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THE ROLE OF WAVELENGTH IN THE HISTORY OF WIRELESS

From the first experiments of Heinrich Hertz to the present, the development of wireless has been a journey of exploration up and down the the radio spectrum. This is the portion of the frequency and wavelength spectrum of electromagnetic waves that we now call "radio waves" (Figure 1). In this article we will trace the journey and the factors that motivated it. A useful online list of frequency allocations is at www.altair.org/labnotes_RadioBands.html

The first systematic investigation of the properties of radio waves was carried out by Heinrich Hertz in Germany in the 1880s. These experiments were designed to verify the electromagnetic theory of James Clerk Maxwell, which had been published in the 1860s. Hertz applied Maxwell's theory to calculate the radiation field produced by an ideal oscillating electric dipole. The predicted radiation was similar to that produced by a short dipole antenna (Figure 2).

Hertz used various experimental arrangements, but the one that most closely resembled later applications to wireless communications is shown in Figure 3. At the source, a high voltage electric spark generated by an induction coil caused electric charge to oscillate back and forth briefly between two metal rods. The oscillating current in the rods radiated a radio wave. Its frequency was of the order of 300 MHz, corresponding to a wavelength of about twice the overall length of the pair of rods.

To detect the waves, Hertz set up a second pair of rods a few meters away. Detection was indicated by a spark in a small gap between the rods of the second pair. The first and second pair of rods would be regarded today as dipole transmitting and receiving antennas, respectively. With this sort of apparatus, Hertz showed that the waves were transverse, like light, and could be reflected and refracted as Maxwell had predicted.

Although his spark source generated damped waves with an appreciable bandwidth, standing waves produced by reflection from a sheet of metal indicated a dominant wavelength of the expected magnitude. Hertz also placed cylindrical reflectors behind the dipoles to enhance the effects, and was able to detect the waves over a distance of about twenty meters.

In the 1890s, further experiments were done by Oliver Lodge of England. He showed the importance of "syntony" (having the transmitter and receiver resonating at the same frequency or wavelength). Alexander Popov of Russia constructed a storm detector that responded to the radio waves from lightning discharges. Jagadis Chunder Bose of India did quasi-optical experiments with radio waves generated by a spark source that were in the millimeter wavelength range.

All of these experiments replaced the small spark gap in Hertz's receiver by some form of a detector that Lodge called a "coherer." The best known type of coherer was a glass tube containing metal powder that clumped together or "cohered" when a radio frequency voltage of the order of a volt was applied to it. When the powder cohered, the resistance of the coherer decreased, and the resultant increase in direct current from a battery was registered on a meter or a paper chart recorder. The coherer basically behaved like a sensitive voltage-controlled switch that was turned on by the received radio signal.

Until about 1895, most experiments were designed to determine the properties of radio waves. The best known and most successful early experimenter who tried to harness radio waves for wireless communications was a young Italian

Frequency	Wavelength	Radio Band
30-300 Hz	10-1 Mm	ELF (extremely low frequency)
300-3000 Hz	1000-100 km	ULF (ultra low frequency)
3-30 kHZ	100-10 km	VLF (very low frequency)
30-300 kHz	10-1 km	LF (low frequency)
300-3000 kHz	1000-100 m	MF (medium frequency)
3-30 MHz	100-10m	HF (high frequency)
30-300 MHz	10-1m	VHF (very high frequency)
300-3000 MHz	100-10 cm	UHF (ultra high frequency)
3-30 GHz	10-1 cm	SHF (super high frequency)
30-300 GHz	10-1 mm	EHF (extremely high frequency)

Fig. 1. The radio spectrum: international frequency and wavelength band allocations.

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named Guglielmo Marconi. After transmitting and receiving radio waves (then called "Hertzian waves") in his attic, he moved his experiments out-of-doors. There he tried to maximize the distance over which radio signals could be detected.

