European Review, Vol. 15, No. 4, 545–559 © 2007 Academia Europæa
doi:10.1017/S106279870700052X Printed in the United Kingdom

A ‘Horrible Conflict with Theory’ in Heinrich Hertz’s Experiments on Electromagnetic Waves

JAMES G. O’HARA

Leibniz-Archiv, Gottfried Wilhelm Leibniz Bibliothek-Niedersächsische Landesbibliothek, Waterloostrasse 8, 30169 Hannover, Germany.
Email: James.Ohara@gwlb.de

In his celebrated 1888 experiment on standing waves, Hertz found the velocity of transmission along a wire line to depend on wavelength and to differ from that for wireless transmission, a result that was in contradiction to theory. Hertz called on others to repeat the experiments and verify or refute his results. The call was heard by two groups of scientists. In Dublin, George Francis Fitzgerald and associates repeated and elaborated Hertz’s experimental discoveries. For wire transmission, their results were in good agreement with those of Hertz. On the other hand Édouard Sarasin and Lucien de la Rive of Geneva obtained the results required by theory. Hertz looked for an explanation of his own results in the ambient conditions of his apparatus. He corresponded with both Fitzgerald and with the Genevan scientists. These letters are an important historical source in reconstructing the circumstances of Hertz’s experiment.

Introduction

The part played by Heinrich Rudolf Hertz (1857–1894) in the investigation of electromagnetic-wave radiation between 1887 and 1891 has earned him a unique place in the history of physics and his name has been adopted as the unit of frequency. The idea of electromagnetic or radio waves was contained in James Clerk Maxwell’s *Treatise on Electricity and Magnetism* (1873), although not explicitly mentioned there. In the decade following Maxwell’s death in 1879 a group of physicists, working in England and Ireland, elaborated Maxwell’s theory.[1] In Germany, Hertz embarked on theoretical and experimental investigations of Maxwell’s and the rival electrodynamical theories. Following his appointment as professor at the Technische Hochschule Fridericiana at Karlsruhe in 1885, Hertz developed the means of producing electromagnetic waves; the culmination of this work was the verification of the finite velocity of the propagation of the waves in 1888. This was subsequently repeated and elaborated by physicists in several European countries. Hertz corresponded with those involved, including George Francis Fitzgerald of Dublin[2] and Édouard Sarasin and Lucien de la Rive of Geneva.

In Hertz's famous series of experiments at Karlsruhe, a primary circuit or transmitter was used consisting of a straight copper wire, 2.6 m long and 5 mm thick and cut in the centre to accommodate a spark gap of about 3/4 cm between two small spheres; at the extremities of the wire were placed two zinc spheres of diameter 30 cm. The poles of a large Ruhmkorff induction coil equipped with a mercury make-and-break device and powered by six large batteries, were then connected across this spark gap.[3] The secondary circuit or receiver consisted of copper wire (diameter 2 mm) arranged in the form of a square (side 75 cm) and broken only by a micrometer spark gap. This detector was later given a circular form. Using this apparatus, Hertz demonstrated the existence of very rapid oscillations and resonance between primary and secondary circuits. He succeeded in showing the existence of standing waves with characteristic loops and nodes along a straight wire attached to the transmitter. He demonstrated interference of waves propagated in air and along the wire line and compared their phases. He was able to verify the finite propagation of the oscillations in air although, much to his surprise, this was in excess of that for wire transmission. The results were published in a paper '*Ueber die Ausbreitungsgeschwindigkeit der elektrodynamischen Wirkungen*' in early 1888.[4]

In the next series of experiments, completed in March 1888, Hertz produced standing waves in air and found the velocity of transmission in air was clearly in excess of that along wires; he reported the results in the paper '*Ueber elektrodynamische Wellen im Luftraume und deren Reflexion*'.[5] Standing waves in air had been produced by the interference of directly transmitted waves with those reflected from a zinc sheet that covered the end wall of a lecture hall. Hertz pointed out in this article that the experiment had acoustical and optical analogies. In optics, an experiment carried out in 1834 by Humphrey Lloyd, who was co-founder of the School of Engineering and had occupied the same chair as Fitzgerald at Trinity College Dublin, was a direct analogue of Hertz's experiment.[6] In the summer of 1888, his conception of the nature of air and wire transmissions underwent a significant transformation. In accordance with Maxwell's theory he now considered the waves to be propagated not in the interior of a conductor but rather in the surrounding space. The idea that electrical energy is propagated not by the current flowing in a wire but rather in the surrounding ether had been developed from Maxwell's theory before Hertz by John Henry Poynting, Oliver

Heaviside and Fitzgerald.[7] He now demonstrated that oscillations could not penetrate metal layers of any thickness and that it was therefore impossible to observe sparks inside a closed metal tube. He investigated transmission not just along a single wire, but rather in the intervening space between two wires or plates or in tubular spaces. These results were reported in the paper '*Ueber die Fortleiting elektrischer Wellen durch Drähte*' in 1889.[8]

