces 0 results (last searched on January 26th 2023).

V) BEACON COMBINATIONS

Finally, the WIR implementation also allows performing operations that combine features of two or more beacons. This may involve, to give some examples, summing together the integrals of all nodes, or calculating the difference between the mean RSSI of two or more nodes, or calculating the difference between their standard deviation, etc. This is particularly useful for localizing activity in the field. Triangulation, which has not been implemented in the system yet, works in such a manner and can therefore be supported by WIR. Furthermore, by comparing the difference between what transceiver 'A' receives from 'B' to what 'B' receives from 'A', one can exploit the phenomenon of *link asymmetry* – which will be discussed in section 7.1.2 - to estimate if motion takes place closer to transceiver 'A' or 'B'.

Chapter 7. COMPOSING HERTZIAN FIELDS

7.1 COMPOSITIONAL STRATEGIES, ELEMENTS AND APPROACHES

7.1.1 *Creation process*

This last chapter begins with a discussion of the strategies, approaches and elements involved in creating works using the *Wireless Information Retrieval* sensing system described in the previous chapter. It then proceeds with a more detailed presentation of each of the three *Hertzian Field* pieces I have created with this system so far. To conclude, it briefly presents some avenues for further research.

In practical terms, composing a *Hertzian Field* work is a fairly complex multi-step process that involves: a) *composing space*, b) *composing sound*, and c) *composing interaction* as a framework for d) *composing movement*. While all these elements are interconnected, my personal process can be broken down in general strokes as follows:

• Designing the *configuration* and the *shape / invisible architecture* of the hertzian field. This involves a number of decisions: How many nodes does the system consists of? How many of them transmit and how many receive? What is their geometric configuration, how far apart are their antennas, and at what heights and angles are they placed? What types of antennas do they use? Practical matters, such as the processing power of the computers available for running a system, are also very important at that stage. For example, while deploying many nodes will produce a denser - and thus more expressive - sensing field, analyzing all the data these nodes generate may require more computational power than what is available. Such limitations were certainly part of my design process when composing the *Hertzian Field* works, as these pieces were independently produced thus involving rigid budgetary constraints on the equipment I could use.

• Composing the *sonic processes* that will be used in the system. This is essentially the sound design element of the composition. The decision-making involved here has to do primarily with what kind of sound environment I want to create for a particular work, and how I envision the hertzian field and the effect of movement to be experienced sonically.

- Composing *interaction*, i.e. defining how sound is controlled by movement. This involves mapping WiFi analysis features to sound synthesis and control parameters, and is a process requiring extensive experimentation. The number of interactors that the system is designed for – e.g. a solo performance versus an interactive work for multiple audience members / participants - plays a significant role in choosing which features to extract, how to configure them (e.g. in what time frames they operate), and how to map them to sound. Decisions on what types of movements should be supported, and what the sonic outcome of certain movements or actions should be, are made at this point.
- *Tuning* the output of these analyses to meaningful, expressive ranges. Tuning is a result of extensive experimentation and a dialectic process between body, movement, mapping, and sound. It usually continues deep into the rehearsal/testing process.
- Creating a *timeline* or *score* of the work (such as I did for *Hertzian Field #2* and *Hertzian Field #3.1*) *or designing complex mappings* that can autonomously create rich and dynamic sonic behaviors (such as in *Hertzian Feld #1* and *Hertzian Feld #3*). To clarify the latter case, even when keeping the system static – i.e. keeping the same mappings and sounds, without a timeline or score - a combination of features and mappings can be used to essentially unfold a dynamic score in space-time, modulating or activating different processes when moving in certain areas and/or at certain speeds or manners.
- For performative works, it is important to *rehearse* extensively before a show so that the piece becomes completely embodied. At the same time, I also find it very important to allow myself as the performer to *forget* the work between performances, so that I put myself in a position where I have to *rediscover* it before a new show. While this can be frustrating at first when revisiting the piece and starting a new cycle of rehearsals, forgetting makes me approach it with fresh eyes and allows me to come across new exciting possibilities. In this manner, the work is never stagnant but keeps evolving with every new showing. To assist me also remember what I have done in the past and to recapture particularly important or successful elements of the performance, I also eventually go through audio and video documentation, past written notes, and through my code (especially when in doubt about operational details). I typically do this a few rehearsals.
- For interactive works, besides testing on my own I found it very helpful – if not essential - to *observe and evaluate how others interact* with the system. Audiovisual recordings and

critical discussions with participants/volunteers have been very helpful to this extent, helping fine-tune or even reconfigure the system to actually function as I envisage. Moreover, input from untrained guests can also be a significant aid in discovering new ways of interacting, or even new ways of experiencing a work that may not be evident to me as the maker after having spent so much time immersed in it and thinking about it in a certain way.

- As the system is very sensitive to environmental influence, investigating *how its tuning changes at different times* and, if possible, *at different spaces* is very valuable. Unless the work is site-specific, it is important to make sure that key elements of the system will function as expected under different conditions – from moving to a space of a different size, to having many audience bodies around, even to slight changes in antenna angles, temperature, humidity, or the water contents of the performing body. A robust calibration mechanism (like the one presented in 6.2.7) is extremely beneficial for achieving this. On the other hand, such condition changes may also be harnessed to become part of the work. Nonetheless, investigating how these changes affect the system allows preparing for them and using them in an optimal manner.
- *Composing movement*: My live electronic works have always included a physical performative aspect, where the music is created in real time by the interaction of the body with a system through an interface. While my artistic trajectory led me to include the physical world more and more in my works, I never specifically set to create an interface that I could perform using full body movement. This was simply where my research path led me, gradually and organically. Sound is my starting point for all three *Hertzian Field* pieces I have created. Movement is not choreographed like in a dance piece, but emerges through interaction with the system, and evolves through the process of composing, rehearsing, and performing a work. While the sensing technology deployed in the three *Hertzian Field* works is essentially the same (the *Wireless Information Retrieval* technique), each piece establishes its own movement language. On one hand, this language is certainly influenced by the context of the work. Interacting with the *Hertzian Field #1* system in an installation setting – possibly with other interactors present in the field or watching from the sidelines - is very different than performing *Hertzian Field #2* solo on stage, while being inside the steam sauna of *The Water Within / Hertzian Field #3* and *#3.1* is its own radically idiosyncratic experience. In that last work, hot steam and architectural design are used to guide the movement and

behavior of visitors and to shape how they interact, enforcing a much slower and meditative approach that is focused on smaller movements and intense listening. On the other hand, apart from the format, setting, and context of each individual work, the types of movements that emerge are greatly influenced by how the WIR system is configured: To this extent, the hertzian topology and spatial layout of the system is instrumental, as is the choice of features to extract from the radio-frequency data, the duration(s) of the temporal windows on which they operate (i.e. the duration(s) of the system's memory), the ways in which extracted information is shaped into control data, the ways in which this data is mapped to modulate, generate, or process sound, and the character, qualities, and temporal development of the actual sound produced. Composing the interaction between body and field, and creating a strategy and movement language to navigate space and connect the two together is not an exact science but a craft, as it involves all the above elements. Composing movement thus requires extensive thinking, testing, experimenting, and practicing, and requires approaching the system with an open and critical ear.

After about 8 years of working with the technology and learning its affordances, my compositional process has become more streamlined and straightforward. This is also facilitated by a number of composition and development utilities that I implemented early on in the SuperCollider environment. This includes:

- *Data viewer:* As an aid for composing and tuning the system, the codebase includes a Graphical User Interface (GUI) environment for displaying live incoming beacon frame data received by each node (figure 7.1). This includes the received RSSI and the real received sampling rate (per transmitter/receiver pair), as well as a graphic display that can be attached to any existing feature extractor to show its values in a 2-dimensional histogram. The viewer is of great assistance during the compositional process, as it allows observing the ranges of output values resulting from specific movements (figure 7.2). It is also very helpful when installing and setting up the system for a performance, as it permits easily and rapidly verifying that all nodes function as expected and it helps positioning and orienting the antennas at the correct angles.

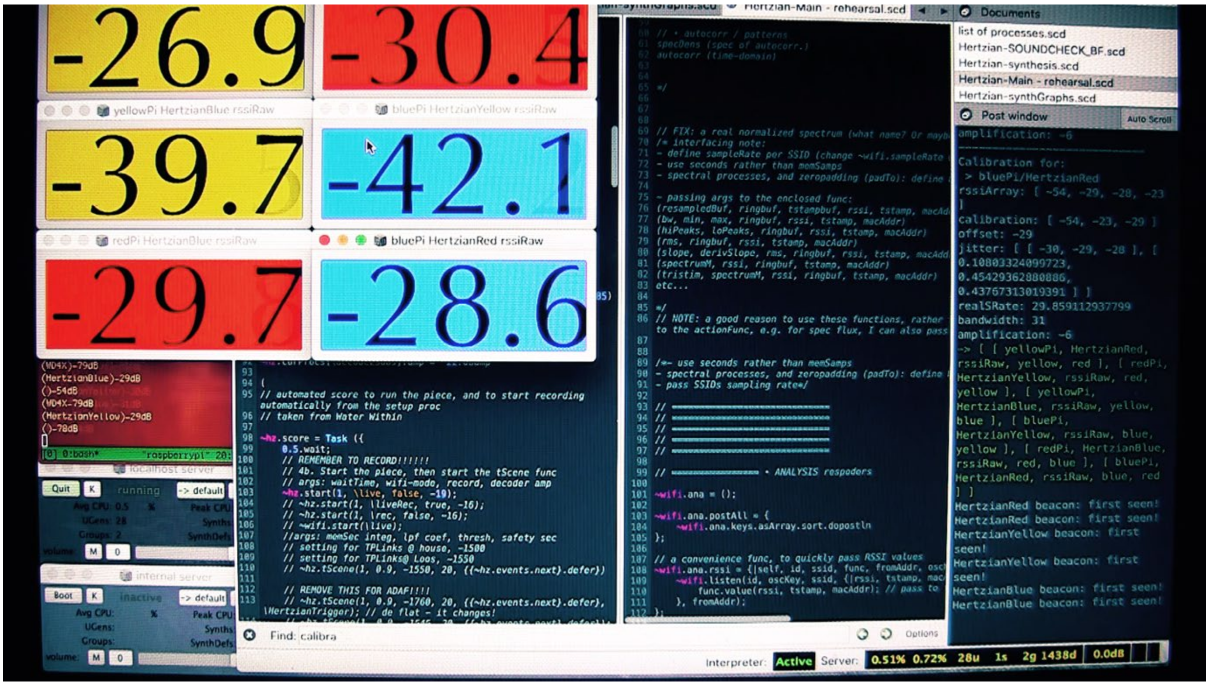

Figure 7.1. Screenshot of the main computer during the calibration of *Hertzian Field #2*. The top left windows display the live RSSI within *SuperCollider* after applying an averaging filter; each window is named after the receiving node and colored after the captured transmitter. The terracotta window behind them is from the *Terminal*; it displays *tcpdump* data directly from a transceiver node - connected via tunneling (ssh). More information is visible on the right of the screen (*SuperCollider* 'Post' window), including calibration data for the 'blue'-'red' transmitter/receiver pair - such as its 'rssiArray' (i.e. *calibration curve*), minimum, maximum, and bandwidth values - as well as notifications that transmitter beacon frames have been detected by the system.

- *Gesture Recorder:* This model can record and playback captured RSSI data – for example the data generated by a performance (see figure 7.3). I implemented this functionality while composing *Hertzian Field #2* and it became an indispensable tool, allowing me to move in the field, capture data, and then play it back while adjusting the feature extraction parameters, mapping, and synthesis controls. Besides speeding up development, it was also helpful for the health of my somewhat aging knees, which would typically complain after a few long and intensive programming and composition sessions.

- *Node-interfacing utilities:* This includes a number of utility functions that interface between SuperCollider and the remote Raspberry Pi nodes, such as opening *Secure Shell Protocol (SSH)* sessions in Terminal, copying code files from the main computer to the nodes, and vice versa. These utilities have also been great time-savers during the development process.

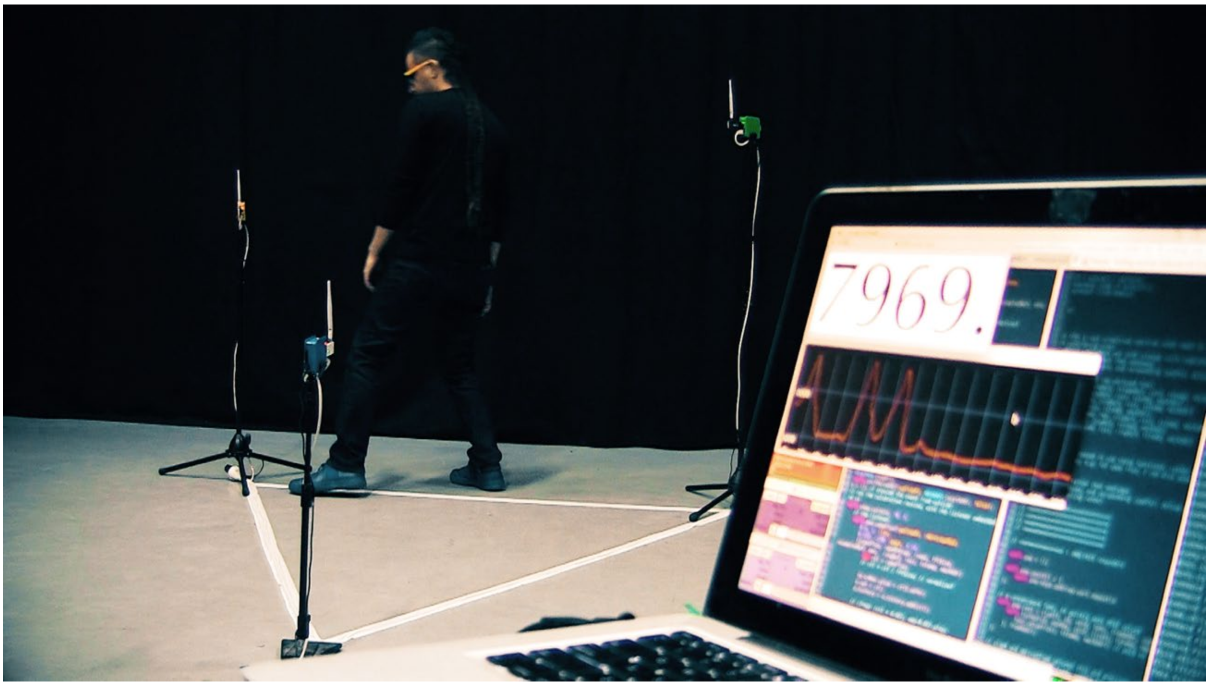

Figure 7.2. Still from a lecture-performance video for *Bergen Electronic Center* (BEK); it shows me interfering with *Hertzian Field #2* in the background, and the computer running the piece in the foreground. Visible on its screen (top left) are a *data viewer* window displaying the current numerical value of an extracted RSSI feature (*Spectral Power)* and a rolling 2D histogram of that feature (with a memory of about 20 sec). The spikes on that graph correspond to my body breaking the LoS beam between the transceivers on the base of the triangle.

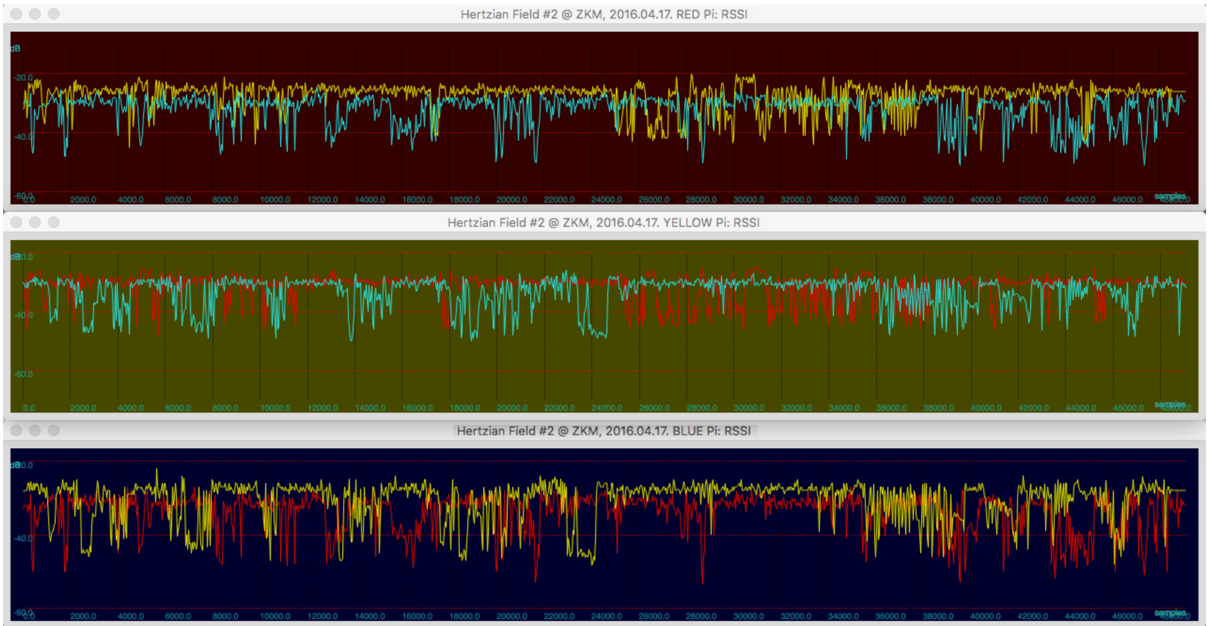

Figure 7.3. Raw RSSI data recorded from a complete performance of *Hertzian Field #2* at ZKM Karlsruhe in 2016. The *Y* axis displays the RSSI in dBm and the *X* axis the index of each sample. Top graph: the 'red' receiver node capturing the 'yellow' and 'blue' transmitters. Middle: 'yellow' receiver capturing 'red and 'blue'. Bottom: 'blue' capturing 'red' and 'yellow'. For the geometry of this configuration, see figure 7.17.

7.1.2 *Sculpting hertzian topologies*

The spatial configuration of radio-frequency sensing space is a fundamental part of a hertzian work. Therefore, composing a *Hertzian Field* begins with designing its topology. This includes deciding on elements such as: the number of transmitters and receivers, the types of antennas, the geometrical layout of the nodes - including the distances and angles from one another - and the characteristics of the space in which the system will operate. The design of a hertzian topology can be thought of as sculpting an invisible interactive architectural space.

One of the technology's primary strength is that it allows creating reactive spaces with radically different shapes and sensitivities, simply by configuring the system in one way or another. Unlike most vision-based motion sensing systems where the camera eye typically aims to produce an 'objective' representation of space and of the movements within (i.e. a representation that largely coincides with our own human visual perception and understanding of space as a cartesian, 3-dimensional coordinate system), each distinct configuration of transmitting and receiving antennas constructs a different kind of space with unexpected properties that can be discovered through movement. I find this particularly inspiring, as it means that a hertzian sensing system does not attempt to replicate a form of knowledge that I can acquire with my own eyes about space, but instead gives me insights into a physical yet inaccessible space which I cannot perceive or interact with in other ways.

Designing a hertzian space involves a number of considerations: artistic, practical – such as the type of hardware, software, and space available – but also purely physical considerations that relate to phenomena stemming from the nature of the radio medium. My own design process is experimental, investigating and fine-tuning configurations that can optimally support and stimulate my creative process and what I have in mind with each work. Through these experiments, I have observed and verified a number of phenomena that should be taken into account when designing a hertzian system. These personal observations are supported by radio/microwave theory, as well as by radio-frequency sensing experiments by ubiquitous sensing researchers, such as Woyach et al. (2006). While some of these observations have been mentioned earlier, it is useful to gather them all together here:

- *Number of nodes*: The more nodes a system contains, the higher its spatial resolution will be. However, as mentioned earlier, there is a computational trade-off as there is a limit to how many feature extractors a system can run.
- *Pulse rate* and *resolution*: The faster the transmitters send out radio pulses (beacon

frames), the higher the temporal resolution of the sensing system will be. However, this introduces another trade-off to consider: Computationally, fast beaconing may generate more data than the available hardware can process; furthermore, it may clog the air interface which will result in drifts in the system's timing because of the *TBTT* mechanism (see 6.2.4).

- *Topology effects*: Different network topologies (i.e. placement of transmitter/receiver nodes) produce different RSSI levels and feature extractor values, even if there are no other changes in the space. This has a number of implications, such as that the system needs to be recalibrated if any antennas are moved when they are meant to remain static.
- *Effects of space*: Conversely, different configurations of a space - caused for example by repositioning furniture or audience bodies in it - will produce different RSSI levels even if the network topology remains the same. This occurs because spatial changes cause different multipath fading patterns to be formed. This inherent *spatial memory* of wireless networks is of particular interest and could potentially become an integral part of a work. *The Water Within / Hertzian Field #3* (in its two iterations) makes use of this effect, modulating the system as interacting visitors reposition themselves within the steam sauna room.
- *Distance between nodes*: The further two nodes are from each other, the weaker the signal will be when it arrives at the receiver. This means that placing nodes at larger distances to each other produces RSSI fluctuations with a smaller bandwidth. Consequently, configurations with nodes further apart generate interference data with a lower resolution. On the other hand, such configurations create larger interactive spaces, which can better support more interactors. For instance, my strategy in *Hertzian Field #1* was to have a fairly spread configuration between nodes (with receivers placed in the corners of a 5x5m square) to allow several people to explore the system together. Interactors that are close to one node are far from the rest; this means that the effects of their interference on the field are fairly localized, exerting most influence on nearby nodes but having much less effect on other nodes with which other participants may be interacting. In this manner, it becomes easier to discern how every interactor's actions influence the system. My strategy was different in *Hertzian Field #2*, as I wanted to create a tighter configuration that allows a single performer to be able to significantly interfere with all fields simultaneously. Nodes are thus placed closer to each other in that piece, increasing overall spatial sensitivity and limiting the performing area to a size that could allow

performing the work on a stage. I also placed each node at a different height to allow tracking the movement of the performing body in 3 dimensions (more on this below). *The Water Within / Hertzian Field #3* operates in a middle ground between the two approaches, creating an interactive area that is smaller than that of *Hertzian Field #1* but larger than that of *Hertzian Field #2*.

- *Fluctuation in relation to movement*: The amount of RSSI fluctuation caused by motion depends on the trajectory of this motion in relation to the topology of the network and the spatial layout of the environment. It also depends on the size and dielectric properties of the moving object; for instance, interfering with one's arm versus one's core produces different results.
- *Moving nodes versus interfering*: Moving a node (transmitter, receiver, or transceiver) has a more pronounced effect on the signal than the interfering movement of an object within the radio field.
- *3-dimensional topology*: Placing transceiver nodes at different heights increases the system's sensitivity considerably as the electromagnetic fields slice 3-dimensional space diagonally. As a consequence, different parts of the body cause most interference at different areas of the interactive space, which increases expressivity, and encourages the interactor to move in all 3 dimensions, including the *z axis* (vertical motion). In my work, I first introduced this type of layout in *Hertzian Field #2*. The results were very satisfactory, therefore I designed a similar topology for *The Water Within / Hertzian Field #3*. Later, during my research for this thesis, I found that Scholtz et al. (2013) also used a similar configuration with nodes placed at different heights, which produced higher accuracy in distinguishing between different types of behaviors.
- *Anisotropic fields*: Radio frequency fields, like the ones in *Hertzian Fields,* are anisotropic, meaning that some areas are more sensitive to interference than others. The most sensitive areas of a field are the Lines-of-Sight (LoS) (i.e. the 0^{th} Fresnel zone) between transmitters and receivers, because that contains the biggest portion of transmitted energy (see section 5.5.2). Thus, an obvious case for motion detection is when an object breaks such a line, as that creates a strong electromagnetic shadow and produces a noticeable RSSI drop. While motion in the LoS and the inner Fresnel zones produces most interference, motion in the surrounding environment further away (the outer Fresnel zones) can also be detected. This happens because of two principal reasons:

Firstly, because the moving object absorbs energy from secondary paths of transmission caused by multipath propagation. Secondly, because it causes new propagation paths by reflecting the signal. These reflections can reach the receiver's antenna in-phase or out-of-phase with the original signal. This has the effect amplifying or of attenuating the original signal respectively, as delayed copies with different phase relationships are added to it.

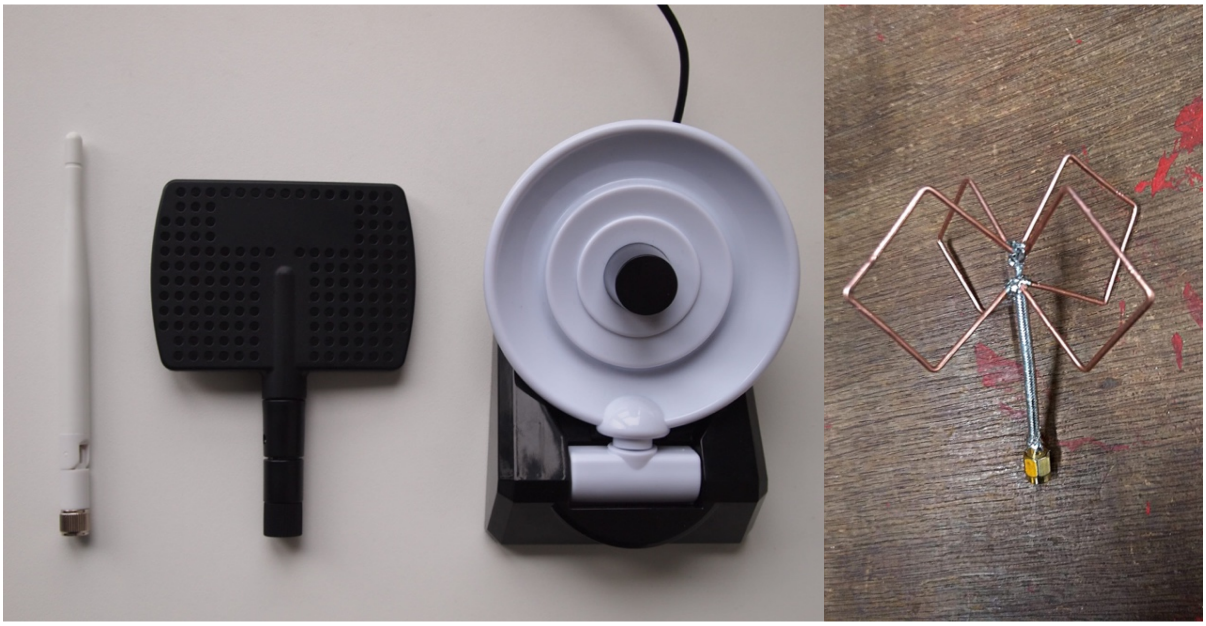

Figure 7.4. Experimenting with different antennas. Left photo: three commercial antennas I have used in my experiments with the WIR system: a normal dipole, the type of antenna I have used in the *Hertzian Field* series so far (left), and two - rather badly designed - directional antennas: a plate antenna (middle) and a parabolic antenna (right). Right photo: an omnidirectional biquad antenna for increased gain transmissions I built after a design by McNeil (2015).

- *Antenna radiation pattern*: Antennas with different radiation patterns can be used to sculpt the shape of a hertzian field, and thus its response and sensitivity throughout the field. Directional antennas are more anisotropic than dipole antennas (which are quasi omni-directional); typically, they produce a more focused beam but to the expense of coverage on the side lobes. Practically, and depending on the exact pattern of an antenna, this means that the inner Fresnel zones will be more sensitive for more directional antennas, while other areas will be less sensitive. So far, I have experimented with dipole antennas, plate antennas and parabolic antennas (figure 7.4). The three *Hertzian Field* works have deployed dipoles as those provide wider coverage; however directional antennas would definitely be useful where one wants to limit resolution to a more focused energy beam.

- *Link asymmetry*: The Line-of-Sight (LoS) is anisotropic as well; this is a phenomenon called *link asymmetry*. While one could readily assume that the connection or link between two transceiver nodes is symmetrical, this is not always the case. Link asymmetry can be caused by a number of reasons (Woyach et al., 2006):
    - It can be introduced if the antennas have different radiation patterns, transmission power, or orientation. The effects of orientation are more apparent with directional antennas, but also influence omnidirectional transmission since no antenna is perfectly isotropic.
    - Link asymmetry can also be introduced in non-LoS scenarios due to the *capture effect,* also known as *co-channel interference tolerance.* This phenomenon, long known in FM radio, describes the capacity of certain receivers to capture and correctly demodulate only the strongest transmissions received by their antennas, while ignoring and filtering out as noise any weaker signals received on the same band. This happens even if the secondary transmissions are significant, as long as it is weaker (Leentvaar and Flint, 1976). The *capture effect* is widely present in my spatial FM radio work '*Act so that there is no use in a centre'.* This phenomenon is also encountered in many other RF systems, including microwave networks like WiFi (Ware et al., 2001 and Whitehouse et al., 2005). In this case, an interfering Access Point may mask the transmission of another AP if it is closer to one of the receiving nodes.
    - The combination of interference and multipath fading (i.e. signal loss and distortion caused by multipath propagation) is probably the most notable cause of link asymmetry: In a closed space, and/or a space with obstacles, the transmitted signal bounces around as it radiates from the transmitter, thus reaching the receiver from multiple points in space. As such, the *wireless channel* (i.e. the radio path) between two transceivers *i* and *j* does not necessarily coincide with a physical straight line between them (i.e. the LoS), and/or is not limited to that LoS. This means that movement close to one or the other transceiver node will cause different multipath propagation trajectories for the two transmitted signals, resulting in link asymmetry.

  Practically, the result of link asymmetry is that movement closer to *i* produces different interference patterns than movement closer to *j*, or movement occurring in between the two. This is a very interesting effect that I noticed in practice while developing *Hertzian Field #2*. Harnessing it contributes significantly to the system's sensitivity and its potential for performative expressivity. WIR exploits this phenomenon through bi-directional scanning, meaning that the field between i and j is sensed by both transceivers, each from their own perspective. The feature extraction results from the two transceivers can be used as control data directly, or they can be combined (e.g. by subtracting one from the other, see subsection 'Beacon combinations' in 6.2.9) to produce a new higher-order feature. See figure 7.5 for a visual example. It should be noted that bi-directional scanning requires more computation, as for a network of n transceiver nodes the system will need *n squared* measurements.

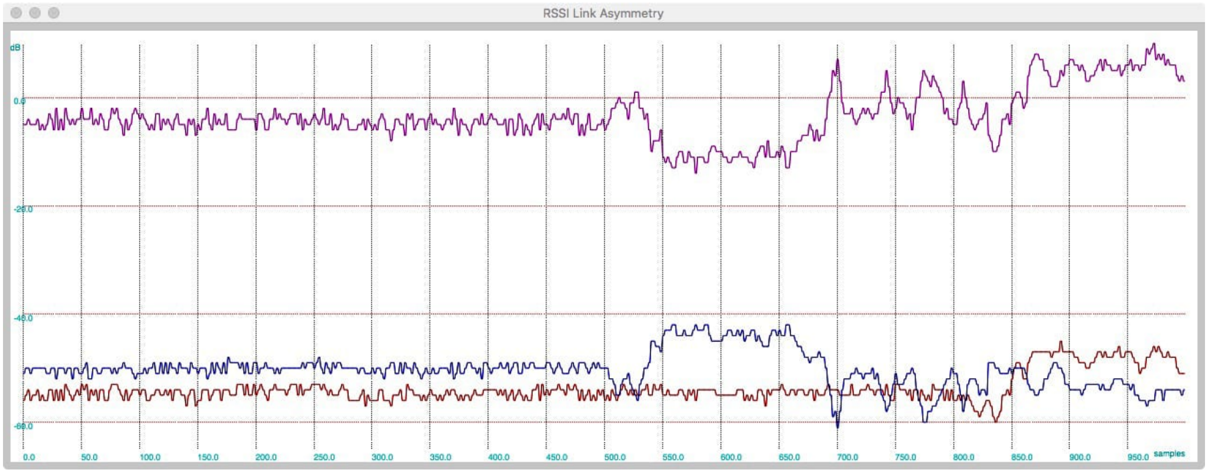

Figure 7.5. An example of *link asymmetry* using recorded RSSI data from *The Water Within (Hertzian Field #3.1).* The *X* axis displays 1000 samples in sequence and the *Y* axis displays their dBm. The lower part of the graph shows the RSSIs of two transceivers captured from one another (i.e. 'blue-tracking-red' and 'red-tracking-blue'). Note that their baseline values differ and that, when there is motion closer to one of them, a significant difference in RSSI variation is produced. The top line (purple) represents the difference between the two RSSI values, i.e. the measured *asymmetry* between the two links/nodes.

- *Effects of architecture*: The size and architectural characteristics of the space where the system is installed play a key role because of how electromagnetic waves propagate and dissipate in space. Depending on the architectural geometry and materials used in a particular space, on the configuration and topology of the system, and on the placement and angle of the antennas in that space, a number of *reflection nodes* and *antinodes* caused by static waves will be created (see figure 2.10 for Hertz's visualization of the appearance of such nodes in the Karlsruhe physics room from 1888). This can be understood as a process conceptually similar to what happens to acoustic signals when they reverberate in a space. Due to multipath propagation, radio-frequency sensing works particularly well in environments with rich scattering - indoor spaces, corridors, etc. - and is less sensitive in open spaces. This is because multipath propagation creates a denser sensing field through reflections, which act as secondary Line-of-Sight paths. While weaker than the direct LoS, such reflections still create areas that are more sensitive than the rest of the field. In smaller spaces there are more reflections, and thus secondary LoSs, which makes the system more responsive and thus more expressive. Due to this effect it is important to keep in mind that, in works like the *Hertzian Field* series, expected responses of the system to particular movements in specific areas - and thus the production of specific sounds and the perceived behavior of the system - can be modified (or even disappear) when placed in a different space, sometimes even when installed differently within the same space. This can be problematic when preparing for a show, as performance spaces tend to be larger than rehearsal spaces, portraying less multipath characteristics, and thus potentially feeling less responsive in certain areas in the field. In my experience, the WIR system has been routinely less sensitive in large open stages, where performances usually occur, than in the smaller studios where I usually rehearse. Fine-tuning the work in the performance space, or in a space with similar dimensions, is thus very valuable. Partly, because this allows determining the overall bandwidth of expected RSSI fluctuation - i.e. how many dBm the field is expected to be amplified and attenuated. For the most part, this seems to make the sensing system similarly responsive on the same spots, whether in big or small spaces - or at least it makes it reliably similar.

- *Effects of audience bodies*: The presence of an audience and any movement on their part will also influence a radio-frequency sensing system depending on their position. As discussed in section 5.6, human bodies absorb part of the energy of radio/microwaves, thus further reducing multipath propagation. In a performance like *Hertzian Field #2*, where the focus is on the interference of the performer's body, it is thus wise to have the audience sit rather than stand, as this significantly reduces how much they move during a show, thus also reducing environmental changes in absorption patterns through the duration of a performance. As a strategy for mitigating the effect of audience's bodies, I have also performed *Hertzian Field #2* on top of a platform (figure 7.6).

- *Effects of weather*: Temperature and humidity also affect RF sensing systems like WIR. This is reflected in the baseline RSSI level changing by a few dBm (I typically observed differences between 2-5dBm in *Hertzian Field #2*). I have welcomed this effect in my existing works, making them somewhat responsive to these changes in environmental conditions by using the raw RSSI measurement for some feature extractors and processes. In this manner, when the baseline RSSI changes, the system sounds different. While the effects of humidity and temperature are secondary on the first two works, they are central to *The Water Within / Hertzian Field #3*, which fills the sensing space with hot steam.

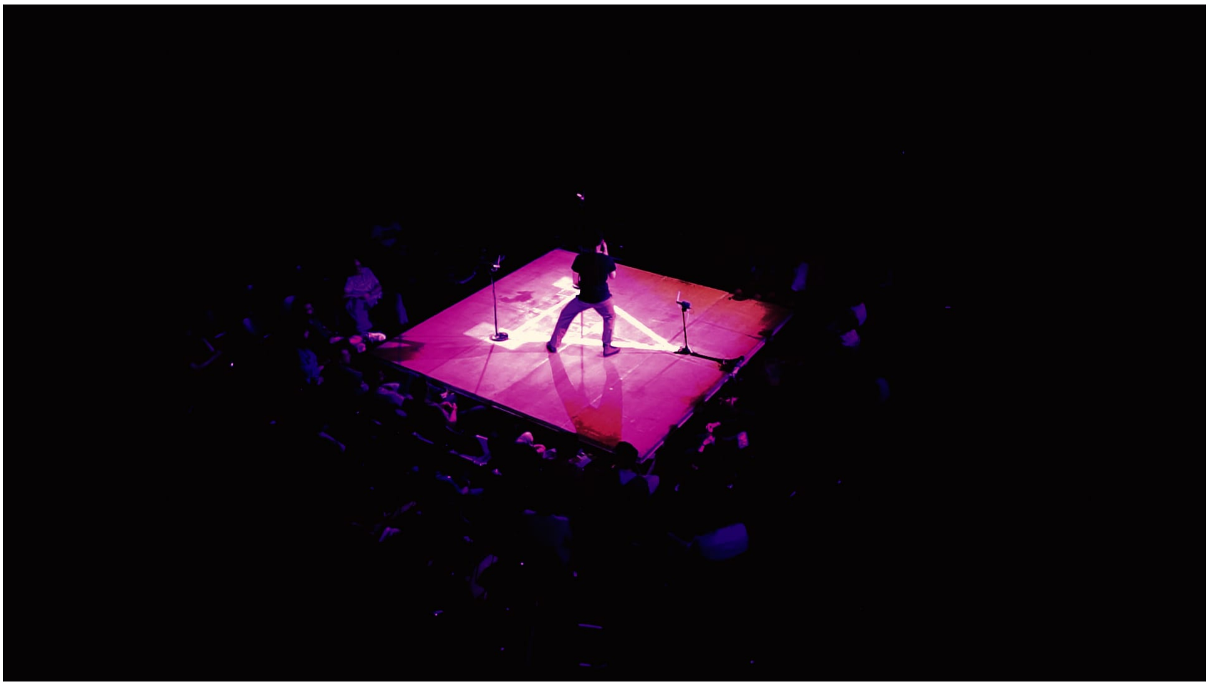

Figure 7.6. Performing *Hertzian Field #2* on a raised platform to reduce the effects of audience bodies (video still by Yiannis Papanastastopoulos, from a performance at Athens Digital Arts Festival, 2018).

- *Effects of hardware imperfections*: Additionally, it is important to keep in mind that the use of specific hardware elements, particularly antennas, may also have an effect on the system, and that they may operate slightly differently than expected especially in regard to their 3D radiation pattern. For example, I experimentally verified that the dipole antennas from different WiFi card models produce slightly different results, even when coupled to the exact same WiFi card. This was not a matter of one antenna being more sensitive than another, but one being more sensitive to a node placed higher, but less sensitive to another placed lower. My hypothesis is that this is likely due to irregularities or design differences, such as variations in antenna length, since antennas of the same brand appeared to behave similarly. In another experiment, I was pleased to find out that using different power supplies to power the microcomputer nodes does not seem to have an effect on the system. While the amount of power supplied to an RF transmission is of fundamental importance to how its energy radiates, transmission power appears to be regulated through the Operating System to be at a certain amperage in the Raspberry Pi.

If using a different AC/DC adaptor had an effect, then the system would become both more moldable but also much more unpredictable. Therefore, and provided that the power supply used is not too weak, differences in amperage should not produce any variation in sensing.

7.1.3 *Composing interaction: Performing the hertzian*

The *Hertzian Field* pieces are artworks; thus, the primary goal behind them and behind the technology developed for them is to provide a complex artistic/aesthetic experience to their audience. An integral part of this experience is the creation of environments through which the nature of electromagnetic waves can be interactively probed and discovered as a physical phenomenon. For this reason, I have felt it is important to design systems that remain 'honest' to the data, as such an approach can produce valuable insights on the nature of the electromagnetic medium. In this sense, the *Hertzian Field* works aim to synthesize a phenomenology of the invisible; they function as sonically augmented reality environments that provide insights on a layer of physical reality that we cannot otherwise sense: the hertzian.

Staying honest to the data is not only a conceptual need but a very critical performative need as well. Due to the fact that the interface is invisible, interaction is only guided by the ear and the performer/interactor's kinesthetic sense. Therefore, it is important that the system performs reliably, intuitively, and with a certain amount of repeatability.

Composing interaction with the WIR system can be thus regarded from two different but related perspectives, as:

- Designing a system in which the body's interference on electromagnetic waves can become a source of expressive data for generating and manipulating sound. From this perspective, the system is designed as a complex *meta-instrument* whose agency can be explored through interaction, i.e. by playing it, and whose objective is to generate sound or music in an expressive and engaging manner.
- Designing a system whose sonic response to the body's interference reveals qualities of the electromagnetic medium and its interaction with the body and space. Regarded like this, the system's aim is to act as a *carrier of information* about the world through its sound - or, perhaps better stated, as *an interface through which to probe and interact with the world so as to gain information* about its nature. Under this perspective, sound becomes a translating medium that allows performers/interactors and viewers alike to

experience relationships with a physical layer of reality that humans cannot otherwise sense.

To explain this dual perspective in more detail:

a) Designing a system or instrument for sonic expression

This perspective is essentially that of the instrument maker. Hunt and Kirk (2000) provide a succinct overview of the attributes that a real-time sound performance system should possess, regardless of whether it is an acoustic or digital instrument:

- The performer is in control, the system reacts.
- The system responds instantly.
- There is repeatability, i.e. *"[s]imilar movements produce similar results"* (Ibid, 232).
- Interaction happens through continuous controls, and not e.g. by choosing a set of options from a menu (as opposed to standard human-computer interfaces).[330]
- The control interface is physical and multi-parametric; the performer learns how to operate it until *"actions become automatic"* (Ibid).
- With more practice, the performer gets better at operating the system.
- Once proficient, the performer can carry-out additional cognitive tasks at the same time (e.g. talking).
- The principal goal is controlling the system, not transferring information in an ordered manner.
- There is no specified order to the interaction between performer and system.
- The *"first point of contact with the instrument"* is a modality Hunt and Kirk call the "*performance mode"* (Ibid, 233). This is a way of interaction that involves continuous exploration of the environment. The performer discovers how to control the system by trying out different things and observing how the system responds, thus exposing new relationship between movement and sonic parameters.
- The response (or feedback) of the instrument can be sonic, tactile, kinesthetic, or visual – though, as Hunt and Kirk point out, the latter is typically less utilized by advanced players.

In short, Hunk and Kirk propose that *"[t]he interaction of a player with a musical instrument could be summarised quite appropriately by considering that the player directly manipulates*

[330] G.W. Raes' gesture recognition systems are somewhere in-between, as they involve both continuous control (the 'confidence' parameter) and, in a sense, choosing from a set of predefined gestures that the system understands.

a complex musical object, thus exploring the sonic and tactile environment which in turn provides continuous feedback." (Ibid, 232).

While most of these qualities can be implemented in a wireless sensing system like WIR, there are a couple of important caveats: In nearly all acoustic musical instruments the mechanism for generating sound is inherently linked to the interface, and both components – sound generation and interface - are tied to the laws of physics. In contrast, in the *Hertzian Fields* the body's interference on WiFi signals does not produce any sound, only RSSI data. This means that actions must be linked to sound through an additional layer that is not intrinsic to the system's physics, but which emerges through a deliberate design process: *mapping*. This is, of course, not specific to *Hertzian Fields* or wireless sensing. Mapping is a fundamental element in the design of electric/electronic/digital musical instrument and in the live performance of electronic music. My own design process has been greatly informed by the deep and extensive research of others in these fields, and builds on my personal experience in designing such systems for nearly 20 years now.

Still, there is another important distinction between playing instruments with an invisible and untouchable interface, and instruments that can be touched – whether those are acoustic or digital. Acoustic instruments provide haptic feedback, which is immensely valuable to the performer. Even the simplest digital interfaces – containing elements such as knobs, buttons and sliders – involve some type of tangible physicality that can be interacted with, and which can help the performer build spatial mental maps for playing the instrument. In contrast, the only feedback modality present in a *Hertzian Field* is the relationship of sound to movement, posture and position in space – much like with the, infamously difficult to master, thereminvox. In such *invisible instruments,* as G.W. Raes calls them, the map is not external, consisting of a configuration of control elements in space, but internal and based entirely on proprioception and listening – i.e. the awareness of one's own body and its relationship to space, and the way that relates to the sounds produced by the system.

While the invisibility of interfaces like the theremin and the WIR system can seem to set them apart from other instruments - making harder to understand how to play them – composer and electronic music / instrument design pioneer Joel Ryan proposes an interesting perspective borrowed from robotics, that allows examining all interfaces through the same lens (Sonic Writing, 2016). He proposes that, rather than focusing on the dimensionality of the interface as an object, we should instead focus on the dimensionality required by the performing body to interact with that interface. Essentially, instead of looking at the instrument (the designer's perspective), Ryan suggests looking at what the performer needs to do in order to operate it (the musician's perspective). As an example, he mentions the trombone slide: Mechanically, it offers just one degree of freedom since it moves in a single axis. However, the motion that the trombonist's arm needs to execute in order to move the slide in this axis requires nine degrees of freedom, involving three joints with three degrees of freedom each. Viewed from this perspective, interacting with a full-body interface like the WIR system entails a very high and complex degree of dimensionality, as it involves all joints, bones and ligaments in the body, for a total of about 244 degrees of freedom (for more on the degrees of freedom of the human body, see Firmani and Park, 2009). This complexity and multi-dimensionality certainly coincides with my own experience of performing *Hertzian Fields*, and the delicate and intricate embodied relationships to sound they establish.

Ryan's perspectival shift from the instrument to the instrumentalist stems from the idea that physical effort is not only a fundamental element of playing music, but also fundamental to performative expression. Consequently, he rejects the notion that computer music performance should be effortless - a vision pushed by music industry marketing as *"one of the cardinal virtues in the mythology of the computer"* (Ryan, 1991, 4). As he points out, music has developed hand-in-hand with the physical objects we have been inventing to make sounds with, and with the ways that we have invented to perform them. Thus, he proposes incorporating physicality and effort in computer music, making the body converse with an instrument's physicality as a way to simultaneously impose constraints and open up avenues for discovery.

Hunt and Kirk concur with Ryan's assessment, positing that utilizing some form of energy produced by the performer is one of the fundamental aspects of designing *"richer interfaces"* (Hunt and Kirk, 2000, 234). Humans are used to interact with complex physical systems, like instruments, by *injecting* some form of energy that *excites* the system and which is "steered *through the system or* damped *(dissipated) in order to achieve the task"* (Ibid). As they note, the injection of energy to a system and its subsequent dampening or steering through it may be carried out *"by different conscious body controls",* such as *"bowing with one arm and fingering notes with another"* in the case of playing the violin*, "blowing a clarinet and using the fingers to key the notes",* or – in a non-musical example – "*pushing bicycle pedals with the legs and steering with the arms"* (Ibid).

In WIR and the *Hertzian Field* series, due to the invisibility and untouchability of the instrument's hertzian physicality the body itself becomes the interface. The relationship between action and output is rather complex, owing both to the high dimensionality of the interface's actions (caused by movement that involves up to 244 degrees of freedom), but also to how these actions are captured, interpreted, mapped, and sonified. To better parse this complexity, the process of composing the relationship between sound and movement/action/effort can be broken down to a series of elements or sub-processes, as seen in figure 7.7.

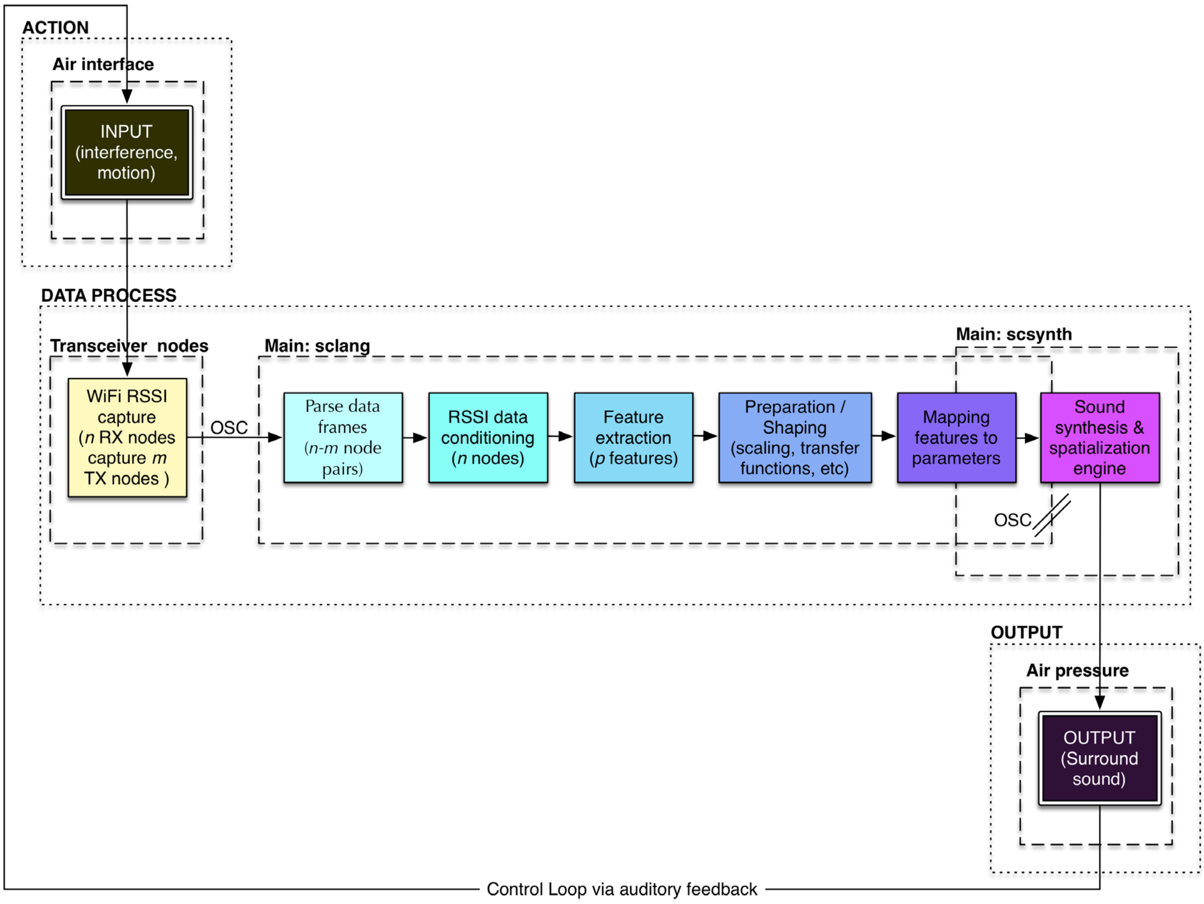

Figure 7.7. Composing interaction in the *Hertzian Field* series by harnessing the body's interference on WiFi signals: A feedback loop involving performative actions, data capturing and processing by the *Wireless Information Retrieval* system, and sound generation and diffusion.