He replaced one rod of Hertz's dipoles by a vertical wire antenna a few meters high, which was top-loaded by a sheet of metal. The other rod was replaced by a connection to the earth. An automatic "tapper" decohered the metal powder in his coherer after receipt of a signal to restore its sensitivity for the next one. As a detector, the voltage-controlled character of the coherer made it well suited to detect the short but strong signal from a spark discharge, and consequently it worked surprisingly well.

Marconi switched his transmitter on and off with a telegraph key to send messages in Morse code. He now had a primitive but complete system which was called the "wireless telegraph." When Italian authorities showed little interest in it, he and his Irish mother took his apparatus to England. England was a great maritime nation, and ships could obviously benefit from the ability to communicate at sea. He patented his system in England in 1896, and formed a company to manufacture wireless apparatus in 1897. His chief market was the shipping companies because the British Post Office controlled all forms of overland communications.

It was observed that the range or working distance of the system increased as the heights of the antennas were increased. In retrospect this could be expected because the electric field of the radio wave transmitted by a simple vertical antenna is proportional to the "effective height" of the antenna, which typically is close to its real height. Similarly, the e.m.f. induced in the receiving antenna by the incident radio wave was proportional to its effective height. This resulted in a rule-of-thumb that said that the range of the system was proportional to the square of the antenna height, assuming that the heights of both antennas were the same, leading to a "bigger is better" philosophy.

Although the wavelength of the system was ill-defined, the dominant wavelength in the radiated spectrum tended to be determined by standing waves in the antennas. Consequently the trend to taller antennas led to longer wavelengths. Radio waves of longer wavelength lost less energy as they passed over the ground, further increasing the range of communications. Electrical interaction with the ground produced a ground-hugging component of the radio wave called the "ground wave" that could travel over hills and even beyond the horizon.

After about 1900, transmitters and receivers were coupled to their antennas by radio frequency transformers. This removed the spark and coherer from the antenna circuits, raising the "Q" of the

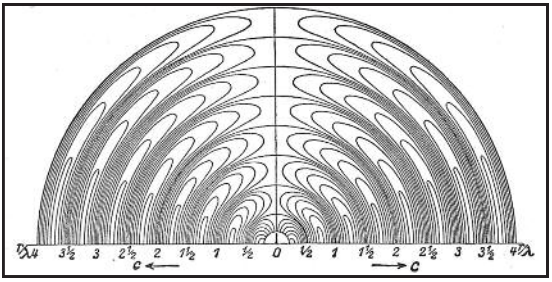

Fig. 2. The pattern of electromagnetic radiation from a short vertical dipole as calculated by Heinrich Hertz and published in 1889. The numbers represent distance from the dipole source measured in wavelengths. The pattern moves a distance of one wavelength away from the source during each cycle of oscillation of the dipole. The diagram shows contours of constant field strength in the electromagnetic wave. The field strength is zero along the vertical line which is an extension of the axis of the dipole, and is a maximum broadside to the dipole where the field lines are closest together. The three-dimensional pattern is obtained by rotating the pattern shown about the axis of the dipole.

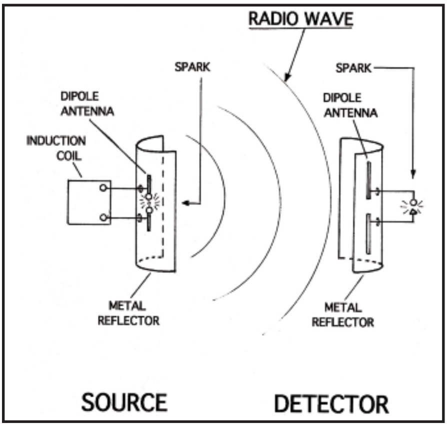

Fig. 3. Hertz's Apparatus. An electric spark between the rods at the source caused the pair of rods (dipole transmitting antenna) to radiate a radio wave. When the wave struck the pair of rods of the detector (dipole receiving antenna) a small spark was observed in the gap between the rods.

circuits and allowing the operating frequencies to be specified more accurately. The antenna circuits could now be regarded as composed of lumped circuit elements. These were mainly the capacitance of the antenna, the inductance of the antenna coupling transformer, and often an additional variable inductance to lower the resonant frequency. Doing this was sometimes called "electrically lengthening" the antenna, because it allowed the operating wavelength to be much longer than the resonant length of the antenna.

