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EDITED BY
ALFRED N. GOLDSMITH, Ph.D.

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RECEPTION THRU STATIC AND INTERFERENCE*

BY

Roy A. Weagant

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Since the birth of radio telegraphy, serious difficulty in reception has existed due to natural electrical disturbances. These disturbances produce in the receiving telephones crackling noises which drown out the signal and are commonly called static, atmospherics, or strays. In what follows the word "static" will in general be used in referring to these disturbances, whatever their nature or origin.

As the distance over which radio telegraphy was worked increased, and it became necessary to use increasingly longer wave lengths, it was found that the troubles from static continually increased and in the case of the most important of long distance circuits, namely those between Europe and the United States, caused such great interruptions to the service that the continuity of communication compared very poorly with that of cable working. It was found that static disturbances were most severe in summer and less troublesome in winter, also that they displayed a daily variation in intensity, being at a minimum between sunrise and noon, and increasing very rapidly to a maximum about sunset, from then on remaining practically constant until shortly before sunrise when the intensity fell off very sharply to a minimum again.

Accumulated experience shows that these disturbances are more severe in locations near or in the tropics than in those of the temperate zone or frigid zone, and also that at any given location they vary from day to day somewhat in accordance with the variations in temperature, being greater on warm days and less on cool days as a rule, altho not invariably so.

A great deal of study has been made in attempts to determine the nature and origin of these disturbances and innumerable attempts to secure methods of reducing their effects at the re-

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ceiving station, but so far as the writer is aware, no success of a major order was obtained with any of these methods prior to the work which is about to be described. One of the most common of these previous arrangements known to the writer made use of a transmitter of undamped waves and beat reception. How far short of meeting the situation in trans-Atlantic working this method fell, may be judged from the fact that from June to October good reception from such continuous wave stations as Carnarvon, Wales, and Nauen, Germany, was usually possible only between sunrise and noon, while during the rest of the day it varied from very poor to totally impossible. An idea of the magnitude of the problem to be met can be gathered from the fact that during these summer months the energy collected by a receiving aerial from static is often many thousands of times as great as that of the normal signal from the above-mentioned stations.

It is a well recognized fact that static disturbances are of different sorts which are apparently due to a variety of causes, and of these different varieties those due to local lightning and snowstorms will be dismissed for the present with the statement that they occur so infrequently as to be of negligible consequence. There then remain three other major types which have been generally recognized and which Eccles has classified under the names of "grinders," "clicks," and "hissing." The last of these types, due generally to an actual discharge from antenna to earth, produces very little disturbance and is not present when antennas are used which have no earth connection. Of the two remaining types, namely, the grinders and the clicks, it is found that the former constitute the major source of difficulty in the reception of trans-Atlantic signals, the intensity of which is that of Nauen or Carnarvon, and when the receiving station is located in the United States. It is this form of static which rises to overwhelming intensity in the summer months and which has hitherto produced such serious interruption in trans-Atlantic radio communication. It should be noted, however, that both types of static are generally present, but that as the grinders increase in intensity, in general the clicks diminish. As will develop in the course of this paper, these two types of static are, apparently, of totally different nature and origin.

To make clear the various steps in the developments which are to be described, reference to certain fundamental facts, which are a matter of common experience in radio reception, is necessary, and, briefly, to various methods of overcoming static troubles which have been tried. In this latter respect it is not to be understood that an exhaustive statement of all the various methods of solution is presented nor an accurate comparison of their relative values, but merely such reference as is necessary in order to trace the steps of the writer's work. It is also to be understood in what follows that the major portion of the work which is here referred to has been with signals from Europe of wave lengths varying between 5,000 and 15,000 meters. Some work has also been done with shorter wave lengths and the results secured were in substantial agreement with those obtained in the range above mentioned, but this work has not been of an exhaustive nature.

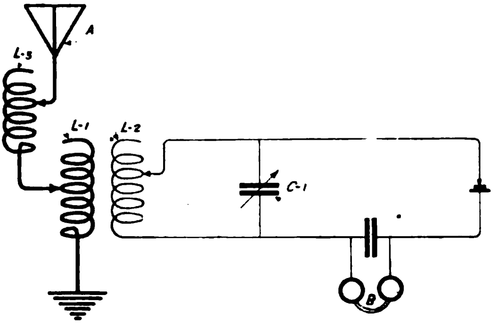

FIGURE 1

Referring now to Figure 1, there is outlined a simple form of common receiving system, the elements of which need no description. When such a system is tuned and adjusted to give best response to the incoming signal it is found that the disturbances from static are also invariably a maximum, regardless of the frequency to which the system is adjusted. A study of the behavior of such a system when acted upon by static very clearly brings out the fact that the disturbing currents which flow therein have a period and damping which is determined by the circuit itself; a fact which shows that the disturbance is in the nature of a shock, the system, when so shocked, vibrating in a way which is analogous to that of a tuning fork struck by a hammer.

It is curious to note the number of experimenters who, while apparently recognizing this principle, immediately attempt to secure relief from static disturbances by detuning methods which result simply in the reduction of both signal and static currents in substantially equal proportion, and consequently with no appreciable improvement. This result is due to the fact that while detuning the aerial circuit does not reduce the intensity of the static in the antenna circuit, it does change the frequency of the currents due to it; and the loss in transfer of energy to the secondary circuit, since the latter is tuned to the frequency of the incoming signal and therefore a different frequency from the detuned antenna, is of exactly the same order as the loss in intensity which the signal currents experienced when the antenna circuit was detuned. Another simple expedient which has been resorted to, has been the employment of loose couplings between the antenna circuits and the secondary circuits, and this method does give some help when the difference in damping between the signal currents and static currents is marked. Attempts to make this difference as large as possible have been made, involving the introduction of resistance into the antenna and secondary circuits, but this always results in the reduction of both signal and static currents by a substantially proportional amount, with a resulting negligible order of improvement. A large number of arrangements with which it was hoped to secure differentiation, and depending on this principle of difference in damping of the two currents involved, have been tried but, so far as is known to the writer, without important results.

Another fundamentally incorrect method of attack is that of differentially combining two circuits, of which the Fessenden interference preventer circuits shown in Figure 2 are typical.

The antenna circuit here shown is split into two branches, each coupled to a common secondary and detector circuit, or these individual branches may be connected to two different antennas. One of the branch circuits was supposed to be detuned slightly with respect to the incoming signal, materially reducing the signal current in that branch, but not appreciably affecting the static current, which was assumed to be a *forced* oscillation and which would not therefore have either its frequency or intensity affected by an amount of detuning which would greatly affect the signal. The remaining static currents would then, supposedly thro the common coupled circuit connected in opposition, cancel the static due to the other branch, leaving a signal current equal to the difference between that existing in the two branches. Several other methods of adjustment were proposed, among which was that of adjusting one branch to a period slightly below the incoming signal, and the other to a period slightly above it. There are many fallacies

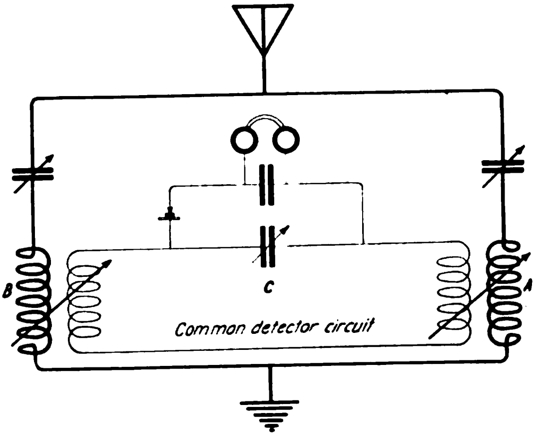

FIGURE 2

in this proposal, but it is sufficient for present purposes to point out the facts stated in connection with Figure 1, namely, that the detuning of one branch circuit affects the intensity of both the signal and static currents in the secondary circuit in the same ratio, and the additional fact that if one circuit is tuned to a period differing from that of the other, the frequency of the static in the first named circuit is different from that in the other circuit, and two alternating currents of different frequencies obviously cannot neutralize each other, but on the contrary, in order that such neutralization may be accomplished it is necessary that the emfs. which are to equalize each other must be of the same frequency, the same wave form, and of opposite phase. Also when these emfs. are due to the flow of damped oscillating currents, these currents must have the same damping factor. If this requirement is complied with in the arrangement of Figure 2, the static currents will cancel out but so also will the signal currents. Many variations of the arrangement of Figure 2 have been tried, including some in which the differentiation is attempted in the audio frequency instead of the radio frequency circuits, but if any of them have seemed to work, the result secured has been entirely due to the looseness of coupling involved.

is to be noted, however, that under some circumstances such an aerial may equally well be acting as a loop; such an aerial is shown in Figure 5 lying on the surface of the ground and it is evident that by virtue of its capacity to the true conducting earth, a return path between its ends exists and therefore that it is a form of loop; which method of consideration will account for many of the observed facts, such as its directivity, in a satisfactory way. It will also account for one observed fact which the usual methods of explanation do not account for, namely, that when an aerial of this type is laid on the ground, or buried underneath it, its effectiveness as an antenna does not increase indefinitely with length but rapidly reaches an optimum value dependent on the circumstances obtaining. This can readily be accounted for under the present hypothesis by the fact that as the length increases its capacity to earth increases and at some point becomes sufficient to close the loop.

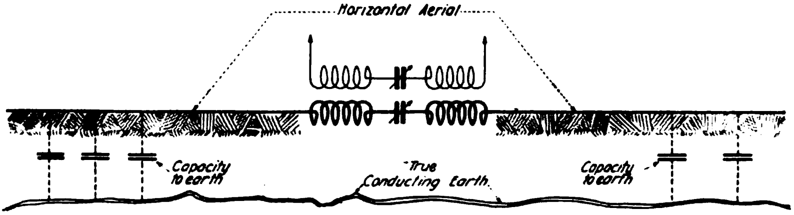

FIGURE 5

As this capacity increases, however, the currents originating in the increased length have various paths in which to flow, one of which includes the receiving apparatus, but others which are thru the capacity to earth between the conductor and the receiving apparatus, and the larger this gets the greater is the proportion of the currents originating in the ends of this antenna, which are diverted and do not flow thru the receiving apparatus. This method of considering such an antenna is further supported by the fact that the greater the capacity per unit of length which exists between the conductor and the true underlying earth, the shorter is the maximum length which can be used to advantage. This capacity is a maximum of course when the antenna is actually buried in the ground or under water, becoming less when the wire is run on the surface of the earth and still less when the wire is suspended at some height above the earth, tests having shown that wires suspended some 10 feet

(3 m.) above ground can be used up to some six miles (9.6 km.) in length, the signal increasing with length; that a length about one-half of this is effective when the wire is laid on the ground and of approximately 2,500 feet (760 m.) when the wire is placed under brackish water.

I have also found that as the distance of such an antenna above ground is increased, its action becomes more nearly that of an ordinary antenna, and that therefore on account of its position relative to the incoming signal, it becomes less effective in collecting this signal energy.

While the two forms of antennas just referred to result in a distinct and important advance over other types of antennas, the improvement in results secured there from falls very greatly below that which is necessary to meet the conditions of continuous trans-Atlantic reception.

Another method of attack is the screen arrangement suggested by Dieckmann and de Groot which has no basis, so far as the writer can see, for differentiating between static and signal, but must, if it has any effect at all, operate on both alike. Furthermore, in attempting to investigate screening arrangements of this sort, it has been found that the problem of screening out an electro-magnetic wave of any sort, either signal or static, is not solved by the methods mentioned by them.

One of the most important investigations of static effects was that carried out by Mr. C. H. Taylor, of the Marconi Company, in which the Bellini-Tosi direction finder arrangements were used in an attempt to find out in what, if any, horizontal direction static disturbances were propagated. Altho this work showed that at times there was some definite evidence of direction of propagation, it did not warrant the hope that a successful method of separation could be based thereon. The writer's observations made at this time, and with the same installation used by Mr. Taylor, and with a similar arrangement erected at the Marconi Company's New Brunswick station, showed that so far as the dominant type of static—namely the grinders—was concerned, no direction whatever could be found, but on the contrary there appeared to be an equality of disturbances from all points of the compass. A further check on this result was made at this time by rotating a loop, shown in Figure 6, about a vertical axis; this also showed equality of average disturbances, regardless of the direction of the plane of the loop and led to the conclusion that if static disturbances of the grinders type were being propagated horizontally, they must be moving in all possible directions; that is to say, one stroke might arrive from the north, the next one from the east, a third from the west, and so on, these occurring at random in such rapid succession as to give no opportunity to determine their direction. There appeared to the writer, however, another possible explanation of this result, which is that these disturbances instead of moving horizontally, might be moving in a vertical direction, the source being under foot or overhead. This latter possibility was of exceptional interest since, if it were correct, the direction of propagation of static waves, assuming of course that they were waves, would be at right angles to the direction of propagation of signals, and such a difference might conceivably be used to separate the two.

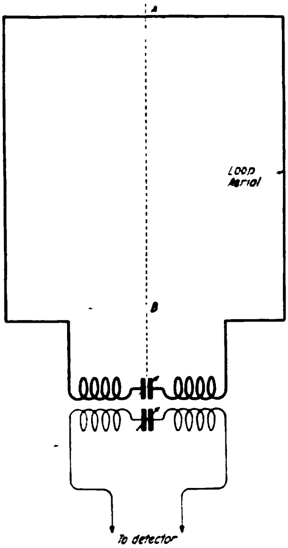

FIGURE 6

Steps were then taken to determine which of the two possible explanations given above was correct, and the investigation seemed to establish clearly and definitely that static of the grinders type produces effects similar to those which would be produced by electro-magnetic waves originating overhead or under foot and propagated in a direction perpendicular to the earth's surface at the point of observation. This investigation also established that static currents produced in loops, the planes of which are perpendicular, cannot be combined to neutralize each other, which result can be explained by assuming that the electro-magnetic waves responsible for static currents are heterogeneously polarized; that is, the axes of the oscillators producing them assumed all possible angles in space. To sum up then, *these results showed that static disturbances of the grinders type behaved as tho due to heterogeneously polarized, electro-magnetic highly damped waves propagated in a direction perpendicular to the earth's surface.*

The apparatus and method used in this investigation resulted in a perfectly practical receiving system which, while retaining useful amounts of signal currents, enormously reduced the currents due to static of the dominant type. The methods and apparatus used in carrying out these tests were as follows:

Two single turn loop antennas were erected 400 feet (122 m.) high each with a base line of 1,000 feet (305 m.) and their centers approximately 5,000 feet (1,520 m.) apart. These loops were in the same plane and the line connecting them was in a direction toward the Carnarvon station of the English Marconi Company. This arrangement is shown schematically in Figure 7. Leads were brought from the loops to a receiving station midway between them. These leads, which were six feet (1.82 m.) apart, and in the same horizontal plane, were supported by poles about ten feet (3.05 m.) high. The diagram of connections is shown in Figure 7.

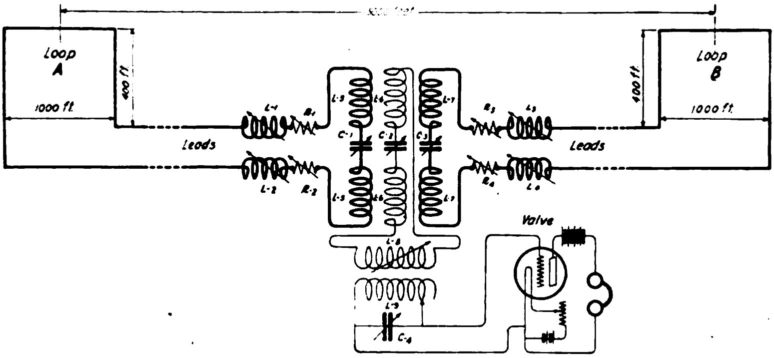

FIGURE 7

Connection from the leads were made thru inductances L_1, L_2, L_3, and L_4 symmetrically arranged relative to the coils

L_5 and L_7, which were arranged perpendicularly to each other, as shown in Figure 8. The winding of each fixed coil L_5 and L_7 was divided into two equal parts, and condensers C_2 C_3 inserted between the halves. Associated with the two fixed coils was a third coil L_6 capable of rotation on a vertical axis, the three coils constituting the well-known Bellini-Tosi goniometer. In the circuit containing L_6 were condensers C_2 and coupling coil L_8 which was associated with a receiver of conventional type with valve detector. The theory of the tests made with this arrangement is as follows:

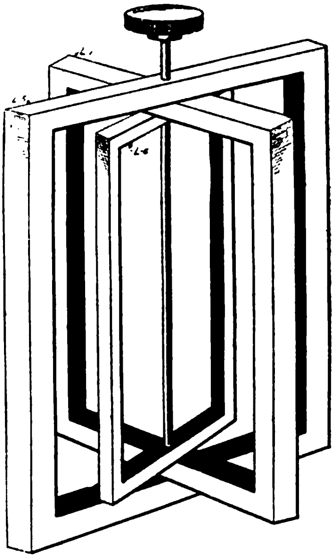

FIGURE 8

Assuming that static waves were traveling perpendicularly to the earth's surface, then the electromotive forces generated in the two loops would be equal in intensity and of the same direction at any instant, and therefore if the circuits were properly tuned, the resulting currents in the system would be in phase. The emfs. generated by the signal would, on the other hand, be out of phase by an amount depending on their distance apart, and a maximum if this distance were one-half the length of the wave received, since the signal wave would arrive at the antenna nearest the transmitting station before it would arrive at the antenna farthest away from the transmitting station. In other words then, the static waves would arrive at the two antennas at the same time, while the signal waves would arrive at the two antennas at different times. It therefore follows that if, at the receiving station, connections and adjustments were so made that the emfs. generated in the rotating coil L_6 by static disturbances were equal and opposite, the emfs. generated by the signal currents would not be equal and opposite, but would combine, giving a resultant depending on the separation of the loops. If this separation were one-half wave length then the emfs. generated in coil L_6 by the signal currents from each loop would be in phase and would therefore be equal to the arithmetical sum of these two emfs. If the loop separation were equal to one-quarter of a wave length, then the emfs. acting on the coupling coil would be 90 degrees apart and the resultant would be equal to 1.4 times that of the individual emfs.; that is, they would continue in quadrature. If, on the other hand, the hypothesis that static of the grinders type arrives from all possible azimuthal angles, and in a horizontal direction, were correct, then the static currents arriving at the receiving station from the two antennas would be out of phase an amount depending on the separation of the antennas and the azimuthal angle which the direction of their propagation made with the base line of the system.

