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XLVI. The effect of ionization of air on electrical oscillations and its bearing on long-distance wireless telegraphy

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to the existence of another term in the solution. If this is true, the real expression of the theory should not be equation (6), but an equation in which N equals the sum of two terms. The first term would be the right member of equation (6), or something very similar to it, and would provide the first maximum and account for the "selective" effect. The second term would provide the second maximum and account for the "normal" effect. The discovery of the equation of the relation between frequency and sensitiveness would be of practical as well as theoretical importance, since it would render possible the use of photoelectric cells as the most sensitive of spectrophotometers. We have not succeeded as yet in discovering such a solution of the theoretical equations.

We are glad to take this opportunity to express our thanks to Professor Augustus Trowbridge for many valuable suggestions with regard to the adjustment and use of the galvanometer.

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XLVI. *The Effect of Ionization of Air on Electrical Oscillations and its bearing on Long-Distance Wireless Telegraphy.*

By EDWIN H. BARTON, *D.Sc., F.R.S.E., Professor of Experimental Physics, and* WALTER B. KILBY, *B.Sc.,* "1851 *Exhibition*" *Research Bursar, University College, Nottingham* *.

[Plate XI.]

IN his stimulating address before the physical and engineering sections of the British Association at Dundee on Sept. 6, 1912, Dr. Fleming dealt with the various unsolved problems of long-distance wireless telegraphy.

One of the points of outstanding difficulty then commented upon was the mechanism of the propagation of the æther radiation round the curvature of the earth in those cases where about a quarter of its circumference is passed over.

In the subsequent discussion Dr. Eccles brought forward his theory †, which attributes the bending of the waves round the earth to a higher velocity of propagation in the upper regions of the atmosphere, owing to the ionization there present. This increased speed of propagation was

* Communicated by the Authors.
† Proc. Roy. Soc. A. vol. lxxxvii. pp. 79-99 (1912).

mathematically shown to follow from the conductivity produced by the state of ionization which is believed to exist in those parts of the atmosphere under consideration.

Other speakers showed that this curvature of the path of radiation could not be attributed to diffraction and spoke highly of the theory propounded by Dr. Eccles.

But although this theory seemed so preeminently satisfactory, it appeared desirable to obtain, if possible, some experimental evidence along the same lines. Indeed, Prof. Fleming expressed to one of us his wish for experimental research as to the effects of ionization on the dielectric constant and on the conductivity. Dr. Eccles similarly expressed his interest in any experimental evidence as to the effect of ionization on the velocity of electric waves.

Other kindred topics also suggested themselves as needing investigation, and various methods of attacking them were considered. It seemed however preferable, at the outset, to examine the relation between the *ionization* of the air and its *conductivity* for the alternating currents occurring in oscillations whose frequency is of the order used in wireless telegraphy. For obviously, if the increased conductivity to such alternations proved detectable, it would favour the theory of increased speed of propagation of which this conductivity is an integral part.

It appeared to us that the change of conductivity due to ionization might be inferred from the change of frequency of a circuit as detected by the Fleming cymometer or some appropriate modification of it. On trying the method, the need for unusual sensitiveness was soon apparent. This was attained by modifications of the capacity and inductance in the responding circuit, and by the substitution of a special electrometer as a quantitative detector of best resonance instead of the neon tube. Frequencies of the order two million per second were used, the wave-lengths being about 150 metres.

A full and rigorous mathematical theory of the phenomena occurring in the primary and responding circuits as used, if developed, might prove intractable or too complicated for real usefulness in the absence of precise knowledge as to the values of the constants involved. But early in the course of the work a simple theory was derived for the discharge of a leaky condenser through an inductive resistance. And it is hoped that this represents with sufficient approximation the salient features of the case. This elementary theory shows that the growth from zero of a leak in the condenser at first increases the frequency natural to the circuit. With further increasing values of the leak, this increase of frequency of the circuit reaches a maximum, falls off to zero, and then changes sign.

