The Stage Is Set:

Developments before 1900 Leading to Practical Wireless Communication

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In 1909, Guglielmo Marconi and Carl Ferdinand Braun were awarded the Nobel Prize in Physics "in recognition of their contributions to the development of wireless telegraphy." In the Nobel Prize Presentation Speech by the President of the Royal Swedish Academy of Sciences [1], tribute was first paid to the earlier theorists and experimentalists. "*It was Faraday with his unique penetrating power of mind, who first suspected a close connection between the phenomena of light and electricity, and it was Maxwell who transformed his bold concepts and thoughts into mathematical language, and finally, it was Hertz who through his classical experiments showed that the new ideas as to the nature of electricity and light had a real basis in fact.*" These and many other scientists set the stage for the rapid development of wireless communication starting in the last decade of the 19th century.

I. INTRODUCTION

A key factor in the development of wireless communication, as opposed to pure research into the science of electromagnetic waves and phenomena, was simply the motivation to make it work. More than anyone else, Marconi was to provide that. However, for the possibility of wireless communication to be treated as a serious possibility in the first place and for it to be able to develop, there had to be an adequate theoretical and technological background.

Electromagnetic theory, itself based on earlier experiment and theory, had to be sufficiently developed that

1. serious attempts to generate and detect electromagnetic waves would be undertaken, to provide a sound experimental basis for future practical communication systems, and

2. the detection of the electromagnetic waves being radiated was recognized as such, being clearly differentiated from induction or conduction.

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These factors came out of purely scientifically motivated investigations into the laws of physics.

Technology had to be sufficiently developed that

3. sufficiently high powers of electromagnetic radiation at useful wavelengths could be produced, and via suitable antenna systems, radiated and

4. a sufficiently sensitive means of detection of the waves was available.

By 1900, the technology had developed so far and so successfully that some routine wireless communications links, over distances of tens of miles, were already in regular service. This introduced additional requirements needed for the much more demanding experiment in transatlantic communication to be successful:

5. for simultaneous wireless telegraphy involving multiple but independent stations, some means of avoiding mutual interference would be required for practical communication systems. In particular, the more powerful transmitter constructed for the transatlantic experiment should not interfere with existing communications already in service, and

6. the more sensitive receiver should not suffer undue interference from other transmitters already in service.

II. BEFORE HERTZ

The first real connection between electricity and magnetism was the discovery by **Oersted** that electric current flowing in a wire could affect a magnetic compass needle. The most astonishing feature of the discovery, at the time, was that it showed that the magnetic force appeared to be circular around the wire, at complete variance with the conventional wisdom of forces acting at a distance along straight lines.

Michael Faraday (1791-1867) was to make the next major step. Faraday was entirely self-taught; his scientific career started as an assistant to Davy at the Royal Institution. He repeated Oersted's experiment. His lack of formal training probably helped rather than hindered, in his introduction of the concept of curved lines of force; this was quite contrary to the established principle of action at a distance along straight lines. In the process of experimenting, he set up in 1821 an experiment to demonstrate that a wire carrying a current would rotate in a circular path around a magnetic, in effect the first electric motor [2].

By 1831, Faraday was able to show that, while electric current produced magnetism, it was indeed possible to produce electric current from magnetism. His lecture to the Royal Society on 24 November 1831 [3] introduced for the first time the fundamental concept of the **change** in magnetic field being able to induce electricity.

One other experiment of Faraday's showed for the first time a direct connection between magnetism and light; he demonstrated the rotation of the plane of polarization of light by a magnetic field. The phenomenon is now known as "Faraday Rotation."

Faraday became convinced that magnetic forces may be considered as moving, gradually expanding; he likened *"diffusion of magnetic forces from a magnetic pole to the vibrations upon the surface of disturbed water"* and was *"inclined to think the vibratory theory will apply to these phenomena as it does to sound, and most probably to light."* [4,5]. Garratt [p.11 of [4]] summarizes *"… knowledge of the propagation of electromagnetic waves can now be traced to these '**Original Views**' that Faraday deposited with the Royal Society in 1832."*

In 1846, Faraday delivered an off-the-cuff and very speculative lecture at the Royal Institution, stepping in to replace the scheduled speaker, who had failed to appear. Faraday presented "*Thoughts on Ray-Vibrations*" [6] in which he considered the nature of fields and radiant phenomena. This was also to become part of the inspiration for Maxwell, but in some ways Faraday's speculations went beyond Maxwell. His first paragraph asks "*whether … vibrations which in a certain theory are assumed to account for radiation and radiant phaenomena may not occur in the lines of force which connect particles, …which … will dispense with the aether, which in another view, is supposed to be the medium in which these vibrations take place*." He continues that he has been led *"… to look at the lines of force as being perhaps the seat of vibrations of radiant phaenomena."* Although pure speculation at the time, Maxwell wrote, 18 years later, that "*The electromagnetic theory of light as proposed by him* [Faraday] *is the same in substance as that which I have begun to develop.*" In his Ray-Vibrations lecture, Faraday speculates further on whether the effect of gravity propagates with a finite velocity – and what the relationship might be between gravitational lines of force and electromagnetic lines of force. Between 1849 and 1851 Faraday tried, unsuccessfully, to find evidence supporting his "*strong feeling of a relation between gravity and electricity*" [7].

Faraday's demonstrated laws of electromagnetic induction, and his concept of lines of force, formed the experimental basis, in fact the inspiration, for Maxwell's theory of electromagnetic waves. Faraday published his discoveries, made from 1831 to 1855, in the three volumes of his *Experimental Researches in Electricity.*

Joseph Henry (1797-1878) had shown that high-frequency oscillations could be generated. Henry had been appointed Professor of Natural Philosophy at Princeton College in 1832. Of his many discoveries, one of the most significant for the future development of wireless technology was that the sudden discharge of a Leyden jar (the early "capacitor") could be oscillatory. The experimental evidence was that when magnetizing very thin steel needles, by discharging the Leyden jar into a solenoid containing the needle, the residual magnetism in the needle was sometimes N-S, sometimes S-N. Henry argued that this anomalous magnetization could be explained by assuming the discharging current from the Leyden jar was rapidly alternating in sign. Several other experimenters confirmed this in the ensuing years. In particular, Rutherford in 1894 made a detailed study of the magnetic needle phenomenon [8], which later became the basis for the magnetic detector used by Marconi and others, becoming a more reliable detector than the coherer. Lord Kelvin [p.57 of [9]] was the first to give, in 1853, the complete theoretical explanation of the oscillatory nature of the discharge from a Leyden jar. The rapidly discharging Leyden jar became the basis for generating sufficiently high frequency waves for radio experiments.