In the autumn of 1888, while investigating the waves in the narrow intervening space between two wires, Hertz found that he could observe nodes at the ends of the wires using very small resonators or receivers (just a few centimetres in diameter). He subsequently developed a form of primary or transmitter to operate with these small resonators and succeeded in observing wavelengths of as little as 24 cm. He repeated his experiments on propagation in wires using waves of about 30 cm wavelength, and found that the velocity of propagation along wire was now almost equal to that in air. Having familiarized himself with the use of short waves he commenced a series of experiments with hollow parabolic metallic mirrors (about 2 m high with an aperture of about 1 m) and large pitch prisms. This series of experiments on the reflection, refraction and polarization of the waves was reported in the paper '*Ueber Strahlen elektrischer Kraft*' in 1889.[9]

The Hertz–Fitzgerald correspondence

The correspondence between Fitzgerald and Hertz began in the summer of 1888. At that point, Hertz's paper '*Ueber die Ausbreitungsgeschwindigkeit der elektrodynamischen Wirkungen*' had been published. Fitzgerald's learned of Hertz's success through a report of an announcement made by Hertz's former professor in Berlin, Hermann von Helmhotz; this led him to write the following lines in a letter dated 8 June 1888 from the School of Engineering, Trinity College, Dublin:[10]

> I saw the other day that Prof. von Helmholtz announced your splendid verification of Maxwell's theory that electromagnetic disturbances are propagated with the velocity of light. You have been so kind as to send me copies of some of your former papers, for which I now thank you as I ought to have done before. Would it be too much to ask you to send me a copy of your paper describing how you have verified Maxwell's theory? I consider that no more important experiment has been made this century.

Hertz replied in German from Karlsruhe on June 11, 1888, and was able to announce that he had in the meantime successfully produced standing waves in air and measured their wavelength. The troubling issue of the difference in the velocity of transmission in air and along wires arises here in the correspondence for the first time. Hertz's words in translation are:[11]

> In sending you … the paper requested I cannot but express my very best thanks to you for your friendly words. From your expressions, however, I am afraid that

> you suppose more than is actually the case and will be disappointed. For, in the first place, one cannot yet speak of a measurement in the strict sense and exact comparisons, and, secondly, the experiments are somewhat complicated … But … I also think that these experiments are not yet a final objective, but much more the beginning and the introduction to better experiments, and in fact I have also succeeded in the meantime in producing waves in the air itself and in measuring their wavelength, so that indeed there can be no further doubt that the propagation from point to point takes place in time … However, I do find a difficulty and deviation from Maxwell's theory which I cannot explain at all. It appears in fact (if my experiments don't contain serious errors) that the propagation of electricity through wires has a very exact velocity, the same for copper, iron, mercury, carbon, etc., but different from the velocity in air, whereas according to Maxwell's theory both must be the velocity of light … I have seen from the *Proceedings* of the British Association that you yourself have considered and perhaps also made experiments about electrodynamic waves.

On 6 September 1888, Fitzgerald announced Hertz's discoveries in an inaugural address to the British Association meeting at Bath. From an entry in Hertz's diary on 12 September 1888 we know that news of Fitzgerald's announcement had reached him.[12] This prompted Hertz to write to Fitzgerald again from Karlsruhe on 23 September:[13]

> I send you my very best thanks for the good and noble recognition which you have given to my simple experiments: I had scarcely hoped that the latter would receive such praise, particularly in England, from where these conceptions first emerged and where, in fact, for years already everyone was convinced of the correctness of the same … Should you want yourself to undertake such experiments, or have them carried out by your assistants, I wish you every success ….

Fitzgerald was prompted to reply to Hertz's letter on receiving a copy of his paper on the propagation of waves in air and their reflection. Meanwhile he had repeated Hertz's experiments together with his assistant Frederick T. Trouton. On 14 January 1889, Fitzgerald writes:[14]

> I should have written to you long ago to thank you for your last letter, and now I have been reminded of that by your sending me your last paper. It is quite splendid. I had repeated your former experiments and with the intention of making others in the direction you mention was trying to get shorter wave lengths but had not succeeded at all satisfactorily. Mr Trouton, my assistant and I are now trying, with imperfect success to follow your splendid leading. The only remaining difficulty I see is how the velocity of propagation near the wires is as different from when there is no wire core to the wave. I say *near* the wire because I don't think any large part of the energy is propagated *by* the wire. When an alternating current is sent by a wire and the alternations are fast enough I think we must be dealing with a wave propagated by the ether round the wire and I don't see why this wave should be propagated at a different rate from the waves in free space.