If the apparatus in the receiving station were assumed to be adjusted in such a way that the signal currents were combined vectorially and in accordance with the aerial separation, then the static currents would be similarly combined; and the curve of reception of the system so adjusted for static impulses equally distributed in all azimuthal angles would be that of Figure 9, which is nearly the same as that of a single loop antenna, and therefore the whole system would show nearly the same signal-to-static ratio as the single loop. If, on the other hand, adjustments were so made that the phases of the currents from one loop were shifted a suitable amount with respect to the phases of the current in the other loop, then the curve of reception would change from that of Figure 9 to that of Figure 10, which indicates that reception through one-half of the azimuthal angles has been moderately reduced, and which would therefore give rise to an improvement in the signal-to-static ratio of the whole system as compared with the single loop of the order of the decrease of the area included by the curve of Figure 10. It will thus be seen that under the three sets of conditions specified and under the two hypothesis considered, there were three possible results, namely, a very large improvement in the signal-to-static ratio under the first hypothesis, a small improvement if the second hypothesis were correct, and the first method of adjustment followed, and a moderate order of improvement under the second hypothesis and the second method of adjustment.

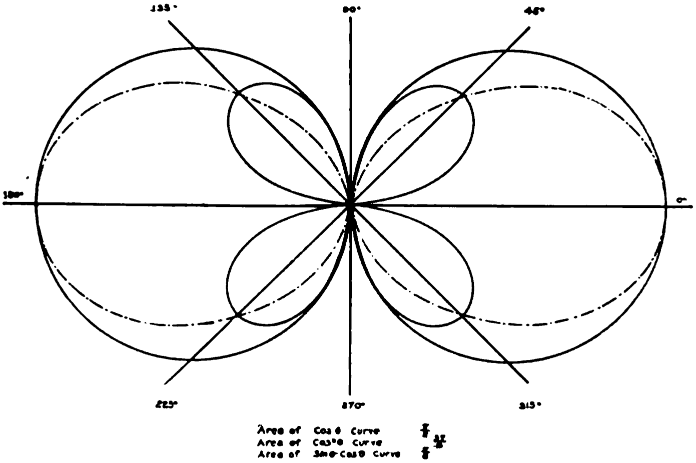

FIGURE 9

Referring now to the arrangement actually used, the spacing between the loops was slightly over one-quarter wave length, for a wave length of 6,000 meters, which was that used by Nauen during some of the tests. Signals were also received from Nauen

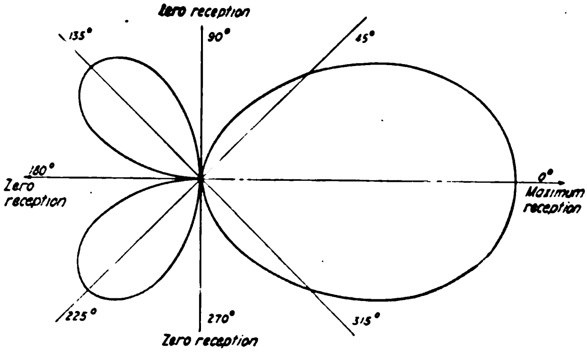

FIGURE 10

at 12,000 meters, Clifden 5,600 meters, Carnarvon 14,000 meters, Eilvese 9,600 meters, and Glace Bay 7,600 meters. In all cases it was found that when the adjustment of the circuits was so made that static disturbances of the grinders type were cancelled or reduced to a minimum, the signal received from the two loops combined, as might be expected from the spacing between them, and the wave length of the incoming signal. In the case of the 6,000-meter signal from Nauen, the resultant signal was approximately forty per cent greater than that due to either aerial alone, while in the case of Carnarvon, with a 14,000 meter wave length, for which the spacing was equal to only one-nineth of a wave length, the resultant signal was materially less than that due to either loop alone.

Since the order of improvement of the signal-to-static ratio of the system as a whole was very great as compared to the single loop, and consequently a given signal was readable thru static disturbances of a very much greater order than was possible with the single loop, it was concluded that the hypothesis of an apparent vertical propagation of static waves (or an electric action of equivalent effect) more nearly expressed the true facts than did that which assumed a uniform azimuthal distribution of their horizontal direction of propagation.

To determine the extent of the improvement in reception made possible by this work, tests were carried out thru the worst summer months, namely, July and August, on various European stations, and it was found possible to receive the 6,000-meter Nauen signal some five or six hours per day during the worst periods when reception otherwise was totally impossible. Complete, continuous reception was not, however, yet possible, since there were times when, due to fading, the strength of Nauen's signal fell so low that it was no longer possible to receive it Very interesting, and surprising also, was the fact discovered thru the constant use of this arrangement, that the heavier the static disturbances were, the more perfect the balance which could be secured, and the greater the improvement in the static-to-signal ratio which resulted. This very significant observatin led to a careful study of the character of static disturbances under conditions of weak and strong disturbance, and it was noted that invariably the strong static consisted mostly of the grinders type, the percentage of this type increasing with the increase of total static energy and decreasing with the decrease of the total, and it may be said that the results of long and continued work since these first experiments has established the facts referred to definitely and conclusively, the occasional variations therefrom being of such infrequent occurrence as to be negligible. It was also noted at this time somewhat unexpectedly, that the disturbances from a nearby thunderstorm were at times quite markedly reduced, the amount being seemingly dependent upon the position of the storm with reference to the receiving station. This improvement, however, was not of a sufficient order to render reception, thru local lightning, generally possible.

Many attempts were made to measure the improvement under various conditions in the signal-static ratio of this system, as compared to a single loop thru the use of the well-known audibility method, and the results obtained varied from more than a thousand times, under very severe conditions, down to five or ten times for very light static conditions. Now the audibility method measures the current in the telephone circuits from which it follows that the energies represented by two different audibility measurements are proportional to the square of the audibility factor; consequently the ratio of one thousand-to-one in audibility means one-million-to-one in energy. Unfortunately this method is a poor one for measuring static disturbances accurately and I cannot say that the above ratio is accurate. I find, from continuous use of this method of measurement, that, while it gives reasonably good results where the sound in the telephones is of a musical character, when this musical character is lacking the ear is unable to judge relative intensity accurately. In addition to this difficulty there is the fact that static disturbances are of extremely irregular intensity and that at any two successive instants widely different energies may exist. No other suitable method being available at the time, it was decided to depend on comparisons of readability of the signal resulting from the use of the complete system, as compared to the single loop, and this method has been used chiefly since that time.

A new method of measuring static intensities has recently been developed, which is the joint suggestion of Mr. G. H. Clark, expert radio aid of the Navy Department, the Research Department of the Marconi Company, and the writer—and which has been put into practical form by the Research Department. It measures the intensity of static disturbances in terms of the signal intensity necessary in order that the signal may be read, and it is hoped that a large number of measurements made by this method can be presented in a later paper.

Since the continued operation of systems of this type has so clearly emphasized the existence and characteristics of the two types of static referred to as grinders and clicks, a brief reference to some of the distinguishing characteristics may be of interest. It is found that the grinders type is most prevalent in the warm season, during warm days, and between the hours of noon and sunrise the following morning. The sounds which they produce in the telephone are generally a sort of continuous rattle, with occasional heavier crashes. This type behaves as tho vertically propagated, *and appears to affect antennas, separated considerable distances, simultaneously.* It can therefore be excluded, thru the use of the system described, while the signal is retained. The clicks, on the other hand, which sound like relatively widely spaced crashes, are most noticeable during the cooler periods of the year and day, but do not, except on very rare occasions, reach an intensity which is sufficient to interfere with the reception of signals, the strength of which is equal to the normal strength of Carnarvon or Nauen, or even Lyons. When the signal to be received, however, is of a lesser order of strength, such as that from Clifden, Ireland, or Eiffel Tower, or when the signals from the previous stations are abnormally weak, as occurs during sunset and sunrise fading periods, the intensity of this type of static is sufficient at times to cause great difficulty. It was found also that this type of static could not at that time be sufficiently reduced, thru the use of the system just described, to overcome the difficulty, and that adjustments which reduced it resulted also in a reduction of the signal. It appears probable, therefore, that this type of static follows the second of the two hypothesis previously given, and that it is in fact a true stray wandering in from all directions in haphazard fashion. How this vagrant was successfully dealt with will appear presently, but before getting to this point, which involves somewhat different arrangements than those shown, a brief reference will be made to certain modifications of the system with which experiments were conducted.

Midway between the loops of Figure 7 a third loop of similar dimensions and disposition was erected and used in conjunction with either of the two loops of Figure 7. This variation is shown in Figure 11, and it is to be noted that while the end loop has the long, horizontal lead, the middle loop has none, it being brought directly into the receiving station. It was with some interest that this arrangement was found to give rather better results than that secured with the loops separated the maximum distance available, and the improvement was found to be in the perfection of balance, which was found to be sufficiently greater than that obtained with the arrangement of Figure 7 to more than offset the loss of signal on balance, due to the shorter spacing. This seemed to indicate, at first, that the farther apart the loops were the less perfectly could the static currents be balanced and the converse. Small loops of a large number of turns were then erected at distances varying from ten feet (3.05 m.) up to 1,000 feet (305 m.), symmetrically located with respect to the receiving station, and in the same line with the big loops. Tests with these showed, however, no more perfect balance than that obtainable with the spacing of Figure 11 which was 2,500 feet (760 m.), and it therefore became evident that something besides the spacing accounted for the improvement in Figure 11 as compared with that of Figure 7. It would take too long to describe the very numerous experiments which were made in the attempt to run down this very elusive matter, but it was finally discovered that the reason for the performance above noted was the action of the long horizontal leads which, notwithstanding the fact that these were in the same horizontal plane and that the system had no earth connection, proved to be very effective aerials, picking up both signal and static. It was found that the static currents generated in them were in a definite direction and that consequently they must be connected to the loop in the same sense, that is, in such a way that the static currents generated in both the loop and the leads tended to flow in the same direction at any instant, so that when balancing at the receiving station all of the static currents generated in each half of the system were similarly affected. Before this fact was found out the arrangement of Figures 7 or 11 was so con-

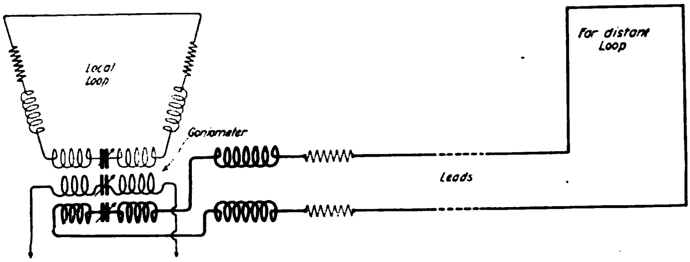

FIGURE 11

nected that when adjustments were made which balanced out the static currents generated in the loop, those generated in the leads were added. The method of getting the right connection was simply to connect in a reversing switch, as shown in Figure 12 and to try the balance with the switches in each side of the system in the various possible positions. The best, of course, was that which gave the most perfect balance and was very easy to find. The results obtained thereafter were found to be better for the long than the short separation by an amount proportional to the separation, and it is interesting to note at this point that in all subsequent work the perfection of balance of static currents obtainable was the same, regardless of the overall length of the system which, as will appear shortly, has been in some instances as much as six miles (9.6 km.), while the signal combined always in proportion to the spacing.

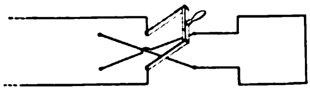

FIGURE 12

In Figure 13 is shown an arrangement in which all three antennas were used. In this arrangement the two antennas at the ends were so coupled and adjusted that the signal was cancelled out, leaving most of the static. This arrangement has been termed the "static tank" since it was a source of static currents of any desired frequency without being a source of signal current. When this adjustment was accomplished the circuits

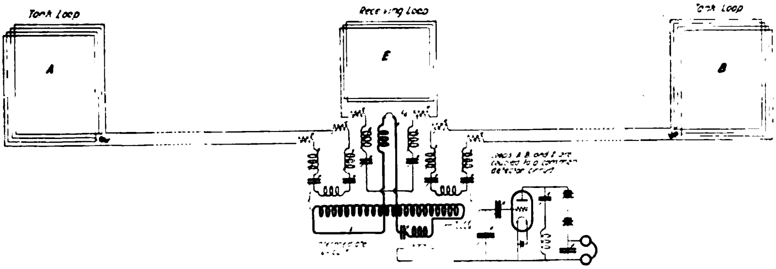

FIGURE 13

connected to these two antennas were opened and the third antenna connected in and tuned. This third antenna provided both signal and static currents in whatever ratio they happened to exist in this loop. The next procedure was to connect the two other loops in again and to adjust the intensity of the static currents from the middle antenna until they were equal to those due to the two end loops by use of suitable resistances, couplings, and so on. This third loop was connected into the system in such a way that the static currents due to it were opposed, leaving the signal due to the third loop. This arrangement resulted in a material improvement in working over those previously tried. From a consideration of the hypothesis of vertical propagation of static waves, it was not possible to account for this improvement, so far as the grinders are concerned, so that it was ultimately concluded that the improvement might be due to the elimination of some of the static of the other type. This possibility was somewhat supported by the fact that it is occasionally not possible to distinguish between the two types from the sounds which they make in the telephones since it happens occasionally that those of one type have the characteristic sound of the other. An analysis of the action of this system when affected by horizontally moving static waves, assumed to be uniformly distributed, brings out some most interesting facts.

Referring now to Figure 13, assume that the two aerials there shown have a spacing which is one-half the wave length of the signal received. Also assume that a static wave is arriving from the same direction and with the same velocity of propagation, and that this wave is so highly damped that no forced oscillation is produced in the aerial but that the only oscillation therein has a frequency and damping which is determined by the constants of the circuit. When this static wave, if it may be so called, arrives at the first aerial, an electromotive force is generated therein and currents start to flow thru it and the connected circuits. Current then begins to develop at the terminals of the detector. The wave continues its motion until it similarly affects the second loop and the resulting currents flow back to the receiving apparatus. Owing ,however, to the spacing which has been chosen, the currents from the first loop have had time to go thru a complete half cycle before that from the second arrives. Suppose now that the connections and position of the goniometer coil L_6 are such that the emf. produced in it by the signal is equal and opposite and therefore the signal cancels out.

Under these circumstances the results due to static will be as indicated in Figure 14, in which the solid line shows the damped oscillation due to the first loop, while the dotted line shows that due to the second loop when the method of connection is that just described. This diagram brings out the interesting fact that the first half oscillation arriving from the first aerial is unopposed; that the first half oscillation from the second aerial is opposed to the second half oscillation from the first aerial which, because the oscillations are damped, is of smaller amplitude than the one opposing it. This condition obtains thruout the entire train so that the resultant of the two oscillations is not zero.

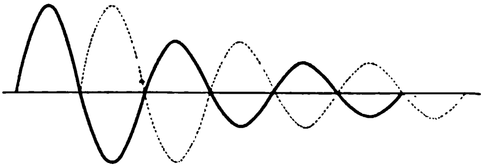

FIGURE 14

If now, the aerial circuits are heavily damped thru the addition of resistance, the wave train due to static becomes shorter and shorter, until when the limit is reached, all of the energy is in the first half swing. Therefore, under these conditions, while the circuits are so adjusted that the signal completely cancels out, yet the entire static current remains and we have the curious condition shown in Figure 15 of the two half oscillations, both in the same direction. It should be here noted that the first half oscillation of the signal is also unopposed, but if the signal current be undamped the percentage of the total signal energy which affects the detector is, roughly, 1/7,000th part of that which arrives during the time occupied by a dot at an ordinary rate of sending.

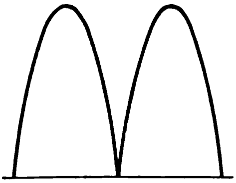

FIGURE 15

If we assume now that static disturbances are uniformly distributed thru all horizontal azimuthal angles, then as the angle, with the direction of the system increases, the intensity of these pulses decreases in proportion to the cosine of the angle; at the same time the effective phase difference between the loops decreases so that these pulses begin to overlap. It is also assumed that the intensity of the oscillation which these pulses can give rise to is proportional to the maximum ordinate as a first rough approximation. It follows then that as these pulses overlap, a distorted curve, as shown in Figure 16, results, but its effectiveness is not materially increased until the maximum ordinate of the resultant curve rises above that of the single pulse.

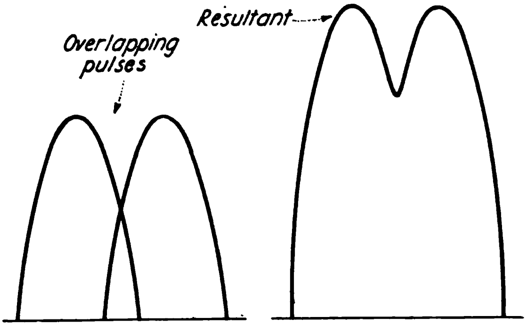

FIGURE 16

It will thus be seen that thru part of the azimuthal angle the intensity of the oscillations produced by static varies along the cosine curve, spreading out somewhat, however, as the angle increases. If, therefore, a third antenna is employed, the curve of reception of which is the cosine curve and in which both signal and static currents are flowing, and if this antenna be oppositely connected to the system just described, the static currents due to the click type of static will oppose and the residue will be of the order of the difference between the dotted curve shown in Figure 17 and the cosine curve shown in solid lines in the same Figure, from which it appears that a very large order of reduction is possible while at the same time utilizing the full signal strength developed by the third antenna. This explanation does not purport to be a rigorous analysis of the system described, but is presented merely as a rough approximation to the facts observed.

The arrangement just described realized these possibilities to an appreciable degree, but in the form then used was not capable of utilizing the possibilities above outlined to their fullest extent, and reference will be made later to another modification which displayed greater capabilities.