The Marconi Company now manufactured wireless equipment for ships designated "Tune A" (3 MHZ or 100 meters), and "Tune B" (820 kHz or 366 meters). Expected ranges were 50-70 miles for Tune A, and 80-150 miles for Tune B[1]. These ranges, and larger ones between shore stations, led Marconi to believe that the Atlantic Ocean could be spanned by wireless. If that could be done, no doubt the whole world could be linked up by wireless!

Most scientists were skeptical, believing that radio waves, like light, should travel in straight lines, and therefore radio transmitters, like lighthouses, should be limited to horizon range. However, Marconi knew that this limit had already been exceeded several times over. For reasons that were not understood, his radio waves seemed to go beyond the horizon and follow the curvature of the Earth.

In 1901, he built wireless stations at Poldhu in Cornwall, England, and at Cape Cod, Massachusetts for transatlantic wireless communications. Unfortunately the large antenna arrays at both stations blew down before he could test communications between them. Marconi then built a temporary transmitting antenna at Poldhu, and settled for receiving its signals over the shorter transatlantic distance to St. John's, Newfoundland.

The test signal was repeated sequences of the three dots of the letter "S" in Morse code, transmitted by Poldhu from 11:30 to 2:30 Newfoundland time each day, beginning December 11. His receiving antenna was a 500-foot wire supported by a kite. No definite signals were received the first day, using a tuned receiver with a paper chart recorder. On December 12, Marconi used an untuned receiver and listened for the signal with an earphone. He claimed to have heard several sequences of S's during the three hour test period. Bad weather terminated the experiment on December 13.

Many people were skeptical of his claim, and still are, because it seems nearly impossible to receive a transatlantic radio signal in the middle of the day at a wavelength of 366 meters. However, the company that operated the transatlantic telegraph cable believed it enough to demand that he cease his experiments, because they had a monopoly on telegraph operations in Newfoundland.

Marconi was confident enough of the results to build a permanent transatlantic station in Glace Bay, Nova Scotia, with financial help from the Canadian government. While it was under construction he tested the range of signals from Poldhu with a tuned receiver and recorder on an east-to-west voyage to New York on a passenger liner. He found that he could only receive signals about a third of the distance between Poldhu and Newfoundland in the daytime, but he could receive weak signals the whole distance at night. This turned out to be a good predictor of what he would achieve with his new Glace Bay station; i.e., intermittent signals at night and nothing during the day.

Keeping in mind that 366 meter (820 kHz) was in the present day AM broadcast band, this is about what one would expect. In fact it was very good, considering the primitive equipment used, even if it was inconsistent with the claimed results of the Newfoundland experiment. Both the day-night variation, and the fact that the radio signals crossed the Atlantic at all, was due to the radio waves being reflected by the ionosphere, but that was not known by Marconi and his contemporaries.

After many trials and tribulations, Marconi transmitted the first official transatlantic wireless message to Poldhu on the night of December 15, 1902. Experiments and modifications to the Glace Bay station over the next two years brought some improvement, but showed that a reliable twenty-four hour service would require more powerful stations operating on much longer wavelengths. The Marconi Company built new stations on both sides of the Atlantic for this purpose. They were at Clifden on the west coast of Ireland, and at a larger site in Glace Bay that was called "Marconi Towers" locally.

The coherers were replaced by magnetic detectors, and later by crystal diode rectifiers. These detectors produced an audio frequency output, and operators with headphones and pencil and paper replaced the paper chart recorder. Although this arrangement seems like a step backwards, the human ear made the whole system far more sensitive. A commercial twenty-four hour (more-or-less) service between Clifden and Glace Bay began October 17, 1907.