From Fitzgerald's next letter to Hertz, dated 23 January 1889, we learn that there had been a further communication from the latter in the meantime and that he and Trouton were in possession of the paper on the production of short waves as well as a theoretical investigation of 1888 entitled '*Die Kräfte elektrischer Schwingungen, behandelt nach der Maxwell'schen Theory*'.[15] Fitzgerald and Trouton had shortly before carried out a public demonstration of the waves in January 1889. Thus, Fitzgerald writes:[16]

> I must have expressed myself badly if you thought I had imperfect success in repeating your experiments. My assistant Mr. Trouton and I have most successfully repeated the experiments on radiation in free space i.e. without a wire. Where our success was imperfect was when we tried to work with shorter wave lengths than about 10 metres and before we had got your paper describing how you had done it. Within the last few days we have been most successful as we could fairly have expected in repeating your recently described experiments. We were successful in repeating your experiment of the interference of a direct and reflected wave that we ventured and succeeded in showing it at a public meeting of the Royal Dublin Society in January … I expect it is nearly the first time your experiments have been shown in public and certainly the first time in the United Kingdom. This afternoon Mr. Trouton and I have been working at parabolic mirrors and on imitations of your recent apparatus … You say you do not know why the longer waves are so difficult to deal with: but it is because of diffraction? With very long waves you cannot get them to proceed in straight lines, they go round corners like sound and their energy is lost in all directions, while with short waves moderate sized mirrors, reflectors etc. suffice.

Fitzgerald then proceeded to give a detailed explanation of his diffraction idea.

From Hertz's letter to Fitzgerald on 11 June 1888 we know that he was acquainted with a brief communication by the latter entitled 'On a method of producing electromagnetic disturbances of comparatively short wavelength', published in the *British Association Report* for 1883.[17] In addition, Fitzgerald had published three other papers giving the results of his investigations relating to Hertz's researches. These had been published between 1879 and 1882 under the title 'On the possibility of originating wave disturbances in the ether by means of electric forces'.[18] In these papers Fitzgerald had proposed a magnetic oscillator, the analogue of Hertz's subsequently devised electric oscillator, to produce electromagnetic radiation. A shorter version of another paper entitled 'On the quantity of energy transferred to the ether by a variable current'[19] had appeared in the British Association *Report* for 1883, along with the note on the production of electromagnetic disturbances. Fitzgerald now sent copies of some of these papers with a letter on 25 January 1889. He writes:[20]

> I am sending you copies of some of my papers … I found that very little energy would be radiated unless the rate of alternation were almost comparable with that

> of light and this again agrees with your observation that it was easier to observe the radiations when they were very rapid.

Fitzgerald also gave further information in this letter to Hertz on the progress of Trouton's experiments. The results obtained by Fitzgerald and Trouton in repeating Hertz's experiments in the autumn and winter of 1888–1889 were published in *Nature* on 21 February 1889 in a paper by Trouton with the title 'Repetition of Hertz's experiments, and the determination of the direction of the vibration of light'.[21] These experiments form the background to Fitzgerald's next letter to Hertz written on 8 February 1889. He explains that:[22]

> The mirrors have proved large enough to observe the reflection from a stone wall 3 feet thick which we long ago observed to be quite transparent and in fact showed to be such at a public meeting of the Exp. Science Association of Trinity College last November. Mr Trouton set up the experiment and has verified that the radiations are polarised by reflection and that the magnetic disturbance is in the plane of polarisation, as it ought to be on Maxwell's theory. We have tried several times for reflection off large sheets of glass with no result and at last Mr. [John] Joly … remarked that we were trying to see the black spot in Newton's rings. We have observed what I hope will be verified as proving some more of Newton's rings in the case of our 3 foot wall. We are getting a pitch tank constructed to make experiments with ….

More than a year passed before there was further correspondence between Hertz and Fitzgerald. In the meantime Fitzgerald and Trouton continued their investigations. Their experiments were reported in a paper published in *Nature* on 22 August 1889 under the title 'Experiments on electro-magnetic radiation, including some on the phase of secondary waves'.[23] Trouton likewise referred to these experimental observations in a theoretical paper 'On the acceleration of secondary electromagnetic waves' in 1890.[24] On Friday 21 March of that year Fitzgerald delivered a popular discourse entitled 'Electromagnetic radiation' at the Royal Institution in London in the course of which he reviewed the investigations of Hertz and those of Trouton.[25] It was no doubt this lecture which came to Hertz's attention and which is referred to in a letter to Sarasin, dated Bonn 22 June 1890. Hertz's words in English translation are:[26]

> In a lecture about the execution of the same experiments by Fitzgerald and Trouton in Dublin, which I read about somewhere, I think in *La Lumière électrique*, they found, just as I did, that the waves in air have a wavelength of 5 metre compared to 9 metre in wires. Similar interference must have been involved.

Fitzgerald and Hertz finally met in person in London at the end of November 1890; in an account to his parents, written on 5 December 1890, Hertz recalls:[27]

> At 6 we had dinner at the hotel with Professor [Oliver] Lodge and Fitzgerald of Dublin, … with whom I now became acquainted as well.