James Clerk Maxwell (1831-1879) began his development of electromagnetic theory by translating Faraday's ideas, expressed in the *Experimental Researches in Electricity*, into mathematical language. His first paper, in 1855, was indeed *On Faraday's Lines of Force.* Maxwell was struck by the similarities between electromagnetism and light phenomena, and in particular by Faraday's experimental demonstration of the effect of a magnetic field on the plane of polarization of light. By 1862, Maxwell was able to present Faraday's experimental results in the form of propagation of electric and magnetic vibrations through a medium, with a velocity given by the ratio of units of magnetic force to units of electric current. Using the latest electric and magnetic data available at the time, the predicted velocity of propagation of electromagnetic vibrations would be 310,740 km/s, within a few per cent of the best determination of the velocity of light. Maxwell regarded this as convincing proof that light was an electric and magnetic phenomenon. He wrote: *"The agreement of the results seems to show that light and magnetism are affections of the same substance, and that light is an electromagnetic disturbance propagated through the field according to electromagnetic laws"* (see p. 27 of ref. [4]). In 1864, he read a paper to the Royal Society on *A Dynamical Theory of the Electro-magnetic Field.* His work was highly mathematical, and his work was known only to a very limited scientific circle. Maxwell's work was published gradually in the period from 1864 to 1873, culminating in his *Treatise on Electricity and Magnetism,* published in February 1873. In his preface, Maxwell strongly recommends Faraday's *Experimental Researches in Electricity* as being the inspiration for the work.

The mathematical complexity of Maxwell's work undoubtedly hindered its becoming known or accepted by the scientists of the day. Even Hertz, who set out systematically to confirm Maxwell's theory, admitted (see the Introduction to reference [10]) having great difficulty understanding Maxwell's work. Maxwell's treatise does not, in fact, contain the now famous four "Maxwell's equations;" in the words of Oliver Heaviside in 1892, they were "latent" in the theory, but hardly "patent" [11]. Maxwell died in 1879, midway through preparing a 2nd edition of his Treatise. However, a select but strong following of Maxwell did emerge, including Oliver Lodge, Oliver Heaviside, G.F. Fitzgerald, Heinrich Hertz and others. "The Maxwellians" interpreted, developed and publicized Maxwell's results in the following years [11].

III. Experimental Verification of the Maxwell Theory

Verification of Maxwell's theory meant generating and detecting waves, which meant in effect building up technology that would ultimately be adapted to communication with wireless telegraphy. However, none of the experimenters who took up this task had any interest, or even saw the possibilities, of eventual communication by wireless. They were interested in the science of electromagnetic waves.

The technology for the transmitter was already in hand; the oscillatory nature of the discharge of a Leyden jar had become well established. In the earliest experiments, a secondary spark produced in the receiving circuit by the electromagnetic wave was used as the detection mechanism. Although not very sensitive, it served its purpose in establishing the validity of Maxwell's equations and the existence of electromagnetic waves propagating with a speed comparable to that of light.

As has been pointed out before [4], the serious work towards confirming Maxwell's theory experimentally split into channels: work by Oliver Lodge, and independently by Heinrich Hertz.

The approach of **Oliver Lodge (1851-1940)**, in attempting to verify Maxwell's theory, was to generate waves along an open transmission line. The frequency would be known from the fundamental parameters (inductance and capacity) of the Leyden jar used for the generation of the high frequency oscillations, and the wavelength could be measured from standing waves in the transmission line. In 1887-1888 Lodge worked on producing and identifying standing waves in wires. Lodge developed the famous "recoil kick" experiment, which showed that a strong spark could be produced at the far end of a transmission line only when the line was resonant. In Lodge's words [12] in 1888:

"The best effect should be observed when each wire is half a wave-length, or some multiple of half a wave-length, long. The natural period of oscillation in the wires will then agree with the oscillation-period of the discharging circuit, and the two will vibrate in unison, like a string or column of air resounding to a reed."

Lodge obtained resonance with wires 95 ft long, corresponding to a resonant frequency of about 5 MHz. In a later experiment, he was able to produce much shorter waves, but with enough voltage that the voltage maxima in the standing wave showed up as a visible glow or brush discharge. Lodge looked forward to presenting his results, which gave overwhelming support to Maxwell's theory, at the September 1888 meeting in Bath of the British Association. However, he was scooped by the earlier publication in 1888 of the results of Heinrich Hertz.

Heinrich Hertz (1857-1894) was the first to show free space generation, propagation and detection of electromagnetic waves, although the work of Oliver Lodge probably had a bigger impact on the development of wireless technology. Heinrich Hertz was born in 1857; Garratt [4] gives a nice summary of his early years, and his choice between the fields of engineering or natural science. In one letter to his parents in 1878, he regrets that he had not lived in an earlier age: *"I do not think that it will be possible to discover anything nowadays that would lead us to revise our entire outlook as radically as was possible in the days when the telescope and microscope were …"* (p. 41, [4]).

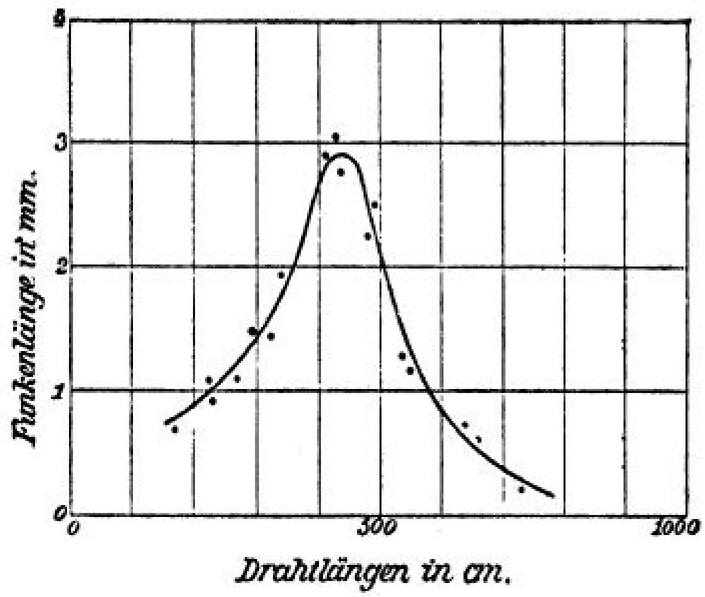


Figure 1. Hertz measured the response of his transmitter-receiver system as he varied the size of his receiving loop. Horizontal axis is the total length of wire in the receiving loop, and vertical the maximum size of spark possible at the micrometer in the receive loop. See reference [10].

In 1880 Hertz became an assistant professor at the Physics Institute of Berlin, working for von Helmholtz, who suggested he work on the need for a proof of Maxwell's theory about the velocity of electromagnetic forces. Hertz studied Maxwell's theory, and appreciated the need for generating short wavelengths and the problems in trying to do so. After a period of about two years at Kiel University, Hertz moved to the Technical High School at Karlsruhe. The Karlsruhe laboratory was particularly well equipped. By his own account [10], at this laboratory he found and used for lecture purposes a pair of so-called Riess or Knochenhauer spirals – this is a flat, spiral coil. He noticed that sparks across one could induce, without direct connection, sparks in the other coil. He studied the effect systematically, leading to a paper in 1887 [13] "On Very Rapid Oscillations." As a quantitative measure of the strength of the signal received in the unconnected spiral, he used a micrometer to measure the maximum size of spark that could be induced. As part of the study, he measured and plotted (Figure 1) resonance curves, showing how variation of the dimensions (i.e., the tuning) of the receiving circuit affected the sensitivity (the size of the induced spark gap) of the system. Figure 2 shows the general arrangement that Hertz used; a spark generator at the center of a capacitively loaded dipole as the transmitter, and a resonant loop as the receiver, with a micrometer to measure the maximum size of spark that can be received.