Some part of the mathematical results was anticipated by general considerations, and other steps may easily be taken after the suggestion is supplied. Thus, it is easy to see that, when the condenser is being discharged by the current in the metallic circuit, the leakage current will assist this discharge and so tend to diminish the period and increase the frequency. But, when the condenser is being charged, the leak retards the process and, so far as this goes, tends to increase the period and diminish the frequency. Hence, the preponderance of the one effect or the other may fitly be expected to depend upon the relation between the leakance and the constants involved, some critical value of the leakance giving no change in the frequency.

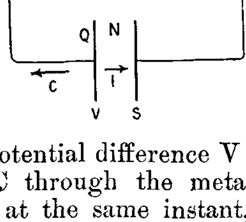
The experiments carried out so far support this theoretical conclusion, that varying ionizations (produced by X-rays or radium) may either *increase or decrease* the frequency of the circuit in question according as the leakance produced is small or large.

The observed changes in apparent capacity were of the order one in a thousand for frequencies of about two million per second. The work accordingly yields some experimental support to the theory of Dr. Eccles as to the propagation of electric waves round the curvature of the earth owing to the ionization of the upper atmosphere.

Theory of Discharge of Leaky Condenser.

Consider the circuit shown in fig. 1, in which the condenser of capacity S is, at time t, charged by the quantity of

Fig. 1.—Leaky Condenser Circuit.



electricity Q to a potential difference V and, at that instant, yields a current C through the metallic resistance R of inductance L and, at the same instant, suffers the leakage current I through the dielectric whose *leakance* (or leakage conductance) is N, its inductance being negligible.

By consideration of the metallic circuit we have

$$V = \frac{Q}{S} = RC + L\frac{dC}{dt}. \quad . \quad . \quad . \quad . \quad . \quad (1)$$

The dielectric current is given by

$$I = NV = \frac{NQ}{S}.$$

But the rate of decrease of Q is the sum of the two currents, that is

$$-\frac{dQ}{dt} = C + I,$$

or

$$C = -\frac{dQ}{dt} - \frac{NQ}{S}. \quad . \quad . \quad . \quad . \quad . \quad (2)$$

Differentiating this, we obtain

$$\frac{dC}{dt} = -\frac{d^2Q}{dt^2} - \frac{N}{S}\cdot\frac{dQ}{dt}. \quad . \quad . \quad . \quad . \quad . \quad (3)$$

Thus, substituting from (2) and (3) in (1), we find

$$\frac{d^2Q}{dt^2} + \left(\frac{R}{L} + \frac{N}{S}\right)\frac{dQ}{dt} + \left(\frac{1+RN}{S}\right)Q = 0. \quad . \quad . \quad (4)$$

The solution of this may be written

$$Q = e^{-\kappa t}(A \sin qt + B \cos qt) \quad . \quad . \quad . \quad . \quad (5)$$

where

$$\left.\begin{aligned} 2\kappa &= \frac{R}{L} + \frac{N}{S}, \\ q^2 &= \frac{1+RN}{LS} - \frac{1}{4}\left(\frac{R}{L} + \frac{N}{S}\right)^2, \end{aligned}\right\}; \quad . \quad . \quad . \quad (6)$$

and A, B are arbitrary constants depending on the initial conditions.

Let us denote by q_0 the value of q for $N=0$. Then we may write

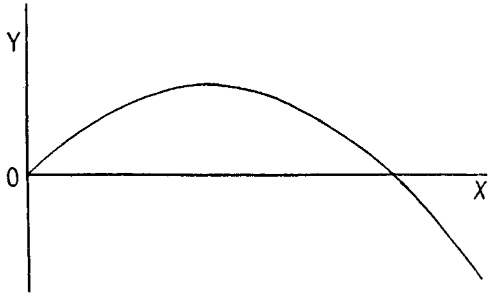
$$q^2 - q_0^2 = \frac{N}{2S}\left(\frac{R}{L} - \frac{N}{2S}\right), \quad . \quad . \quad . \quad . \quad (7)$$

or, plotting the relation as a graph, we have the parabola

$$y = x(a-x) \quad . \quad . \quad . \quad . \quad . \quad . \quad (7\,a)$$

shown in fig. 2.