To briefly explain the process of composing interaction described in this figure:

i) The input to the system is interference on microwave WiFi signals. Interference is actuated when a human body stands or moves in the electromagnetic field created by the system and results in patterns of attenuation and amplification of the transmitted signals.

ii) The interference caused by the actions of the body is captured by the antennas of the system's nodes as signal strength fluctuations. These RSSI fluctuations are transmitted via OSC, either internally to the same computer (in *Hertzian Field #1*) or to a nearby computer via Ethernet (in *Hertzian Field #2* and *#3*).

iii) There, the RSSI data is conditioned (shaped) upon arrival.

iv) Then, it is analyzed to extract features that provide insights on the quality of interference, and thus on the type of actions occurring within the field.

v) This produces a number of control data streams which are mathematically shaped (e.g. by scaling them, inverting them, applying a transfer function, an exponent, etc.).

vi) Then, these shaped streams are mapped to sonic parameters.

vii) These parameters control the sound and spatialization engine, generating a sonic output that provides a sensory experience of the interaction between body and hertzian space.

viii) In this manner, the resulting sound is both the artistic outcome of this interaction as well a carrier of information on its nature. In this capacity, it is used to further guide the performer/interactor's ensuing actions, and to help the audience or non-interacting visitors build a perceptual/mental understanding of the system and its underlying (invisible) physicality.

The types of sounds generated and their behavior, the ways in which they are generated, and the type of connection between action and output are fundamental in creating the *feel* or *response* of the instrument (Ryan, 1991). The control data produced by an interface, like WIR, can be reinterpreted, modified or radically changed to create a new musical *feel* of that instrument, even when the physical aspects of the interface remain unaltered.

When I am designing the sound, feel, and behavior of a *Hertzian Field*, a number of fundamental questions arise: Should the system feel like it has an agency? How complex is the interaction? How does interaction produce sound? For composer Joel Chadabe, similar questions relating to the behavior of an instrument and the role of the performer are in fact more relevant to understanding an instrument than the physical form of its interface (SEAMUS, 2007). Chadabe offers some interesting metaphors on how the interaction between performer and instrument can be modeled:

- *Action leading to a reaction*: This is akin to interacting with an acoustic instrument; in computer music this is often implemented as a simple model where, for instance, pressing a key produces a sonic event.

- *'Fly-by-wire'*: Here sound is controlled as if flying a plane. The performer operates at a higher level of abstraction, with the system implementing an intermediate layer for controlling the sound engine. This is essentially a real-time version of Iannis Xenakis' vision of computer-assisted composition, when he wrote: "*With the aid of electronic computers the composer becomes a sort of pilot: he presses the buttons, introduces coordinates, and supervises the controls of a cosmic vessel sailing in the space of sound, across sonic constellations and galaxies that he could formerly glimpse only as a distant dream"* (Xenakis, 1992, 144).

- *Conversation between performer and (meta)-instrument*: In these systems, the instrument behaves similar to a musician, as if it had ears and a mind of its own. This involves implementing some sort of machine listening and decision-making mechanism. Chadabe mention the works of George Lewis and Robert Rowe, who have both developed automated software instruments to respond to music similarly to an instrumentalist.
- *'Sailing a boat in windy seas'*, or *'interacting with life'*: In this model, the performer is interacting with an instrument that cannot be controlled, only influenced. The instrument is almost like a natural force – a complex world with many dimensions. Chadabe compares this model with navigating through *"windy seas"* or the unforeseen events of everyday life, where one's actions exert some influence but cannot necessarily dictate the result. My approach in *Hertzian Fields* comes closer to this modality, although it incorporates elements from the other three as well./

b) Designing a system or instrument that reveals qualities of the hertzian medium

To gain more insights on how the second perspective of composing interaction can be approached - that is, creating a system whose sonic response reveals the nature of the hertzian medium - it is useful to turn to the field of *Sonification*. *Sonification*, or *Auditory Display*, is a fairly recent emergent field of research that studies techniques and strategies for making data audible, aiming to provide new insights into the phenomena described by the data – such as earthquakes, the stock market, public health, etc.[331] In essence, sonification involves designing non-speech audio that can be used to communicate information about a particular data set. Sound is particularly suited for the representation of multidimensional data because of its multidimensionality (Grond and Berger, 2011).

There are many different definitions and approaches to the field as well as ways to categorize

[331] The field was established in the first International Conference for Auditory Display (ICAD) in 1992, in which many of the sonification techniques used today were introduced.

these approaches. To use Carla Scaletti's *"working definition"* from 1994, sonification is *"a mapping of numerically represented relations in some domain under study to relations in an acoustic domain for the purpose of interpreting, understanding, or communicating relations in the domain under study"* (quoted in Barrass and Vickers, 2011, 147). Or, to use a more recent definition by Hermann from 2008, "*[s]onification is the data-dependent generation of sound, if the transformation is systematic, objective and reproducible, so that it can be used as scientific method"* (quoted in Hunt and Herman, 2011, 274). These remarks provide a good conceptual guideline as to how one can use sound to communicate information on the physical nature of the hertzian medium and hertzian spaces.

Sonification is used for a various types of tasks (Walker and Nees, 2011):

- Monitoring to detect events. This typically results in an alert or warning triggered upon detection of an event.
- Helping become aware of how a situation or process unfolds in time, such as listening to financial data over a period of time.
- Exploring data sets. This task can be broken down into several subcategories, such as:
    - *Point estimation and point comparison:* deducing information on a specific data point, or comparing different data points to one another
    - *Trend identification:* recognizing a particular pattern or trend in the data
    - *Data structure identification:* where the focus is on identifying structures in the data
    - *Exploratory inspection*: exploring the data without a specific predetermined goal.

In this regard, *Hertzian Field* environments can be thought of as *exploratory inspections* of hertzian phenomena. Certainly, they are not the only artworks that perform such explorations of extra-musical worlds, which is why Walker and Nees include a 4^{th} category of tasks, specific to explorations that involve the arts as well as entertainment, sports, and exercise. The use of extra-musical data in music is in fact a very old artistic practice whose traces we find already in the 15^{th} century, and which has become increasingly more widespread since the second half of the 20th century (Barrass and Vickers, 2011).[332] Such artistic explorations of data can be thought of as the aesthetic flipside of the more rigid and goal-oriented scientific field of sonification. Barrass and Vickers (2011, 146) call this type of practice *musification*, noting that in these cases *"[g]enerally, the composer is concerned with the*

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[332] Examples include Guillaume Dufay's use of architectural proportions in *Nuper Rosarum* (1436) and Mozart's dice games, Joseph Schillinger's systems, Iannis Xenakis' use of statistics and stochastic processes, and Alvin Lucier's use of EEG to trigger percussive sounds in *Music for Solo Performer* (see Grond and Berger, 2011 and Barrass & Vickers, 2011).

musical experience, rather than the revelation of compositional materials. However, when the data or algorithm is made explicit it raises the question of whether some aspect of the phenomenon can be understood by listening to the piece. When the intention of the composer shifts to the revelation of the phenomenon, the work crosses into the realm of sonification." In such works, sonification strategies are pushed beyond information to become part of the aesthetic experience, which is very much the case for the *Hertzian Field* series.

In terms of sonification strategies, there are four main modalities (see Hunt and Hermann, 2011; Walker and Nees 2011; and Barrass and Vickers, 2011):

1. *Auditory Icons* and *Earcons* are the simplest form of sonification: When an action occurs a sound accompanies it, so as to create a semantic link between action and sound through repetition.

2. *Audification* is the 'prototypical' sonification modality (Walker and Nees, 2011). Data is typically directly translated into variations of sound pressure, often after shifting it in a different frequency register or time scale so that it can be perceived and understood as sound (for instance lowering high-frequency radio data, or speeding up financial or seismic data). The act of transducing VLF or other electromagnetic signals into audio, like in Kubisch's *Electrical Walks* for example (section see 3.3.4), is an act of audification.

3. *Parameter Mapping Sonification* (PMSon) is possibly the most common auditory display strategy (Hunt and Hermann, 2011). It involves mapping a data set, or specific features of that set, to sound synthesis parameters which control the production and modulation of sound. Mapping data to parameters rather than directly to sound, as in audification, involves a layer of interpretation. Mappings that are symbolic or more interpretative have a low indexicality - meaning that they are more arbitrary - while those in which data is used to directly produce sound have a higher indexicality, resulting in a closer connection between sound and data (Barrass and Vickers, 2011). Sonic changes can be discrete or qualitative - e.g. when a threshold is passed, then an event occurs - or they can be continuous, modulating a sonic stream with a data stream to create the impression of continuity from data that is discrete. In PMSon implementations, the temporal progress of the phenomenon described by the data is typically very important.

4. Finally, *Model-based Sonification* (MBS) goes beyond mapping data to sound. Instead, data is encoded into a dynamic system or a virtual sonic model that can be excited into a

> sonic response through user interaction. This typically involves a high degree of dimensionality and many data points (Walker and Nees, 2011). The data is experienced by interactively probing the model, and the system's response to such actions conveys information about the data set. As Hermann suggests, *"we can think of interaction as actively querying the object, which answers with sounds"* (Hermann, 2011, 403). MBS systems benefit from using interfaces with many degrees of freedom which thus permit simultaneous control of many dimensions, as opposed to using standard HCI devices such as sliders.[333]

The strategies I followed in the *Hertzian Field* pieces more closely align to *Parameter Mapping Sonification*, with features being mapped to sound synthesis parameters in various configurations. My approach also displays some kinship with *Model-based Sonification*. For example, in *Hertzian Field #1* movement is used to create audio waveforms directly via a sound synthesis model inspired by *scanned synthesis*. Furthermore, in my two subsequent works the absorption and reflection of radio waves by the body is modeled as a spectral filterbank, which in its turn 'absorbs' and amplifies parts of the sound's spectrum to control digital feedback networks. These strategies, and their relationship to sonification, will become clearer in the following sections that discuss each work and the mapping of data to sound in more detail.

7.1.4 *Mapping features to parameters*

Mapping is a fundamental component of interaction design, with a significant part of the compositional process for *Hertzian Fields* devoted to it. Devising an optimal mapping strategy involves a number of considerations that any sonification or musification project has to take into account, such as: What exactly is the task - is it, for example, sounding an alarm, monitoring a data stream in real-time, or performing a piece of music? How much data is necessary - in terms of both temporal resolution or granularity, as well as in terms of *data polyphony* (meaning how fast and how many data streams should be sonified at a time)? What type(s) of sound sources, synthesis and/or processing algorithms are to be used? Which sound parameters work best with which data streams? How to prepare or condition the data to better control a given parameter?

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[333] Overall, interactive explorations allow changing perspectives so as to acquire multiple sonic views on the data (Hunt and Hermann, 2011). Whether a sonification model is interactive or not can also be considered another form of categorization according to Walker and Nees (2011).

Designing a system that can be operated in an expressive manner that resembles an acoustic instrument (i.e. through Hunt & Kirk's *performance mode*) requires being able to control multiple parameters in continuously and simultaneously. In WIR, there are many different ways in which RSSI features can be mapped to parameters. Possible *mapping topologies* include (for more see Hunt & Kirk 2000, Hunt and Wanderley, 2002; Grond and Berger, 2011 and Baalman, 2022) (figure 7.8):

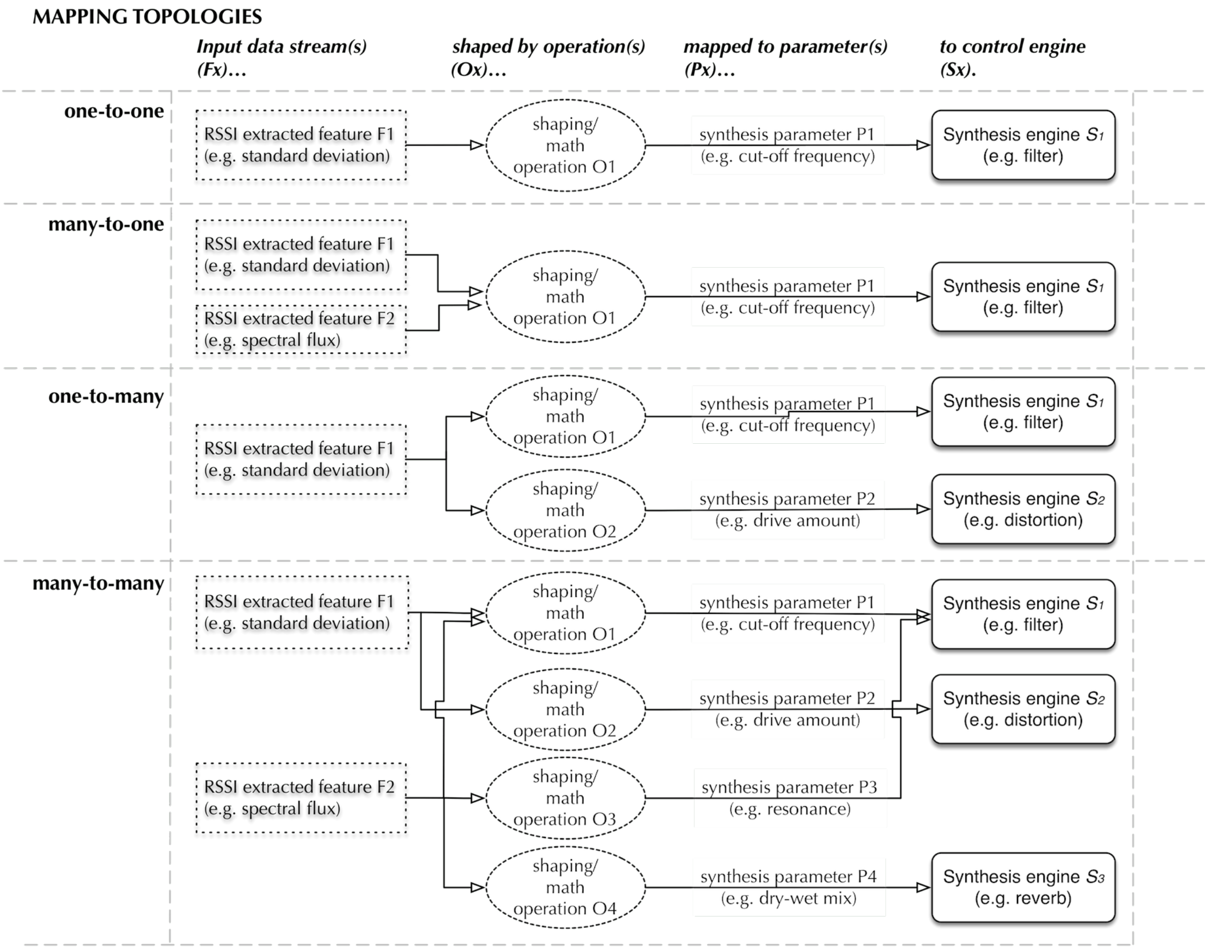

Figure 7.8. Simplified overview of possible mapping topologies for controlling sound via data streams of RSSI extracted features.

- *One-to-one*, in which a feature is mapped to a single parameter. This is the stereotypical modality of simple Human-Computer Interfaces, as well as of commercial synthesizers and MIDI control devices, where for instance moving the mouse changes values on a slider that is mapped to a sonic parameter, e.g. a filter's cut-off frequency.
- *Many-to-one*, or *convergent* mapping, in which several features modulate one parameter (Rovan et al., 1997). For instance, the volume of a violin's sound is controlled in this manner, as it emerges through a combination of *"bow-speed, bow pressure, choice of*

string and even finger position" (Hunt and Kirk, 2000, 234). The effect of the different input parameters to the output does not need to be equal. Instead, they can be summed or averaged after being multiplied individually through a weighing function, so that one input exerts more influence than another. This happens in regards to the pitch of the violin, for instance, which is controlled by a combination of finger placement on a string and pressure applied via the bow, with the former having a stronger effect than the latter. Such relationships can be expressed through a simple mathematical equation. Rovan et al. (1997) also discuss another form of non-linear many-to-one gestural interaction – which Hunt & Kirk (2000) call biasing – inspired by single-reed instruments where a control input parameter only starts to have an effect once another parameter exceeds a threshold. In instruments like the clarinet, the airflow passing through the reed is a function of the amount of pressure applied to it and the firmness of the embouchure. The reed, which acts as a *"pressure-controlled valve"*, will close earlier with the same amount of breath pressure if the embouchure is tighter (Rovan et al., 1997, 69). This type of mapping is used for artistic purposes more frequently than it is used for sonification. The reason is that, while in the case of an instrument it helps increase expressivity by allowing finer control of its sonic output, it also obscures the effect of individual control data streams, as it combines them together.

• *One-to-many*, or *divergent* mapping, in which a feature is mapped to several parameters. Using the violin again as an example, the way in which the bow is played affects many parameters of its sound: its loudness, its timbre, the articulation of different notes, even pitch to some extent (Hunt and Kirk, 2000). In a system like WIR, this can happen for example by splitting the output range of a feature to several parameters, so that when the magnitude of fluctuation for that particular feature changes a new parameter is being affected. For instance, slow movement and its variations may be mapped to control overall volume, with faster movement activating a distortion filter that amplifies the sound while adding non-linearities. It should be noted that the WIR system could be considered as stemming from a one-to-many paradigm inherently – at least in purely technical terms - as it involves extracting multiple features or control streams from a single stream of data: the RSSI of a transmitter-receiver pair.

• *Many-to-many*: In this case, many control parameters are mapped to many synthesis parameters to collectively produce a sonic result. This is essentially the way in which much of the mapping in *Hertzian Fields* operates: it involves multiple mapping networks of varying complexities connecting control streams (RSSI features) to various parameters of synthesis and processing modules. Another example of this type of many-to-many mapping is Alberto de Campo's *MetaControl* technique, in which *m* control parameters (sliders, in de Campo's case) affect *n* synthesis parameters, each with different weights. This approach produces a very dynamic way of performing sound, where *"[m]oving a single control element traverses the parameter space along a multidimensional diagonal, changing every process parameter to some degree; moving a different control does the same along a very different axis."* (Hildebrand Marques Lopes et al., 2017, 354-355). Overall, many-to-many mappings excel in creating framework for intuitive navigations of the parameter space of an instrument or environment.

Such complex interwoven mappings are also common in the physical world, because of the way matter and energy interact with one another. Acoustic musical instruments, in particular, acquire their greatly non-linear character by integrating an intricate network of interconnected convergent, divergent, and many-to-many mappings, configured with different biasing and weightings. The resulting non-linearities make these instruments more expressive and more interesting to both play and listen to - but also harder to master. As such, beyond utilizing the performer's energy input, coupling multiple control parameters together in this manner is another fundamental aspect of designing expressive interfaces (Hunt and Kirk, 2000).

In the *Hertzian Field* works, mapping is declared explicitly as part of the composition. In *Hertzian Field #1* it remains static throughout the piece, while in the following works mapping changes as the score progresses. This happens in several ways, such as by changing which receivers track which transmitters (i.e. the configuration of the sensing field), adding new sound generators or processors, adding and removing extracted features, changing the mapping of features, or shaping their output ranges in different ways.

Shaping the output of the control streams to prepare them for the particular parameters they control is a fundamental part of the system's design and of the compositional process; it has an immense impact on the response, expressivity, and sonic output of an instrument or environment. Typically, this involves applying mathematical operations on the control data to steer it to a range that produces desirable sonic results. Ryan (1991, 5) gives an overview of possible operations: *"Controller data can be shifted or inverted [addition], compressed and expanded [multiplication], limited, segmented or quantized [thresholding]. Methods which keep track of the history of a signal allow measurement of rates of change, smoothing and* *other types of filtering to amplify specific features in the signal or to add delays and hysteresis in the response [differencing, integration, convolution]. The rates of data transmitted can be reduced and expanded [decimation and interpolation]. Linear and nonlinear transforms allow the shaping or distortion of the signals to any desired response [functional and arbitrary mappings].”*

7.1.5 *A cybernetic experience of multidimensional space*

The *Hertzian Field* works take place in performative spaces/environments conceptually designed as second-order cybernetic systems. Cybernetics is the study of systems – how they are structured, how they operate, what their possibilities and limitations are, how they can be regulated (see Wiener, 1948/1985 and Ashby, 1956/1999). In *first-order cybernetics*, systems are observed from outside and with an ‘objective’ eye - as much as that is possible. In *second-order cybernetics* the approach is not observational but decidedly discursive: The observer becomes part of the system as an interactor, not just influencing results as a consequence of the act of observing, but possessing the agency to actively probe and steer the system from within. Thus, in second order cybernetics the agency of the observer and the agency of the system engage in a dynamic dialogue.

In the *Hertzian Field* series the performer/interactor is an integral component of the system and becomes its driving force through movement and interference. Body, electromagnetic fields, space, and sound are entangled in a complex feedback loop within an augmented environment that has an agency of its own (the agency of its material and that of its software) and which operates under somewhat unfamiliar but intuitive physical laws. This enables the performer/interactor – but also the viewer to a certain extent - to construct a lived, embodied, performative understanding of the system, and through it an understanding of the nature of the hertzian medium.

As a result, these works produce a radically different way of experiencing space. The field/environment is perceived as a dynamic object, force, or energy that envelops the human body and responds to its every move, like a living system. Space acquires an intricately complex dimensionality that extends beyond the three dimensions of our vision-centric notion of cartesian space. This is a function of the high dimensionality involved in the system being performed by the body (and the many degrees of freedom required, as mentioned earlier) combined with the distinct physics of microwave fields and their interaction with space and the body. As a result, the invisible *Hertzian Fields* of these works operate with a slightly different set of rules than the ones our eyes have accustomed us to, which can be discovered by the body and the ear working together. The feeling of increased spatial complexity and multidimensionality of the hertzian space is something that can be programmed into the work, as it emerges through the perceived relationships between body, space, and sound. This relationship is founded on the physical interaction between microwaves and the body, and in the ways in which this relationship is captured by hardware, interpreted by software, and translated into perceivable sound waves. This feeling was thus more pronounced in *Hertzian Field #2* and *#3* in comparison to *Hertzian Field #1*, primarily because: the configuration of the electromagnetic field was more complex (using 3 transceivers rather than one transmitter and four receivers); the sampling rate of the sensing system was faster; the WIR framework was further developed; and finally, because the sound engine featured intricately interconnected feedback networks of audio processes that made even the most minuscule of motions have an effect when it occurred at the right location.

In essence, the hertzian spaces that *Hertzian Fields* create can be imagined as invisible three-dimensional pulsating fields of energy that can be touched, poked, shaped, blocked and diverted by the performer's body to produce sound. The (sonic) response of the environment is spatially immersive, enveloping interactors and audience alike through surround sound diffusion. It is localized, with sound most activated and/or most modulated around the location of the action. It is also distinctly digital, giving the environments/instruments the character of alien, machinic, yet life-like idiophones that react to every movement of the body. This all contributes to the sense of immersion and to the intuitiveness and responsiveness of these environments.

A number of factors contribute to and influence these sensations. These relate to the material and software-induced agency of the system, and can be grouped into physical and non-physical. In short, physical factors include:

a) The non-Newtonian nature of the hertzian medium
b) The geometry of the sensing system which creates an invisible anisotropic field; this is more pronounced and more effective in *Hertzian Field #2* and *#3* than in *Hertzian Field #1*, as their sensing field is a fusion of three individual fields, each with a different orientation in three-dimensional space (for a layout of the sensing fields of these works, see figures 7.10, 7.17, and 7.42)
c) The fact that the interface, i.e. the human body, has 244 degrees of freedom that can be manipulated at any time to produce sonic results that are highly dependent on the

position, orientation, and posture of the body in relation to the sensing field

Contributing and influencing non-physical factors include:

a) The sampling rate of the RSSI data (higher sampling rate feels more responsive)
b) The combination of particular features extracted (extracting a different set of features will produce a different sensation)
c) The durations - windows of time - over which these features are extracted (which affect the response and hysteresis of the system)
d) How extracted feature outputs are shaped, processed, or combined to function as control data
e) To which actions or parameters these control data are mapped
f) What are the sound engines they control/modify/steer
g) How these sound engines are configured – e.g. how different processes are affecting each other, how sound is spatialized, and so forth.

7.1.6 *Context considerations for an expanded sonic practice*

All works in the *Hertzian Field* series employ the *Wireless Information Retrieval* system to create a multistatic indoor radar system out of ordinary WiFi infrastructure. While I developed this technology in order to create sound/music performances and sound art installations, the context and socio-political significance of that technology is an important element of these works that contributes to an audience's experience. In this regard, my perspective of what this particular technology means for these works resonates with Seth Kim-Cohen notion of *non-cochlear sonic art* (Kim-Cohen, 2009).

Kim-Cohen developed this concept in analogy to Marcel Duchamp's 'non-retinal' visual art, with which Duchamp cast aside the long-established importance of notions such as beauty and taste to emphasize conceptual and other non-visual elements in contemporary art. Similarly, Kim-Cohen proposes expanding our idea of what sonic art practice is by turning our attention to concepts, processes, and other inaudible elements. He points out that sonic art that deals with those elements does not have to reject sound or the act of listening, it merely has to embrace the notion that sound is not the *only* thing that matters in a work, and that other elements that are present in the work also need to be given attention. He proposes that a non-cochlear sonic practice necessarily engages *"both the non-cochlear and the cochlear, and the constituting trace of each in the other. (...) A non-cochlear sonic art responds to demands, conventions, forms, and content not restricted to the realm of the sonic. A non-*

cochlear sonic art maintains a healthy skepticism toward the notion of sound-in-itself" (Ibid, xxi - xxii). Essentially, what Kim-Cohen suggests is that there are more ways to experience sound and create art with that medium than the traditional idea of music as a kind of language or system, where sound is a value in and of itself, and where the referential framework of sounds does not extend beyond the framework of the musical or cultural tradition they are created in. Furthermore, he postulates that the experience of a sonic work is not limited to pure listening, but instead branches out into a vast contextual network of often ignored elements that should be taken into account. He writes: *"An expanded sonic practice would include the spectator, who always carries, as constituent parts of her or his subjectivity, a perspective shaped by social, political, gender, class, and racial experience. It would necessarily include consideration of the relationships to and between process and product, the space of production versus the space of reception, the time of making relative to the time of beholding. Then there are history and tradition, the conventions of the site of encounter, the context of performance and audition, the mode of presentation, amplification, recording, reproduction. Nothing is out of bounds"* (Ibid, 107).

Kim-Cohen utilizes the concept of non-cochlear sonic art on one hand to explain works, ideas, and tendencies in the history of sonic art practice (which includes both music and sound art), and on the other to provide a clear critical framework through which we can understand such practices using other tools beyond just our ears. For this purpose, he points the reader to the schism between music and sound art. As he comments, the idea that sound art is a separate field from music emerged largely owing to music *"closing off its borders to the extra-musical"* and failing *"to recognize itself in its expanded situation"* (Ibid, 107). Historically speaking, not all sonic practitioners chose to regard the formal frameworks imposed by music tradition as immutable. Many avant-garde composers attempted to redefine and expand them, such as Edgard Varèse stating that *"music is organized sound"* (Varèse, 1966), or John Cage who famously said *"you don't have to call it music, if the term shocks you"* (Cage, 1982). Some have looked inward, *"toward the essential, fundamental concerns of the field"* and others outward, *"toward that which lies beyond the traditional borders of the field"* (Kim-Cohen, 2009, 261). In this sense, sound art could be thought of as the field of sonic practice that is occupied with what (western) music - in its rigid, traditionalist and mainstream incarnations - has rejected or did not pay enough attention to. Sound art thus places *"meaning or value in registers not accounted for by Western musical systems"* (Ibid, 107). Because of its seeming rejection of musical values, and for reasons of politics - cultural and other - sound art became readily accepted by visual arts and galleries practically as soon as it emerged, but was initially rejected or ignored by the music establishment, its organizations, and its venues.

Personally, I am not particularly interested in whether the *Hertzian Field* works should be called music or sound art. Instead, I view them simply as an expanded and contemporary form of sonic art, in which - to paraphrase McLuhan - the hertzian medium is a fundamental component of the message. In this regard, what is more relevant for me is how these works extend beyond music and sound, not only in their form – for example by the fact that full-body movement, typically associated with dance, is an integral part of sound making, or by the fact that to experience *The Water Within* one has to enter a steam sauna - but also conceptually and experientially. The *Hertzian Field* works, thus, acknowledge and embrace their extra-musical context through their concept, theme and description, and through their creative use of a technology with considerable social and political implications that have yet to fully unfold. Part of this extra-musical context is phenomenological: understanding the physicality of microwave fields and how they interact with the human body, and providing a way to experience this interaction through our senses - particularly by listening. Another important part is conceptual: commenting on the implications of the WiFi-sensing technology itself, and the context and purposes for which similar technologies are currently being developed.

As such, one of the goals of the *Hertzian Field* series - and one of the elements that audiences most strongly respond to - is bringing attention to the fact that our telecommunication infrastructure can be subverted and transformed into a decentralized panopticon by anyone with the right set of easily accessible tools. The side-effect of WiFi acting as an indoor radar has serious privacy and security implications and can be regarded from an intelligence perspective as a *TEMPEST* phenomenon (see section 2.4.2). This is especially true because *WiFi technology* can be turned into *radar technology* without the knowledge of the person that installed the infrastructure, of the people that use the infrastructure, or for that matter of anyone who happens to be tracked simply by being in physical proximity to the infrastructure. Following *TEMPEST* terminology, the WiFi router/AP can be regarded as the unclassified '*Black'* equipment, connecting us to the Internet and other users of the cyberspace but also radiating outside of the home and thus reachable by anyone out there. The physical space within which it is meant to radiate, the home, can be regarded as '*Red'* – private and confidential, it carries information about our bodies and lives within it. The unwitting but unavoidable coupling of the two, *Black* and *Red,* broadcasts potentially sensitive information relating to changes in the configuration of our spaces. These changes, primarily involving the movement of our bodies or objects, become accessible to anyone keen to 'listen' since there is no encryption in the Physical layer of WiFi. Under this perspective, the *Wireless Information Retrieval* technique can be thought of as a *TEMPEST listening tool* (Friedman, 1972 and Boak, 1973) enabling a form of *electronic warfare* (Quilter, 2010): It intercepts publicly available beacon frames through the air interface and performs multi-layered *"fine structure analysis"* (Boak, 1973) of their signal strengths. Through this analysis, it reveals hidden interference patterns, which in turn produce knowledge on the activities taking place in our private physical spaces.

Understanding that WiFi can be used for surveillance brings forth grave concerns. One of them is that it is practically impossible to know whether a place is monitored or not and by whom, as radio waves and microwaves are ubiquitous. A communication infrastructure can easily be a cover for RF surveillance hiding in plain sight; or, it can simply be highjacked by a third party for this type of purpose, unbeknownst to anyone. Such systems can easily be near-invisible even to those casually looking for them – for example by transmitting as hidden WiFi networks that do not offer a service and thus do not appear in our devices. RF-sensing also allows to easily hide antennas out of sight: While the camera eye needs to look at the space it captures, and thus risks becoming visible to the human eye, the antenna as a ‘radio eye’ or ear can be hidden behind or inside any non-dielectric object.[334] The ability to hide this equipment is in fact often mentioned in Ubiquitous Sensing literature as one of the advantages of RF-sensing technology. The only way to uncover such stealth networks is to use tools like WIR and *tcpdump* to perform some form of counter-surveillance in the Physical layer, thus revealing any and all present transmissions. Still, that would not provide any information beyond the simple detection of a hidden, and thus possibly malicious (or possibly used for whatever other reason), infrastructure. Establishing that the beacon frames of a WiFi network are actually used for surveillance is practically impossible.

As the field of radio-sensing evolves and new technologies emerge, the grip of these surveillance systems on our everyday reality will only become stronger. As an artist and a citizen, I find the uncritical tone with which such technologies are being developed and

[334] This was the case in my collaborative site-specific installation *Proxy Kabinet: Raamweg 47,* created together with Tivon Rice, and Nicolás Varchausky (Manousakis, 2014c). The piece took over the surveillance control room of the former EuroPol building (European Police) in The Hague, the Netherlands, with sensing antennas hidden inside the surveillance desk and inside the false ceiling of the room.

discussed about in Ubiquitous Sensing research to be at the same time fascinating and profoundly unnerving. Researchers propose applications ranging from saving lives, to security and policing, to commerce and advertisement, and more. Any use is presented as good use in the literature, without any second thoughts or even the semblance of critical thinking, particularly by researchers based in the US. When privacy is mentioned, the typical narrative is that radio-frequency sensing raises fewer concerns than other surveillance technologies. While this is of course factually true, the reasons are more complex than what is implied: For one, these are rather unknown and quite abstract technologies. What minuscule percentage of the public actually knows that tracking uninstrumented bodies via WiFi is even possible? How many even have an understanding of radio/microwaves and that they can be used as urban or indoor radars? Furthermore, while almost everyone understands what it means for our voice or face to be captured and registered in media - regardless of whether they accept or object to that - how can anyone picture how our bodies and actions are represented by RF-sensing? It is really hard to know how such a system works, what kind of ‘image’ or knowledge of what happens in space it produces because the technology inherently involves a layer of translation from the hertzian to another modality which humans can perceive with our senses. The information extracted and the ways in which it is interpreted and represented is purely a matter of design. Thus, it is impossible for anyone to know what a given system does or how it interprets sensing data without being privy to information on that design. When the public does find, it often comes back with questions and objections, like we saw earlier with the Macy's localization controversy (see section 5.2.3), or with controversies over the introduction of full-body millimeter-wave scanners in airports some years ago. In that last case, privacy concerns were similar to those around when X-rays were first discovered, focusing on the ability of technology to ‘strip’ people of their clothes and have them appear as if they were naked in front of 'the men in control of the radio gadgets'. Overall, due to the novelty and obscurity of RF-sensing, the technology is completely opaque to the public - a black box that can only be understood by experts and which the rest grasp only in vague terms as a surveillance mechanism with unknown properties, most likely similar to cameras (see for example the long-established trope about 'seeing through walls').[335]

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[335] A number of reasons may contribute to the comparison between cameras and radio-sensing. First, cameras are a ubiquitous mode of surveillance that everyone is familiar with. Secondly, most RF-sensing technologies themselves are generally developed with a visual output in mind. This becomes evident when reading about such technologies and how they are described, especially those that reach public discourse. Nonetheless, this

My personal belief is that it is the responsibility of the artist to present perspectives that come in sharp contrast to the typically uncritical take of the engineer, to recognize and point out the complexity of our relationship to technology. In terms of RF-sensing, this complexity is aptly exemplified by the life and work of Leon Theremin – in whose work the roots of such technologies can be traced, at least as far as the human body is concerned - as it embodies the entanglement of RF-sensing, surveillance/espionage, and music (see section 3.1). As such, the *Hertzian Field* series subtly but deliberately feeds off and into some contemporary insecurities and some - not entirely unwarranted - paranoias relating to subjects of surveillance, hacking, and to the possible unknown effects of these technologies on human health and well-being.[336]

My artistic strategy is not to approach the subject principally as a cautionary tale, encouraging audiences to put themselves in the place of the unknowing defenseless victim of larger forces at play (which I find very often to be the goal of artworks dealing with surveillance subjects). Instead, it is to propose taking control of the technology, to reverse-engineer, re-invent and re-contextualize it in order to create a conceptually strong and critical *sensory experience* that generates visceral, aesthetic, and discursive responses from the audience. In *Hertzian Fields*, instrument design becomes *critical engineering* (Oliver et al., 2011), and hacking the technology becomes a subtext of the work's message. The outlook of these works thus aims to be rather positive and certainly subversive, pointing towards empowerment rather than powerlessness and positing that, even if we cannot be liberated from our technologies, once we understand them we can shape them to our desire.

7.2 HERTZIAN FIELD #1

7.2.1 *About the work*

Hertzian Field #1 is the inaugural work of the *Hertzian Field* series created using the *Wireless Information Retrieval* technique. The piece, and that first iteration of WIR, was developed in June 2014 during a month-long artist residency at ZKM Center for Art and Media Karlsruhe. The text describing the work follows:

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tendency of RF-sensing to be treated as yet another modality of seeing should not come as a surprise, as radar technology was also developed in a similarly visually-oriented manner.

[336] In this regard, it is worth mentioning that while health-related subjects are not touched upon in any of the texts supporting the work, there are always audience members approaching me with questions about this, their thought process being: if the body affects the field, does the field also affect the body, and how much?

"How do we move within the network when we can hear its shape?

Hertzian Field #1 is an immersive augmented reality environment that exposes the raw materiality of the WiFi communication medium, exploring its physical interaction with our spaces and our bodies through sound. Body, sound, and WiFi waves become entangled, creating spontaneous choreographies within a viscous and moldable radio architecture.

Our increasingly digitized lives are flooding our spaces with rivers of radio waves. We live engulfed in wireless fields, moving unawares through turbulent streams of data. The WiFi network has imposed its very material presence in our living spaces – a parallel stratum we cannot see or feel, but as real as the air we breathe. While we may lack the capacity to sense them, wireless networks can feel our presence as our bodies block, reflect, and displace radio waves. This material reality seeps into the communication channel; beyond simply carrying and distributing our data, wireless communication has a side effect: it also transmits information about physical space and our own bodies. Our data networks are effectively public radars, readily sharing their secrets to anyone listening." (Manousakis, 2014b).

Hertzian Field #1 was first exhibited in the ZKM_Kubus theater on July 1sr 2014 at the end of my residency. In that occasion I investigated the system's potential in two settings: a) as a solo live-interference performance, with myself as performer, and b) as an interactive installation open to the public (figure 7.9).

The piece was also shown 9 months later at the University of Sussex's Creativity Zone in Brighton, UK, following another brief residency in which various ideas were workshopped. This more informal demonstration featured the system in a similar dual setting - performance / interactive installation - with dancer Eugenia Demeglio as the main performer (figure 7.14).

With this piece I wanted to reclaim the term *augmented reality* from the visual arts proposing a dynamic experiencing of space that transcends the visual and what we can perceive through our eyes. *Hertzian Field #1* augments our perception of reality by rendering audible the flows of electromagnetic energy and their physical interaction with space and our bodies. To achieve this, an interactive sensing system captures, analyzes, and sonifies the dispersal of microwaves WiFi signals in the exhibition space caused by bodies and their movement within the field. In this work, the system's primary focus is identifying motion and its different speeds and patterns. Depending on how much and how fast the body moves, different sonorities and behaviors emerge – rhythmical, resonant, reverberant, melodic, noisy, glitchy.[337]

[337] Overall, this first version of the WIR system performed best with slower movements, as its sampling rate was fairly low (about 10Hz).

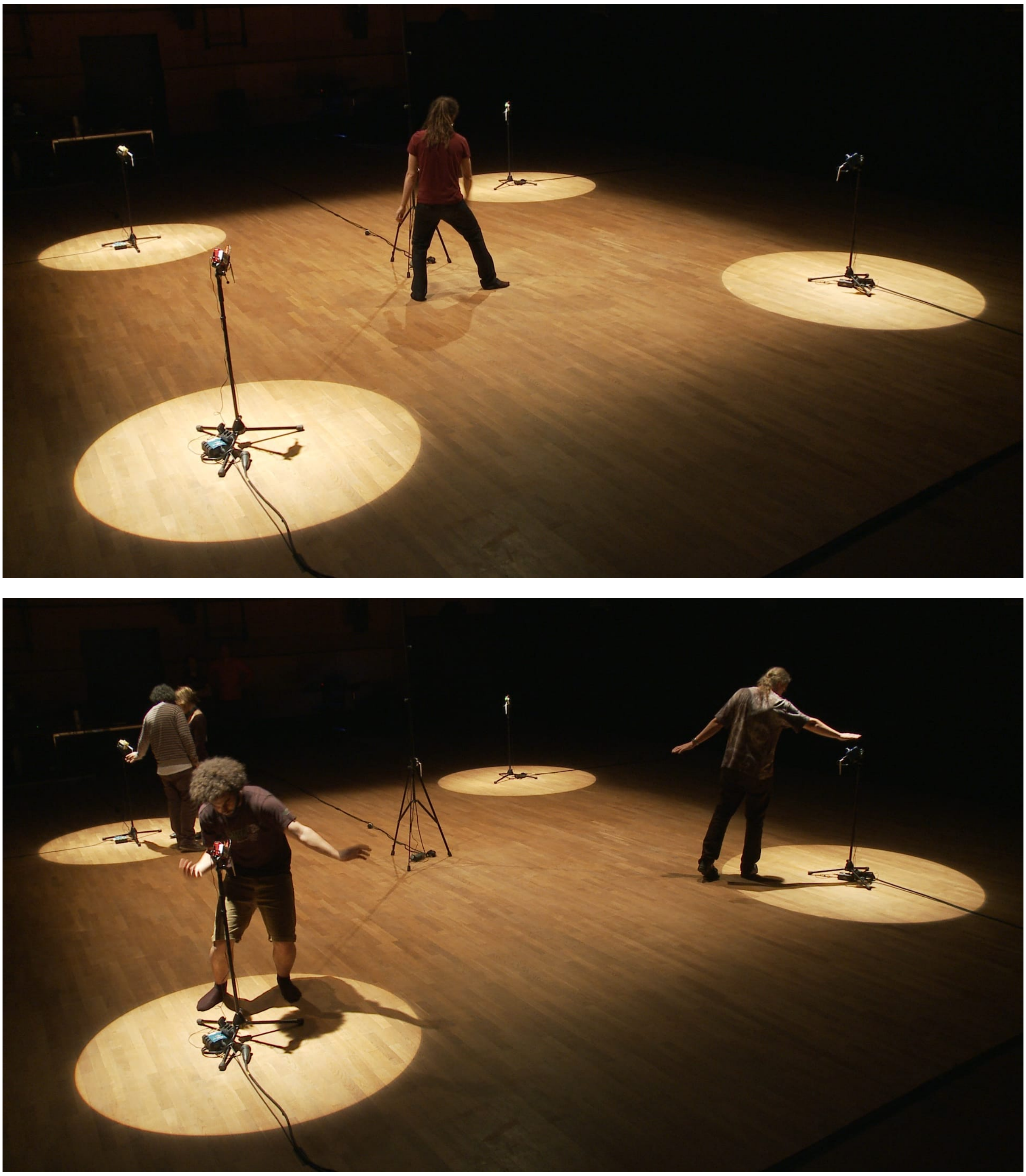

Figure 7.9. Photos from the premiere of *Hertzian Field #1* at the ZKM_Kubus in Karlsruhe, July 1st, 2014. Top: video still from a solo performance, showing me interact with the transmitter in the middle. Bottom: audience interacting with three of the system's receivers (video stills by Fabian Selbach and Anna-Lena Vogel respectively).

Although it is hard to describe the experience in words, *Hertzian Field #1* produces the feeling of being immersed in a viscous liquid, with the body's motions causing waves to ripple through it and reverberate through the walls of the architectural space. My goal was to create a rich, dynamic, and immersive sonic environment, shaped in direct response to the motion of bodies within the field. When motion stops, the soundscape comes to a calm – but not silent – state with some hysteresis, which is primarily where the feeling of viscosity comes from. Hysteresis is programmed into the system in three principal ways: First, in the manner the sound is generated (see scanned synthesis, section 7.2.3); secondly, by extracting RSSI features in a combination of shorter and longer memory windows, thus dispersing the system's response into various temporal phases; and thirdly by using integration as a way to 'store' energy in the system (this will be discussed in section 7.2.4).[338]

7.2.2 *Configuration*

"Materials: WiFi network, Raspberry Pi computers with WiFi cards, software, stands, loudspeakers, sound, light
Software: SuperCollider, Unix Shell networking tools" (Manousakis, 2014b).

At the core of *Hertzian Field #1* is a dynamic electromagnetic field generated by a WiFi network. The piece features a simple layout and configuration of the WIR sensing system: A Raspberry Pi first generation Model B microcomputer equipped with a WiFi antenna functions as a WiFi transmitter (Access Point) and is placed in the center of a space. It emits an omni-directional, donut-shaped pulsing radio field at around 2.425GHz (the exact frequency/WiFi Channel depends on the radioscape of the site). As this pulse propagates, it is intercepted by four Raspberry Pi 1 Model B+ receivers, each equipped with a WiFi antenna and a simple audio interface. These scanning/sniffing nodes are placed symmetrically at equal distances in the corners of an imaginary square with the transmitter at its center (figure 7.10). They are mounted on microphone stands and each of them is lit from above with a circular light; the field is also lit by a more diffuse flood light.

This configuration creates an invisible architecture dissecting the space with four strong sensing 'beams' - the Lines-of-Sight between the antenna of the transmitter and those of each receiver - that form an 'X' or diagonal cross. These strong microwave links are complemented by weaker sensing Fresnel zones filling the area between them. The interaction area of this *Hertzian Field* is approximately 5x5 meters. It is mostly responsive in the LoS between transmitter and receivers and fades quickly outside the square, with the exception of the areas behind the receiver nodes as the presence and movement of a body there amplifies the transmitter's signal through reflections, thus effecting the system. The

[338] A few years later, while writing this dissertation, I discovered that the two last strategies have also been used by Liz Phillips to achieve a similar effect in her work, see section 3.4.3.

antennas are all placed at the same height, about 1 meter from the ground. In this manner, the field passes through the core of the interactors' bodies, thus producing maximum interference.

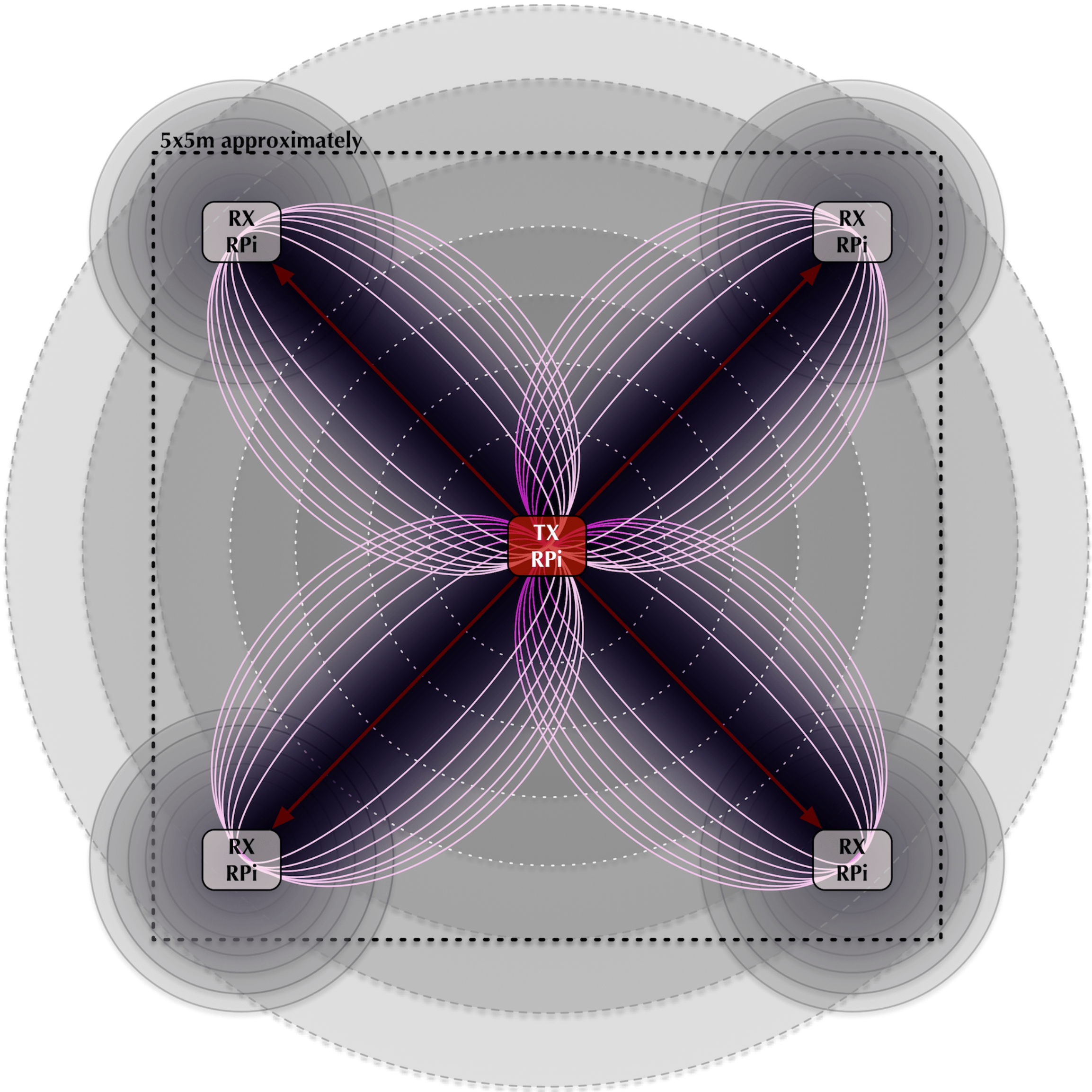

Figure 7.10. Spatial configuration of *Hertzian Field #1.* The diagram shows the placement of the transmitter and four receivers, as well as simplified visualizations of their fields (concentric circles), of their Lines-of-Sight (arrows), and of the most sensitive Fresnel zones that are formed between them (concentric ellipses).