This achievement indicated that the road to reliable long distance wireless communications lay in the use of wavelengths of thousands of meters. Now the race was on! Countries with far-flung empires built high powered long wave stations to communicate with their colonies, and military powers with navies built them to communicate with their ships in distant parts of the world.

The corresponding low frequencies of tens of kilohertz enabled transmitter technologies other than the spark to be used; namely the oscillating arc and high speed generators. The Poulsen arc transmitter was developed in Denmark, and high powered versions were built in the United States. The largest of these was an American-built one-megawatt monster at Bordeaux, France.

A high frequency alternator was designed by Reginald Fessenden, a Canadian working in the United States, who was an early competitor of Marconi in transatlantic wireless. A high powered version of his alternator was built by Ernst Alexanderson of the General Electric Company, and became a popular type of transmitter for long wavelength stations. The German Goldschmidt alternator utilized internal frequency multiplications to reach radio frequencies.

The arc and high frequency alternators produced a steady "continuous wave" instead of the impulsive "damped wave" of the spark transmitter, permitting much sharper tuning. The continuous wave also permitted amplitude modulation at audio frequencies, pioneered by Fessenden with his 1906 Christmas Eve broadcast of voice and music. This application, called "wireless telephony," was not used as much as wireless telegraphy initially because of practical difficulties with the methods of modulation.

One method was to insert a carbon microphone, or combinations of them, in series with the ground connection of the transmitting antenna. Needless to say, the microphone became hot, and speakers had to keep their lips a safe distance from it. Alexanderson developed a better method for modulating high powered transmitters, in which the audio frequency current from a carbon microphone controlled the radio frequency current of the transmitter by means of a magnetic amplifier.

Although increasing the wavelength increased the range and reliability of radio wave propagation, diminishing returns set in at very long wavelengths because of the decreasing efficiency of antennas of practical size. The problem is best described in terms of the "radiation resistance" of an antenna, which is a measure of its ability to radiate. For efficient operation, the "loss resistance," representing antenna energy losses of all types must be kept small compared to the radiation resistance, with which it is effectively in series.

Since the radiation resistance of a simple vertical antenna depends on the ratio of its height to the wavelength, it tends to be small for antennas of practical size, making it difficult to make the loss resistance even smaller. For example, the Marconi Towers antenna at Glace Bay, which was a large umbrella about 200 feet above the ground, had a radiation resistance of about a tenth of an ohm at its operating wavelength of 8000 meters. In the end, low efficiencies often had to be tolerated.

Similar problems arose with long wavelength receiving antennas, because before the introduction of electronic amplification, efficient transfer of power from the antenna was needed to operate the detection apparatus. This required the resistance of the detector to be matched to the radiation resistance, and the loss resistance to be much smaller than either of them. In a receiving antenna, the radiation resistance represents the re-radiation of part of the received signal power.

The next major innovation in wireless was the vacuum amplifier tube, or "valve" as it was called in Great Britain. This revolutionized radio and ushered in the age of electronics. Although it was invented in 1906 by the American, Lee de Forest, its development was slow until about World War l (1914-1918). Tubes made receivers thousands of times more sensitive, so that they no longer needed huge antennas to actuate their detectors. Satisfactory reception now depended less on a strong received signal, and more on just a good signal-to-noise ratio. Radio frequency amplifiers, detectors, and audio frequency amplifiers all employed tubes.

It was discovered that when sufficient positive feedback was provided to compensate for signal losses in an amplifier circuit, continuous wave oscillations could be produced. As high-powered tubes were developed, they were employed in transmitters as radio frequency oscillators, power amplifiers, and modulators. Vacuum tube transmitters began replacing the arc and high frequency generators. Multiple stages containing tubes and resonant circuits allowed both transmitters and receivers to be tuned sharply, and transferred the role of determining their operating frequencies from the antennas to the transmitters and receivers themselves.

These improvements, together with affordable receivers that required relatively small antennas, led to the radio broadcasting boom of the 1920s. Regulators, who initially regarded broadcasting as a frivolous use of wireless, assigned LF and MF bands for broadcasting that became the present AM radio bands.

