Hertz and Marconi: A Comparison Between The Apparatus of Their Landmark Experiments

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We all know that Heinrich Hertz [Hamburg, Germany, 1857 – Bonn, Germany, 1894] (Figure 1a) first proved the existence of electromagnetic waves in his laboratory. His spark-based experiments [1, 2] demonstrated not only the existence of waves by showing that the transmitter in the proximity of a conducting wall generated nodes and antinodes that were compatible only with wave propagation [3], but also confirmed the theoretical prediction by James Clerk Maxwell [Edinburgh, Scotland, 1831 – Cambridge, England, 1879] that the speed of such waves was equal to the speed of light [2, 4]. On the other hand, the phenomenon remained limited to his laboratory and, even if replicated, remained confined to scientific demonstrations or little more up to 1895. It was at that point that Guglielmo Marconi [Bologna, Italy, 1874 Rome, Italy, 1937](Figure 1b) managed to have his receiver buzz well over a mile away from the transmitter, and behind a hill [5, 6].

Both of these events deserved an IEEE Milestone:

- "First Generation and Experimental Proof of Electromagnetic Waves, 1886-1888" was dedicated in Karlsruhe, Germany, on December 5, 2014;
- "Marconi's Early Experiments in Wireless Telegraphy, 1895" was dedicated in Pontecchio Marconi, Bologna, Italy, on April 29, 2011.

It ought to be said that Marconi's priority in achieving long-range transmissions were contested by Nikola Tesla [Smiljan, Croatia, 1856 – New York, USA, 1943] in the USA, who claimed beginning similar experiments in 1891 [7] and claimed a successful 30-mile link "prior than 1897." It is also fairly well known that Aleksander Popov [Krasnoturinsk, Russia, 1859 – San Petersburg, Russia, 1906] obtained successful communications on March 26, 1896, seven days after Marconi's filing for his first patent in England [8]. The location of Marconi's first experiments has also been a matter of discussion [6, 9].

It is an interesting matter to understand the differences in the two devices used by Hertz and Marconi: the advancements done in those eight years that allowed the second person to bring human-generated electromagnetic waves out of a laboratory and into an enterprise that would change the world.

Figure 1a. Heinrich Rudolf Hertz [Hamburg, Germany, February 22, 1857 – Bonn, Germany, January 1, 1894].

Figure 1b. Guglielmo Giovanni Maria Marconi [Bologna, Italy, April 25, 1874 – Rome, July 20, 1937].

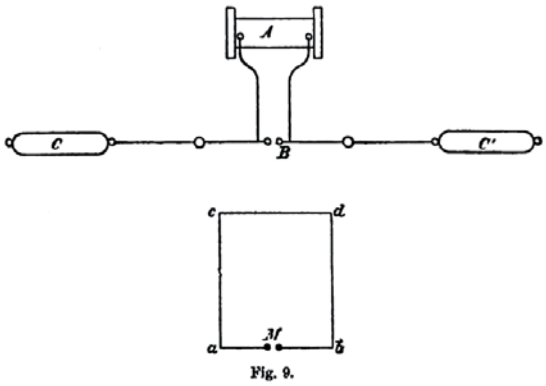

Figure 2a. A schematic of Hertz's apparatus [1].

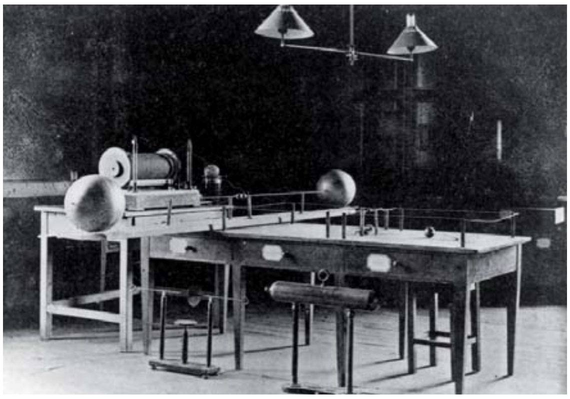

Figure 2b. A photo of Hertz's laboratory, with an apparatus such as that used in 1888 (photo made in 1901 by A. Schleiermacher [1857-1953], Hertz's assistant).

1. Hertz's Apparatus and Indoor Experiment

Hertz's experiment has been revisited very competently in a couple of recent papers [3, 10], so we will briefly recall it here. Hertz's apparatus is shown in Figure 2.

As pointed out in [1, 3, 10], the two large spheres (30 cm in diameter) placed 1 m apart formed a capacitor, while the rod connecting them, 5 mm in diameter, formed an inductance. The spark gap was defined by two spheres 3 cm in diameter. Some quick computations lead to the following estimates [10, 11]:

$$C = 9.82\ \text{pF},$$

$$L = 746\ \text{nH},$$

and hence a resonant frequency of $f = 58.77$ MHz, and a wavelength of $\lambda = 5.10$ m.

We are not aware of the voltage provided by the Rhumkorff coil, but we can assume 5 kV for the sake of comparison for both apparatus: Hertz's and Marconi's. Furthermore, we shall assume 100 Hz as the frequency of repetition of the sparks, that is, the capacitors were charged 100 times per second. Oscillations at 58.77 MHz excited by each single charge/discharge were completely damped due to radiation and losses before the next charge/discharge.