In this work, the four receiver nodes are completely autonomous and independent in how they scan the air interface and how they produce sound. The software of each node (i.e. the first iteration of the WIR system) consists of various UNIX command line tools and SuperCollider code. It performs the following series of functions:

a) It captures WiFi beacon frames sent from the transmitter;

b) it extracts RSSI data from these frames;
c) it analyzes this data and extracts features from it to find patterns of interference;
d) it shapes the output values of these features in a number of ways (such as scaling, integrating), and finally
e) it maps these features to parameters of the sound engine to produce and modulate sound.

The four nodes are not completely identical, but feature small variations to make the space somewhat feel less uniform. These deviations principally concern how the feature extraction values are shaped and mapped to the sound engine of these nodes.

7.2.3 *Sound synthesis and diffusion, feature extraction, and mapping*

A human body entering the field interferes with it, shaping and distorting its microwave flows. The body's relationship to the *Hertzian Field* and its interaction with it generates all sounds in the work. The *body-as-microwave-shadow* conducts the system through movement; in its turn, the system's sonic response influences how and where interactors move.

A generative algorithmic system performs a *composed transduction* of WiFi microwave signals into sound from the point of view of each receiving node. Each node sonifies how transmitted signals get scattered into the exhibition space by interfering bodies and their movement. To achieve this, audio waveforms are synthesized directly in the 'atomic level' of digital samples according to the fluctuation of the WiFi signal's strength (RSSI) when it reaches a receiver's antenna. When there is no movement, there is little fluctuation - only whatever is caused by multipath propagation - and thus sound remains fairly static. This is accompanied by further multi-layered analysis and RSSI feature extraction that is used to turn the body into an intuitive and engaging interface for manipulating, modulating, and processing these seed synthesized waveforms through movement.

Sound is diffused to create an immersive surround environment, *Hertzian Field #1* was initially created for the *ZKM_Kubus*, or *Cube Theater,* a space of 20x14.5m featuring one of the most marvelous surround sound installations in the world: the *Sound Dome*, which surrounds the audience with 47 loudspeakers in a half-sphere formation (Brümmer, 2009) (see figure 7.11). The piece outputs 4 channels of audio – one from each receiver node. Each channel is mapped to the quadrant of the half-sphere that is directly behind the receiver. In this manner, sound is more localized to the receiver closest to which an interactor moves, mirroring the spatial configuration of the hertzian field. When exhibited in other venues, the system requires at a minimum 4 full-range speakers, placed at 4 corners of the space, and one subwoofer to provide the necessary low end.

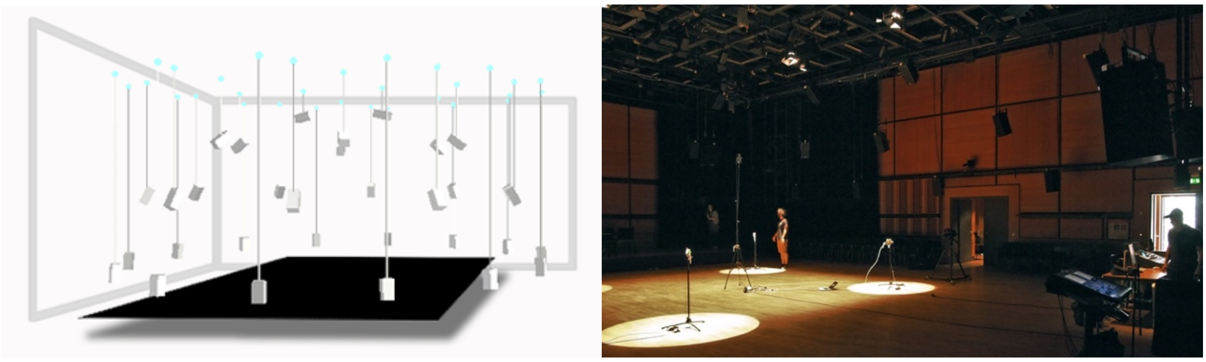

Figure 7.11. Sound diffusion of *Hertzian Field #1* at the ZKM_Kubus. Left: A diagram of the surround sound speaker configuration at the theater (from Brümmer, 2009). Right: Photo from the buildup of the work showing its placement and the speakers surrounding it.

In terms of sound design and sound coding for this work, I limited myself to processes that could operate on the underpowered first generation Raspberry Pi Model B microcomputers, as I wanted the work to be easy and quick to install, with the nodes being autonomous and not requiring a laptop and networking wires.[339] Creating an autonomous interactive system with a rich, dynamic, immersive and expressive sound environment with these resources presented an interesting and edifying challenge. Running SuperCollider on these limited machines was very experimental at the time. Getting it to work, optimizing the operating system for audio, and optimizing my SuperCollider code to save precious processing cycles took a significant chunk of the development process.[340]

To generate sound, I turned to a type of segment-based wavetable synthesis I had conceived and developed in 2011, and with which I could create complex sounds without needing much computational power. This technique came as the result of several years of research and development work with *non-standard sound synthesis* techniques I had undertaken in the past (for some of that work see Manousakis, 2009b).[341] It was also particularly inspired by the *scanned synthesis* technique developed between 1998-2000 by Bill Verplank, Max Mathews and Robert Shaw (Verplank et al., 2000).

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[339] This Raspberry Pi was released in 2012 and run on a single ARMv6 core at 700MHz.

[340] Community efforts to run SuperCollider on the Raspberry Pi on these devices were spearheaded by Fredrik Olofsson.

[341] Non-standard sound synthesis is a family of experimental digital sound synthesis techniques which are based *"on mathematical models and compositional abstraction rather than the human ear (as in spectral synthesis), physical properties of objects (physical modeling), or reproduction of actual sound sources (sampling-based synthesis)."* (Manousakis 2009, 85). The term was first introduced by Holtzman (1979).

In essence, scanned synthesis is a more advanced and dynamic version of wavetable synthesis that puts emphasis in real-time performative control of timbre - often through physical gestures of a performer – as a strategy for decoupling the control of timbre from that of pitch. It is based on psychoacoustic research and in particular on the discovery that the speed of spectral variations that the human ear and cognitive system finds timbrally interesting – i.e. neither too fast nor too slow - *"is the same as the frequency range of movements of our body parts"* (Ibid, 368). The original *scanned synthesis* technique involves a slowly changing dynamic system, like a string, that vibrates at a low, non-audible frequency (15Hz or slower); this defines timbre. The 'shape' of this dynamic system is scanned periodically at a faster rate to produce audible sound and define its pitch.

The idea behind the development of scanned synthesis was to create a system in which performers can use their body to alter the timbre of the synthesized instrument, for example by haptically manipulating objects. This concept comes very close to what I aimed to achieve in *Hertzian Field #1*. In this work, dynamic timbral change is generated by the variation of RSS values caused by a moving body. Every time a new RSS value is received, a seed wavetable is rewritten. This wavetable is played back dynamically by the *Dynamic Table Oscillator* (DTO), a synthesis model that I conceived and implemented as a pseudo Unit Generator (UGen) in the SuperCollider synthesis server. The resulting signal is recorded in real-time to another wavetable or memory buffer, which in its turn is read by a normal buffer-reading (i.e. wavetable) oscillator (see figure 7.12).

The *DTO* is at the core of the interactive sound engine for this piece. It reads a static wavetable and dynamically writes it to another table, sample-by-sample, at a sub-audio rate. I have implemented several *DTO* variants, each using a different type of wavetable oscillator.[342] These variants contain an array of control parameters, such as which wavetable to read from and which to write to, how fast to read, how fast to write, options for repositioning the writing head with another signal or control input, and more. In this piece, I used a standard interpolating wavetable oscillator to read and write RSS feature extraction data to a wavetable.

[342] This includes an oscillator that reads the contents of a memory buffer, an interpolating wavetable oscillator, a variable wavetable oscillator that can read across several wavetables of the same size, and a similar variant that uses 3 oscillators to read across many wavetables.

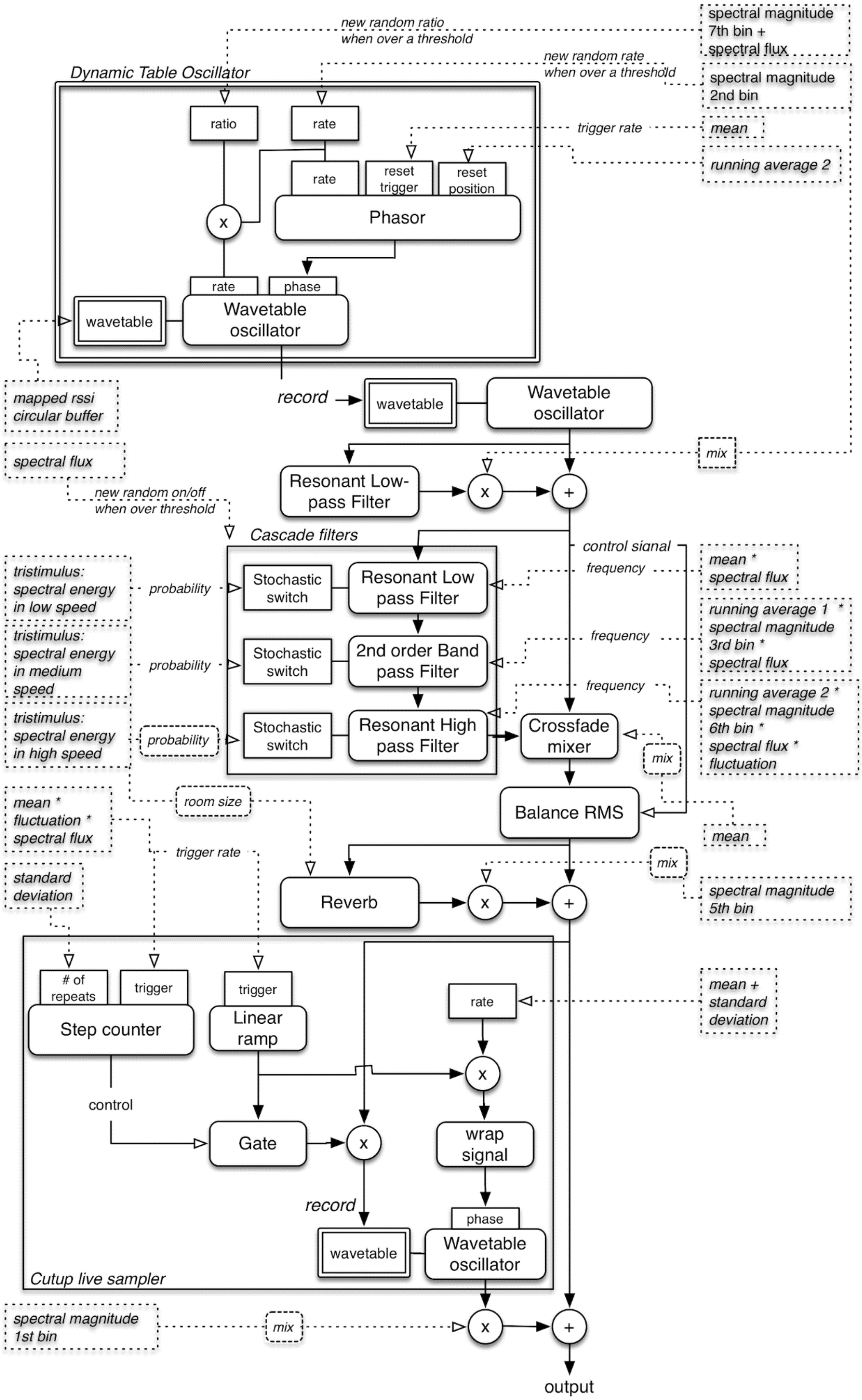

Figure 7.12. *Hertzian Field #1:* a diagram of the sound synthesis engine and the extracted RSSI features controlling it.

In comparison to traditional wavetable synthesis, one of the most important advantages of the *DTO* is that it allows dynamically modifying the contents of the wavetable - and thus the resulting timbre - while avoiding the clicks and jerkiness that occur in wavetable synthesis when the contents of a table are altered while the oscillator is playing. Due to the way this dual-oscillator synthesis technique operates, it can also produce some interesting sonorities that go far from wavetable synthesis. For instance, when using the same wavetable to both read from and write to, it can create some very interesting feedback-type effects. Overall, the *DTO* technique can be thought of as a hybrid between a number of existing sound synthesis techniques: wavetable/vector synthesis, feedback-delay, scanned synthesis, and non-standard sound synthesis.

The seed wavetable for each receiver is created as follows (see figure 7.12):

1. Each incoming RSS value is first mapped to a range between -1.0 to 1.0 as explained earlier (see *'Cooked' RSSI* in section 6.2.8). It is then added into a circular memory buffer (this is similar to the *resampled buffer* feature presented in section 6.2.9 but generated without resampling, as that was not yet implemented). With each new value, all previous data is shifted by one index towards the past, dropping the oldest sample value and adding the newest one in the front of the memory buffer. In this manner, the first value is the most recent, and the last one is the oldest.
2. These values can then be adjusted by subtracting the *mean* within the memory buffer to center the amplitude around zero, thus removing any DC content. Removing the DC content completely results in a silent buffer when there is no movement, as all data-points will be equal to the mean. In practice, this would mean that the piece is silent when nobody is within the field, or when the interactor remains still for a certain amount of time. However, while this type of mapping would be more transparent in demonstrating how the system works, I found these moments of silence quite problematic for the experience of the work. As such, I chose to only subtract a predefined fraction of the mean when generating the wavetable, so that the remaining DC offset results in a soft sound being always present. This sound is almost static but not completely frozen, as some RSS variation is almost always present due to a number of factors - complex multipath propagation, slight visitor motion in and around the field, but also the occasional glitchy antenna measurements that were plaguing the system, and which were filtered out in *Hertzian Field #2* with the implementation of the *Spurious Peak Filter* (see 6.2.8).

3. The memory buffer, consisting of the DC-adjusted values, is then converted into a *segmented envelope function* (the *envelope* feature described in 6.2.9). The datapoints are treated as the peaks of equispaced segments. The first value marks the beginning of the envelope, and the last its end. The values between successive peaks are produced through interpolation. A number of interpolation curves can be used: sinusoidal, exponential (with a user-defined exponent), stepwise, and parabolic (see *Welch window* in "Window Function", 2022). This resampled envelope function is then written as a wavetable and is immediately fed to the *DTO* replacing its previous wavetable. In *Hertzian Field #1*, the memory buffer contained 16 data-points, and the produced wavetable consisted of 512 samples. This length was a compromise to produce a wavetable with a decent enough resolution for the oscillator and a good rate of timbral change, while also being lightweight enough for the Raspberry Pi nodes to compute.

Apart from the *Dynamic Table Oscillator*, the sound engine for *Hertzian Field #1* is quite simple, and therefore requires little processing power. First, as mentioned above, the wavetable that the *DTO* dynamically produces is read by a simple wavetable oscillator. The signal is then sent through a chain consisting of a cascade of filters, reverberation, a cut-up algorithm that slices, rearranges, and pitch shifts the input, and an analog-style distortion/limiter (figure 7.12).

The signal's routing through this chain – including choosing how much each of these processes will effect it - and many of the synthesis and processing parameters involved are controlled by RSSI features extracted by the *Wireless Information Retrieval* sensing system. The following features are used as real-time controls:

- *Mean* RSSI, a feature that operates on a window of data
- *Average* RSSI, extracted directly from the incoming data (without windowing) by two *Low-Pass / running average* filters tuned with different coefficients
- *Standard deviation* of RSSI
- *Fluctuation* of RSSI
- *Magnitude spectrum* of RSSI
- *Tristimulus* of RSSI
- *Spectral flux* of RSSI

The output of each feature is adjusted, scaled, and mapped with a simple transfer function curve (e.g. exponentially, linearly, etc) to a range appropriate to the sound parameter that it controls. The features responsible for mixing the overall sound - controlling, for example, the amount of filtering and reverberation - are mapped to those specific parameters via *leaky integrators*. A *leaky integrator* is a filter that takes the integral of the input, slowly and over time leaking a small amount from it.[343] This has the effect of slowing down rapid changes, similarly to a low pass filter. In *Hertzian Field #1*, the use of leaky integrators produces quite expressive results, such as when it is applied to spectral energy for instance; in that case it produces the sensation that kinetic energy is stored in the system and slowly released once motion stops, producing the feeling that the system has a 'viscous' response to motion.

In more detail, the signal proceeds through the chain and is controlled by RSS data as follows (see again figure 7.12):

1. First, the signal is generated by the *DTO*, which is modulated by a number of RSSI features:
   - The rate with which the *DTO* reads the seed wavetable randomly changes when the *magnitude of the 3rd FFT bin* of the RSSI data exceeds a threshold (meaning, when there is significant amount of medium-speed motion, which corresponds to that bin)
   - The ratio of the speed of the writing head of the *DTO* in relation to the rate of its reading head changes stochastically – i.e. with controlled randomness - every time the *magnitude of the top-most FFT bin* (the 8^{th} bin) exceeds a threshold (meaning, when there is significantly fast motion). The bandwidth of randomness depends on the amount of *spectral flux*.
   - The reset position of the writing head of the *DTO* is controlled by the *moving average* of the RSS. The low-pass filtering is set to a high coefficient to flatten out change, resulting in smooth scrubbing across the wavetable.
   - The rate of the reset trigger is given by the *mean* RSS.
2. The resulting audio signal passes through a resonant low-pass filter whose amplitude is controlled by the *leakily integrated magnitude of the 2nd FFT bin* of the RSS. The filtered signal is mixed with the original.
3. This mixed signal is then stochastically routed through a cascade of *filters* – low-pass, band-pass, high-pass. These filters are controlled by a combination of RSSI features:
   - The frequency of a resonant low-pass filter is controlled by multiplying the RSSI's *mean* by its *spectral flux*.

[343] The leaky integrator formula is: out(0) = in(0) + (coef * out(-1)).

- The frequency of a band-pass filter is controlled by the *magnitude of the 4^{th} FFT bin* multiplied by the *spectral flux* and the *running average*.
- The frequency of a resonant high-pass filter is controlled by the *running average* multiplied by the *magnitude of the 7th bin* and the overall *spectral flux*.
- A new filter configuration, i.e. a decision on which of these filters will be activated, is triggered when the amount of *spectral flux* exceeds a (fairly low) threshold. This produces frequent, but not continuous, timbral shifts when the type of motion changes.
- The percentage of probability of the signal passing through these filters is controlled respectively by the low, mid, and high spectral energy of motion as detected by the *tristimulus* algorithm. The high-pass probability, corresponding to fast motion, is smoothed out through a leaky integrator.
- The mix between original and processed signal from these filters is controlled by the *mean* RSS via leaky integration.

4. After the *Subtractive Synthesis* processing of the former two steps, the signal then passes through another process, *Balance,* which adjusts the RMS of the processed signal to match that of the original. This essentially boosts sounds that have become softer through filtering, thus limiting the extreme variations in amplitude that can be caused by narrow-band, high Q filtering.

5. The signal then can pass through a simple reverberation algorithm. The room-size parameter is controlled by the amount of high-frequency energy detected by the (leakily integrated) *tristimulus* feature. In practice, this means that by performing continuous fast motions one can add increasingly more reverberation to the signal.

6. The next process in the chain is an *algorithmic real-time cut-up sampler*.[344] In a somewhat analogous manner to the *DTO*, this is also based on reading and writing wavetables, but this time containing many more samples (1-second memory buffers) that are not generated using RSSI but filled by recording the output of the signal chain. The manner in which playback/recording happens here is different: Receiving a trigger increases a counter; when the counter equals zero the sampler records, otherwise it plays back repeating the section it just recorded for a - dynamically modulatable - number of times. The following features control this process:
    - The speed with which the sampler's recording trigger is activated is modulated by the

[344] This is based on a slightly modified version of Fredrik Olofsson's SuperCollider pseudo UGen *RedLive*.

mean of the RSSI over a *brief window* of time.

- The rate of the playback oscillator is controlled by the *mean* as well, but with some stochastic randomness, the amount of which is given by the *standard deviation* of the RSSI.
- The triggering speed of the cut-up is controlled by multiplying three features: the *mean*, *fluctuation*, and *spectral flux* of the RSSI.
- The overall amplitude of the process is controlled by the *leakily integrated magnitude of the* 2^{nd} *FFT bin*, meaning that fairly slow motion makes it louder.

7. Finally, the overall output is limited using analog-style distortion (*.tanh*) to color the sound and safeguard against too loud signal values.

7.2.4 *Remarks on performativity, and subsequent experiments*

As mentioned, *Hertzian Field #1* was first presented at ZKM in July 2014 as a performative environment and as an interactive environment open for the public to interact. The system felt very responsive, almost magical, to perform with. Creating sound by moving in the field with my body, without being tethered to any wires or wearing any electronics, was both exhilarating and deeply enjoyable. It was also entirely out of my comfort zone; I had certainly not set out to create a system that I would perform in this manner. Nonetheless, it was definitely something I wanted to explore further, though I understood that if I were to perform again with this technology I would need to train my body for it and rehearse extensively. Overall, I was inspired by WIR's potential as a full-body interface for live sound performance, and intrigued to explore possible contexts and formats. I was also keen on getting input from dancers and choreographers, as it was obvious that they would have much feedback to offer, given the nature of the interface.

Consequently, a few months later - in April 2015 - I made a short research trip to the UK, to visit three dancer/choreographer/movement artist colleagues and workshop the performative potential of the system with them. I first worked with Bridget Fiske and Joseph Lau at a dance studio in Manchester for 1 day, and then with Eugenia Demeglio at the Sussex Creativity Zone in Brighton for 4 days.[345]

[345] These short work sessions took place with the kind support of the University of Salford (in Manchester), and the University of Sussex, Thor Magnusson and Thanos Polymeneas Liontiris (in Brighton).

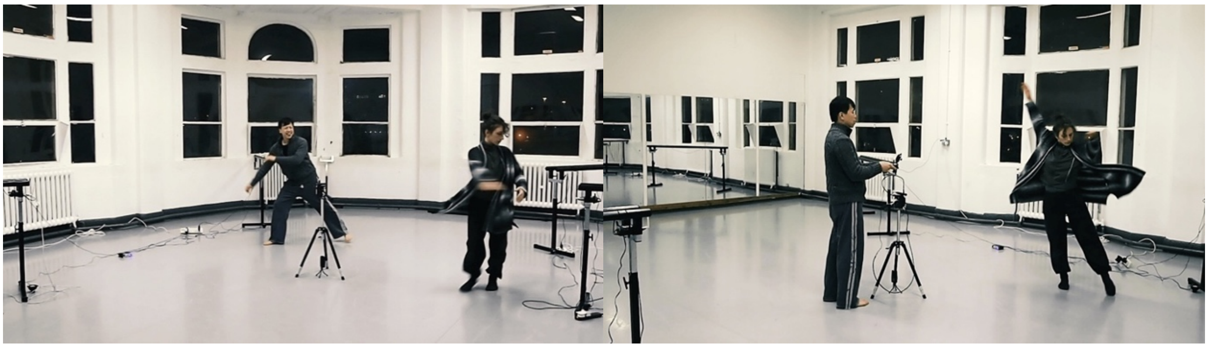

Figure 7.13. *Hertzian Field #1*: Video stills from my workshop sessions in Manchester (Salford University) with Bridget Fiske and Joseph Lau, April 2015. Left: both dancers interacting with the standard square geometry of the work, with the transmitter mounted in the center (on a camera tripod) and the receivers around it (on ballet-barres). Right: Lau holding a directional transmitting antenna which he points towards Fiske to 'illuminate' motion of specific body parts.

During the Manchester session we focused on exploring the system in solo and duo settings. We also performed a number of other experiments. This included different spatial configurations besides the original cross/square formation of *Hertzian Field #1*, such as a triangle with a transmitter in the middle; a duo in which one of the dancers handled a directional transmitter, dynamically changing where it pointed; a solo in which Fiske wore the transmitter and moved within the field (figure 7.13). In that last configuration, we found that placing the transmitter on her hip produced the best results in terms of sensitivity, interaction and facilitation - or perhaps better stated, non-impediment - of movement. That height placement approximately corresponded to that of the receiver antennas, and it also allowed the dancer to interact using a variety of motions, e.g. more focusing on arms and hands, performing subtle motions of the waist, rotating so that her entire core was brought between transmitter and receiver. Furthermore, we experimented with three types of transmitter antennas: the typical omnidirectional dipole used in *Hertzian Field #1*, a directional plate antenna, and an even more focused parabolic antenna. Each had its own merits, with the sensitivity of the dipole antenna being better when used with static nodes and for creating perimetric sensing zones. On the other hand, the more focused sensing beams of the other antennas were very promising in some situations, such as when one dancer used it as a kind of focused sensing beam or *microwave flashlight*, pointing it to a particular body part of the other dancer to more intensely 'illuminate' its motion. Unfortunately, the dance studio where this workshop took place presented some technical limitations in regard to sound. We thus had to alternate between a subpar stereo soundsystem mounted on one wall, and a set of bare and underpowered speaker drivers that I had brought with me, which I could place by the nodes for a more directional and surround sound. While this meant that the dancers experienced the system's sonic response in a suboptimal and somewhat detached manner (missing clarity, spatial resolution, and low end), it was an interesting test that confirmed my earlier thoughts from when developing the work on the importance of using surround sound with subwoofers to produce a spatially immersive, spatially responsive and full-bodied sound with a deep low-end, as that results in a much more connected, intuitive and fulfilling interaction.

In Brighton, with more time and much better technical conditions, I wanted to workshop the performative potential of the system for a solo mover. The majority of time was dedicated to Eugenia Demeglio exploring *Hertzian Field #1* as a complete environment, without further modifications. The rest was devoted to a number of experiments (figure 7.14). This included:

using a wearable transmitter with different types of antennas mounted on her arm or hip; covering or extending her body with a radio-reflecting material (aluminum foil); listening to the effects of the transmitter swinging as a pendulum from different angles - an experiment inspired by Steve Reich's *Pendulum Music* (1968) using WiFi transmission instead of audio feedback; changing the configuration of the space by moving the position of walls. Two videos documenting this workshop can be found online: one featuring excerpts from a 'live interference improvisation' by Demeglio, and another in which she improvises with the transmitter worn on her left hip (Modularbrains 2015a and Modularbrains 2015b respectively). The brief residency at Sussex concluded with an informal presentation of *Hertzian Field #1* consisting of a short performance by Eugenia Demeglio, a short duo where I joined her, and closing with an exploration of the environment as an interactive installation by visitors.

These two condensed R&D sessions were very informative for my understanding of the nature and potential of the system as well as of the elements that needed to be further developed. They were also eye-opening in regard to understanding what it means for a musician like myself to perform the system, and what it means for a professional mover to do it instead. Rather surprisingly, I found out that the latter is not by definition better than the former, and that there are a number of advantages and disadvantages in either case. The most significant outcome of these workshops was the realization that the work proposed a way of moving that is radically different to what dancers are trained for and used to. The main difference is that movement is what generates sound and not a response to sound, neither an end in and of itself that occurs in parallel to sound – which are the relationships between movement and sound that dancers are most used to. While it is possible to develop a WIR system that is meant to be in service of movement, my approach has been deliberately sound-centric. This is essentially hardcoded into the software of the *Hertzian Field #1* environment. When performing a *Hertzian Field* work*,* I move by listening, tuning my motion and stance according to the sound, and I move in order to hear something, executing this or that gesture to produce a known sound or to discover an unknown sound. On the other hand, dancers by definition have an incentive to move, built through years of practice. Furthermore, they have been trained to think about motion from the body and for the eye – i.e. how it feels internally, and how it looks to an audience - and to have a goal-oriented approach that usually involves stringing together a sequence of moves to get from where they are to another specific point in space following a certain trajectory. While this approach is appropriate for dance-oriented performances, such choreographed movements interrupt the experience for the type of environment that I have created, which aims to create a deep and intense sense of entanglement between body, movement, radio and sound. Moving in the *Hertzian Field* in the same manner as one would move on a dance stage breaks the direct feedback loop between movement and sound, turning it into a linear relationship where sound becomes merely the residue of motion. Retaining the feedback loop means that both the audience's experience and the performer's act of discovery are synaesthetic: the performer moves to listen and listens in order to move; the audience sees that relationship and hears its result, allowing them to vicariously explore the field through the performer's actions. As such, while professional movers possess highly developed body control, and can perform much more varied, intricate and aesthetic motion than a musician like myself can, it can be a challenge for them to perform with the system without more extensive practice. Practice is necessary to learn how the system responds, but also to temporarily forget – or, better re-invent - key concepts of a dancer's training, relating to the relationship between body, space, and sound. As I began realizing during these sessions, creating a movement-centric performance guided by the ear and not the eye is perhaps one of the most interesting, important, fertile, but also challenging proposals of the *Hertzian Field* series.

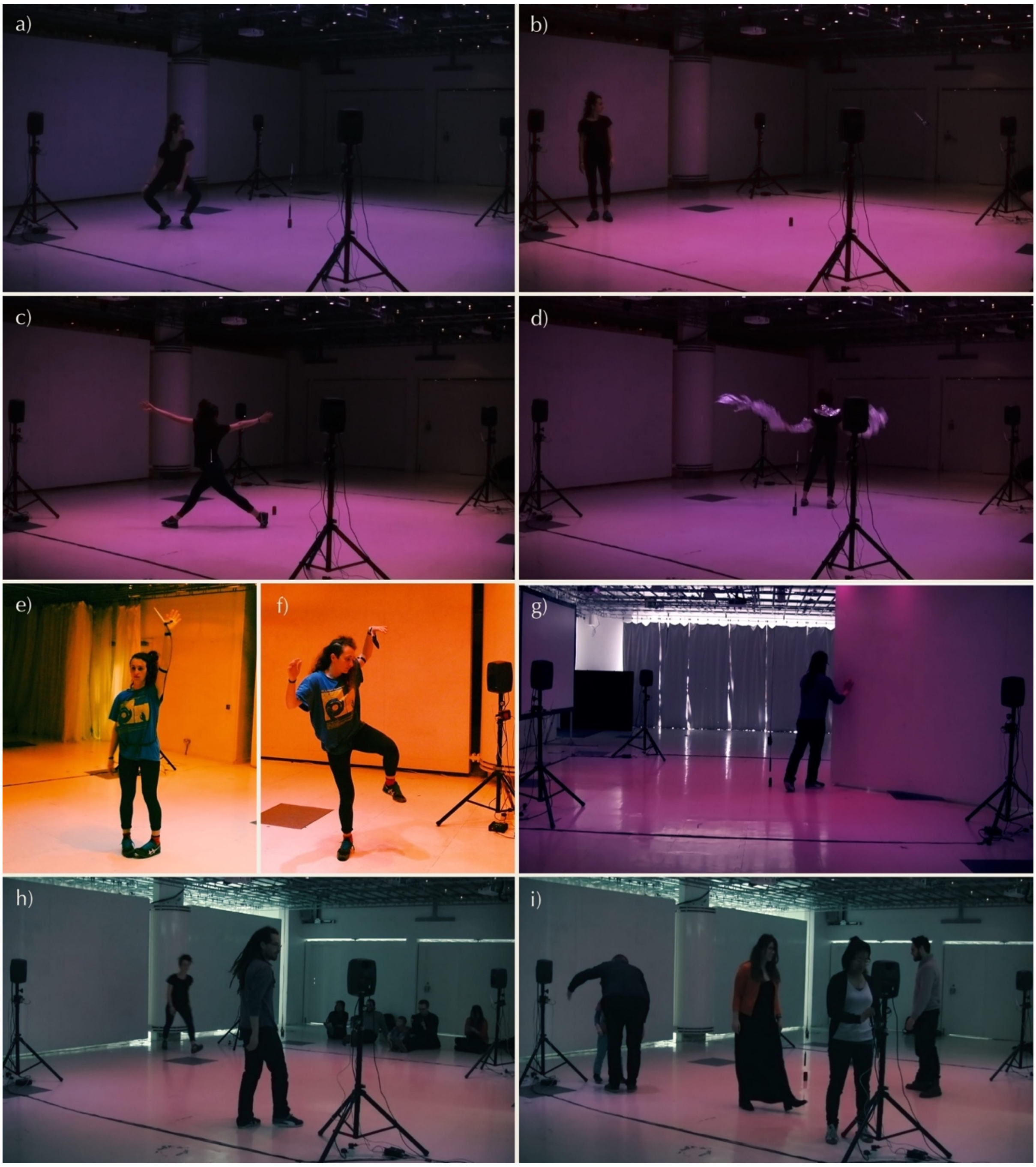

Figure 7.14. *Hertzian Field #1:* video stills from a brief residency in Brighton (Sussex University, April 2015) with dancer/choreographer Eugenia Demeglio showing various experiments conducted with the system: (a) performing with a standard configuration, but with the transmitter hanging from the ceiling in the center of the field; (b) transmitter as a pendulum; (c) transmitter worn on the hip (dipole antenna); (d) transmitter in the center, dancer moving with aluminum foil extensions; (e) transmitter worn on the arm (dipole antenna); (f) transmitter worn on the arm (directional plate antenna); (g) moving walls to affect the system by changing the room's architecture; (h) performing a short duet; (i) visitors interacting with the system.

7.2.5 *Remarks on visitor interaction*

In terms of the system's potential in an installation setting, one of the most interesting observations was witnessing how untrained visitors moved and interacted with the system and with each other while in the field. Overall, people tended to approach with an exploratory and performative mindset, actively trying to 'play' the system. However, it was interesting to observe that different people moved in very different ways, even if their mindset was perhaps similar. When several visitors shared the space, most appeared to limit themselves to types of movement they were comfortable showing to others, finding their own balance between timidly exploring and expressively performing. As a general tendency, individuals and groups tended to politely avoid nodes that others were interacting with, directing themselves to the closest unoccupied node and exploring the field around it. Since each node was producing sound independently, it was still possible to play with the system without much interference from the actions of others – unless someone was interacting with the central transmitter. As expected, when there were many interactors (more than 5-6), it became harder for individuals to understand how they affected the system themselves, as the interference exerted by their body was compounded to that of the bodies of others. Solos, duos, and trios appeared to be the most satisfying. Overall, it was very fascinating to witness people devising their own personal movement language on the fly with which to explore the field, and to examine how the system guided everyone to move distinctly, creating rather unique emergent choreographies.

Nevertheless, while the work drew some fascinating displays of very personal movement languages from its visitors, there were also moments where I felt that the experience folded upon itself, breaking down. I believe this was primarily a *death-by-association*: Presenting a work in a manner that makes it be perceived as 'interactive art' suggests to some visitors that they should approach it in a certain very specific way - namely 'wave your hand in front of the sensor to incite a clear response'. At times, I felt this was also a kind of meta-performative action from certain interactors, aiming to project to other visitors that they have encountered similar works and are well versed in how they operate. Unfortunately, the artistic experience has little room to develop when a visitor is primarily concerned with 'getting it' – i.e. trying to figure out the techniques under the hood rather than allowing oneself to be immersed in the work. This mode of interacting could be called *technological interacting*, in analogy to Dennis Smalley's term of *technological* or *recipe listenin*g, proposed as an extension to Pierre Schaeffer's four modes of listening (Smalley, 1997).

In many ways, such responses are the unfortunate baggage that decades of cliché interactive works have put on the shoulders of new media audiences. However, while I find such works to be rather facile, uninteresting and trite, and while their experience, goals and inner workings often seem closer to commercial product design than art, the reality of the matter is that they in fact form the majority of interactive art, and have thus been shaping audience expectations for decades. In *Hertzian Field #1*, when the mode of interaction stays at that level the results are neither the most interesting to listen to nor the most engaging to watch. Still, putting the blame on the 'sinful past' of interactive art is not at all productive. Instead, I found it much more constructive to search for my own failings and claim artistic responsibility for them, as that meant I have the agency to make different choices in future works. As such, besides the successes and promises of *Hertzian Field #1* and the interaction system I developed for it, I realized that it had two crucial shortcomings: it looked like new media art, and it was exhibited in a new media art setting. This context predisposed the audience to act in a certain way. The fact that the antennas featured prominently in the work only exacerbated the situation. This was an important point of reflection that had a strong influence in the format of the subsequent *Hertzian Fields*.

Overall, opening the environment to interaction brought forth two important realizations. First, that it can be very demanding to ask from regular visitors to express themselves with their bodies when others are present. Secondly, that it is fundamental to create a context conducive to this type of self-expression; to find strategies that help visitors feel safe to express themselves instead of feeling watched; to create a system and conditions that suggest and inspire new ways of engagement, that guide visitors to actually experience the work rather than to take the default role of '*performing-being-the-visitor-of-an-interactive-installation'*. Creating a different context that pushes away the familiar conventions of new media and interactive art becomes a necessary step to support visitors in discovering for themselves how to use their bodies as a sound-making interface.

For these reasons, *Hertzian Field #1* showed me that while the system had an incredible performative promise, developing an interactive environment required deeper thinking in how to compose the right context. Consequently, with the next work, *Hertzian Field* #2, I chose to focus on the performative potential of the system. With the work after that, *The Water Within / Hertzian Field #3*, I returned to the idea of the interactive environment, but this time creating a radically different context to support it.

7.3 HERTZIAN FIELD #2

7.3.1 *About the work*

In 2015-2016 I continued my research and development of the *Wireless Information Retrieval* system, creating a much more advanced, precise, and versatile iteration. In the meantime, I had remained in contact with ZKM who was interested in presenting a subsequent work in their upcoming festival, *GLOBALE*. This was a 300-day artistic manifestation - a festival of festivals - organized and hosted by ZKM in 2015-16 in the occasion of 300 years from the founding of the city of Karlsruhe. It was a *"multipolar event"* that proposed a new, expansive format for thematic exhibitions, consisting of a *"set of interwoven exhibitions and performances, installations and environments, research presentations and film screenings, readings and lectures, actions, concerts, and conferences"* (Weibel 2015a, 6). These events were organized together into different sub-themes, each one exploring certain aspects of *globalization* and *digitalization*, "*two thematic fields that are currently immensely changing human life on Earth"* (Ibid).

The work I created for *GLOBALE* was *Hertzian Field #2*, an immersive sound and movement solo performance, with a duration of about 20-25 minutes and myself as performer. Developed between 2015-16, it was created as a response to the festival's thematic of the *Infosphere* (see sections 1.1.2 and 1.1.3). The text describing the work reads:

"“We do not think right away of the distances that separate objects from one another. For space is never empty: it always embodies a meaning. The perception of gaps itself brings the whole body into play"
Henri Lefebvre: The production of space, 1974

"We no longer have roots, we have aerials"
McKenzie Wark: Virtual Geography, 1994

Hertzian Field #2 is an augmented reality immersive performance – an urban ritual for the 21st century, exposing the sympathetic resonance of the human body to the invisible flow of wireless communication.

We live engulfed in radio fields, moving unawares through turbulent streams of data. Wireless networks have imposed their very material presence in our spaces, layering invisible strata as real as the air we breathe. While we lack the capacity to sense them, they feel our presence as our bodies block, reflect and displace radio waves. Material reality seeps in the communication channel; beyond distributing our data, the infosphere has a side effect: it transmits information about physical space and our bodies within. Our data *networks are public radars, lending a radio ear to anyone listening.*

In Hertzian Field #2, 3 WiFi transmitters/scanners form an isosceles triangle radiating a dynamic electromagnetic architecture at 2.427GHz. As the performer enters the field, the water molecules in his body spin, brought into resonance by radio waves. Electromagnetic energy is transduced into molecular kinetic energy and then heat inside the body, leaving radio shadows behind. The radio field's fluctuation is captured and analyzed, revealing the body's electromagnetic resonance. The WiFi sensing system is coupled to an audio feedback network surrounding the audience – a sonic mirror of the field – to create an environment in which body, space, movement, sound, and WiFi waves are entangled in a quantum embrace.

Hertzian Field #2 uses a new sensing technique developed by the artist, inspired by research in radio astronomy, surveillance, and acoustics." (Manousakis, 2016a).

Figure 7.15. Photo from the premiere of *Hertzian Field #2* at the ZKM_Kubus in Karlsruhe during *GLOBALE: Performing Sound, Playing Technology* on February 6, 2016 (by ZKM Onuk).

Hertzian Field #2 premiered on February 6th 2016 at the ZKM_Kubus during *GLOBALE: Performing Sound, Playing Technology*, a festival on contemporary musical instruments and interfaces (ZKM, 2016a) (figure 7.15). A video excerpt from the performance can be viewed in Manousakis (2016a). Following the premiere, I was invited by ZKM director Peter Weibel - present in the audience - to perform the work again at the festival's closing event, *GLOBALE: Finale,* on April of the same year. That concert was programmed in the context of the *New Sensorium* exhibition under the title *Sonic Senses* (ZKM, 2016b). Since then, the piece has been shown in several music and new media festivals across Europe (figure 7.16).[346]

The piece uses an algorithmic approach for interaction, aiming to create intuitive and dynamic ways of experiencing and interacting with hertzian space. While the updated version of WIR provided a wealth of newly implemented feature extractors, I decided to focus on a smaller subset to best evaluate their potential and investigate the kind of behaviors they support and encourage. My aim was to design a system in which the *Hertzian Field* becomes at the same time a dynamic environment and a score to be explored by placing and moving the body in the field: an immersive sound organism, at times violent, at times soothing, at times resonant and reverberant, at times noisy, at times digital-sounding, at times rhythmical, and at times like a thick tsunami of waves gushing through the space. In this work, the performing body becomes a semi-transparent filter of microwaves and movement becomes a process of modulating electromagnetic fields and shaping sound. The primary sensation is like being immersed in flows of energy, which can be partially shaped and moved in space by the body, but which also pass through and curve around it. In *Hertzian Field #2* the sensing system is concerned as much with motion as it is with static interference and the discovery of electromagnetic nodes and antinodes – special, sensitive spots within the field in which interesting behaviors or sonorities emerge through interaction. The approach, performing strategies, and emerging movement language are thus different than those of *Hertzian Field #1*, as the system encourages the exploration of static postures, minuscule motions, and large flowing movements.

[346] Beyond the two performances at ZKM and a ‘preview’ performance at Studio Loos in The Hague in January 2016, *Hertzian Field #2* has been performed at: *Audio Art Festival* in Krakow, Poland, November 2016; *Athens Digital Art Festival*, in Athens, Greece, May 2018 (Festival theme: *Singularity Now*); *Gogbot Festival*, Enschede, Netherlands, September 2018 (Festival theme: *Future Flash 200, From Frankenstein to Hyperbrain*); *RIXC Art Science Festival*, September 2018, Riga, Latvia (Festival theme: *Global Control)*; *Latent City: Invisible Fields* festival at Bergen Center for Electronic Arts, Bergen, Norway, November 2020. *Flipchart #2: Resonating Bodies*, at Instrument Inventors Initiative workspace (WD4X), The Hague, the Netherlands, May 2022.

Figure 7.16. Photos from various performances of *Hertzian Field #2:* (a) at the ZKM_Kubus in Karlsruhe during *GLOBALE: Finale / Sonic Senses*, in April 2016 (video still by Stephanie Pan); (b) at *Audio Art Festival, Krakow*, in November 2016 (photo by Mikołaj Zając); (c) at *RIXC Art Science Festival*, Riga, in September 2018 (photo by Tivon Rice); (d) at *Flipchart #2,* The Hague, May 2022 (photo by Naomi Moonlion); (e) at *Athens Digital Arts Festival,* May 2018 (video still by Yannis Papanastasopoulos).

7.3.2 *Configuration*

The performance takes place on a 4x4m stage, typically placed a few meters off the center of a large space. The audience is seated in a circular or polygonal formation around it, with a ring of loudspeakers surrounding them (at a minimum 4 loudspeakers and 1 subwoofer, although bigger setups, like the *Sound Dome* of the ZKM_Kubus are much preferable). On the otherwise empty stage area, 3 microphone stands are placed in an isosceles triangular formation, each at a different height. The stands hold small boxes – Raspberry Pi microcomputers - with WiFi cards and antennas coming out of them at a slight angle.

This configuration creates a tilted triangle of Line-of-Sight beams and Fresnel zones dissecting different parts of the body at different areas of the stage (figure 7.17). This slanted configuration both significantly increases the spatial resolution of the sensing system and also encourages the performer to explore movements of the body in the vertical axis. The size and tilt of the triangle – i.e. the distances between nodes and the heights and angles of the antennas - are tuned to the performer's height and wingspan. The idea is that the performer can: a) reach any spot within the triangle from its center with a single large step, and b) simultaneously block the Line-of-Sights of two node pairs with open arms. In the latter case, what is particularly important is that the performer is able to obstruct the LoS between both base nodes and the tip node by opening their arms and holding their palms in front of the antennas at a distance of about 1 wavelength (~12.5cm). Thus, the distance between the two base nodes is linked to the performer's wingspan. The distance between the middle of the triangle's base and the tip node is set at somewhere between 1.085 to 1.15 times its base length. In terms of height, the three nodes are positioned at consecutive multiples of a base number (which when I am the performer corresponds to 33,3cm), measured between the ground and the bottom of the antenna: the lowest node is at the tip of the triangle and set at a height that the performer can comfortably bring their core in front of (66,6cm in my case); the middle one, on the righthand side of the triangle's base, is at the height of the performer's core (99,9cm), and the highest one, at the left of the base, is placed chest-high (133,2cm).

A triangle is marked on the floor with thick white gaffer tape under the Line-of-Sight paths between the antennas – like the markings of a strange ritual, in a subtle nod to the age-old connection of electromagnetism with the occult. The tape marking on the stage visually demarcates the LoS as a reference for the performer. It also demarcates the inside and the outside of the triangle for the audience, indicating the presence of an invisible but seemingly responsive barrier. Overhead lights shine a radiating circle of about 1m diameter around each stand.

