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XXXI. *The Variation of Potential along a Wire transmitting Electric Waves.* By C. A. CHANT, *University of Toronto, Toronto, Canada**.

[Plate VII.]

I. *Introductory.*

HERTZ† was the first to explore a wire along which electric undulations were passing. His oscillator consisted of two sheet-brass plates 40 cms. square, connected by a copper wire 60 cms. long, in the middle of which was a spark-gap. Opposite and parallel to one plate was placed another of equal size, from which was led off a copper wire, the first metre of which was curved and the rest of it straight. As a detector he used his circular resonator, 70 cms. in diameter. The nodes were well marked in two wires, the length of the straight portions of which were 5·5 m. and 8 m. respectively. The half-wave-length was determined to be 2·8 m.

These experiments were repeated and extended by Sarasin and de la Rive‡, who somewhat increased the effect by using two wires led off from two plates placed opposite the oscillator plates, the resonator being held between them. These experiments showed very clearly that the apparent wave-length measured along the wire was dependent purely on the size of the resonator, the wave-length being equal to eight times the diameter of the resonator.

Somewhat similar results were obtained by Waitz§, who used a circular resonator to which were attached two wires, one joined near each terminal knob, and led off either parallel to each other or in opposite directions. In the former case, by sliding along a bridge laid across the wires, the sparks between the resonator knobs passed through maximum and minimum intensities; in the latter case, by hanging capacities on the wires and sliding them along, the sparks varied similarly. He worked with plate oscillators of two sizes, as well as cylindrical and spherical ones. He found that his minima depended entirely on the dimensions of his circular resonator.

The conclusion naturally drawn by Sarasin and de la Rive and Waitz from their experiments was that the oscillator

* Communicated by Prof. Trowbridge.

† H. Hertz, *Wied. Ann.* xxxiv. p. 551 (1888); 'Electric Waves,' p. 106.

‡ E. Sarasin and L. de la Rive, *Archives des Sciences Physiques et Naturelles*, Genève, t. xxiii. p. 113 (1890).

§ K. Waitz, *Wied. Ann.* xli. p. 435 (1890).

emitted waves of various lengths, extending over several octaves; but this hypothesis has been shown to be improbable, a more satisfactory explanation being based on the fact that the oscillations of the oscillator are very rapidly damped, while those of the resonator are very persistent*

In Lecher's† experiments the exciter consisted of two sheet-metal plates, 40 cms. square, joined by a bent wire 2 m. long, with a spark-gap in the middle of it. Opposite each plate and parallel to it was another of the same size, from which ran long straight parallel wires. On the farther ends of these was laid a vacuum-tube, and across the wires at different points were laid metallic bridges. When these were properly placed, namely, at the potential nodes, the tube at the ends lighted up. The wave-lengths he obtained, however, were not those proper to the exciter, but those of that part of the wire-system on that side of the first bridge next the plates which was in resonance with the rest of the wire-system.

In Cohn and Heerwagen's‡ experiments with Lecher's method a condenser was added to the ends of the wires.

Blondlot§ also experimented with parallel wires, but used an oscillator of quite different construction. In Lecher's arrangement the capacity is large compared to the self-induction; in Blondlot's the reverse is the case. The latter has the advantage that the damping is much diminished.

These "wire-waves" have been the subject of numerous investigations, a notable one being that by Drude||. He found that the oscillator must be considered as composed of the Blondlot semicircular primary exciter, together with that portion of the secondary wire-system as far as the first bridge; and that when the bridges are properly placed there is resonance between this oscillator and the rest of the system. Very convenient forms of this apparatus are given by Coolidge¶ and Hormell**.

Donle††, who used chiefly the Blondlot oscillator, joined the ends of the parallel wires with a glow-lamp. His aim

* See Poincaré, *Les Oscillations Électriques*, Art 55 & fol.; J. J. Thomson, 'Recent Researches,' p. 340.