In the course of these experiments, he developed all the tools – the generator, the radiator, the detector, and the means of ensuring resonance between a transmitting and receiving circuit – needed for an experiment to verify Maxwell's predictions. Hertz well understood this fact and after referring to the possibility of confirming Maxwell's theory,

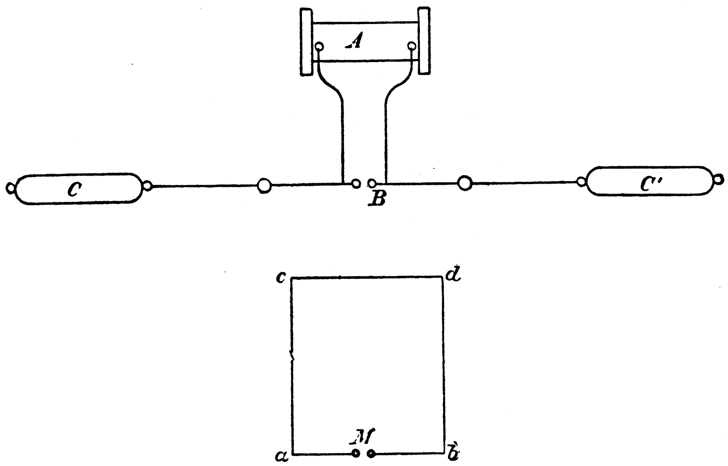


Figure 2 . The general arrangement used by Hertz; the spark at B energized a capacitively loaded dipole, and a resonant loop was the receiver, with a micrometer M to measure the maximum size of the spark

concludes this 1887 paper with: *The purpose of the present research is simply to show that even in short metallic conductors oscillations can be induced, and to indicate in what manner the oscillations which are natural to them can be excited.*

The key papers as regards confirmation of Maxwell's theories are *On the Finite Velocity of Propagation of Electromagnetic Actions* and *On electromagnetic Waves in Air and their Reflection,* both published in 1888. These are just two of the papers reproduced in *Electric Waves* [10], a collection of his papers which Hertz published in 1892. In order to

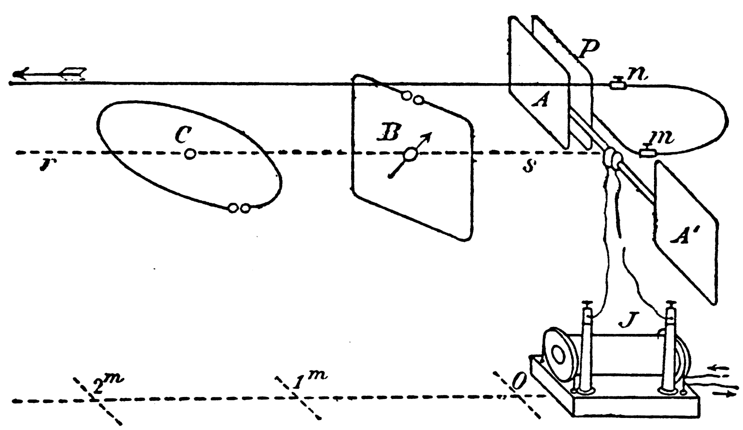


Figure 3. Hertz tried to compare the velocity of waves in free space and along a wire by looking for constructive and destructive interference between the two propagation modes. The wire was capacitively coupled to one side of his radiator.

support Maxwell, it would have been sufficient to prove that electromagnetic waves traveled with a finite velocity. By setting and measuring up standing waves, both along a wire and in free space, Hertz deduced a velocity of about 200 km/s. Figure 3 shows Hertz's arrangement; a long wire is capacitively coupled to one side of his radiator by a parallel plate. In his original papers, Hertz also concluded that the velocity was different for waves traveling along a wire, compared to waves in free space or air; he commented that this was not in agreement with the Maxwell theory, and required further study. In his introduction to *Electric Waves,* published four years after the original papers, Hertz acknowledges his earlier errors. There had been a square root of 2 error in one of his calculations in the original paper, which would have taken his velocity to 280 km/s. The difference between free space wavelength and that along the wire turned out to be problems with unwanted reflections within his laboratory. Hertz acknowledges in this introduction the subsequent work of Sarasin and de la Rive using a larger laboratory – the great hall of the Rhone waterworks at Geneva, where reflections were less of a problem [14] – which showed no significant difference in propagation velocity between waves in air and waves along a wire.

Hertz calculated his frequency from the dimensions of the capacity loading and the inductance intrinsic to his transmitter circuit. His receiving antenna was a loop containing a small spark gap; he adjusted transmitter and receiver to be in resonance. For the velocity measurements he used a circular wire loop of radius 37.5 cm, and a square loop with a side of 64 cm. With modern electromagnetic code, the resonant frequency of these receiver circuits can be calculated very much more precisely than was possible for Hertz. With some minor assumptions, the modern calculations give frequencies close to 60 MHz, for both the square and the circular loops. In later work published in December of 1888, *On Electric Radiation,* Hertz used shorter wavelengths to measure rectilinear propagation, focusing, reflection and refraction of electric waves. In these experiments, he found less discrepancy between the velocity along wire and in free space. He used a circular loop of diameter 7.5 cm for some of these short wavelength measurements. Again, the dimensions of the loop define the frequency Hertz must have been using fairly well, at ~580 MHz, a little lower than, but not entirely inconsistent with, one of his own estimates (e.g., p.175 of [10]) of ~900 MHz. Note that a modern analysis in effect **assumes** the known velocity of electromagnetic waves, which is the very parameter that Hertz was trying to establish.

The key point from Hertz's measurements is not the precision of his measurements, but that he demonstrated for the first time that electromagnetic waves traveled in free space, and along wire, at a finite velocity, and that the velocity was comparable to that of light in free space. This was a resounding confirmation of Maxwell's predictions.

IV. Near Misses

Although Hertz was the first to intentionally generate and detect electromagnetic radiation and to recognize it as such, he was not the first to have produced and detected such radiation. Charles Susskind [15] gives a nice summary of numerous "Observations of Electromagnetic-Wave Radiation before Hertz." Two of the more intriguing cases are mentioned here.