The next correspondence between Hertz and Fitzgerald was in the following summer and concerns the work of a certain Walter Thorp, who was carrying out experiments in Fitzgerald's laboratory on the propagation of waves along wires of different thicknesses and along gas pipes. Fitzgerald's correspondence with Thorp forms a prelude to this second phase of his correspondence with Hertz.[28] Thus, in a letter dated 13 July 1891 from Glasnevin, Dublin, Thorp gave the following account of his investigations:

> Mr. Trouton would tell you that I found the thickness of the wire I have been using, made a material difference in the position of the nodes on the wire … It appears probable that if I would use a wire sufficiently fine I should obtain results identical with those of Prof. Hertz. The ratio of 17 to 12 is approaching his ratio of 7 to 4. On the whole I consider it easier to work with a thin wire than with a thick one, i.e. the nodes were easier to find in the former case …

At this juncture Fitzgerald wrote to Hertz again giving him details of Thorp's work. Although the letter has not been found we can infer its contents from Hertz's reply from Bonn on 20 July 1891. Hertz writes:[29]

> I am very much indebted to you for the notice you kindly gave me about Mr. Thorp's experiments. Permit me firstly to state my own present opinion about the matter in question. The only reason I have to believe that there may be any difference in the rate of propagation in air and wires is the result of my own experiments. The contrary was made probable to me, 1) by the theory 2) by the fact that for short waves I could not find any difference 3) that I could not detect any influence of the size or form of the section of the wires 4) by the experiment of Sarazin and de la Rive, who get the same velocities. I think the odds are entirely in favour of the latter view and though I do not think possible that I made so large a mistake in the observation; I think it possible, that special reasons [which] spring from the form and size of the room in which I worked deplaced [sic] the nodes so that I was deceived. I was confirmed in this view when during the last Easter Holydays [sic] I tried to repeat the experiments in my present lecturing room. This is a very beautiful room but [as] the elevated seats prevented me to choose [sic] a direction which was symmetrical to the walls, I was forced to make use of directions of propagation inclined to the walls. Now under these circumstances the nodes were so badly pronounced, that I could not make observations which could compete with the much better ones I made formerly, and that even I could not with certainty say if the observations agreed better with Sarazin's and de la Rive's or with my own. So I gave up and acquiesced with the idea that a hall 12 mtr square which is not absolutely empty is much to[o] small to make prooving [sic] experiments with waves 3–4 mtrs long and that the proove [sic] of the theory was better taken from short waves … Now this all of course becomes very much changed if the results of Mr. Thorp proove to be exact. Again some mysterious difference would come in. So I think that very great interest is attached to this observation especially from my own personal standing point. So I think it will be necessary to repeat these experiments over and over again and make them quite sure.

> Permit me to make some observations … I should advise Mr. Thorpe [sic] always to make use of two wires … As the wave is conducted in the air between them, the conditions are much purer in this case than with one wire … I myself never observed any difference of rate in different wires from the thickest to the thinnest, nor can I say anything that should look like an explanation …

Hertz's suggestion to use two parallel wires was passed on to Thorp, but as can be seen from the final remark in the next letter to Fitzgerald, sent from Headingly, Leeds, on 5 August 1891, this came too late to be tried by him. With this letter Thorp sent Fitzgerald the results of the experiments he had carried out between 2 June and 13 July 1891. Thus he writes:[30]

> I have written out a short notice of my experiments and will send it to you with this letter. I doubt if you will be satisfied with it, for I am not myself. I had intended to get the wavelength in air for both receivers accurately and also measurements for the larger receiver with fine wire before publishing my results; but if you can find time to go on with the work yourself, the final result will, I am sure, be more reliable though I am pretty confident of the accuracy of the figures given in the accompanying paper … It would be very interesting to have experiments with two parallel wires and I wish I had known of the idea earlier.

The final account of Thorp's investigation was published in the *British Association Report* for 1891 with the heading 'On the propagation of electromagnetic waves in wires by Walter Thorp'.[31] Thorp explains that

> These experiments were undertaken with the hope of throwing some light upon the results previously obtained by Professor Hertz … He found the ratio of the velocity of propagation of electromagnetic waves in air to the velocity in copper wires to be as 75 : 47, or 1.6. His wave-length in air was 7.5 meters. Using much shorter waves (0.68 m) and wires of different diameters, the author obtained a ratio varying from 1.77 for very fine wires to nearly unity for thick wires … The author thinks that these experiments show that Professor Hertz's results were due to the comparative thinness of the wire he used as judged by the length of his waves.

The concluding letter from Hertz to Fitzgerald on this topic, written on 12 December 1891, was a brief note requesting information about Thorp's investigations. Hertz writes:[32]

> Half a year ago you wrote to me about Mr. Thorp, making experiments in your laboratory and finding traces of a different velocity of electromagnetic waves in air and in wires. Will you have the kindness to tell me quite in a few words, if it has proved to be an error, or if anything has come out of it? You may well think I am interested in this, and I shall be ever thankful to you. I have not experimented about the waves all this time.