† E. Lecher, *Wied. Ann.* xli. p. 850 (1890).

‡ Cohn and Heerwagen, *Wied. Ann.* xliii. p. 343 (1891).

§ R. Blondlot, *Comptes Rendus*, cxiii. p. 628 (1891).

|| P. Drude, "Eine bequeme Methode zur Demonstration des electrischen Brechungsexponenten von Flüssigkeiten," *Wied. Ann.* lv. p. 633 (1895).

¶ W. D. Coolidge, *Wied. Ann.* lxxvii. p. 578 (1899).

** W. G. Hormell, *Am. Journ. Science*, xii. p. 433 (1901).

†† W. Donle, *Wied. Ann.* liii. p. 178 (1894).

was to diminish the wave-length, which he reduced to 130 cms. Coolidge's smallest wave-length was 12 cms.

In Rubens's experiments the exciter was of the Hertzian form, with plates 40 cms. square. The two opposing parallel plates were but 10 cms. square, though the smaller plates are not quite as efficient as those of equal size*. From these smaller plates the parallel wires went out—in this instance to a distance of 570 cms.—and were explored by a bolometric method. Rubens† found that the oscillations along the wires were not the same as those of the oscillator; in other words, the oscillations were not forced along the wires, but were those natural to them.

These experiments were verified by Rutherford‡, who substituted a magnetic detector for the bolometer, and found it equally sensitive.

In all these experiments it will be observed that the wave-lengths determined along the wires are not those proper to the oscillator, but are either due to the detector used or to the wires vibrating naturally.

In Birkeland's§ and Jones's|| researches the reverse seemed to be the case. The wire-systems were both similar to that of Sarasin and de la Rive, but the means of exploration were different. Birkeland examined the potential at various points of his wire, which was 30 m. long, by measuring the length of the spark which leaped from it to an earth connexion, the existence of the spark being indicated by a telephone receiver held to the ear. He obtained minimum points which varied as the period of the oscillator was changed, thus indicating that the measured wave-length depended on its period. These minima were unequally spaced, which irregularity was attributed to the damping of the waves and the loss on reflexion at the ends of the wires; but the explanation does not seem entirely satisfactory¶.

Jones used a thermal junction inserted at different points of his wire which was 130 m. in length, the effect being indicated by a low-resistance galvanometer in circuit with it. The oscillator was of the usual type, with plates 40 cms. square, but the length of the connexion between the plates is not given. Several well-defined maxima and minima were observed, and the wave-length was determined to be approximately 4·3 m. It is interesting to read that "several

* Drude, *Physik des Aethers*, p. 446.

† H. Rubens, *Wied. Ann.* xlii. p. 154 (1890).

‡ E. Rutherford, *Phil. Trans. A*, 1897, vol. clxxxix. p. 1.

§ Kr. Birkeland, *Wied. Ann.* xlvii. p. 583 (1892).

|| D. E. Jones, *Brit. Assoc. Report*, 1891, pp. 561–2.

¶ See Poincaré, *Les Oscillations Électriques*, p. 176.

curious results were recorded for which no explanations were forthcoming”*.

It may be worth while to recall how the wave-length of Hertz's plate oscillator was determined. He obtained it with the aid of his circular resonator, but, as has been already remarked, the wave-length thus found is always eight times the diameter of the resonator. If, then, we could know when the resonator was exactly in unison with the oscillator, the wave-length could be deduced with considerable accuracy. But this is not at all possible; the resonance is far from being sharply defined. Indeed, Hertz says that the same resonator, of diameter 70 cms., was in resonance with three different oscillators. The first consisted of two spheres of diameter 30 cms., connected by a wire 70 cms. long, with a spark-gap in the middle; the second, of two plates 40 cms. square, joined by a wire 70 cms. long with a spark-gap as before; the third had plates of the same size, but the wire was 60 cms. long†.