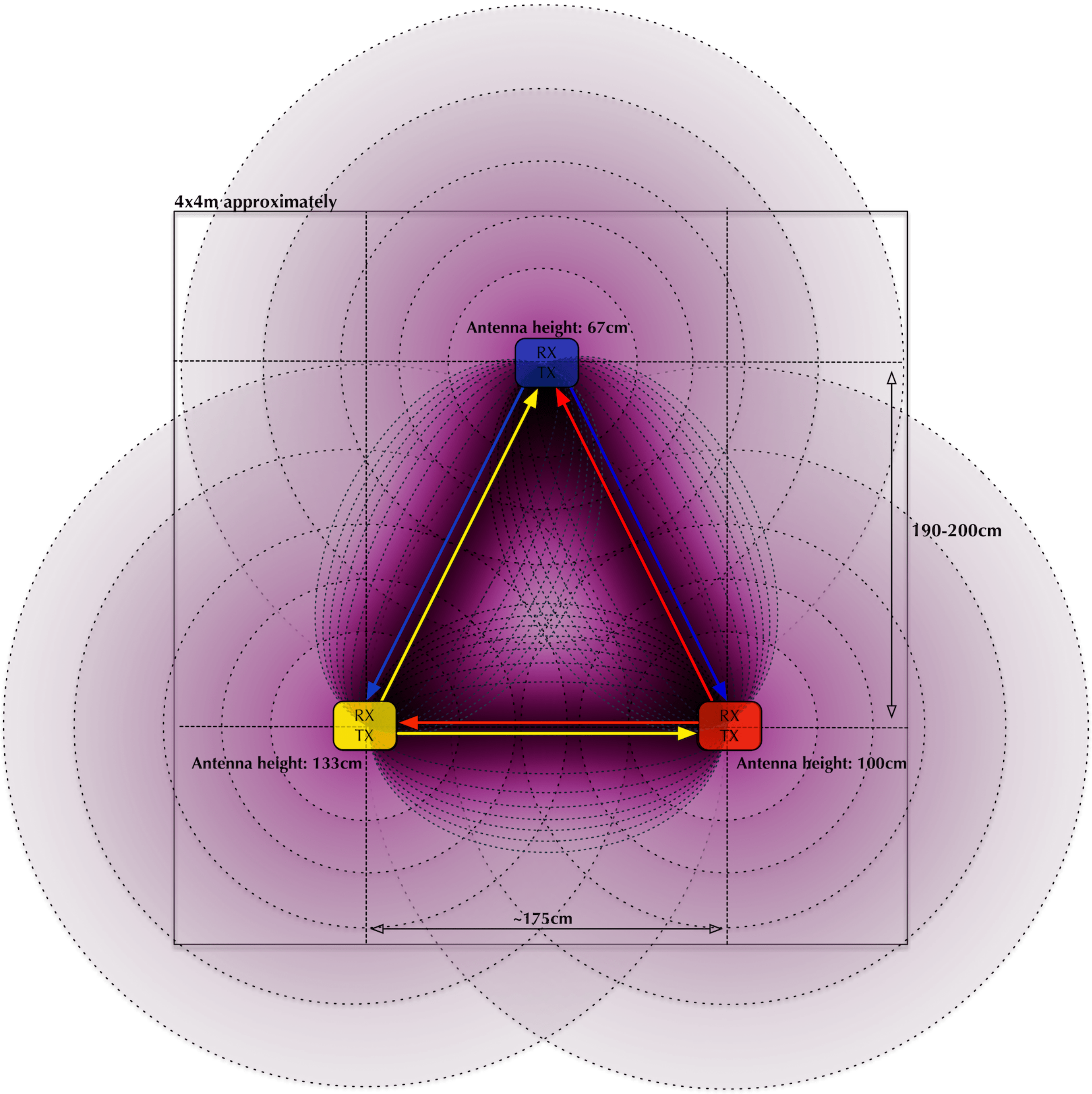

Figure 7.17. Spatial configuration of *Hertzian Field #2.* The diagram shows the placement of the 3 transceivers, as well as simplified visualizations of their fields (concentric circles), their Lines-of-Sight (arrows), and of the most sensitive Fresnel zones formed between them (concentric ellipses). The dimensions correspond to a performer with a height of about 175cm.

The sensing system for *Hertzian Field #2* consists of 3 transceiver nodes. Each emits about 32 WiFi beacon pulses/frames per second, while simultaneously scanning the air interface for the beacon frames of the other nodes. The sensing hardware is the same as in *Hertzian Field #1* - Single Board Computers (Raspberry Pi B v.1) equipped with WiFi cards and omnidirectional (dipole) antennas. The nodes are not equipped with sound cards, however, as they do not produce sound in this work. Instead, they are connected via Ethernet cables to a more powerful laptop which gathers all data, analyzes, processes, and sonifies it.

7.3.3 *An overview of the work's sound, movement, spatialization, and sensing strategies*

The principal concept of the sound engine and its relationship to WIR sensing data is to use movement as an excitation mechanism and the body as a filtering system. Moving excites the field to sound; generally, the sonorities produced when movement occurs outside the triangular field are noisier and more broadband; when it occurs within the field they are more resonant and reverberant - as if stirring the field and listening to its sound from within its belly. The sounds thus produced are filtered by the body; they become more narrowband and resonant depending on the its location and orientation relatively to the field, and on how it absorbs, reflects, and interacts with the microwave signals of the *Hertzian Field.*

Below is a brief summary of the work's soundworld from the (unpublished) score, addressed to the performer (Manousakis, 2019a)

"The performance begins in silence; thin and noisy streams of sound are generated by small movements of your body and arms as they start breaking the microwave line on the triangle's base. Like waves created by this motion, the noise grows in mass and density enveloping the space as you move further into the field. When you reach the heart of the sensing triangle for the first time, a reverberant and metallic liquid mass smothers the digital noise, creating a viscous soundscape - like swimming in electromagnetic honey. Through this movement, the soundscape coagulates into a bass heavy rumble; microwaves can now be felt by the audience as sound and thick air moving from the subwoofers around them. Out of this rumble, rhythmical bursts of aggressive noise emerge; they lead to heavy rhythmic beats, shifting from dense polyrhythms to an almost minimal noise-techno texture – a trance-inducing rhythmic wall of sound. You continue stirring the energies from within the triangle, creating an ever-increasing mass of sound; you draw this to an end by exiting the field and letting the system calm down to silence."

A verbal mini-score summarizing and describing the actions and mindset required to perform the work with broad strokes follows (Ibid):

"Your every movement produces a sonic response, therefore it should be guided by your ear. Performing the piece requires intensive and focused listening. Move slowly at first, discover the hidden soundworlds in the environment by exploring different configurations of the body in the field – static and dynamic ones alike. Repeat motions to find the same sound again and again. (Repetitions are important; they help audience and performer alike to grasp the relationship between space, body, sound, and field). Slightly alter the patterns to make the world you discovered evolve. Stay still to scan your body. Discover how the system behaves when you stand in absolute standstill at different spots. Stasis is important as a counterpoint

to movement - sonically, but also visually. Move only a little, change something small and stand still again. Discover how minuscule a movement is enough to modulate the system, or even to destabilize it entirely - from noise to resonance, from stasis to chaos, from stability to instability."

The sound engine is largely based of digital feedback. It consists of interconnected networks of generator and processor modules that feed into and from themselves and each other. Intertwining these sound modules in complex feedback networks creates an intricate sonic mesh, conceptually similar to the electromagnetic mesh formed by the waves of the 3 WiFi networks used in the piece. The result is that the performer's body has an effect on the sound of the entire system from any and all locations – though how much each particular process is influenced depends on location and orientation – just like it has on the entirety of the electromagnetic field. This gives the performer some control of the entire soundscape from everywhere in the field.

The generator modules synthesize sound on the level of digital samples. RSSI feature extraction is used to map motion within the field into air pressure fluctuations directly. This technique belongs to the family of *non-standard sound synthesis* models (see section 7.2.3) and has its conceptual roots in the work of composer Iannis Xenakis (Xenakis, 1992). Layers of frequency-domain and time-domain processing are used to further sculpt these sounds. Some of these processes use RSSI feature extraction data to manipulate an abstract mathematical representation of the moving body as a filter of WiFi microwave signals; the system then uses this model to filter and control the generators' sound. In this manner, while microwaves pass through the body physically, the generators' sound waves pass through these (abstract) virtual models of the body as a dielectric/filtering object, which results in combing out parts of their acoustic energy. The physics of the interaction between body and hertzian field thus becomes embedded into the Digital Signal Processes (DSPs) of the work.

Data generated by the performer's movement is mapped to sound both quantitatively, as parameter modulators, and qualitatively, producing state changes when significant events occur in the field, such as when there is sudden full-body movement or sudden fast movement, or when the LoS between a transmitter-receiver pair is broken by the body. Overall, in *Hertzian Field #2* I reduced the amount of stochastic data processing when shaping the output of extracted features (i.e. before the mapping phase) in comparison to *Hertzian Field #1*, so as to make it simpler to repeat sounds and sonic behaviors through repetitions of movement. While stochastic shaping is a strategy I use in *Hertzian Field #1* with overall positive results for that work, it also has some drawbacks: While, for instance, triggering a random value every time a physical threshold is crossed can have very interesting sonic results and can produce the sensation that the environment has complex agency, this clouds the interaction mechanism making the system more opaque as repeated movements may produce different results. As such, in this performative work I chose to embed chaotic behavior in the synthesis instead of in the mapping, using stochastic processing of control values more sparingly.

The use of complex feedback networks, combined with mapping many features to many parameters within the same sound module (*many-to-many* mapping), makes the system very sensitive, exceedingly responsive, and highly complex in the ways it responds.[347] Due to the configuration of both the synthesis engine and the sensing system (and particularly because of placing sensors at different heights) the space in *Hertzian Field #2* is *anisotropic*, creating specific zones where certain sounds or behaviors occur – e.g. heavier bass, a particular resonance, a turbulent behavior, a certain polyrhythm, etc. These zones, which can be imagined as 3-dimensional 'bubbles' within the field, can be very small and precise - typically when closer to a node's antenna - or they can spread over a larger area. It should be noted that their exact location may vary in different sites due to the system's interaction with architecture and the effects of multipath propagation. Therefore, soundchecking before a performance is very important.

In *Hertzian Field #2*, like in all works of the series, spatialization emerges purely through movement and is completely integrated within the radio sensing system. In this manner, sound becomes the radio field's synaesthetic double: a sonic mirror that envelops the audience just like the WiFi fields envelope the performer on stage. I have found that this approach works very well.

In technical terms, *Hertzian Field #2* presents a refinement of the spatialization strategy used in *Hertzian Field #1*. Sound is encoded into a half sphere or ring and is diffused by loudspeakers surrounding the audience.[348] The diffusion technique used is *First Order Ambisonics*, an algorithm that excels in producing immersive soundfields (Zotter and Frank, 2019). Sound-generating and processing modules are dispersed through this area. The idea is

[347] At the same time, this also made it more difficult to troubleshoot during development, especially as the system's complexity was compounded to the fact that I was still learning how environmental factors – humidity, temperature, changes in the room's layout, etc. - affected WiFi sensing.

[348] For practical reasons, namely the very rare availability of 3D soundsystems, in all performances of *Hertzian Field #2* so far, the work has been diffused through 2-dimensional arrays of speakers surrounding the audience (thus creating a sonic ring rather than a half-sphere). Nonetheless, 3D renderings of the soundscape are also possible.

to create a system in which soundwaves created by movement occupy the same space as the microwaves that control them. As such, generator and processor modules are placed in the general location that corresponds to the area of the field that they respond to: For instance, a series of processes controlled by features extracted from the transmission of the tip node as received by the bottom-left node (i.e. 'yellow' tracking the interference on 'blue', when looking at figure 7.17) will be spatialized somewhere along the left side of the soundfield. These process will be placed somewhere between 7' and 9' o' clock. I chose to not modulate the spatial location of any modules but to keep them static, so as to strengthen the connection between hertzian field and sound-field. Nonetheless, sound does not itself remain completely static in space; owing to the intricate feedback patching between modules, sounds and behaviors appear to originate from the location of interference and then radiate towards the rest of the field.

The following section, 7.3.4, examines sound generators and processes individually. The section after that and its figures (7.3.5) map out the how these modules are controlled, spatialized and interconnected to one another in feedback networks.

7.3.4 *Core sound modules: synthesis and WiFi-sensing control*

Throughout the piece, a number of different synthesis and processing modules as well as control configurations appear. The latter involves several control functions created for specific parts of the piece, each with its own combination of RSSI analysis features and variations in how their output is shaped, how it is mapped, and which synthesis parameters it controls. Here below I will present the core generator and processor modules and how they are controlled by the WIR system. This section is quite detailed and technical, as it is meant to provide an exact documentation of the strategies that I found successful in mapping WiFi sensing data to sound.[349]

I) NO-INPUT FEEDBACK MODULE (AKA 'PRIMEVAL')

The seed sound in *Hertzian Field #2* is synthesized by a no-input feedback module, which functions as a generator and as filter at the same time (see figure 7.18**)**. This module is inspired by a synthesis algorithm I devised for my digital feedback suite, *Primeval Sonic*

[349] There are a handful of less important processes involved in the work that I will not discuss to prevent this section from getting too long.

Atoms (Manousakis, 2020).[350] All pieces in that suite use the same software instrument and are performed with the same hardware - a midi interface with many knobs, buttons and switches (Behringer BCR2000), employing a total of 100 distinct controller elements mapped to various synthesis parameters. Performing that instrument and these pieces has required long and sustained rehearsing to develop the necessary virtuosity.

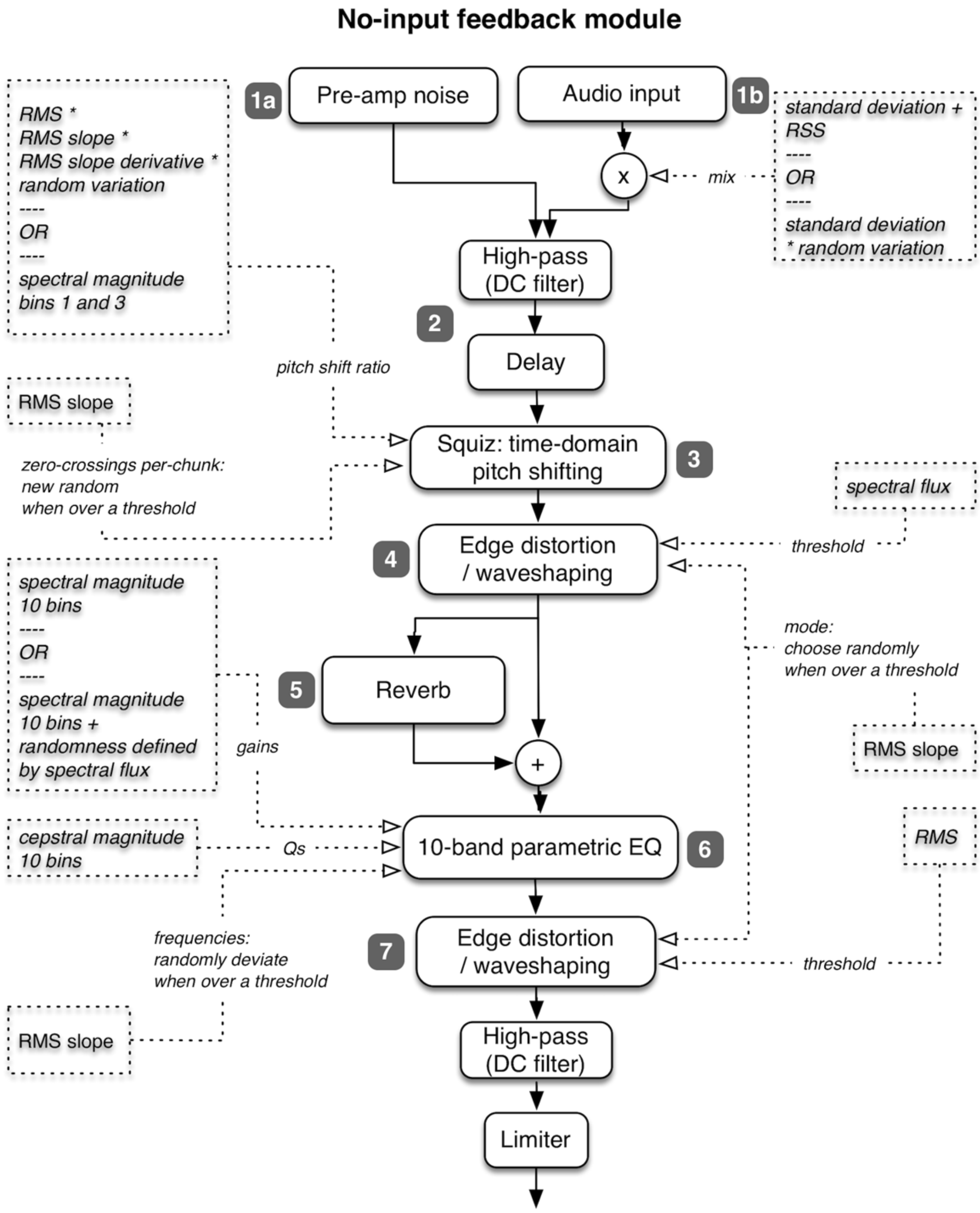

Figure 7.18. Synthesis and control schematics of the core audio generator/processor in *Hertzian Field #2.* This module generates sound via 'no-input' feedback and is controlled by multiple data streams (extracted RSSI features) corresponding to various performer actions.

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[350] The suite consists of four pieces: *Fantasia On A Single Number* (Manousakis, 2009a), *Megas Diakosmos* (Manousakis, 2011)*, L'Hypothèse de l'Atome Primitif Sonore* (Manousakis, 2010) and *Snow* (Manousakis, 2019b). The first and third are composed for live performance, while the second and fourth (a piece written for dance) are fixed medium works produced in the studio by performing them live in layers.

Creating a variant of this system for an instrument in which the whole body is the interface - not only the hands and fingers – introduced a number of fundamental differences to this synthesis module, in comparison to how it was configured in the *Primeval Sonic Atoms* series. While there is a limited number of knobs and buttons two hands can simultaneously control, the WIR system presents an abundance of ways with which to examine how the body occupies space and moves within the field. This allows controlling multiple sonic parameters at the same time and with the same movement, producing small or radical changes depending on the volume of the gesture, its orientation, its speed, character/quality, etc. However, while with a knob-box one can be very precise and clinical, setting parameter values in specific spots, the process of making sound in the *Hertzian Field* is radically different and much less precise. It is only possible to repeat gestures and get the same sounds if the entire body and all its parts move in the same exact way, place, and direction, and if environmental conditions, such as humidity and the placement of objects of other bodies, is the same. Practically, this means that a certain type of accuracy is possible, but finding the same exact sounds on different days and different environments – like, for example, one can do with the Theremin - can be an exercise in futility. Furthermore, while in the *Primeval Sonic Atoms* performances I could take my hands away from the controller to stop producing control data, there is always some fluctuation present in the microwave signals - especially as the performance typically takes place inside a closed space and with living and breathing bodies around. This makes stasis near impossible, unless the sensing system is switched off, or aggressively quantized, or the synthesis system is radically simplified.

The following RSSI features are used to control this module throughout the piece, sometimes in different combinations:

- *Raw RSSI*
- *RMS*
- *RMS slope* and its *derivative*
- *Standard deviation*
- *Spectral magnitude*
- *Spectral flux*
- *Cepstral magnitude*

As in *Hertzian Field #1*, the values produced by these features are scaled and adjusted to the appropriate range, and are mapped with a curve/transfer function appropriate to each synthesis parameter (e.g. exponentially, linearly, etc).

The signal path is configured as follows (see figure 7.18):

1a. *Seed sound (pre-amp noise):* The seed sound is produced by the internal noise of one of the soundcard's pre-amplifier when no cables are plugged in it. This replaces the minuscule signal that sparks the feedback chain in the *Primeval Sonic Atoms* series (which consists of the softest mathematically possible signal in a 32-bit system: a tiny DC offset as inaudible as the least significant bit) with a comparatively much heftier noise source. This analog source provides a continuous noise of extremely low, practically inaudible amplitude, ensuring there is always some signal feeding into the system. Firstly, this enables more points in the *phase space* of the feedback system to actually produce sound.[351] As a consequence, this makes it easier to map out when the instrument is expected to produce sound and when to be silent. This comes in contrast to the *Primeval Sonic Atoms* instrument, in which many control parameter combinations (i.e. many points in the *phase space*) render the instrument mute. For that reason, when developing that instrument I had to spend a long time practicing to learn and memorize in which configurations the feedback loop stopped, and which knobs and buttons of my interface to handle in order to revive it. This was not a viable option for the much more intuitive full body control of *Hertzian Field #2*; I wanted to specifically avoid extended moments of silence, where the body moves and nothing happens as that would break the synaesthetic connection between movement and sound.

1b. *Signal/Audio input:* In parallel to the seed noise source, or sometimes alternatively, other signals can be fed to this 'no-input' module. For example, in the beginning of the *Hertzian Field #2* performance, four of these process are configured in pairs of cross-coupled feedback loops with one feeding into another to produce a complex and dynamic sound (see figure 7.23). Later in the piece, other types of processes are also used as input. A module's own output can also be fed back directly back to its input to create a self-sustaining feedback loop.

- Signal input control*:* The amplitude of the audio signal fed as input to the process is controlled by the amount of overall motion of the body in the field. This is deduced by the *standard deviation* of the RSSI (which is indicative of motion), in combination with

[351] *Phase space* is defined as an n-dimensional space consisting of as many dimensions as the parameters that define the system. A specific point in that n-dimensional space represents a particular state of the system, i.e. a particular configuration of its parameters. See "Phase Space" (2014).

either the *raw RSS* value - which is indicative of position, with higher values generated when the body is blocking more of the signal - or some random deviation (±10%). The latter is used in a rhythmical section towards the end of the piece to inject additional variation in its rhythmic timing.

2. *Delay*: The seed and/or input sound subsequently pass through a high-pass filter to remove any DC content and then through a delay. Delays are fundamental components of feedback systems, with their exact duration exerting a great influence on the characteristics of the resulting sound, particularly its frequency. As Sanfilippo and Vale (2013, 14) point out: *"From a theoretical point of view, we can think of a zerodelay feedback loop as a system whose fundamental frequency is infinity; in practical terms, any implementation and performance of a feedback system implies a delay greater than zero"*. In *Hertzian Field #2,* each no-input module is tuned to a unique delay time that remains static for as long as that module is playing.

3. *'Glitchy' pitch shifting*: The delayed signal is then routed to a rather idiosyncratic filter: The *Squiz* SuperCollider Ugen.[352] This is a time-domain algorithm that can raise the pitch of an input signal in a manner that (intentionally) produces a number of very interesting sonic artifacts. The algorithm operates on a short memory (typically, a couple hundred ms), whose contents it splits into segments, or chunks, by counting positive zero-crossings (*zerocrossings-per-chunk*). The chunks get squeezed in the time domain by playing them back faster at a modulatable rate (the *pitch shift ratio)*. However, because each chunk's starting point remains fixed, pitch shifting also produces silences between chunks – the higher the shift, the longer the silence. This combination of pitch shifting and amplitude gaps introduces a great variety of interesting effects in the feedback loop.

   This algorithm is interactively controlled as follows:

   - The amount of *pitch shift* is controlled in one of two ways, depending on the section of the performance:

     a) By multiplying the *RMS RSSI* value (which is indicative of the amount of movement and the position of the body between transmitter and receiver) with the *RMS slope*, and the *derivative of this slope*; these two features produce large values with sudden changes in movement. This control mechanism works very well because, as a general rule, the larger and more sudden the movement, the larger the pitch-shift and

[352] This UGen was designed and coded by Dan Stowell.

hence the more the feedback loop gets destabilized.

b) In other parts of the piece, the pitch-shift amount is controlled by the *spectral magnitude of the 2nd or 4th FFT bin* (with the two modules in each cross-feedback pair alternating between the two), i.e. by the amount of slower movement detected.

- The amount of *zerocrossings-per-chunk*, at certain times in the piece, is controlled by the *slope of the RMS*: When the slope is higher than what is defined by a threshold value (meaning that motion was more sudden than that defined by the threshold), a new random *zerocrossings-per-chunk* value is passed to the process.

4. *Waveshaping*: The *Edge* pseudo UGen is a simple but very versatile time-domain filter for shaping feedback on a sample-by-sample basis. It is essentially a type of non-standard distortion with several modes, which I've designed by building on my past work on non-standard sound synthesis (see Manousakis, 2006 and Manousakis, 2009b). A threshold value defines the bandwidth of the amplitude space - what the minimum and what the maximum possible amplitude can be. The mode of the filter defines the character of the edges of this amplitude space, and determines what happens to any incoming samples whose amplitude lies under the lowest or above the highest possible values. *Hertzian Field #2* uses a subset of eight of the available modes (see figure 7.19):

   a) *Wall*: exceeding values are clipped to the defined range.

   b) *Elastic barrier*: exceeding values are reflected back. The more energy in the sample (i.e. the further away from the threshold), the larger the reflection away from the boundary.

   c) *Circular space*: exceeding values are wrapped around and enter from the other edge of the amplitude space, as if that space was circular with its high and low edges connected.

   d1-d5) *Stochastic reflectors*: exceeding values are reflected back stochastically. The amount that the value exceeds the threshold defines how far back it may be reflected. The amount of reflection is given by randomly picking a value between the edge value and the maximum reflection value. A number of random distributions can be used - *white, pink, brown, gray* and *binary noise* - representing different kinds of reflective materials.[353]

[353] The first three types of noise are well known: *white noise* has an equal distribution, *pink* or *fractal noise* is proportionally denser in the low end, and *brown noise* typically models the movement of particles in liquids or gasses and is also called *random walk*, or *drunk's walk*. The other two noises are more obscure. As the SuperCollider documentation reads, *gray noise* "*results from flipping random bits in a word",* it has *"a high*

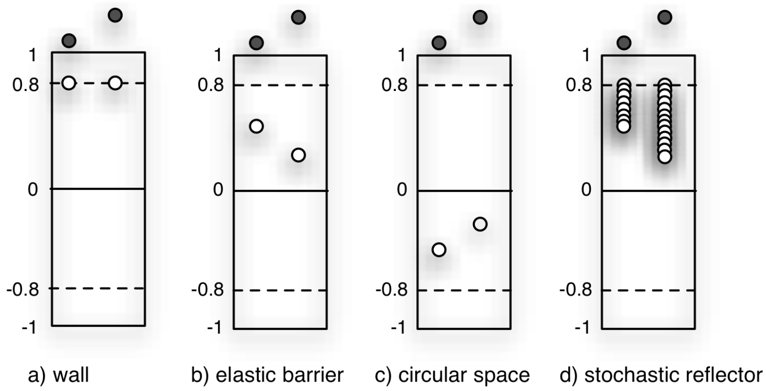


Figure 7.19. Confining values that exceed a threshold through 4 possible types of 'edge' behavior, i.e. waveshaping algorithms applied to values surpassing a defined range. In this example, threshold values are set to -0.8 and 0.8, input values are shown as black circles, and output values as white circles.

This process is controlled as follows:

- The *mode* changes when the *RMS slope* of the RSS exceeds a threshold. One can think of this as an *onset filter* triggering a new mode when a new gesture starts. The new distortion mode is chosen through a weighted random selection process.
- The *threshold* is controlled by the *absolute spectral flux* value of the RSSI, i.e. by the difference in spectral energy between two consecutive FFT frames. When the same type of motion continues across frames (from a receiver node's point of view), the spectral energy is similar, therefore the spectral flux is small. When the type of motion changes, flux is higher and thus the threshold is lowered, which produces a more distorted and noisier signal. Practically, this feels as if sound is generated by an intangible material around the body that can be pushed, shaped, and distorted the more one moves within it.

5. *Reverberation*: The resulting signal can be routed through a simple reverb algorithm, whose output is then mixed back with the non-reverberated signal. Reverbs can be very useful and powerful in sculpting a feedback loop as they can essentially function as a rich resonator bank with its own internal feedback-delay mechanism. The algorithm used here is *FreeVerb*, a computationally cheap – and somewhat cheap sounding, if used as a plain reverb - but versatile tool for shaping sound in complex ways with just 3 parameters (dry-wet balance, room size, and range of high-frequency damping). In this 'primeval' process, the reverb is not controlled interactively but through the score - mostly using slow fades,

RMS level relative to its peak to peak level" and has even more energy in the low end ("GrayNoise", 2022). *Binary noise* outputs either the maximum or the minimum possible value, and *"produces the maximum energy for the least peak to peak amplitude"* ("ClipNoise", 2022).

curves, and envelopes when progressing across the work's different 'scenes'.

6. *Equalization*: The signal is then routed through a 10-band equalizer. This consists of a cascade of second order filters - a low-shelf, a series of eight peak filters, and a high-self filter. The *frequencies*, *quality factors* (or 'Q'), and *gains* of the filters can be controlled algorithmically, through the score, or interactively via RSSI feature extraction. This sub-module allows carving the spectrum of the feedback loop in rather clinical way and is fundamental for effectively strengthening the relationship between sound and body. Overall, tuning the frequencies and gain responses of these filters is a very important part of the sound design and compositional process, as it helps steer feedback into specific parts of the spectrum.

   This EQ sub-module is controlled in various manners throughout the piece:

   - Filter *frequencies* are for the most part set within the score, except towards the middle of the piece ('scenes' 6 and 7) when sudden movements in and around the inner Fresnel zones trigger slight random deviations in the filters' center frequencies. This occurs when the *RMS slope* of the RSSI exceeds a threshold.
   - *Q factors*, i.e. the filters' *bandwidths*, are controlled by the *cepstral magnitudes of the first 10 FFT bins of the signal*. This feature relates to the rate in which movement changes in specific frequencies (corresponding to movement speeds); slow movement speeds are mapped to the lower frequency filters, and fast speeds to high frequency ones. Higher cepstral magnitudes – i.e. higher rates of change - produce larger Q factors, and thus wider filters, which results in feeding more noise into the system at the respective frequency bands.
   - The *gains* of the filters are controlled in two ways: For most of the piece, they are mapped to the *spectral magnitude of the first 10 FFT bins* of the signal. This type of spectral mapping is very expressive as it essentially transforms the microwave response of the moving body into a filter curve that shapes the audio feedback loop. In this manner, it feels as if the body is being constantly radiographed, with its spectral response to WiFi pulses converted into an audio filter. Spectral magnitude is highly dependent on position and remains stable when the body stands still. Furthermore, slow and large movements produce more energy in the lower bins, boosting the lower end of the sound, while smaller and faster movements - e.g. moving the hands - shift the feedback loop to higher registers. In a scene towards the end of the piece, this mapping is complemented with some weighted randomness that is controlled by the amount of

RSSI spectral flux.

7. *Waveshaping, filtering, limiting*: As a final stage, the equalized signal is routed through another waveshaping *Edge* filter then a DC-removing high-pass filter, and finally a limiter which makes sure the signal's samples remain within a safe amplitude bandwidth.

   The WIR controls involved are:

   - The *mode* of this *Edge* filter is controlled in the same way as that of the filter earlier in the chain (i.e. by the *RMS slope*).
   - The *threshold* value is controlled by the *RSSI RMS*, which means the process becomes sensitive to the amount of motion and the body's position.

II) ADAPTIVE WINDOWED-SINC RESONATOR (AKA 'FIRBELLS')

The feedback network also includes a number of processing modules which do not produce sound internally and on their own, but process incoming signals. One such module is a type of adaptive, convolution-based, spectral filtering process (figure 7.20). I have informally named this process *'FIR-Bells',* owing to the sound it produces and its core technique; a more technically-oriented name is *'Adaptive Windowed-Sinc Resonator.*

This module generates *Finite Impulse Response* (FIR) filter kernels from an audio input in real-time, which it uses to filter another audio signal through convolution, or a processed copy itself (for more on convolution and FIR filtering see Loy, 2006). At the core of this module is a mechanism implementing the *'window method'* for designing Windowed-sinc FIR filters (see Smith, 1999 and Smith, 2011).[354] The method involves dynamically creating filter kernels with a desired response for processing input signals. In this manner it is possible to design filters with practically any Impulse Response (IR). Here, the IR of the filter is derived by analyzing an audio input signal in real-time, thus converting its spectrum into an FIR kernel which is subsequently used to process a mix between a second input signal and white noise.

In more detail, the module works as follows (figure 7.20):

1. *Pre-processing / tuning the filter*: First, and prior to creating the filter kernel, the input signal from which the kernel will be extracted can be pitch-shifted using a time-domain granular process. The signal is typically pitched down in this piece.

[354] This is a rather obscure sound processing technique that I learned about from Dr. Joseph Anderson during the *Spectral Modeling* class he taught together with Dr. Juan Pampin, which I took in Winter 2012 at DXARTS.

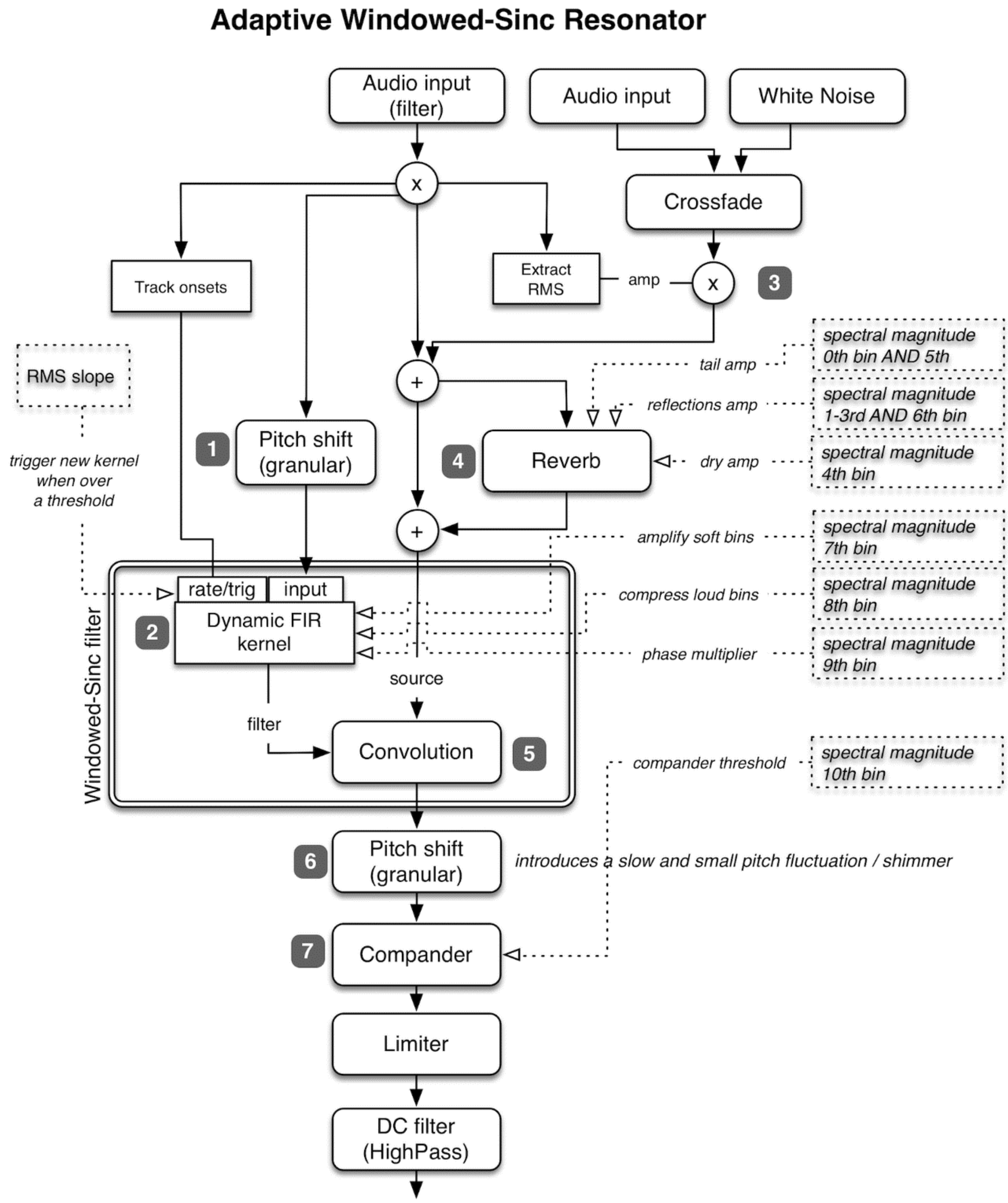


Figure 7.20. Synthesis and control schematics for the *Adaptive Windowed-Sinc Resonator* process in *Hertzian Field #2.*

2. *Creating the convolution kernel*: The following process creates the *Windowed-sinc* filter:

a) The FFT of the pitch-shifted filter signal is computed, extracting its spectrum.

b) The peak magnitude value of the FFT is used to normalize the resulting spectrum. Normalization is desired to produce filter kernels with similar gains, regardless of the loudness of the incoming signal. In this manner, the spectral envelope of the signal is decoupled from its amplitude, ensuring that there are no amplitude jumps when the sound used to create the filter is very soft or very loud.

c) At this stage the spectrum can be also compressed: FFT bins whose energy is too soft can be amplified, and those that are too loud can be clipped to a threshold.
d) Subsequently, the phases of FFT bins can be linearized. This is optional, but typically happens throughout the piece.
e) Then, the inverse FFT is calculated.
f) Finally, the result is windowed and written into a memory buffer for use as a convolution kernel.

The kernel writing process can happen continuously, at a given rate whose period is slower than the duration of each frame, or at irregular intervals through the use of a triggering signal. This can produce a range of different effects, from mapping the spectrum of one continuous sound to another, to time-stretching the filter sound when the kernels are produced sequentially but at a slower pace, to spectral freezing when they are only triggered intermittently. The timing of FIR kernel-writing is controlled internally within this module using an adaptive mechanism that analyzes the filter sound and extracts audio features from it. Specifically, an *onset detector* produces a trigger, which is translated into a *triggering period* when it detects the beginning of a new sound event. For instance, this occurs when sudden motion causes the *Primeval* module to abruptly produce a loud sound. This trigger signal is fed through a 1-pole filter to smooth it out into an exponential curve, which is mapped to the *triggering rate* of new filter kernels. The effect is that a few frames are rapidly created at a fast rate when an onset occurs, but then this rate exponentially drops down to zero, thus freezing the spectrum until a new trigger is produced.

3. *Input mixing and shaping*: The input signal that will be convolved with this FIR kernel is a mix of three different signals: A) The first is white noise, whose flat spectrum is the best source for revealing the entire spectral envelope of the filter kernel. By feeding white noise into the system, one can produce the effect of freezing the filtering sound, stretching it, or cutting it up. B) This noise can be mixed/crossfaded in the time domain with a separate audio input, such as the output of one or more other active modules in the feedback network. Further audio analysis and feature extraction of the filter sound is used to shape this mix. This happens by extracting the audio RMS energy of the filtering sound, subtracting that from a maximum amplitude (so that the louder the filtering sound is the smaller the resulting number), and mapping that result onto the amplitude of the mix between white noise and audio input. This type of process is usually referred to as *ducking*

and is commonly used for compressing the dynamic range of a signal. C) The third signal is a reverberated version of the filter input, as discussed below.

4. *Reverberation*: The amplitude-controlled signal mix of an audio input with white noise passes through a reverberation algorithm used as a complex resonator. There, it is also mixed with the filter input sound (without pitch shifting). The reverb algorithm used here is Juhana Sadeharju's *GVerb* (ported to SuperCollider by Josh Parmenter), which has a characteristic rich metallic sound when the room size is small. This is where part of the bell-like quality of this module is derived from.

5. *Convolution*: The resulting signal is fed into a convolution algorithm as the input, with the dynamically created kernel from step 2 as the filter.

6. *Pitch shifting*: The convolved sound passes through another granular pitch shifter, which introduces a small upwards pitch fluctuation. This adds a kind of shimmering effect that is accentuated through the iterations of a feedback loop.

7. *Dynamic shaping*: Finally, the signal passes through a compressor/expander, a limiter, and a high pass filter to remove any DC offset. This ensures that the output can be further fed into a feedback network without producing amplitude explosions, infinities, or NaNs (*Not-a-Number*).

Microwave sensing control: This module is controlled mostly by the *RSS magnitude spectra* extracted by the WIR system. Different FFT bins (i.e. movement speeds) are mapped to different parameters. The result is that moving in certain speeds in the field modulates specific parts of the processing algorithm and not others. This allows the performer to control different parts of the processing engine by moving at different rates. In this regard, one should keep in mind that, as mentioned earlier, the body is rarely seen as a single mass by the system. The spectra produced by the WIR system do not represent a blob-like unit, moving all at once and producing energy in a single frequency like a sinusoid, but instead reveal a much more complex shape - the human body with its core and limbs moving at independent speeds. This results in a spectrum with harmonics, the amount and dispersal of which depends on the type of motion and the position and orientation of the body in the field. As a result, more than one parameter are typically modulated at once.

Features are mapped as follows:

- The *spectral magnitude of the 0^{th} FFT bin*, i.e. the signal's DC-offset which is dependent on the body's position in the field, is used to control how much of the *reverb's tail* will be applied to the input sound-mix before it passes through the convolution filter. The *magnitude of the 6th bin* (corresponding to movement at a rate of about 1.5Hz in this case) is also used in parallel as a second control. This creates a somewhat glitchy effect of switching on and off the reverberations/resonances of a space.

- The *sum of the magnitude of the 1st (0.25Hz), 2nd (0.5Hz) and 3rd (0.75) bins* is used to control the amplitude of the reverb's *early reflections*. Similarly to above, the *magnitude of the 6th bin i*s used in parallel as a second simultaneous control.
- Finally, the *magnitude of the 4th bin* (movement speed of 1Hz) controls how much of the *dry* and how much of the reverberated or *wet* signal is mixed with the reverberated signal.

The kernel generation is controlled by the fluctuation of higher FFT bins, corresponding to faster motion:

- The *magnitude of the 7th bin* (1.75Hz) sets the *minimum amplitude* of the softest bins in the filter kernel.
- The *magnitude of the 8th bin* (2Hz) controls how much the loudest filter bins will be *compressed*.
- The *magnitude of the 9th bin* (2.25Hz) is a multiplier that affects how the kernel's phases are *linearized*.
- Finally, the *RMS slope* of the RSSI is used to *trigger new filter kernels* when a threshold is exceeded. This is essentially an *RSS onset-tracker* that triggers a new filter shape when the performer executes a sudden movement. This is combined with the audio-based onset detection mechanism described above, in step 2, making it so that new filter kernels are triggered both with a sudden movement and with a sudden change in the amplitude of the sound used as the filter input (which in its turn, can be the result of a sudden movement as well as explained above).

III) ADAPTIVE VOCODING REVERBERATOR MODULE ('VOCVERB')

Another quite complex core process used in the feedback network of *Hertzian Field #2* is the *'Adaptive Vocoding Reverberator'* module which is based on a combination of analog-style vocoding and tape-style feedback-delay (figure 7.21). This process is inspired by a patch I created in the voltage-controlled (analog) studio of the Institute of Sonology in The Hague in

2011. It is an adaptive process, controlled by a combination of audio analysis, WiFi sensing, and other control signals, most of which are synchronized to a global clock.

The module's components and signal-path is the following:

1. *Vocoder*: Vocoding is a time-domain process used for the analysis and re-synthesis of audio signals, originally speech (for more on the history of the vocoder, see Mills, 2012). It requires a modulator (the audio input to process and extract the filtering characteristics from) and a pair of carrier signals - typically a harmonic source and a noise source.[355] The vocoder here works in a fairly standard manner, but combines audio signal analysis with WiFi signal analysis for controlling sound. This creates a hybrid radio-sonic vocoding algorithm that is influenced both by sound and the moving body.

   The *modulator signal* - the output of other processes in the feedback network in this case - passes through a set of 19 parallel time-domain band-pass filters, which split its spectrum. These split signals are individually analyzed to extract their pitches and amplitudes. The extracted pitch information is used to tune the frequencies of a matching set of 2-pole resonant filters. The *amplitude* of these filters is controlled by a combination of the amplitude information extracted by the analyzed audio signal with the *cepstral magnitude of the first 19 FFT bins* of the (upsampled) WiFi RSSI. The modulator audio signal is further analyzed to deduce if it is harmonic or noisy (using time-domain autocorrelation analysis) so as to define which carrier signal, harmonic or noisy, will pass through the tuned 2-pole filters at any given moment. The output sound of the vocoder results by shaping the carrier signal – which is a constantly alternating mix of the harmonic and noise audio generators - by the spectral characteristics of the input modulator sound.

In more detail, the carrier signals are generated as follows:

2. *Carrier: noise source*: The noisy signal consists of a gray noise generator passing through a band-pass and then a high-pass filter. The band-pass filter's center frequency corresponds to the pitch of the modulator sound, extracted through time-domain auto-correlation. Its Q factor or resonance, affecting the noise source's resulting bandwidth, is modulated by the following mechanism: The impulses of a global clock pass through a stochastic gate which only lets a certain percentage of impulses through. Each of these impulses triggers a new random Q factor within a defined bandwidth.

[355] Originally, this type of vocoder analysis and resynthesis was used to distinguish between consonants and vowels in speech, replacing them with synthesized sounds. The SuperCollider vocoder pseudo-UGen used in *Hertzian Field #2* was coded by Joshua Parameter.

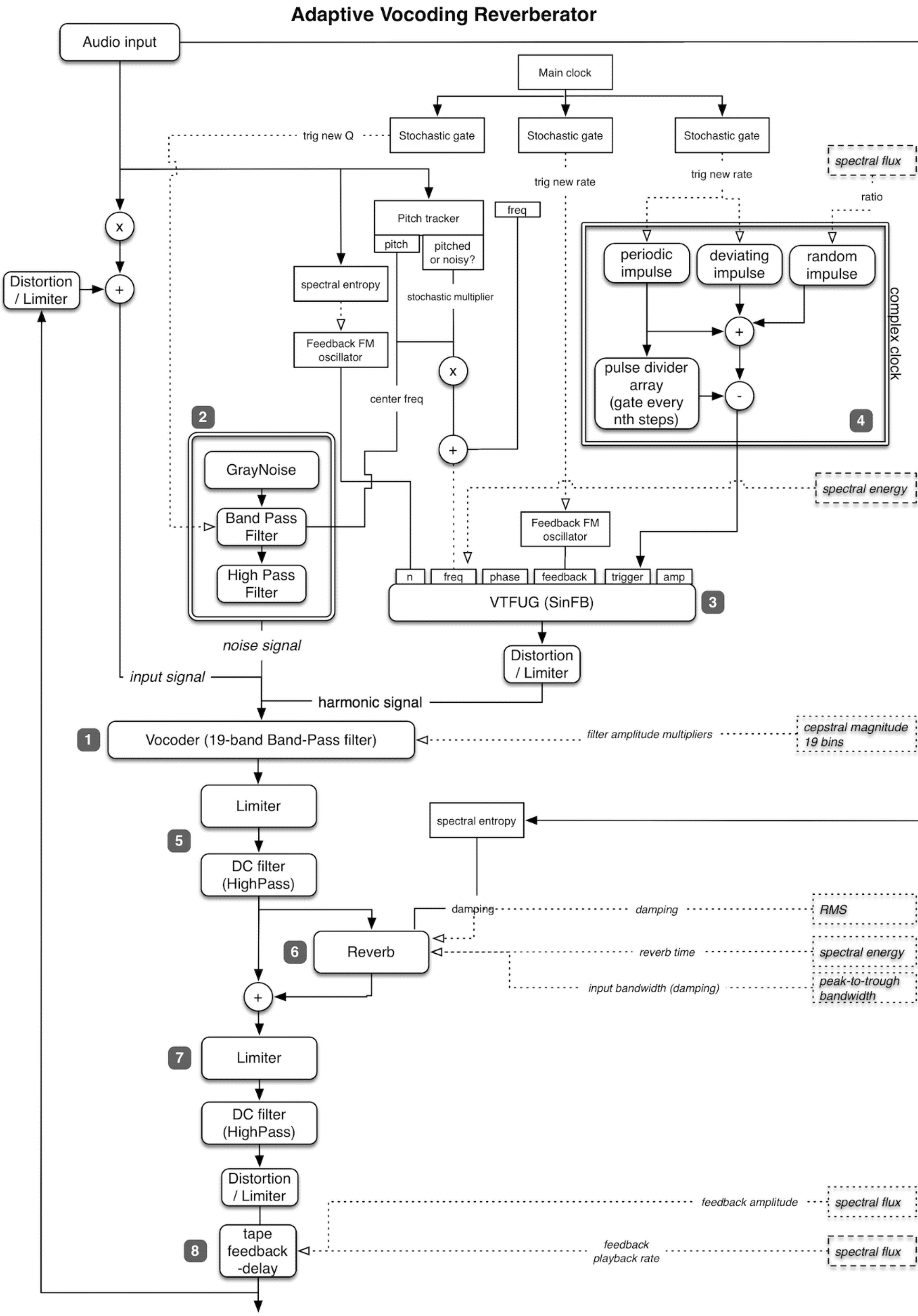


Figure 7.21. Synthesis and control schematics for the *Adapting vocoding reverberator* process in *Hertzian Field #2.*

3. *Carrier: harmonic source*: The harmonic signal is generated in a much more complex manner. At its core is a SuperCollider pseudo-UGen that I designed, inspired by a signal generator in the voltage-controlled studio of the Institute of Sonology (BEA 5) - the *Voltage-Trigger Function Generator* (VT-FUG) (Tazelaar, 2005).[356] The original VT-FUG was inspired by the *VOSIM* synthesis module by Kaegi and Tempelaars (Kaegi and Tempelaars, 1978 and Kaegi, 1986). It is an oscillator which, upon receiving a trigger, produces *n* periods, with *n* being a modulatable parameter. It then goes silent until it receives another trigger. If a trigger is received while the oscillator is still playing, frequency dividing occurs.

   I have coded a number of variants emulating and expanding on the VT-FUG concept, each based on a different type of oscillator - sinewave, triangle, sawtooth, wavetable-based, cubic, parabolic, band-limited, pulse, and impulse. The VT-FUG variant used in this piece employs a self-feedback sinewave oscillator: The oscillator's output is connected to its phase input, producing phase modulation through self-feedback; this is a type of synthesis sometimes referred to as *single-oscillator feedback-FM*. When the feedback input is silenced, the oscillator produces ordinary sine waves; with a bit of feedback it approaches a sawtooth, and with even more it begins to oscillate chaotically. The oscillator's output is processed through a soft distortion algorithm to accentuate its harmonic content and limit its peak amplitude to a desired value.

   The parameters of this oscillator are controlled as follows:

   - The *amount of feedback* is mapped to the output of a low-frequency self-feedback FM oscillator (a kind of LFO), whose rate is modulated stochastically in sync with that of the main clock.
   - Two methods are used to control the frequency of the VT-FUG:
     a) For part of the piece, the *frequency* follows the pitch contour of the input sound. The frequency extracted from the audio input is multiplied by a stochastically produced value. A new value is produced whenever an audio feature extractor detects a change in the input's texture, namely a vowel-like sound becoming consonant-like, or vice versa.
     b) In another section of the piece, the *frequency* of the VT-FUG is modulated by the *spectral energy* of the WiFi RSSI. In that manner, the pitch contour of the

[356] The name of this analog function generator contains the word 'voltage' because it can be voltage-controlled and 'trigger' because it can be triggered.

harmonic signal follows the overall energy of motion, with more kinetic energy resulting in higher frequencies for the VT-FUG oscillator.