Fig. 2.—Variation of Frequency with Leakance.



Thus y has the maximum value $a^2/4$ for $x=a/2$,

i. e., $$\left.\begin{array}{c} q^2-q_0{}^2 \text{ has the maximum value } R^2/4L^2 \\ \text{for } N/S=R/L \end{array}\right\} \quad . \quad . \quad (8)$$

(N.B.—This is analogous to the relation K/S=R/L for Oliver Heaviside's distortionless telephone circuit.)

Again,

$$y=0 \text{ for } x=a;$$

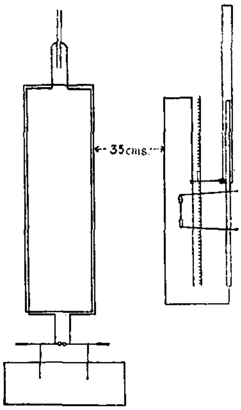
or

$$q=q_0 \text{ for } N/2S=R/L. \quad . \quad . \quad . \quad . \quad (9)$$

For values of the leakance exceeding this, q is less than q_0 and decreases continuously with increase of N, as shown in the graph.

Initial Experiments.—In the primary circuit of a Fleming cymometer a spark-gap of 3 mm. was used, and the usual rectangle of wire had a second turn added, an air-condenser being used for the capacity. The latter consisted of two polished tin plates, 30·4 cm. in diameter and placed 1 cm. apart. Parallel to the above circuit and at a clear distance of 35 cm. was the responding circuit of the Fleming cymometer (see fig. 3, p. 572). The long helix serving as a self-inductance was disconnected and replaced by a straight wire (0·5 cm. diameter) of equal length. With the apparatus in this more sensitive form a good neon tube was used as detector. The air between the plates of the condenser was ionized either by X-rays, by the radiation from 5 mg. of radium bromide, or by both these agencies together.

Fig. 3.—Diagram illustrating Initial Experiments.

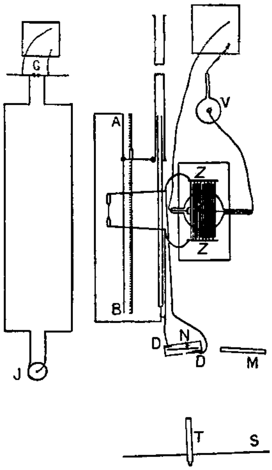


The method was to take readings alternately for the air ionized and un-ionized, the exact positions on the scale where the tube just commenced and also just failed to glow being in each case observed.

Another plan was to use a leyden-jar as the capacity in the primary circuit, and to place a multiple-plate air-condenser in parallel with the cylindrical capacity of the responding circuit, and to observe the change needed in the induction and in the latter capacity to compensate for that in the former when the air between the plates was ionized. A large number of readings showed that the fractional change, if any, in the capacity was very small. Moreover, as with the straight wire inductance in use the neon tube glowed over a length of at least 15 cm., it appeared desirable to use some still more sensitive device.

Final Arrangement.—The method described below, and shown in fig. 4, was thereupon devised, and it was along these lines that the work proceeded. The primary circuit was that of the Fleming cymometer in its original form, having a spark-gap G of 2 mm. at one end and a leyden-jar J (quart size) at the other. The circuit had a frequency of $1{\cdot}93 \times 10^6$ per second. At a clear distance of 10 cm. from the primary circuit was placed the responding circuit, having a straight wire AB of 0·5 cm. diameter soldered on at one end in place of the usual helix. Connected to the terminals of the variable cylindrical condenser of the cymometer, and thus in parallel with the same, was a special zinc-plate air-condenser ZZ.

Fig. 4.—Final Arrangement.