Figure 3a. The Celestini hill, as seen from the window of Marconi's laboratory at villa Griffone, looking towards the receiver location. In the foreground is the structure holding the IEEE Milestones (courtesy of Marconi Foundation).

Figure 3b. A map with the positions of the transmitter, the receiver, and the hill in between (courtesy of Marconi Foundation).

Figure 3c. The Celestini hill, seen from the receiver location, looking towards the transmitter at Villa Griffone (completely hidden by the trees) (courtesy of Marconi Foundation).

Figure 4a. A reconstruction of Marconi's 1895 antenna in the garden of Villa Griffone, Marconi's house (courtesy of Marconi Foundation).

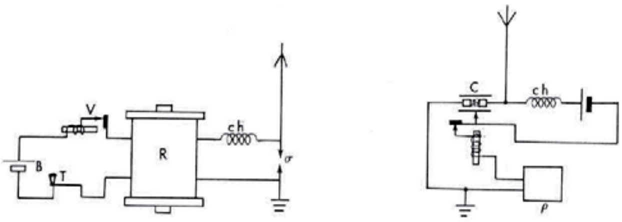

Figure 4b. Schematics of Marconi's transmitter and receiver, from [12].

For this voltage, the capacitor stored 122.5 μJ at each charge. In continuous operation, the power was hence the energy of the 100 charges happening in one second, ideally $P = 12.25$ mW. In practice, part of this power was dissipated in the conductor and not radiated. We might safely assume that only half of this power was actually radiated, or about 6 mW.

Of these few milliwatts, a large part must have been collected to allow visible sparks in the receiver, hence Hertz and others duplicating these results could never put too much distance between the transmitter and receiver.

2. Marconi's Apparatus and Outdoor Experiment

Marconi's initial experiments were basically similar to Hertz's, but in 1895 Marconi soon shifted to outdoor experiments. There, the radiating conductors were vertical and halved, that is, just one vertical wire, the other end being grounded. He also worked with longer and longer wires, loaded at the higher end with plates or metallic cubes. The breakthrough experiment, with the receiver more than one mile away and behind the celebrated "Celestini hill" (Figure 3), used a 8 m high pole, with four metallic cubes of 1 m edges connected at the higher end, the transmitter still being based on a Rhumkorff coil and a spark gap [12] (Figure 4).

What was completely different was the receiver, which was somewhat "active," even if not in our modern sense of being capable of amplification. It contained a battery providing the energy to ring a bell once the radio-frequency signal caused the shortening of a peculiar and sensitive device named a coherer.

Here, the evaluation of the working frequency was more difficult, due to the odd antenna (Figure 4). We can approximate the four cubes, 1 m on a side, with a surface of 6 m^2 each, as four spheres of equal area, that is, a radius of 70 cm, placed 8 m above a perfectly conducting ground, hence 16 m from their image according to the image theorem. By applying the same formula as above [11] to each pair, and considering the four pairs in parallel, one obtains

$$C = 162.9 \text{ pF.}$$

On the other hand, the 8 m wire inductance, assuming 1 mm diameter, gives

$$L = 15.0 \text{ μH,}$$

which yields $f = 3.22$ MHz and a wavelength of $\lambda = 93.1$ m. Hence, in this case, the 8 m wire was indeed short.

Again, let us assume for comparison the same 5 kV and 100 Hz for the excitation. In this case, the capacitor stored 2.03 mJ, for an ideal power of $P = 203$ mW and possibly ideally 0.1 W radiated.

Absolute numbers are not really meaningful, due top the unconfirmed hypotheses of 5 kV and 100 sparks per second, but the relative values are important. Marconi managed to radiate about twenty times the power radiated by Hertz, but, as already mentioned, this would not have been enough.

In 1884, Temistocle Calzecchi-Onesti [Lapedona, Italy, 1853 – Monterubbiano, Italy, 1920] observed a drastic reduction of resistivity in a tube filled with iron filings when a circuit with an inductor was opened and closed [13]. In 1890, Édouard Branly [Amiens, France, 1844 – Paris, France, 1940] studied the same phenomenon, independently and unaware of [13], and observed that the device switched to conductivity if a spark was generated, even at a distance. In 1894, Oliver Lodge [Penkhull, England, 1851 – Wilsford, England, 1940] repeated Hertz's experiments by using such a device, which he named a coherer, and which proved to be a much more sensitive detector than the wire loop used by Hertz. Branly and Lodge focused their research on the mechanisms of powder conductivity, neglecting the practical applications, which were, on the other hand, crystal clear in Marconi's mind.

According to Lodge, the grains became dipoles and were mutually attracted, forming conductive chains. Branly did not believe this was the mechanism, and indeed showed that grain motion was not behind the phenomenon, since particles embedded in wax or resin still behaved the same way, and indeed a column of six steel balls a few centimeters in diameter also did. However, the invention of the diode and the triode early in the XXth century made the coherer obsolete, and stopped further research. Indeed, the mechanism behind the coherer is still not fully understood [14].

However, it was in bringing this approach to the extreme, with higher vertical antennas and more and more powerful spark-based transmitters that Marconi managed to cross the Atlantic in 1901.

3. Acknowledgments

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