The Loomis (1826-1886) Patent. One pre-Hertz demonstration of electromagnetic signalling resulted in U.S. Patent 129,971 [16], *Improvement in Telegraphing,* being issued in July 1872. The "improvement" was the ability to dispense with wires – truly the first U.S. patent for "Wireless Telegraphy." Mahlon Loomis used two kites, each carrying a metal wire, separated by perhaps several miles. He found that shorting the base of the wire going to one of the kites generated a spark – as it discharged the natural static electricity picked up from the atmosphere . This caused a measurable electric disturbance at the base of the wire to the second kite. He used this technique in 1886 to send signals between mountains 14 miles apart [9], and later between ships 2 miles apart. The 1872 patent speaks of "*shocks or pulsations, which traverse or disturb the positive electrical body of the atmosphere above and between two given points* …". Loomis was unsuccessful in an appeal for $50000 from the U.S. Congress to develop the invention. Loomis used no tuning of any kind in his system – other than the natural resonance of the kite antennas. His system may have been the first "Ultra Wide Band" wireless communication system.

Professor David Hughes (1831-1900) successfully generated and detected electromagnetic waves in about 1879, several years before Hertz. He also noted and used coherer action, again several years before Branly and Lodge (see below.) The wireless results of Professor Hughes have always been somewhat controversial, with conflicting accounts from different authors, and from Hughes himself, about his experiments. There is, however, general agreement and indisputable evidence that he did produce and detect electromagnetic waves over a distance of several hundred yards, nearly a decade before Hertz. The disagreement is with Hughes' own interpretation of his experiments.

David Edward Hughes was born in London in 1831, and died also in London in 1900. He spent the early part of his life in the United States, becoming Professor of Music at St. Joseph's College, Bardstown, KY [9], and subsequently simultaneously holding the Chair of Natural Philosophy at the college. Although a professor of music, he clearly enjoyed inventing and had a flare for new technology. He took out a patent in 1855 for a type-printing telegraphy instrument that went into extensive use in America and Europe. He built a microphone formed of a carbon rod resting in grooves in two carbon blocks, wired in series with a battery and telephone. This was the forerunner of the carbon microphone, which was to come into widespread use with the telephone. In Dunlap's 1944 "Radio's 100 Men of Science" [9] Hughes is given the title "Pioneer of the Microphone."

Although Hughes' wireless experiments took place in 1878-1880, no account of the experiments was published in any form until well after Hertz's experiments. In 1892, Sir William Crookes [17] published a far-sighted article called "*Some Possibilities of Electricity,*" in which he speculated on future uses of wireless waves. His article talked about the possibility of world-wide communication, the penetration of wireless waves through fog and buildings, and about tuning to specific radio wavelengths and the need

Figure 4. A cylindrical microphone developed by Hughes, including a loosely contacted carbon cylinder with loose filings inside the tube. Note the similarity to later Branly and Lodge coherers. Hughes abandoned this as a detector of electromagnetic waves because it did not self-restore. (Science Museum, London)

for confidentiality of messages carried by wireless waves. In this article he pointed out that *"This is no mere dream …"*, and he alluded to events witnessed several years earlier, when he had "*assisted at experiments where messages were transmitted from one part of a house to another without an intervening wire …*" In his researches for his 1899 book [18], J.J. Fahie followed up on this report, and Crookes referred him to Hughes, who had carried out these experiments.

Hughes 1899 account of his earlier researches: In correspondence with Fahie in 1899, Hughes described his 1879 researches [19]. In 1879, while experimenting with a microphone, he had found that a loose contact or microphone contact was responsible for generating a sound in a telephone receiver, even though this receiving circuit was disconnected and several feet from the source. Hughes investigated further, searching for the "*best form of a receiver for these invisible electric waves, which evidently permeated great distances, and through all apparent obstacles, such as walls, etc.*"

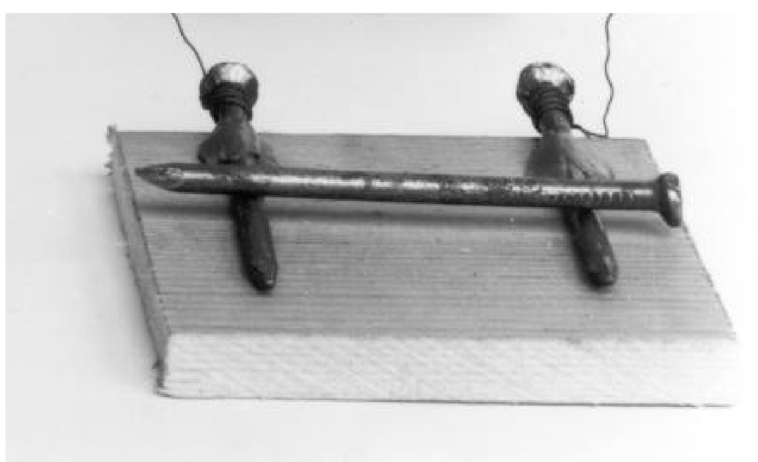


Figure 5. Another microphone from Hughes, using poor electrical contact as the sensitive element. Note the similarity with one of Branly's coherers seen in Figure 6. (Science Museum, London)

Hughes invited several eminent scientists and electrical engineers of the day to observe his results, including (December 1879) Preece and Crookes, and in February 1880

Spottiswoode (President of the Royal Society) and Professors Huxley and Sir George Stokes (Secretaries of the Royal Society.). *"They all saw experiments upon aerial transmission …"* Hughes was able to demonstrate reliable signalling up to 500 yards and, from the variation in signal strength with distance, apparently observed standing waves.

In his 1899 account of the 1879-80 experiments, Hughes talks about "aerial electric waves" or "aerial transmission," but admits that Hertz's experiments were more conclusive than his own, although, not having a coherer, Hertz's receiver was much less effective. Although Hughes' 1899 account talked about waves and aerial transmission, a later examination of his notes made at the time (see below) indicate that he thought conduction through the air was the mechanism. Very unfortunately for Hughes, the

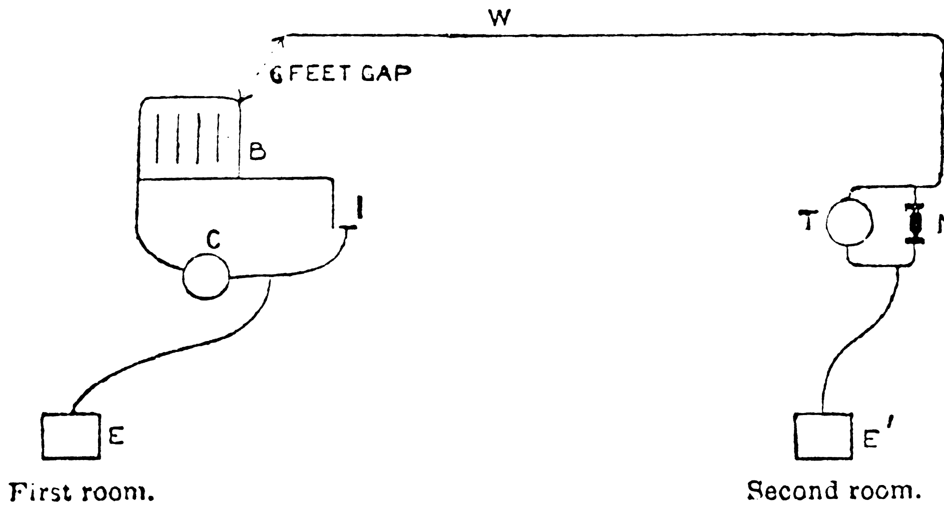


Figure 6. Hughes' experiment of October 15-24 1879. He transmitted between rooms in his house, with at first a 6 feet gap between transmitter and receiver. By the end of the year, his range had extended to several hundred yards. B is the battery, C the induction coil, I an interrupter. At the receiver, T is a telephone earpiece, and M the microphone used as a coherer. This diagram was produced by J.J. Munro, from Hughes' notebook, after his visit to Hughes in

eminent scientists, in particular Stokes, pronounced that it was all due to induction, not waves, and assured Hughes that his demonstration was nothing remarkable. This so discouraged Hughes that he never published his results, and abandoned further experimentation in this area.