4. *Carrier trigger:* The VT-FUG triggering mechanism is a complex clock inspired by a patch I made in the BEA 5 voltage-controlled studio in 2004. The clock mixes impulse triggers from 3 generators:

   a) A periodic generator that produces impulses at a given rate. Some of these impulses are filtered out to create complex rhythmical patterns with syncopation.[357]
   b) A stochastic generator that produces impulses with a (modulatable) gaussian deviation around the same rate as the periodic generator.
   c) A random impulse generator that produces impulses at a specified modulatable density (defined as impulses per second). This is used to interject random triggers that can range from adding a rhythmic 'swing', to creating dense textural clouds.

   These triggers are controlled as follows:

   - The *frequencies* of the two first impulse generators are modulated in a similar manner as the bandwidth of the noise source filter: impulses from the global clock are stochastically filtered out, with remaining impulses triggering a controlled random generator to produce a new value.
   - During certain sections of the piece, the *density* of the random triggers is controlled by the *spectral flux* of the RSSI. The higher the flux - i.e. the more the type or speed of motion changes - the denser the triggers.

5. *Sanitization*: Once the carrier signal has been vocoded, it passes through a limiter and DC-filter. This assures that the signal is sanitized for reverberation and further feedback, eliminating the danger of producing amplitude explosions, infinities, or NaNs.

6. *Reverberation*: The vocoded and sanitized signal passes through a stereo reverberator (GVerb), used once again as a complex resonator bank. The reverberator's impact on the feedback loop is quite important, and is thus controlled by the WIR system in the following manner:

   - *Reverberation time* is controlled by the amount of *spectral energy* of the RSS.
   - The reverb algorithm contains a low-pass *filter* controlling the bandwidth of the input

[357] This occurs by sending the impulses through a set of parallel pulse dividers (4 in this piece) that are used as a gating system to remove every n^{th} pulse – for example every 15th, 35th, 45^{th} and 60^{th}.

signal. The reverb's *bandwidth* parameter is linked to the *short-term bandwidth of the RSS*, which is found by calculating the difference between its peaks and troughs in a 1-second window of memory. Certain movements produce large variations – such as when moving from a blocking position to a reflecting position – which result in more of the input signal's frequencies passing through the reverb, thus producing a fuller, brighter sound. Slow movements on the other hand generally have a low RSS bandwidth which produces darker and more subdued reverberation.

- The reverb implements a similar filtering process on its output, called *damping*, which affects the tonal quality of its early reflections and tail. The amount of damping is controlled in two ways through the piece: via WiFi analysis and via audio analysis.
    a) At certain times, *damping* is controlled by the *RMS of the WiFi signa*l: High energy motion produces less damping, and therefore more resonant and brighter sounds.
    b) Other times, the spectral entropy of the audio signal is used as a modulator. Spectral entropy is a feature that measures the peakiness of the signal (Toh et al., 2005). It is quite effective in separating vowels from consonants in speech, and therefore noisy from harmonic signals in general. It also excels at detecting sharp resonances, and thus I often use it as a self-regulating 'Larsen tone' suppression mechanism inside feedback loops, like in this case. The result is that the peakier the signal, the higher the damping. Apart from suppressing feedback, this also produces a very organic-sounding modulation of the reverberator resonance that is coupled to the input signal's spectral character.

7. *Final shaping/sanitization*: Reverberation is followed by what should be a familiar chain by now consisting of a limiter, a DC-Filter and soft distortion.

8. *Tape-like feedback-delay*: Finally, the reverberated and sanitized stereo signal is routed through a tape-delay emulator. The resulting sound is sent to the speakers, to other processes, and it can also be fed back into the module itself to create a dynamic, self-sustaining feedback loop.
    - The *amount of feedback* is controlled by the *spectral flux* of the RSS.
    - During certain parts of the piece, the *playback rate* is also controlled by the same feature.

IV) ADAPTIVE PHASE-VOCODER 'SPLIT-AND-FREEZE' (AKA 'PVSYNTHFREEZEBF')

Finally, the *Adaptive phase-vocoder 'split-and-freeze'* is another fairly complex adaptive spectral process that accentuates and freezes parts of the spectrum. The module contains four instances of the algorithm in figure 7.22, dispersed around the ambisonic soundfield. Each instance processes a different audio signal from the feedback network. The module is activated towards the end of the piece and is controlled by a mix of audio analysis and WiFi sensing.

The signal chain for each processor functions as follows:

1. *Splitting the spectrum*: The input audio signal is first analyzed with an FFT to extract its spectrum. The spectrum is then split in two parts containing the stable and unstable bins, thus separating the harmonic from the noisy parts of the sound.
   - The *threshold* over which a bin is considered noisy is controlled via WiFi sensing. Two spectral features are combined through multiplication: the *spectral energy* of the RSS and the *magnitude of the first 4 bins of its spectrum*, with each bin mapped to control one of the four instances of this process.
2. *Re-mixing the spectrum*: The harmonic and noisy parts of the input sound's spectrum are mixed back together with a control mechanism combining WiFi sensing and audio analysis.
   - Depending on the amount of motion in the field, this process contradicts or exaggerates how harmonic or noisy the input is. This happens in the following manner:
     a) The input sound is analyzed by an autocorrelation-based pitch tracker which produces a trigger when it detects it shifting from harmonic to noisy or vice versa.
     b) A stochastic gate is used to filter out a percentage of these triggers.
     c) The triggers control a sample-and-hold mechanism, taking snapshots of the values of another audio feature: an estimate of how clearly pitched the input sound is. This estimate is used to define the mix of pitched and unstable parts of the sound.
     d) WiFi-sensing comes in effect at this point: When the *RSSI RMS* rises above a threshold – signifying a large movement – the *ratio* between harmonic/noisy is inverted, going from exaggeration to contradiction or the other way around.
3. *Harmonic distortion*: Next, the resulting audio spectrum is further exaggerated by adding partials of an arbitrary harmonic ratio to it.

- This *ratio* is defined by WiFi sensing: the four instances of this process in the module are controlled by the *cepstral magnitudes of the 1st to 4th bin* respectively. The outcome is that higher rates of change in slower movements produce higher harmonics.

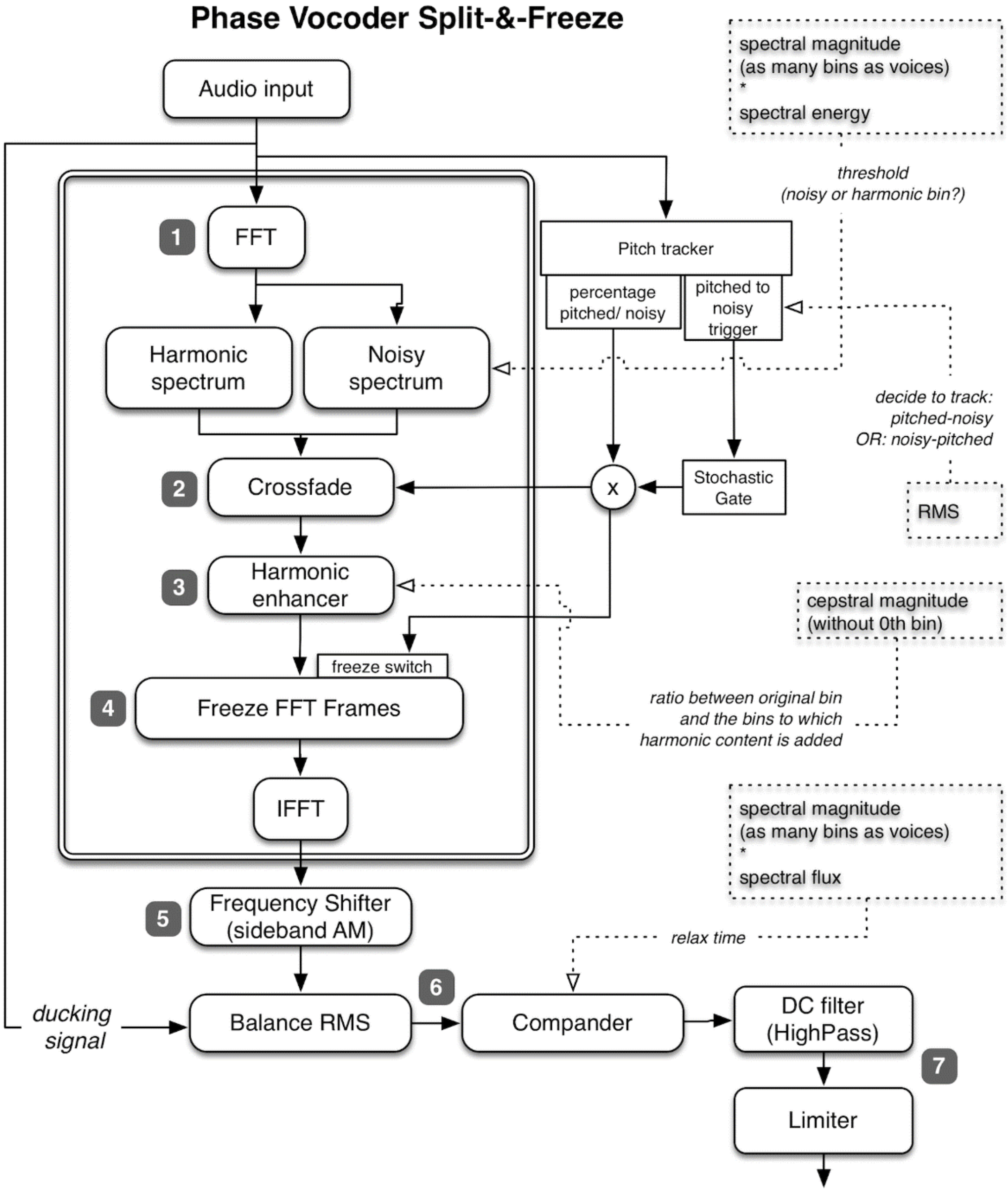


Figure 7.22. Synthesis and control schematics for the *Adaptive Phase-vocoder Split-and-Freeze* process in *Hertzian Field #2.*

4. *Spectral freezing*: As a final frequency-domain process, a single FFT frame of the spectrum can be frozen until a control signal exceeds a defined threshold.
   - The control signal is the same signal used for mixing between the harmonic and noisy parts of the spectrum (see step 2c above).

The resulting frequency-domain signal is then converted back into the time-domain by applying an inverse FFT. This is followed by:

5. *Frequency shifting:* The signal is subsequently frequency shifted in the time domain via single sideband amplitude modulation. This process is different to pitch shifting, in that it does not preserve harmonic relationships in the signal, as it moves all its partials by the same frequency amount. The amount of shift per instance is defined programmatically, when the process is activated in the score.

6. *Dynamic shaping*: The next processes in the chain shapes the sound's dynamics. First, a balancing filter matches the RMS level of the resulting audio signal to that of the input sound. The signal then passes through a compressor/expander.
   - The *release time* of this compressor/expander is controlled by a combination of WiFi features: the *spectral flux* multiplied by the *spectral magnitude of the first 4 FFT bins* of the RSS, each bin mapped to one of the four instances of this process.

7. *Sanitization*: Finally, the signal is sanitized for the feedback network by passing though a DC-blocking high-pass filter and a limiter.

7.3.5 *Score*

The performance consists of 4 sections and a total of 12 'scenes'. Throughout these *scenes* the active sound modules and their configuration changes, as well as the configuration of the WIR system. Changes in the WIR system concern how many WiFi APs are being tracked, which RSS features are extracted, how their outputs are shaped, and on which sound modules and synthesis parameters they are mapped.

Before delving into the specifics of these scenes, it is relevant to discuss how the score progresses from one scene to the next:

During the R&D process of the work, I attempted to implement a triggering mechanism controlled by the WIR system to advance the score via sensing. The idea was that new scenes would be triggered when certain actions where performed in specific areas. I tested a few higher-order extractors such as using the *integral* feature of the RSSI *Peaks Distribution* to produce a trigger when I stood behind a node for a few seconds. Another experiment involved using the *onset density* and *RMS slope* features to track particularly fast changes in movement. However, these types of solutions were neither optimal for the performance itself, as I could only advance scenes from certain spots, nor as robust and trustworthy as this use case required.

I therefore decided to turn to a different solution, which I used in the first performances of the piece: making a hotspot (Access Point) with a mobile phone that I carry in my pocket while performing and tracking its RSSI from the system's transceiver nodes. Practically, this means that a new scene can be triggered when the performer blocks the phone's antenna for a few seconds. This can easily happen by placing a hand over the pocket where the phone is located. Technically, the system looks for the *integral* feature within a window, and if it exceeds a predefined threshold the next scene is triggered. To prevent double-triggers, triggers received before the time when the following scene is expected to occur are ignored.

While this method works quite well, it is unfortunately not perfect, which is a problem when the performance relies on it for progressing through the score. Problems arise because of the following two reasons: a) The baseline RSS of the phone's AP can differ significantly depending on the performer's location, for example when in the center of the sensing triangle compared to when outside of it. Therefore, calibration is both crucial but also somewhat delicate, as one needs to make sure that a scene can be triggered in most locations - and most importantly not by accident. Nevertheless, given that the calibration of this mobile AP needs to happen before the audience enters (walking on stage right before the show to go to different spots to calibrate with the audience present is not an option!), I have had situations when there were false triggers, or when due to the system not triggering I had to move or rotate expressedly for the trigger to occur. This felt quite distracting and certainly not ideal, even though the audience did not realize that something unexpected was happening. As a result, since 2018 I have opted for a more traditional, tried-and-true system: Signaling to an assistant who advances the score by clicking a button on the performance laptop.

A more detailed description of the performance follows. The text in italics comes from the work's score and describes the performance from the point of view of the performer (Manousakis, 2019a). The accompanying figures map out important elements for each scene, such as the performer's movement trajectory (on the left) and sound/mapping information (on the right). More specifically, they show:

a) Which receivers scan which transmitters (see arrows pointing between the nodes)
b) the movement path of the performer (see circles on the left-hand figures)

The right-hand figures display the following information:

c) what processes are used in a scene (see abbreviated names in the rectangles)
d) which receivers control these processes via RSSI feature extraction (see colors of the rectangles)

e) which transmitters these receivers scan (see colors of the rectangles' borders)

f) how processes are patched in the feedback network, which are their inputs (see arrows pointing *to* the rectangles) and their outputs (arrows pointing *from* the rectangle)

g) if the output of a process is monophonic (the rectangle border is a single line) or stereophonic (double line)

h) where processes are placed in the ambisonic field (see placement in the larger circle enveloping the nodes). In this graph, the rectangles representing stereo processes are placed in the center of their diffusion area, meaning that the left and right channel are actually at an angle of e.g. +45° and -45° respectively from where these processes appear in the graph.

SECTION A (Timing: 0’ - 5’)

Noise / Exploring the triangle from the outside

The piece begins with the system in its simplest configuration. In the first section, which consists of two scenes and lasts about 5 minutes, the performer explores the space outside the triangle. This section establishes the space/field, the sound world, and the interaction between body and system before more complexity is introduced in scene 3. The sound produced is rather noisy – I imagine it as the sound of data bouncing around the space. It is also very responsive to small movements and to the position of the performing body.

- **Scene 1** (0’ - 1’45”)

Touching a double line: Introduction - exploring the radio beam at the triangle’s base

The first scene features two pairs of cross-feedback *Primeval* processes. These processes are positioned in the ambisonic field according to the vantage point of their controls in the hertzian field - one pair placed left and one right of the center of the triangle’s base; the four processes are spaced at a 40° angle from each other. The parameter settings and hence the sound of these 4 processes vary, but they all share the same functions that map RSSI features to synthesis parameters.

The processes are controlled via radio sensing as follows: One pair is mapped to the Yellow receiver tracking the Red transmitter (*Yellow-tracking-Red*), while the other is mapped to *Red-tracking-Yellow*. This means that the processes are ‘scanning’ the same area – whose LoS is at the base of the triangle. However, they do so from different vantage points: While the performer's body is in the center of the radio beam they receive about the same signal, but when it approaches one of the transceivers then link asymmetry leads to variations in RSSI.

This effect is accentuated by the differences in heights between the two nodes, as the field passes through different sections of the body.

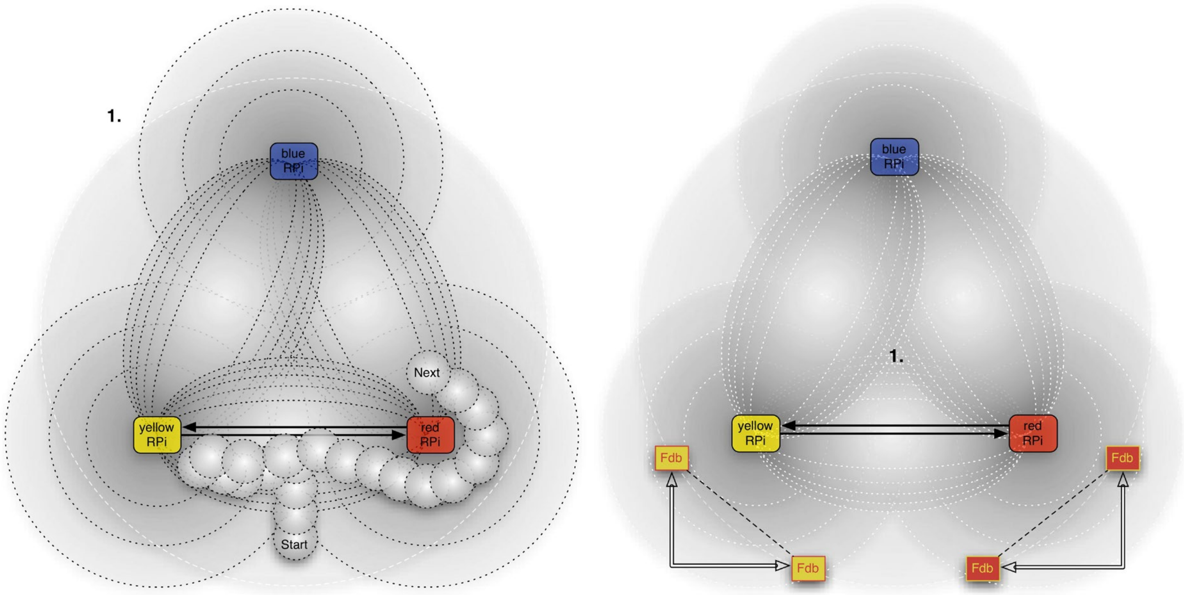


Figure 7.23. *Hertzian Field #2* score for *scene 1*. Left: Movement path. Right: synthesis/processing diagram, spatialization, and mapping of transceivers to processes.

"The performance begins in silence. You are standing outside the triangle, in front of the center of its base (between Yellow and Red transceiver, as seen in the above figure). Slowly, you move towards the center of this beam, entering the inner Fresnel zones with your body, and extending your arm. Thin noisy streams start to sound, modulated by small movements, particularly of your hands. You move laterally towards the Yellow node, then the Red, slowly, rotating your torso, moving arms and hands with round motions, looking for different patterns in the feedback loop. Like undulations created by the moving body, the noise grows in mass and density enveloping the body as you move further into the field. Parts of the body enter the first Fresnel zone, but you do not step inside the triangle yet. You slowly move behind the Red node, affecting the system through reflections; the feedback sound becomes thinner, shifting towards the higher registers" (Manousakis, 2019a).

- **Scene 2** (1'45" - 5')

Outlining a triangle: Exploring its exterior and surface, straddling its borders

Once the performer reaches in front of the Red node, but still outside the triangle, the score progresses to the second scene. Two more pairs of cross-feedback *Primeval* process are added, on the left and right sides of the triangle. Their configuration is slightly different than in the first scene, with the two processes of the pair each scanning their beam from opposite viewpoints (i.e. *Yellow-tracking-Blue* and *Blue-tracking-Yellow*; *Red-tracking-Blue* and *Blue-tracking-Red*). Their sound is spatialized accordingly. The output of each *Primeval* pair on the sides is routed to the input of the base beam pair, thus forming two complex feedback loops that split the soundfield in two.

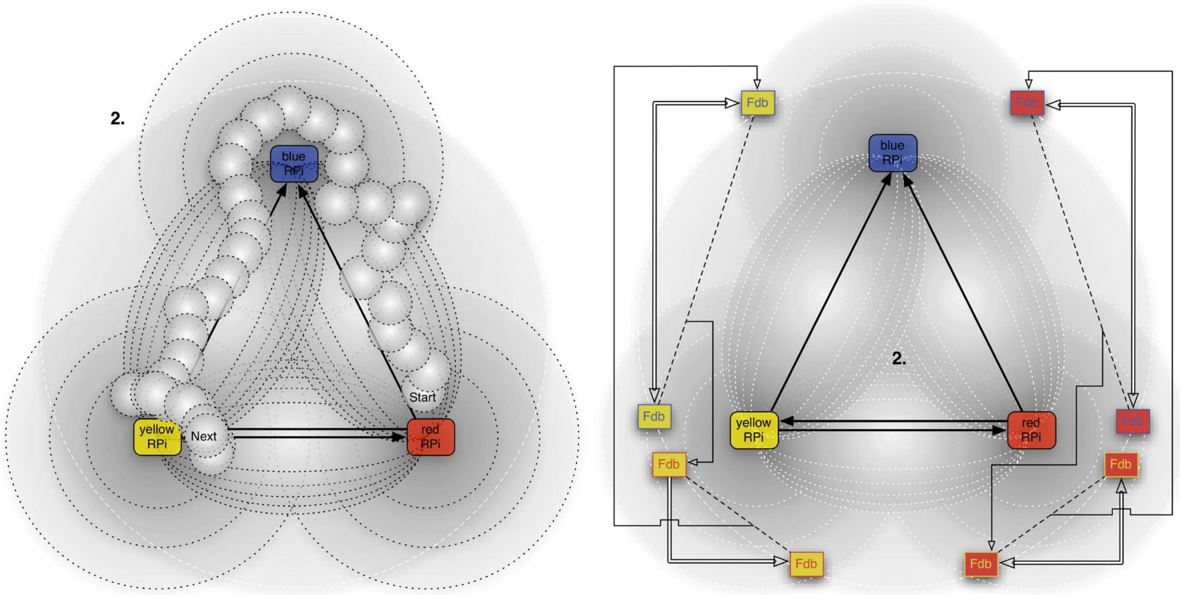


Figure 7.24. *Hertzian Field #2* score for *scene 2*. Left: Movement path. Right: synthesis/processing diagram, spatialization, and mapping of transceivers to processes.

"Walk slowly straddling the Red-Blue microwave-beam from the outside of the triangle, with your body within the inner Fresnel zones. Your left arm disrupts the Line-of-Sight; its motions are clearly reflected in the sound coming from that part of the soundfield. As you move along this 3-dimensional diagonal line, from in front of the Red node to the middle of the Red-Blue line, the sound evolves, revealing changes in the spectrum of your body's microwave resonance. Walking away from the triangle causes the sound to quiet down; this makes the interaction between body and field more apparent, helping establish the triangle as a space with a kind of invisible skin.

Still at a very slow pace, move behind Blue; this makes the sound quiet down even more, sometimes to the point of momentarily disappearing. There, you are the least visible to the system with its current analysis configuration - until you bring the center of your body down. When behind the node, you are affecting the system purely through reflections. As you enter the LoS of Blue-Yellow, the system can clearly sense you again and responds with a reverberant rumble. Walk slowly towards Yellow, straddling the LoS. Towards the middle, and especially when you slowly move a step away from the triangle, the system approaches silence. You trigger reverberant, chaotic echoes by moving further towards it. When you are near Yellow, the processes at the base of the triangle sense your body, filling the soundfield with washes of noise as a response to your movement.

Near the end of scene 2, you enter the triangle for the first time. You push with your body through the two microwave-beams on the left corner of the triangle (Yellow-Blue, and Yellow-Red), back and forth, back and forth, faster and faster and faster, to generate momentum. The noise bursts caused by breaking through the triangle's base bring forth the *next scene, feeding sound to the new processes that scene introduces."* (Ibid).

The performer's path around the triangle through these first two scenes establishes the different sound characters of the three radio beams that form the basis for the rest of the piece: the noisy base (*Yellow-Red*), the tenor right-hand side (*Red-Blue*), and the bass-heavy left-hand side (*Yellow-Blue*, which is the longest of the three diagonal Lines-of-Sight as *Yellow* is the tallest node and *Blue* the shortest).

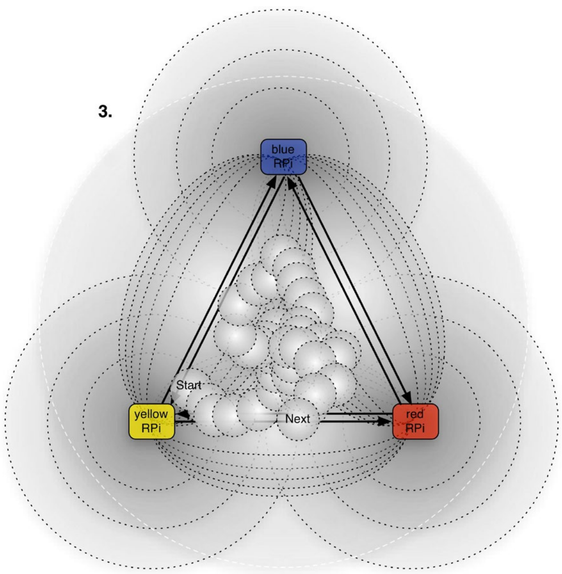
SECTION B (5' - 11'15")

Resonance / Breaking / Exploring from inside

The second section is slightly longer, lasting about 6' - 6'30". It begins with the performer pushing through the triangle's imaginary borders and entering it. This brings a radical change to the sound world. I think of it as immersing oneself inside the previous soundscape and exploring it with a sonic microscope from within. That brings forth the resonances of the noisy soundscape present outside the triangle, mutating them into rich reverberant layers to the point of – eventually - completely smothering down the noise.

- **Scene 3** (5' - 7'45")

The world inside: Entering the triangle and sinking into the resonant fields within it



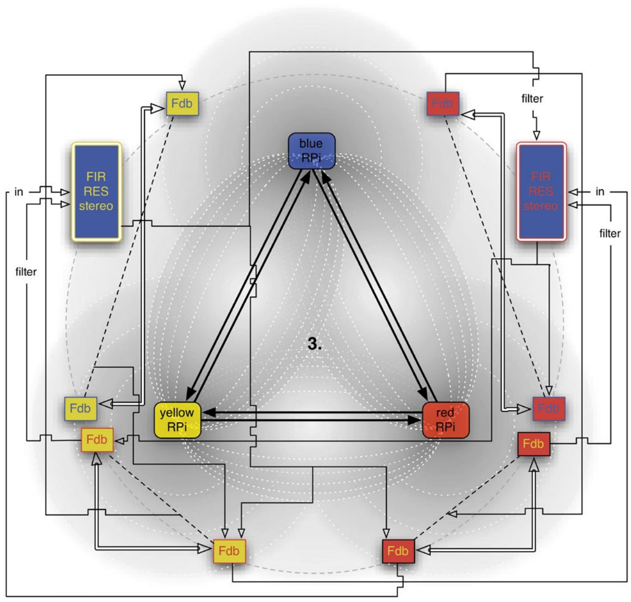


Figure 7.25. *Hertzian Field #2* score for *scene 3*. Left: Movement path. Right: synthesis/processing diagram, spatialization, and mapping of transceivers to processes.

In scene 3, the performer enters the triangle causing the very rich and resonant sound of two *Adaptive windowed-sinc resonators* to begin ringing. Each of these processes outputs a stereo signal whose center is at 60° from either sides of the triangle’s top. These processes are controlled by the fluctuation of the field’s side beams from the point of view of its base – i.e. *Yellow-tracking-Blue* and *Red-tracking-Blue*. Each resonator has two inputs, whose signals it cross-modulates to produce a new sound. Both sounds come from the four no-input feedback processes at the base of the triangle. The left-hand resonator combines the sounds of the two central processes, and the right-hand resonator of the two outer ones.

“Entering the triangle reveals a seemingly different sonic world - as if all the noisy sonorities from its outside are filtered through an invisible and viscous metallic liquid that follows your body’s flow. Explore this liquid with your ears guiding your body, starting from the triangle’s center. When you bring your center of gravity lower, the system becomes even more resonant; when you stand it gets noisier, and when you break the base microwave-beam with your arms the system fires thick bursts of noise into the feedback loop, like an invisible digital thunder sheet.

In this scene, play primarily with the passage from noise to resonance, exciting the system then shifting through its different resonances and harmonic contents with your body. Circle around the triangle from within, choosing one direction in which to move and explore, clockwise or counter-clockwise (probably best to explore clockwise as a counterpoint to your counter-clockwise path from scenes 1 and 2). Spend time on the base of the triangle, like in scene 1 but from the inside this time, striking, shaking and scraping its invisible matter. End the scene by building a thick and turbulent wall of noise when located in the inner middle of the Red-Yellow beam.” (Ibid).

- **Scene 4** (7’45” - 9’15”)

Exploration: Exploring inside the triangle, probing its borders, taking distance to observe from outside

Scene 4 is triggered when the performer's body pushes again through the triangle’s base. Breaking through waves of noise shaped by these movements, a new rich and even more resonant soundscape begins to surface, as the *Adaptive vocoding reverberator* modules fade in. These are stereo processes whose center faces the base nodes of the triangle. They are fed by the *Primeval* processes active at the base, as well as by each other in a cross-feedback configuration, which makes the feedback network – and with it, the sensing field - even denser.

Overall, this scene is more resonant than the previous. Most of the noisy sounds from the no-input feedback modules are suppressed. They are not routed to the speakers as much, but are used mainly as the input for further processing, only at times peeking through the harmonic and noise signals of the vocoder. Some rhythmical elements float over the surface of the soundscape, foreshadowing the pulsing rhythmic textures that will appear later on *scenes 9, 10,* and *11*.

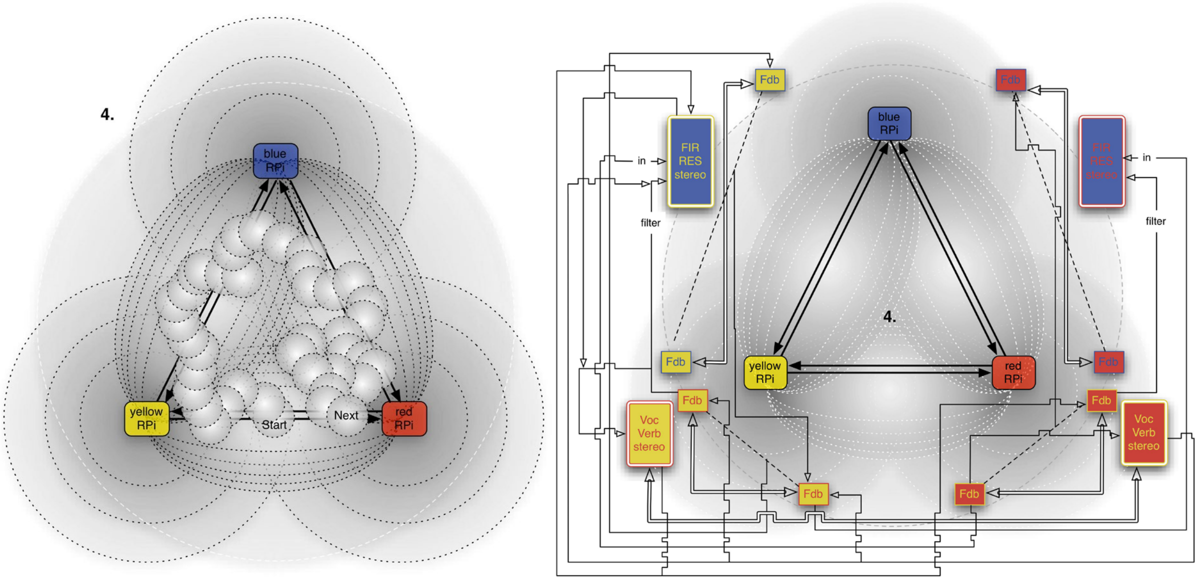


Figure 7.26. *Hertzian Field #2* score for *scene 4*. Left: Movement path. Right: synthesis/processing diagram, spatialization, and mapping of transceivers to processes.

"Continue your exploration inside the triangle, this time straddling its edges, breaking through its borders, then stepping outside and away from it and shaping it from those spots. Move and then stand still for a moment to listen to the system breathe more quietly as it tries to sense your body from afar. Move again, then stop to listen - again and again and again. Back inside, stir this viscous hertzian space with circular movements of your hands to bring forth low-frequency noise chirps and deep rumbles. In certain spots, and with your body in certain orientations, poly-rhythmic bursts reveal themselves, making the whole system resonate. The spots around the two corners on the triangle's base are particularly sensitive; small movements generate much sonic variation. For example, motion in the area close to Yellow's antenna causes a wide fluctuation on the frequency of the Vocoding Reverberator's harmonic source. Explore these areas and the sonorities they produce with various types of subtle movement." (Ibid).

- **Scene 5** (9'15 - 11'15")

Exploration continued: surrounded by rhythmic bursts and focusing on sensing sweet-spots

The next scene introduces a layer of pitched rhythmic elements from 10 granular processes distributed around the ambisonic ring. These processes are fed the output of the *Vocoding Reverberators*. This scene also adds another control layer for these vocoding modules, which is generated by both Yellow and Red tracking interference on the Blue node's signal.

"During this scene, stay almost entirely inside the triangle, breaking the beams with your hands and arms, and a few times with your whole body. Move slowly, accelerating,

decelerating, and standing still. The granulators are mostly sensitive around the nodes, in front and behind them. Focus on these areas, placing yourself at their sweet-spots, moving and slowing down - especially in front of the Blue node. Towards the scene's end, you will find yourself in another sweet-spot at the base of the triangle. Rotate your torso left, then right, again and again, morphing sound by creating different blocking and reflecting patterns. This brings into the foreground rhythmical elements of the No-input Feedback process; it also modulates the pitch of the harmonic carrier of the vocoding processes, especially when you are at the base near Yellow. Structurally, these gentler rhythms fading in and out are a preview of the harsher beats that will take over in the later scenes."

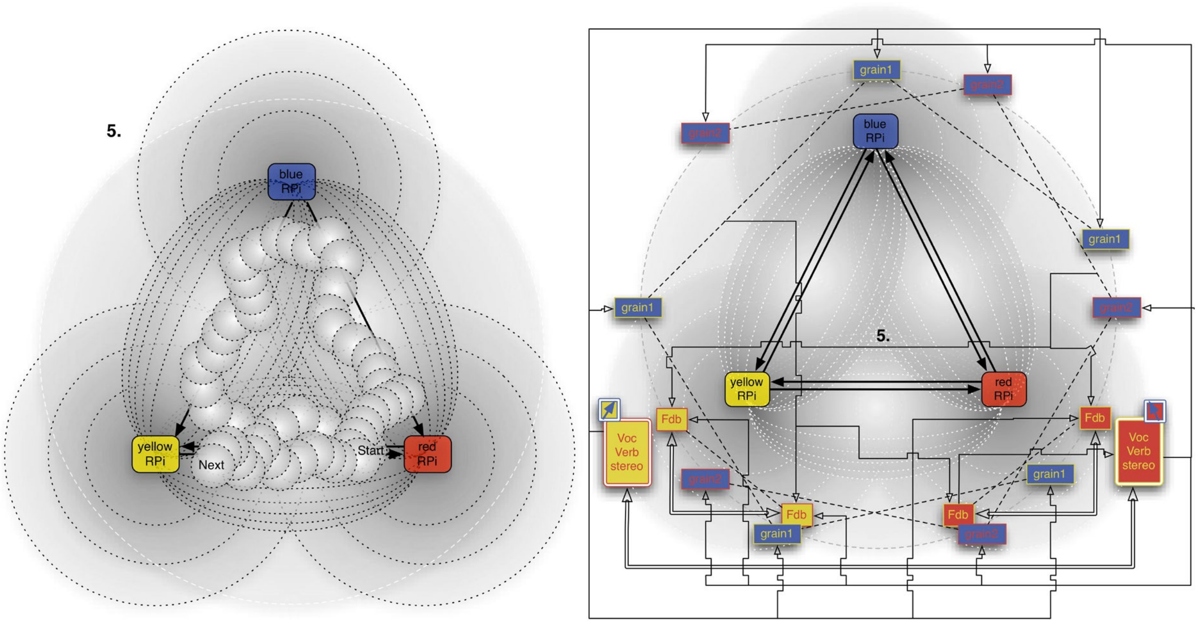


Figure 7.27. *Hertzian Field #2* score for *scene 5*. Left: Movement path. Right: synthesis/processing diagram, spatialization, and mapping of transceivers to processes.

SECTION C (11'15" - 17'35')

Rumble / Bass / Subterranean soundscapes

The third section lasts about as long as the second. It consists of 3 scenes, including a 'bridge' to the last section. The smoother resonances of the previous section subside, with low frequencies taking over.

- **Scene 6** (11'15" - 13')

Entering deep bass fields: making air move

In the next scene, the granular processes are slowly faded out and another pair of cross-feedback no-input processes (*Primeval)* are introduced into the feedback network. These are mapped to sense the long sides of the triangle (*Blue-tracking-Yellow* and *Blue-tracking-Red*). The overall resonance of the soundfield shifts, as the center frequencies of the no-input EQ filters change. Pitch-shifters are also added to the output of the *Vocoding* processes, shifting one process by a semitone and doubling the other by an octave to add more mass in the low end.

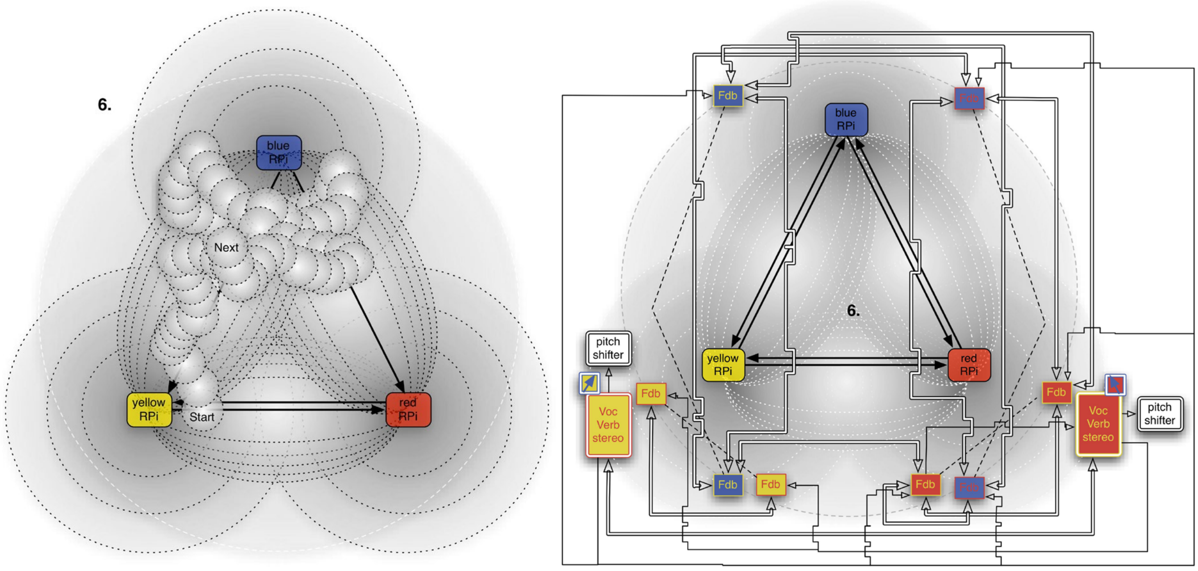


Figure 7.28. *Hertzian Field #2* score for *scene 6*. Left: Movement path. Right: synthesis/processing diagram, spatialization, and mapping of transceivers to processes.

"Move into this scene by taking one step from the triangle's base to block the left beam (Yellow-tracking-Blue/Blue-tracking Yellow). The rhythmic and noisy elements subside, and you find yourself in a field full of deep bass, rich in harmonics. The soundscape is now stripped off the rich resonances of the previous scenes. The vocoding reverberators are still active, but only as an input to the bass drones. You are pulled by the gravity of this low, distorted sound; lower your body to better locate it, especially as you approach the low Blue node. As you lower your body, the bass begins to grow more and more, coagulating into a heavy rumble. You and the audience can now feel the displacement of microwaves as sound pressure - thick air moving around you from the subwoofers surrounding you. Straddle the Yellow-Blue LoS, stepping in and out of the triangle. Raise one arm to change the drone's harmonic structure. Keeping your arms in motion within the inner Fresnel zones, slice through the field in front of and around the Blue node, and explore the top section of the triangle and its two side-beams. During this scene, spend most time in the upper half of the 4x4m stage. Look for nodes and antinodes in the microwave field - straddling the triangle's borders, moving a few steps in or out, testing how far away from the triangle you can go. Move back into it and break through to the other side to create call-and-response patterns between the bass roar on the left (tuned to the tonic), the tenor growl on the right (tuned to the dominant), and the noise of the base beam." (Ibid).

- **Scene 7 (**13' - 15'30")

Echoes of motion: deep waves rolling and crashing

The next scene features an even more complex configuration of the feedback network, as two quartets of bandpass-filtered feedback-delay processes are added (loosely modeled after the filtered tape-delay process chains used in Jamaican Dub music). These are spread around the ambisonic circle, and are mapped to the nodes sensing the sides of the triangle (*Yellow-Blue* and *Red-Blue*).

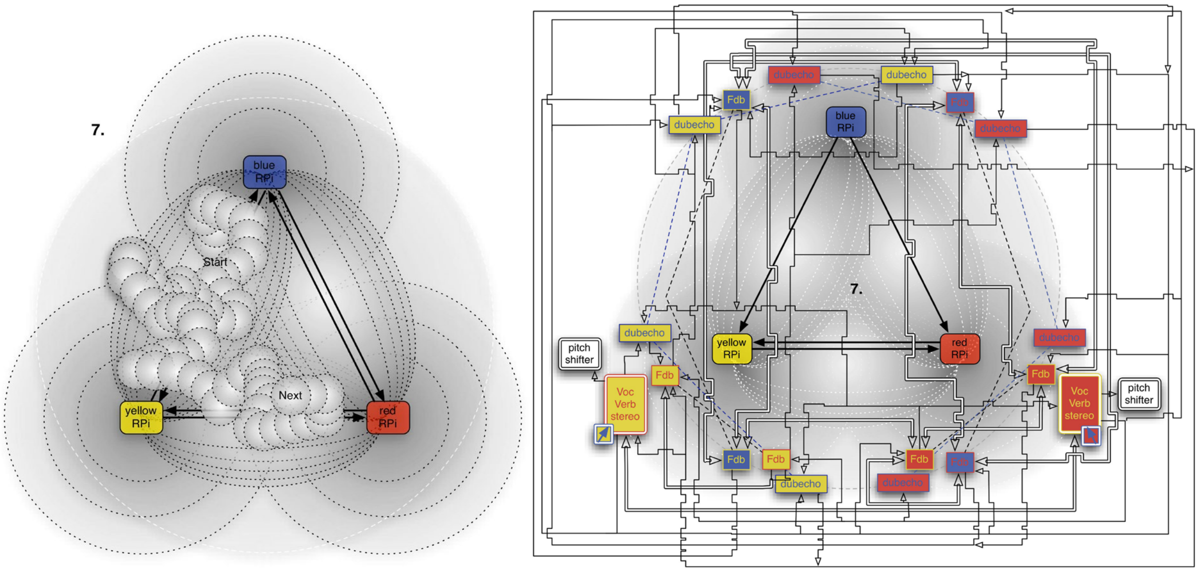


Figure 7.29. *Hertzian Field #2* score for *scene 7*. Left: Movement path. Right: synthesis/processing diagram, spatialization, and mapping of transceivers to processes.

"The scene is triggered when you are positioned on the left LoS beams of the triangle. It brings forth an even deeper bass, an octave lower than before, with the harmonic structure shifting from the tonic to the dominant. The bass becomes particularly present when you bring you body in front of the Blue node.

The feedback-delay of the newly added processes generate a pronounced feeling of hysteresis. Your moving body causes noise bursts that echo through the space, as if every movement creates waves that ripple through the field before settling down. Because of this, the sense of being surrounded by a dense viscous liquid becomes augmented.

Spend most time on the left radio-beam, pumping low frequencies into the hall, and some time on the base beam, feeding the system with noise. Your movement becomes more fluid, and you bring your center of gravity even lower, especially when straddling the left beam. Move slowly, rotating your body within the inner Fresnel zones, coming in and out of the triangle. Positioning yourself outside it brings the system to an even lower, almost subterranean rumble. Walk slowly to the base microwave-beam, slicing through it to feed noise bursts in the system, again and again. Find your place in its center between Yellow and Red - moving your body, then standing still in different configurations to shape the waves of noise with your body as filter. Throughout the scene, follow faster movements by complete stasis, giving space to the system's echoes to become more apparent. Breaking momentary stillness with motion interjects noisy and distorted swishes into the system. Keep searching *for nodes and antinodes to bring out different resonances.*

Step back into the triangle, pointing yourself towards the left beam. The soundscape shifts back into a distorted bass, and the next scene is triggered." (Ibid).

- **Scene 8** (15'30" - 17'30")

Bridge: concatenators and frozen trails of sound leading bass into polyrhythm

Scene 8 functions as a bridge between *sections C* and *D*. The *Vocoding Reverberators* and *No-input* processes mapped to the base microwave-beam are removed. Therefore, during this scene there are no processes mapped to that LoS. A pair of *Concatenative Cross-synthesis* processes are fed the output of the *No-input* processes of the right beam: These processes capture, analyze, and repeat small chunks of the (noisy) input sound to create a 'glitchy', pitched sound source that is triggered and modulated by the performer's path around the triangle. Overall, the spectrum of the soundfield becomes less dense and lightens up.

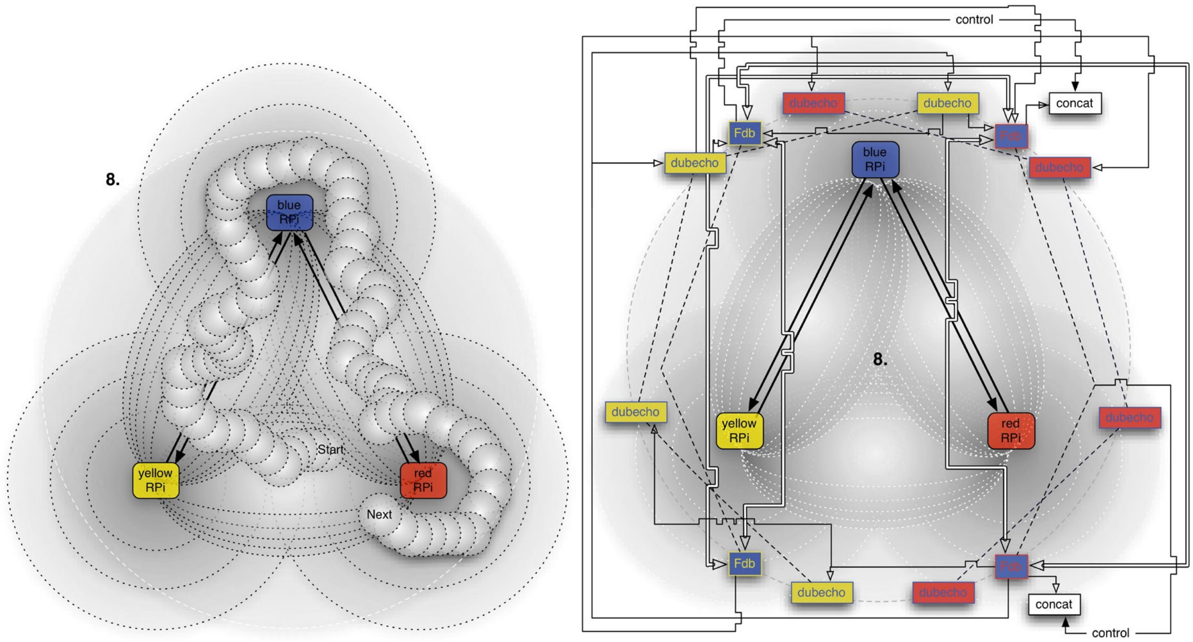


Figure 7.30. *Hertzian Field #2* score for *scene 8*. Left: Movement path. Right: synthesis/processing diagram, spatialization, and mapping of transceivers to processes.

"Move from the inner Fresnel zones of the base beam back into the left beam. The distorted bass is now coupled with the granular sound of the concatenators, freezing the sound of the no-input processes to create long trails of pitched textures in the mid and mid-high part of the spectrum.

Slowly criss-cross the left microwave-beam, bringing your body in and out of the triangle's borders. Move clockwise around it, inverting the path you took in the 2^nd^ scene. Walk slowly behind the Blue node; at this point the low frequencies will disappear almost entirely.