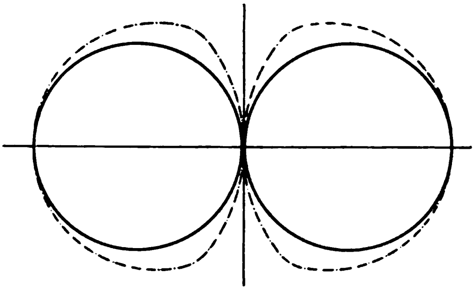

FIGURE 17

Various other combinations of the installation at Belmar were made. In Figure 18 the leads were disconnected from the loops and their ends joined, thus making of them horizontal aerials tuned to earth. It will be noted that this arrangement consists

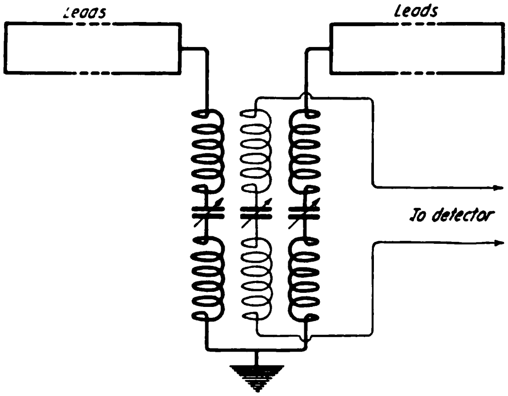

FIGURE 18

of two directive Marconi antennas and that the ratio of length to the height is unusually large. From this it follows that the aerial, which is pointed in a direction away from the transmitting station is a much better receiver of the signal energy than that aerial which runs in a direction toward the transmitting station. Both aerials, however, pick up the same amount of static. From this it is evident that the two aerials may have a very marked difference in their signal-to-static ratio, and this effect will add to the effect resulting from their phase separation particularly when this separation is small, and constitutes at times a factor in the results obtained. This principle operates in all of the arrangements which will be described in which horizontal aerials are used, regardless of whether they are above the earth's surface, on the earth's surface, or underneath it. Figure 19 shows one of these in which the loop leads were connected together and each loop converted into an ordinary antenna tuned to earth. In Figure 20 one loop was used in its normal way and balanced against the leads of the other loop tuned to earth. Figure 21 shows one loop connected in its normal way while the other one was arranged as an earthed antenna. All of these arrangements gave good results, but since it was impossible to investigate them all at once, the loop arrangements were chosen for first attention. Variations in the circuits were also tried. Figure 22 shows the parallel condenser arrangement, which was quite useful in se-

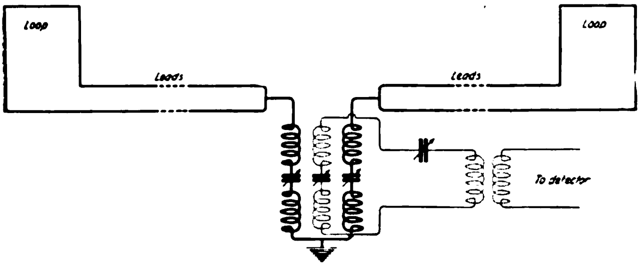

FIGURE 19

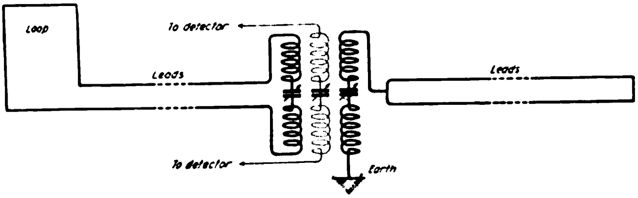

FIGURE 20

curing tuning to wave lengths shorter than could be obtained from the series condenser arrangement. Figure 23 shows another arrangement, in which most of the tuning was effected by condenser C_1 and inductance L_1 common to both circuits. Condensers C_2, C_3, C_4, and C_5, in addition to taking some part in the tuning, provided phase control and coupling.

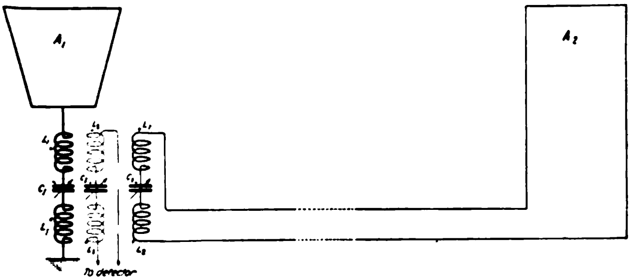

FIGURE 21

In addition to the capabilities of the arrangements described for receiving thru static, they have marked capabilities in working thru interference from other stations. When adjusted to

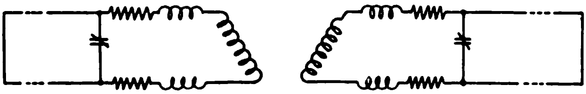

FIGURE 22

annul static of the grinders type this system has a reception curve of the form shown in Figure 9; its equation is $v = V \cos^2 \theta$, while that of the single loop is a cosine curve. It will be noted that the directional effect in this case is materially greater than with the single loop. When desired, adjustments can be so made

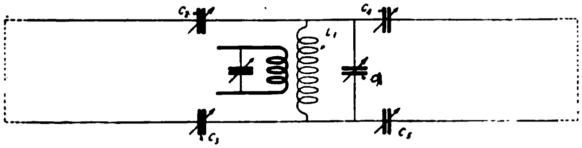

FIGURE 23

that the reception curve becomes that of Figure 10. Between $\theta = 0$ and $\theta = \pi$, the curve is a (cosine)^2 curve while between the angles $\theta = \pi$ and $\theta = 2\pi$, the curve is a (sine) · (cosine) curve when the loops are one-quarter wave length apart. This curve indicates that while reception in one direction is a maximum, reception from the opposite direction is zero, while it is also materially reduced in the third and fourth quadrants. This line of zero reception can be swung around at will thru the third and fourth quadrants by alteration of the phases of the currents in the two loops so that interference from any station arriving in this quadrant can be annulled, while reception is maintained from signals arriving in the first and second quadrants. It is to be noted that advantage can be taken of this property to eliminate strays, if they happen to be coming from a direction other than that from which the signal arrives, and this fact is of great help when a thunderstorm is gathering in the vicinity of the station. The necessary method of adjustment is as follows:

Suppose that the two loops of the system are one-quarter wave length apart and that the desired signal arrives from right to left. Then the currents in the left-hand loop are 90 degrees behind those of the right-hand loop, if the circuits are accurately tuned, and they will add in quadrature. Next, suppose a signal arrives from left to right; then the currents due to this signal in the left-hand loop are 90 degrees ahead of those in the right-hand loop and therefore also combine in quadrature. Then currents due to both signals exist in the common receiving circuit.

Suppose now, the phases of all currents in the left-hand loop are shifted forward 90 degrees; then the currents due to the desired signal in this loop are shifted around until they are in phase with those from the right-hand loop, while the phase of the currents due to the interfering signal in this loop, and which were previously 90 degrees ahead of those due to the right-hand loop, are now 180 degrees ahead of those in the right-hand loop, so that they oppose and neutralize. Because of the unusual characteristics of the antenna used, this shift in phase is readily accomplished by a small adjustment of the condenser in the loop circuit. If the interfering signal is not in line, the phase shifting can be made the right amount to take care of it, and this general order of result is obtainable to some extent with any spacing between the loops, although one-quarter wave length is best. The reception of Carnarvon's signal, 14,200 meters, thru the powerful interference of the 200-kilowatt

Alexanderson alternator at New Brunswick, only 25 miles (40 km.) away, working at 13,600 meters, has been an everyday performance of the system, while at the same time preserving a good static balance. All forms of the arrangement described have capabilities of reception thru interference, these capabilities varying with the type of antenna employed, the loop antennas and the horizontal aerials giving similar curves.

Work with the original installation soon indicated the desirability of increasing the spacing between loops both to secure greater signal intensity and also to determine whether or not the static currents would be simultaneously generated in the two aerials, when the spacing was thus increased. Antennas were therefore erected approximately 8,000 feet (2,430 m.) apart, each antenna consisting of 12 turns approximately 77 feet (23 m.) long by 30 feet (9.2 m.) high, supported from cross-arms attached to telephone poles. This construction is shown in Figure 24. The receiving apparatus was located at a point near the northeast loop instead of in the middle, and leads similar to those of the original arrangement run out to the southwest loop. When this was tried it was found that the leads picked up more signal and static than the loops and that the intensity of all currents from the southwest loop was so much greater than that from the northeast that successful working could not be obtained. Leads running along the ground, spaced at various distances, were then tried, and it was found that their effect was a minimum when the leads were close together. Next, a duplex lead-covered cable was tried and the effect of the leads very greatly reduced thereby. These leads of course had enormous capacity for a circuit of this sort with the result that the southwest loop was connected to the receiving station thru a capacity coupling of very small value, and in order to get equal signal from the distant end it was necessary to use four similar loops at that point connected in series-parallel. It was also found necessary to have a tuning condenser and inductances,

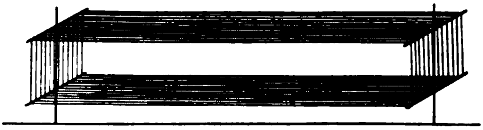

FIGURE 24

shown in Figure 25, located at the remote loop and an operator stationed there to make adjustments in accordance with instructions telephoned to him by the observer in the receiving station, using the cable wire for this purpose. It was also necessary to use the reversing switch previously described, since even the lead-covered cable picked up signal and static in appreciable amounts.

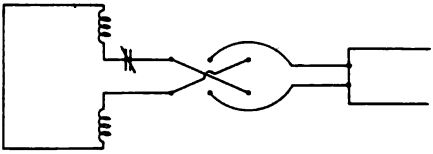

FIGURE 25

By the time this work was completed the season had advanced well into the winter and the amount of static available for working was so small that the results obtained were inconclusive and the work was abandoned for the time being.

In view of the entrance of the United States into the war and the great national importance of the improvements previously described, a full disclosure of the most fully developed two-loop arrangement was made to the Navy Department and an official test carried out by Mr. G. H. Clark, expert radio aid of the Bureau of Steam Engineering of the Navy. The following is a quotation from the report received by the Marconi Company from the Bureau relative to this test:

"The Weagant circuit in its present form will enable trans-Atlantic reception to be carried on without interruption in so far as elimination of static is concerned."

The next experiments were conducted at Miami, Florida, where loops were arranged at varying distances, the maximum being six miles (9.6 km.) and the minimum about 100 feet (30.5 m.). Having in mind the difficulties due to the leads, a special lead construction was used in which a pair of number 18 wires*, spaced about two inches (5.08 cm.) apart, were run thru pasteboard tubes about three inches (7.62 cm.) in diameter, these tubes being in short lengths joined together and covered on the outside with tinfoil. It was thought that this arrangement would give a reasonable value of capacity between the leads

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* Diameter of number 18 wire = 0.041 inch = 0.16 cm.

while the tinfoil covering might act as a screen in preventing signal and static currents from being picked up by the leads. This latter result was a desirable one since the greater the extent to which the leads act as aerials, the shorter is the effective spacing between the two aerials for a given total length. The results obtained with this lead construction were slightly better than those obtainable with any other, but the improvement over the results secured from the use of two similar wires, similarly spaced, but not surrounded with a shield, was of too small an order to warrant the expense and trouble of the other type of construction. Two loops of the type shown in Figure 24 but 150 feet (46 m.) in length and three miles (4.8 km.) apart, were connected to a receiving station located midway between them, and tests were conducted with various European stations, and it was found that the balance of static currents secured was as good as that obtainable with loops a short distance apart, while the signal strength at balance was much greater. This arrangement was not, however, generally satisfactory, as the loops were not large enough to give a satisfactory intensity of signal for practical working, while the effect from the leads was about equal to that from the loop. Two other loops were therefore constructed 7,200 feet (220 m.) apart, of the same general type and height, but of twice the horizontal length, and with these two, very satisfactory practical working was secured. With both of these arrangements the local tuning at the loops previously described was necessary, and this always involved a tedious adjustment until the correct setting for a given wave length was obtained, and even when this setting was known, it was necessary for some one to go to each of the loops,—not a convenient procedure with antennas three miles (2.2 km.) apart.

In order to overcome the objection just mentioned, the arrangement of Figure 26, which was the joint suggestion of Mr. Frank N. Waterman, and the writer, was constructed. As is indicated by the Figure, each loop consisted of a single turn extending from the station out and back again, thus being both loop and lead simultaneously, and being free from points where abrupt changes in circuit constants take place, as in the previous arrangement. The loops of this form which were constructed varied in length from 1,000 feet (305 m.) each up to approximately 9,000 feet (2,750 m.) each, the upper wire being supported on stakes only three feet (92 cm.) above ground, while the lower wire ran along the surface of the ground. Much difficulty was experienced in maintaining this construction long enough to get satisfactory observation, due to the fact that about 2,500 feet (760 m.) northeast from the receiving station, they had to cross a canal, while at other places they ran thru cow pastures and were frequently broken.

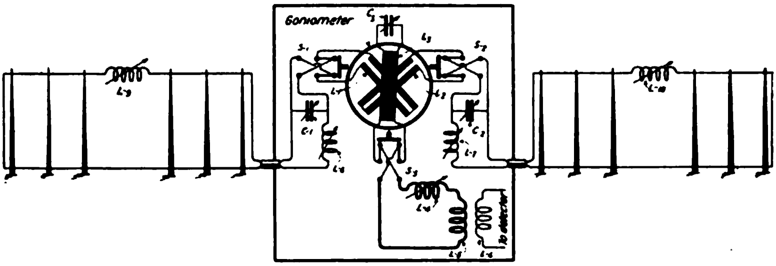

Figure 26

When first tested it was found that the loop then used, which was approximately 3,600 feet (1,100 m.) long, would not tune, the inductance and capacity inserted at the receiving end of the station apparently having no effect. This result was believed to be due to a current distribution in the loops of such a nature that there was a current node at the point of insertion of the tuning devices. It was therefore determined to attempt to alter this distribution by the insertion of inductance at some suitable point. An inductance such as L_9, L_{10} in Figure 26 of 30 millihenrys was inserted successively in the upper wire at a large number of points between the receiving station and the other end of the loop. It was found that the tuning improved constantly as the coil was moved from one end toward the middle, and constantly became poorer as the coil moved from the middle toward the end, the curve of the resulting effect being of the form shown in Figure 27. Insertion of the inductance in the lower wire produced no result and in fact if inserted in the middle point of the lower wire at the same time that inductance were inserted in the middle point of the upper wire, the effect of the latter was annulled. Having determined the best point for the inductance, its best value was next obtained, and while the results showed that a value of 30 millihenrys was about right for a wave length of 12,000 meters, and 5 millihenrys for a wave length of 6,000 meters, either value was sufficiently acceptable for both wave lengths.

As soon as tuning control of this type of antenna was accomplished it was found possible to use this system in a most satisfactory way for the elimination of static. The effective spacing of two such loops was found to be approximately the distance between the centers and complete control could be effected at the central receiving station, the over-all results obtained being even better than those obtained with the previous forms. A variation in the form of this type of aerial is shown in Figure 28, in which the area enclosed is approximately a triangle, it being assumed that this arrangement would give a greater effective separation if the loop receiving antenna extracted energy from a passing electro-magnetic wave in accordance with the usually accepted theory. Conclusive results on this form were not obtained until later work at Lakewood, New Jersey, and they showed that the very long triangle there used, *did not* behave in accordance with this assumption. In fact it may be stated that this whole work has demonstrated that our ideas of the mechanism by which a loop antenna extracts energy from a moving electro-magnetic wave, will have to be considerably modified, but this matter is too extensive to go into in detail at this time. The exact mode of vibration of the long, low loops just described is also a matter of great complexity and can only be determined by an exhaustive experimental and mathe-

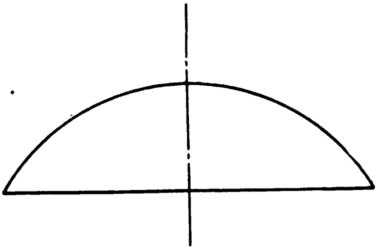

FIGURE 27

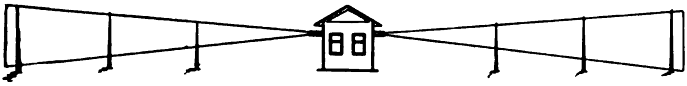

FIGURE 28

matical analysis. This work is already quite well under way, Mr. Louis Cohen having kindly consented to undertake the mathematical work for me, but it is not yet completed.

During the early part of the work at Miami, the Navy Department was experimenting with underground antennas, several of which had been installed by Mr. G. H. Clark. This afforded an opportunity for the writer to try these in the system described. These were tried in a large number of combinations, which are shown in Figure 29. As will be seen from the Figure, these arrangements were essentially the same as those of the original Belmar installation, resembling most closely that one which employed the horizontal lead wires and differing from it only in the fact that the wires were buried under ground or laid on the surface instead of supported some distance above the ground. All of these various combinations operated satisfactorily, but there was no material difference between those laid on the ground, those under ground, or those under water, which was present only a few feet under the surface. The lengths used were not great enough to give a material fraction of a wave length effective spacing, and attempts were made to extend this by increasing the length of the wire. It was found, however, that this could not be done, but that, on the contrary, increasing the length of the wire made the performance poorer rather than better, and this is probably due to the loop action and other causes referred to in the preliminary description of this type of aerial. The best working of all these arrangements was the combination of one of the ground wires with one of the loops, due to the fact that this gave a much greater effective separation, the loop being situated 3,600 feet (1,100 m.) away from the receiving station.

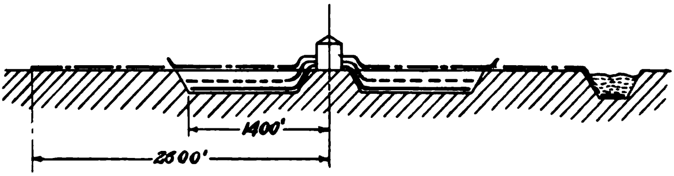

FIGURE 29

Having secured a practical form of this system which could be operated with the half-wave-length spacing, namely, the long, low loop, an installation was made in the spring of 1918, in the vicinity of Lakewood, New Jersey, in accordance with the results of the Miami tests. This installation consisted of two aerials, each three miles long, of number 14 hard drawn copper*, in a line directed toward France. These antennas were supported by telephone posts 30 feet (9.2 m.) high and were at first triangular in form, having a vertical leg 28 feet (8.5 m.) high at their outer ends, and brought together at the receiving station. This is shown in Figure 28. This form was later modified to a rectangle three miles (4.8 km.) long, ten feet (3.05 m.) in vertical dimension, the lower wire being about ten feet (3.05 m.) above ground, and this modification was found to be appreciably more satisfactory. Inductance coils of 30 millihenrys were inserted in the middle points of the upper wire of each loop. This station was operated continuously from the middle of July until the end of September with a force of three operators, each working eight hours, copying messages sent out by Lyons, Carnarvon, and Nauen regularly, and occasionally other stations. This continued operation was undertaken to determine the capabilities of the system in a practical, commercial way, during the worst period of the summer and at all hours of the day. The results secured were most gratifying, the total interruptions experienced being of no greater total duration than those of good cable working between the same points and at the same time of year. It was found that when the signal from the European stations was of normal intensity the heaviest static experienced at any time was unable to interfere in the slightest, but that on the contrary it might have been very much more severe without causing trouble. Reception under this condition was almost invariably good enough for high speed automatic reception. A few thunder storms occurred during this time and some, but not all of them, prevented reception while they lasted. There were also periods recurring regularly every day between four and six o'clock in the afternoon and between twelve and two o'clock in the morning when the intensity of the received signals from Carnarvon and Nauen fell off enormously, on some occasions falling as low as 1/100th of their normal intensity. During a few of these fading periods interruptions were experienced varying from five or ten minutes to perhaps one hour. The worst of these periods was usually, but not always, the midnight-to-two-a.m. period when, altho the static was generally lighter than during the afternoon fading period, at which time its maximum intensity occurred, the decrease of signal strength was rather greater.