As a result of the 1899 publication in *The Electrician*, J.J. Munro called on Professor Hughes, and inspected Hughes' apparatus and his notebooks. An account of the interview was published in reference [20]. Munro confirms Hughes' claims: the systematic work of developing a coherer receiver system, and performing long distance (several hundred yards) transmission and reception of wireless signals. Munro summarizes:

"Prof. Hughes had step by step put together all the principal elements of the wireless telegraph as we know it to-day [1899], *and although he was groping in the dark before the light of Hertz arose, it is little short of magical that in a few months, even weeks, and by using the simplest means, he thus forestalled the great Marconi advance by nearly twenty years!"*

Commenting on the bad advice given by Sir George Stokes, after appropriate tribute to Stokes, Fahie says (p. 315 of [18]): *"but in this case, as events show, the great weight of his opinion has kept back the clock for many years. With proper encouragement in 1879-80 Prof. Hughes would have followed up his clues, and, with his extraordinary keenness in research, there can be no doubt that he would have anticipated Hertz in the complete discovery of electric waves, and Marconi in the application of them to wireless telegraphy, and so have altered considerably the course of scientific history."*

The story takes up again in 1922, after Hughes' widow died, bequeathing some of his remaining notebooks to the British Museum. A.A. Campbell Swinton (Campbell Swinton had given Marconi his original letter of introduction to Preece in 1896) examines these, and is able to recover even more of Hughes' original equipment and further notebooks [21]; material had been stored and forgotten about in a furniture depository in central London since 1900. The report from Campbell Swinton [22] includes: "*They* [the newly discovered notebooks] *prove that Hughes undoubtedly noted some of the effects now known to be due to high frequency waves. He used a small spark coil as a generator, and a Bell telephone and a battery generally connected in series with a microphone as a receiver. The microphone apparently acted sometimes as a coherer … He received signals up to distances of about a hundred yards … nine years before Hertz's memorable discoveries.*"

Campbell Swinton in [23] quotes directly from Hughes' notebooks, written on the occasion of this visit by Mr. Spottiswoode (President of the Royal Society) and Professors Stokes and Huxley (the two secretaries of the Royal Society).
Hughes had written: *"Stokes commenced maintaining that the results were not due to conduction but to induction … Although I showed several experiments which pointed conclusively to its being conduction, he would not listen, but rather pooh-poohed all the results from that moment…"*

Commenting on the advice that had been offered to Hughes in 1879 by Stokes, Campbell Swinton wrote [22]: *"George Stokes stated that the effects were due to ordinary electro-magnetic induction. It would be interesting to speculate what might have happened had they encouraged him to proceed with his researches. …"*

Where does this leave the Hughes saga? From Hughes' 1899 account of his 1879 work, where phrases like "aerial telegraphy" appear, and also from Munro's 1899 interview with Hughes, the claim of being the first to generate and detect electromagnetic waves would seem very well-founded. There is now no dispute about the successful demonstration of wireless generation and detection over hundreds of yards, nor of Hughes' early discovery and refinement of what became known as the coherer.

However, Hughes' notebooks of the time, as pointed out by Campbell Swinton, indicate that Hughes himself had no suspicion that he was generating waves; he thought the mode of transmission was conduction through the air. This is an extreme contrast to the work of Hertz and Lodge, who had set out explicitly to try to confirm Maxwell's wave theory. Remembering that Hughes was a professor of music, Hughes in 1879 had almost certainly never even heard of Maxwell's theory.

The tragedy is that the experts of the day, Stokes, Huxley & Spottiswoode, did not recognize Hughes' experiments for what they were – a valid demonstration of electromagnetic waves. Stokes' interpretation as "induction" was as far off the mark as Hughes' own interpretation of "conduction through the air." This reflects how Maxwell's theory was far from accepted, in fact little understood, by the contemporary scientists.

Hughes clearly did demonstrate generation and detection of electromagnetic waves nearly a decade before Hertz, but neither he nor contemporary experts recognized the experiment as such.

V. TECHNOLOGICAL DEVELOPMENT AFTER HERTZ

After the publication in 1888 of Hertz's generation and detection of electromagnetic waves, and his verification that they possessed similar properties to those of light, a

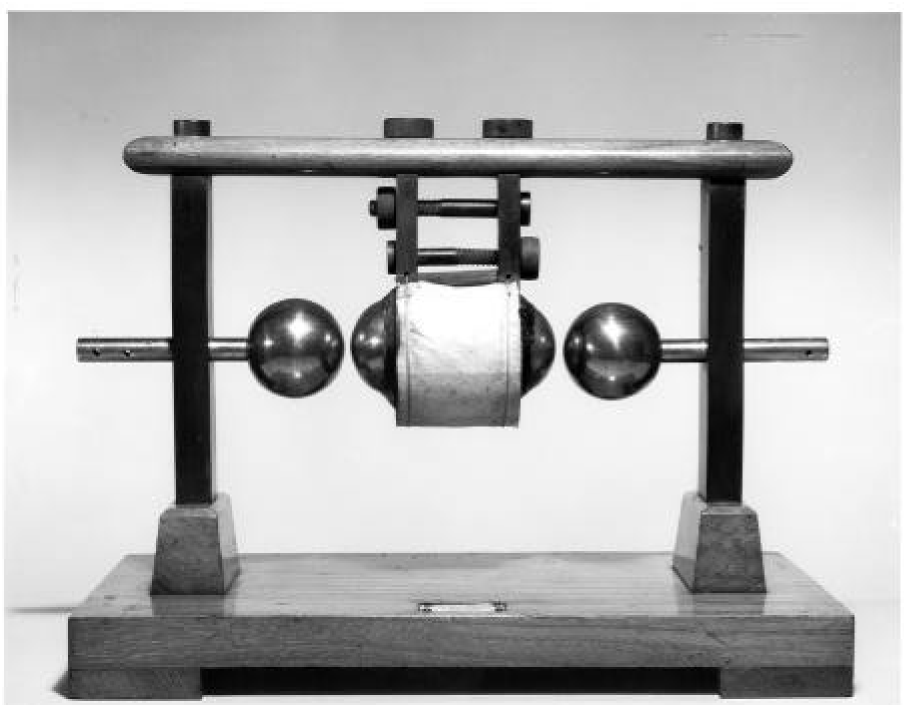


Figure 7. The "oscillator" used by Marconi, c. 1895. This spark gap system was described by Marconi by his first patent, granted in July 1897. The gap between the center spheres is filled with vaseline-oil. This is a modified Righi exciter. (Science Museum, London)

number of experimenters (e.g. Lodge, Slaby, Trouton, Fitzgerald, Righi, Popov, Bose…) soon repeated and extended his experiments. Although mostly developed to help in the scientific study of the newly discovered waves, these technical enhancements were crucial to the eventual support of communication systems.