Hertz's correspondence with Sarasin and de la Rive

The results of the repetition of Hertz's experiments by Édouard Sarasin (1843–1917) and Lucien de la Rive (1834–1924) were published in a series of papers between 1890 and 1893.[33] Hertz's collaboration with the Genevan physicists is documented in their correspondence, particularly in Hertz's letters, copies of which are preserved at the Deutsches Museum in Munich; the most relevant extracts are quoted below in English translation. Thus, writing to Sarasin from Bonn on 27 June 1889 Hertz outlined the circumstances of his Karlsruhe experiments:[34]

> the apparatus with which I worked was not constructed by a skilled technician from good drawings in elegant fashion but rather put together partly by myself and partly by the technician of the Physical Cabinet in Karlsruhe in a rough and provisional manner out of pieces of wood, wires, sealing wax, and then continually altered … I have to admit that I do not believe that the problem can be the apparatus since this was too simple. I still believe that the problem is most likely the action of some subsidiary discharge or some other unknown cause, since I could not find an explanation for all irregularities and at the outset I had many unsuccessful trials. In the end it operated for whatever reason so continuously that I demonstrated the experiments twenty times without a hitch …

In a subsequent letter to Sarasin, written on 16 September 1889, Hertz enquires about the principal problem:[35]

> Have you any experience about whether the longer waves in air are propagated just as rapidly as in wires? I have discovered that the former are faster with waves which are 2–3 m long. According to theory both velocities ought to be the same and for short waves of 2–3 decimetres they are found to be the same. The more I think about the matter, the more I fear that something or other in my experiments could have deceived me. If my experiments are correct, that would be very remarkable and would suggest something new. I myself have not repeated the experiments because I was very certain of getting the same result again under the same circumstances with the same apparatus. But in the completely different rooms of others, with different apparatus, a certain confirmation or refutation might be expected. I could indeed have deceived myself; at the time I understood only very incompletely reflections from the walls etc.

Writing to Sarasin again on 2 May 1890 Hertz returns to the issue of the different velocities of propagation in air and along wires:[36]

> As far now as the different wavelengths in air and in wires are concerned, it would indeed be more pleasant for me for the present if you had simply found my observations to be confirmed, but nature has to be respected and can't follow our desires. The facts of the matter are as follows: From the beginning I had expected to find the velocity in air and in the wires to be the same, since theory requires this. But my first experiments clearly provided a different result for the long waves of 3 m. I was very surprised but I had to take the phenomena just as I found

> them. After I found in addition that for short waves the velocity in air and in the wires was the same, that the velocity in all kinds of wire lines, even in the intervening space between two wires, was the same, my amazement grew and I confess that I also know no cause nor do I understand why the waves should move slower in the wires.
>
> If therefore you can prove that the velocity is the same, you will come to the assistance of theory and remove an essential gap in the latter. But it would be very good if you succeeded at the same time in finding that, and why, under certain circumstances the matter seems different and the nodes appear further removed from each other. For you may believe me that I also observed very exactly, particularly as I anticipated equality, and my conditions were indeed more favourable than yours as I had a space of 13m. I think therefore that some particular special circumstance adulterated my experiments and that yours provided purer results, but I do not know at present what my mistake can have been. To my earlier experiments by direct comparison I attach less weight, as the reflections from the back wall, which were unknown to me at the time, could have deceived me somewhat here …

In the next letter to Sarasin, written on 22 June 1890, the same issues dominate. Hertz writes:[37]

> As far as your investigation is concerned, I am coming to believe more and more that you are right and that the velocity in air and in the wires is the same. Everything speaks in favour of this and I would never have believed anything else myself if my experiments had not so clearly required a different interpretation. What the cause for this was I don't know. With the interference experiments, reflections from neighbouring objects, of which I had no understanding at the time, could have deceived me … In the meantime it is less a question of why I erred than of how the matter is in reality, and then I can feel pleased if this horrible conflict with the theory disappears and harmony is completely restored and everyone will be grateful to you for this. I will contradict you least of all, but rather assent, provided later experiments of mine don't turn out like the earlier ones.

Writing again on 12 April 1891 Hertz recalls, as in his letter to Fitzgerald on 20 July 1891, his final attempt to repeat the experiments at Easter 1891:[38]

> I had intended in the Easter holidays which are now ending to repeat the experiments on the reflection of long waves from a conducting wall in order to explain if possible the different results obtained by you and by myself … I took two large zinc sheets 4 m high and 2 m wide and placed them opposite each other … I expected that it would now be easy for me to obtain either my earlier results or yours, by varying the distance of the primary conductor from the wall. This did not happen but rather something different which I hadn't expected. I was namely completely unable in my present lecture theatre here to replicate the effects with the same certainty and clarity as in the Karlsruhe lecture hall … My personal conviction is now the following, that one should best draw conclusions from the experiments with short waves, and that for the experiments with long waves one would need, in order to be certain, much larger rooms than hitherto

used, or at least rooms from which all disturbing benches etc. have been removed and which are at least 20 m long, 10 m wide and 6 mtr high. That the effects observed in the lecture hall in Karlsruhe were so clear, would then to a certain extent be an accident, just as one hall has good acoustic properties and another does not …