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* Diameter of number 14 wire = 0.064 inch = 0.162 cm.

A careful study of the conditions during these fading periods convinced me that the difficulty was due to the fact that when the signal weakened greatly the click type of static was present in sufficient quantities to cause the trouble, and that when the signal intensity was greatly amplified in order to be heard, the amplification also brought up this disturbance with its ratio to the signal unaltered.

As has already been pointed out, the two-aerial arrangement has not as yet shown itself capable of sufficiently differentiating between this horizontally moving type of static and the signal to meet the severest conditions of signal fading. In the hope of successfully overcoming even this condition, existing occasionally during the fading periods, recourse was had to the three-aerial arrangement, but in a modified form, as shown in Figure 30.

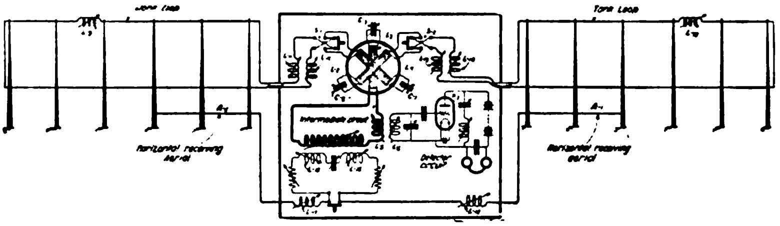

Figure 30

This was operated in accordance with the principle previously set forth, namely, the two loops were adjusted to balance out signal instead of static, and the retained static was used to balance out that in the third antenna. The third antenna in this case was a horizontal wire approximately 6,000 feet (1,820 m.) long, about three feet (92 cm.) above the ground, running underneath the loop antennas and supported by the same poles. When this arrangement was operated it was found that all of the hoped-for improvement, and much more, had been realized, in fact that the improvement of reception thru static of the stray or click type was of the same order as the improvement which the two-antenna arrangement made possible thru static of the grinders type; also, most fortunately, that the adjustment which reduced one type of static was the exact adjustment for eliminating the other, so that both types went out together, leaving all of the signal supplied by the third antenna. This was approximately the same in strength as that which could be received using the two loops so connected that their signal strengths added.

So great was the general improvement in reception made possible by this arrangement that signals from stations in Europe of a very much smaller order of power than Carnarvon or Nauen could then be received. Of these stations it is sufficient to mention Eiffel Tower, working at about 8,000 meters, and Lyons, working at 8,000 meters, the signal strength of Lyons at this wave length being very much less than the signal received from the same station when using his usual wave length of 15,000 meters, and it is assumed, though not definitely known, that the amount of power being used was much less. The installation at Eiffel Tower is understood to be an arc, the input of which is about 100 kilowatts. Many attempts had been made during the summer to copy these stations with the two-antenna arrangement, but the results were satisfactory only occasionally and when the grinders type of static was that which existed. When the other type was present these stations could not be read. During the test with the three-antenna arrangement on one occasion, in the evening, static of extreme intensity was experienced and the intensity of the signal from Eiffel Tower was much below normal, with the result that with the two-antenna arrangement it was barely possible to tell that the signal was present. Using the three-antenna arrangement the signal was not only readable but of such intensity that it could be read with the telephones a couple of feet from the ear. Continued use has established beyond question that this performance is not occasional or accidental, but consistent, and that with this arrangement trans-Atlantic radio telegraphy can now be carried on free from interruptions due to static of any kind whatsoever except local lightning. This cannot always be neutralized, but since the cables are also interrupted by this latter cause it follows that a continuity of communication equal to that of cable operation is now possible by radio telegraphy, while the latter has the great advantages of cheapness and greater speed of operation. For many years, attempts to work automatic high-speed radio telegraphy have been made, but they have been successful only when static was absent. It is therefore evident that use can now be made of this method of working to a very great extent, thereby greatly increasing the number of messages which can be handled over a given circuit. It may also be stated that the great barrier in the way of successful, practical radio telephony has been removed since static has interfered with radio telephony to a much greater extent even than with radio telegraphy.

One of the outstanding features of the systems thus far described has been their need of a considerable stretch of territory, and it would obviously be an important advance if the same results could be secured without this necessity. It is pleasing, therefore, to be able to state that a considerable number of such arrangements have been worked out, in which the necessity for large space does not exist; in fact some of them are of such small dimensions that the entire equipment necessary, including the antennas, could be arranged in a lecture room, and between the floor and the ceiling. Only one of these arrangements will be described at this time, the others being reserved for a later communication.

Referring now to Figure 31, A_1 represents an aerial of the linear type several times referred to, but so arranged that it can be moved thru a considerable angle in the vertical plane and swung around thru any desired azimuthal angle. If this aerial is swung from the vertical position to the horizontal position, while being directed toward a desired transmitting station, it is found that a particular vertical angle can be obtained at which the signal goes out entirely while some of the static re-

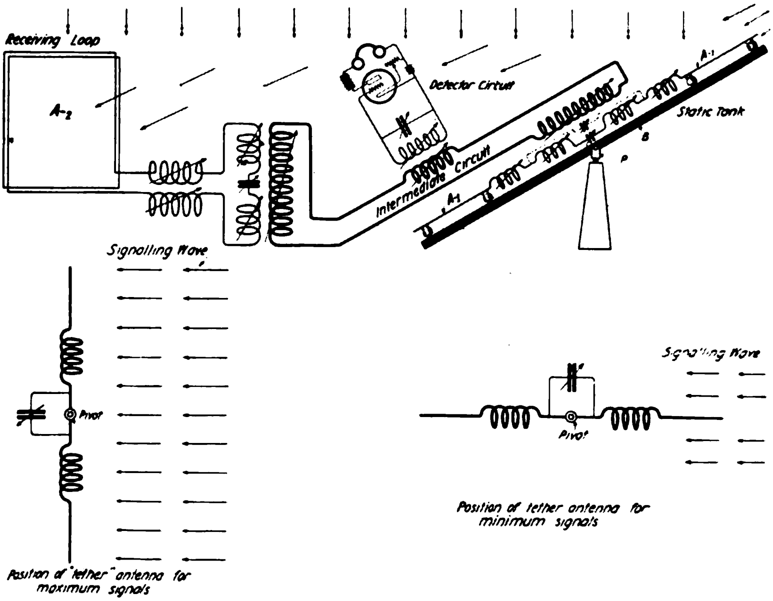

FIGURE 31

mains. The arrangement therefore constitutes another form of static tank. If then we take a second antenna, such as the loop A_2 shown in the Figure, which supplies both signal and static, we can, thru the use of the circuits already explained, couple these together in such a way that the static is cancelled, leaving the signal. This arrangement works quite as well as any of those previously described, except the three-antenna arrangement, and the difference is due to the fact that this particular arrangement does not as completely eliminate the static of the horizontally moving type.

To secure the full practical benefit of this arrangement it is desirable that the length of the aerial A_1 be conveniently short, say about 30 feet (9.2 m.), which, for trans-Atlantic reception of course makes necessary the employment of amplifiers of extraordinary capabilities. In the work which I have done with this arrangement I have used two amplifiers, developed by the Research Department of the Marconi Company, of five and eight stages respectively, with which it is possible to receive signals of a satisfactory strength from Nauen or Carnarvon when the antenna is of the dimensions stated. The reason for the use of the very small antenna is simply that it is then possible to secure a conveniently operated mechanical support, the principle of operation holding good, however, when much greater lengths are employed.

No attempt has been made in this paper to set forth exhaustively the complete theories of the arrangements used, but simply to give a brief description of the methods used and results obtained .It is realized that quantitative data of many sorts have not been given, due in part to the unsatisfactory nature of the methods of measurement available, and also to the fact that the whole work was dominated by the practical requirement of securing readability of trans-Atlantic signals, which was of vital consequence to the Marconi Company. It is hoped, in subsequent communications, to remedy the deficiencies referred to and to describe a considerable number of other arrangements which have been discovered, the operating characteristics of which are being more fully investigated.

With reference to the hypothesis stated in the early part of this paper to the effect that static of the grinders type is due to electro-magnetic waves heterogeneously polarized and propagated in a direction perpendicular to the earth's surface, it should be clearly understood that while this hypothesis has been of great use in explaining the very large number of observations made over a long period of time, it cannot however be regarded in the light of a proven theory, since certain observations have been made which it does not readily cover. It does appear, however, that the most important fact contained in this hypothesis, namely, that static effects of the grinders type are simultaneously produced at points separated a distance of the order of the longest waves at present employed in radio telegraphy, is firmly established. With respect to the rest of the hypothesis, further work, which is at present in progress, will be necessary before the complete truth is proven or otherwise.

The writer would greatly appreciate the opportunity to demonstrate the actual working of the systems described thru a committee to be selected by THE INSTITUTE OF RADIO ENGINEERS should they be sufficiently interested, during the coming summer, when static disturbances are at their worst.

In conclusion the helpful and valuable assistance of the following gentlemen is acknowledged: Mr. C. L. Farrand, Mr. Frank N. Waterman, Mr. George H. Clark, Dr. Alfred N. Goldsmith, Mr. Louis Cohen; and of the Research Department of the Marconi Company. Messrs. Weinberger and Dreher of the Research Department deserve special mention in this latter connection.

SUMMARY: The effects produced by static (strays) are considered, and the Eccles classification of static as grinders, clicks, and hisses is adopted. Previous attempts to eliminate strays are described with explanations of their non-operativeness.

Researches are described which indicate that grinders, the predominantly objectionable summer static, act as if propagated vertically. A balanced antenna structure consisting in effect of two horizontal loops is used to eliminate grinders. Signals in the loops add in the secondary circuit in proportion to the separation of the loops relative to the wave length, while vertically propagated grinders in the loops balance out in the secondary.

Clicks are found to be horizontally propagated strays, and a special three-antenna arrangement for practically eliminating them is described and explained.

Experimental work at various stations using these arrangements is described, and the capabilities of the new systems indicated.

DISCUSSION

Michael I. Pupin: I have been very much interested in the paper, since it is a report of work actually done. Perhaps one does not care so much about the theory which has been advanced to explain the balancing described; whether the theory is correct or not, the effects produced show that it is a theory not so very far removed from the truth, if it is not exactly the true theory.

What strikes one most in listening to the paper is that we have here a new attempt to advance the art of radio telephony and radio telegraphy, an attempt, namely, in the direction of adjusting phases. In the beginning of the art, we had pulse excitation and nothing else;then came loose coupling and less damping, which made tuning available; it is still holding its own in the art; and then came attempts to produce continuous oscillations, and now we have a new addition to the art: namely, the art of adjustment of phases in the receiving antennas.

I myself am a great believer in this new departure. I have been its advocate for some time; namely, the adjustment of phases, and as we are dealing in radio telegraphy and telephony with wave propagation, it goes without saying that in wave propagation we can accomplish a great many effects by the proper treatment of phases, a feature which is not possible in ordinary transmission, which does not depend upon wave propagation.

The effects produced by loops pointing in the direction of the station which transmits, properly adjusted as to their length, and provided at the point of symmetry with a suitable receiving apparatus, can be adjusted so as to get a good signal, because you arrange the phases in a suitable way, which at the same time can be made to neutralize the static effect, if that static effect is not propagated in the same way as the signal. I say this seems to be obvious—*when you are told about it*, and that is what I like about the scheme. A scheme, which appeals to you as obvious after you are told about it, is the right scheme, as a rule.

It is very easily understood, and everyone will say "Why, of course, that will work." But it is rather difficult to understand why an electric wave due to the propagation of a grinding "stray" or a grinding static should affect a long conductor, several thousand feet long, in such a way that the motions of electricity in all its parts are affected in the same phase. It is very difficult to understand.

Mr. Weagant explains it by assuming that the wave is propagated vertically downward, and perpendicularly to the surface of the earth, as the wave is due to heterogeneously polarized oscillators—I think that is what they are called. Well, these oscillators must be not only heterogeneously polarized, but they must be somewhere above, because if they are at a distance, say one thousand miles (1,600 km.) away, or even five hundred or three hundred or even two hundred miles (800 or 400 or 300 km.) away, then their waves would not affect all parts of a long antenna alike. It is not easily seen how these oscillators start waves (which after awhile must become spherical) which, as far as the receiver is concerned, appear as if they came from above.

That is the difficulty. What of it? The more difficult the thing appears, the more interesting it is. It may be that these oscillators throw out spherical waves which are reflected back and forth between the conducting upper layer of the atmosphere and the earth, an assumption which has been advanced by other men and accepted, and that the "strays" which bother you most are the "strays" from the last reflection from the upper layer. This assumption is just as good as any other. If it does not suit you, find out some other assumption that will suit you better. But whatever the explanation may be, the fact remains that the waves coming from the grinders act like vertically propagated waves, because they affect every part of the receiving system in the same phase and, of course, the signaling waves are horizontally propagated waves.

Mr. Weagant arranges his balance in accordance with this assumption and he proves in a very successful way that he can receive messages practically continuously. Of course, to do that, you have to use long antennas. I felt a little bit unhappy when antennas several thousand feet in length were mentioned. I said to myself "This investigation is evidently being made for a big corporation—no college professor could indulge in anything like that." Then once or twice a generator of two hundred kilowatts, the Alexanderson generator of two hundred kilowatts, was mentioned. Of course, such a machine a poor college professor can never have or possess, and if he did possess it, he would probably sell it and retire for the rest of his life instead of bothering with investigations with such a machine.

The static effects are probably cosmic effects; that is to say, they are terrestrial effects of almost cosmic dimensions. The investigation requires to start with large experimental apparatus, large facilities for the purpose of producing certain definite effects.

Of course, one idea about the static problem, and I must confess that it is my idea too, is this. If you use a device of the ordinary dimensions that you can conveniently place in any little room, and reduce the static by some means or another, enabling the sender to use about one-one hundredth part of the energy he is usually using, then instead of using anywhere from one hundred to two hundred kilowatts, which almost makes me shudder, he can use from one to two kilowatts. That is my opinion, altho I do not say that my opinion is correct, but in my opinion the real static problem is to reduce the effect of the static by using receiving circuits of very ordinary dimensions, such as we use on board of a ship, and enable one to receive signals free from static interference even if the power of the sending station is reduced one-hundred-to-one. Of course, that is a very, very ambitious proposition.

The proposition described by Mr. Weagant is not so ambitious—it is very much less ambitious. From many points of view it is much more sensible, because advances in an art, as a rule, are made step by step—there is no sudden jump in the development of an art, but a gradual development. Now, this improvement is in the direction of gradual advance. We have here a marked improvement as the first step in the direction of getting rid of the natural interferences of the static, and as such I hail it with delight. It is an accomplishment, a decided accomplishment.

I am surprised, however, that in all this work the name of the vacuum tube amplifier has not been mentioned at all, until towards the last, when the short rectilinear antenna which was described, in which case the energy which was received was very small, and then a five-step to eight-step amplifier was used, which was said to have been designed by the Research Department of the Marconi Company. I would like to see that eight-step amplifier. I have a nine-step amplifier. I know what a tremendous trouble it is to a man to develop a multi-step amplifier, and all of a sudden to hear that some man, who did not say anything about it, had developed an eight-step amplifier. Well, I wonder how many times it amplifies. Ten times, a thousand times, a million times, or what is it?

However, I am glad that Mr. Weagant was finally forced to use the amplifier. I know from private information that as long as you use a long antenna the amplifier is not necessary, because the antenna itself picks up a sufficient amount of energy, being so long, being such a large trap for the electrical wave to drop in, that an amplifier is not necessary. As long as Mr. Weagant has started to use it, I am satisfied and glad of it, because I do believe that the amplifier is one of the finest inventions in radio telegraphy that we have to-day, and that no problem in radio telegraphy including the elimination of the static can, in my opinion, ever be solved without the full use and full knowledge of the amplifier; and, delighted as I am with the accomplishment recorded in his paper, I am equally delighted with the fact that Mr. Weagant and the Research Department of the Marconi Company have started to use the amplifier in connection with this scheme.

Alfred N. Goldsmith: Several years ago, I had the opportunity of witnessing a demonstration of Mr. Weagant's system of stray elimination under conditions that were entirely under my control. That is, the wiring and connections of the apparatus were completely open; it was permitted to make full wiring diagrams of the equipment, and (after proper instruction) to handle and adjust the apparatus myself. This was the first of a number of opportunities of this sort, and always with the same successful result. It has also been my privilege to have been associated with Mr. Weagant in the development of many phases of the remarkable system which he has originated and particularly in its more recent and advanced forms. In every case, the extreme orderliness of the phenomena presented has been striking and the extent to which theoretical deductions have been verified by experimental evidence was highly gratifying. Particularly has this been the case since, prior to Mr. Weagant's work, strays were regarded as of such random and erratic character that any systematic or logical manipulation of them or their effects seemed hopeless. This state of affairs has been completely reversed, and a powerful weapon of research placed in the hands of pure scientists as well as an instrument of tremendous importance at the disposal of the radio engineers.

Strays are practically omnipresent in radio receivers. Indeed their ubiquitous character has led workers in this field to associate strays and signals as inseparable twins. All the greater is the amazement of the radio manipulator when, on turning a handle, he hears barely audible signals previously smothered by overwhelming crases of strays, emerge finally, loud and well-defined, while the strays dwindle to negligible proportions. The experience, particularly to skilled workers in the art, has an air of unreality because it is so far removed from all that has previously seemed possible.

