The Coherer Era

The Original Marconi System of Wireless Telegraphy

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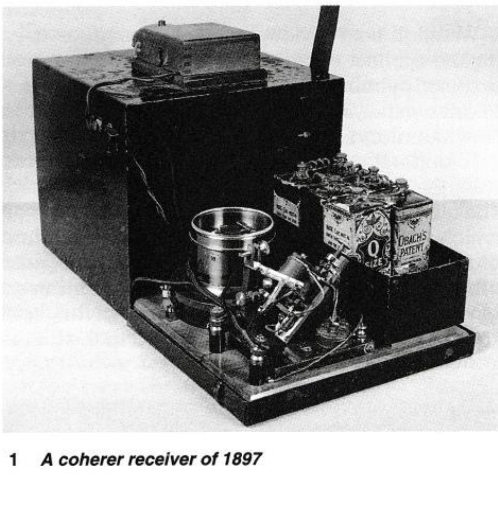
The quest for a means of wire-less communication has exercised the minds of scientists and engineers since the early days of electricity. In fact, it is over two hundred years since the original proposals for wireless telegraphy by the Spanish Physicist, Salvá; he presented a paper entitled 'On the Application of Electricity to Telegraphy' before the Spanish Academy of Sciences on December 16th 1795[1]. Serious attempts at practical implementation, however, began in the 1830s. By 1895, numerous workers had demonstrated wire-less communication over modest ranges[1–3] and there were several instances of unsuccessful exploitation. There was little commercial prospect for systems which did not outperform established signalling media such as flags, lamps, semaphore and the heliograph.

Guglielmo Marconi overcame initial rejection of his approach – particularly from the scientific and engineering 'establishment' and the cable companies with their vested interest – by demonstrating that he could communicate over tens (in 1896), then hundreds of miles; and finally, in 1901, two thousand miles across the Atlantic from Poldhu in Cornwall. The secret of long-distance commercial wireless telegraphy lay partly in the detector – the filings coherer (see Appendix 1) – which he developed to give a combination of sensitivity and reliability which even the best modern copies are pressed to match. Marconi succeeded because he painstakingly characterized his coherers and adapted every other part of his system to provide the most appropriate type of signal waveform across the coherer terminals at the receiving end.

The Coherer

The Marconi Museum[4] holds original equipment from the 1890s, including unused coherers with their original test certificates (fig. 1). Tests on these and on modern reproductions have shown that the ideal receiver waveform consists of a single, very sharp initial voltage pulse applied across the device in its high-impedance state; this must be followed immediately by typically less than a nanojoule of energy transferred to the device as its impedance falls towards the conducting state.

This paper shows that Marconi's early transmitters and their aerials were designed to provide a sharp initial pulse, followed by a short damped oscillation. The sharply impulsive waveform is ideal for a filings coherer but is incompatible with efficient syntony (tuning). Syntonic wireless was first developed by other workers, notably Oliver Lodge[1], but was initially handicapped in range by the lack of an efficient mean-sensitive detector.



1 ***A coherer receiver of 1897***

The need for tuning became pressing in 1901 when test transmissions from Marconi's high-power transatlantic station at Poldhu interfered with other services. Marconi understood syntony and was already exploring ways to incorporate it[5], but he believed that a sharply impulsive transmission was essential to long-range communication. The enormous wide-band cone aerial at Poldhu was designed to radiate pulses of high peak power.

Fate intervened; the Poldhu aerial was blown down and had to be replaced by a simpler and smaller arrangement. Insulation problems at the transmitter limited the peak voltage. Marconi's assumption about long-range transmission appeared to be correct: although the transmission was inadequate to operate a filings coherer at 2000 miles range, he was able to hear the transmission by substituting an 'Italian Navy coherer', a primitive mean-sensitive detector using a globule of mercury and now recognized to be a form of contact rectifier (see also Appendix 1).

This was a turning point – from then on, Marconi transmitters and their aerials were designed to maximize oscillatory energy content; selective tuned receivers were introduced using improved mean-sensitive detectors such as the carborundum contact rectifier, the magnetic detector, and the Fleming diode[4]. Though more sensitive than the filings coherer, the Italian Navy coherer could not be used to operate a Morse inker, because of the lack of suitable amplification. The Italian Navy coherer played no part in the commercial development of wireless telegraphy. Manufacture of coherers ceased and 'The Marconi System of Wireless Telegraphy' evolved into what we now call Radio.

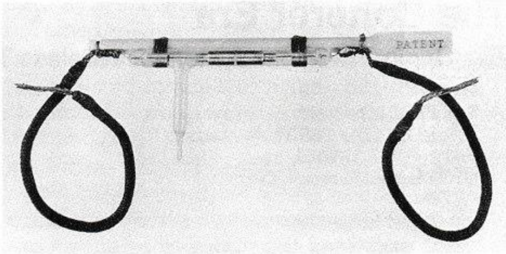
System Developments: Transmitters and Aerials

Introduction

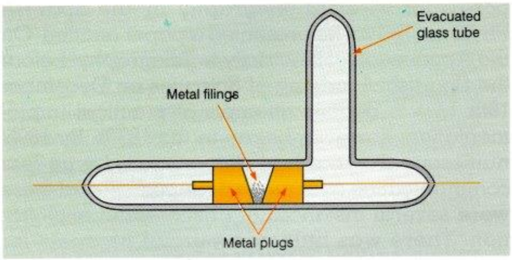
We shall next review antenna* design as used for the earliest experiments employing untuned systems, culminating in the December 1901 transatlantic experiment from Poldhu, UK to St Johns, Newfoundland.