The generation of sufficient power doesn't seem to have been an issue. Even the early experimenters appeared to have several kW of radio power at their disposal. A report on a public demonstration including radiation from a Leyden Jar transmitter system by Lodge in 1889 [24] included: *"During the course of this experiment, the gilt paper on the wall was observed by the audience to be sparkling, every gilt patch over a certain area discharging into the next, after the manner of a spangled jar. It was probably due to some kind of sympathetic resonance… For instance, a telescope in the hand of one of the audience was reported afterwards to be giving off little sparks at every discharge of the jar…"*

Key areas needing improvement were the sensitivity of the detector, and the selectivity of the transmitter and receiver system.

A. The Coherer

Hertz used a tiny spark gap in a resonant loop as the detector. Other experimenters repeated and extended Hertz's experiments, but a much more sensitive detector became available: to be named by Lodge, the coherer.

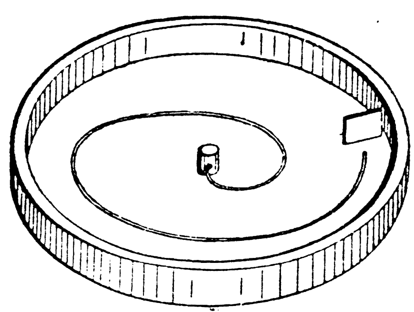


Figure 8. A spiral spring coherer designed and made by Oliver Lodge. At the left is Lodge's own diagram, taken from [e], while at right is the actual coherer made by Lodge. The spiral is an iron wire, which pushes on a small aluminum plate. The reverse side of the coherer has a lever which is used to adjust the pressure of the contact. (Science Museum, London)

Although even earlier experimenters had observed the phenomenon [15], Hughes too noticed the effect of a "loose contact" in the neighborhood of a machine generating

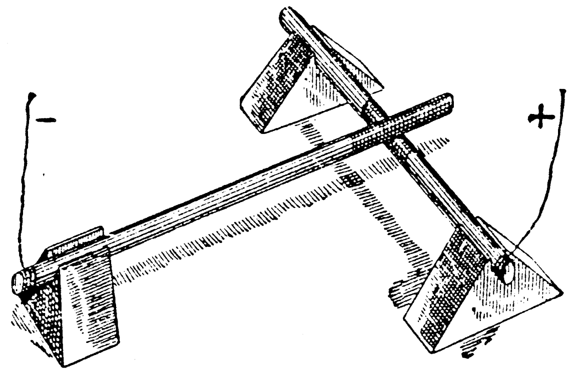


Figure 9. One of Branly's coherers, consisting of two oxidized copper, or of oxidized steel, rods. Note the similarity to the rusty nail microphone of Hughes, shown above in Figure 5.

sparks, and was almost certainly the first to apply the technique (1879) systematically to the detection of what were later realized to be electromagnetic waves. Hughes had been experimenting with microphones (Hughes is credited with the first use of the word microphone) involving loose contact between conductors, including the carbon granule microphone. Although the physics of operation is different, some of his microphones designed to detect acoustic waves were serendipitously also coherers (a name given to

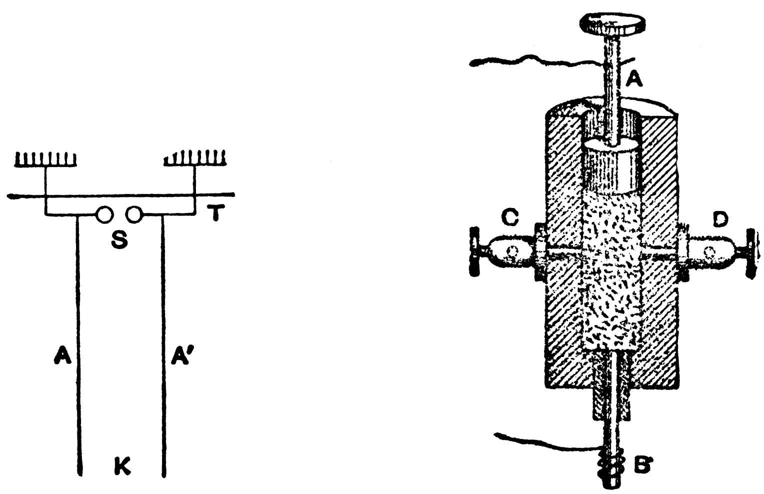


Figure 10. One of the arrangements used by Branly to investigate the change of conductivity through metallic filings. At left is the transmitter, with spark gap S and radiating elements A. At right is a coherer containing aluminum powder. The resistance horizontally between plates C and D, or vertically between plates A and B, could be measured independently. Branly found the conductivity through the coherer changed simultaneously in both directions. Taken from Branly's 1891 article, reproduced in [27].

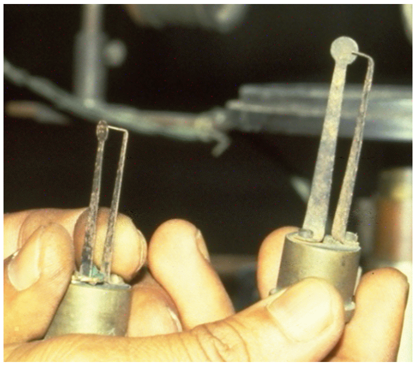
this type of detector by Lodge several years later) capable of detecting electromagnetic waves. Hughes used this type of detector in his 1879 experiments described above.

Quite independently, **Branly (1844-1940)** investigated "the variation of resistance of a large number of conductors under various electrical influences." [25]. Branly used the term "radioconducteur" for what Lodge later named coherer; this was probably the first

Figure 11. A filings coherer used by Lodge, 1894.
(Science Museum, London)

use of the term "radio" in the context of what were then known as wireless phenomena. He found the powders or filings of metals to be most effective. Figure (9) shows one of the arrangements he used to investigate the effect – here showing that the cohering had happened throughout the material, not just at the connection points. Within France, November 24 1890 is taken as the beginning of wireless – the date of Branly's coherer [26].

Oliver Lodge describes [27] work prior to1892 by a number of experimenters on the cohesion principle, but himself only became aware of Branly's work in 1892. He tried the Branly filings detector arrangement, and found it superior to other configurations in detecting electromagnetic waves. Although not alone in working on the detector, the main credit for the refinement of the coherer into a reliable, reproducible detector of electromagnetic waves is usually attributed to Lodge; his book *Signalling through Space without Wires* [27] contains a chapter devoted to "*The History of the Coherer Principle.*" Most of the experimentation and signalling experiments after Hertz, during the last decade of the nineteenth century and well into the start of the 20th century, used some type of coherer as the main receiver element.