Thus the wave-length emitted by each of these was taken to be the same, namely, 560 cms. Now the period and wave-length of the first oscillator have been found theoretically. Hertz‡ calculates the period to be 1·26 hundred-millionths of a second, and the wave-length to be 4·6 m., while Drude§ makes the latter 4·8 m. Both values differ considerably from that obtained by resonance. Again, the second and third oscillators differ considerably in period, though that of the second was found to be the same as that of the first (see below). We must conclude that the wave-length 5·6 m. is not a very close approximation.

In the experiments to be described presently it will be seen that oscillators of the same type may differ decidedly in their behaviour; that some seem able to force their vibrations upon a wire, while others cannot. The wave-length of an oscillator the same as the third of the three just described was concluded to be 5·88 metres.

II. *Experimental Arrangement.*

While engaged during the session 1900–1, in the Jefferson Physical Laboratory of Harvard University, on another

* ‘Nature,’ vol. xliv. p. 454 (1891).

† Hertz, ‘Electric Waves,’ Art. V. pp. 81–2; Art. VI. pp. 96–7; Art. VII. pp. 108 & 113.

‡ Hertz, *ibid.* pp. 51 & 270 (note 6).

§ Drude, *Physik des Aethers*, p. 397. See also J. J. Thomson, ‘Recent Researches,’ Arts. 289 & fol.

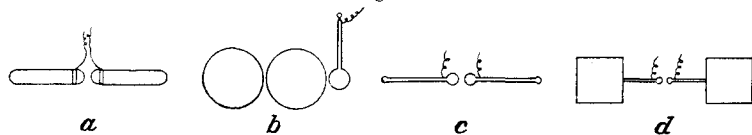
investigation* in which the magnetic detector was used, the fact that an electrical disturbance about a wire parallel to the wings of the detector exerted a strong action on the detector was continuously and painfully evident. Indeed, the effect arising from the connecting wires at first entirely masked the true radiation from the oscillator.

This suggested the possibility of conveniently exploring the field along a wire by shortening the wings of the detector and then placing it close to the wire at various points in its length. The experiment was tried, but the demagnetization of the detector was small. However, on removing one wing and placing the other near the wire the effect was much greater and easily measurable.

But the action with one wing is not at all the same as with two. When the detector with two wings is placed along the wire, the surging in its helix and the consequent demagnetization is greatest at points where the current oscillation is greatest, *i. e.* at a current loop; the effect is least at a current node. With a single wing these results are exactly reversed, the effect is greatest at a current node, which is, of course, a potential loop. This can be explained in the following way:—The little wing and the portion of the wire just beside it act as a miniature condenser, and when there is a maximum variation of potential in the element of wire there will also be a maximum variation in the detector wing, which will cause currents to surge back and forth in the helix, and so to demagnetize the iron core. At a current loop (or potential node) the variation in potential is a minimum, and so the detector when placed there will show minimum demagnetization. Indeed, the indications of the magnetic detector should be precisely similar to those of the bolometer as used by Rubens.

An attempt was then made to force standing waves in a wire, and preliminary experiments seemed to show the possibility of determining the wave-lengths of oscillators in this way. Some measurements were made then, which, since the writer's return to Toronto, have been considerably extended.

Fig. 1.



The oscillators were of four kinds, illustrated in fig. 1.

* C. A. Chant, 'An Experimental Investigation into the "Skin"-effect in Electrical Oscillators,' *Am. Journ. Sci.* xiii. p. 1 (1902); *Phil. Mag.* [6] vol. iii. p. 425 (1902).

The cylinders of (*a*) were 2·5 cms. in diameter and 12·5 cms. long, with hemispherical ends; the spheres of (*b*) were of two sizes, namely, with diameters of 10 cms. and 30 cms. respectively; the larger spherical ends of (*c*) were 19 mm., the smaller 6 mm., and the straight portion 4·2 mm. in diameter, while the length over all was 12·5 cms.; in (*d*) is shown the ordinary Hertzian plate oscillator.