To understand the system it is necessary to consider the method by which signals were detected. The filings coherer (see Appendix 1) is a device on which Marconi himself was probably the leading practical expert. It consists of an evacuated glass tube partially filled with filings (Marconi used various combinations of nickel and silver), and containing two electrodes immersed in the filings

* The terms 'antenna' and 'aerial' are entirely synonomous and differ only in their historical context. Marconi himself referred only to 'aerials'; nowadays 'antenna' is the more usual word.



2 A Marconi coherer



3 A diagram of a coherer (the metal plugs were generally silver, with platinum connecting wires)

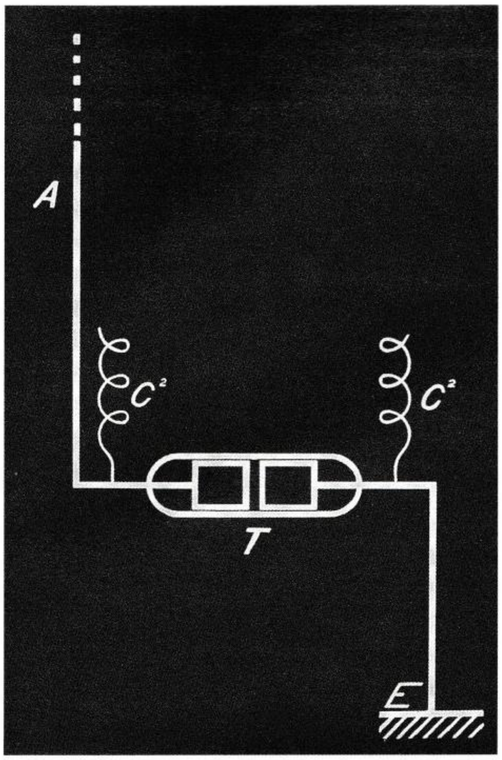
(figs. 2 and 3). It is a two-state device: it is either 'cohered' or 'restored'. In the restored state it exhibits a large resistance by virtue of the thin oxide layers covering all particles. The very brief application of a threshold voltage of 3–5 V breaks down sufficient of these layers to create a conduction path and the coherer then exhibits a linear resistance of $\sim 1000\,\Omega$. This was used to complete the primary circuit of a relay controlling a pen recorder. The coherer remains conducting until physically tapped, a process that was controlled by the same relay.

When in use, the coherer was normally connected in series between the receiving antenna and a low-resistance earth rod (fig. 4). To send Morse code, the coherer would have to be cohered and restored at least once during each Morse code element (a dot), Thus the pulse repetition frequency controlled the speed of transmission.

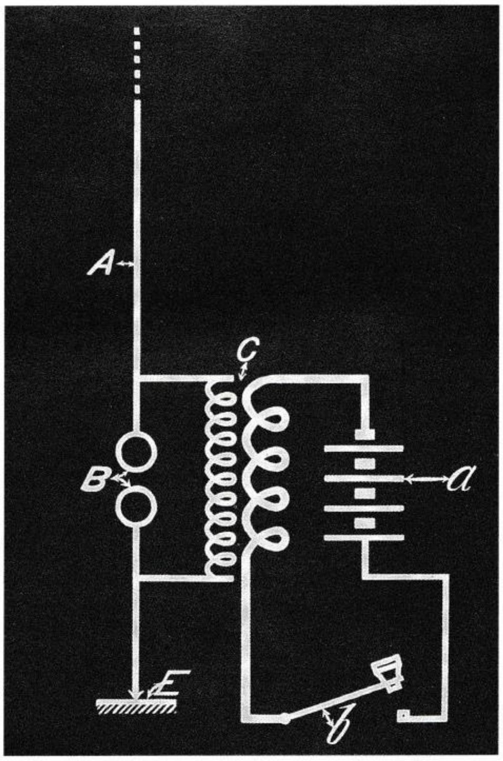
From the system point of view each pulse was the same, and the requirement for each pulse was to produce a sufficiently large instantaneous pulse of voltage in the receiving antenna to cause the coherer to cohere. Viewed in this way the system can be considered as a time-domain system.

At the other end of the communication link, each pulse was transmitted by raising the transmitting antenna to a high voltage and then suddenly shorting it to earth via a spark (fig. 5). This immediately caused a pulse of energy to radiate, eventually producing the desired effect at the receiver.

The spark acted as a high-voltage switch that automatically closed once the voltage across the air-gap reached the breakdown voltage, which



4 ***An early receiver***†



5 ***An early transmitter***†

might have been 100 kV for a 50 mm spark-gap. This discharged to earth the electric charge previously stored in the antenna capacitance of 200–2000 pF, depending on the size and type of antenna. Although, as we now know, the gap voltage was capable of collapsing to a few volts in tens of nanoseconds, the actual rate of discharge was determined by the characteristics of the antenna, including the inductance of the down-lead (~0.5–5 μH). We believe the discharge was completed in well under a microsecond, radiating the pulse of electromagnetic energy necessary to activate a filings coherer, and setting up the well-known damped oscillations

Whilst Marconi was aware of Lodge's tuned systems, and stated that the Poldhu system was 'tuned', it is not clear that the system would have fitted today's clear definition of the word. For the present purposes it will be assumed that both the early direct-coupled system and the Poldhu system produced essentially an initial transient that would operate a filings coherer. The antennas will be assessed here against this assumption, which as far as Poldhu is concerned, is supported by Ratcliffe[6], who shows the results of a calculation of the antenna current waveform for the Poldhu system. An initial transient of antenna current is shown which, in both magnitude and rate of increase, greatly exceeds the subsequent oscillatory waveform. The transient is not identical to that predicted from a step voltage drive, but is not dissimilar.