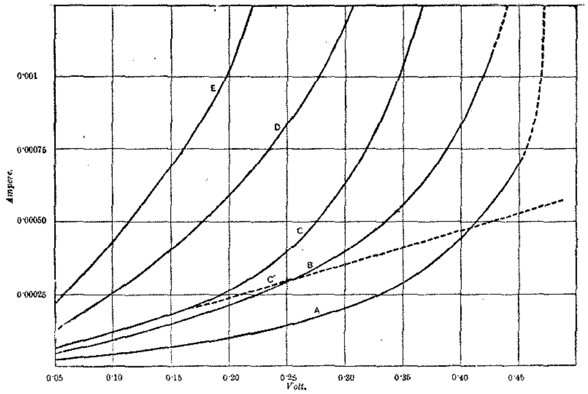


Figure 12. The iron point contact coherer developed by J.C. Bose, and used at millimeter wavelengths [29]. The graphs on the right show the I-V curves he plotted for different pressures on the junction. The knee in the characteristic is at about 0.4 volts.

There are two distinct modes of operation of the "coherer."

(i) The classic coherer (e.g., see Fig 11) consists of a glass tube containing metal filings, with a contact at each end. Initially there is very high resistance through the coherer – perhaps as much as a few Megohms. After a small voltage is received across the coherer – perhaps induced by a nearby spark or other source of electromagnetic wave – the insulation (for example, oxide) between the particles in the coherer tube breaks down, and the resistance through the coherer tube falls to perhaps a few hundred ohms. In this mode of coherer, the low resistance state persists even after the voltage is removed;

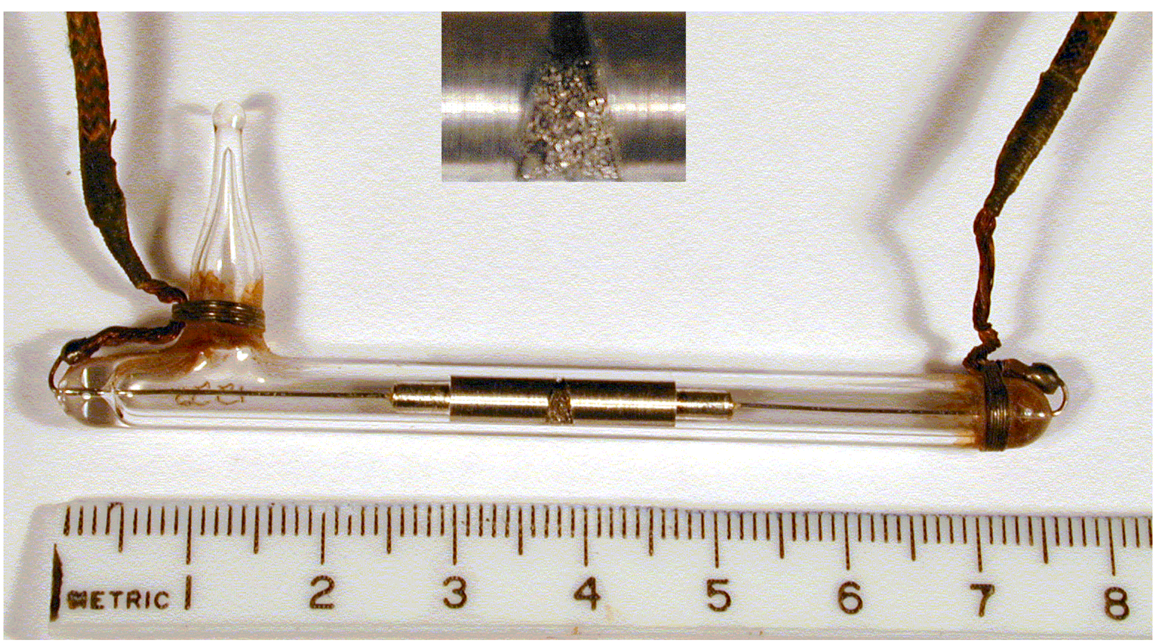


Figure 13 A Marconi coherer. Note the small gap in the metal plugs, containing metal filings, (enlarged in inset at top) and also that the tube is evacuated. (Courtesy of John Jenkins.)

for continued operation, the coherer needs to be "decohered" or restored. Usually, this was achieved by a mechanical shock, such as from the clapper of an electric bell. The name "coherer" is particularly appropriate, because of the small particles in the coherer tube effectively adhering or "cohering" to each other after the signal voltage has been received.

(ii) There was a search for a "self-restoring coherer," the second mode of operation of a so-called coherer. Rather than using the permanent breakdown of resistance between contacts as in the conventional coherer, a self-restoring coherer uses the non-linear resistance at the junction of two different materials – which we would today call a semiconductor junction. Fig 12 shows measurements that J.C. Bose, experimenting in Calcutta, made on some of his point contact junctions [28]; as Bose points out, the knee in his current-voltage curve occurs at about 0.45 volts. Bose also divided substances into positive and negative types, according to their behavior in junctions, so anticipating [29] p-type and n-type semiconductors. Bose was later recognized [30] as having priority in the use of a semiconducting crystal as a detector of radio waves.

Bose, in developing one filings coherer to be used for laboratory experiments, had used a small quantity of mercury at each end of the coherer tube [31], which apparently gave the detector a "self restoring" property. A similar scheme was later used by Marconi in one of the detectors he used for his transatlantic tests in 1901.

Fleming [32] gives a summary of theories of the principle of coherer operation, as seen in the year 1910. There is a remarkable collection of different mechanisms proposed, including welding action between the small metallic filings, minute sparking between the particles, electrostatic attraction between the particles, and a transfer of ions across a gap of only a few atomic diameters. Guthe and Towbridge [33] carefully measured the current I vs. voltage V relationship for a simple ball coherer, and found the empirical relation

$$V=v(1-e^{k.I})$$

with k and v constants

Although the principle of operation of the coherer was not well understood, a good deal of experimental work had been done. Many different experimenters introduced variations in coherer design. Some very similar designs involved mercury as a key constituent within the coherer, although it is not always clear who was responsible for which development. See, for example, accounts of "The Italian Navy Coherer Scandal" (recent appraisals are given in [34] and [35]), with a cast of characters including Lord Rayleigh, Sir J.C. Bose, Marconi, Fleming, Lodge, Lieutenant Solari of the Royal Italian Navy, Corporal Castelli, Prof. Tommasini and others.

For the evolution of wireless communication, the key point is that by the time the first commercial wireless links came into operation, towards the end of the 19th century, it had become possible to make detectors - coherers - routinely, in fact commercially, and with surprising sensitivity and reliability.