The sparks were produced by an induction-coil capable of giving sparks 12·5 cm. long, and fed by five accumulators in series.

The interrupter was similar to that used in the other investigation. It consisted in a platinum-tipped rod, which, by means of a motor, was alternately plunged into and withdrawn from mercury, the surface of which was kept clean by a stream of water continually flowing over it. In series with this were a pendulum interrupter and a contact-key. This key was depressed during any desired number of vibrations of the pendulum—usually five swings—during which time the coil was interrupted approximately 60 times. This number, of course, varied somewhat with the speed of the motor, but it did not change much during any series of readings.

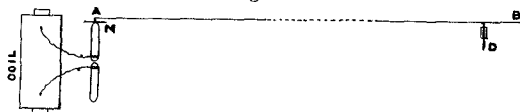
The magnetic detector was the same as that used in the other research. It had twenty pieces of iron, 0·014 cm. in diameter and 1 cm. long, insulated from each other by paraffin, and wound over with 90 turns of fine insulated wire. It was mounted in the end of a glass tube, and all held on a small sheet of hard rubber by means of wax. It is shown one-half of natural size in fig. 2.

The magnetometer and telescope, as well as the method of placing the detector behind the magnetometer, were as described in the former paper.

The manner of producing the oscillations along the wires is shown (for the cylinders) in fig. 3. AB is a long straight



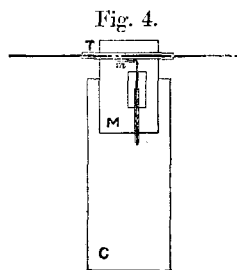
Fig. 3.



wire (0·7 mm. in diam.) ending at A in a small knob 6 mm. in diameter, which was separated from an end of one of the cylinders by a piece of mica, M, usually 0·15 mm. thick. By this means the surgings on the cylinders were impressed

upon the wire, which was explored by placing the little detector near it at different points in its length.

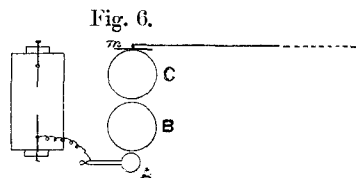
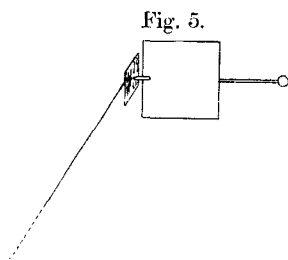
Since the magnitude of the effect depends on the distance the detector wing is held from the long wire it was necessary to regulate this accurately. To do so a small glass tube about $\frac{1}{4}$ cms. long, T, fig. 4, with bore just great enough to allow it to slide over the wire, was taken, and to the outside of this was fastened a bit of finely-drawn tubing, *m*, into which the wing fitted snugly. In all the experiments the wing was 1 cm. long.



The glass tube was attached to a piece of hard rubber (or mica), *M*, which, again, was cemented to the top, *C*, of a carriage which moved along beside the wire.

Thus, to examine any portion of the wire, the carriage was moved along to the required place, the distance of which from the end of the wire was measured by a scale on the ways on which the carriage moved. The detector was magnetized, then placed in its pocket beside the glass tube, and sparks made to pass at the oscillator for a certain length of time. The detector was then removed and examined by the magnetometer. This process was systematically carried out, beginning at the end of the wire and advancing by equal spaces.

For the linear oscillator, shown in fig. 1, *c*, the arrangement was precisely the same as for the cylinders. For the Hertzian oscillators, fig. 1, *d*, a rounded end was given to one of the plates by taking a piece of brass rod 6 mm. in diameter and about 2 cms. long, rounding the ends, and then making a slit in one end, which allowed it to be slipped over the plate. This is shown in fig. 5.



The arrangement for the spherical doublet is shown in fig. 6. When the coil was in action sparks passed between

A and B and B and C, and the oscillations on the sphere C were transmitted to the wire across the mica plate, *m*.