The coherer as described above is a latching device and is therefore a nonlinear circuit element. When connected to the receiving antenna it presents a high impedance until induced to change state. An analysis of the process is best carried out in the time-domain, that is, by calculating the waveform (in time) of the voltage produced by the receiving antenna. This approach has been adopted in the detailed analysis of the performance of the antennas considered below. There is an interesting historical implication: a time-domain approach does not need to consider the frequency that might have been in use, because the concept of frequency

† Figs. 4 and 5 are copies of the slides used in Marconi's lecture to the Royal Society of Arts in 1901. He continued to use them for several years himself and they were also used by Prof. Sir Ambrose Fleming in his commemorative lecture in November 1937.

becomes irrelevant. The coherer was operated by a sharp rising voltage waveform, so the system required this type of waveform from the transmit antenna – a requirement that was certainly met by Marconi's early direct-coupled system and also by the Poldhu transmitter. The following sections deal with the ability of various types of antenna to radiate an impulsive waveform.

The Early Marconi Aerial System

The standard type of aerial used both for transmission and reception at other Marconi stations of that period consisted of a fairly thick insulated wire, 80 to 100 feet (24–30 m) long and suspended vertically from a mast and yard arm (or by means of a kite*), with the upper end well insulated and the lower end connected to the Tx/Rx set approx 3 feet (0.9 m) from the earth plane. The characteristic impedance (Z_0) of this arrangement, considered as a charged single-wire transmission line reflected in the earth plane, is between 500 Ω and 600 Ω for the first 200 ns of discharge. This suggests that, whenever reception of a radio impulse induced the necessary coherer threshold voltage across the ends of the aerial wire, a discharge from the lower end of the aerial to earth, *via* the coherer, would provide sufficient current to cause coherence. Note also that the cohered resistance is a good match to the Z_0 of the aerial, ensuring maximum energy transfer to complete the cohering process.

In short, Marconi appreciated the need for receiver matching and he designed his system so that if the coherer operated at all it did so reliably. This was one of the secrets of his success where his predecessors and contemporaries failed.

Antenna Options

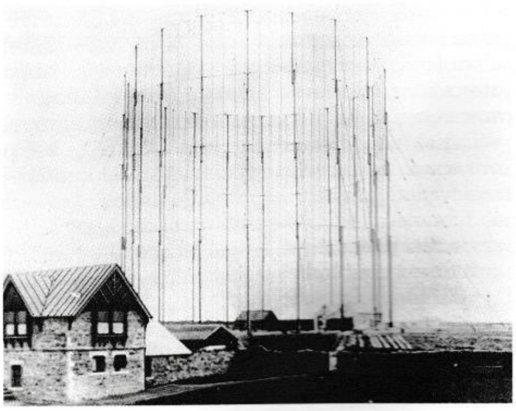
A vertically-polarized electromagnetic wave is produced by a varying electric current in a vertical wire. In general, the vector potential at a remote point is given by the time-retarded volume integral of the electric current density function, and the electric field is then given by the time derivative of the vector potential (see, for example, Stratton[7]). Thus any current, other than a constant direct current, gives rise to RF radiation.

The transmitted pulse was produced by sparking a previously charged antenna to ground, thus radiating the stored energy. It was known that the stored energy could be increased both by raising the voltage and by increasing the capacitance of the antenna. Probably Marconi himself favoured the simple monopole antenna. However Fleming, who was given charge of the design of the Poldhu experiment, conjectured that the rate-of-change of current flow could be maximized by providing many parallel current paths to ground. This led to the use of cone and fan antennas.

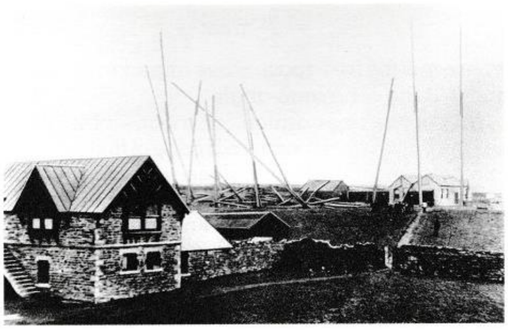
In his early experiments Marconi used a vertical monopole antenna. A variant of the monopole was produced by connecting a horizontal wire at the top of the monopole, and this 'top-loaded' antenna (the 'T' or inverted-'L') eventually became the preferred configuration for tuned-carrier systems. Many examples of this type of antenna are in use a century later for broadcasting and communications below about 1 MHz. Top-loaded antennas can be shown to provide the largest radiation-resistance for a given frequency and height, but the results here show that they are inferior to fan and cone antennas for pulsed systems.

There are several photographs of the Poldhu antennas in circulation, but it is probable that only two such photographs were ever taken (see Appendix 2). The first (fig. 6) was taken to show the original antenna, a multiple-wire cone supported by twenty wooden masts. Because of technical limitations the photograph was afterwards retouched, the antenna being drawn in by an artist who might never have seen the antenna and who drew in a cylindrical shape that perhaps never existed. The second photograph (fig. 7) shows the same structure after its collapse in a gale. The first photograph was later again retouched to depict the fan antenna that was rigged afterwards for use in the transatlantic experiment (fig. 8). It would seem from this that no true photographs exist of either of the two working Poldhu antennas.