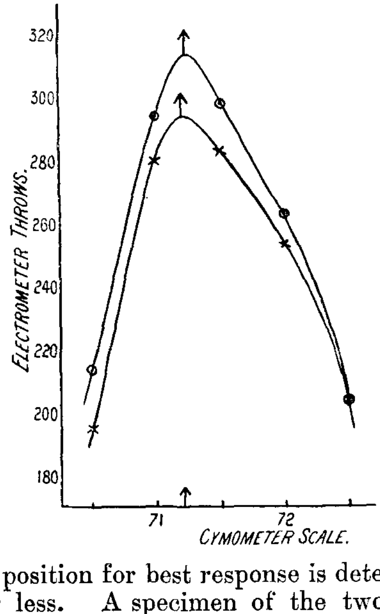


This consists of two sets of plates—one of eight, the other of seven, each plate being 30·4 cm. diameter and 0·2 cm. thick. The inner surfaces of the plates in each set were 1·2 cm. apart, leaving air-spaces of 0·5 cm. between the plates when in mesh. The plates were separated by wooden distance-pieces. Good connexion is ensured by pieces of tinfoil and a metal rod by which the plates are held securely. By sliding the plates of one set between those of the other a condenser of variable capacity could be formed. Throughout the work the maximum capacity was used; the plates were placed on clean, dry blocks of wax, and two bridges of wax were put across them to afford greater rigidity.

As a more sensitive detector than the usual neon tube a special electrometer was then used. This was of the form used by J. R. von Geitler and by one of the present writers when working under Hertz in Bonn. The needle is of aluminium and carries a small plane mirror for reading the deflexions, and a tiny magnetic needle for control. In the horizontal section shown in fig. 4, N is the aluminium needle in a vertical plane suspended by a quartz fibre; DD are two metal disks equal in size to the circular ends of the needle and attached to the inside of the wooden case. On to the projecting rods from these disks were soldered the wires from the condenser terminals. The needle is controlled by a magnet M, and the deflexions observed by means of a telescope T and a metre-scale S. The needle is charged by *induction only*, and therefore deflects in the *same direction whatever the sign* of the potential difference under examination. The readings taken are those of the first throws, which are sensibly proportional to the time-integral of the square of the potential difference of the disks.

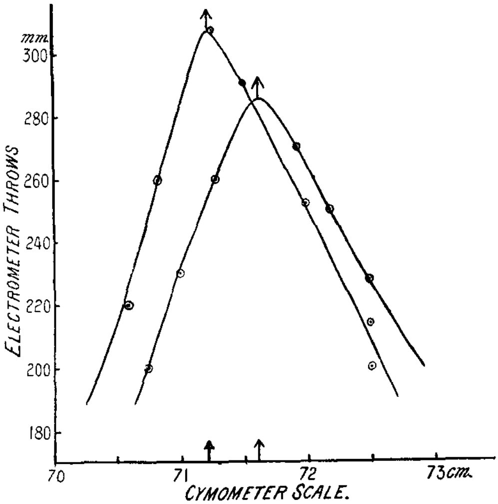
Now the capacity of the zinc-plate condenser is of the order fifteen times that of the portion of the cymometer in use. Consequently, if we maintain constant the frequency of the primary oscillations which force the responding circuit, then for the best response a given fractional *decrease* in the capacity of the zinc-plate condenser will involve a fractional *increase* in the cymometer capacity of nearly *fifteen* times this amount. In making observations the region where resonance occurs on the cymometer was first determined by means of a hydrogen tube. This was then removed and electrometer throws were taken at half-centimetre steps over a range of 2 cm. The main peak of the resonance curve comes well within these limits, and is found to be of considerable sharpness. Further, readings were taken in the reverse direction, and from the two resonance curves thus

Fig. 5.—Resonance Peak from Two Curves.



obtained the position for best response is determined correct to 1 mm. or less. A specimen of the two curves which determine a single resonance peak is shown in fig. 5. A similar set of readings was then taken when the air between the plates of the condenser was ionized. The curves showing the shift of the peak for one case are given in fig. 6.

Fig. 6.—Shift of Resonance Peak due to Ionization.