With Professor Pupin's view as to the importance of the vacuum tube amplifier *in the development* of Mr. Weagant's methods of stray elimination, I cannot concur. The basic ideas of these methods were quite independent of amplification of this sort, and their main development equally so. Mr. Weagant assuredly owes no debt whatever to the amplifier for his original discoveries and their main reduction to practice.

With Professor Pupin's opinion that the amplifier, in some form, will be used in the more compact stray eliminating systems which Mr. Weagant has more recently developed, I find myself in accord. Convenience dictates receiving antennas of small dimensions. These, being unable to gather considerable energy for the incoming signal, call for amplifiers. As to the amplifiers actually used in this work, the voltage amplification of which they are capable is of the order of Professor Pupin's largest figure rather than of his smallest.

Of the improvements which will result in the radio art because of this advance, little need be said. High speed long range communication and radio telephony assume an entirely new order of importance and a tremendous growth in the radio field becomes the inevitable result of the elimination of the worst obstacle to reliable long distance reception.

No doubt, the auditors of Mr. Weagant's paper have felt the complexity of the methods used, to some extent, particularly at a first hearing. The general impression must be that an ingeniously elaborate electrical means for utilizing the new law which has been found to govern the action of most of the strays which interfere with the reception, namely, "grinders," is employed. However, the salient feature of the methods used to eliminate grinders is based on the simultaneity and equality of effects produced by strays on two similar systems properly oriented and in the same horizontal plane. This simultaneous action is the key-note to the situation and, however it may arise, has been the furnace in which the powerful weapon against strays has been forged. The treatment of strays of the "click" class, which are, incidentally, much less serious so far as interference with reception is concerned, has been based on a combination of directional and electrical features ingeniously adapted to the desired end.

Apropos of the differences in the methods of elimination of the two types of strays, one of which is highly vital and the other at least of considerable practical importance, it may be stated that a new scientific instrument has been produced whereby re-rch in the radio field will have many added possibilities. The borate forms of antenna systems with distributed constants, with directional characteristics, and with neutralizing or balancing arrangements, suggest a host of investigations on long-distance transmission and reception. A large amount of very important work of this sort is now being conducted and will undoubtedly be made public when properly collated.

George H. Clark: The most pleasant duty to which I have ever been assigned during my association with the Navy Department has been to follow the progress of Mr. Weagant's work on the static eliminator. It has indeed been a pleasure to watch the development of so practical an invention, worked out on such highly technical lines. Mr. Weagant, as one might expect from the nature of his invention, has obtained a perfect balance between theory and practice.

I consider that this invention is one of the most fundamental and far-reaching ever made in the realm of radio telegraphy, ranking with the few that really mark the milestones of the art. There will undoubtedly be many developments made in the near future along the same general lines, and hence I am all the more glad that it has been my privilege to assist in these pioneer tests.

A little over a year ago, I was ordered by the Department to witness and report on a system of static elimination on test at the Marconi Belmar station. Of so-called static eliminators there had been many in the past, all failing in their purpose, and so my expectations of this new claimant in the field were not great.

On arriving at the station, which was a rough little shack of the standard Marconi coast station type, I saw a number of pieces of apparatus, very crudely wired, and many of obviously home-made origin. It was a cloudy day, with frequent lightning flashes around the horizon, a typical day for "summer static." Two large rectangles of wire supported by the tall masts of the Belmar main station formed two loop antennas, each of these leading into the shack by connecting pole lines. Listening in on one of these loops alone, static was deafening, so loud, indeed, that not a trace of signal of any sort could be heard. Mr. Weagant threw a switch, and even with this crude, preliminary apparatus static died down to a weak murmur, and the signal became clearly readable. I consider that this demonstration was the most impressive one I have ever witnessed.

During the rest of the week, static continued very strong, and many experiments were made. Small concentrated inductances, ground aerials, different forms of tuner connections, and so on, were tried, and in all tests a remarkable increase in signal-static ratio was obtained, whether this ratio was measured in terms of audibility or of readability.

Later tests were carried on at the main Belmar station, in an attempt to make the system more practical for the operator. The first changes lessened the efficiency of the system to a marked degree, but Mr. Weagant persisted in his experiments, trying one thing after another, until the reason for the failure was clearly shown. During this work, I had more than once to fall back on my faith based on the first week's showing.

It became difficult to make further tests at Belmar, as the Navy Department wished to use it for war-time communication, so the experimental work shifted to Miami, Florida. Here Mr. Weagant demonstrated that his analysis of the failures at the Belmar station was correct, and the new Miami circuits worked much better than the original one. As a result of these successful tests, a commercial form of receiving station was erected at Lakewood, New Jersey, the behavior of which during the summer months of 1918 amply justified the claims of the inventor.

Mr. Weagant has omitted the human interest from his account of the Miami work. Yet I can well remember the hours I spent in a drygoods box, miles out in the desert, waiting for the Weagantian command to vary coil, or condenser, or reverse the ever-inverted switch. Again, Mr. Weagant in his paper has referred, quite casually, to the tinfoil-coated pasteboard tubes which covered the connecting leads. Yet the actual construction of this was far from being a casual affair. To direct the activities of fifty colored workers, and to keep them all engaged in placing sheets of tinfoil, one foot square, over six miles of pasteboard tubes, was a task not unworthy of the most determined investigator. At night, especially, this long line of silver, gleaming in the Florida moonlight, seemed more like a monument to Mr. Weagant's persistency than a part of a radio system.

I wish to take this opportunity of referring to the painstaking logical way in which Mr. Weagant has worked out his problem. His skill as an investigator and experimenter has equalled his ability as an inventor. But, above all, he is one of the few investigators who, when confronted with facts at variance with theory, would dismiss the theory rather than the facts. Such investigators are rare; hence such results are rare.

Ernst F. W. Alexanderson: I feel rather bewildered to discuss such a complicated and deep subject as Mr. Weagant has presented in his paper. Many times when I have been talking with Mr. Weagant about this subject, without knowing the details of his work, I have said: "I certainly do hope that you are right and that the developments will prove to be all that you expect them to be."

Almost every radio engineer must plead guilty of having at some time or other thought that he had a solution for the static problem, only to find later that he was more or less mistaken, usually more so.

Now, what is encouraging, in a very great degree, in Mr. Weagant's paper, is that he gives us a key to the solution by announcing that he has found a new law of nature. Up to the time that I had heard it rumored that Mr. Weagant had found a new law of nature, I was afraid that he might be in a class with the rest who had failed in their efforts. Well, I had a sinking of the heart when he said that perhaps his theory is not altogether proven, perhaps it is not; but the evidence that he has presented to us is so convincing that I hope we will find that a very material advance has been made.

Mr. Weagant, and particularly now Mr. Sarnoff, have pointed out the great importance of a static eliminator in radio telephony. Radio telegraphy has been very reliable during the recent years in trans-Atlantic communication.

I may mention, in this connection, that I happened to be in the New Brunswick radio station, when a call suddenly came from Washington, that a set was needed immediately, and the station operator immediately came in and said that the station was calling Germany. It was the first time since the war that Germany had been called by a United States radio station; and the message that went was the important announcement of President Wilson, stating that the United States could not deal with Germany under its present form of Government, upon which announcement the abdication of the Kaiser followed.

This bears out, further, what Mr. Sarnoff has touched upon, that radio has broken the precedents of international practice, by permitting direct communication between the responsible parties in the belligerent nations, thereby short-circuiting the usual channels of diplomacy.

President Wilson is now on the sea, and arrangements have been made whereby telephone messages are being sent to the President every day. This apparently has nothing to do with Mr. Weagant's paper directly, but Mr. Sarnoff's discussion leads the thought from one to the other, and that is that the use of radio telephony across the ocean is limited in its possibilities by the degree to which static can be eliminated.

I wish I had with me a photograph which I was examining on the train; a photograph of the radiated waves from the New Brunswick station—being the electrical equivalent of Secretary Daniel's voice when he was speaking to President Wilson on his way over. We hope that in the future, when the best kind of receiving devices are in existence on both continents, that many such photographs will be taken of the rulers of the world.

David Sarnoff: Some time ago, I asked Mr. Weagant to tell me, if he could, the particular thought or idea responsible for his faith in the ultimate solution of the static problem. I asked the question specifically, because of the apparent disbelief of so many others that a real solution of this vexatious problem could be obtained.

In answer to my question, Mr. Weagant stated that he had always considered Nature reasonable and logical; it followed, therefore, that it would not, on the one hand, bestow upon mankind a boon, such as electrical communication thru space; and, on the other hand, place in its way a deadly barrier such as static has been, without offering means of nullifying it and attaining the full advantages that space communication offers to the world.

It was this implicit faith in the justice of Nature which spurred Mr. Weagant on in his determination to master the disturbing elements. The task, has, perhaps helped to add a few gray hairs to his otherwise young head. He has told you himself how he reached his goal, and I merely wish to call attention to the original inspiration and conviction, characteristic of the man.

In my judgment, the elimination of static interference marks the most important practical advance in the radio art since Marconi's original invention.

International radio telegraphic communication, a child of the past, will now grow rapidly to sturdy manhood. Radio telephony over long distance and across the oceans—impracticable heretofore—is now in full view, and commercial radio telephone service between the United States and Europe may confidently be expected.

Think what this means. Electric signaling, now more than three-score years old, has not provided means for talking to our friends across the great oceans. Whatever we had to say, others said for us by telegraph code. And now, for the first time in the history of electrical science, the spoken word may be uttered by us in our own language and heard by the desired ears across the oceans. I predict that trans-oceanic radio telephony will in time revolutionize international business, and diplomatic and social intercourse in the same way that the Bell telephone revolutionized our daily affairs on this continent.

Mr. Weagant made reference in his paper to the possibility of conducting long distance radio communication with less power at the transmitter than is now generally employed. This, it seems to me, should logically follow as one of the results of his great invention, and one is now justified in expecting that, before long, communication across the Atlantic may be carried on successfully with transmitters of, say roughly, fifty kilowatts, or perhaps less, and receivers of the compact type described by Mr. Weagant.

Nothing brings nations and peoples closer together than reliable, rapid, and cheap communication, and radio now promises to be the international courier, fulfilling these three vital requirements.

The present high cable rates between widely separated countries have limited the amount of news or press matter exchanged between the United States and such countries as, for example, China, Japan and Australia. The mail service is, of course, too slow to record important events.

With the elimination of static interference and the possibility of reduced power at the transmitters, it is conceivable to me, and no doubt to many others, that two or three long distance transmitting stations, located in the most important and suitable parts of the world, could be devoted to the exclusive transmission of daily news or press matter, broadcasted to all the countries, where, with the use of the proper receiving system, the broadcast messages could be received by all and published in the press of the world.

Cable companies and the interests they represent have long made use of their favorite argument that communication by radio is not secret, and whereas by cables it is. Of course, I need not tell you practical men that no system of communication is really secret; but the very fact that several transmitting stations can simultaneously communicate with the entire world, gives to radio an advantage that the cables never had and never can possess.

Philip E. Edelman (by letter): Having recently completed similar work with different means I was naturally much interested in Mr. Weagant's paper, and would like to ask Mr. Weagant whether he has been able to balance out strays other than "grinders," and if "clicks" are eliminated or not?

As described, apparently the plan would be limited to a fixed wave length to keep the correct loop spacing, but doubtless could be worked out into the same flexibility as the usual old style receiving stations.

The correct explanation seems to me to be that the single turn loops shown are directional with respect to strays as well as signals. Experiment shows that a vertical loop oriented east and west does not usually receive the same strays as one in the same position, but oriented north and south, does. If strays came only directly from above and below, as seemingly stated, it would appear that two loops placed at right angles to each other would also get the same strays simultaneously. Experiment shows that this is not the case, for simultaneous records prove that one loops receives strays the other does not. Accordingly, it makes no difference where the strays come from, because all three loops are oriented the same and receive only such portion of the strays as come within their directional locus. All strays originating from a sufficient distance can accordingly be balanced out whether they come from overhead or under foot or at any angle in the receiving cone of the loops.

The loop apparently owes its directional property to the fact that for maximum induced current therein, it is essential that the advancing waves cut the turn of the loop at right angles thereto, which means that the axis must be in alignment with the shortest distance to the transmitting station or source of strays. Waves from other sources at other angles to the axis have a lesser effect, roughly (*Maximum*) $\cos a$, where a is the angle, until at right angles there is no effect and this proves to be the case experimentally. Accordingly part of the stray mitigation is due to the fact that strays arriving from sources outside of the cone of the loop have slight if any effect thereon in the first place. Such as do affect the three loops in alignment apparently affect all alike and can be balanced out. A similar argument would appear to hold for a linear ungrounded antenna such as Mr. Weagant shows.

I would like to ask what operating ratios of signal-to-stray audibilities were obtained under the new method of measurement outlined and how they compared with the usual old method of audibility measurement. The latter is notoriously not precise because depending upon the sensibility of the operator's ear which varies widely in different people.

This is an excellent demonstration of stray mitigation, but still leaves many problems, not the least of which is the so called "fading" effect. Even if total stray elimination could be effected at the receiver, the media between the transmitter and receiver remain outside control, so that signals can still fade erratically due to fluctuations therein.

A NEW METHOD OF USING CONTACT DETECTORS IN RADIO MEASUREMENTS*

By

Louis W. Austin

(United States Naval Radio Laboratory, Washington)

For many measurements in radiotelegraphy it is necessary to use a radio frequency current indicator of known resistance. If the current to be measured is small, it is generally customary to use a thermoelement and galvanometer. The most sensitive thermoelements are either of the vacuum type or the welded tellurium type. The vacuum thermoelements can be obtained of any desired resistance and are very sensitive, but are slow in action and frequently show a bad zero drift. In addition, the deflection usually shows considerable divergence from the current-square law. The tellurium platinum elements are quick acting and follow the current-square deflection law with sufficient accuracy for all practical purposes. They are, however, so fragile and difficult to manufacture and transport that no manufacturer has yet undertaken to supply them commercially. It is also impossible to make the contact resistance much less than 10 ohms. It is to be noted that the resistance in both the vacuum and tellurium types changes considerably with the amount of current flowing.

On account of the difficulties mentioned, the sensitive thermoelements in our laboratory have been replaced, for the most part, by a shunted contact detector circuit arranged as shown in Figure 1. Here *L C* is any oscillating circuit having inductance and capacity, *D* is a contact detector, *G* a high resistance galvanometer, *K* a paper condenser of one microfarad capacity, and *R* a resistance which may have any value from 0.1 to 100 ohms. The greater part of the radio frequency current passes thru *R*, while a small portion is shunted thru the condenser *K* and the detector. The direct current from the detector after passing thru the galvanometer returns thru *R*. On account of the high resistance of the detector, the total resistance of the detecting

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* Received by the Editor, December 23, 1918.

system is practically identical with *R*, as has been experimentally tested between 0.1 and 100 ohms.

The sensibility of this arrangement is much greater than that of the best vacuum thermoelements of equivalent resistance.

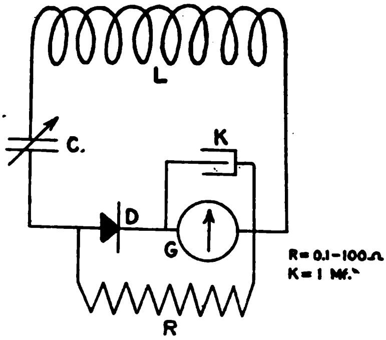

FIGURE 1

In the case of most of the well-known detectors the proportionality between deflection and current-square is excellent. Galena, while the most sensitive of any of the detectors tried, shows a slight deviation from the square law. For absolute current measurements the system may, of course, be calibrated by comparison with a known thermoelement at the time of experiment.

Since the fraction of the total current passing thru the detector is, for a wide range, practically proportional to the shunt resistance, it is possible to calibrate the apparatus approximately with a 1-ohm shunt which, with a galvanometer of a sensitivity of 5×10^{-9} amperes, and with an average silicon detector gives a deflection of 1 millimeter for about 2×10^{-3} amperes radio frequency current. Thus 300 millimeters on the galvanometer scale represent about 34×10^{-3} amperes. This can be read conveniently on the small hot-wire instruments found in most laboratories, which give full scale deflection for from 80 to 100 milliamperes. The shunted detector can then be used for other shunt values by dividing the sensibility by the shunt ratio.

The following table gives the approximate radio frequency current required for 1 millimeter deflection on a galvanometer having a direct current sensibility of 5×10^{-9} amperes. If the sensibility is 5×10^{-10}, 1 millimeter with a 100-ohm shunt will represent approximately 6×10^{-6} amperes, radio frequency current. The third column gives the maximum radio frequency current which can be safely sent thru the system without danger of materially changing the detector resistance. The values are based on a detector resistance of 3,000 ohms and a maximum safe detector current of 12×10^{-6} amperes.[1]

TABLE I

Approximate R. F. Sensibility and Maximum R. F. Current for Various Shunts with a Silicon Detector.

Shunt (Ohms)	R. F. Sensibility (10^{-6} Amperes)	Maximum R. F. Current (10^{-6} Amperes)
1	2,000	36,000
5	400	7,200
10	200	3,600
25	80	1,400
50	41	710
100	21	360

Of course, much larger currents can be used with good proportionality between deflection and current square provided exact constancy of resistance is not required.

In using this circuit care may be taken that there is no direct action of the outside driving circuit on the detector shunt loop *D K R*.

SUMMARY: An arrangement for using crystal detectors in radio measurements is shown. It is based on the original use of a low resistance shunt across detector and galvanometer and calibration of the arrangement using r.f. currents which can be measured with hot-wire instruments. By increasing the shunt resistance, the necessary much higher sensibility is directly obtained. Performance data are given.

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[1] See "Contact Rectifiers of Electric Currents," "Bulletin—Bureau of Standards," volume 5, 1908, page 133, Reprint 94.

THE POSSIBILITIES OF CONCEALED RECEIVING SYSTEMS*

By

A. Hoyt Taylor

(Professor of Physics, University of North Dakota)†

No one who has had any considerable experience with continuous wave receivers can fail to note the remarkably loose coupling which may be successfully employed between the antenna circuit and its secondary.