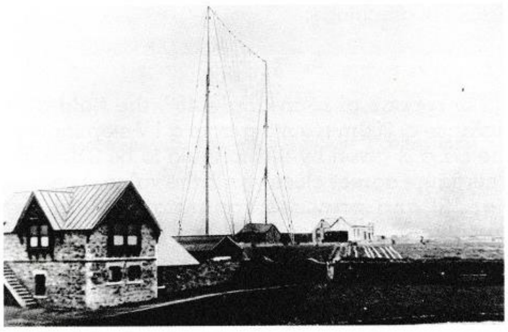
* The use of a kite is known only at St John's. This was originally to have been a gas balloon but the wind was too strong. A kite or balloon will require very thin, light wire for which Z_0 would be higher.



6 *The first inverted-cone aerial*



7 ***The effect of bad weather on the first Poldhu aerial***



8 ***The replacement fan aerial at Poldhu***

Theoretical Modelling

To compare the performances of these antennas we have modelled four alternatives:

- a monopole antenna,
- a 'T' antenna (that is, a monopole with a horizontal top-loading wire),
- a fan antenna, and
- a cone antenna.

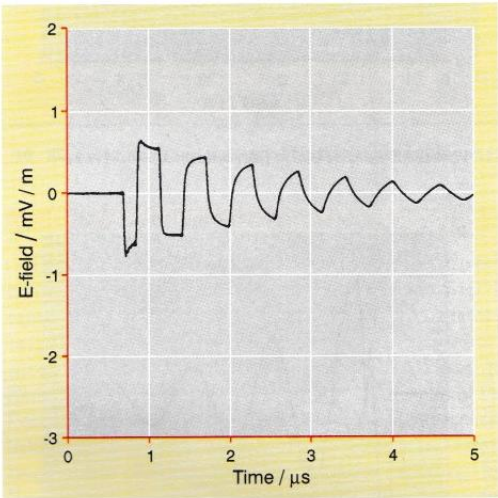
All were modelled as 43 m high, and the last three as having a horizontal extent of 45 m. Supporting structures were not included in the simulation.

Modelling Results

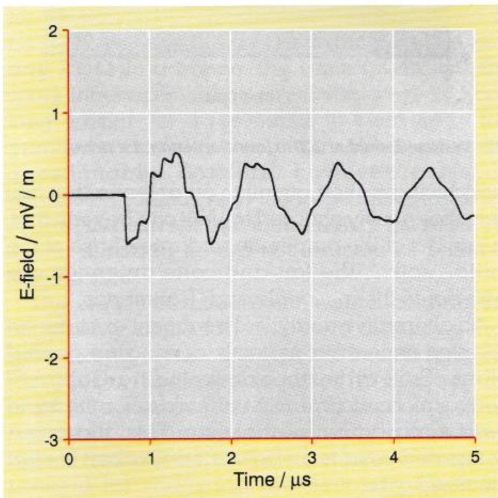
The antenna performance was computer-simulated by running a wire-grid model (NEC-4) over a range of frequencies and transforming the results into time-domain waveforms by FFT processing. In a typical run, 512 frequencies were used from 62.5 kHz to 32 MHz.

In the wire-grid model, the fan antenna was represented by a 25-wire fan. The number of wires used in the Poldhu fan antenna was 50 – 60 (see, for example, Marconi[8]), but fewer wires were used in the simulation, for practical reasons connected with the software. The larger number of wires does not increase the capacitance of the antenna but improves its ability to accommodate a high voltage without electrical breakdown occurring in the air around the conductors. Similarly, the cone antenna was modelled as a 16-wire cone. The results are not thought to be affected significantly by these simplifications.

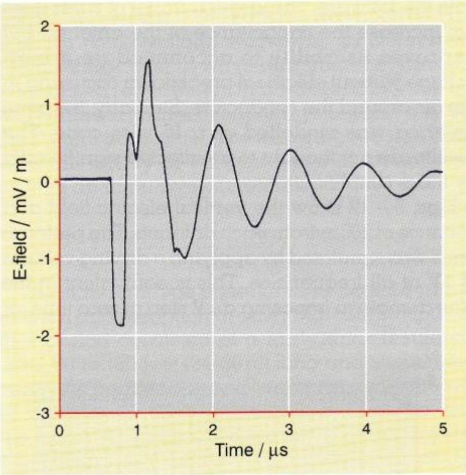
Figs. 9 – 12 show the vertical electric field at a distance of 200 m from each antenna. The performance was simulated by applying a driving voltage of 1 V at all frequencies. This is equivalent in the time domain to imposing a 1 V step at zero time, or



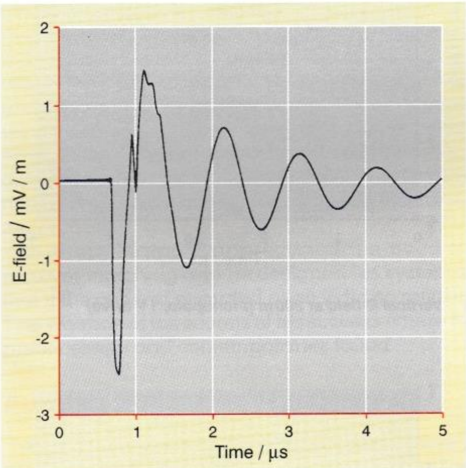
9 ***Vertical E-field at 200 m (monopole, 1 V drive)***



10 ***Vertical E-field at 200 m ('T' antenna, 1 V drive)***



11 Vertical E-field at 200 m (fan antenna, 1 V drive)



12 Vertical E-field at 200 m (cone antenna, 1 V drive)

introducing a short-circuit to an antenna that has been previously charged to 1 V. It can be seen that, in respect of the amplitude and rate-of-rise of the initial 'spike', the fan and cone antennas are superior to the monopole and 'T' antennas.