The two induction-coils used were each placed on end (see figs. 4, p. 573, and 7, Pl. XI.), as it was observed that in the ordinary position their magnetic fields affected the magnetically controlled electrometer-needle. To shield the zinc-plate condenser from the effects due to the field across the X-ray tube, an earth-connected lead plate was placed below the bulb and at a height of 22 cm. above the zinc plates. The lead screen had in the middle an opening 10 cm. square, on which could be placed piles of aluminium plates of varying thicknesses. The 5 mg. of radium bromide, when used for ionization, was placed about 5 cm. above the level of the lead screen. Moreover, to guard against dust and air-currents, the wooden framework supporting the earthed plate was enclosed on three sides with cardboard, one portion of which was removed when taking the photograph reproduced in fig. 7 (Pl. XI.). A Lodge valve V (fig. 4) was used in connexion with the X-ray tube to assist in ensuring that the discharge was unidirectional.

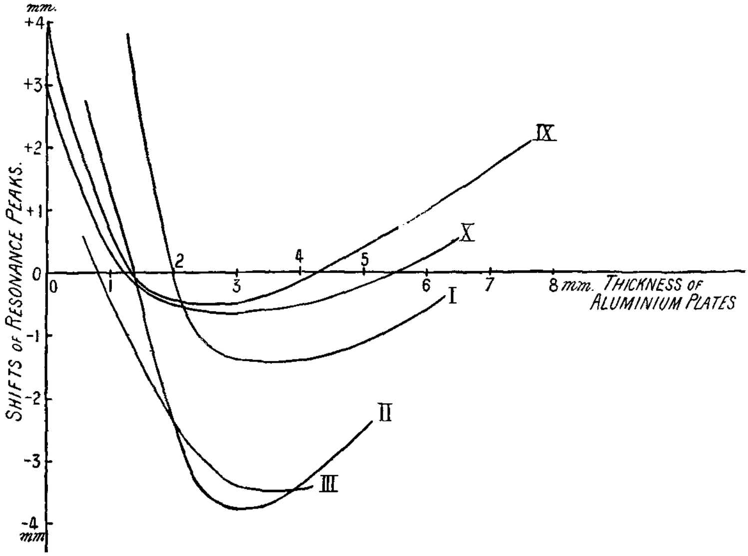
Results.

The results given in the accompanying table show in each case the shift of the resonance peak necessary to compensate for the change in frequency of the responding circuit when

Table showing Shifts of Cymometer Readings for Various Ionizations.

Thickness of Plates in mm.		0	·57	1·28	2·56	3·84	5·12	6·40	7·68	0·13	0·26	0·39	0·52	0·65	0·78	1·04	Ref. No.
Shift of Resonance Peak in mm.	Ionization by X-rays.			+3·8	−1·3	+0·8	0·0	−0·9									I.
			+2·6	+0·9	−3·7		−2·4										II.
			+0·6	−1·0		−3·5											III.
											−1·0		−3·0		−1·0	−2·3	IV.
										−0·2	−0·6	−2·1	−1·4	+1·2	−1·5		V.
										+3·9	−4·6	−2·2	−3·1	+0·3			VI.
										+2·3	−0·1	+0·2					VII.
										+1·1	−0·2	+1·9					VIII.
	Ionization by 5 mgrms. of Radium Bromide.	+4·0		−0·2	+0·2	+0·4	+0·5		+2·1								IX.
		+3·0		−0·4	0·0	+0·2	−0·8	+0·5									X.
										+0·9	−2·3	+0·9					XI.

Fig. 8.—Variation of Frequency with Ionization.