The wires used were quite short, ranging from 1 metre to 8.6 metres in length.

III. Results of Experiments.

It will be convenient to divide the results into two parts:—
A, those obtained with the oscillators *a, b, c* of fig. 1; and
B, those with the Hertzian oscillators.

A. Cylindrical Oscillator (fig. 1, *a*).

In Pl. VII. fig. 7, *a, b, c* are shown curves obtained with the cylindrical oscillator, which was made of sheet platinum on a wooden form with well-shaped hemispherical ends. Here, as always, the greatest variation in potential was at the end of the wire. It gradually fell until a minimum was reached at approximately 20 cms. from the end, and after another rise it dropped again to a minimum at approximately 60 cms. Each of the last two curves gives a half-wave-length of 40 cms., the first one 38 cms., or a mean wave-length for the oscillator of approximately 79 cms.

In every instance the actual readings are shown.

Linear Oscillator (fig. 1, *c*)

Curves obtained with this oscillator are shown in Pl. VII. fig. 7, *d, e*. Curve (*d*) is the mean of two sets of readings with five swings of the pendulum. The mean of five sets, each of two swings, gave the same minima, though the curve was not so good. Curve (*e*) is a repetition of the second portion of the readings; it is the mean of two sets of five swings each.

Here three minima are easily seen at 19, 59, and 99 cms. respectively, from the end; and the wave-length is thus approximately 80 cms.

Spherical Doublet (fig. 1, *b*).

Curves for this oscillator are given in Pl. VII. fig. 8. It was much more difficult to get consistent series of readings with it. Curves (*a*) and (*b*) are for the 10-cm. spheres. The half-wave-lengths deduced are respectively 19 and 19.5 cms., with a mean wave-length of 38.5 cms. Curves (*c*) and (*d*) are for the 30-cm. spheres. The half-wave-lengths from these are 61 and 62 cms. respectively, with a mean wave-length of 123 cms.

These curves are not as smooth as the former ones, but

are perhaps as good as one should expect with so dead-beat an oscillator.

From the results with the 10-cm. spheres the ratio of wave-length to diameter is 3·85, while with the 30-cm. spheres this ratio is 4·1*. The theoretical value given by J. J. Thomson† is 3·6. Further exploration of the wire revealed no more minima.

B. *The Hertzian Oscillators.*

With the Hertzian oscillators the results were quite different from those just given, and indeed they differed considerably amongst themselves.

The first oscillator tried had sheet-zinc plates 40 cms. square, with the straight wire between them 60 cms. long; and the wire transmitting the waves was 860 cms. long. One minimum was very well marked, but there were no more clear ones. Then a second oscillator, with 20-cm. plates, and otherwise of just half the size of the former was tried, but the minimum, instead of being half the distance from the end, was much farther from it. This led to the making of additional oscillators, with plates 10, 15, 25, 30, 35, 50 cms. square respectively, and with the wires between of proportional length. The spark-knobs were 19 mm. in diameter, the same knobs being used with all the oscillators.

Using these oscillators, readings were taken with wires from 100 to 860 cms. long; and the results obtained are exhibited in the accompanying table and curves. In the table the positions of the minima are given by stating their distances in centimetres from the free end of the wire. There was always one more marked than the others, and this one, indicated in the table by more prominent type, will be referred to as the *chief* minimum.

* It may be interesting to compare values of this ratio obtained by other experimenters. Some are given in the following table, taken from a paper by Hull in the 'Physical Review,' vol. v. p. 231, 1897:—

Diam. in mm.	λ . in mm.	λ /Diam.	Experimenter.
80	200	2·50	Righi
37·5	106	2·83	"
8	26	3·25	"
7·8	18·4	2·36	Bose
19·3	91	4·71	Hull
9·3	43	4·62	"
7·9	40	5·18	"

† J. J. Thomson, 'Recent Researches,' p. 370.