An alternative analytical treatment exists for an inverted cone on a perfectly conducting ground plane. Several textbooks, including Collin's[9] derive a formula from first principles for the input resistance of a bicone antenna. This allows our computed results to be verified, albeit for an idealized case.

For an inverted cone the input impedance is half that quoted for a bicone:

$$Z_c = \frac{\eta_0}{2\pi} \ln \cot \frac{\theta_0}{2}, \quad (1)$$

where η_0 is the free-space wave impedance (377 Ω) and θ_0 is the cone semi-angle.

This is the impedance for a cone of infinite height, but is useful because a cone of finite height exhibits an impedance close to this value at frequencies where it exceeds a half-wavelength in height. At low frequencies the finite cone exhibits a capacitive reactance, with a first resonance occurring when the height is approximately one seventh of a wavelength high.

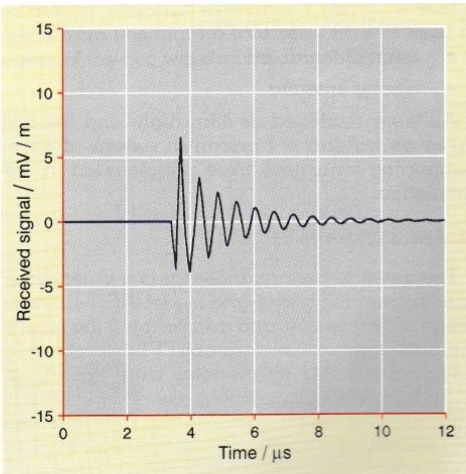
For a solid cone antenna the field at distance R metres resulting from a step input voltage at ground level may be shown to consist of a step in E-field of amplitude:

$$E_z = \frac{\eta_0 V}{4\pi R Z_c}. \quad (2)$$

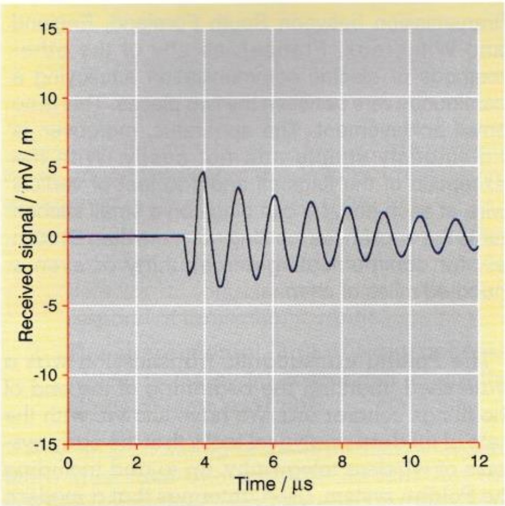
For a cone of semi-angle 45°, the field at a distance of 200 m resulting from a 1 V step input at the base is given by this formula to be 2.8 mV/m. This figure agrees closely with the value shown in fig. 12, and provides confirmation that the computation of the initial value of the waveform is correct.

Figs. 13 – 16 show the received signal when two identical antennas are placed 1 km apart. This was done by considering a resistive load connected at the base of the second antenna, and computing the current in the load. Again, it can be seen that the cone and fan antennas are better than the monopole or 'T' antenna.

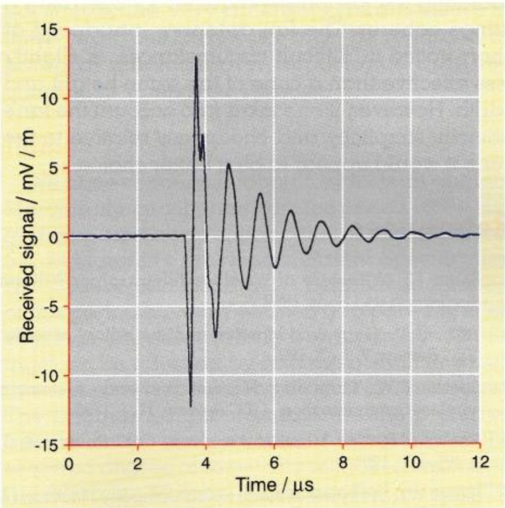
The fields and voltages in the figures are of course proportional to input voltage. Thus it can be seen, for example, from fig. 13, that if the fan



13 Signal transmitted between identical monopoles

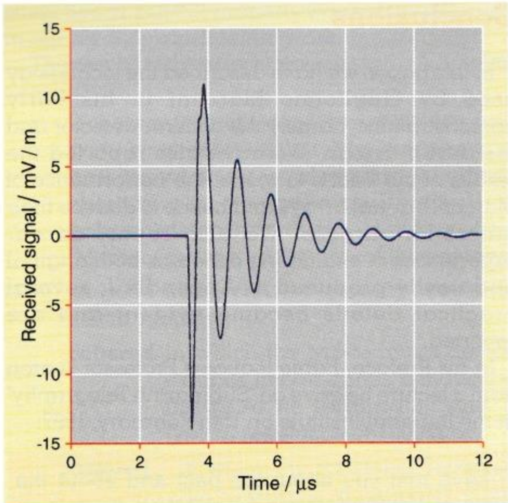


14 ***Signal transmitted between identical 'T' antennas***



15 ***Signal transmitted between identical fan antennas***

antenna is sparked down from 50kV the resulting field will produce a voltage pulse of 700V in an identical antenna at a distance of 1km (assuming perfect ground). At slightly larger distances the effect is inversely proportional to distance. Above about 20km the received pulse is subject to the mechanisms of groundwave propagation, and at larger distances the vicissitudes of skywave propagation become apparent. In principle it is possible to carry out a complete analysis of the transmission of the waveform by separately calculating the propagation loss for all the spectral components, and transforming to the time domain at the receiver.