Hertz met Sarasin and de la Rive in the spring of 1892 during a visit to Geneva. A letter to Sarasin on 22 March 1892 contains an inquiry about his intended visit.[39] Another of March 28[40] contains an announcement of his visit and in a letter of 18 April[41] he reflects on his visit having returned to Bonn. The final letter Hertz wrote to Sarasin is dated 19 May 1893. Sarasin's and de la Rive's paper '*Sur l'égalité des vitesses de propagation de l'ondulation electrique dans l'air et le long de fils conducteurs, vérifiée par l'emploi d'une grande surface métallique*' had appeared in *Comptes Rendus* and seemed to provide a resolution at last of the central outstanding issue. The letter reveals Hertz's ambivalent mood on learning of the outcome. Thus he writes:[42]

Above all I have not expressed sufficiently the joy I have derived from these great experiments of yours. I always felt that these should have been carried out in this fashion; that this has happened, and that you in particular have the glory for it, is a great satisfaction for me. I had however to the end entertained the secret hope that my results might indeed be verified and for this reason I preferred that not I but another should carry out the task. This hope has now been dashed, but the principal matter is indeed that now every doubt has been removed, and I hope that the picture of your large-scale arrangement will be preserved as a permanent monument in science. Now for the first time, in my opinion, the matter is complete and settled.

The picture referred to by Hertz is probably one of the two photographs preserved at the Deutsches Museum which show the experimental arrangement used by Sarasin and De la Rive. The oscillator and the transmission line are mounted on timber trestles in a large hall. The equipment is covered with timber and fabric cladding presumably to darken the space near the transmission line. One photograph contains greetings[43] and a dedication to Hertz. The other[44] shows Sarasin in front of the elevated equipment holding a resonator. The photographs were probably taken in the summer of 1692; Hertz expresses thanks for photographs in a letter to Sarasin dated 18 September 1692.[45]

Conclusions

Hertz's investigation of electromagnetic-wave radiation laid the foundation for the development of wireless broadcasting. At the heart of his experiment on standing waves however was a single-wire (with ground return) or two-wire transmission line. Such transmission lines were later to have immense importance in electrical engineering and in telecommunications. The velocity of transmission along such a two-wire open line depends on the permittivity and permeability of free space, but not frequency, and is approximately 3×10^8 m/s. Two publications on the occasion of the centenary of Hertz's work in 1988 have stressed the significance of the transmission line in his experiments. In *Heinrich Hertz. The Beginning of Microwaves*, John H. Bryant has analysed the line in the experiment as the 'wire-over-ground-plane transmission line'.[46] On the other hand Helmut Friedburg in '*Die Karlsruher Experimente von Heinrich Hertz*'[47] has pointed out that Hertz did not consider the ground-return connection and that he thought the waves were transmitted along one wire only. Thus, he did not have the later conception of a transmission line. Hertz's experiment with a single wire was, for a twentieth-century physicist, 'physically undefined'; furthermore, influences in the neighbourhood had not been adequately eliminated. Friedburg also discusses the issue of the retardation of the waves along wires. He points out that nobody was subsequently able to account exactly and in detail for the unexpected results Hertz got.

That the issue of the apparent retardation of the waves was more than a peripheral technical detail is evident from the attention paid to the matter in the Introduction to the volume of Hertz's electrical papers in 1891 and in his correspondence. At stake was the integrity of Maxwell's theory or of his own experimental method. He attributed the retardation to the ambient conditions of his experiment. He looked to the other scientists to repeat his experiment in other environments. In Dublin, Fitzgerald, Trouton, and Thorp, repeated the experiment and confirmed the apparent retardation in wire transmission. On the other hand, the experiments of Sarasin and de la Rive indicated equality in the rates of transmission. Hertz long remained sceptical because these experiments had been carried out in a smaller room than his own. When, however, the experiments of Sarasin and de la Rive with longer waves carried out in a large hall appeared to confirm equal rates of transmission the matter seemed to have reached a conclusion and the 'horrible conflict with theory' ('dieser hässliche Gegensatz gegen die Theorie') had been removed. Nevertheless Hertz's letters continue to be tinged with a note of regret that he had been unable to account for the anomalies of his own experimental arrangement.

Acknowledgement

I am grateful to Professor Denis Weaire for helpful comments and suggestions.

References

1. See B. J. Hunt (1991) *The Maxwellians* (Ithaca and London: Cornell University Press) and (2007) *'Our Friend of Brilliant Ideas': G. F. Fitzgerald and the Maxwellian Circle*, **15**(4), pp. 531–544.