B. Wavelengths, and the Antenna

Clearly, use of an appropriate antenna was a key development, but inseparable from the wavelength in use. Hertz's experiments were at wavelengths of a few meters down to decimeters. Most early experimenters were interested more in the science of wireless waves rather than signalling over long distances. Lodge carried out experiments at wavelengths of a few cm, while J.C. Bose[29, 36] used even shorter wavelengths, down to a few mm. The radiators used were commensurate with the wavelength; many of Bose's antennas were essentially waveguide horns. From experiments in the 1890s by Marconi and others, it became apparent that longer wavelengths propagated further, while shorter wavelengths could be blocked too easily by obstacles. The rule of thumb, which became known as "Marconi's Law," was that the range achievable increased as the square of the height of the antenna – but of course the antenna size was one of the things that controlled the effective wavelength. The use of elevated long wires is one way of achieving efficiency at the longer wavelengths. The experiments of Loomis[16] in 1872 had already used kites to elevate a wire antenna for wireless telegraphy, as did subsequently Marconi for his 1901 transatlantic experiments. The ionosphere, and the possibility of effective long-distance propagation with low power at shorter wavelengths were of course unknown at that time.

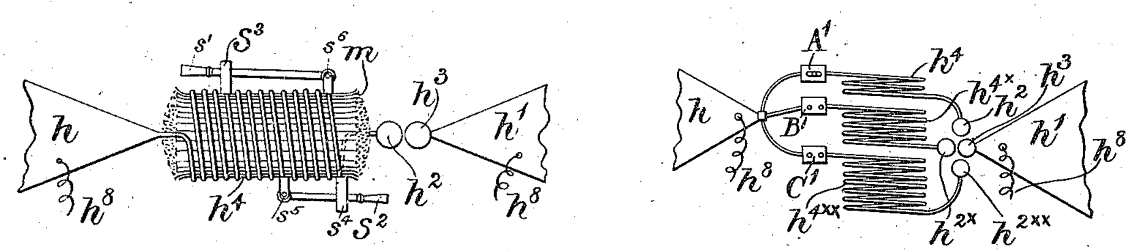


Figure 14. Figures from Lodge's patent 11575/97 on "Electric Telegraphy," filed in the UK in May, 1897. It shows a method of tuning an antenna ("h"-"h1") by adding inductance in series with the antenna. To the left is a continuously variable inductance, while at the right there are different present inductances h4, h4x or h4xx. The switching arrangement allows one of the 3 preset frequencies to be chosen, corresponding to different frequency channels.

C. Tuning or "Syntony"

Hertz had realized the importance of tuning, as a way of optimizing sensitivity. Fig.1 shows a resonance curve measured by Hertz in his early experiments; he changed the dimension of his receiving loop, and measured the relative responsivity from the size of the spark that could be induced at the gap in his loop. Lodge made an important step in his patent UK No. 11,575, applied for in May 1897 (in 1898 the corresponding US patent number became 609,154); this patent was submitted just two months after Marconi's first patent was published. The key step in Lodge's patent was adding a variable inductance in the antenna circuit to change the antenna resonant frequency, and to select one transmitting station in preference to others (see Fig. 14). The wording in the patent includes: "*… individual messages can be transmitted to individual stations without disturbing the receiving appliances at other stations which are tuned or timed or syntonized to a different frequency*." Marconi's famous UK patent No. 7777 in 1900 (the corresponding US patent is No. 763,772) featured tuning also. It is interesting to note that, after a legal battle, in 1911 the Marconi Company bought out Lodge's patent, vindicating Lodge's earlier prior pioneering work [37]. Marconi shared the Nobel Prize in 1909 with Carl Ferdinand Braun. Braun considered that Marconi's 1900 patent was very similar to his own 1899 patent on tuning; this also led to a lawsuit, between the Braun-Siemens and Marconi companies, which cited the Lodge settlement.

By the time that Marconi was preparing for his transatlantic tests in 1901, there were already several commercial wireless communication systems in use well within range of his planned transmitter, in the south of England. It was a serious concern for Marconi that the more powerful transatlantic transmitter would cause interference to the existing commercial links. Tuning, so that different stations could operate simultaneously without mutual interference, was taken very seriously: the beginning of EMC considerations.

VI. THE STAGE IS SET

The key technological developments – adequate transmitter power, antenna, choice of wavelength, receivers with adequate sensitivity, appreciation of tuning and selectivity ("syntony") – were all there. The realization of the potential and importance for communications, with the motivation to exploit the technology, was no less important. Several experimenters and entrepreneurs began to develop viable wireless communication systems, and the range was gradually being increased. By 1895, even before Marconi, there had already been public demonstrations of wireless signalling by Lodge, Bose, Popov and others. Precisely who holds precedence is really a matter of definition of "signalling." Transatlantic wireless communication had by 1901 become technically feasible, provided the theorists were ignored; the ionosphere was of course unknown, and diffraction around the curvature of the earth over the transatlantic path was calculated to present an impossibly high attenuation. The development of technology to this point had been hindered by the lack of understanding of the theory – i.e., Maxwell's equations – by most experimentalists. Now, the disregard of the theorists by Marconi became an advantage.

VII. WHY DID IT TAKE SO LONG?

From the appearance of Maxwell's theory to the successful detection by Hertz took a dozen years, although all the technology used by Hertz had been readily available even before Maxwell. However, Maxwell's treatise was difficult to understand even for the experts of the day; it needed to be interpreted into more intelligible form by "The Maxwellians" [11]. Even from the successful and well-publicized Hertz experiment, soon to be repeated by many other experimenters around the world, it took about 8 years before practical communications systems began to emerge. This was perhaps because the scientists doing the experimentation were not interested in communications possibilities, but rather the properties of the newly discovered form of waves. Even Oliver Lodge originally said the discovery of electromagnetic waves would never be of practical use, although he was to reverse that opinion and later developed practical communications systems himself, in competition with Marconi.

Ignorance of the theory, misapplication of the theory, negativeness of the theoreticians (e.g., the early discouragement given to Hughes over his demonstrations) all led to delays in development. Fortunately, Marconi the experimenter had the good sense to ignore the pessimism of the theoreticians about waves propagating over the Atlantic – the ionosphere was of course unknown at the time.

VIII. Conclusion

The necessary developments leading up to practical communication systems were derived often from an uncomfortable alliance between the theory and the experiment. Maxwell's theory predicting electromagnetic waves was difficult to understand, not immediately accepted by the scientists of the day, and not widely known. The poor and unnecessarily discouraging advice given to Hughes in 1879 by the "experts" of the day abruptly stopped that line of experimentation; if only Lodge or Heaviside had seen Hughes' experiments in 1879, the development of wireless might have been accelerated by nearly a decade. On the other hand, if Marconi had heeded the experts who told him that it was not possible for waves to diffract around the curvature of the earth and so across the Atlantic, he would never have attempted his transatlantic tests.

Whatever the perspective, the last decade of the 19^{th} century must have been an exciting time for those involved in the emergence of the science and technology of wireless.

Acknowledgements

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