In Pl. VII. fig. 9 are shown readings and curves obtained with the 20-cm. oscillator, with various lengths of wire, and in fig. 10 are similar readings with the oscillator of double the size, *i. e.* with 40-cm. plates; while in fig. 11 is shown a series of three successive curves given by the 20-cm. oscillator with the same length of wire. These illustrate the method moderately well.

Remarks on the Table and the Curves.

A glance at the table will show that the oscillators used can be divided into two distinct groups, the first including the four smaller ones, and the second the three larger ones, while the oscillator with 30-cm. plates lies between the two groups. The results with each group are consistent amongst themselves, while the 30-cm. oscillator behaved in a very irregular manner.

For the first group (the smaller ones) the positions of the minima for any particular length of wire are independent of the size of the oscillator, *i. e.* they depend only on the wire's length. In this case the oscillator does not force its period on the wire.

In the second group, on the other hand, the positions of the minima depend only on the size of the oscillator, not at all on the length of the wire.

The conclusion seems natural that, in this latter case, the distance of the minimum from the free end is one quarter of the wave-length of the oscillating system. The values of this quarter-wave-length deduced from the table are:—

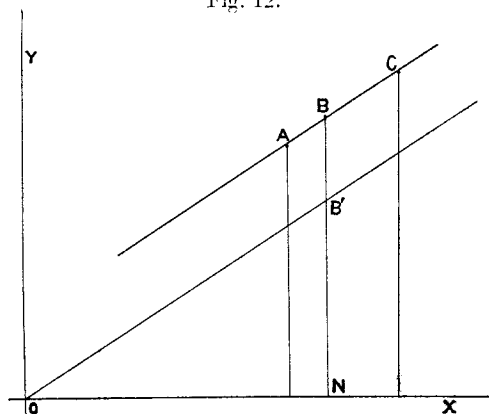
For 35-cm. oscillator...	132.7 cms.	(mean of 11 results).
„ 40	„ ... 147.1	„ („ 21 „).
„ 50	„ ... 171.5	„ („ 6 „).

Now it is possible that the proximity of the wire to the oscillator may have the effect of virtually increasing the size of the oscillator, and if such is the case all the quarter-wave-lengths so determined are too great. According to Poincaré's* deduction from the homogeneity of the fundamental equations, the wave-length of an oscillator or resonator varies directly with its linear dimensions. In fig. 12 the points A, B, C have abscissæ proportional to the dimensions of the three larger oscillators and ordinates proportional to the quarter-wave-lengths given above. It is seen that they lie very approximately on a straight line, but this line does not pass through the origin. Let us now draw a line parallel to it and passing

* Poincaré, *Les Oscillations Électriques*, Art. 53.

through the origin. The ordinate $B'N$ of this line, corresponding to the 40-cm. oscillator, has a length of approximately 103 cms. Thus if the principle of direct proportionality,

Fig. 12.



stated by Poincaré, held without limit to its application, the arrangement of the wire as in the experiments, should be equivalent to adding 44 cms. to the quarter-wave-length of each of the three larger oscillators. On the other hand, the fact that varying the length of the wire from 3 m. to 8.6 m. had no effect on the position of the minimum, seems to show that the wire did not act in the manner referred to. In other words, the quarter-wave-lengths given are proper to the oscillators.

Experiments with the first and second Hertzian oscillators referred to above, gave the following values for the quarter-wave-length:—

For 40-cm. plates, straight connexion	70 cms....	154.4 cms.
30 „ spheres, „ „ „	„ „ „	... 153.9 „

These are practically identical.