Reaching the right microwave-beam, interact with it like you did with the base beam during the 1st scene. Small movements of your hands change the spectral flow of noise and the pitched sound of the concatenators. Look for nodes and antinodes, alternating between fluid movements and complete stasis. Straddle the Blue-Red LoS, moving your arms and rotating your body to bring in different drawn-out tones and to shape the noise. As you approach the triangle's base, the system shifts back to lower registers. Walk in front of Red, and then around it from behind, shifting the sound back to a higher register. Look for the spots where you can trigger brief noises and tones. The scene ends as you find your place back on the base beam." (Ibid).

SECTION D (17'30" - 23'30")

Pivoting / polyrhythms

In the last section, the rhythmic elements that had been intermittently flowing in and out throughout the piece take over. The soundfield builds into ever-denser polyrhythms, filling the space with pulsing sound masses that slowly crescendo into a thick and vibrant ocean of sound. The performer explores the field by traveling along the triangle primarily with pivoting motions that cut through its Lines-of-Sight. Sound is brought to a maximum density, volume, and tension before it disintegrates as the performer walk outside the triangle to end the piece.

- **Scene 9** (17'30" – 19'15")

Pivoting through polyrhythmic fields

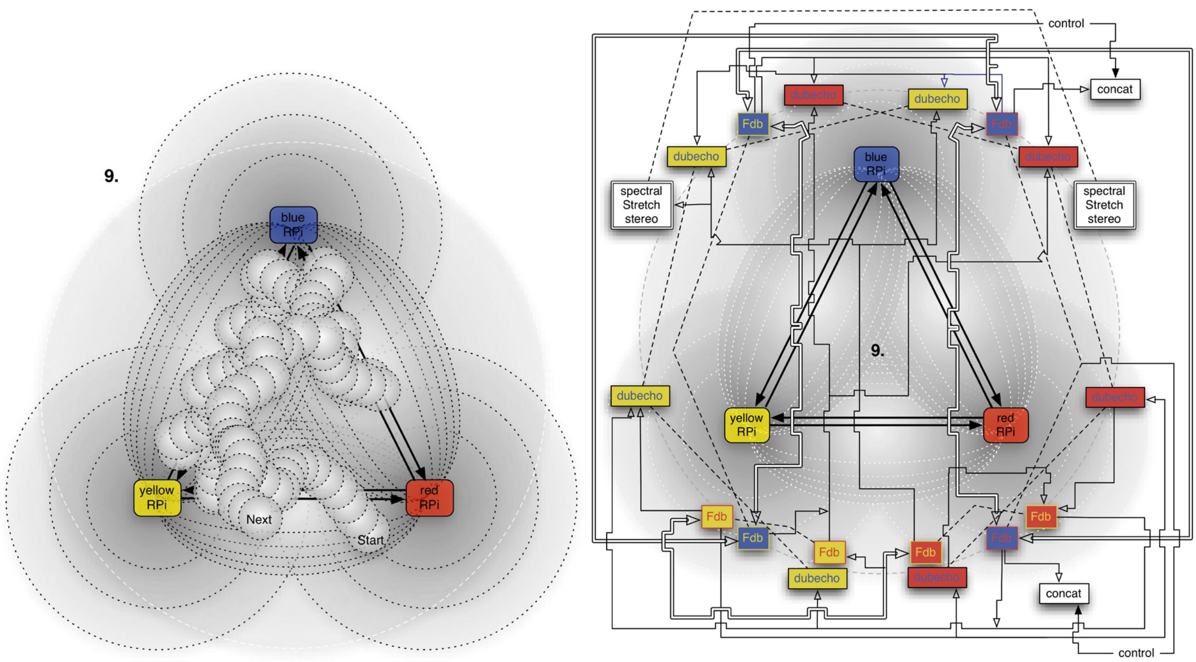


Figure 7.31. *Hertzian Field #2* score for *scene 9*. Left: Movement path. Right: synthesis/processing diagram, spatialization, and mapping of transceivers to processes.

In the next scene, the base beam (*Yellow-Red*) becomes active again. The two nodes (*Yellow-tracking-Red* and *Red-tracking-Yellow*) are mapped to two new pairs of *no-input* modules, injecting heavy and noisy rhythmical textures into the soundfield. Two more *Spectral Stretching* process modules are activated in this scene; these are adaptive processes that:

a) use onset detection on a mono input signal (from a *no-input* process) to freeze the magnitudes of its spectrum for a certain period,
b) harmonize the resulting signal through a set of 4 granular pitch-shifters,
c) normalize the resulting signal's dynamics, keeping its amplitude steady, and
d) use very short delays to create a stereo image of the signal by introducing phase differences between two channels.

These two modules are diffused on the left and right of the triangle and are only controlled through audio analysis, not WiFi sensing.

"As your body blocks the base LoS, fast rhythmical bursts of aggressive noise emerge. Move into the triangle to soften them, then move back to the inner Fresnel zones to make them stronger. They shift from dense industrial polyrhythms to a kind of industrial techno beat. Explore this space. Step into the triangle and away from the LoS moving in semi-circular motions, pivoting your body with a foot fixed to the ground. Transverse the triangle clockwise, with slow movements used to modulate both the spectrum and tempo of the rhythmical layers. Pay special attention to 3 sweet spots: in front of the Yellow node, in front of the Blue nodes, and in the middle of the Red-Blue beam on the right. The left beam produces a somewhat intense and turbulent noisy soundscape often masking the rhythms underneath it. Step in and out of it to mix rhythm into noise into rhythm into noise. Stand still, move back into the base radio-beam, and stand close to Yellow to make the rhythm grow stronger before triggering the next scene." (Ibid).

- **Scene 10 (**19'15"-21'15")

Pivoting and standing through a dense polyrhythmic fog

Scene 10 crescendos from the previous scene, bringing more complex polyrhythms, more noise, and ever-growing sound masses that pump energy into the hall. Two more rhythmical pairs of *no-input* processes are added, mapped to the triangle's left and right beams. They replace the bass-heavy processes that were added on *scene 6* (which were controlled via *Blue-tracking-Red* and *Blue-tracking-Yellow*). They scan the same space but from an opposite viewpoint, as they are mapped to the Red and Yellow receivers tracking the Blue transmitter. One of the *tape-delay* processes is faded out, and another pair of stereo *spectral stretching* effects is added. Furthermore, a set of *analog-style resonant low-pass filters* are added to process the rhythmical *no-input* modules and accentuate their impact.

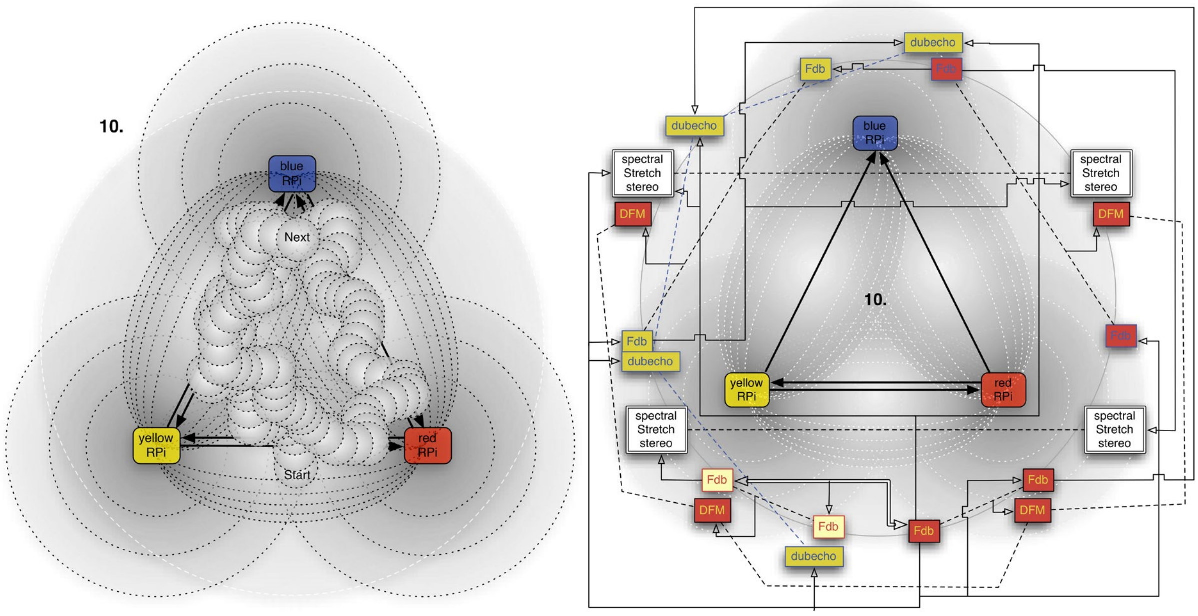


Figure 7.32. *Hertzian Field #2* score for *scene 10*. Left: Movement path. Right: synthesis/processing diagram, spatialization, and mapping of transceivers to processes.

"The flow of your body modulates pumping rhythms full of noise as you continue pivoting around the triangle. Starting from the center of the base beam, pivot around the triangle, traversing it 1.5 times throughout the duration of the scene. Stay mostly inside it, and mostly straddling the inner Fresnel zones of the field. Do not quite reach the triangle's center, unless you want to make the sound quiet down a bit. Throughout the scene, make sure to stand still at certain moments so as to let the system's machine-like rhythms come through with minimum modulation. Once you move, the fluctuation of wireless flows will make it all more organic, almost living. Pay attention to the many sounds to be discovered in front of Red, and in front of Blue. When at the tip of the triangle, lower your body so that your torso blocks both LoS paths (Blue-Yellow and Blue-Red), swaying left and right. When you are back in front of Blue for the second time, trigger the next scene." (Ibid).

- **Scene 11** (21'15" - 23'15")

Shaping the spectrum of a polyrhythmic fog

This penultimate scene introduces sonic content in the higher parts of the spectrum, complementing the low rumbles of the previous scenes. This happens principally through the introduction of four *Adaptive Phase-vocoder split-and-freeze* modules. These are spread around the ambisonic circle, processing the output of various generators and filters. They are controlled by *Red-tracking-Blue*.

"In this scene, circle around the triangle 1.5 times again. Continue your pivoting movements, taking larger and quicker steps, sometimes back-tracking to find a sound or to create a pattern through repetition. Stop to accentuate the high frequency textures, and move to modulate the rhythms and noise. Once more, when you find yourself again in front of Blue,

sway left and right to cause different rhythmic patterns to emerge. When your body approaches within a distance of a couple of wavelengths from the Blue transceiver (less than 30cm), the soundfield's spectrum shifts from the mid-low register to high, then to very high frequencies. When it enters the near-field of the antenna, it causes particularly interesting behaviors in the high register - as if a great amount of energy is suddenly trapped in a narrow band of the spectrum up there. Explore this.

Towards the end of the scene, move slowly in the direction of the triangle's center, with your back facing its tip in front of the Blue node. Sound shifts to the higher part of the spectrum. With firm steps, legs open into a wide stance and your center of gravity lowered, move towards the base of the triangle. Come closer to the center of the Yellow-Red LoS, and while facing it, break that microwave-beam with your body to give rise to a final resurgence of intense and full sound. Turn around and slowly exit the triangle, letting the system calm down." (Ibid).

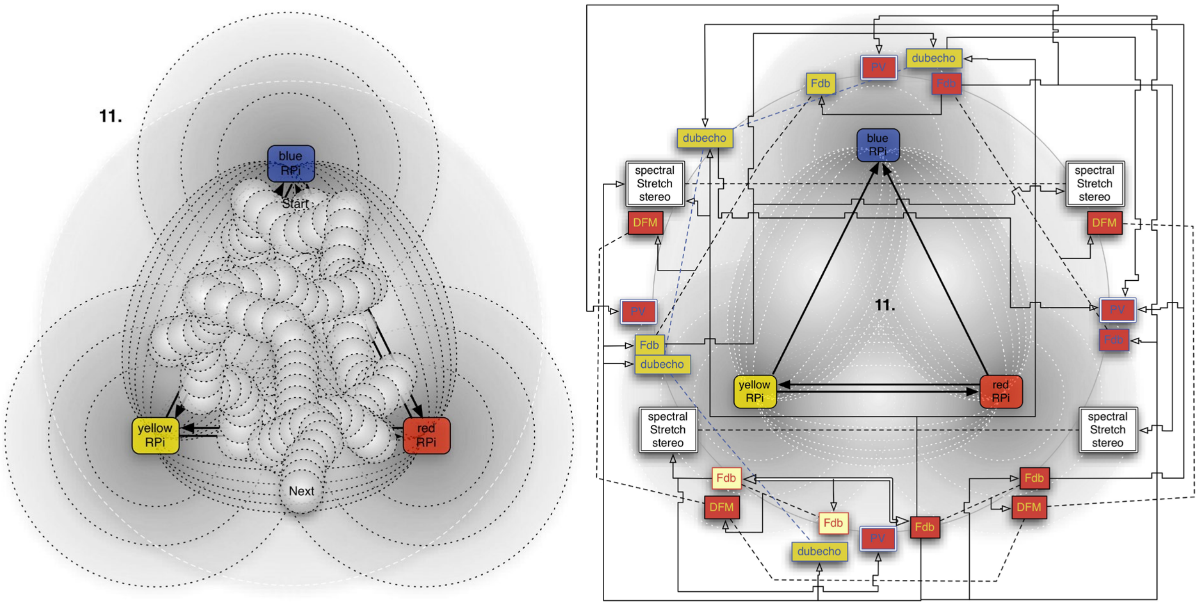


Figure 7.33. *Hertzian Field #2* score for *scene 11*. Left: Movement path. Right: synthesis/processing diagram, spatialization, and mapping of transceivers to processes.

- **Scene 12** (23'15" - 23'30")

End: Exit the triangle to release the sound

The final scene slowly fades out all processes as the performer walks out of the triangle.

"Your body is in the outer Fresnel zones of Yellow-Red, and you are facing the triangle. Bring back your hand closer to it, extending it as if to grab the invisible microwave-beam at its base. Close your fist and bring it slowly back towards your body as the sound fades out and the performance reaches its end." (Ibid).

7.4 THE WATER WITHIN / HERTZIAN FIELD #3

"Space dissolves in steam. Distances collapse, the borders of bodies are rubbed out, and disjecta membra loom through the fog"
(Wilkinson, 2018, 98)

7.4.1 *About the work*

The most recent work of the *Hertzian Field* series exists in two iterations, created in 2016 and 2018 respectively. The technology and construction of both iterations is the same, with the main differences concerning how the work is experienced, and how sound and light develop over time.

Figure 7.34. *The Water Within (Hertzian Field #3)* at Modern Body Festival 2016.

The first iteration is titled *The Water Within (Hertzian Field #3)* and was created for *Modern Body Festival 2016: I/WE/THEY*, a biennial interdisciplinary festival in The Hague, the Netherlands, that I co-founded and co-direct with my duo partner Stephanie Pan.[358] The work

[358] See: https://modernbodyfestival.org/2016/, last retrieved 28 January 2023.

was a direct response to the theme of the festival, *I/WE/THEY*, which was centered around explorations of the *social body.* I conceived the piece as a new kind of social place and presented it as a continuously running installation in which visitors could enter and exit as they pleased. My goal was to create an immersive multi-sensory environment that targets body and mind, and which produces a near-synaesthetic shared experience that becomes greater than the sum of its parts. To execute it, I collaborated with London-based Taiwanese architect Ping-Hsiang Chen who designed the structure of the installation. Figure 7.34 shows a photo of from the work's premiere at Modern Body Festival 2016.

The text description of this first iteration of the piece reads:

*"*The Water Within (Hertzian Field #3) *is an interactive wet sauna: an intimate multi-sensory environment of complete immersion combining a cutting-edge sensing system based on WiFi waves, machine listening software, embedded 3D sound, hot steam and architectural design.*

Steam rooms, saunas, hammams and public baths have been an integral part of the social network of many cultures – a place to refresh one's body and mind, but also to meet, talk, listen, socialize. The Water Within (Hertzian Field #3), *a work by Stelios Manousakis in collaboration with architect Ping-Hsiang Chen, re-imagines the form, function and experience of a bathhouse within the context of an art exhibition or festival and from the perspective of today's world of wirelessness, ubiquitous computing, and continuous connectivity. It provides visitors a space to slow down and recharge, but also engage with their bodies, with technology and with other visitors in unexpected ways. The piece uses a new sensing technique developed by the artist for the Hertzian Field series. Inspired by radio astronomy and obscure surveillance research, the system analyzes the interference patterns of ordinary WiFi waves to detect and respond to the flow of water molecules in the space – those of the steam, and those within the bodies of visitors. The extracted data is used to generate a dynamic soundscape that submerges visitors into a sonic bath full of gushes of noise and resonant droplets of sound, melodic drones and rumbling bass, rhythmical waves and oceanic roars."* (Manousakis, 2016b).

In 2018 I created a new version of the work. Titled *The Water Within (Hertzian Field #3.1),* it was developed for the exhibition of another event from the Modern Body initiative, *Modern Body Laboratory #2: Intelligent artifacts and breathing spaces*, which also took place in The Hague.[359] This was a further developed iteration in which - having more time on my hands as I was not also producing a festival while making the piece - I realized my first concept about the work: namely composing an interactive experience as a multi-sensory journey with a beginning, middle and end. In this version, groups of up to 6 visitors enter together to share a composed, though still interactive, 20-minute experience, in which sound, interaction, but

[359] The piece was also subsequently presented during *Azimuth #6*, a 2-day event on spatial electronic music, headlined by Francisco López.

also light evolve over time following a score, in a similar manner to *Hertzian Field #2*. Figure 7.35 shows a photo of that second iteration.

Figure 7.35. *The Water Within (Hertzian Field #3.1)* at Modern Body Laboratory #2 in 2018.

Owing to the different format, the description text for this version was rewritten:

*"*The Water Within (Hertzian Field #3.1) *is an intimate 20-minute experience of complete multi-sensory immersion. Groups of up to 6 visitors enter a parametrically-designed structure, developed in collaboration with architect Ping-Hsiang Chen. The space has its own very hot and humid microclimate and is monitored by an autonomous software agent. An electromagnetic bubble engulfs the steam room, acting as its sensing apparatus. The agent's sensing system harnesses the interference of water on radio waves to conduct something akin to a continuous X-ray or MRI of the space – but with ordinary WiFi signals. The system was entirely developed by the artist, inspired by obscure surveillance research. The agent performs an algorithmically-driven dynamic soundscape in response to the density and flow of water molecules in the space from the steam and the water inside visitor's bodies. Lights and 3D sound projection is embedded in the structure. Six ceiling-mounted full-range speakers envelope visitors with a canopy of sound, while two subwoofers project deep vibrations that can be heard but also felt through the seats and wooden floor.*

The piece uses the raw materiality of wireless communication to expose the sympathetic resonance of the body to its flows and to celebrate interference, signal-loss and disconnecting, both metaphorically and through its (ab)use of WiFi technology. It creates a place for visitors to slow down, listen, relax, and playfully communicate with the system and with one another through the body – by being there, experiencing heat, space, and sound together." (Manousakis, 2018).

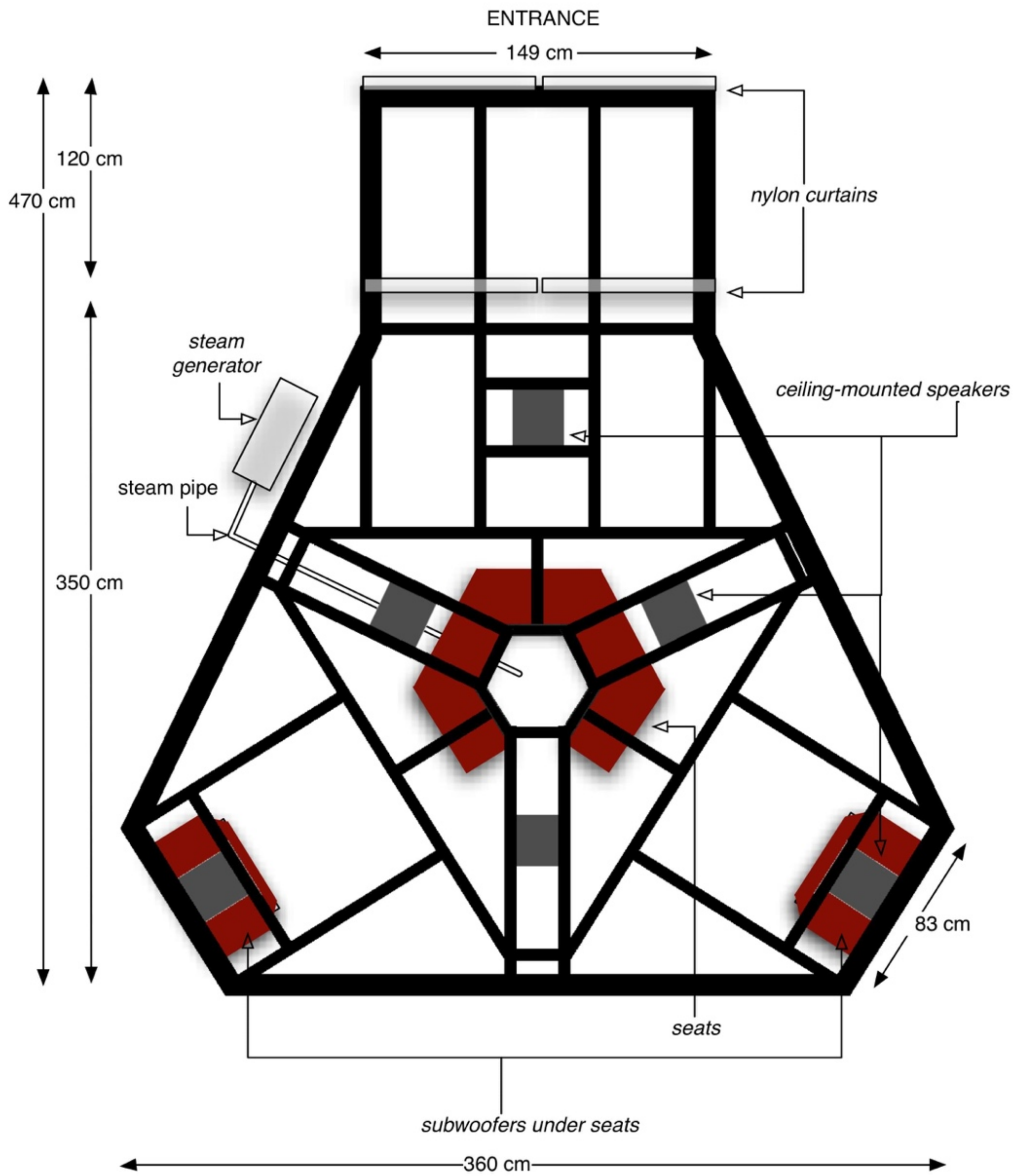


Figure 7.36. Top view diagram of the architectural structure and embedded equipment of *The Water Within (Hertzian Field #3.x).*

In both iterations, the experience takes place within an enclosed space full of hot steam which creates a wet tropical microclimate. Architecturally, this steam room is a water-tight polyhedral structure made from light materials. The frame is made out of pine wood beams, the floor out of plywood, and the walls and roof out of white parachute fabric. The room is designed to contain and guide the flow of people, steam, WiFi interference, and sound. Steam is led into the room from under the floor through a pipe, and comes out of a column in the center of the structure. There are 7 seating places: a polygonal bench with 5 seats around this column and two more seats on the structure's sides furthest from the entrance (figure 7.36).

While there is enough space for more than 7 people inside, the latest version (*Hertzian Field #3.1*) is best experienced with fewer participants – between 3-5 being the ideal – as that provides more room for everyone to move, sit down, stretch, explore, change perspectives, etc. It also makes it easier to grasp the system's response to one's own body.

The piece utilizes the same version of the *Wireless Information Retrieval* system as *Hertzian Field #2,* and a similar configuration. An electromagnetic bubble, formed by a trio of WiFi transceivers placed in a triangular formation just outside the steam room, is acting as the sensing apparatus of an autonomous software agent monitoring the space. This agent generates – or rather, performs - a dynamic soundscape in real-time and in response to the environmental conditions, as well as to the position, orientation, and overall activity of visitors within the steam room. As I found out later, it also responds to the amount of sweat and condensation on visitors' bodies (more about that in section 7.4.11). Essentially, the inside of the steam room is sensed by the agent as one large body of water in constant flux, consisting of low-density areas (where the steam is flowing) and higher-density areas (where human bodies are located); via the WIR sensing system, both of these control the flow of sound pressure waves inside the room.

In both iterations of the work, sound is diffused using an embedded, custom-made 6.2 audio system: Six ceiling-mounted full-range speakers create a canopy of sound that envelopes visitors from above. In addition, two subwoofers are placed inside the single-person seats at the far sides of the structure, producing deep vibrations that can be not only heard but also felt through the wooden floor and through all 7 seats connected to it.

7.4.2 *Context: Modern Body Festival and the social body*

The Water Within (Hertzian Field #3) constitutes a nexus point bringing together several threads of my artistic research. A significant part of these threads has been picked up and followed throughout this thesis, however there are also others whose scope extends beyond this document and which have thus not been mentioned. One of these threads is the *Modern Body Festival,* whose 2nd biennial edition gave both the impetus and support to create this work, and whose theme became inextricably linked with its concept, form, and experience.

Briefly, the *Modern Body* initiative is an artist-run intermedia platform at the convergence of art and technology that is founded, directed, and produced by me and Stephanie Pan. Our most ambitious projects to date have been a trilogy of thematic multi-day biennial festivals. The festival's mission states: *"Modern Body Festival examines the nature of our current* *existence through thematic editions that curate experiences – physical, visceral, immersive and intimate. We seek the modern body within the new worlds that emerge when different artforms intersect, collide, and modulate each other. We focus specifically in the open field that exists between artforms – new media, dance, music, installations, interactive art, performance, theater, architecture, robotics, bio-art, video art"* (Modern Body Festival, 2018).

The inaugural edition, *Modern Body Festival 2014: Art as research through experience* introduced our concept of the 'modern body'; it explored how we experience the world around us from a first-person perspective, our relationship to technology, and its effects on our understanding of our own bodies (Modern Body Festival, 2014). The following biennial in 2016 extended this exploration. The curatorial statement declared: *"For our second biennial edition, we develop the theme I/WE/THEY to reach beyond the physical body to the social body, to explore how we exist and belong in today's networked world, and what the cultural borders of a globalized society are. We are particularly interested in the effects of technology, digital communication and architecture as they are fundamentally transforming the way we exist as a society, culture, species. We focus on identity and community: how we interface with I/WE/THEY. Where do the limits of the self extend and where do the social bodies of group and community begin? How do we understand and position ourselves as individuals, while still feeling a sense of belonging and connection to an expanding global community? How do we exist, identify, and interact? Furthermore, how does architecture and technology influence our interactions with each other, and how can we in turn, influence architecture and technology?"* (Modern Body Festival, 2016).

For that edition, *Modern Body* collaborated with *Dezact*, a cutting-edge architecture platform from London and Taipei.[360] Together, and before the edition in The Hague took place, we co-founded, co-curated, and co-produced *Space Media Festival Taipei: I/WE/THEY*, a sister edition of our festival.[361] It took place in Taiwan in the summer of 2016 (August-September) and consisted of four simultaneous 10-day architectural studio workshops, each led by an artist-architect pair and followed by a month-long exhibition of the produced works in public space. The second *Modern Body Festival* edition in The Hague followed in the autumn (November-December 2016). It took the form of a 13-day event in various repurposed locations in the city, featuring day-long workshops, evening symposia, performances, and an

[360] See: https://www.dezact.org, last accessed 29 December 2022.
[361] See: https://www.dezact.org/?s=space%20media%20festival. Last accessed 29 December 2022.

exhibition in two venues which included some of the works created in Taipei.

During the preparation for this edition in The Hague, we were considering presenting the festival's exhibition in a very large, quite spectacular but also unheated industrial space - the turbine hall of an old electricity factory.[362] This presented a significant challenge, as the Netherlands can be very cold in November/December. We knew too well - partly from our personal experience of living and working for years in a squat with no heat in The Hague - that this lack of heating would be decidedly unpleasant for our visitors, making it hard for them to devote time to experience the artworks. In a moment of epiphany soon after the premiere of *Hertzian Fields #2*, I got the idea to make a new hertzian work that could help alleviate this very practical problem: This new work would essentially be a reactive steam sauna through which festival visitors would load up on heat while experiencing it, so that they could comfortably spend time at the exhibition experiencing the other works. Besides presenting a practical solution to the problem of heating, this idea also provided a compelling and exciting artistic response to the theme *I/WE/THEY* in a rather radical and positively challenging manner. While in the end we did not use this unheated venue for a variety of reasons, once we arrived in Taipei during monsoon season for *Space Media Festival* I realized that with such a piece I could re-create the hot and sticky conditions we encountered there inside an exhibition space back in The Hague. With this small weather bubble, *Modern Body* could thus not only help our audience in the Netherlands fight off the harsh winter, but also give them a taste of the experience during our sister festival, establishing yet another link between the two editions in Taipei and The Hague.

7.4.3 *Post-relational aesthetics*

My approach for this work was informed by Nicola Bourriaud's concept of *relational aesthetics*, which he developed in the late 1990s-2000s (see Bourriaud, 2002). Relational aesthetics is an artistic approach in which the artwork does not begin with an object or material. Instead, the *prima materia* of the piece is human relationships and their social context. By transposing these relationships and contexts from private spaces to the public space of a gallery, the artwork becomes a framework and catalyst for new relationships to emerge between the visitors as members of a group, but also within visitors' own selves. An example of Bourriaud's concept of relational aesthetics is Rirkrit Tiravanija's *Untitled (Free/Still)* (see Tiravanija, 2011 and Stokes, 2012). In this work, first presented in 1992, the

[362] See: https://www.electriciteitsfabriek.nl/. Last accessed 29 December 2022.

artist converted a gallery space into a Thai kitchen serving rice and curry for free. By emphasizing the act of forming human connections, the goal of this work is to create *active* experiences. Overall, the focus of relational artworks is not to imagine and design *utopian* situations - worlds that can only exist within the context of the arts - but instead to imagine and create *"ways of living and models of action within the existing real"* (Bourriaud, 2002, 13). The end goal of the relational artist's creation is not an artwork in the traditional sense, but the relationships created through the situation that the artwork frames, encourages, instigates. Relational artworks are inherently designed as open systems, fed by and actualized through the desires, expectations, decisions and actions of their visitors. As Bourriaud writes, "*[t]he first question we should ask ourselves when looking at a work of art is: – Does it give me the chance to exist in front of it, or, on the contrary, does it deny me as a subject, refusing to consider the Other in its structure?"* (Ibid, 57).

While I find the concept of relational aesthetics very pertinent and inspiring, as a maker I feel that, in this day and age, it is in need of an update – at least in how it relates to my own practice and my personal understanding of the world. A number of things have changed since the concept of relational art was formulated. While relational aesthetics seeks to deal purely with human relations, I believe that it is impossible to truly separate ourselves from our environment – both natural and man-made, material and abstract – and that everything around us affects our interactions with each other and our surroundings, even within ourselves. For example, the Internet, whose emergence was an important factor in the development of relational aesthetics in the 1990s, has grown into a kind of central nervous system of humanity to which we are all connected through our computers and smartphones. Systems and algorithms steer our lives everyday in a much more intense manner, from what we buy, to the news we read, to the friends we make, to the lovers we meet, to the jobs we work at, to the way economies move. Separating the human from the non-human is becoming increasingly harder – or perhaps more irrelevant - in today's society as we are all agents in the same network, as Latour and Pickering have argued (see section 1.1.4). I feel that, by following a post-anthropocentric approach and cultivating points of view and understanding that are not entirely human-centric, one has the potential to imagine, and thus create, alternative symbiotic relationships between humans and the world.

Post-Relational Aesthetics is thus a term I developed to describe and understand practices that have integrated interactive art / new media / systems art / object art with the awareness of human-to-human interaction that was developed through the Relational Art movement. Such works move beyond the idea of human-to-human relationships, extending their focus to also include the non-human. Rather than being primarily concerned with the relationships between those experiencing a work, such pieces offer a lived experience of the symbiotic, destructive, accidental, and other types of relationships between the different actors that form the fabric of our society: human, animal, object, matter, but also abstraction – e.g. inanimate systems, algorithms, networks, protocols, technologies. A *post-relational artwork* may begin with *crafting* an artistic environment or situation that has an agency of its own (emerging, for example, through the inclusion of responsive computation) whose role is to become the catalyst for exploring relationships. In *The Water Within (Hertzian Field #3.x)* - and particularly in the work's second iteration - the role of artistic *craft* is as fundamental to the work as its social context and relational implications. The piece is actualized through the interactions and relationships between a multi-layered system and its visitors, but at the same time it is a composed artistic experience.

7.4.4 *On steam rooms and sweat bathing*

> *"Sitting in a sweat bath could be the most vigorous activity you've had all day. The heat produces an artificial 'fever' and urges every organ of the body into action. While outwardly relaxed, your inner organs are as active as though you were jogging or mowing the lawn. At the same time, you are being cleansed from inside out by the skin, your body's largest organ and its excretion, sweat."*
> (Aaland, 1978/2018).

Prior to discussing *The Water Within* in more detail, it is particularly illuminating to first delve into the function and historical context of the steam room and the related ancient practice of *hot-air bathing*, *vapor bathing*, or *sweat bathing*. This rich tradition, whose origins are lost in the depths of human history, involves spending 10-20 or more minutes at a time in a very hot room - often filled with hot steam - then cooling down using a variety of methods, such as taking a cold shower or plunging into a cold pool or snow. This process may be repeated multiple times. As architecture historian - and *"early pioneer of Sauna Studies"* (Tsonis, 2017, 62) - Sigfried Giedion writes (1948, 644), *"[b]athing in steam-saturated air is at once the simplest and cheapest type of bath that will cleanse the body with desirable thoroughness".* Beyond simply cleaning, this ancient practice has multiple other functions: Medicinal, social - sweat bathing typically being an important component of the social fabric of cultures that practice it - and in many cases also spiritual.

Presumably, sweat bathing began with the use of controlled fire in closed spaces and was likely further developed by covering the fire with stones to create *a "mound or hearth"* (Tsonis, 2017, 61). It has been practiced by various cultures around the world, in both cold and warm climates, including in places such as Finland (*sauna*) and Russia (*banya*), Japan (*sentō, mushi-buro, ishi-buro, kama-buro, kara-buro* and other variants) and Korea (*jjimjilbang*), the Islamic world (*hammam* and *Turkish bath*), Mesoamerica (*temescal*) and North America (indigenous *sweat lodges*), across the Arctic, even in sub-Saharan Africa (Tsonis, 2017; Wilkinson, 2018; Aaland 1978/2018).[363] The minimum requirements for creating a sweat bath are a closed space, some heated stones, and some water to pour on top of them to create hot steam.[364] The space need not be a fixed structure but can also be portable (e.g. a tent created with animal skins).[365] In many cases, particularly in larger sweat baths, bathers can move between seats placed at different heights or proximities to the heat source in order to find their preferred temperature.

There are many variations in the methods and facilities used for sweat bathing, but two principle categories can be distinguished: those based on dry heat (like the Finnish *sauna* and the Russian *banya*) and those based on wet heat (i.e. steam rooms like the *hammam*, or *The Water Within)*).[366] The former types are much hotter and drier - e.g. the Finish sauna functions at 80-95ºC and only has 15-25% humidity – thus causing the body to sweat more than in the intensely humid but less hot steam rooms. In the latter, humidity ranges between 90-100% thus necessitating temperatures to be lower – at around 45°-50°C - to avoid scalding bathers. Nonetheless, the feeling of acute warmth is still very much present in steam rooms, as moisture is much more effective than dry air in conducting heat to the skin (Tsonis, 2017). Overall, these differences in heat and humidity produce slightly different physiological effects and influence how long a bather can spend in such a facility, with higher temperatures requiring a shorter stay.

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[363] The wide distribution of this practice in so many climates can be explained because sweat bathing does not only make one feel warmer in cold environments, but also cooler in warm environments as it cleans and opens the skin pores, making them work more efficiently which contributes to a feeling of coolness in hot climates.

[364] Even more simply, sweat bathing practices by certain tribes in Alaska, the Pacific coast and the Southwest US only involve a large closed space heated by placing flaming logs in its center (Aaland, 1978/2018).

[365] Tents are the original space for sweat bathing, as the practice first emerged in nomadic societies (Aaland, 1978/2018). This is likely because it was a practical way for such people (like the Fins before migrating to Scandinavia from central Asia thousands of years ago, or indigenous tribes in North America) to keep clean while constantly on the move and regardless of weather or access to running water.

[366] Lopatin (1960, 977) proposes a broader typology of bathing in general consisting of four main categories: "*1) the pool or the plunge bath, 2) the direct fire sweat bath, 3) the water vapor sweat bath, and 4) the mixed type*", with the latter combining elements from the other types.

The body responds as follows in the sweat bath: The intense or humid heat stimulates the skin and the sweat glands within it. On average, a 15-minute session in a sauna results in about one litter of perspiration to be sweat out of the body (Aaland, 1978/2018). Sweating in these baths occurs primarily through the eccrine glands that produce odorless clear sweat, and which are most abundant in the body (Ibid). These glands are triggered by the acetylcholine produced by heat-sensitive nerve endings in the skin. The apocrine sweat glands, located in the armpits and pubic area, respond to emotional stimuli and are thus not activated in the sweat bath. Sweating is fundamentally important to the human body and fulfills multiple functions, from regulating temperature, to keeping the skin clean and healthy, to purging waste products. This last function includes excreting heavy metals, urea, as well as lactic acid from the body (which is why muscles feel relaxed and less tired after a steam bath) (Ibid). Owing to this, the skin is often called the 'third kidney'. During a sweat bathing session, the skin slowly becomes redder. This is evidence of a complex process taking place within the body, which involves the capillaries dilating to increase blood flow to the skin so as to pull heat away from the body's surface and distribute it inwards. A consequent increased demand for blood makes the heart work faster, while the *"rapid flexing"* of the heart and blood vessels improves blood pressure (Ibid). The ensuing quick flow of fluids helps flush out waste products in the muscles, stomach, liver, kidneys, and most organs – even the brain. The increased temperature inside the body also appears to positively affect the brain's pituitary gland, responsible for regulating metabolism, producing key hormones, and directing other glands in the endocrine system to release hormones into the bloodstream. Finally, the cooling process following a sweat bath reverses these effects as the body's temperature returns to normal: the heart calms, vessels contract back to normal, sweat pores close, and so forth.

Throughout the years, many physicians and enthusiasts have vouched for the positive effects of sweat bathing in its different forms, namely that it not only relaxes the body and improves bathers' moods, but it also gives relief from various ailments or can even help cure them (Aaland, 1978/2018 and Tsonis, 2017). Such claims are ancient; they can be found in sources like the Ayurveda, a medical text written in Sanskrit around 586BC which prescribed sweat bathing among 13 other ways of sweating, as well as in the texts of Hippocrates (a 5th century BCE Greek), who is considered the 'Father of Medicine' (Gianfaldoni et al., 2017). These medicinal properties of sweat bathing – possibly together with the sterilizing properties of the intense heat - likely also contributed to sweat baths becoming integral for a variety of traditional rites of passage and medical operations across different cultures. This includes sweat baths being used as a place for birthing children and performing medical operations, for purification rituals, for preparations for marriage and wedding rituals, even a place where elders chose to die in (Aaland, 1978/2018). Unsurprisingly, this has often contributed to sweat bathing acquiring a spiritual significance across cultures – even theological in certain cases.

Nonetheless, and despite a growing interest in the practice during the last few decades, there is a dearth of publicly available academic and scientific research, particularly in the English language (Tsonis, 2017).[367] This became rather evident to me when I was conducting research for *The Water Within*. In an erudite article aiming to establish *Sauna Studies* as an academic field, Tsonis (2017) catalogues some of the most relevant existing research and proposes a map for investigating three principal areas, namely: [368]

1) Health Science - the area most relevant for funding and with most representation. As Tsonis notes, existing studies are limited in scope, have not touched on key areas (such as the effects of sweat bathing on mental health and psychology, and its potential for promoting public health), have few references, and little connection with one another. He remarks that *"[v]irtually every aspect of sauna's effect on the human body requires further investigation"* (Tsonis, 2017, 54).
2) Technology and Design. Academic research on these field is practically non-existent. My own attempts to discover pertinent information on steam room designs and technologies invariably led me to commercial sources, such as steam generator manuals. Tsonis (2017, 53) pointedly comments that *"[w]hatever technological expertise exists seems almost entirely confined to folk traditions, popular books, and the private archives of sauna manufacturers."*
3) History and Culture. This is an area that combines history, ethnography, sociology and critical analysis to examine the *"fascinating history"* of sweat bathing (Ibid, 78) but also to shed light on the social dynamics involved and examine the profoundly social aspect of sweat bathing across cultures.

[367] More research exists in other languages, particularly in Finnish, Russian, and German. This is not limited to recent years; Aaland mentions, for instance, that between 1877-1911, 30 medical dissertations on the healing effects of the *banya* were published in Russian.

[368] As part of this effort, Tsonis set forth to establish the *International Journal of Sauna Studies.* While the inauguration of the Journal was announced at the XVII International Sauna Congress in 2018, a first issue is yet to be published. A preparatory meeting was scheduled for 2020 but was most likely thwarted by the COVID-19 pandemic. The supporting website (http://www.saunaresearch.org/) is still void of any content as of 2022 (last accessed 29 December 2022). A 'coming soon' announcement in 2020 stated that *"The IJSS is taking a long time to materialise, but it will arrive eventually."*

In regard to the relationship between sweat bathing and culture, Giedion's writing is deeply illuminating. In his overview of bathing as a cultural practice and the evolution of its meaning in different eras and societies, he distinguishes between two principle forms: Bathing as a strategy for *"total regeneration"*, and as *"mere ablution to be performed in swiftest routine"* (Giedion 1948, 628). Generally speaking, bathing as ablution is often private and happens in spaces such as a shower or a bathtub, whereas bathing as regeneration is typically a social and relational practice that forms an integral part of communal life. For a number of cultures, from the ancient world, to Islamic societies, and much of Europe until the Middle Ages, regeneration was considered *"a basic social responsibility"* (Ibid). While these two perspectives – regeneration and ablution - often coexist, societies commonly have a preference of one over the other, influenced by the social importance they give to bathing. For Giedion, the way in which a society regards taking care of one's body provides valuable insights on the character of the culture, especially on its attitudes around relaxation and how much it cares about people's well-being. He postulates that regeneration forms part of a broader notion of leisure which *"in this sense, means a concern with things beyond the merely useful"* (Giedion 1948, 712). He adds: *"Leisure means to have time. Time to live. Life can be tasted to the full only when activity and contemplation, doing and not doing, form complementary poles, like this of a magnet. None of the great cultures has failed to support this concept"* (Ibid).

I find both this notion of regeneration and the deeply social nature of sweat bathing to be particularly relevant and inspiring. Even though I was not aware of Giedion's writing when creating *The Water Within (Hertzian Field #3),* these concepts were integral to the work. Bathing in contemporary societies of the Global North is certainly practiced as ablution, stripped of any social aspect, or – most often – of any ambition for 'total regeneration' of mind and body. The notion of 'regeneration' in connection to bathing has instead become rather niche. It is limited to specialist venues like spas, and to specific target audiences - typically the upper financial echelons of societies with free time and money to spend for such purposes. Furthermore, such spa outings are considered special occasions even for these audiences.

This was however not always the case, even for the ancestors of today's Global North. In fact, two of the founding cultures of western civilization – ancient Greeks, especially during the Hellenistic times, and Romans – practiced highly social forms of bathing. The Romans, in particular, made hot steam bathing a central part of their culture, having borrowed, developed, and further technified the Greek concept of the gymnasium through their cutting-edge engineering. They devised technical systems to distribute heat evenly inside rooms by moving it through the walls and floor, thus making it possible to create spaces with a variety of controlled microclimates (Giedion, 1948).[369] The Roman invention was not only technological but also sociological. By the 1st century BCE, the Roman *thermae* – precursors of modern spas - had grown into a fundamental nexus of social activity were all people came together. Soon, aided by the development of the aqueduct, public baths were spread throughout the empire – subsidized to provide free or nearly free access to *"daily regeneration"* for all - with some monumental structures even built to fit thousands at once (Ibid, 633). A variety of architectural paradigms were developed across the Roman empire through a continuous discourse with local cultures and customs. One of these paradigms eventually led to the development of the *hammam* in the Islamic world.[370] Between the 3rd-6th centuries CE, a new type of small-scale bath emerged in the Eastern Roman Empire (Byzantium) in the region of contemporary Syria. Small and intimate like the original sweat bath archetype still found in Finland and Russia, these Syrian baths were made of stone like the roman *thermae* and incorporated a simplified version of their technology. [371] Once the Arabs conquered the region in the 8th century CE, they quickly adopted and adapted these baths and started spreading them through the Islamic world, much like the Romans had done earlier in their empire. In big Arabic cities, like Cairo or Cordova, one would find hundreds of hammams. Like the Romans before them, these baths became a core centre of social life for Muslims, being accessible to all - with the crucial difference that an instituted segregation by sex established a much-needed safe space for women to congregate together. Among the Muslim tribes to adopt them, the Ottoman Turks also dispersed them throughout their own growing empire later on.

Westerners came in contact with various sweat bathing practices several times in history, such as when the nomads plundered Rome, when the Moors were driven away from Spain (15th BCE), and through the expansion of the Ottoman empire. Nonetheless, the Christian populations – even those within the Ottoman empire - did not adopt the hammam, in part

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[369] Roman baths involved a number of rooms: the *tepidarium* (warm space, with bathers spending about half an hour there), the *caldarium* (hot, for shorter stays) and the *laconicum* (which was extremely hot and dry, nearly 99ºC, for a very short stay). Bathers would also soap, receive a massage from trained personnel, and plunge into the cold *frigidarium* pool.

[370] The word hammam means *dispenser of warmth* and derives from the Arabic verb *to heat* ("hamma") (Giedion, 1948).

[371] Giedion (1948, 642) likens the difference between these Syrian baths and the Roman thermae to *"what a primitive Romanesque mountain chapel is to the finesse of a Romanesque cathedral"*.

because it was too strong a symbol of Islamic culture. Perhaps more importantly, the west also developed a rather complex relationship to bathing that is worth briefly revisiting, as it helps shine light on contemporary attitudes.

Sweat bathing had spread westward to Europe from Finland and Russia during the late Middle Ages, particularly between the 12th – 15th centuries (Giedion 1948). The practice established itself as a popular social institution and was further developed, giving rise to local variations. Swimming, tub baths, and social bathing – combined with other social activities such as playing music or discussing politics - were common at the time supporting Giedion's assertion that the reputation of the Middle Ages as a dirty era is deeply misguided (see figure 7.37). However, developments in the 16th century caused the practice of sweat bathing to decline in most of Europe besides Scandinavia, Russia, and the Ottoman-occupied territories. A growing population and urbanization made bathhouses less hygienic. Furthermore, the advent of Reformation and Counter-Reformation brought forth a tightening of social morals that led, among other things, to the perception of nakedness as a sin (Tsonis, 2017 and Giedion, 1948). As a result, westerners in the 17th century - and to a slightly lesser extent the 18th century –celebrated the spirit and the mind (as is evidenced by their interest for philosophy, music, architecture and refined living) while at the same time showing utmost neglect for the physical body - an attitude exemplified by the notorious disdain of western aristocracy for bathing.[372] Outside of Europe, the puritan morals of European colonizers, combined with their attitudes towards bathing and the forced Christianization of indigenous populations, pushed the custom of sweat bathing into the underground in many other places (like Mesoamerica) or, at the very least, pressured it to lose much of its ritualistic character.

While we still suffer the repercussions of the prejudiced attitudes of that era, attempts to repair the damage were slowly beginning in the 18th century, to the clergy's fierce opposition, as part of a call for returning to nature (e.g. by Rousseau) and a newly found veneration of ancient Greek ideals that promoted a balance between mind and body (Giedieon, 1948). In the 19th century, the need to live more hygienically became much clearer through the work of Louis Pasteur and Joseph Lister. Bathing also started to shift from being considered part of medicine to a regenerative practice, often with the goal being to clean the body inside-out - a tradition that the west had to reinvent, even though it had always remained vibrant in other nearby cultures.

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[372] Giedieon writes (1948, 654): *"The stunting of the sense for cleanliness and, in the broader sense, for regeneration in the seventeenth and eighteenth centuries is so far as we know a phenomenon without parallel in any other highly civilized period".*

Figure 7.37. Albrecht Dürer's *Women's Bath* (1496), portraying a scene from a Nuremberg vapor bathhouse of his time.[373]

The form of our contemporary bathing facilities, which we take for granted today, was developed throughout the 19th century in Northern Europe. It emerged through the competition of mechanized versions of several forms of bathing – such as bathing with hot air or hot steam in communal baths or at home (which involved sitting or lying down in small one-person cubicles that were typically enclosed for moral reasons), by immersion in a tub, or with running water in a shower (Giedion 1948).[374] Ideas on what a bathroom should look

[373] While Dürer used the bath as a pretext to draw the female nude form in various postures, in doing so he also documented the social aspects of this practice, and the configuration of the bath - simple and primitive but equipped for daily use, with a fireplace, various levels and vessels for hot water.