2. See J. G. O'Hara and W. Pricha (1987) *Hertz and the Maxwellians* (London: Peter Peregrinus Ltd).
3. H. Hertz (1887) *Wiedemanns Annalen* **31**, 421–448, 543–544. Also H. Hertz (1892) Untersuchungen ueber die Ausbreitung der Elektrischen Kraft (Leipzig: Johann Ambrosius Barth), pp. 32–58. English title: On very rapid electrical oscillations, in H. Hertz (1893) *Electric Waves Being Researches on the Propagation of Electric Action with Finite Velocity through Space* (London: Macmillan and Company), pp. 29–53.
4. H. Hertz (1888) *Wiedemanns Annalen* **34**, 551–569. Also *Untersuchungen*, pp. 115–132; On the finite velocity of propagation of electromagnetic actions, *Electric Waves*, pp. 107–123.
5. H. Hertz (1888) *Wiedemanns Annalen* **34**, 609–623. Also *Untersuchungen*, pp. 133–146; On electrodynamic waves in air and their reflection, *Electric Waves*, pp. 124–136.
6. H. Lloyd (1837) On a new cause of interference of the rays of light. *Transactions of the Royal Irish Academy* **17**, 171–178. German translation (1838) *Poggendorffs Annalen* **45**, 95–104. See also J. G. O'Hara 'Humphrey Lloyd 1800–1881'. In M. McCartney & A. Whitaker (eds), *Physicists of Ireland Passion and Precision* (Bristol and Philadelphia: Institute of Physics Publishing, 2003), pp. 44–51.
7. See J. G. O'Hara and W. Pricha (1987) *Hertz and the Maxwellians* (London: Peter Peregrinus Ltd), pp. 29, 132.
8. H. Hertz (1889). *Wiedemanns Annalen* **37**, 395–408. Also *Untersuchungen*, pp. 171–183; On the propagation of electric waves by means of wires, *Electric waves*, pp. 160–171.
9. H. Hertz (1889) *Wiedemanns Annalen* **36**, 769–783. Also *Untersuchungen*, pp. 184–198; On electric radiation, *Electric waves*, pp. 172–185.
10. J. G. O'Hara and W. Pricha (1987) *Hertz and the Maxwellians* (London: Peter Peregrinus Ltd), p. 23f. Deutsches Museum, Archiv, HS 2886.
11. J. G. O'Hara and W. Pricha (1987) *Hertz and the Maxwellians* (London: Peter Peregrinus Ltd), p. 25f. Original in Fitzgerald Collection, Royal Dublin Society.
12. *H. Hertz, Erinnerungen. Briefe. Tagebücher; Memoires. Letters. Diaries*. Arranged by Johanna Hertz. Second enlarged edition prepared by Mathilde Hertz and Charles Susskind (Weinheim: Physik Verlag; San Francisco: San Francisco Press, 1977). Cf. p. 259.
13. J. G. O'Hara and W. Pricha (1987) *Hertz and the Maxwellians* (London: Peter Peregrinus Ltd), p. 26f. Original in Library, Trinity College Dublin, MS 4233/2.
14. J. G. O'Hara and W. Pricha (1987) *Hertz and the Maxwellians* (London: Peter Peregrinus Ltd), p. 28f. Deutsches Museum, Archiv, HS 2887.
15. H. Hertz (1889) *Wiedemanns Annalen* **36**, 1–22. Also *Untersuchungen*, pp. 147–170; The forces of electric oscillations, treated according to Maxwell's theory, *Electric Waves*, pp. 137–159.
16. J. G. O'Hara and W. Pricha (1987) *Hertz and the Maxwellians* (London: Peter Peregrinus Ltd), pp. 30–32. Deutsches Museum, Archiv, HS 2888 & 2888/2.