16 ***Signal transmitted between identical cone antennas***

Modelling Conclusions

The antennas have been evaluated in a 'direct-coupled' circuit in which the spark gap is connected at the base of the antenna. This was the original system. The Poldhu transmitter used a more complicated arrangement, as described by Ratcliffe[6] and others. A detailed simulation of the Poldhu transmitter circuit is beyond the scope of this article. However, Ratcliffe's 1974 simulation begs some comment. As has been pointed out by Bondyopadhyay[10], the equivalent circuit assumed for the antenna was not accurate because it failed to represent the radiation resistance of the real antenna, which is known to be highly variable with frequency, settling down at frequencies over 3MHz to a value between 80Ω and 250Ω. In addition, the assumption that the spark introduces a short circuit that stays in place long enough for a resonance to build up in the primary circuit of the output transformer is also questionable. Ratcliffe, however, correctly predicted (qualitatively) the large initial transient of antenna current that immediately followed the spark, although he did not indicate its possible significance.

The results of modern simulation confirm the superiority of the fan and cone antennas that replaced the earlier monopoles, in radiating the fast pulses that were required to operate the original coherers. The fan and cone are good radiators over a wide frequency range, and indeed are still the preferred antennas in use at present for radiating picosecond pulses for time-domain microwave applications, as described, for example, by Sandler and King[11].

Conclusions

In this paper, we have described the technology used by Guglielmo Marconi in his early demonstrations, namely the coherer detector and the aerial design. We have also reported the results of our efforts to model the performance of Marconi's aerial arrays and hence to deduce their fitness-for-purpose. We also report on our experiences of evaluating coherers, both original and newly-produced in Appendix 1; several practical details became evident and are reported.

In his Preface, Fahie[1] quotes Professor Ayrton from a lecture he gave on 'Submarine Telegraphy' at the Imperial Institute on 15th February, 1897:

'I have told you about the past and about the present. What about the future? Well, there is no doubt the day will come, maybe when you and I are forgotten, when copper wires, gutta-percha coverings, and iron sheathings will be relegated to the Museum of Antiquities. Then, when a person wants to telegraph to a friend, he knows not where, he will call in an electromagnetic voice, which will be heard loud by him who has the electromagnetic ear, but will be silent to everyone else. He will call, 'Where are you?' and the reply will come, 'I am at the bottom of the coal-mine,' or 'Crossing the Andes,' or 'In the middle of the Pacific'; or perhaps no reply will come at all, and he may then conclude the friend is dead.'

Marconi was instrumental in bringing this perception of the future to fruition in less than a decade.

Finally, in the concluding section, Fahie quotes from a letter to 'The Times', dated 3rd April, 1899, written by Professor J. A. Fleming of University College, London; this encapsulates the scale – and yet the simplicity – of Marconi's achievement, after only two years in England, through careful attention to detail and persistent development of his system, relentlessly advancing towards the goal of transatlantic communication:

'... I cannot help thinking that the time has arrived for a little more generous appreciation by his scientific contemporaries of the fact that Signor Marconi has by minute attention to detail, and by the important addition of the long vertical air wire, translated one method of space telegraphy out of the region of uncertain delicate laboratory experiments and placed it on the same footing as regards certainty of action and ease of manipulation, so far as the present results show [transmission between South Foreland, England and Wimereux, France], as any of the other methods of electric communication employing a continuous wire between the two places. This is no small achievement. The apparatus, moreover, is ridiculously simple and not costly. With the exception of the flagstaff and 150 feet of vertical wire at each end, he can place on a small kitchen table the appliances, costing not more than £100 in all, for communicating across thirty or even a hundred miles of channel....'

The Poldhu transatlantic transmission was a watershed, marking the beginning of the end of the filings coherer era. We have shown, with the help of modern analytical tools, that the early systems of wireless telegraphy, up to and including the Poldhu system, used antennas that a modern antenna engineer would find difficult to improve upon. The cone antenna is the ideal device for radiating the fast pulses required for operating a filings coherer. The fan antenna, introduced at short notice in difficult circumstances, is slightly less effective than a cone of the same height and width. However, if one takes into account the fan's obvious simplicity and cheapness relative to the cone it would appear to be a better choice.

References

1 FAHIE, J.J., 'A History of Wireless Telegraphy', William Blackwood and Sons, 1899.

2 ISTED, G.A., 'Guglielmo Marconi and the history of radio', *GEC Review*, **7**, 1 – 2, 1991.

3 SIMONS, R.W., 'Guglielmo Marconi and early systems of wireless communication', *GEC Review*, **11**, 1, 1996.

4 RODWELL, R, 'The Marconi Archives', *GEC Review*, **6**, 3, p. 172–178, 1991.

5 BAKER, W.J., 'A History of the Marconi Company', Methuen & Co. Ltd., 1970.

6 RATCLIFFE, J.A., 'Scientists' reactions to Marconi's transatlantic radio experiment', *Proc. IEE*, **121**, 9th September 1974.