Some time ago, it occurred to the writer that even for long distance reception it ought to be possible to dispense with the antenna and ground connection by expanding the secondary circuit into a form which would cut sufficient magnetic lines in the wave to give, with a sensitive receiver, readable signals. The excuse for reporting these experiments is that while the principles involved are not new, the results obtained have been rather surprising, and indicate possibilities which may have been overlooked by some earlier experimenters.[1], [2].

The secondary circuit of the receiving set at "9XN" (Grand Forks, North Dakota) was accordingly replaced by a rectangle 10 feet (3 meters) square, of 40 turns of number 27 double cotton covered wire.[3] The rectangle was hung up inside a room in a brick and steel building which is full of wiring conduits and gas, water, and steam piping.

Audible signals from "NAA" (Arlington, Virginia), "WSL" (Sayville, Long Island), "WGG" (Tuckerton, New Jersey), and "NAJ" (Great Lakes, Illinois), were received.[4] The turns

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*Received by the Editor, July 8, 1916. This paper will be followed in early issues of the Proceedings by three papers by Commander Taylor on the use of ground wire systems, the elimination of strays, and remote control stations.—Editor.

†Now Lieutenant-Commander, United States Navy.

[1] F. Braun, "Jahrbuch der drahtlosen Telegraphie und Telephonie," January, 1914.

[2] Pickard, "Electrical Review," 50.

[3] Diameter of number 27 wire = 0.0142 inch = 0.36 mm.

[4] (The distances from Grand Forks of each of the stations mentioned are respectively 1,210 miles (1,950 km.), 1,190 miles (1,915 km.), 1,170 miles (1,885 km.), and 620 miles (995 km.) practically all over flat country, one moderately high mountain range intervening in the first three cases. Arlington is equipped with a 60-kilowatt arc set and a 100-kilowatt spark set, Sayville with a 100-kilowatt alternator-frequency changer set, and Tuckerton with a 60-kilowatt arc set.—Editor.)

of this rectangle were evidently too close together, giving a bad distributed capacity effect. A new rectangle with the wires wound side by side in a flat band gave better results, and a third one with 16 turns spaced about 2 millimeters (0.08 inch) apart gave such satisfactory reception of all waves from 2,500 meters up that it was decided to continue the experiments at the writer's home where the rectangle was hung up in a tree and arranged so that it could be rotated so as to take advantage of the directive effect. It was found unnecessary to have the lower wires more than 5 feet (1.5 meters) from the ground.

Figure 1 shows the complete receiving system. The adjustments are very simply made by simultaneous variation of the condenser *C* and the plate circuit inductance *L*. The bulbs used

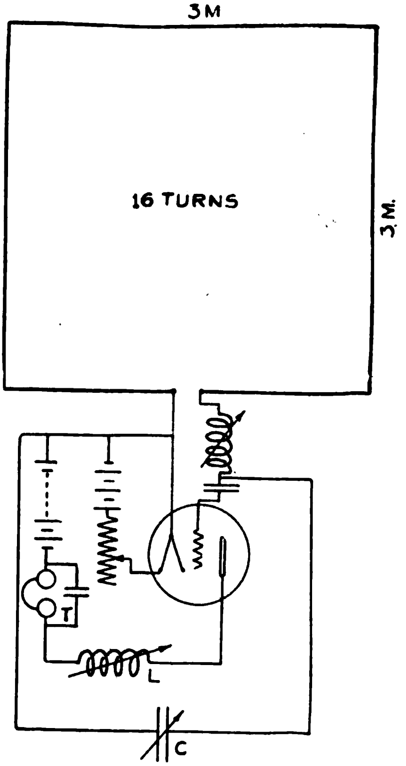

Figure 1—Wiring of Receiver

were cylindrical, with cylindrical plate, spiral grid, and two straight filaments, only one of which was used. Nineteen of these bulbs were tested, and only one found which with proper choice of high potential battery and heating current failed to give satisfactory results. The voltages used on different bulbs were found to vary between 22 and 40 volts, and the filament current from 0.78 ampere to 0.90 ampere. For any one bulb, the adjustments were exceedingly constant and certain of duplication. The writer regrets to report that attempts to measure audibilities by the shunted telephone method, using a Brandes 3,200 ohm telephone receiver, were not very successful, since the bulbs began to give the siren effect as soon as the shunt was reduced to between 100 and 300 ohms. Shunts were occasionally made with two receivers in series. For Arlington working on 6,000 meters by daylight, this shunt was usually about 200 ohms when they were working with "NBA" (Darien, Panama Canal Zone). The writer is of the opinion that such shunts cannot readily be translated into audibilities, since shunting a receiver unquestionably affects the conditions of oscillation in the bulb, and the effectiveness of the shunt depends on the pitch of the signal observed. Bulbs giving equally loud signals will shunt down to very different values.

Observations were begun in the latter part of April, 1916, and daylight signals from Arlington, Virginia; Key West, Florida; Darien, Panama Canal Zone; Sayville, Long Island; Tuckerton, New Jersey; Great Lakes, Illinois; New Orleans, Louisiana; San Diego, California; Bolinas, California, and South San Francisco, California, were always readily readable when the plane of the rectangle coincided with the direction from which the waves arrived. The distance from Darien is 3,000 miles (4,800 km.). During June and July, the strays prevented the reception of Bolinas and very often of South San Francisco. The most remarkable performance was the almost daily reception of the 2,500 meter mid-day time signals from Arlington up to date (July 6). The tone of the spark was destroyed, as it was absolutely necessary to have the bulb oscillating in order to get the signals.

The 7:30 P. M. Central time press reports sent out on the same wave length were copied nearly every day up to June 15, altho it is broad daylight here at that hour.

In connection with these results it may be pointed out that the efficiency of a receiving system in the period of summer strays depends not so much on the absolute audibility of the signals as on their relative audibility as compared with strays and other disturbances. In this respect, the rectangle has a very great advantage. If the strays are equally distributed from all points of the compass, the rectangle, owing to its directivity, cuts out a considerable part of them.

The selectivity may of course be greatly increased by using a variable condenser in series with the rectangle and adding an inductive coupler. The set then becomes a standard set with the antenna and ground replaced by rectangle and variable condenser. The signals are about 50 per cent. stronger when all adjustments are carefully made, and the strays are a little weaker. Such an arrangement was used when working at night, when an arc light less than 300 feet (100 m.) distant created bad interference below 6,000 meters. With this standard and well-known arrangement, however, the set loses the prime advantage of simplicity. The operation involves just twice as many adjustments.

Experiments were continued with two other rectangles, each of sixteen turns wound edgewise, or in the plane of the rectangle. One rectangle, having an area of 103 square feet (9.57 sq. m.) was hung against the east and west wall ot a second floor room, and the other, of 77 square feet (7.15 sq. m.) area was hung against the north and south wall. Figure 2 shows the connection used. By closing the switch S_1 and throwing the switch S_2 to the left, the east-and-west rectangle could be used; by closing S_3 opening S_1 and throwing S_2 to the right the north-and-south rectangle was in circuit; by opening S_1, throwing S_3 to the right and closing S_2 to the left both rectangles were in service, and so connected as to have directivity to the southeast. By reversing the connections of the north and south rectangle (by throwing S_3 to the left) the resultant directivity could be changed from northwest and southeast to southwest and northeast. With this arrangement signals from all points of the compass could be received with a fair degree of directivity.

This set permits most of the selective advantages of the single rotary rectangle in a convenient and easily concealed permanent installation. The rectangles may be readily concealed behind a tapestry or, if need be, inside of the wall, except in the case of steel structures where they could not be used inside for reception over distances greater than 500 miles (800 km.) depending on the type of building and its surroundings.

An example of the usefulness of the two rectangle combinations may be cited. When Darien 19 degrees southeast from Grand Forks is sending at the same time as south San Francisco 58 degrees southwest, there is no interference even on the same wave length if the switch S_3 is thrown so as to give southwest directivity in the one case and southeast in the other. Similar results were obtained in eliminating interference between Arlington and Bolinas. The southeast combination eliminates San Diego while the southwest combination greatly weakened Arlington signals altho they were still readable. If Arlington and San Diego were sending simultaneously, they could readily be separated.

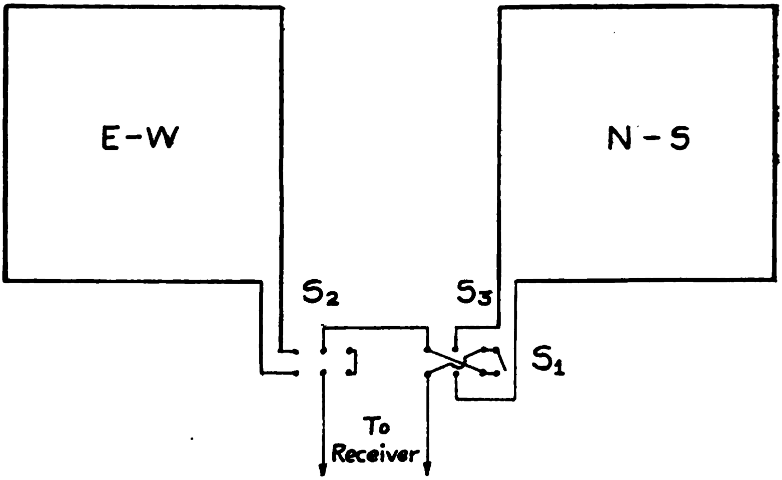

FIGURE 2—DOUBLE LOOP ARRANGEMENT

For best results, the two rectangles should be separated so as to cut no common flux, altho this was not done in the experiments here described.

With a single rectangle of 16 turns, a loading coil was used above 3,500 meters, and also with two rectangles above 5,000 meters. A larger and variable number of turns on the rectangle will permit the omission of the loading inductance and a maximum reception at all waves. The latter is of no great advantage after a certain number of turns have been reached, as the gain in signal strength is no longer proportional to the number of turns. Sayville, distant 1,170 miles (1,885 km.), could be read with 5 turns, on one rectangle, in the evening, during April.

Reception with the rectangles was compared from time to time with reception on the regular set at Grand Forks, using the 800-foot (243 meters) three-wire antenna the far end of which is 120 feet (37 meters) high, and near end 60 feet (18 meters) high. Altho the signals at Grand Forks are very much louder, they are, with few exceptions, not so readable thru the summer strays.

The advantage of the set here described may be summarized as follows; it is cheap; compact; immune from storm damage; sufficiently sensitive; thoroly reliable; simple in adjustment; and, by its directivity, partially eliminates strays and reduces interference. Moreover, it is readily concealed, if, for military or other reasons, it is desirable to do so.

SUMMARY: A closed 3-meter square loop of 16 turns of wire, hung about 1.5 meters from the ground, was used for long distance reception with an oscillating audion. Daylight overland reception from stations as distant as 3,000 miles (4,800 kilometers) was regularly accomplished.

A combination of two similar loops was also employed, and considerably increased the directional selectivity.

The inherent directional qualities of these receivers were utilized in the reduction of strays and interference.

ON MEASUREMENT OF SIGNAL STRENGTH*

By

W. H. Eccles, D.Sc.

(Professor of Applied Physics and Electrical Engineering, City and Guilds of London Technical College, Finsbury, England)

The theoretical discussion below has been written with the object of emphasizing the difficulties that arise in the interpretation of the shunted telephone method. Besides this difficulty of interpretation, it is notorious that the measurements by the shunted telephone are not susceptible of accuracy. Now that the War is over, it is to be hoped that new measurements by improved methods will be attempted and that those to whom will fall the great opportunity of carrying out the work will select methods capable of yielding trustworthy information.

The American investigators of the strength of signals from great distances have made much use of an aural method of measurement called variously the "shunted telephone" or "parallel ohm" method. The measurement consists in connecting a variable resistance across the telephones and finding the value of the resistance that will just reduce the sound of the signals to a standard intensity called the unit audibility. This value substituted in a formula gives a number called the "audibility factor." "Unit audibility" is defined for any given set of apparatus as that at which dots and dashes may just be discriminated. The formula used by L. W. Austin and by J. L. Hogan for calculating the audibility factor A from the value of the shunt is

$$A=\frac{(R+S)}{S} \tag{1}$$

where S is the resistance of the shunt in ohms and R the impedance, or perhaps the resistance, of the telephones. There is some doubt about accepted usage with regard to the symbol R, but, as will be shown later, the use of impedance or resistance is less material than will at first sight appear. Where it is helpful to distinguish the two cases we may write

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* Received by the Editor, February 25, 1919.

$$A' = \frac{(Z+S)}{S}. \qquad (2)$$

The typical circuit for the measurement of the audibility factor is given in Figure 1. It will be obvious that the chief effect of varying S is to change the proportion in which the pulsating current from the detector divides between S and the telephone. But, in addition, varying the shunt alters the resistance in series with the detector, and the shunt, it will be noticed, permanently affords for radio oscillations a path additional to the condenser C_3. However, to remove this defect, it has been proposed to insert a choking coil in the lead between C_3 and the telephone at the point marked χ. Sometimes instead of including a condenser C_3 in the detector circuit, the capacity of the telephone leads and windings is entrusted with the task of passing the radio oscillations, the telephone then replacing C_3.

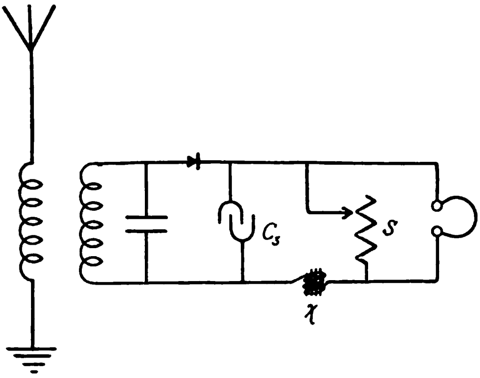

FIGURE 1

Let us imagine that continuous waves are being received and heterodyned and that an audible note is being produced in the telephone. The question arises: How does the audio frequency current distribute itself between the telephone and the shunt? We shall investigate this problem by supposing that an audio sine voltage of amplitude V exists at the terminals of the parallel circuit, superposed upon a steady component which may be disregarded in the analysis.

The circuit and its vector diagram are drawn in Figures 2 and 3, the circuit being regarded for the purpose as an auto-transformer with resistance coupling, the common part being S with a current $I+J$ traversing it, the telephone having a current J thru it, and the sine current of amplitude I being the current from the detector smoothed by condenser C_3 and choking coil χ.

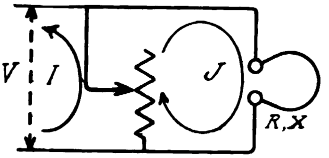

FIGURE 2

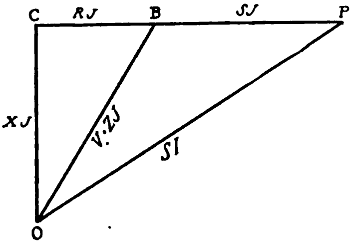

FIGURE 3

First the triangle OPB for the I circuit is drawn; it may be of any convenient shape for trial so long as the vector SJ is shown less than SI. In the triangle the potential drop SI is represented by OP and is shown as made up by the applied voltage $OB = V$ together with the reaction $BP = SJ$ from the secondary circuit. This latter circuit is represented by the right-angled triangle OPC, wherein the potential drops are $PB = SJ$, $BC = RJ$ and $CO = XJ$, where X is the audio reactance of the telephone. These are shown made up by the action $PO = SI$ from the I circuit. From this triangle it is clear that OB represents ZJ as well as V, as is otherwise evident.

The reactance of a telephone has been studied in great detail by many observers, and especially in recent years by A. E. Kennelly, G. W. Pierce, and H. A. Affel. From these researches it is known that the resistance of a telephone increases with frequency, while the reactance undergoes fluctuations near frequencies related to the natural frequencies of the diafram. The value of the reactance is never zero or negative, and as the audibility factor in a definite set of experiments is concerned with only one frequency, we may treat both R and X as positive constants.

Now in the practice of the method the telephone current J is always brought to the same value, namely, that giving "unit audibility." Therefore OC, CB are constant, and as S is varied, BP varies in simple proportion. The ratio of OP to PB is the ratio $\frac{I}{J}$. It is the ratio of the current from the detector thru the parallel circuit to the current giving unit audibility. It will be called the strength ratio a, so that $a=\frac{I}{J}$. The ratio $\frac{\text{CP}}{\text{PB}}=\frac{(R+S)}{S}=A$, the audibility factor according to equation (1).

When the current I from the detector is just equal to J the strength ratio is unity and S must be infinite. Then P is at infinity and OP is parallel to BP. Also BP and CP are both infinite and the limit of their ratio is unity, that is the audibility factor is unity. At the other extreme, when the current from the detector is very great, S must be a very small resistance and therefore P is very near to B. The ratios $\frac{\text{OP}}{\text{PB}}$ and $\frac{\text{CP}}{\text{PB}}$ are then both infinite. The strength ratio is not equal to the audibility factor except near the limit $A=1$.

The diagram enables the connection between a and A to be expressed easily. It is only necessary to write down the well-known trigonometrical equations for the cosine of the angle OPC in terms first of OP and OC and then in terms of OP, PB, and OB in order to obtain the relation

$$a^2=\left\{\frac{(A-1)Z}{R}\right\}^2+2A-1 \tag{3}$$

The equation is exhibited as a hyperbola in Figure 4, which by its departure from the dotted line indicates that the value of A, the audibility factor, is in general considerably different from that of a, the strength ratio.

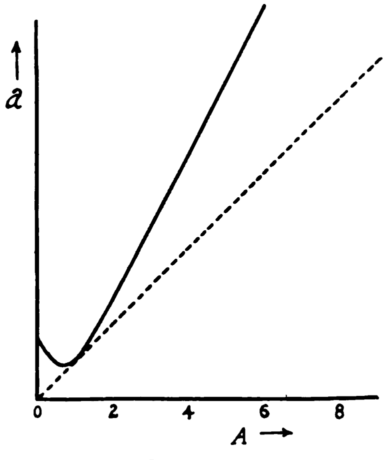

FIGURE 4

Austin, Hogan, and others have therefore used instead of equation (1) as the definition of audibility factor the equation

$$A' = \frac{(Z+S)}{S} \tag{2}$$

In order to examine the connection between them we rewrite the equations in the form

$$S(A-1)=R, \quad S(A'-1)=Z \tag{4}$$

and then by division obtain

$$A'-1=\frac{(A-1)Z}{R} \tag{5}$$

Then by substitution in equation (3) we get

$$a^2=(A'-1)^2+\frac{2(A'-1)R}{Z}+1 \tag{6}$$

This is a rectangular hyperbola and is traced in Figure 5. Comparison with the dotted line proves that the revised definition of the audibility factor still differs considerably from the strength ratio. However, since either audibility factor is readily computed, it is best, when the strength ratio is required, to compute A or A' first, and then deduce a by aid of the appropriate formula.