17. J. Larmor (Ed) (1902) On a method of producing electromagnetic disturbances of comparatively short wavelength. *The scientific writings of the late George Francis Fitzgerald* (Dublin: Hodges, Figgis & Longmans, Green), p. 129.
18. G. F. Fitzgerald (1883) *Transactions of the Royal Dublin Society* **1**, 133–134, 173–176, 325–326. Also J. Larmor (Ed) (1902) On a method of producing electromagnetic disturbances of comparatively short wavelength. *The scientific writings of the late George Francis Fitzgerald* (Dublin: Hodges, Figgis & Longmans, Green), pp. 90–101.
19. G. F. Fitzgerald (1883–1887) *Transactions of the Royal Dublin Society* **3**, 57–63. J. Larmor (Ed) (1902) On a method of producing electromagnetic disturbances of comparatively short wavelength. *The scientific writings of the late George Francis Fitzgerald* (Dublin: Hodges, Figgis & Longmans, Green), pp. 122–126.
20. See J. G. O'Hara and W. Pricha (1987) *Hertz and the Maxwellians* (London: Peter Peregrinus Ltd), p. 33. Deutsches Museum, Archiv, HS 2889.
21. F. T. Trouton (1889) *Nature* **39**, 391–393, 412. See also J. G. O'Hara 'Frederick Thomas Trouton 1863–1922'. In M. McCartney & A. Whitaker (eds) *Physicists of Ireland Passion and Precision* (Bristol and Philadelphia: Institute of Physics Publishing, 2003), pp. 161–167.
22. See J. G. O'Hara and W. Pricha (1987) *Hertz and the Maxwellians* (London: Peter Peregrinus Ltd), pp. 37f. Deutsches Museum, Archiv, HS 2890.
23. F. T. Trouton (1889) *Nature* **40**, 398–400.
24. F. T. Trouton (1890) *Philosophical Magazine* **29**, 268–276 and Pl. IV.
25. G. F. Fitzgerald (1893) *Proceedings of the Royal Institution of Great Britain* **13**, 77–84. Also J. Larmor (Ed) (1902) On a method of producing electromagnetic disturbances of comparatively short wavelength. *The scientific writings of the late George Francis Fitzgerald* (Dublin: Hodges, Figgis & Longmans, Green), pp. 266–276.
26. Deutsches Museum, Archiv, HS 3139.
27. *H. Hertz, Erinnerungen. Briefe. Tagebücher; Memoires. Letters. Diaries.* Arranged by Johanna Hertz. Second enlarged edition prepared by Mathilde Hertz and Charles Susskind (Weinheim: Physik Verlag; San Francisco: San Francisco Press, 1977). Cf. p. 310–311.
28. Six letters to G. F. Fitzgerald from Walter Thorp. Fitzgerald Collection, Royal Dublin Society.
29. See J. G. O'Hara and W. Pricha (1987) *Hertz and the Maxwellians* (London: Peter Peregrinus Ltd), p. 46f. Original in Fitzgerald Collection, Royal Dublin Society.
30. See J. G. O'Hara and W. Pricha (1987) *Hertz and the Maxwellians* (London: Peter Peregrinus Ltd), p. 48–50. Original in Fitzgerald Collection, Royal Dublin Society.
31. W. Thorp (1891) On the propagation of electromagnetic waves in wires. *British Association Report* **41**, 562–563.

32. See J. G. O'Hara and W. Pricha (1987) *Hertz and the Maxwellians* (London: Peter Peregrinus Ltd), p. 52. Original in Fitzgerald Collection, Royal Dublin Society.
33. L. de la Rive (1890) Sur la theorie des interférences de l'onde électrique propagée dans un fil conducteur et du résonateur. *Archives des Sciences Physiques et Naturelles* **23**, 391–401, 547–549. E. Sarasin, L. de la Rive (1892) Sur la production de l'étincelle de l'oscillateur hertzien dans un diélectrique liquide, au lieu de l'air. *Archives des Sciences Physiques et Naturelles* **28**, 306–330; *Comptes Rendus* **115**, cols 439–440. E. Sarasin, L. de la Rive (1892–1893) Sur l'égalité des vitesses de propagation de l'ondulation electrique dans l'air et le long de fils conducteurs, vérifiée par l'emploi d'une grande surface métallique. *Comptes Rendus* **115**, cols 1277–1280; **116**, col 32. E. Sarasin, L. de la Rive (1893) Égalité des vitesses de propagation dans l'air et le long des fils conducteurs. *Archives des Sciences Physiques et Naturelles* **29**, 358–393, 441–470.
34. Deutsches Museum, Archiv, HS 3154.
35. Deutsches Museum, Archiv, HS 3134.
36. Deutsches Museum, Archiv, HS 3138.
37. Deutsches Museum, Archiv, HS 3139.
38. Deutsches Museum, Archiv, HS 3141.
39. Deutsches Museum, Archiv, HS 3143.
40. Deutsches Museum, Archiv, HS 3144.
41. Deutsches Museum, Archiv, HS 3145.
42. Deutsches Museum, Archiv, HS 3149.
43. Deutsches Museum, Archiv, HS 3263.
44. Deutsches Museum, Archiv, HS 3262.
45. Deutsches Museum, Archiv, HS 3148.
46. (1988) Exhibition Catalog (New York: IEEE).
47. (1988) *Fridericiana: Zeitschrift der Universität Karlsruhe*, **41**, 39–57.

About the Author

James G. O'Hara is a Research Editor for the Leibniz Edition, a project of the Berlin-Brandenburg Academy of Sciences and of the Academy of Sciences in Göttingen and he is based at the Gottfried Wilhelm Leibniz Bibliothek, the State Library of Lower Saxony in Hannover. He has co-edited three volumes of the mathematical, scientific and technical correspondence of Leibniz. He previously worked on the manuscript papers and letters of nineteenth-century mathematicians and physicists including Carl Friedrich Gauss and Heinrich Hertz. He has a special interest in Anglo-Irish science and technology in the period from the seventeenth to the nineteenth centuries.