Wavelengths shorter than 200 meters had been considered of no commercial value, and were largely relegated to amateurs. As time went on, reports began coming in of occasional reception at long distances, using short wavelengths and relatively little transmitter power. The question arises as to why this was not observed sooner[2]. One reason was that there was not much motivation to look for reception beyond the relatively short range of the ground wave at these wavelengths. Perhaps more important was the fact that amateurs now had sensitive vacuum tube receivers.

Short wavelength transmitters were installed at Poldhu, and Marconi began observing how far he could receive their signals on his yacht "Elettra," which was a floating radio laboratory. Impressed by the results, he changed a proposal for an "imperial chain" of stations connecting Britain's colonies to the motherland from long wave to short wave. The first link opened between London, England, and Montreal, Canada in 1926, and the venerable long wave service between Britain and Nova Scotia was shut down.

Another victim of the abrupt change to short wave was RCA's "Radio Central" long wave station. Powered by Alexanderson alternators, it was intended to reach anywhere in the world. Construction of its huge antenna array with arms pointing in twelve compass directions, was stopped after only two arms were completed. Although investment in such long wave stations was halted, some were retained as a backup, and some military applications of very long wavelengths continue to the present.

Short wave had several advantages over long wave. The shorter wavelength allowed antennas of practical height to have a large radiation resistance, and therefore high efficiency. Transmitting antennas could increase their effective radiated power by being highly directional, because strong directivity requires the dimensions of the antenna to be much greater than the wavelength. Directional short wave antennas with multiple elements were constructed as antenna design matured from cut-and-try to sophisticated engineering. Reception benefited from much lower atmospheric noise levels at short wavelengths.

Short wave reception is strongly affected by variations of the ionosphere with time of day, season, and latitude, plus rapid variations. However, as the ionosphere became better understood, users learned to work around these difficulties, and short wave became the preferred medium for long range wireless communications. The use of vacuum tubes in short wave stations meant that the signals could be modulated, and short wave stations began broadcasting to the whole world.

In the late 1930s, and particularly after the development of radar during World War II, attention turned to the final frontier in the radio spectrum: wavelengths of meters to millimeters. These wavelengths had been investigated by Chunder Bose in the 1890s, but they were largely ignored for another two or three decades as the quest for long distance communications led to longer wavelengths.

It now was realized that propagation at very short wavelengths is essentially in straight lines, and is hardly affected by the ionosphere. This made these wavelengths suitable for satellite and space communications, as well as for horizon-limited communications when propagation to long distances would cause interference between users.

Very short wavelengths enable antennas of practical size to have high efficiency, gain and directivity. Relaying radio signals via satellites largely replaced short wave for long distance communications by providing reliable propagation free from ionospheric variations. The broad spectrum of frequencies available in this part of the spectrum made them suitable for bandwidth-hungry applications such as FM radio, television, and cell phones.

As wireless communications progressed over the years, there was a parallel development of wireless applications for navigation and position finding. As in communications, the wavelengths employed were determined largely by the needs of the applications. The worldwide Omega position finding system used wavelengths of about thirty kilometers. Radio beacons use a range of wavelengths from long to short. Satellite-borne GPS and highly directional radar use very short wavelengths.

Our chronological tour through the history of wireless initially led us down the frequency scale from Hertz's UHF experiments to giant long wavelength stations for long distance communications, and then back up again following the development of short wave and finally microwave technology. Now all wavelengths are utilized according to their suitability for particular applications, and international agreement brings order to the multitude of demands on the radio spectrum.

FOOTNOTES

1. "Naval Radio," in *Warship International*, page 119, Volume XXXVII, No. 2, (2000).
2. Perhaps Marconi had observed it in the Newfoundland experiment of 1901 without realizing it. The poorly tuned Poldhu transmitter may have radiated a significant amount of energy at short wavelengths. This may be why he claimed to receive the transatlantic signal with an untuned receiver, but not with a receiver tuned to the intended wavelength of 366 meters.