7 STRATTON, J.A., 'Electromagnetic Theory', sections 6.2, 8.2, McGraw Hill, 1941.

8 MARCONI, G., 'Wireless Telegraphic Communication', Nobel Lectures in Physics, 1901–21, Elsevier, 1967.

9 COLLIN, R.E., 'Antennas and Radiowave Propagation', section 3.1, McGraw-Hill, 1985.

10 BONDYOPADHYAY, P.K., 'Investigations on the correct wavelength of transmission of Marconi's 1901 transatlantic wireless signal', *IEEE Antennas and Propagation Society International Symposium Digest* (IEEE Catalog 94CH3466-0), **1**, June 1994.

11 SANDLER, S.S. and KING, R.W.P., 'Compact conical antennas for wideband coverage', *IEEE Trans. Antennas and Propagation*, **42**, 3, March 1994.

Appendix 1
Coherers and Receivers

Detector Performance

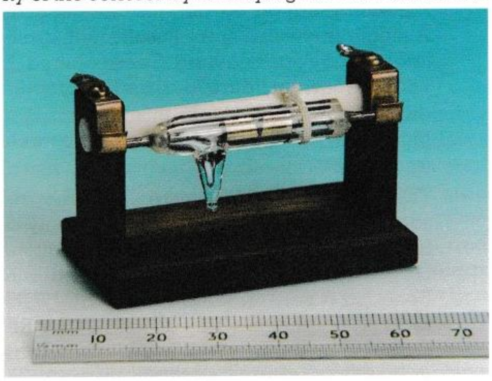
Two very different types of detector are relevant to an understanding of the Poldhu transatlantic experiment of December 1901. These are:

1. The then well-established Marconi filings coherer; this was the intended type of detector although, in the event, it did not respond at transatlantic range.
2. The experimental 'Italian Navy coherer' which, in the event, responded where the filings coherer had failed.

Any understanding of the transatlantic experiment must take into account the fact that the Poldhu transmitter was designed primarily to operate a filings coherer but, at extreme range, would work only with an 'Italian Navy coherer'. In particular, the very different characteristics of these two types of detector must be regarded as being of much greater importance than the question of 'tuning' the receiver.

Filings Coherers

We have conducted laboratory tests on original Marconi filings coherers from the period 1899-1902, and also on a new replica coherer made according to Marconi's Provisional Patent Specification No. 12039 of June 1896 (fig. 17). Most filings coherers of this period have a V-shaped gap partially filled by filings. The effective length of gap bridged by filings can be adjusted by rotating a shaft to which the coherer was bound (by thread) in the receiver. The original test records indicate the preferred orientation for each sample in order to give the required degree of sensitivity without compromising reliability. Marconi also controlled the sensitivity of the coherer by modifying the ratio of nickel to silver filings, but this property was not investigated in our recent experimental work.



17 ***The replica coherer used in these investigations***

The results of these tests leads us to the following conclusions:

- Coherers in good condition, both old and new, have relatively stable, measurable, and repeatable characteristics. It is these characteristics we must consider in order to gain a better technical understanding of the 'Marconi System' at the turn of the century.
- A 'good' filings coherer has only two stable states, namely:

  cohered, in which the two-terminal device exhibits linear, ohmic conduction between its terminals, with a typical resistance of 1000 Ω, or

  restored, in which the resistance between the terminals is typically more than 1 MΩ.
- A device in the cohered state can be restored by tapping gently, shaking the filings. Measurements are usually taken on coherers with a 1.5 V DC bias applied through a series resistor to limit the cohered current to less than 1 mA.
- Until the device is tapped or shaken, the cohered state remains ohmic and linear indefinitely, provided the external current passing through device does not exceed about 1 mA. The passage of higher currents causes cumulative deterioration of the device .
- A device in the restored state can be made to cohere by the application of a short duration voltage impulse over, and above, the DC bias voltage. This impulse is the expected characteristic of the early spark transmitters and is what would be received by an untuned receiver. Tests on both new and old coherers, in their most sensitive orientations have indicated that the application of a sharp voltage pulse of 3 V amplitude will cause reliable and repeatable coherence. This pulse was derived from the charge on a small value capacitor and it was found that, assuming all the stored energy was dissipated in the coherer, a level as low as 10^{-10} J would cause reliable coherence.
- If the peak voltage applied across a restored coherer is less than the threshold voltage, no measurable current flows (even with alternating voltages at moderately high radio frequencies) and the device does not cohere, even if the voltage is applied for some while.

- If the threshold voltage is exceeded, but a high resistance is placed in series so that no appreciable current can flow if the device resistance begins to fall, the coherer will typically cohere to an unstable 'half-way' state in which the device resistance is roughly commensurate in value to the series resistance inserted (being unstable, this state is difficult to measure with any confidence). This half-way state is not apparently damaging but it is highly undesirable for operational reasons.
- Original Marconi coherer receivers were fitted with an inductive bypass across the coherer so that static electricity picked up on the aerial could leak to earth without affecting the restored state of the coherer.

In summary, the filings coherer was essentially a peak-sensitive device requiring an applied signal voltage of 3V to 5V (but only instantaneously) to change its state. Once cohered to about 1000Ω, a 1.5V cell in the receiver could pass enough current through the coherer to operate a sensitive relay recording the detection. The relay in turn operated a tapper to restore the coherer in time for the next (spark-type) transmitter pulse. Meanwhile, the coil resistance of the sensitive relay limited the coherer current to less than 1 mA, in order to prevent damage to the filings.