[374] Giedion remarks that, historically, the popularity of the shower rose together with that of the tub with the two being generally symbiotic (as they still are today). He also writes that, during the second part of the 19th century, many public showers were built as a way to efficiently and cheaply provide enough facilities for the

like became solidified around 1900, introducing the private, convenient, efficient bathroom found in today's homes, at the cost of moving entirely from communal regeneration to isolated ablution. Initially developed in the global North, this mechanized bathroom soon spread to the rest of the world, being first adopted by the wealthier classes who were lured but the prestigious and technologically advanced western ways.

As Tsonis (2017, 82) observes, the shift from bathing as a social regenerative practice to today's swift private routine should be understood within a broader social context as a reflection of *"the atomizing forces of modern capitalism"*. He points out that such systems are essentially built on the exploitation of the bodies of those without power by those in power and thus, predictably, these systems are not too preoccupied with people's wellbeing. With this in mind, he proposes that sweat bathing as a widespread regenerative practice can help address some of the problems contemporary societies are facing, by contributing to *"physical and mental health around the world in a time of increasing stress and social fracture"* (Tsonis, 2017, 41). He adds: *"At a social level, it brings people together. At an individual level, it makes the body feel alive. The world is only getting faster, and the previous century shows that technological progress will only lead to more deadlines. Emancipation from work is a mirage – nothing will change. Instead, societies need to find effective ways to help people regenerate inside this storm of movement. "* (Ibid, 82).

7.4.5 *Working with steam*

Before embarking in the creation of this work, I knew from my research and personal experience that humidity and temperature have an effect on wireless transmission and WiFi signals. As mentioned in section 4.2.6, my first personal experience of this sort was during the documentation of *The Network Is A Blind Space* in 2012, when I noticed that work behaving differently in terms of its sound, but also noticing devices disconnect due to bad signal coverage caused by snow thawing. More recently, in 2015-16, I was repeatedly noticing that changes in humidity and temperature were detuning the *Hertzian Field #2* performing system. During both the development and rehearsal process, it had become an almost daily occurrence that a couple of hours after the sun set and the temperature dropped, the system's sound and behavior would change noticeably, requiring a recalibration of the

booming urban populations to clean themselves. Interestingly, as he points out, the architecture of these facilities in Northern Europe had much more to do with the aesthetics and philosophy of a public urinal rather than a regenerative bath like the thermae, the sauna, or the hammam (Giedion, 1948).

sensing system every time.[375]

The idea I was eager to experiment with in this new piece was the opposite of what had plagued my R&D in the past: instead of making the space colder, like my studio, making it much warmer and incredibly humid - just like a steam sauna. Before proceeding much further with this idea, I conducted a brief experiment to practically verify if hot steam does indeed affect WiFi communication: My experimental setup involved putting two WiFi antennas on two sides of a closed cardboard box (at about 60cm from each other), and using a water boiler to fill that box with hot steam. While the box filled with steam, I monitored the RSSI data with my computer and WIR and discovered that while the change was small it was in fact traceable. Thus I assumed – and hoped - that the piece I had in mind ought to work.

Intrigued, I began my research on sauna-grade steam generators, trying to wrap my head around how to make this piece. Part of this research involved finding a way to calculate the necessary wattage of a steam generator that would be appropriate for the size of the space I had in mind. This involved reading the manuals of multiple steam generators, as well as pouring through guides for wellness and spa centers, given that – as mentioned in the previous section – I could not find any academic sources. This research led me to the following formula, which I used for my calculations (Helo, 2016 and Helo, 2013):

$$Power\ (kW) = V \times K_1 \times K_2$$

where V is the volume of the room in cubic meters, K_1 is a coefficient measuring ventilation, and K_2 a coefficient for the interior material.

The ventilation coefficient K_1 becomes lower the less a space is ventilated, meaning that less ventilation requires less power. A K_1 value of 0.75 corresponds to a space with active ventilation (air conditioning unit or fan) and a value of 0.52 to a space with no ventilation. The K_2 coefficient helps calculate the amount of heat absorbed by the material used to close off the space. It is set to 1 for an acrylic wall and higher for more absorbing materials which thus require more power (e.g. 1.25 for a light wall made of board and tiles, and between 1.5-2 for heavy walls made of stone, concrete and tiles).

Using this equation I calculated the volume and dimensions of the steam room for the work, chose the type of materials, and began looking for an affordable steam generator with

[375] At the time, my studio and living space were in a squat in The Hague without central heating, therefore temperature and humidity changes after sunset were very pronounced.

adequate power. An important practical consideration was that the electrical specs of the generator (its voltage, amperage capacity, and number of electricity phases needed) should be compatible with those of the exhibition venue's power grid. In the end I settled on a 9kW, 380V steam generator, operating on 3-phase power to be more efficient.[376] This proved to be a good enough size for the space, particularly when the exhibition venue has central heating.

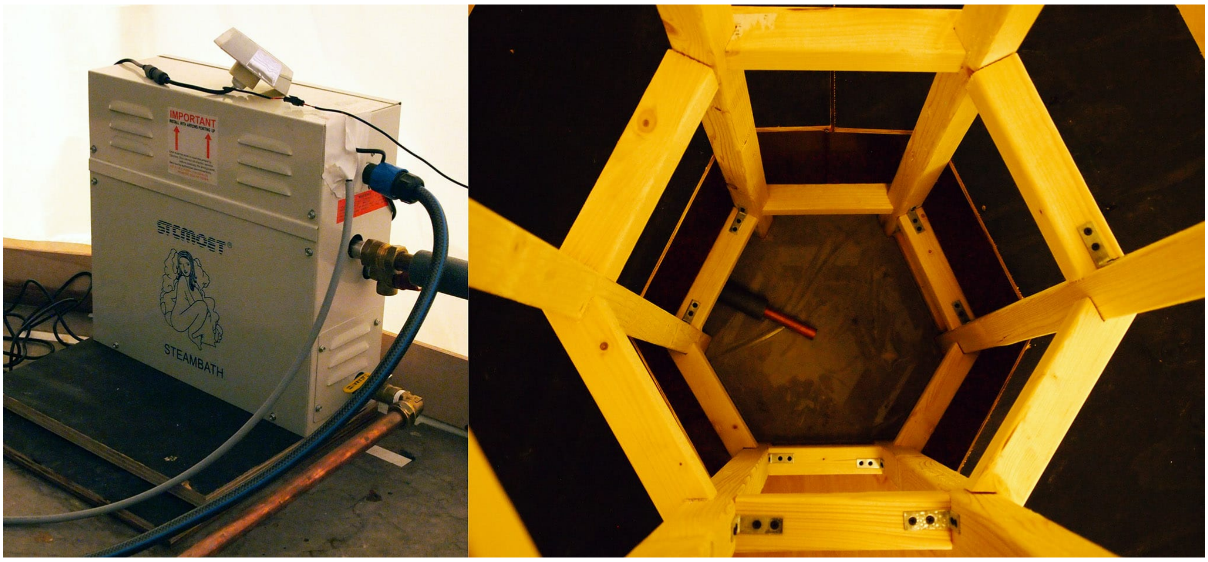

Figure 7.38. *The Water Within (Hertzian Field #3)*: Steam generator (left) and copper pipe bringing steam through the central column of the room (right).

Preparing to install the work involved additional considerations. Working with steam is not exactly child's play, as there are some significant health and safety concerns to take into account. The generator is a high voltage device and one needs to make sure that it is correctly configured so that there is absolutely no chance that condensation leaks into the circuitry. Furthermore, when designing the plumbing for the piece it is very important to eliminate any loops in the piping, and to not create areas where water or condensation can gather for too long. This is because of a type of bacteria that grows in places were warm water gathers, such as coils in plumbing or U-shaped pipes (for the same reason, it is also important to be able to

[376] After much research, I ordered the device from an ebay seller from China. When it arrived I was very puzzled to see a metallic box with a bunch of unmarked pipe outlets from different material but without any cables, switches, or even a manual. There was a circuit-board inside, and a control interface that could be plugged to the device, but nothing else. I educated myself by devouring dozens of manuals from other generators to understand the general installation principles and what I needed to do with my generator to get it to work. Eventually, I acquired an – apparently very poorly written - manual in Chinese from the vendor which Ping-Hsiang Chen, my Taiwanese architect collaborator, could thankfully translate thus helping me verify what each pipe was meant for (i.e. which was the water input, steam output, safety pressure valve, and water outlet for cleaning out the machine after use). Then, to generate steam with the device, I first had to educate myself on 3-phase electricity, as I needed to safely wire a cable feed and an on/off switch to the generator in order to test it. This also involved cultivating some plumbing skills and asking the help of a handy friend to connect the device appropriately.

flush the water from the steam generator after daily use). These bacteria can cause Legionella, a type of severe pneumonia also known as *Legionnaires' disease* ("Legionella", 2022).

Having worked through and sorted all these matters, the final design of the steam room places the the steam generator outside the right-hand side of the structure, raised some centimeters from the floor. Steam is led into the structure's central column through a copper plumbing pipe that passes under the floor. This pipe is out of reach so that it cannot be accidentally touched by visitors (figure 7.38).

7.4.6 *The steam room: structure and design process*

Since the beginning of my experimentation with wireless communication technologies, I have been very interested in investigating how they interact with architecture. This interest first materialized in - and was further fueled by - *The Network Is A Blind Spac*e, which in a way a performed a site-specific exploration of an architectural space through its effects on WiFi communication. The setting for my following wireless works was much simpler architecturally, however, partly because those pieces were designed to live within rooms, rather than buildings: '*Act so that there is no use in a centre'*, *Hertzian Field #1* and *Hertzian Field #2* all operate in the architecturally 'flat' and neutral space of a stage or of a large room, like a gallery. Generally, the installation area for these works is open, level, and empty of other objects outside the system's nodes.[377] Movement in these spaces is supported by visual cues such as the placement of nodes, lighting and markings on the floor, but is guided primarily through sound. As such, the 'character' of these spaces is defined almost purely by the configuration of the hertzian transmission/sensing system and by its interaction with the body, which is experienced through sound.

However, after completing the first two *Hertzian Field* works, I was keen to explore the potential of the WIR system in an architectural space specifically designed for it. The idea of a reactive steam room was an excellent impetus for this investigation. I imagined creating a work where visitor behavior and movement would be guided not only by sound and visual cues, but also by the space itself – its architectural features and the way it contains and guides steam. The collaboration of the *Modern Body* initiative with Dezact architecture platform and the festival theme *I/WE/THEY* provided the perfect circumstances to realize this exploration,

[377] The 2019 showing of *'Act so that there is no use in a centre'* is an exception to this, as it was exhibited in a space with multiple levels. See figure 4.11.

in both practical and conceptual terms. Therefore, I invited architect Ping-Hsiang Chen, co-founder and producer of Dezact, to help me realize the work by designing a space that would form an integral part of the experience.

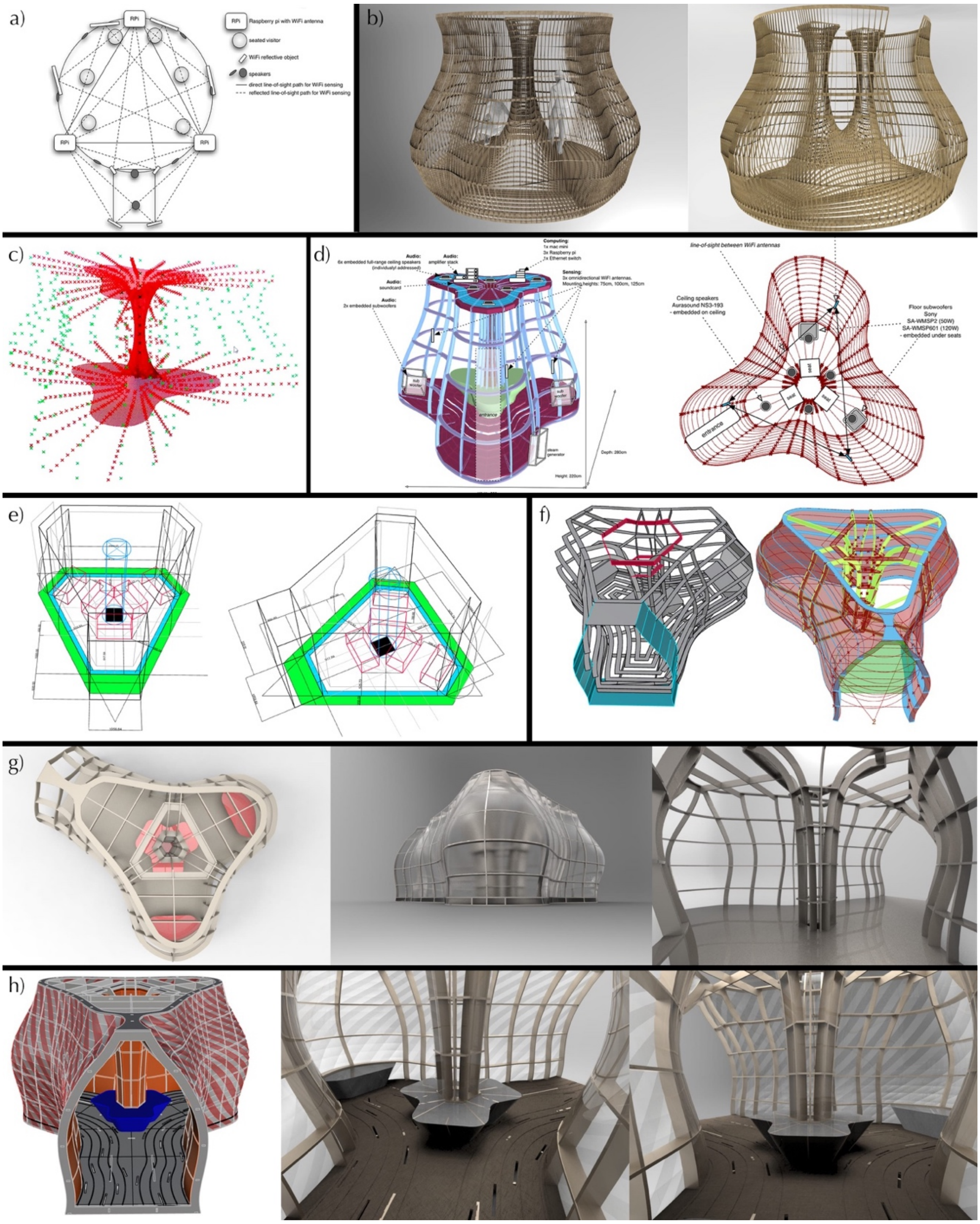

Figure 7.39. Progressive iterations of the design of the steam room for *The Water Within (Hertzian Field #3)*: (a) initial prompt sent to architect Ping-Hsiang Chen; (b) first proposal by Chen with two options; (c) redesign of the steam column following feedback; (d) complete design by Chen, followed by my marking of the placement of electronics. Bifurcation of designs: (e) first iteration of a geometrically simplified design; (f, g, h) consecutive iterations of a more complex design requiring CNC fabrication.

As a starting point, I provided Chen with:the following: a) a preliminary schematic of the system's electronics and their configuration (sound, light, sensing, and steam), b) a spatial diagram giving a rough idea of the shape of the space I had in mind and the placement of all electronics within it (see figure 7.39a), and c) a set of guidelines. These were the following:

- The structure (i.e. the steam *room*) should be able to contain steam inside it so that it can get as hot as a wet sauna / hammam.
- It should be large enough to accommodate up to about 6-8 people at a time, with enough seats and open space to move around.
- It should be no taller than 2.5 meters, so as to minimize the overall volume of the space and with that the steam generator power requirements.
- The structure ought to be modular, re-usable, and relatively easy to build-up, breakdown, transport and store, so that the work could be exhibited again.
- All exhibition visitors ought to be able to see the structure or part of it from the outside and to hear the sound it generates, without having to enter the steam room or partake in the entire experience.
- The room's walls should be opaque for privacy as well as aesthetic reasons; one should be able to see the structure's form from outside, but not what is inside. The walls could nevertheless be a bit transparent, so that one could discern diffuse shapes, light, and perhaps the presence of steam from the outside, but not enough to clearly see or identify any of the human bodies inside.
- The electronics – sound, lights, computing, WiFi sensing - should ideally be embedded into the structure.
- More practical elements ought to also be considered, such as devising a way to drain condensation and water gathering inside the steam room.[378]

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[378] Exhibiting the work involved a number of additional logistic considerations. For example, the space from which visitors would enter the steam room had its own set of requirements, with privacy concerns being the most important. These included:

- This 'foyer'/changing room should be closed, without visibility from the rest of the gallery. Only visitors coming in or out of the steam room should have access.
- It should be configured so that visitors feel comfortable to undress, shower, and enter the work. There ought to be a place with chairs or benches where visitors can change to a towel and leave their clothes.
- There ought to be a closed shower in that space or very nearby for visitors to use with privacy.
- While I, Chen, and the festival initially hoped that this 'changing room' area formed part of the architectural design, this was in the end not possible as there was neither enough time to design and build it, nor enough funds and helping hands. As such, every time the work is exhibited, this area is configured in a more informal manner that takes into account the specific layout of the site. So far, this has involved curtaining off part of the exhibition space, bringing in benches or seats and installing a shower cabin (with plumbing being the most challenging part).

Taking into account all these parameters, Chen began working on a design. His initial idea involved building a Lego-like frame, in which the different parts of the structure would be machined out of plywood with a CNC mill so that they easily snap together. While the form was both beautifully organic and functional, the design was unfortunately too costly for the budget available through our independent festival, as it required around 50 sheets of plywood and many milling hours. Chen and I also had to discard a subsequent idea, 3D printing connector joints, as there was neither enough time nor access to facilities that could produce them. We worked together through various iterations, constantly balancing our wishes with practical requirements, logistics, and budget limitations (figure 7.39b-h).

The process was greatly facilitated by Chen's skillful use of parametric design, which enabled him to easily adjust the size of the structure as well as the complexity of its form. He developed a system that split the structure into three independent layers:

a) The primary layer, a wooden structure around the central steam column which also functions as the structure's basis
b) the secondary layer, consisting of the floor and ceiling
c) the outer layer, or walls, consisting of a heat resistant and water blocking material acting as a 'skin'

These layers could be adjusted and fine-tuned independently. Chen used serial parametric optimization to find forms that maximized structural integrity while minimizing the required material, thus making the structure easier to build and giving it a more 'airy' feeling.

The final design significantly simplified the form to a more minimal geometry that required a minimum amount of materials and which could be built on-site using standard power tools (figure 7.40). We fabricated the structure on the exhibition site with the help of a small crew of volunteers (figure 7.41).[379] The framework consisted of pine wood beams that Chen cut to the right sizes and angles using a jigsaw and a mitre saw. These beams were fastened together with metal L-bars and screws. The floor was made out of plywood sheets, cut with a plunge saw. All seats and speakers were also made with a plunge saw, using recycled plywood from

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Another practical issue was finding enough towels so that exhibition visitors could experience the work. One cannot, of course, expect festival or gallery visitors to bring their own towel. Thus, being offered a clean towel becomes part of the ritual of experiencing the work. Being underfunded, neither the festival nor I could afford to purchase enough towels for the work. Stephanie Pan, *Modern Body Festival*'s ever-resourceful producer, came through with a solution: After placing many phone calls to a number of hotels, she found a linen service that was happy to donate us over a hundred white towels that were no longer hotel-grade, but still quite new.

[379] The structure was built by Ping-Hsiang Chen, and myself with precious help from festival co-director/producer Stephanie Pan and volunteers Dave Kalle, Gijs Termorshuizen, Djurre Kooistra, and Johannes Fischer.

an old theater set that had been donated to the festival.

Besides the structure, compromises also had to be made in regard to the skin layer. Chen's initial concept involved using bendable plastic and then fabric – the first layer to contain the steam inside the structure and the second to embed and hide all electronics. This concept was eventually reduced to a single layer of parachute fabric, a minimal but very effective solution suggested, designed, and sewn together on site by Stephanie Pan. The electronics were moved out of sight, hidden on the ceiling of the exhibition space.

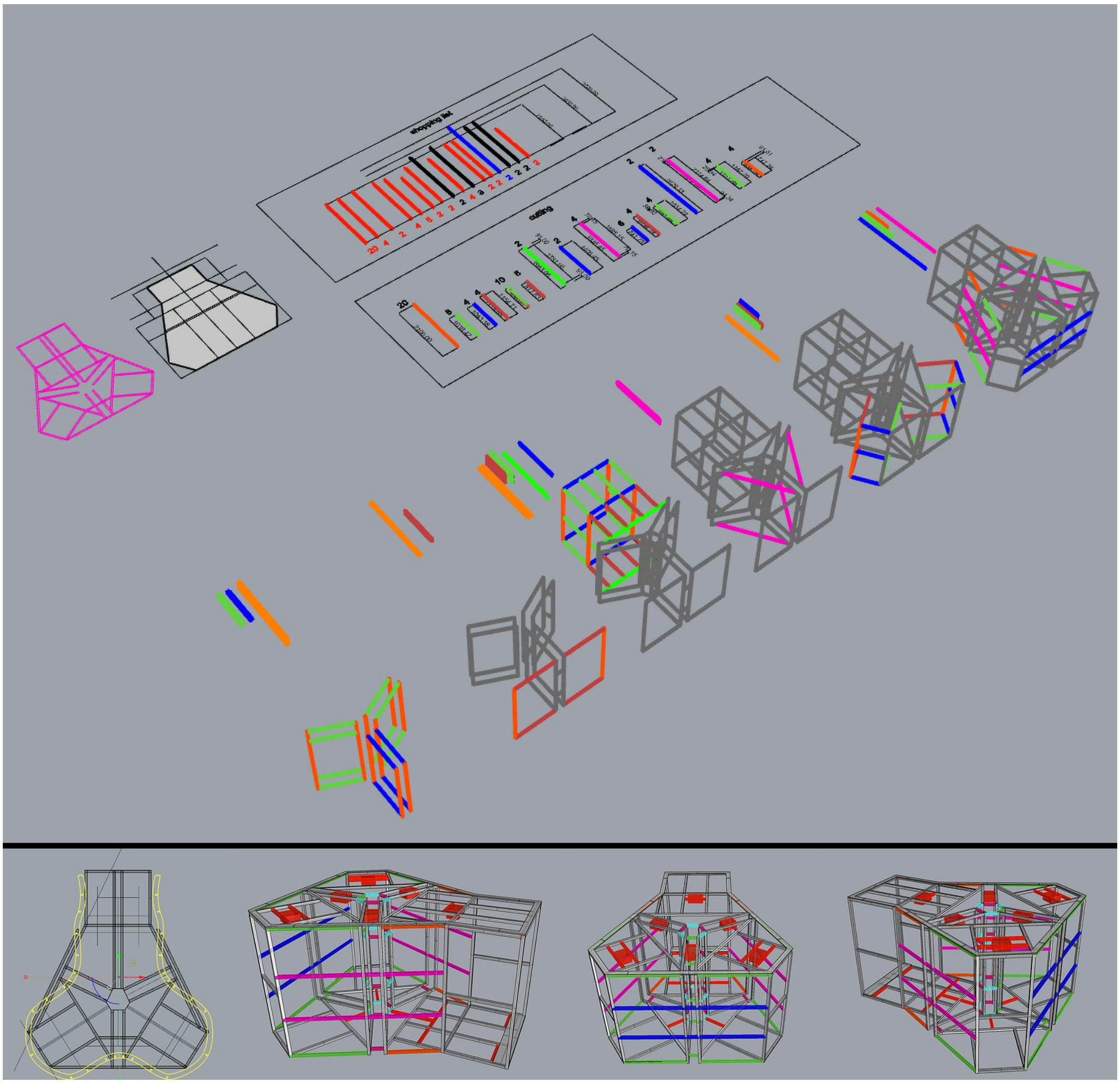

Figure 7.40. Final simplified design of the steam room for *The Water Within (Hertzian Field #3)* by Ping-Hsiang Chen. The top image shows the assembly plan. The first image in the bottom row superimposes the geometrically complex to the simplified design; it is followed by 3 different views of the final design.

Figure 7.41. On-site fabrication and buildup of *The Water Within (Hertzian Field #3)* steam room during *Modern Body Festival 2016.*

7.4.7 *Sensing system configuration*

In order to investigate and better understand the effects of steam, I decided to work with a hertzian configuration I was already familiar with: a triangle formed by 3 nodes placed at different heights. This was similar though not identical to *Hertzian Field #2*, as the triangle in *The Water Within* is scalene not isosceles. The structure was designed with this layout in mind, hence its final shape and seats placement. The asymmetrical positioning of the nodes in a scalene triangle offsets the system so that the Lines-of-Sight of the 3 nodes dissect the seats and the room's walking paths instead of its middle point, where the steam column is located. Furthermore, in this manner the center of the field, where the 3 transmissions are equally powerful, takes up spots that can be occupied by visitors as well (figure 7.42).

The tallest node is placed right by the entrance to produce a sensitive zone in that area. With its antenna at a height of 167cm, this node is set to pick up movement from bodies that are walking or standing, rather than sitting. Anyone entering the steam room crosses diagonally through the outer and inner Fresnel zones of the field around that node, thus generating strong interferences that are modulated as they cross through different zones. This destabilizes the system and generates an audible response, which I felt was important both for the person entering, as well as for those already inside.

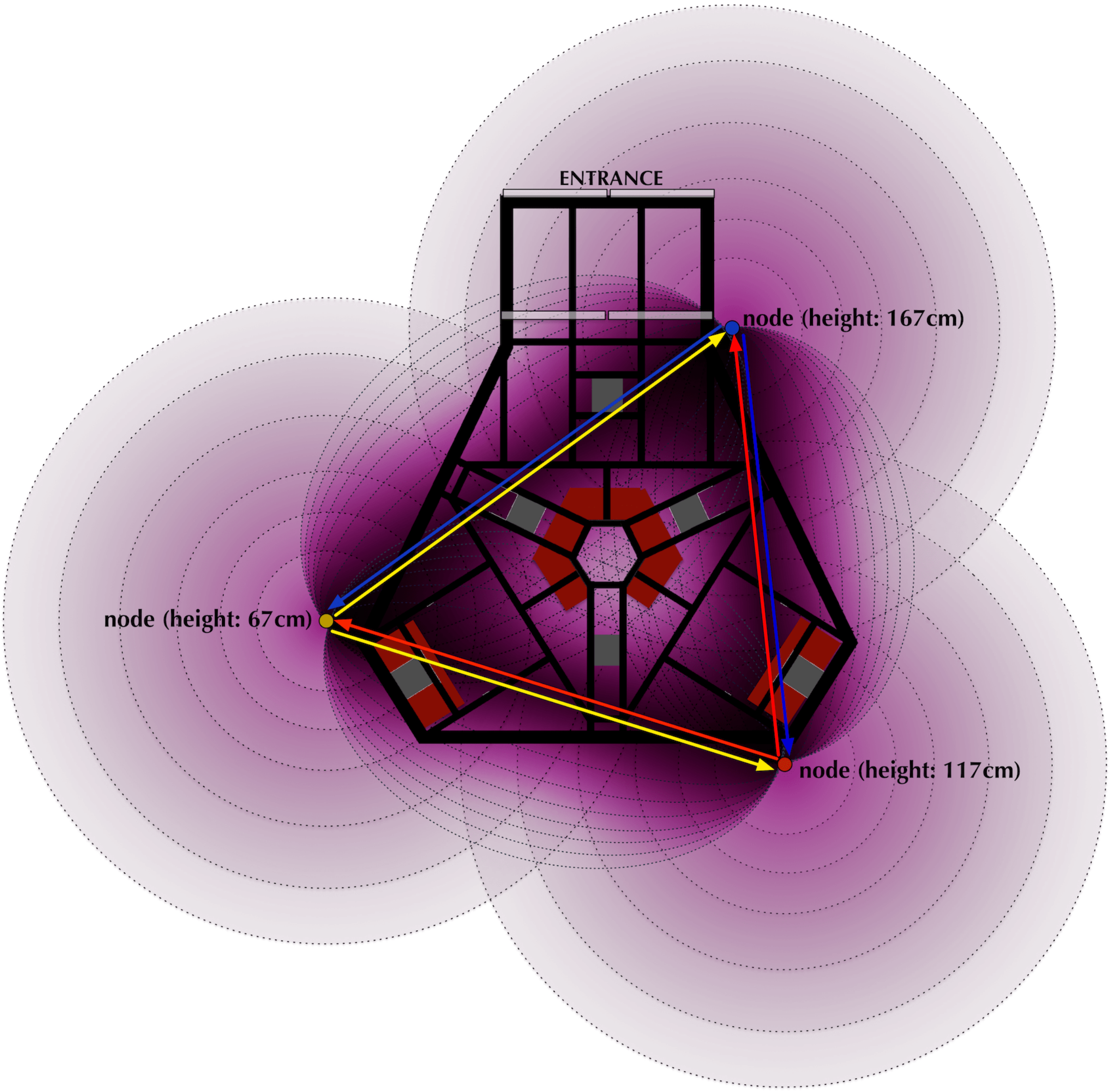

Figure 7.42. Spatial configuration of the sensing system in *The Water Within (Hertzian Field #3* and *#3.1)*: the diagram shows a simplified visualization of the transceiver fields (concentric circles), their Lines-of-Sight (arrows), and their most sensitive Fresnel zones (concentric ellipses).

On one hand, having this sonic response as a first reaction of the system when visitors enter contributes to the initial jarring sensation they feel as they come in, caused principally by the dense steam, heat, and light they encounter. As visitors step inwards, the continuing response clearly suggests that the work reacts to presence and movement; the complexity and non-linearity of the response also suggests that there is some form of agency involved. On the other hand, I also wanted the system's response to be a sonic manifestation of the momentary psychological/mental tension that the visitors already inside may experience upon the entrance of a new person in the space. This is a situation I have both felt and observed firsthand in normal saunas and steam rooms: The stillness and concentration of everyone in the room (their motions minimized as heat has taken over their bodies) and the familiarity built within minutes of sharing such a small and intense space with a group (each person having found their own place and having gotten accustomed to others' near-naked presence) always become sharply disrupted for a brief moment when someone new enters and at least until they have found their seats. By placing a node by the entrance, the system augments this sensation through sound.

The other two transceiver antennas are positioned on the left-hand side of each corner seat, one at a height of 67cm and the other at 117cm. They are not placed directly behind the seats, as in that case their LoS and all inner Fresnel zones would get completely blocked by the torso of the seated person; that would reduce their resolution to near binary – essentially an on/off switch. Instead, offsetting their placement allows the system to keep a 'microwave eye' on the rest of the space. From their vantage points, they can scan the seated bodies near them diagonally, while retaining some unobstructed view of the open space/pathways and the other seats. This placement makes them particularly sensitive to the acts of seating and standing - as the body then crosses through a number of Fresnel zones - and to small motions when a visitor shifts around their seat. Movements of the torso, shoulder and arm produce very strong interferences as well, which can be heard as well as felt haptically through the vibrations of the subwoofers placed under these seats.

Figure 7.43. *The Water Within*: An evolving approach in mounting transceiver antennas: In the 2016 iteration the antennas were attached directly to the structure (left). In the 2018 version, the transceiver nodes were mounted on stands next to the structure, putting them safely out of the reach of participants (right).

In the first iteration of the work, in 2016, I attached the antennas on the structure (figure 7.43, left). This proved to not be an ideal strategy, however, as visitors would sometimes bump them when they sat, so the antennas would get accidentally moved slightly out of position during the exhibition. This detuned the system and made it less sensitive until it was manually recalibrated. To solve this problem, in the 2018 iteration I mounted the nodes on stands a couple of wavelengths away from the structure (about 25cm). That version was experienced as a cave-like environment, with visitors only seeing the entrance of the steam room from the outside, therefore the stands and nodes were not visible.

7.4.8 *Immersive sound diffusion*

Like the design of the structure, the design of the sound diffusion system also went through a few iterations and was a result of compromise. My initial concept involved embedding speakers in the structure itself and having sound resonate through it, so that it would feel like the sound comes from the structure itself rather than from speakers. I imagined this would be achievable, for example, by using hollow pipes for the frame, or if we were to build hollow columns from wood that could double as speaker boxes. At these early stages, I also investigated the potential of creating intricate acoustic resonators via 3D printing to improve the sound quality of such embedded speakers. However, all these ideas would make the design much more complex than the available time and finances permitted.

Ultimately, my solution was to design an idiosyncratic embedded 6.2 soundsystem, consisting of 6 integrated full-range speakers projecting sound from above, and two subwoofers. The full-range speakers were custom-designed to fit on the structure's frame, and were fabricated from the same plywood as the steam-room's center seats.[380] They are simply fixed on top of the frame outside the skin layer, face down, thus becoming part of the ceiling (figure 7.44). The subwoofers are commercial boxes repurposed from second-hand off-the-shelf home cinema sets. They are placed inside the hollow corner seats of the steam room, laying on top of the wooden floor. This 6.2 setup creates an immersive and balanced soundfield, while additionally transferring acoustic vibrations through the seats and floor of the structure that are felt haptically.

[380] The speakers were designed around the Aurasound NS3-193 3" driver with the help of my brother, sound and acoustic engineer Dionysis Manousakis, using the BassBox Pro software (http://www.ht-locus.com/). They were fabricated on location during the exhibition's build up. For the technical specifications of the Aurasound driver, see https://www.madisoundspeakerstore.com/approx-3-fullrange/aurasound-ns3-193-8a1-3-black-cone-wide-range/. Both websites last accessed 29 December 2022.

Figure 7.44. Images of the fabrication process of the embedded speakers for *The Water Within (Hertzian Field #3)* during *Modern Body Festival 2016*: From schematics, to building their cabins from leftover plywood, to adding drivers and cables, to mounting them to the structure.

During the work's R&D process, I installed an approximation of this 6.2 setup in my studio, hanging an array of small speakers on the ceiling and coupling them to a subwoofer to test various possible diffusion and spatialization algorithms. My aim for this piece was to create a fully immersive sound environment in which visitors felt they are bathed with sound – like they are with microwaves and with steam - rather than creating a perfect listening situation at a sweet spot. Moreover, I wanted the system to produce a clear, full, and balanced sound image of the entire soundscape at all listening points within the steam room, while still giving the sense of sound enveloping the entire space and moving within it. I briefly considered using *Vector Based Amplitude Panning* (VBAP), an extension of stereo panning for multi-speaker setups (Pulkki, 1997). VBAP works very well for point sources and for moving sound in space with defined trajectories, and I had achieved very satisfying results with it through the ceiling-mounted quadraphonic sound system of *The Network Is A Blind Space.* However, rather than *moving* sound sources as in that piece, I felt that using a similar strategy as in the other *Hertzian Fields* would be more successful: i.e. creating an immersive and dynamic soundscape by *placing* multiple *static* sound sources in space, and modulating their sound using interference data from the WIR sensing system so that the soundfield in the room moves in response to the flows of visitors and steam.

As a result, the technique I decided to use for spatial sound diffusion is ambisonics (Zotter and Frank, 2019); or rather an improper - at least by the book - application of ambisonics that worked really well in this configuration and for what I wanted to achieve. The speaker configuration is unorthodox for this spatialization technique, with the speakers placed above the audience, all on the same level and facing downwards - instead of being placed in a ring around the space, facing each other in diametrically opposite pairs as is the standard for a 2D ambisonic system. Furthermore, the ceiling is fairly low and thus the speakers are closer to the visitors' ears than in a normal ambisonic setup. Typically all this would be a problem: In ambisonics all speakers work together to create the soundfield; they all play all sounds but with amplitude and phase variations depending on where the sound source is placed in the ambisonic field. This means that when listeners are closer to one speaker they perceive most of the sounds to be coming from that speaker. This is the so-called *proximity effect* and a weakness of the technique in most situations, which however proved to be a welcome feature for what I aimed to achieve in this work.

In the end, and after experimenting with a more 'proper' ambisonic encoding of the ceiling as a dome, I decided to treat this unorthodox speaker layout as a normal 2D ambisonic ring, because that produced the effect I desired. The system uses two separate decoders, one for the ceiling-mounted speakers and another for the two subwoofers. The ceiling diffusion is encoded as a circular soundfield (2D First Order Ambisonics), with each speaker's output decoded according to its distance and angle from the center of the structure. The subwoofer diffusion is generated by applying a series of transformations to the ambisonic field - rotate, dominate, and direct - to extract the sound of the soundfield at the location of each speaker (for more on these transformation techniques, see Anderson, 2009 and Lossius and Anderson, 2014). Among other effects, the result is that movement closer to the subwoofers, near the corner seats, will typically introduce more low frequencies in the soundfield.

In all other respects, my strategies for linking the presence and movement of water molecules to sound in space is very similar to those use in *Hertzian Field #2* (discussed in section 7.3.3), therefore I will not discuss them again.

7.4.9 *Sound, mapping, and score*

Both iterations of *The Water Within (Hertzian Field #3* and *#3.1)* share most sound generators and processes with *Hertzian Field #2*. Therefore I will only briefly discuss one of the central sound processing modules that were developed specifically for this work (for the rest, refer to section 7.3.4). This new module processes an input audio signal to generate a variety of sonorities, ranging from soft resonant drones, to wave-like bass rumbles, to dense fields of sound events reminiscent of water-drops. Apart from its sound, this module also produces a serendipitous non-sonic effect in its low frequency register: the cones of the speakers mounted on the ceiling cause the fabric of the 'skin' layer to vibrate, shaking loose the condensation formed by the steam and gently showering those directly under the speakers with actual water droplets – often as accompaniment to droplet-like sounds.

This process consists of a perceptually-modeled array of spectral feedback-delay filters. It is built around a bank of 25 parallel second-order bandpass filters coupled to delays. These filters are tuned according to the *Bark scale* - a psychoacoustics model designed to emulate how the human ear differentiates sounds at different frequencies (Zwicker, 1961).[381] The relationship between the bandwidths of these filters is fixed so that each filter appears to occupy a perceptually equal bandwidth regardless of center frequency. Audio input passes through this filterbank and is split spectrally into 25 bands. The output of each filter is then fed into a separate delay line, whose delay time, amplitude, and internal feedback coefficient (i.e. how much of the output of the delay is fed back directly into its input) can be set individually. Subsequently, the sound of all filter-delay pairs gets mixed back together, then is 'sanitized' by a DC-blocking filter and a limiter, and finally is routed to the output of the module. From there, it can be sent to the ambisonic decoder and then to the speakers, to another process in the feedback network, or even fed back to its own input. Twelve instances of this process are activated during the piece, placed symmetrically around the ambisonic soundfield at an angle of 30° from each other.

These processes are controlled by the WIR system using 4 different receiver-transmitter combinations (*Blue-tracking-Yellow*, *Yellow-tracking-Blue*, *Red-tracking-Blue*, *Blue-tracking-Red*). Each process is controlled as follows:

- Each of the filters in the bank is mapped to features extracted for a specific frequency

[381] Acoustics scientist Zwicker introduced the Bark scale to subdivide the frequency range of human hearing into a set of critical bands. The SuperCollider pseudo-UGen used for this filter was coded by Josh Parmenter.

of motion. In this manner, slow movements control low frequency filters, and fast movements high frequency filters. More specifically:

  - The *gain* of each filter is controlled by the *spectral magnitude* of the RSS FFT bin corresponding to the specified speed of motion. The result is that the fastest a body moves, the louder the higher part of the spectrum will be, with slow movements producing more energy in the low end.
  - Similarly, the *internal feedback amount* for each filter-delay pair is controlled by the *cepstral magnitude* of the corresponding FFT bin of the analyzed RSS. High rate of change at a particular frequency denotes erratic movement at that particular speed; the more erratic the movement, the more the delayed output of the filter will be fed back into itself, producing a stronger resonance at that frequency.

- The *delay times* for each filter are randomized every time there is a sudden motion, which produces a distinct sonic effect - as if a lot of water droplets are falling on a metallic surface. Technically, this happens when the *standard deviation* of the RSS exceeds a threshold.
- Similarly, when a new gesture begins – i.e. when an *onset* is detected, or more technically, when the *derivative of the RMS slope* (i.e. the slope of the slope) exceeds a threshold – the frequency of each filter is multiplied with a random factor, causing it to deviate around its central frequency with a brownian walk.

In contrast to the other *Hertzian Field* works, in the 2018 iteration of *The Water Within (Hertzian Field #3.1)* I also incorporated a non-synthesized, non-reactive sound source: field recordings from the *Taroko Gorge National Park* in Taiwan, which I made during Space Media Festival in August 2016. These sounds create a cooling and calming effect, giving the sensation of being immersed in a vibrant but peaceful natural space.

Taroko is a gorge formed by a river (Liwu) cutting through marble rock – a material that very subtly colors the recording. On either side of the river there is lush subtropical vegetation, inhabited by a plethora of cicadas and birds all singing their hearts out (figure 7.45). The soundfile used is surround, it lasts 9.5 minutes, and contains 6 different recordings I made while standing and walking the trail next to this river. The soundscape consists mostly of bird- and cicada-songs; it also contains some water sounds from the river flowing in the background - more present in the first quarter of the recording - and the sound of my footsteps towards the end.

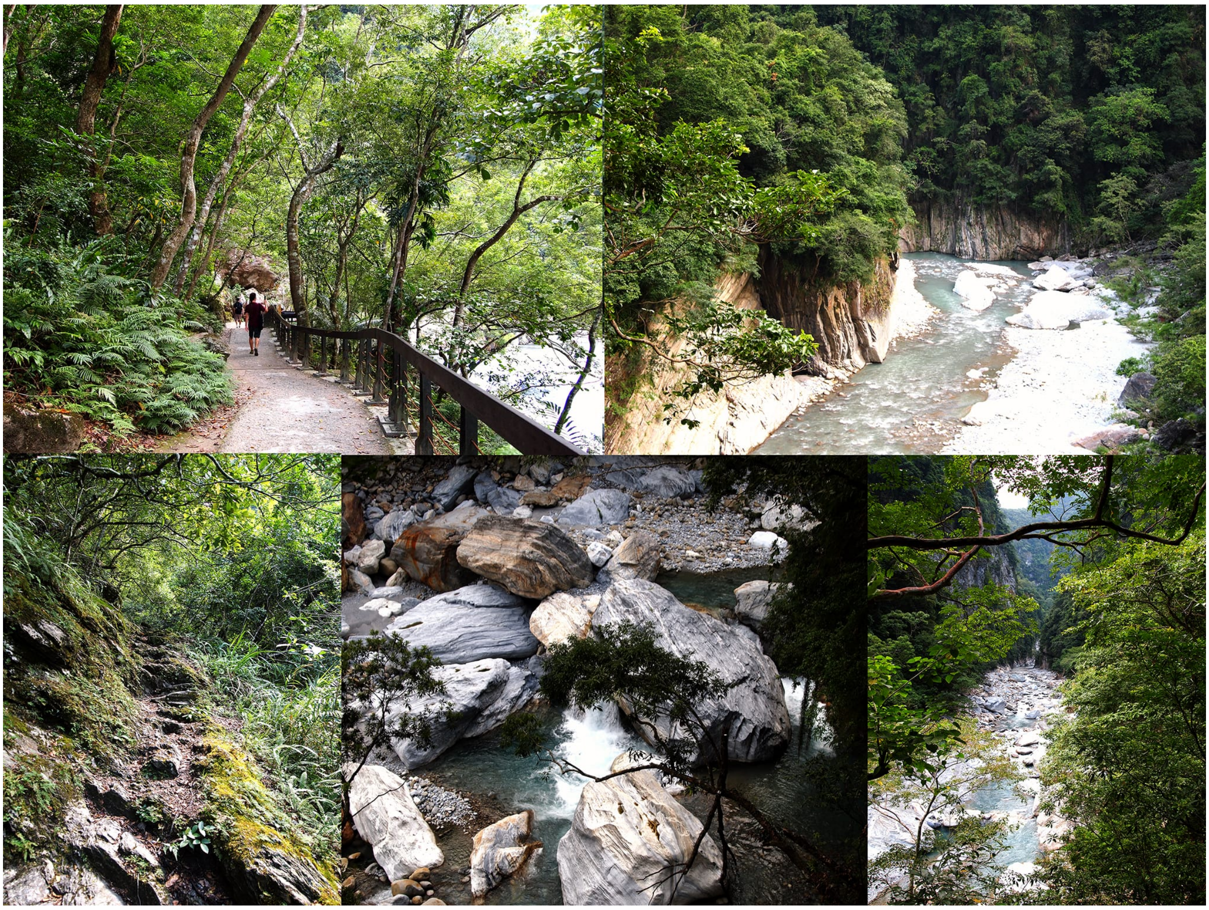

Figure 7.45. Photos from *Taroko gorge*, the site of the field recordings included in *The Water Within (Hertzian Field #3.1)*.

An automated score is used to run the piece. This score is a pre-composed sequence consisting of a number of 'scenes' - 4 in the 2016 version and 12 in the 2018 version. Similarly to *Hertzian Field #2*, the code of these scenes defines the following elements in static or dynamic manners:

- Fading in and out all sound processes.
- Modulating how these processes are mixed together to produce the soundfield.
- Setting how these processes are routed in the feedback network, i.e. their inputs and outputs.
- Controlling synthesis parameters and their mapping. This includes:
  - setting parameters to a certain configuration – like selecting a 'preset'
  - scaling or modifying the output of extracted WiFi-sensing features and mapping them to synthesis parameters for interactive control
  - setting-off dynamic pre-composed gestures (e.g. a gesture that takes 2 minutes to unfold and which modulates a specific parameter, like reverberation amount).

- Additionally, in the 2018 iteration, the score also includes lighting cues that control the hue and intensity of 4 RGBW LED lights. This typically involves smooth fading gestures that change the intensity or hue slowly over a number of seconds.

7.4.10 *Lighting, and strategies to withstand heat*

Lighting is an important element of the environment of *The Water Within*, contributing to the overall experience. For the first iteration of the piece, me and Chen initially discussed embedding LED strips in the structure, which would be controlled via an Arduino microcontroller. My early thoughts about lighting involved creating monochromatic spaces, possibly shifting through different hues but mostly playing with light intensity.

However this was not achieved in 2016, due to – yet again - timing and budget restrictions. Instead, for that version of the work I implemented a simpler non-embedded solution, which involved mounting 3 static lights with a warm yellowish-white hue above and a few meters away from the structure. Two of these lights were spots pointing into the steam room; to those inside, they appeared as diffuse and hard-to-pinpoint light sources coming from the horizon. Steam accentuated them, producing a really interesting disorienting effect. An additional flood-light was placed in front of the entrance, shining bright on the eyes of visitors when exiting the steam room to exacerbate the disorientation felt by the sudden change of environment and temperature, and to function as a marker of the experience ending, and normalcy starting once again.

Having more time to work on a light plan in 2018, I designed a new configuration, more integrated and with more possibilities in terms of color, intensity, and dynamic control. For that version of the work, I placed 3 RGBW LED floodlights on the rooftop, pointing upwards to the ceiling of the installation room. The steam room was thus lit uniformly from above by the reflections diffused by the containing room. This was perfect for the smaller, low-ceiling space that hosted the work in its 2018 showing - light reflectors may be needed to achieve a similar effect in spaces with higher ceilings. This triplet of floodlights was accompanied by an RGBW LED spotlight mounted a few meters away from the back of the steam room. This light pointed on the rear side of the steam room creating a circular light source that appeared to be far in the horizon - like an artificial sun. An RGBW floodlight placed in front of the entrance, like in the 2016 iteration, could also be added but was omitted in the 2018 showing as there was enough light shining into the entrance from the changing room that led into it.

Figure 7.46. *The Water Within (Hertzian Field #3.1)*: Photos showing the inside area of the steam room illuminated by different light configurations throughout the work. These pictures were taken without much steam for clarity; the two photos on the bottom right are more representative of how low the visibility can get inside the steam room.

Control of these lights is achieved via the DMX (Digital Multiplex) protocol, a digital communication standard for controlling lights and visual effects ("DMX512", 2022).[382] The ceiling lights are addressed as a unit, always producing the same hue and intensity to provide uniform illumination of the space. The spotlight is independent; sometimes it has the same hue as the ceiling lights, others a complementary one, and others it is switched off. The lights change color and intensity slowly throughout the piece. WiFi sensing is not used to control them at any moment, because I wanted lighting to be quite specific and changes in hue and intensity to be very smooth - nearly imperceivable in most cases. As such, light changes are predefined and form part of the composed automated score. Figure 7.46 contain snapshots of the light progression throughout the piece.

Following a fairly dark beginning in deep purple hues – somewhat resembling the dim illumination of the time just before daybreak - the light generally progresses from warmer to cooler hues.[383] This is part of an intentional strategy I developed for the piece, which involves using increasingly cooler light hues and sounds – such as the 'droplets' of the process discussed in the previous section and field recordings - to help visitors cope with the increasing sensation of heat they feel the longer they spend in the steam room. I conceived this strategy intuitively and as a kind of experiment. It was informed by my own personal experience in saunas and steam rooms (and in very warm and humid weather), by my experience in the particular steam room while developing the work, and by anecdotal testimonies from a few friends and their own experiences. Informal discussions with some participating visitors during the work's presentation verified my hypothesis that color and sounds do in fact help make the intense heat more bearable as time passes.

Having more time to research literature on this subject while writing this dissertation, I found that there is indeed mounting evidence of a cross-modal connection between these three different sensations – thermal, visual, and acoustic - all of which appear to influence one another. A number of experiments support this hypothesis, although it should be pointed out that many of them are based on limited numbers of participants (often students) and many take place in controlled environments. Still, there is an agreement across multiple studies on there being interesting complex interactions between these sensations.