For all wires of 3 metres and upwards in length there is a well-defined minimum between 10 and 15 cms. from the end next the oscillator. In figs. 9, 10 (Pl. VII.) is shown a portion of each curve near the oscillator in continuous line, and also in broken line. In this neighbourhood the oscillator exerted a strong action directly on the detector. In order to allow for this, readings were first taken as usual (shown by continuous line); then the wire was removed and readings taken at exactly the same points. These latter were then subtracted from the former, and the broken line shows the

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TABLE

Size of Oscillator Plates.	Distance, in centimetres, of minim							
	Wire 860 cms.	Wire 850 cms.	Wire 840 cms.	Wire 830 cms.	Wire 820 cms.	Wire 810 cms.	Wire 800 cms.	Wire 790 cms.
10 cms.								187...635 ...780 655 ...781 625?...780 187 193 645 ...781
15 cms.								188...635 ...780 185...618?...780 182
20 cms.	200	192	182...710	190..675..820	198 200	208...645 205...650	188..620?...790 190..650 ...790	193...638 ...780
25 cms.								180..... 655... 186..... 630... 190
							MEAN	187.1
30 cms.								130...230...585... 140...220...620... 130
35 cms.								132..... 630... 135..... 620... 133
40 cms.	148...735?	150.. 740?	145...750	150...745	150...720?	150...645 148...655	150...650...790	150..350..625?... 150..345. --- ...
50 cms.								

MINIMA.

from free end of wire.

Wire 700 cms.	Wire 600 cms.	Wire 500 cms.	Wire 400 cms.	Wire 300 cms.	Wire 200 cms.	Wire 100 cms.
	175 178 178 177		197 197 199 203			
	183 178 182 186		148...205 152...197 150...200 203 152			
185..... 540..690 245...345. 542..690 170 175	177...460...590 175...480...590 175...450...590 175	207...350 ...490 195...347 ...490 195...365 ...490 188 ? 195 ?	202...390 210...390 206...390	154...290 155...290 152	150 148	85 85
	177 182 184		205 208 207 200			
.....	178.8	202.6			
	125 142 ? 119...200 ? 136		124...196...260 140...200...262 142...215 125...207...271 127...197...272 122...200...260			
	134 134 132 132		133 132 132 131			
150...360...550...688 142...355? 550...690 144	154...430 ...590 146...430 ...590 147...430?...590 150...440 ...590	152...355?...490 150...355 ...490 150...335?...490 154	149...387 147...387 149	143...290 150...290 150	140 138	82.5 82
	170 170 172 170	170 177				

result. Here it is assumed that the action of the oscillator and of the wire singly are equivalent to the two together. To examine this minimum more closely readings were taken at intervals of one centimetre. There is no doubt of its existence; it is about 10 cms. from the end for the smaller oscillators and slightly farther for the larger ones. I find it difficult to give the significance of this.

Other minima were found, but they were not so well defined. They are, no doubt, due to natural oscillations of the wire, but they are hard to identify.

For the wires 300 and 400 cms. long the chief minima are at the middle points.

The question of the dependence of the positions of the minima on the detector is interesting and important; and that there is no such connexion was shown in the following way. A second helix, similar to that of the detector, was soldered to the free wire running up beside the one bearing the wing, thus practically doubling the capacity and inductance; but there was no displacement of the minima. The period of the detector must be many times that of the oscillators.

In the near future I hope to apply the magnetic detector to the exploration of much longer wires, in which case the phenomenon of standing waves should be more distinctly shown.

University of Toronto.

XXXII. *On the Spectrum of an Irregular Disturbance.*

By ARTHUR SCHUSTER, *F.R.S.**

IN the February number of the Philosophical Magazine Lord Rayleigh quotes under the above title the following remark, which I made in a paper on the "Periodogram of Magnetic Declination as obtained from the Records of the Greenwich Observatory during the years 1871-1895:"

"Absolute irregularity would show itself by an energy-curve which is independent of the wave-length, *i. e.*, a straight line when the energy and wave-length or period are taken as rectangular coordinates, while the perfect regularity of homogeneous vibrations would show itself as a discontinuity in the energy-curve."

Discussing the same problem, Lord Rayleigh arrives at the different conclusion that the energy of an arbitrary disturbance is proportional to dk or $k^2 dk$, according as the

* Communicated by the Author.