The 'Italian Navy Coherer'

The so-called 'Italian Navy coherer' is an entirely different class of device. It consists of a glass tube containing a globule of mercury between two end plugs, usually of iron but sometimes of carbon. One (fixed) end plug is treated so that the mercury wets it. The other end plug has a screw adjustment so that it *just* touches the globule. There is some evidence to suggest that the best results were obtained when the mercury was none-too-clean.

We have not been able to obtain and test an original Italian Navy coherer, but tests on modern recreations suggest:

- Measurable characteristics are very variable; it is not easy to be certain when the device is working 'properly', that is, as intended. Perhaps this has never really been defined.
- A properly wetted contact behaves ohmically.
- The non-wetted contact seems to behave as a metal/oxide contact rectifier (some of the time).
- Current can be passed through the device in either direction but at low applied voltages (less than a volt) the characteristic is neither linear nor symmetrical.
- A weak diode-type rectifier characteristic can be obtained with no external bias applied.
- A somewhat stronger amplitude detector characteristic can sometimes be obtained by biasing the device by a few hundred millivolts to find the 'knee' of the non-linear characteristic.
- The rectifier characteristic is very variable and is easily destroyed by large spark signals.
- When carefully (or luckily) adjusted, the rectifying action is much more pronounced for weak signals than for stronger ones.
- Provided only weak signals (less than a volt) are received, the rectifying action remains fairly stable for a period, so the coherer does not need to be restored after receiving each pulse.

The Italian Navy coherer was sometimes referred to as a 'self-restoring coherer' for the above reason. However, when used in this way its detection properties are clearly those of a diode rather than of a coherer. As such, the detected signals could be heard on headphones but would not activate a relay or Morse inker. Because of this, and because it was successful only in the hands of experts, Marconi preferred the (relatively) robust filings coherer, despite its lower sensitivity.

Comparison of the Two Types of Coherer

- The filings coherer is a peak-sensitive detector, requiring of the order of 3V – 5V for reliable operation, but only instantaneously. A single impulsive spike is sufficient; oscillatory decay adds nothing. Once cohered, it will pass current from a local battery to operate relays, inkers, etc. In this sense it is a high-gain, low-bandwidth amplifier as well as a detector.
- The Italian Navy Coherer is a mean-sensitive diode detector, requiring only a fraction of a volt for optimum rectification. Larger signals may not be rectified at all. Because it self-restores immediately, its rectified output lasts only as long as the RF pulse is present. To obtain sufficient detection energy to produce an audible 'click' in headphones requires a burst of

long, oscillatory pulses. An initial impulsive spike adds nothing and could disable the device.

It will be apparent that the two types of coherer are in some respects opposites; certainly they require very different RF pulse envelopes for best operation. It will also be apparent that they will respond very differently to tuned RF signals. This was a key factor in the early development of Marconi's system, and in the transatlantic experiments.

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Appendix 2

Some Comments on the Photographs of the Poldhu Aerial

As far as is known, only three such 'photos' exist, all widely published. These are:

1 The complete ring aerial, taken (well?) before the storm, as shown in fig. 6.

2 The wreckage of the ring aerial, taken shortly after the storm, as shown in fig. 7.

3 An artist's impression of the temporary fan aerial, created by heavily retouching photo 1, as shown in fig. 8.

The original plates of these photos are now 'lost', presumably long destroyed, but we have carefully examined good copies of the prints in the Marconi archives. These lead us to the following conclusions.

Photo 1 (fig. 6)

Photo 1 is basically genuine and was probably taken soon after the ring aerial was first completed in mid-1901 (ground details – for example, material spread out to dry on the grass – suggest high summer). The photographic technology of the time did not permit clear imagery of buildings and ground features at exposures suited to clear imagery of the poles, stays and wires. It is clear that the aerial details in photo 1 have been heavily retouched in the studio.

Close examination suggests that the retouching artist was not working 'from life' and may, indeed, have never seen the aerial structure for himself; even if he did, he probably did not understand the technical significance of the wiring details. In our opinion, this accounts for some of the peculiar features of photo 1, such as the array appearing to be cylindrical rather than conical, and the presence of only 19 masts rather than the 20 known to have been erected. If, as is suspected, the artist retouched the original negative plate, it would have been impractical to correct even such obvious defects at a later date.

Photo 2 (fig. 7)

Photo 2 is believed to be essentially genuine throughout and seems to have been retouched only minimally, if at all. We regard this as the only true photographic evidence now available showing genuine details of the actual structure and rigging. However, surviving archival evidence suggests that due to 'top end' insulation problems, considerable changes had to be made to the rigging in the months after the aerial was first completed. Note that the appearance of ground detail suggests that this photo was taken much later in the year than photo 1.

Photo 3 (fig. 8)

Photo 3 is definitely a modified reprint of photo 1 – the same material can be seen drying on the grass in the same place compared with photo 2! It would appear that no useful photographs were ever taken of the temporary fan aerial, and that photo 3 is an artist's impression produced for publicity purposes some time (months?) after the event. In our opinion, the artist concerned had never seen the aerial he (or she) was drawing.

Archive documents suggest that the wreckage was cleared from the site after the storm and that the temporary aerial was designed to use a selection of unbroken mast sections salvaged from the wreckage, but that these were stacked and rigged differently, giving the new aerial a somewhat different overall height. By contrast, photo 3 shows two masts exactly as originally sited and rigged, with the others painted out.

In these circumstances, we would place little trust in any details of photo 3; indeed, we would go so far as to distrust even the orientation of the aerial structure relative to the site. However, photo 3 was widely published during the working lives of many of the engineers closely involved, so we can probably assume that it portrays a reasonably faithful general impression of what the temporary aerial would have looked like.