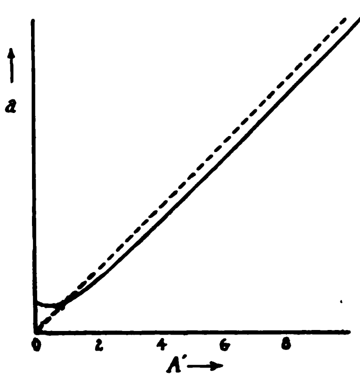

FIGURE 5

This method of measuring audibility can be applied legitimately to the determination of the variation of the strength of received signals from a moving sending station such as a ship, but it is not suitable for the comparison of different fixed stations having different note frequencies. In what follows, it will be supposed that the application is made to problems of the former kind. It is then necessary to examine what radio quantity the audibility factor and the strength ratio actually measure.

First it must be noticed that since the telephone current J is always adjusted by ear to the same value, the terminal voltage V is always the same. Therefore the total work done in the telephone and shunt, which is $\frac{1}{2} VI \cos \phi$, where ϕ is the phase angle of Figure 3, depends on the first power of I. The power absorbed by the antenna is $\frac{1}{2} (R_1 + R_1') I_1^2$, R_1 being the antenna resistance, R_1' being the image in the antenna circuit of the detector resistance, and I_1 being the antenna current amplitude. The proportion of this power passed to the detector is $\frac{1}{2} R_1' I_1^2$. Let η be the efficiency of conversion of radio energy to audio energy by the detector. Then we have by equating the expressions obtained above

$$V I \cos \phi = \eta R_1' I_1^2 \tag{7}$$

The image resistance R_1' depends on the couplings of the circuits between the antenna and the detector, and therefore these ought always to be rigidly constant in the application of the method. Then R_1' and V are the constants in this formula, and introducing a, the strength ratio, we may put $a J$ for I. We thus obtain

$$I_1^2 = \frac{V J}{R_1'} \frac{a \cos \phi}{\eta} \tag{8}$$

If η were constant the energy collected by the antenna would be represented perfectly by $a \cos \phi$ and the antenna current would be proportional to the square root of $a \cos \phi$; but η is not constant, tho for loud signals the efficiency is practically constant, and then we conclude that the square of the antenna current is measured by the quantity $a \cos \phi$. This may be evaluated from Figure 3 by expressing the value of the cosine of ϕ, which is the angle BOP, in terms of the lengths of the vectors. We obtain the equation

$$a \cos \phi = \frac{a^2 (S^2 + Z^2) - S^2}{2 a Z S} \tag{9}$$

which is easily evaluated numerically from experimental data. For small values of S, that is for loud signals, we may say that approximately

$$a \cos \phi = \frac{a Z}{2 S} \tag{10}$$

For large values of S, that is for faint signals, we may write approximately

$$a \cos \phi = \frac{(a^2-1)\,S}{2\,a\,Z}.$$

The quantity $a \cos \phi$ may be called the audio power ratio. If the detector were of the same efficiency for all magnitudes of radio current, this quantity would also be the radio power ratio. But until the efficiency is thoroly investigated at low powers, the extant measurements on the propagation of signals to great distances cannot be confidently interpreted.

Some progress towards this interpretation has been made by B. van der Pol. Damped trains of oscillations were induced in a typical receiving circuit by means of a variable magnetic coupling with a circuit in which constant oscillations were being produced. The calibration of the mutual inductance gave the relative magnitudes of the oscillatory current passed to the detector at various settings. The receiving circuit contained a shunted telephone and measurements of the audibility factors were made at all settings. The results are seen in Figure 6 from van der Pol's paper in the "Philosophical Magazine" of September, 1917. From abscissa 0.6 (where $A=4$) to 2.2 (where $A=160$), the curve is straight with gradient 0.5. This indicates that A is proportional to the square of the radio current delivered to the detector, or that the audibility factor is a fair measure of the signal energy for medium strengths. With weaker signals, however, while A ranges from 4 down to 1.2, the logarithmic curve bends downwards so as to pass thru the origin corresponding to unit audibility. During this stage the audibility factor is proportional to powers of I gradually changing from 2 to 0.7.

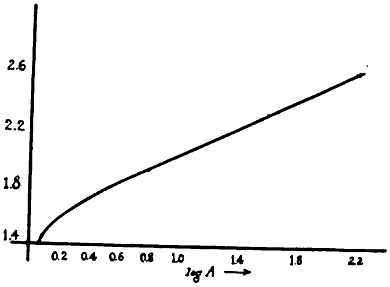

FIGURE 6

It has been pointed out by G. W. O. Howe that the use of A' instead of A, that is to say, the use of the telephone impedance instead of its resistance in the calculations, would bring the straight part of the curve slightly lower on the diagram. The straight parts are, however, not of great interest. The important part of the curve, for the purpose of interpreting the results of measurements on long distance signalling, is the curved part. Since A and A' are connected by the linear relation (5), the substitution of one for the other leaves the general appearance of the curve unchanged tho tending to straighten it a little. The effect of using $a \cos\phi$ is, however, significant. The relation between these modes of measuring is best seen by redrawing Figure 3 so as to exhibit $\mathrm{OD} = \mathrm{OP} \cos\phi$, and, after dividing every line by SJ, marking them with their values. Then keeping the unit line constant and imagining S to decrease a little, we get the consequent increases of A, a, and OD as marked in Figure 7. Clearly $\partial\,(\mathrm{O\,D}) > \partial a > \partial A$. The longer the unit, that is the weaker the signal, the more does ∂ (OD) exceed ∂a, but the less does ∂a exceed ∂A. This is indicated in Figure 8. The curves a and $a \cos\phi$ tend to approach and run together when signals get very strong.

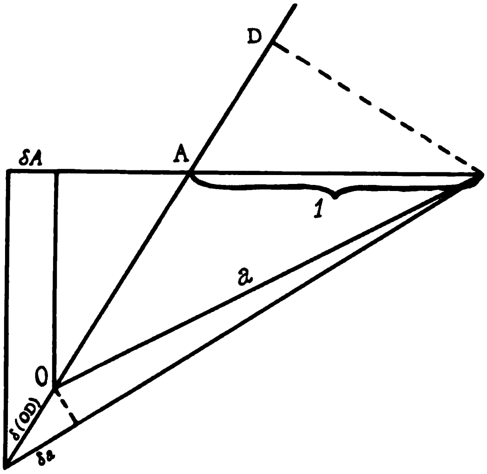

FIGURE 7

The main result is that van der Pol's curve of Figure 6 becomes greatly straightened when the power ratio is taken as the measure of signal strength, which in turn seems to show that the detector is not losing its efficiency as fast as at first sight appears with decreasing signal strength.

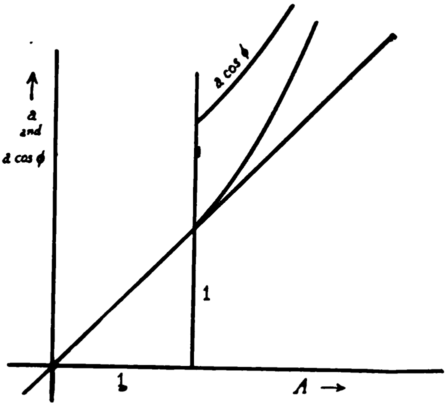

FIGURE 8

The practical importance of the measurement of signal strength arises out of the fact that for purposes of design the law giving strength of signal with distance of propagation should be accurately known. At the present time we have to use the Austin-Cohen formula, which is apparently based on observations of the quantity A'. The records could be reduced to terms of the power ratio $a \cos \phi$ by means of the formulas and diagrams above if Austin and Hogan had made it clear which of their various definitions had been used on the various occasions and had fully chronicled the relevant details of their apparatus.

The difficulties attending the use of the audibility method of measurement of signal strength, including the prime difficulty of the uncertainty of the behavior of the crystal detector, may all be overcome by calibrating the detector and circuits repeatedly, or, what is perhaps better still, by measuring the strength of the received signals by balancing their telephone sound against locally produced signals of the same pitch and of adjustable measurable intensity.

A number of circuits for doing this have been proposed for damped waves, and some that have been used by the author and found trustworthy at sea are shown in Figures 9, 10, and 11. They were used with damped waves, but can be used with chopped continuous waves without change. The method consists in exciting the antenna by means of a tuned circuit giving very feeble oscillations of adjustable strength, which is coupled to the antenna to an extent decided upon beforehand as suitable. These locally produced signals are of course heard in the telephone at the same time as the signals from a distance and can be adjusted to the same audibility. The local oscillations are pro-

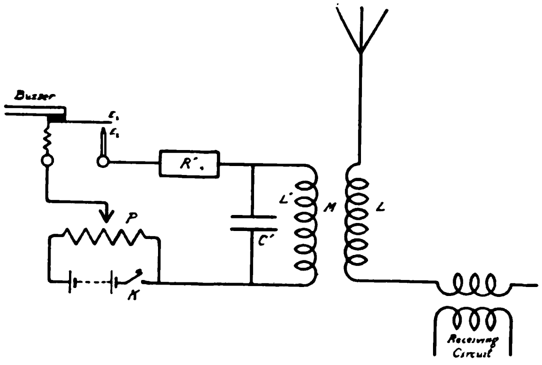

FIGURE 9

duced in the circuit $L'C'$ by means of the contact $E_1 E_2$, which is rapidly made and broken by the buzzer B and thru which, when contact is made adjustable, electromotive force is applied from the potential divider P. The beating contact E_1 E_2 must be carefully insulated from the buzzer, and the magnet of the buzzer is partly short-circuited by a resistance to prevent sparking at the driving contact breaker. The coil L' is coupled to the an-

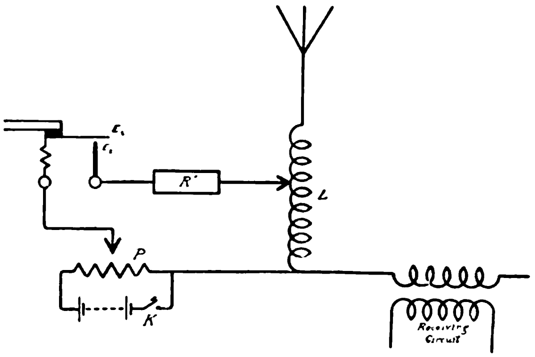

FIGURE 10

tenna loading coil L, and M is set before the experiments at a convenient value. The key K in the circuit of the potential divider enables the operator to send dots and dashes. The buzzer should be adjustable in pitch and made to give the same note as the signals being made. The circuit $L'C'$ must be tuned

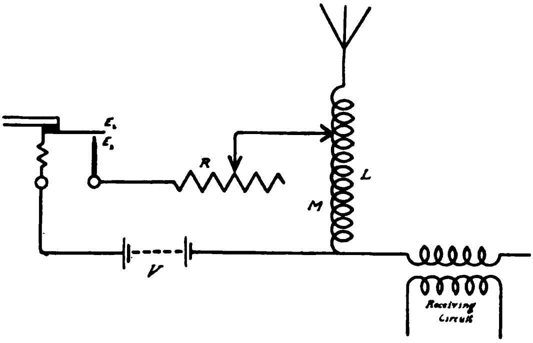

FIGURE 11

to the antenna and to the waves. Ideally the damping of this circuit should be made the same as that of the signals received. Instead of the tuned circuit $L'C'$ a plain inductance coil may be used; that is to say, the condenser C' could be removed; or, even simpler, L' may be made to coincide with a portion of L, as indicated in Figure 10. In this case also it is well to insert a large resistance R' in the circuit of the potential divider. The antenna is in this mode of operation said to be excited by "impulsing." A simpler circuit still is shown in Figure 11, where R is a high resistance consisting of an electrolyte in a glass tube with one moveable electrode. With this last apparatus the signal strength is matched by varying the high resistance. All these methods gave, during such trials as the author could carry out on commercial stations working their ordinary programmes, practically the same measures, and appeared easier to operate with confidence than the shunted telephone method.

The above three methods are sketched in order to show how very simple the apparatus may be for improving upon the unassisted audibility method. So far as the author's experience goes with, for instance, the last of the three, the possible accuracy is much greater than with the audibility method. But it should be mentioned that in truth no really satisfactory comparison between the diffraction theory of the propagation of waves round the globe and the experimental facts can ever be obtained with trains of damped waves, if only for the reason that the theory has regard only to sustained waves. Thus it is to be hoped that future experimenters will use sustained waves, which, besides being nearer to theoretical conditions, will enable all sorts of difficulties arising from the unknown behavior of detectors and from the presence of audio harmonics to be eluded. It is possible also, by the aid of sustained waves, to escape all the doubts which arise from the use of that crude measuring instrument, the telephone receiver. The author has recently been conducting laboratory measurements in which oscillations were received, heterodyned, rectified, the low frequency results amplified, and then measured by a tuned vibration galvanometer, and has found that conditions can be kept very steady even with high amplifications. The necessary modifications of the damped oscillation circuits of Figure 9 are obvious; the buzzer must be replaced by an ionic relay so as to sustain oscillations in the circuit $L'C'$ and the intensity of the oscillations induced in the antenna for heterodyning must be varied either by varying M or varying the intensity of the oscillations in $L'C'$. The receiving circuit would of course be one adapted for beat reception.

SUMMARY: The "shunted telephone" method of measuring audibility of received signals is discussed, and it is shown that the audibility factor as usually calculated, may vary widely from the true strength ratio. This is true whether shunted resistance or shunted impedance is taken as the basis of calculation.

The author then determines the radio quantity corresponding to any determined audibility factor or strength ratio. This is of importance in connection with quantitative measurements on long distance transmission.

An alternative comparison method of measuring incoming signal strength is described, wherein the antenna may be excited from a local buzzer of adjustable pitch and having an independent contact for the antenna "impulsing circuit." This method is regarded as more accurate than the usual one.

Sustained waves should be used for transmission experiments, and these may be received, heterodyned, rectified, amplified, and measured quantitatively by a vibration galvanometer.

DISCUSSION

Louis W. Austin (by letter): Doctor Eccles' paper is of great interest to me on account of the long use of the shunted telephone method in my laboratory. His Figure 5 shows that the audibility, when the impedance of the telephones is used in the calculations, is practically proportional to the strength ratio, except for the curved portion of the hyperbola lying to the left of unit audibility, where, of course, it has no physical meaning, as there Z would be greater than infinity.

On account of the difficulty in determining the effect of the shunt with high frequency oscillations, I always prefer, in my work, to calibrate the apparatus by a comparison of the telephone shunt readings with the readings of a galvanometer, which can be connected in place of the telephones. In the case of silicon, perikon, and many other crystal detectors, the galvanometer readings are strictly proportional to the squares of the radio frequency currents. The method used in the calibration for oscillating audion reception have already been described to the Institute (PROCEEDINGS OF THE INSTITUTE OF RADIO ENGINEERS, volume 5, page 239, 1917).

In one place in his paper, Doctor Eccles refers to uncertainty in regard to whether resistance or impedance was used in the calculations of the Brant Rock experiments. ("Bulletin of the Bureau of Standards," volume 7, page 315, 1911.) Professor Love has assumed ("Transactions Royal Society," London, Series A, volume, 215, page 105, 1915) that the resistance of the telephone, 600 ohms, not the impedance, 2,000 ohms, was used, and has used his conclusions to support the MacDonald transmission theory. I have never been able to understand how such an uncertainty could have arisen, as the question of resistance or impedance does not enter into the plan of calibration used, which is shown on page 319 of the paper and is explained in the text. There Table 1 gives the currents measured in the antenna with the silicon detector "D" and the corresponding shunts required to reduce the telephone currents to audibility. As has been said, the deflections of a galvanometer with a silicon or perikon detector are proportional to the squares of the radio frequency currents. Table 1 was made from the smooth curve giving the relation of telephone shunt to observed antenna current. The values given in the table show that using the impedance of the telephone, 2,000 ohms (note 8, page 318 of the paper) the antenna current is approximately proportional to the square root of the audibility calculated from the equation $A = \frac{Z+S}{S}$.

I have made many experiments with Doctor Eccles' comparison methods, examples of which are shown in his Figures 9, 10, and 11, but cannot say that I have found them better than the shunted telephone. For several months last year, experiments were carried on in matching the beat tone in telephones used in oscillating audion reception, by means of a known variable current of the same frequency in a circuit into which the telephones could be connected. This was practically the same arrangement recently described before the Institute by Doctor Van der Bijl in his paper on detecting efficiency of the thermionic detector. This is, undoubtedly, the most accurate method of measuring telephone currents in the laboratory, the results agreeing within two or three per cent. But unfortunately when atmospheric disturbances are present, as is usually the case in long wave reception, their presence in one circuit and absence in the other, renders the accuracy of measurement no greater than with the shunted telephone.

THE CABOT CONVERTER*

By

Claude F. Cairns

During the years 1912 to 1915, the writer had the pleasure of working with Mr. Sewall Cabot of Brookline, Massachusetts on the development of a polyphase commutator, or machine for converting polyphase alternating currents of commercial voltages to non-fluctuating voltages as high as 100,000. During that time machines were built to deliver voltages within these limits, some of which are still in commercial operation.

The field for the Cabot converter is that covered by all machines now employed for the production of direct current of any desired voltage from an alternating current or direct current source of another voltage, and furthermore as direct current generating machinery is unsatisfactory for voltages over 2,000, the Cabot converter fulfills a long felt want in efficiently supplying voltages greater than this.

The Cabot converter consists of a constant potential polyphase transformer with a primary winding exciting a relatively small number of magnetic circuits, and a secondary winding of a relatively large number of phases, from which wires are led to commutating parts driven by a motor in synchronism with the alternating current supply. The transformer is the essential part of the apparatus, as it is here that the secret of the successful operation lies. The primary is usually wound as a three-phase delta-connected winding directly connected to the alternating current source, and the secondary is usually a nine-phase ring-connected winding. Altho the primary may be wound for any number of phases greater than one and the secondary any number greater than nine, as will later be seen, three-phase to nine-phase winding readily lends itself to good mechanical and electrical practice. The method of obtaining a nine-phase ring winding can best be shown diagrammatically. Figure 1 indicates the method.