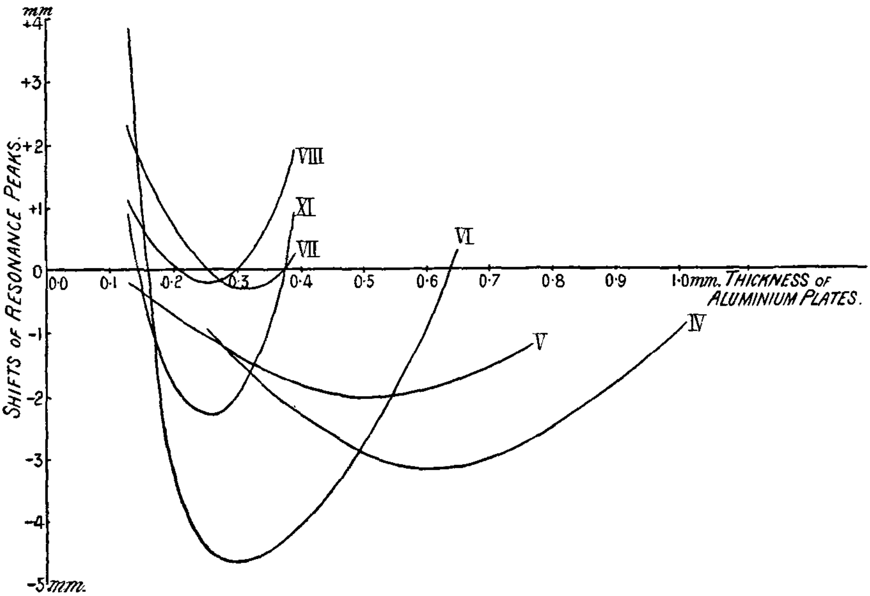


Fig. 9.—Variation of Frequency with Ionization.

the air in the zinc-plate condenser was ionized. A displacement of one centimetre of the cylindrical condenser of the cymometer corresponds to a change of 4·54 E.S. C.G.S. units in the capacity of the zinc-plate condenser which, in its normal state, had a capacity of 2099 E.S. C.G.S. units. This shift of one centimetre accordingly compensates a fractional change of 0·0022 in *apparent capacity* or in the *square of the frequency* of the circuit.

The experimental results are also plotted as graphs in figs. 8 and 9, in which the thicknesses of plates penetrated by the ionizing agents are the abscissæ and the compensating shifts on the cymometer are the ordinates.

In comparing the theoretically derived curve shown in fig. 2 with the experimental graphs, these latter should be rotated in their own plane through 180°. Their ordinates have then the correct algebraic signs for this comparison, and the greater ionizations (obtained by penetration through thinner plates) are to the right also. But absolute agreement cannot be expected, for in the theoretical curve the leakances are *proportional* to the abscissæ, and this cannot be asserted of the experimental graphs, even when in the rotated position.

Roman numerals are inserted in the right-hand column of the table. Each such numeral serves to identify the series of observations given on that line. Each graph is based on the observations occupying a single line, and, in the figure, the graph bears the numeral by which the observations are characterized in the table.

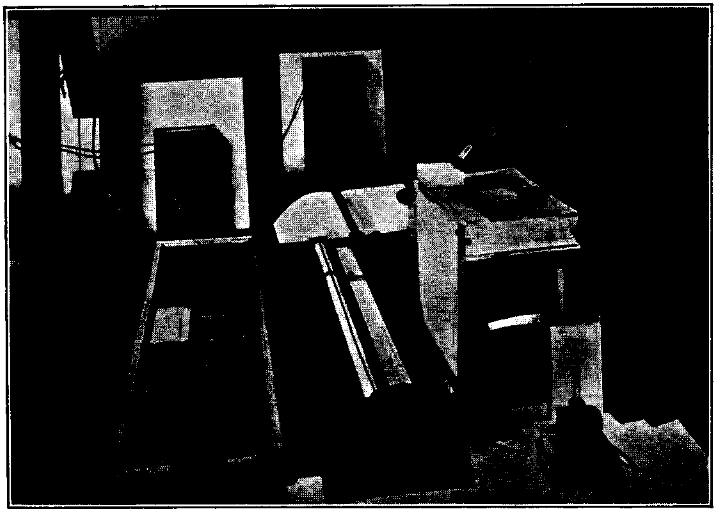
It may be noted that the results given in the table are based on nearly nine hundred electrometer throws.

The curves show that the separate observations in each series were fairly consistent but that the ionizations differed from one series to another, so that the separate curves occur in different positions.

Further, the curves follow the general form theoretically derived, but several show positive ordinates for the thickest plates instead of very small negative ones as theory would indicate. It appears that, from some unknown cause, these experimental curves are shifted up somewhat from the position theoretically deduced. But considering the smallness of the effect to be measured, the agreement is perhaps as close as could be expected.

University College, Nottingham,
July 5, 1913.

Fig. 7.



General view of Final Arrangements.