The connection between the sensation of temperature and the color of visual stimuli – known

[382] The lights are controlled by the software via an Enttec Pro DMX USB interface (https://www.enttec.com/product/lighting-communication-protocols/dmx512/dmx-usb-pro/).

[383] Warm colors are those at the lower end of the visible spectrum (towards red) with lower frequencies and longer wavelengths. Cooler colors (towards blue and violet), have higher frequencies and shorter wavelengths.

as the *hue-heat hypothesis* - has been investigated for nearly a century (Mogensen and English, 1926). Various experiments during this time have produced some ambiguity over the veracity of this hypothesis. This ambiguity however is most likely owed either to the subtlety of the effect – for instance, a study by Fanger et al. (1977) found that subjects preferred ambient temperature to be 0.4° Celsius higher in a room with blue lights when compared to one with red lights – or, according to Ziat et al. (2016), because older experimental methods were imperfect. More recent studies have in fact demonstrated a stronger relationship between *color temperature* and *thermal sensation* (essentially how hot a space feels) or *thermal comfort* (if a particular temperature feels comfortable). Subjects of these studies have considered warm colors preferable in cold environments and cool colors preferable in warm environments, as they produce a sensation of warmth and coolness respectively (see Albers et al., 2014; Ziat et al. 2016; and Wang, Liu et al., 2018).[384]

The influence of sound in this regard has been studied more crudely than light, and typically in a quantitative rather than qualitative manner. Most relevant research originates in the fields of environmental studies, architecture and city planning and is as such primarily concerned with how the sensation of comfort, or lack thereof, is affected by heat, visual stimuli (particularly illuminance) and sound levels. In regard to acoustic studies in particular, most often the sounds investigated are unwanted background noise - such as traffic, noise from fans or other machines, and noise from other people like conversation or other sound-producing activities. There are also a few pertinent papers with qualitative examinations of sound, including a study by Yang and Moon (2019) in which they found that recordings of water sounds positively affect the sensation of thermal comfort in higher temperatures (thus supporting my intuition about the cooling effects of such sounds included in *The Water Within*). Conversely, they also found that temperature affected the perception of sound. In another study relevant to this work, Jin et al. (2020) found that different types of sounds (e.g. birdsong, dog barking, conversation, traffic, slow and fast dance music) have different effects on how we perceive environmental factors like temperature. Interestingly these effects change depending on season. Most pertinently, birdsong in summer temperatures in particular – a combination of special interest for my installation – appeared to improve the sensation of thermal comfort, i.e. making weather feel cooler.

While in the past most such research looked at the influence of one sensory factor at a time,

[384] Interestingly, Wang, Liu et al. (2018) also detected physiological indications of this relationship, namely: a) an increase in heart rate with warm temperatures and/or warm colors, and b) a linear correlation between the sensation of heat and heart rate when the temperature stays the same but colors change from cool to warm.

this has recently changed, with multisensory approaches gaining more ground (Nitidara et al., 2022). I will briefly mention here three studies that can help shed some light on how such combined stimuli – sound, light and heat – influence those experiencing *The Water Within (Hertzian Field #3.x).* It should be however noted that whereas in these studies comfort is – at least implicitly – something to strive for, in *The Water Within*, particularly in the 2018 iteration, I am very consciously using this sensation of comfort as a modulatable parameter of the overall experience; that is, as a parameter expected to change over time, and which I try to shape throughout the duration of the work using heat, steam, lights, and sound.

Very recently, Nitidara et al. (2022) conducted a study of cross-modal sensory interaction between thermal, visual and auditory stimuli with a focus on tropical climates, which makes it particularly interesting given that those essentially correspond to the microclimate inside the steam room. The study found that increased thermal sensation (i.e. a space feeling warmer) also increases visual sensation (i.e. a space feeling brighter) as well as auditory sensation (i.e. a space feeling noisier). They also found that sound affects comfort more than thermal and visual stimuli, with higher noise levels decreasing thermal comfort. Another interesting - though not very surprising - finding that relates to this piece was that, according to their survey of past studies, the relationship between humidity and comfort appears to depend on the climate that queried subjects were accustomed to.

An earlier study by Matsubara et al. (2004) confirmed the hue-heat hypothesis and, more pertinently, found indications that recordings of environmental sounds (such as crickets, cicadas, waves, and birds) facilitate the connection between the sensations of color and temperature. This is particularly relevant for my installation, supporting the notion that the field recordings and water-like sounds contributed to combatting the feeling of extreme heat.

In a more recent study conducted during the COVID-19 pandemic, Bourikas et al. (2021) investigated how different sensations influence one another and people’s perception of comfort.[385] The study’s special focus on quality of air is rather relevant, given that the room of *The Water Within (Hertzian Field #3)* is completely filled with hot steam which - like every steam sauna - can at first feel that it impedes one's breathing. According to their findings, thermal sensation is linked to the perception of both noise and air quality.

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385 Bourikas et al. (2021) offer an interesting distinction of three different ‘dimensions’ of comfort relating to: a) expectation (relating to non-sensory stimuli), b) sensation (of sensory stimuli), and c) relative perception (relating to preference and satisfaction).

7.4.11 *A multi-sensory experience in an embodied cybernetic environment*

The work is a fully immersive environment that engages multiple senses simultaneously. Upon entering the space, visitors become submerged in and consumed by steam, heat, light, sound, and scent - a sudden combination that is initially disorienting. Their *eyes* encounter a dark space colored deep purple by the overhead lights and shrouded in a thick haze that obscures everything around them. At the same moment, they feel their *lungs* fill up with hot steam, which can be a quite strange respiratory sensation – even perhaps a little oppressive for the first moments as they may feel it inhibits their capacity to breathe. Their *nose* fills with the scent of essential oils (tea tree or other, applied to the exit pipe of the hot steam) and of the structure's pine-wood frame. Sounds fill their *ears* and touch their *skin*, enveloping them from above their head and under their feet, not only heard but also vibrotactily felt through the floor and seats. The coupling of these sounds to the invisible microwave fields that they interfere with quickly makes them aware of the relationship between their bodies and space, targeting their sense of *proprioception* – and to a lesser extent *equilibrioception*, i.e. the sense of balance - and coupling both to their sense of hearing. Within a few minutes upon entering, the hot steam causes a feeling of extreme warmth that leads to profuse sweating, targeting their sense of *thermoception*. Experiencing *The Water Within (Hertzian Field #3.x)* engages thus with visitors' *exteroceptive* senses - sight, hearing, smell and touch, i.e. senses that are concerned with the world outside the body - as well as with *interoceptive* ones that involve sensing changes within the body, such as proprioception and thermoception (for a discussion on the different types of senses see Macpherson, 2011).

The intense humid heat, in particular, is strategically used in the work to shape interaction and the ways in which visitors approach and experience it. The steam room's heat significantly heightens sensory awareness. On one hand, it makes visitors much more sensitive and attuned to sound - something I experienced myself, but also received as an unprompted comment from many visitors.[386] On the other hand, the extreme heat also appears to heighten people's interoceptive awareness and their sensation of their own bodies, a feeling that increases throughout the piece as warmth intensifies. While heat enhances the sense of proprioception (where and how the body is placed), it also quickly makes visitors slow down and approach the system in a much more subtle and delicate – even meditative -

[386] Regrettably, and despite repeated efforts, I was unable to find any in-depth research on the effects of heat on the auditory sensitivity of humans besides the studies mentioned (I did however find studies on its effects on the hearing of a variety of other animals such as insects, fish, lizards, and turtles).

way than what is common in interactive works. Using heat to this extent was a very deliberate strategy of mine that proved exceedingly successful, as visitors interact with the work in very attentive and engaged modalities, giving a lot of weight to sound and its connection to action, which was not always the case in *Hertzian Field #1* as was discussed earlier.

In relation to this response of slowing down *physically* because of the hot steam, it is worth noting that heat appears to have the opposite effect *mentally*: namely, it influences one's perception of the passage of time, effectively speeding it up. The hypothesis that humans possess a biological internal clock that is affected by temperature is not new. In a review of over a dozen studies conducted between 1927-93, Wearden and Penton-Voak (1995) found that there is in fact a non-linear correlation between heat and perceived time: The speed in which time passes feels faster when body temperature exceeds a certain threshold above normal (this threshold being below the temperature induced by the steam room) and slower when it falls below a low threshold. They also found evidence of a *"parametric relation"* above this threshold in a few studies, *"with higher temperatures producing more rapid appreciation of time"* (Ibid, 136). These findings have been supported by more recent studies as well, such as by van Maanen et al. (2019). Nonetheless, limited preliminary studies by Tamm et al. (2014) and Kingma et al. (2021) suggest that this speeding up of perceived time may be substantial only after experiencing some amount of physical fatigue, thus hinting at the existence of *"not only a thermosensitive internal clock but indeed a thermoemotional internal clock"* (Tamm et al., 2014, 206).[387]

The Water Within (Hertzian Field #3 and *#3.1)* is not a passive sensory experience, but one that engages with visitors in many levels. They discover and co-create their experience by navigating and negotiating the multiple layers of interdependencies and interactions between the different components of the work: space, hot steam, sound, microwave sensing system, but also with visitors and within visitors themselves. Overall, the work is designed as a second-order cybernetic system like *Hertzian Field #2*, although it consists of many more components than its predecessor. The notions of interaction and connectivity are fundamental: The steam reacts to the space, its flow guided by the architecture. The system reacts to the steam's flow and to the increased humidity and temperature inside the space.

[387] Regrettably, both these studies were conducted only on male subjects, a problem I was surprised to find plaguing much of this type of research; moreover, all of them were young. This fact combined with the rather small number of subjects (just over 50 for both studies together) means that these results should be considered indicative but not conclusive.

Visitors react and interact with the space and the steam within it, for example changing to a more comfortable position, or moving to a new spot seeking more steam and heat. Visitors interact with the system through sound, by actively moving to create or modulate the soundscape but also simply by being there and interfering with the microwave transmissions that control it. Visitors also interact with other people in the steam room. This requires some internal negotiation - a form of interaction with one's own self - as to how one should behave in such an unfamiliar and out-of-the-ordinary situation, especially in the context of an art exhibition or festival. The fact that visitors only wear towels, being naked underneath and feeling intimately vulnerable together, tends to make them much more open with one another after the first few minutes – something I witnessed firsthand, but also heard as a comment from many participants. Some visitors even interact with the system as a group while experiencing the piece, working together to shape its sound; this may involve non-verbal collaboration/co-ordination, or even active discussion trying to understand and 'perform' the system together. The latter happened more in the work's first iteration, as that was closer to a conversation sauna, than in 2018 as that version felt to visitors much more like a performance thus making visitors hesitant to talk. After completing the work and while writing this thesis, I found that there is yet one more complex, but very physical layer of interaction between body and system: The response of visitors' bodies to microwaves changes during the piece due to the accumulation of steam and, most importantly, due to the buildup of sweat and condensation on the skin. This is evidenced by experiments that reveal a difference in the permittivity and conductivity of dry versus wet skin measured in vivo. As Gabriel (1996, 2) notes, wet skin *"results in a marked shift of the RF dispersion to lower frequencies and an increase in the magnitude of both dispersions"*.

One of the most interesting and rather unique elements of this piece is that it creates a setting where the dynamic relationship between steam, body, and WiFi fields can be observed through changes in the work's sound. For instance, differences in steam density and temperature between various sessions produce noticeable sonic variations. The result is that, in practically every single time I experienced the work, I was surprised by at least one new sound or sonic behavior. Such variations are particularly pronounced when the same calibration of the sensing system is used in different environmental conditions. My most memorable experience in this regard occurred during one of my last experiences of the 2018 iteration, when documenting the work before dismantling it. This took place during the small hours on a cold March night; the central heating of the building had been switched off a few hours earlier and I had turned the steam generator off for a couple of hours as well to take photos, before turning it switching it back on in preparation for that session. Consequently, the temperature inside the steam room was a few degrees lower than when I had last calibrated the system. As it was quite late, I did not wait long enough to let the steam build up to the point of condensation in the room before starting the automated score - even though it appeared to be visibly as dense as in other sessions. These different conditions introduced several radically new sonic elements, such as some interesting and persistent bass-heavy sonorities that I had never heard before. At the same time, there was a near absence of other characteristic sounds, like the water-droplets that are usually very present in the later part of the piece.

More recently, I was able to closely examine and verify these observations regarding the dynamic relationship between the various elements of the work and how they influence its sound. The opportunity presented itself while I was working on an audio edit of the 2018 version for a podcast (Psarra and Manousakis, 2022). Making this edit involved lining up recordings from 13 different sessions. These recordings were accompanied by brief notes on environmental factors and on how many visitors participated in each session, and in some cases by video documentation. Carefully listening to these recordings and having the possibility to compare them side by side made sonic differences and their causes evident. Unsurprisingly, the number of visitors in the steam room and how active they were had the most influence on the types of sonorities and how they were modulated, on their distribution in space and the overall density of the soundscape. Additionally, the effects of environmental factors, such as similarities or large discrepancies in temperature and humidity (like in the session mentioned above) were also apparent when listening.

7.4.12 *Overview and synopsis of the experience*

Since the work is time-based, in this section I will provide a brief synopsis of the 2018 iteration. While it is very hard to describe the overall experience and soundworld in words - especially as it is generated interactively - I will paint a picture with broad brushstrokes informed by my memory, notes, audio and video documentation. This will be complemented by photos and video stills from the various scenes. For a documentation in more dynamic media, a video excerpt can be found in Manousakis (2018) and an audio edit of the complete work in Psarra and Manousakis (2022) starting at 40'50".

First and foremost, and before presenting this synopsis, it should be noted that both a consideration of how heat affects visitors as well as the timing of this affect have been central to the composition of the work as a time-based experience. The scoring of sound, light, and interaction in the 2018 iteration was fine-tuned through extensive testing inside the steam room to ascertain that the progression of these elements is deeply connected to how physical and psychological sensations develop over time in that environment.

To briefly summarize how heat impacts the experience: entering the steam room is typically a moment of shock at first, as the difference in temperature and humidity compared to the changing room is drastic. The heat is quite pleasant, however, so it soon feels quite comfortable, especially once the lungs get used to the steam. After a few minutes, and as the first sweat starts to break, one begins to feel hotter and hotter, to the point that this becomes increasingly more pleasurable - but also a bit uncomfortable at the same time. This conflicting sensation becomes progressively more intense until, after already sweating a lot, one reaches a point of finally being completely acclimated, sweating profusely, hot, and happy. This sensation generally lasts for a few minutes and until the last section of the work, with most visitors beginning to feel increasingly more overwhelmed in the final minutes. Naturally, everyone's experience is different and so are attitudes and tolerances towards heat; the piece is designed to not only accommodate these differences but to actively take advantage of them, using them to feed movement data into the system: As visitors shift around the space to find areas with more desirable temperatures (higher or lower), they perform the system and shape its soundscape.

Overall, in terms of sound, the piece starts quite turbulent and sonically present with the system being very sensitive in its responses. As heat builds up and visitors slow down, sound becomes increasingly fuller and deeper, more resonant and reverberant, and slower to react. When heat starts to feel increasingly overbearing, water-like sonorities (waves of noise and raindrop-like sounds) begin to slowly take over until they submerge visitors into a digital-sounding underwater-feeling soundworld. The end is full of low frequencies that approach being overpowering, making visitors feel almost as if they are swimming through steam and sonic vibrations, both heard and felt.

The lights start dim and become increasingly warmer and brighter before they begin to cool down again, as if slowly plunging deeper and deeper underwater, coming back out for a breath as the piece comes to an end.

The overall experience of the work lasts about half an hour. It consists of 3 'acts' and 15 different ‘scenes’, including changing and showering. The duration of the automated sound and light performance inside the steam room (i.e. 'act 2') is just under 20 minutes. A *host* or *sauna master* (essentially a facilitating performer, a role that I have most often taken on) guides visitors and introduces them to the work in 'act 1'. The host also activates the automated score before the first visitor enters the steam room, and monitors steam and temperature levels between performances to ensure there is a thick layer of steam and a temperature of about 40-43°C.

A more detailed synopsis of *The Water Within (Hertzian Field #3.1)* follows:

- **Act 1, Scene 1** (Welcome)

A group of up to 6 visitors that will experience the work together is welcomed by the host. They are introduced briefly to the work and its concept and are guided through practicalities. This includes what to expect, where to change, where to shower, when to enter, warnings and advise against potential health hazards, and other such considerations.

- **Act 1, Scene 2** (Preparation)

Figure 7.47. *The Water Within (Hertzian Field #3.1)*: act 1, scene 2, the steam room as seen from the changing room (photo by Thijs Geritz).

Visitors enter the changing room, where they take their clothes off and change into one of the clean towels provided. After taking a quick shower, they can enter the steam room.

- **Act 2, Scene 1 (**0' – 50")

Figure 7.48. *The Water Within (Hertzian Field #3.1)*: act 2, scene 1, entering the steam room (video still).

When visitors enter, they are immediately confronted with the heat and visual presence of a dense layer of steam. The space is dimly lit from the roof in deep purple tones, which - compounded with the steam and the unfamiliar architectural layout - creates an initial disorienting feeling. The smell of pine-wood accompanied by essential oils is one of the first things to notice, as visibility is diminished and all senses are acutely sensitized in an attempt to get accustomed to the new space and its intense microclimate. Sonically, the system responds with gushes of noise to visitors entering one by one, interfering with the inner Fresnel zones of the WiFi fields. As they move further in the steam room, the soundscape becomes increasingly turbulent. Visitors tend to explore the space, walk around, and eventually find their first seating or standing spot.

- **Act 2, Scene 2 (**50”-2’20”)

Figure 7.49. *The Water Within (Hertzian Field #3.1)*: act 2, scene 2, finding one's spot (video still).

The intensity of the ceiling lights is slowly raised making the room a bit brighter; the spotlight is switched on, slowly fading in at the same magenta hue. Two *no-input* feedback processes controlled by the microwave beam in the back of the steam room are switched on and fade in as well, further activating that space both sonically and in its interactive capacity. The full sensing system is now deployed, with sound coming from all speakers. Out of the turbulence and the gushes and waves of noise generated by the feedback processes, sound slowly transforms into more and more rhythmic and bubbling sonorities, sometimes flowing like slightly metallic rumbling waves. Typically, all visitors have found their places by the two-minute mark, sitting or standing still.

- **Act 2, Scene 3 (**2’20” - 4’10”)

The lights very gently and slowly shift from magenta to a red hue. Some resonant tones start peering through the turbulence, caused by a slowly increasing reverberation added onto the feedback networks of the *no-input* modules. This is accompanied by rhythmical phrases appearing and disappearing in response to visitor movements. There are increasingly more low end frequencies present.

Figure 7.50. *The Water Within (Hertzian Field #3.1)*: act 2, scene 3 (video still).

- **Act 2, Scene 4** (4’10” - 5’40”)

Figure 7.51. *The Water Within (Hertzian Field #3.1)*: act 2, scene 4 (video still).

The spotlight shifts towards orange with increased intensity. A disc of light slowly begins to appear through the fabric in the back of the room, like the sun during sunrise. The ceiling lights slowly follow, changing into a more yellow hue. Sonically, the rhythms subside. By now, more and more resonant clusters peer through the sonic turbulence, shaping it into a more solid and slowly moving mass. After the five-minute mark, and very slowly, the soundscape of a mid-day Taiwanese rainforest begins to peer through. Rhythmic waves from loud cicada calls echo the rhythmical noise gestures of the no-input modules from the previous section.

- **Act 2, Scene 5 (**5’40”- 6’ 40”)

Figure 7.52. *The Water Within (Hertzian Field #3.1)*: act 2, scene 5 (video still).

The sonic tension appears to reach a peak and then relax. The noisy textures become rounder and tamer, slowly fading away as slower and more resonant sonorities are introduced. The space is enveloped by the sound of three *Adaptive Vocoding Resonators* and their deep and rich reverberant tones. Sound gets deeper, with low resonant rumbles sounding and vibrating through the seats and the floor, while the sinusoidal bird calls of the Taiwanese rainforest become clearly audible in the higher register. These more soothing and/or somewhat underwater-sounding textures help body and mind overcome and accept the profound heat, which by that moment has started to become overwhelming.

- **Act 2, Scene 6 (**6’ 40” - 8’50”)

The ceiling lights gradually shift to a whiter hue. The space is still colored by the orange-yellow spotlight. Sound becomes deeper and more resonant, with visitor movement in certain areas of the steam room stirring waves of rhythmical elements as a set of additional WiFi sensing controls for the *Adaptive Vocoding Resonators* become activated. Motion in other areas causes sharp changes in the soundfield's sonorities. Overall the soundscape is ‘rounder’, calmer and less noisy. Calls from birds and cicadas travel through the space. ‘Watery’ resonant tones emerge as the *Spectral/Bark Feedback-Delay* processes fade in.

Figure 7.53. *The Water Within (Hertzian Field #3.1)*: act 2, scene 6 (video still).

- **Act 2, Scene 7** (8’50” - 11’50”)

Figure 7.54. *The Water Within (Hertzian Field #3.1)*: act 2, scene 7 (video still).

Figure 7.55. *The Water Within (Hertzian Field #3.1)*: act 2, scene 7 (video still).

While the spotlight remains yellow-orange, the ceiling lights gradually shift to a slightly green color. By this time, most visitors are feeling very, very hot and thus make minimal movements. As if suddenly some of the 'watery' resonant tones begin to melt, a set of water-like, somewhat metallic and sometimes decidedly digital droplets start to sound through the space above areas in which the system traces more than minuscule motions.

Once the rain of droplets starts to fall, the ceiling lights gradually move towards an aqua blue hue. The water-like quality of these sounds and the cooler hues help make the intense feeling of warmth more bearable.

- **Act 2, Scene 8** (11' 50" - 13')

The spotlight shifts to match the ceiling lights, turning the space into a vibrant blue. Then it all shifts to a slightly deeper blue, as if diving another few meters underwater. The deep resonances of the *Adaptive Vocoding* processes are slowly fading out, but the bass persists. The density of the soundfield lightens up, especially in the mid-range. Visitor motion stirs localized waves of turbulent but smooth digital noise, like a sea of data flowing through the steam room.

Figure 7.56. *The Water Within (Hertzian Field #3.1)*: act 2, scene 8 (video still).

- **Act 2, Scene 9** (13' - 14'50")

Figure 7.57. *The Water Within (Hertzian Field #3.1)*, act 2, scene 9.

The spotlight slowly shifts to a high-intensity magenta color, which mixes with the blue color of the ceiling lights into a kind of night sky. The sound feels oceanic and/or almost underwater by now: turbulent low frequency drones, droplets that get stronger with every movement, and waves of noise flowing through the field.

- **Act 2, Scene 10** (14’50” - 17’10”)

Rhythmical waves of noise and bass patterns – like musical phrases - emerge when visitors move in certain areas; they become increasingly more present and longer lasting. The soundscape becomes more turbulent and unstable, and at the same time more rhythmical and clearly articulated. This is partially the result of slowly removing reverberation from the feedback processes within a timeframe of three minutes. Bass frequencies travel through the structure, enveloping the space and making it shake and tremble from underneath the floor and seats.

- **Act 2, Scene 11** (17’10” - 19’10”)

Figure 7.58. *The Water Within (Hertzian Field #3.1)*, act 2, scene 11 (video still).

All lights shift to an even deeper blue, as if several meters under the ocean. The bass takes over, accompanied by waves of rhythmical digital sonorities. Noisy and heavy-moving rhythmical elements flow in and out. Overall, the soundscape becomes very sensitive to movement, especially in particular areas of the field.

- **Act 2, Scene 12** (19’10” – 20’)

Sound slowly fades out, process by process, ending with traces of bass and some last few water droplets. At the same time, the light intensity slowly fades to a black-out signaling the end of the piece. A few seconds later, after the sound has rang out and dissipated for a few seconds, the ceiling lights turn back on with a white hue, signaling to visitors that the piece is over and that they can exit the steam room.

- **Act 3, Scene 1** (Exit)

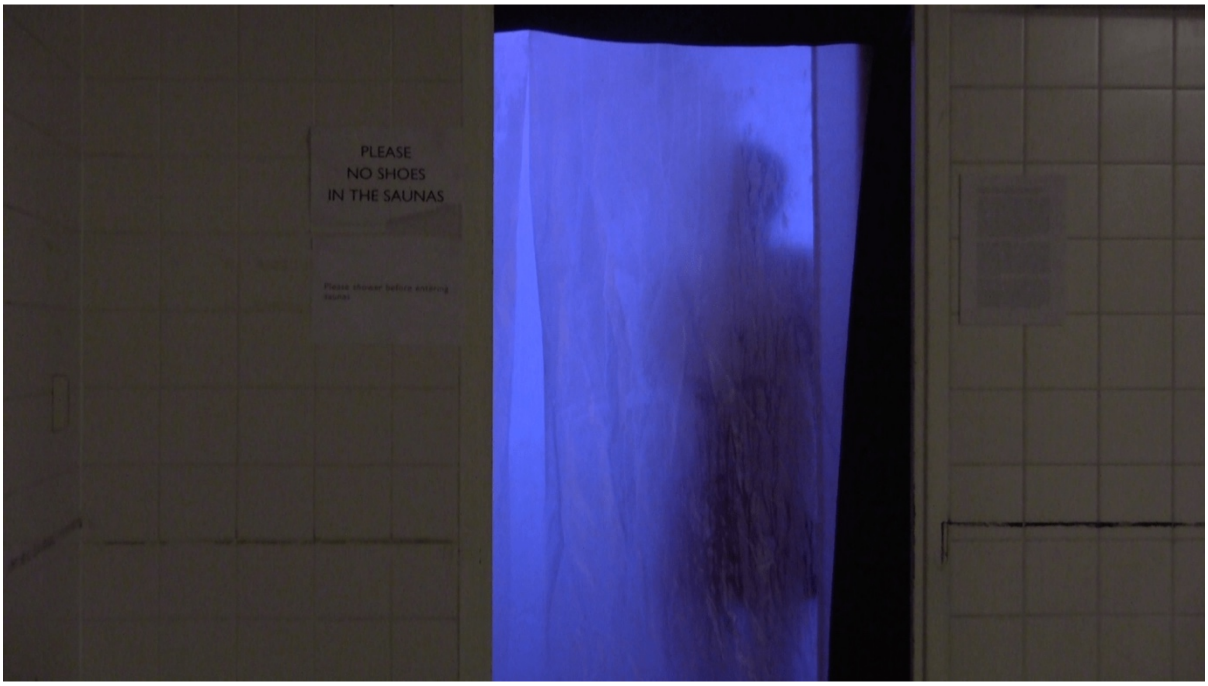

Figure 7.59. *The Water Within (Hertzian Field #3.1)*, act 3, scene 1 (video still).

Visitors exit the steam room and return to the changing room where they can shower and change back to their clothes.

7.4.13 *Audience response: A few thoughts and observations*

Creating this unusual project proved very challenging but also immensely educational, as it involved researching and getting my hands dirty in fields and with elements that I had little to no prior knowledge of. It also proved to be intensely rewarding, especially once the work was complete and I could enjoy being in it and experiencing it on my own and with others.

Due to the hectic nature of preparing a new work while also running a festival, the first time I experienced the work's first iteration in its complete form was during the opening of *Modern*

Body Festival 2016. The piece was presented alongside a second sauna work, conceived and created by myself and Stephanie Pan, with which we aimed to deepen our exploration of post-relational aesthetics and the social body. That project, titled *Hot Listening Booth,* is an even more intimate and even hotter (70°-90°C) listening venue: a wooden dry-sauna cabin, heated by infrared lamps, accommodating up to 3 visitors sitting side by side, and containing an embedded soundsystem (see Manousakis, 2016c). While it also uses electromagnetic energy (infrared heating elements) it does not use radio or microwaves as a material, therefore it is not discussed in detail here. These two sauna works function exceptionally well as a complementary pair, principally due to the very different microclimates they create: one very humid and hot like the tropics - *The Water Within (Hertzian Field #3)* - and the other extremely hot and dry like a desert *(Hot Listening Booth)*. This combination made it exceedingly pleasant and effortless for visitors to spend hours going from one work to the other and back – with showers and cooldown in-between. Because of their synergy, we presented updated iterations of both works together a year and a half after their premiere, during *Modern Body Laboratory #2* in 2018.

While promoting the two events (*Modern Body Festival 2016* and later *Modern Body Laboratory #2*) or talking to people on site about the program, I made a rather interesting and unexpected observation: almost nobody expects to encounter an actual sauna in an art context! In both presentations of these two pieces (and another of the *Hot Listening Booth* as part of the *Sensing Sound* exhibition at the *Musical Utopias* festival in 2018)[388] it was a common occurrence that I would inform people that such and such a work was part of the exhibition, they would nod as if they understood what that meant while showing no sign of surprise, only to later be astonished when they were faced with the actual work(s) at the exhibition. I have been told by numerous people that they thought '*sauna'* (a term everyone in the Netherlands is familiar with, and which thus I used for these works) was either an overstatement, a metaphor, an approximation, a simulation of some sort, or even just plainly a joke as it seemed so bizarre and foreign an idea to them that this type of environment would be part of an art exhibition. A few had to literally peer through the door to see the steam and feel the heat of *The Water Within* for themselves in order to believe it.

I consider the experience of the work to begin at that exact point: when one is confronted with the nature of the piece and the inevitable subsequent dilemma - to enter the steam room or not? In order to fully experience the piece, visitors must make a conscious decision,

[388] See: https://www.ensembleklang.com/musical-utopias/. Last retrieved 29 December 2022.

carefully weighing the pros and cons: Should they put themselves in a vulnerable and awkward position, undressing and walking around with a towel in a place, time, and context they least expected to do so, simply to experience an artwork that they do not know if they will like? *"Is it worth it, will I like it, am I with the right company, do I have enough time"?* For most, choosing to participate when surrounded by strangers - or in some cases even worse: surrounded by friends and acquaintances - requires a significant emotional investment, mentally preparing and building up the courage required. On the other hand, the potential payoff of the experience is exhilarating and revitalizing for both body and mind, especially in the middle of a cold winter - something that most people that have been in a sauna before are aware of. Putting visitors into a position where they have to make the choice to commit or not is a fundamental part of the work. It manifests in an upfront and personal way what I believe to be one of the core elements of good interactive or participatory art: an implicit *pact* between maker and audience that you give something to get something back.

The two pieces, *The Water Within* and the *Hot Listening Booth,* were a highlight in terms of audience participation in both events, leaving us with the feeling that we certainly achieved what we were hoping for in our exploration of post-relational aesthetics. Visitors spent much more time than in a typical exhibition, with many spending several hours moving between the two saunas. Some had never been inside a sauna before, so they only grasped the intensity of the experience after spending time with the work. Others were so excited by the idea of going into a sauna during winter that they immediately headed inside expecting a more conventional environment (perhaps a *relational art* piece), becoming very surprised when they realized they were suddenly in a multisensory interactive artwork (a *post-relational* one). Throughout the duration of the exhibition, practically every visitor I saw coming out of the enclosed area of these works exited with a wide smile on their face, many loudly exclaiming to others how exciting and rejuvenating they had found the experience, prodding them to try it for themselves. A few returned on subsequent days and less busy hours to experience the work with more privacy or more time on their hands, some bringing friends to introduce them to the two sauna pieces.

Naturally, there were also visitors who chose not to experience these works for a variety of reasons - from simply not liking intense heat to being intimidated by the idea of undressing at a gallery space or in the same space as others, to finding the whole thing a bit too weird (this was more the case for the, mostly older and more conservative, contemporary music audiences), feeling vulnerable, or finding undressing, showering, and spending time with the work too much of an investment for the moment. Nonetheless, several of those who opted out still engaged in long conversations about the piece, its concept, and about what they could see and hear, expressing sincere interest and often priming others to experience it. This occurred particularly in 2018, as during that exhibition I had more time to be there as a host and had created a loose script introducing visitors to the work.

As mentioned, the format and thus the actual experience of *The Water Within* is quite different in its two iterations. In 2016 (*Hertzian Field #3*), the steam room was first and foremost a social place. Visitors would flow in and out, and there would often be large groups inside – a few times during the opening weekend I counted even up to a dozen. The atmosphere inside was very welcoming and friendly, relaxed and lively at the same time. People were very open and friendly to each other and generally talkative, particularly those visiting with friends. Several times I noticed visitors entering the work a bit shy, feeling perhaps unsure or awkward, only to find them long time later in other parts of the exhibition, beaming after having spent hours with the two sauna works, and chatting in very familial terms with other visitors they met there for the first time. It was particularly exciting to hear visitors discussing the work and how they were experiencing it – a subject which I noticed became a common icebreaker. Several times I overheard people enthusiastically explain or discuss parts of the work to others – about their personal experience, the way they bonded with others, the interaction, the sound, the concept – in ways that revealed that the various elements functioned as I had hoped for. Talking with visitors in person was also extremely informative. Overall I was pleasantly surprised by how genuinely people opened themselves to one another during and after experiencing the work. Even though this was one of the main goals of creating and presenting the work in that context, the result surpassed my expectations both as an artist and as a curator of the *Modern Body Festival.*

While I was very excited about the success of this first iteration, I quickly realized its approach involved a compromise: the more social the place, the more people talked and thus the less they listened. A few months after the work's premiere, I decided thus to try and investigate my original idea of a timed and authored experience that is performed for visitors, with visitors and by visitors participating as a group; a version that prompted participants to listen and interact with the work more intently, within a framework that has a beginning, middle and end.

Consequently, in its second iteration (*Hertzian Field #3.1,* presented in 2018) the steam room is first and foremost a meditative place, and secondly a social one. I have been told by visitors that the piece made them 'travel', that the intensity of the environment made them listen in a different way, that they felt like they gave in to the experience. The most important factor contributing to this is that the work is both timed and discernibly performative - to the point that some groups even clapped when the piece was finished. Participants stay mostly silent throughout the experience. In general, people tend to move around a bit in the first part of the piece, exploring the space before their bodies surrender to the heat. Typical behaviors involve pacing, standing, seating, swaying one's body, moving one's arms, wiping the sweat off, holding on from the structure, stretching.[389] Those that find themselves in the more sensitive inner Fresnel zones seem more inclined to shift their bodies or arms around to perform the system. As the piece progresses, visitors tend to stand still for longer stretches of time, often with eyes closed. They may change places to find warmer or cooler spots through the piece, for example standing on the bench in the center to become more exposed to heat and steam, or sitting on a corner seat for the opposite effect. With fewer people and more open space, some visitors lie down on the central benches. Rarely, someone will briefly come out before the piece is finished because they overheat. Overall individual behavior appears to be strongly influenced by the dynamics within the group. Some groups are more shy about moving around, with visitors finding a seat and remaining there for most of the piece, only shifting about. This seems to happen more when the people in the group are not familiar with one another.

As a closing remark, when considering the audience response from a wider perspective, I feel that the work - particularly in its first iteration – successfully proposes a concrete *post-relational methodology* for instigating the formation of bonds, groups or micro-communities. This involves the following:

a) Creating a situation whose strangeness throws the established social codes of a given context (such as an exhibition) off balance, thus instigating people to actively renegotiate how they interact with others in a way that makes them behave in a less prescribed and more genuine and personal manner.
b) Creating an intense (multi)sensory experience that: targets mind and body alike; may require some form of 'work' or effort to 'get through'; is shared by group of people; can be shaped by that group; and over which the group can bond.
c) The quality of the shared experience, whether it makes visitors feel positively or

[389] I made these observations in person, and with the help of video documentation capturing different sessions (with the consent of participants).

negatively about what they are going through together, exerts a strong influence on the process of bonding and its character. The intense heat in this piece is of strategic importance. While for many visitors it may initially feel as an overwhelming, almost impossible to withstand environment, the body quickly adapts. One starts to feel the short-term positive physical effects of the hot steam a few minutes into the work – relaxing the muscles and joints, alleviating pain, releasing toxins, reducing stress, even helping get over a cold (a comment I received a handful of times). I believe this clearly helps people become more open to others, as everyone's mood invariably brightens up. The mind relaxes and the body drops some of its social barriers, turning individuals into a temporary community. To summarize and paraphrase the feeling expressed by several visitors: "*We are all here together, covered with just a towel, immersed by steam and sound, incredibly hot but happy. This is strange and unexpected, but we are doing it together and it feels good.*"

7.5 Future Work

7.5.1 *Technological improvements to the WIR system*

The *Wireless Information Retrieval* system that I have developed so far is very powerful and intuitive, however I feel that I have only begun scratching the surface of its possibilities. In terms of the technology itself, there are a number of avenues for further research that I plan on undertaking, concerning both hardware and software developments.

These include:

- Testing a wide variety of WiFi cards to find ones that are more sensitive, provide more resolution, give access to more metadata (such as the amount of noise received by the antenna), and/or are more powerful and thus have an increased range.
- Experimenting with WiFi cards that support *Channel State Information* (CSI) and *Multiple-In-Multiple-Out* (MIMO). Thankfully, while the possibilities were extremely limited when I started developing the WIR system, there are several more options currently available and one can expect that there will be more in the future. CSI and MIMO will allow creating a much more sensitive and fine-grained system, as is evidenced by recent Device-Free Activity Recognition (DFAR) research. It should also enable implementing quite accurate gesture recognition and localization algorithms. The increased resolution of CSI should also allow extracting more information from low-

powered signals of other Access Points present in the environment, making it thus possible to create expressive *passive* systems that do not need a transmitter.

- Delving deeper into the ‘dark art’ of antenna design and experimenting with a variety of different types of antennas. I have already significantly increased my knowledge and performed some initial experiments with fabricating more ‘exotic’ antennas by hand.
- Further experimenting with materials that reflect or absorb radio waves and microwaves. This could be used as a way to sculpt hertzian space and create 2nd and 3rd order RF-sensing Line-of-Sight beams between transmitter-receiver pairs. Essentially, this will allow increasing the spatial resolution of a sensing system. I had already considered using such reflectors in the entrance of the steam room of *The Water Within (Hertzian Field #3)* to amplify the system’s sensitivity and thus its response when someone enters. My initial thoughts involved embedding perforated metallic panels or a metallic mesh tuned to reflect radio frequencies at about 2.4GHz as reflectors. However, the material was not fitting for the space - potentially sharp metal, hot steam, and bare skin felt like a bad combination. I thus turned to experimenting with something more appropriate and more fitting to the materials of that work: electromagnetic-reflecting fabric (sold as 'RFID-blocking fabric'). While I performed some promising tests, in the end I decided to not use this material because the system was already sensitive and dynamic enough, and I did not feel this fabric was visually matching the rest of the structure, or that it offered anything to the concept. Nonetheless, I believe continuing these experiments will produce some interesting results that could be at the core of future works. The fabric, in particular, could be used to design special garment for performing hertzian works.
- Implementing the sensing system using different microcontrollers, including smaller and more portable formats, such as the Raspberry Pi Zero or the ESP32.
- In terms of efficiency, further software optimization is necessary for creating projects that involve large numbers of nodes, particularly so as to be able to extract multiple features for an array of such nodes at once - at least for configurations like in *Hertzian Field #2* and *The Water Within (Hertzian Field #3)*, where a central computer gathers all data and performs all calculations. The main reason is that the current system is implemented in the SuperCollider language (*sclang*), which is unfortunately somewhat ill-suited for quickly processing vast amounts of data. Additional optimization within the SuperCollider codebase, as well as in the ways that I am using the system, will certainly

also help.[390] I am also curious to explore other solutions – such as moving some calculations to the more efficient SuperCollider server (*scsynth*), or implementing real-time feature extraction in another language. In any case, the operational ceiling of the system will certainly be raised with more powerful hardware than what I have used so far (a 2012 MacBook Pro). This is a very straightforward and immediate path of improvement. Using more powerful microcomputers than the 1st generation Raspberry Pi as transceiver nodes may also allow outsourcing some of the feature extraction calculations to them.

- In terms of increasing the system's functionality, I aim to look more closely at DFL and DFAR research to incorporate, modify, and build on some of the work that could be potentially useful in my artistic practice. So far, my approach has been strictly bottom-up: creating complex networks of features mapped to sound synthesis and processing parameters, so that sound emerges from the relationship of body and WiFi fields. While I am still a believer of this approach and its wonderfully expressive potential, I am particularly interested in extending the system with elements that can be used for high-level control, such as localization and gesture recognition. To provide a simple, practical example of what that would achieve in an existing piece, such functionality could enable the system to automatically proceed through the sequence of scenes in the *Hertzian Field #2* score simply by following my path through annotated areas around the triangle (using localization), or by identifying a certain gesture or situation (using activity recognition). One caveat is that the system would need to be very accurate: In the case of high-level control, errors like false triggers or failures to trigger can make such implementations unusable in performance. This is why the automated score follower method I developed for *Hertzian Field #2* based on feature extraction proved unsatisfactory, as it was hard to tune it so that it was neither too sensitive, nor not sensitive enough.
    - To this extent, one of the first investigations I plan to undertake is to use Machine Learning to identify different states and gestures. I am particularly interested in this

[390] A specific point of optimization that can already be implemented is limiting the number of possible window durations of the frequency-domain features to just two or three such windows, e.g. a short (0.4 sec), a medium (0.8sec) and a longer one (1.2 sec). This would enable performing only two or three FFT analyses which the feature extractors could retrieve spectral data from. Instead, in the pieces presented in this dissertation the system performs a separate FFT analysis for every single feature, which is far less efficient. The reason for this choice was that I wanted to have the freedom to test what windows each extractor performs best at, as that allowed me to better understand the system without limiting analysis to a set of predefined windows. I plan to examine and consolidate my findings from these three works and to optimize my use of the WIR sensing system for the next work.

technique as a way to embed different forms of high-level control within the sensing mechanism. This will involve feeding the Machine Learning algorithm combinations of extracted feature data to enable the recognition of gestures, of body positions and postures, of types of behaviors within the system, of the amount of bodies in the field - but also temperature, humidity and steam density in the case of future works along the lines of *The Water Within (Hertzian Field #3)* and beyond. I have performed some brief experiments with *Wekinator*, a software for real-time Machine Learning, which have produced promising results.[391] This type of mechanism would be very effective for switches, for example, such as to change the state of the instrument when I perform a certain action or gesture, turn on / off a process, etc.

  - Furthermore, I am interested in implementing some form of localization and orientation tracking. This could be a Device-Free system but could also involve a wearable transmitter combined with triangulation and Machine Learning to create a Device-bound system. It would also be interesting to incorporate some simple mathematical models of the body in WIR to produce more accurate sensing results. Device-free localization should also be feasible through the use of CSI data. I envision using localization not as a tool for directly mapping sounds to space, as this feels rather mundane and literal to me, but for creating zones where certain sonic behaviors occur (e.g. a kind of process), as well as for higher level controls, such as to trigger events and sound processes, to change system states, and so forth.

- Finally, I plan to extend my investigation of Radio-Frequency sensing to other protocols and parts of the spectrum. I have already undertaken some preliminary experiments in creating a gestural instrument based on microwave Doppler radar modules and have been very excited about the results. Since Doppler requires motion to produce sensing data, it has a different feel than the WIR system with both pros and cons. While WIR excels in scanning a static body, a Doppler system is much more responsive in tracking motion, as the modules produce voltages which can be sampled at high rates, just like audio signals. The technologies developed by G.W Raes provide a good compass in regard to both what I would like to achieve and what to avoid with such a system. Experimenting with Software Defined Radio is another avenue of research that I am interested in undertaking. For a few years now, inexpensive SDR receivers have hit the market

[391] Wekinator is a free and open-source Machine Learning tool developed by Rebecca Fiebrink, first released in 2009. Its current version was released in 2015. See: http://www.wekinator.org/. Last retrieved 29 December 2022.

(originally sold as digital television tuners) which makes SDR a potentially interesting platform for developing receiver nodes.[392] More accessible SDR devices with transmission capabilities are also becoming increasingly more available nowadays – although they are still about a dozen times more costly than simple receivers at best. Still, this all makes developing a system entirely based on SDR more accessible to independent artists than it has ever been.

7.5.2 *Artistic paths*

The technologies that I have already developed have opened many possibilities for inspiring artistic paths. I am certain that the results of the technological experimentations I plan to undertake, mentioned above, will open numerous exciting new doors for artistic creation that are hard to even imagine. In any case, I plan to continue and expand on the work I began with the *Hertzian Field* series, experimenting with different configurations, situations, formats and experiences.

Some of my ideas for future artworks include staged performances such as:

- Sound performances with acoustic instruments and/or voice, processed by software that is controlled by WiFi/RF-sensing data generated by the movement of the performer. Planned works include a piece for long-time duo partner Stephanie Pan (voice and live electronics) and a piece for my feedback-augmented alto clarinet.
- Dance and dance-theater works created in collaboration with a choreographer and a director. On one hand, I am very interested in further exploring what movement languages emerge when a trained dancer is primarily guided by the ear, while still having their movement be designed and choreographed in as sophisticated and detailed manner as the sound of my existing works has been. On the other hand, I am very eager to create a work, with text, that delves deeper and more explicitly into the conceptual and societal implications of the WIR technology, particularly the fact that through our telecommunication technologies we are weaving an ever-tightening surveillance web around us that is impossible to opt-out of.
- The WIR system may also be useful as a complementary sensing system in more 'standard' electronic music settings, such as in performances by *Center no Distractor*, a

[392] See in particular the infamous RTL-SDR dongle: https://www.rtl-sdr.com/about-rtl-sdr/. Last retrieved 29 December 2022.

very physical taiko and live electronics duo project by myself and Stephanie Pan.[393]

Other ideas and visions for non-stage works and installations include:

- A new steam sauna work, building on findings from *The Water Within (Hertzian Field #3* and *#3.1)*, using an updated version of the sensing system and a more elaborate architectural form, in collaboration with an architect - and this time with more funding.
- An expansive series of interactive installations and interventions in public spaces featuring different configurations of hertzian fields. These works will involve combinations of the following elements: varying numbers of nodes and geometries (from just a few to dozens or even hundreds); different types of antennas; reflectors and absorbers; specially designed architectural interventions on existing spaces; RF-augmented objects and mobile sensing nodes, portable (battery powered) and motorized (e.g. like radar equipment). I have numerous sketches and ideas for such works that I hope to start realizing soon.
- Finally, the microwave-sensing capabilities of the WIR system, on which this thesis focuses, is only one of the possibilities afforded by sniffing wireless signals. I am also interested in exploring the WIR system's artistic potential when using other WiFi data beyond beacon frames.

[393] See http://modularbrains.net/portfolio/center-no-distractor/. Last retrieved 18 September 2022.

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Vita

Stelios Manousakis (1980 | www.modularbrains.net) is a Cretan-born, Netherlands-based artist exploring relationships between time, space, body, system, and sound. His practice lies in the convergence of art, philosophy, science and engineering; it extends from performances, to environments and installations, to compositions, fixed media pieces, and music for dance and film. His work is particularly concerned with the invisible and the ephemeral, and with shaping sensation, perception and experience in time. It often employs listening as a key interface for understanding the world – being here and now – and as a medium for targeting the deeper strata of the psyche and the brain. Visceral, yet cerebral and research-based, his works aim to communicate through raw sensory experience while being complex and multilayered. They are often designed as emergent (eco)systems or organisms, unearthing vibrant immersive worlds through reinventions of models from cybernetics, complexity science, biology, and game theory. They most often involve software that he develops, and merge algorithmic finesse with the immediacy of audience participation, or the expressiveness of improvisation. Many of his works involve some type of feedback process – audio-based, algorithmic, between systems, machines and/or humans. Over the last dozen years, he has been exploring the impacts, side-effects and hidden properties (physical and otherwise) of communication infrastructure, with a particular focus on wireless media.

Stelios' work has been shown in 35 countries and 5 continents in varied festivals, performance venues, centers, museums, galleries, film houses, underground spaces and public spaces, such as ZKM Karlsruhe, Ars Electronica, dOCUMENTA, Museum Reina Sofia, London National Gallery, Seattle Art Museum, The Place, The Lowry, Dutch National Opera, Eye Filmmuseum, International Documentary Film Festival Amsterdam, Rewire festival, Audio Art festival, November Music, Athens Digital Arts Festival, IEM Graz, International Computer Music Conference and New interfaces for Musical Expression. His compositions have received international awards from Gaudeamus, the European Conference of Promoters for New Music, and Cittá de Udine among others. Besides his solo work, he has co-founded several music ensembles and multi-/inter-media groups – such as They Gather, Computer Aided Breathing and Center no Distractor. He also frequently collaborates with other artists as a maker or in a supportive or advisory role, and has been a jury member for art institutions and international conferences, such as International Computer Music Conference and Sound and Music Computing. Together with duo partner Stephanie Pan, he is the co-founder, co-director, and co-curator of the intermedial Modern Body Festival and Modulus Foundation (Stichting Modulus).

Stelios studied music (Diploma Cum Laude in Highest Music Theory, GR) and linguistics in Greece (BA from the National University of Athens, GR), Sonology in the Netherlands (MMus from the Institute for Sonology at the Royal Conservatorium The Hague, NL), and holds a PhD in Digital Arts and Experimental Media (DXARTS, University of Washington, Seattle, US). As an educator, he has created and taught graduate and post-graduate courses at the University of Washington (Seattle, US) and ArtEZ (Arnhem, NL), as well as seminars and workshops in universities and art centers in the US, UK, the Netherlands, Australia, Spain, Germany, and Austria.