The six-sided symmetrical polygon shown in Figure 1 has

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* Received by the Editor, November 26, 1917.

adjacent sides the ratio of which are 1.79 to 1.49, and which are 120° apart. A circle with its center at the center of the polygon may be drawn which will cut the sides in nine points equally spaced or 40° apart. It can readily be seen that if the number of

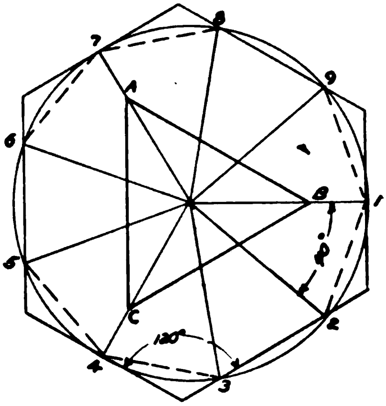

FIGURE 1—Diagram of 3-Phase to 9-Phase Transformer

turns used in the secondary winding are such that their ratio is the same as that of the symmetrical polygon, if they are connected in the proper direction, and if leads are brought out at the proper points, a ring winding will be formed the same as with a Gramme ring having nine phases. Inside of the diagram is shown the three-phase delta-connected primary winding marked *A*, *B*, *C*. Three of the nine phases are made up of windings which are in phase with the primary windings and the other six phases are made up of two windings connected together, one of which is in phase with one of the primary phases and the other in phase, or rather 180° out of phase, with another primary phase. If the turns of one of the nine phases totally in phase with the primary is taken as 1, then the turns of the windings which make up the other phases will be 0.395 and 0.743. The secondary of a three-phase to nine-phase transformer has therefore inherently about fifteen per cent. more copper than a straight three-phase to three-phase transformer, for in order to get a given voltage for six of the phases it is necessary to use two windings of unequal voltages, 120° out of phase.

The leads from the nine points equally spaced, which means equal voltage between them, are connected to the commutating parts just as are the leads of an ordinary armature winding. When using a four-pole motor for driving, the commutating parts consist of nine brushes on nine slip rings, an eighteen-segment commutator, and four brushes, for low voltage machines, or nine brushes equally spaced around a four-segment commutator and two slip rings for high voltage machines. In the case of low voltage machines, the voltage between segments is that of each phase or $\frac{1}{4.05}$ of the total d. c. voltage; and in the case of high voltage machines is the vector sum of the voltages of two phases, as every other phase lead is connected to adjacent brushes, and the opposite segments are connected to the same slip ring.

In all machinery used for producing non-fluctuating direct current, the practice is to have a stationary electrical field and to rotate the iron and wire. The Cabot converter, however, has a rotating electrical field and holds the iron and wire stationary. The problems of commutation are very similar except that the Cabot converter has no armature reaction and for this reason readily lends itself to mathematical treatment and allows the use of a higher voltage between segments on the commutator. As in d. c. armature construction, the load current of the Cabot converter passes into and out of the secondary of the transformer at opposite points, and divides equally thru the two paths of the system. For successful commutation, the current flowing in any one of the phases must come to zero and reach an equal magnitude in the opposite direction during the time such phase is kept short circuited by the brushes on the commutator. As is well known, the inductance of the phase keeps the current flowing in the same direction, this necessitating an e. m. f. being built up in the opposite direction in order to bring the current to zero, and to establish it in the opposite direction. The force tending to keep the current flowing in the coil is known as the reactance voltage and is specifically equal to the inductance times the rate of change of current: $L\frac{di}{dt}$. As the current falls along practically a straight line, this can be written $L\frac{I}{t}$, where I is one-half the full load current and t is the time of short circuit. In all previous work on commutation of stationary polyphase windings, it was without doubt felt that the inductance of the phase commutated is the total inductance of the winding. On the contrary, however, it is the leakage inductance of the phase which makes itself felt at the commutator.

The transformer is therefore wound so that the leakage inductance of the phases shall be a minimum consistent with good practice. This is accomplished by having each of the phases and each of the windings used in making up a phase of the secondary linked thruout their winding length with a complete primary winding. By so winding the transformer, it is possible to employ the well-known formula for leakage inductance:

$$L = \frac{4\pi N^2 p}{l}\left(\frac{x}{3}+\frac{y}{3}+g\right)10^{-9} \text{ henries.}$$

This applies to a two layer winding on a core type transformer, where

N = number of turns in phase or winding,
p = mean turn in cms.,
l = length of winding channel in cms.,
x = radial depth of primary in cms.,
y = radial depth of phase or winding in cms.,
g = width of the gap between primary and phase or winding in cms.

Of course, by further sandwiching the coils, the leakage inductance can be further reduced.

The leakage inductance of a transformer so wound is very much less per turn for a given output than in armature construction which necessitates an air gap; and, as mentioned before, there is no such phenomena as armature reaction with which to contend. This readily explains why successful commutation can easily be obtained with only nine phases with the Cabot converter against sixty or more with armature construction, without employing any electrical or mechanical means of producing a commutating e. m. f.—other than the resistance of the circuit—or shifting the angle of commutation. For low voltage machines, up to 220 volts, the leakage inductance of the transformer is so small that very low resistance brushes may be employed, thus effecting a great saving in the size of the commutator and the watts lost due to friction and $I^2 R$ losses.

When, however, the d. c. voltage to be delivered attains higher values, the leakage inductance of the transformer increases about proportionately, and means must be provided for shifting the angle of commutation in order to utilize the e. m. f. induced in the winding, or for providing some form of commutating e. m. f. successfully to reverse the current. If the brushes are given a permanent forward shift so as to have sparkless commutation at full load, sparking will occur at no load and vice versa. The amount of necessary shift can, however, be readily calculated by a simple mathematical process.

Consider the circuit shown in Figure 2.

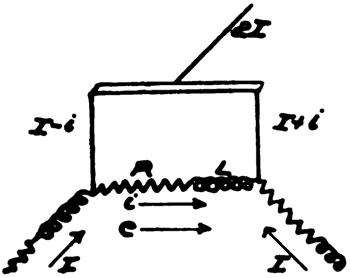

Figure 2

The resistance of the brush has been neglected, as in high voltage machines it is negligible compared with the winding.

L = the leakage inductance of the phase under commutation,
R = the resistance of that phase,
I = the current flowing in the ring or one half the load current,
i = the current in the phase at any instant,
e = the e. m. f. at any instant induced in the phase.

Then
$$L\frac{di}{dt}+Ri+e=0,$$
$$L\frac{di}{dt}+Ri+E\sin(\omega t+\phi)=0,$$
which, when solved, gives
$$i=\left[I+\frac{E}{\sqrt{R^2+\omega^2L^2}}\sin(\phi-\theta)\right]\varepsilon^{-\frac{Rx}{360fL}}-\frac{E}{\sqrt{R^2+\omega^2L^2}}\sin(x+\phi-\theta),$$
where
$$\theta=\tan^{-1}\frac{\omega L}{R},$$
ϕ = the angle at which the short circuit comes on,
x = electrical degrees of duration of the short circuit,
f = frequency of alternating current supply,
E = maximum e. m. f. induced in the phase,
$\omega=2\pi f$.

This equation gives the value of the current in the coil being commutated at any instant after the short circuit comes on, provided we know the other quantities. All the quantities are constants of the transformer except ϕ and x. The quantity x is the number of degrees the short circuit has been on at the instant at which the value of i is to be determined. Therefore only ϕ is left as an unknown which it is necessary to determine. In order to have commutation complete at the instant that the short circuit is removed, i must be equal to $-I$. With this value of i, putting x equal to the number of degrees of short circuit, ϕ can be determined.

Then the equation will be

$$-I=\left[I+\frac{E}{\sqrt{R^2+\omega^2L^2}}sin(\phi-\theta)\right]\varepsilon^{-\frac{Rx}{360fL}} - \frac{E}{\sqrt{R^2+\omega^2L^2}}sin(x+\phi-\theta).$$

I is one half the load current, and therefore for different values of I it will be necessary to have the short circuit come on at different times in order that the current may be completely commutated. Now ϕ is the angle at which the short circuit comes on, and the difference between the value of ϕ when $I=0$ and $I=\frac{1}{2}$ of the full load current is the necessary angular shift, to have sparkless commutation from no load to full load.

It is interesting to note that if intermediate values of the necessary shift between full load and no load be computed, they will be directly proportional to the load current within a very considerable degree of precision.

From the above it is evident that the requisite shift may be obtained by any leading quadrature e. m. f. which is proportional to the d. c. load or the brushes themselves may be mechanically moved forward or the commutator retarded a predetermined amount proportional to the load.

To produce a quadrature e. m. f., there could be inserted in the leads to the transformer three series transformers across the secondaries of which are connected condensers. As the load comes on, the voltage across the condensers increases, and hence the voltage impressed on the transformer is shifted forward in regard to time in proportion to the load, since the capacity reacts thru to the line as the square of the ratio of transformation. The same results may be obtained by using synchronous machinery. Either on the same shaft with the commutating parts, or driven by a separate motor, is a rotor having a field winding thru which is passed the d. c. load current, or a part of it, by means of a shunt. Surrounding the rotor is a stator on which is a three-phase winding left open in order that the three-phase a. c. leads to the transformer may be connected in series. In this way an e. m. f. is induced in the main leads. The magnitude of this e. m. f. is determined by the field strength, and the time phase is determined by the position of the field relatively to the stator. In this way the angle of the impressed e. m. f. may be shifted proportionately with the load and in the right direction to produce a commutating e. m. f. In addition to this feature, compounding is obtained, for as the load increases the magnitude of the induced e. m. f. increases, which increases the impressed e. m. f. and also changes its angle.

To shift the brushes forward mechanically, or to do what amounts to the same thing, that is, to retard the commutator, the best method is shown in Figure 3. A copper disc, mounted on the shaft with the commutator, is made to rotate in a magnetic field produced by a winding in series with the d. c. load current. As the load current increases the eddy currents induced in the disc retard the rotor of the driving motor and change its running angle by an amount proportional to the d. c. load.

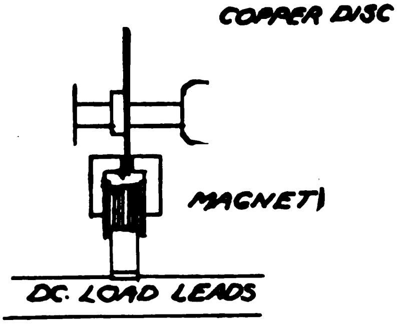

FIGURE 3—Mechanism for Changing Angle of Commutation

The same results can be obtained by introducing resistance into the circuit in which the commutating current is at any instant flowing. By this method the current flowing in the short-circuited coil is brought to zero by dissipating itself in heat and is established in the opposite direction by the e. m. f. induced in the same coil by the primary. When a four pole machine is used for driving, the commutating parts consist of nine brushes, a four-segment commutator, and two slip rings. This construction readily lends itself to a form whereby the same resistance may be employed for all phases, thereby eliminating the necessity of putting resistance in each phase or brush. The two opposite segments on the commutator are connected to the same slip ring and since the phase being commutated at any instant is short-circuited by these two segments and slip ring, resistance may be inserted in the wires connecting these three in series. The amount of resistance necessary can readily be calculated by the same method as that employed in calculating the necessary angular shift for complete commutation. To do this, it is necessary to find what value of R in the previous formula will give practically the same value for ϕ when $I=0$ and when $I=$one-half the full load current. In determining the value of R to insert in the wires, the cut-and-try method very often serves very well, as the angle of commutation is not very critical and a slight excess is detrimental only to efficiency.

When the d. c. voltage reaches values as high as 80,000 to 100,000, the leakage inductance of the transformer attains such values that the necessary shift in the angle of commutation becomes very appreciable. Altho a complete investigation has never been made it was found that with such voltages the use of what has been termed serial subdivisions gave satisfactory results for low power. The serial subdivisions consist of brushes and segments so timed by their position on the shaft that when the circuit of the coil being commutated is broken the break occurs at several points simultaneously. This procedure brutally breaks the current which at that time may still be flowing in the circuit, and has no practical value for larger powers than a few kilowatts.

Altho machines of large power output have never been built, the design of such machines show that the problems in commutation are the same as for small power, and that the reactance voltage is independent of power for a given voltage, since the increase in current is offset by the decrease in the leakage inductance of the windings. In low-voltage machines of high power the inductance of the leads from the transformer to the commutator, will, unless properly grouped, be in excess of the leakage inductance of the winding.

The production of non-fluctuating direct current from alternating current by the rotation of iron and wire is accompanied by losses in electrical energy greatly in excess of the copper losses in the armature, and the active material used for magnetization purposes is nearly three times the amount used in the armature for conversion purposes, because of the necessary air gap. The Cabot converter, however, accomplishes the desired result with a relatively large efficiency as the losses are only those of the transformer, the brush I^2R, the input into the motor used to overcome the brush friction, and the losses (in high voltage machines) due to the method used for shifting the angle of commutation or for providing a commutating e. m. f.

The losses in the transformer are of course small. In low-voltage machines, the reactance voltage is so low that the lowest resistance carbon brush may be used, resulting in small brush I_2R and small friction watts owing to the higher current density permissible with a low resistance brush. In high voltage machines, the brush resistance becomes negligible, and the power used for aids to commutation is relatively small especially for high power output.

The space occupied by a Cabot converter is much less than that required for a rotary converter or motor generator capable of handling the same amount of power owing to the small amount of active material necessary for excitation purposes in the transformer and the small commutating parts necessary to handle the load.

The Cabot converter has already been used for various purposes where non-fluctuating direct current is needed both for high- and low-voltage work.

For low-voltage work, a machine was employed for charging storage batteries, converting 220-volt three-phase 60-cycle alternating current to 90- to 150-volt direct current, with a current value of 100 amperes. A machine has been employed for exciting a direct current arc lamp and one has been tested for its ability to run direct current motors with marked success.

For high-voltage work several machines have been in use for the excitation of X-ray tubes giving voltages up to 100,000 at 5 to 7 k. w. Some of these machines are still running today after five years of service. Machines have also been built for radio telegraph and telephone work at voltages from 900 to 2,000, to deliver in the neighborhood of 2 k. w. These machines have been adapted to spark gaps with tone circuits, but could easily be used wherever high voltages are employed in radio work.

The advantages of the Cabot converter over the other forms of apparatus for converting alternating currents to non-fluctuating direct current and machines for producing high potential non-fluctuating direct current are very marked. For storage battery charging and general low-voltage work, the advantages are the ease with which the voltage may be varied by changing the primary turns, the greater efficiency, the lower first cost, and the smaller floor area.

In the high-voltage field, the advantages are even more marked than in the low voltage field. In X-ray work, the ability to read the true voltage across the tube together with current and the time of exposure gives the operator a direct measurement of the watts per second, and hence the dosage given to a patient. Furthermore in radiographic work results can be duplicated as the penetration or quality of X-rays is proportional to the voltage and the quantity is proportional to the current and time.

In radio work, machines with rotating iron and wire become unreliable above 2,000 volts because of commutation and the difficulties of insulation. With the Cabot converter the insulation problems are no greater than with any high potential transformer, and sparkless commutation can be obtained for even higher voltages without the use of mechanical or electrical means of shifting the angle of commutation but simply by the addition of resistance to the commutating circuit. For use on ships the Cabot converter would readily adapt itself because of the fact that any break-down could easily be attended to by the operator assuming him supplied with a small box of spare parts.

Below are given the specifications for the transformer of a 2,000-volt, 1 k. w., radio transmitter.

A. C. supply voltage: 136 volts, 3-phase, 120-cycles,
D. C. volts: 2,000,
D. C. amperes: 0.5,
Iron watts: 50,
Copper watts: 60,
Iron weight: 16 pounds (7.3 kg.),
Copper weight: 4.2 pounds (1.9 kg.),
Percentage efficiency: 90,
Temperature rise: 50°,
Reactance voltage: 15.7 volts for 12° (electrical), short circuit,
Necessary shift in the angle of commutation from no load to full load: 0.5 electrical degrees.

The transformer is wound as shown in Figure 4.

Under each secondary winding is wound a complete primary winding, all of which, on the same leg, are connected in parallel. By so winding the transformer, each secondary winding is completely linked with a primary winding and therefore the leakage inductance formula may be applied to each section.

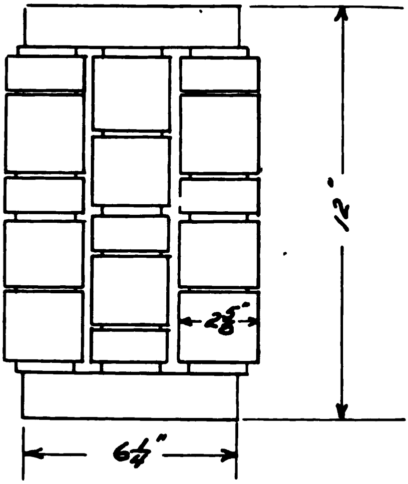

FIGURE 4—1 K. W. Transformer for 2,000 Volt D. C. Cabot Converter

Altho the angular shift is only 0.5 degrees, by the addition of a few ohms of resistance in the commutating circuit the necessary shift can be reduced to zero which means that sparkless commutation will occur from no load to full load. This transformer was actually built and used.

There has been built and put into operation a 5 k. w. machine to convert 220-volt, 3-phase, a. c. to 110-volt d. c. from which a 10 k. w. load was taken for 24 hours and a 15 k. w. load for several minutes with sparkless commutation! The reactance voltage was only 0.356 volts against a reactance voltage of 2 to 3 volts for a standard rotary converter of 5 k. w. output. The over-all efficiency of this apparatus was 90 per cent. at full load with a very flat efficiency curve.

SUMMARY: **The Cabot converter is a combination of a few-phase primary and many-phase secondary transformer and a secondary circuit commutator driven by a synchronous motor. Direct current of high voltage can be readily produced, e. g. for radio transmitters. The converter has a lower reactance voltage than the standard rotary converter and has other constructional and electrical advantages.**

ON THE POULSEN ARC AND ITS THEORY*

(SUPPLEMENTARY NOTE)†

BY
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A. MAGNITUDE OF PEAK ARC VOLTAGE REQUIRED FOR MAINTAINED OSCILLATIONS OF THE FIRST KIND

An approximate solution of this question is quite simply obtained, and may, therefore, be of some interest. Figure 1 shows the arc current, i_1, and arc voltage, e_1, in the case of sustained oscillations of the first kind. The arc voltage is supposed to be

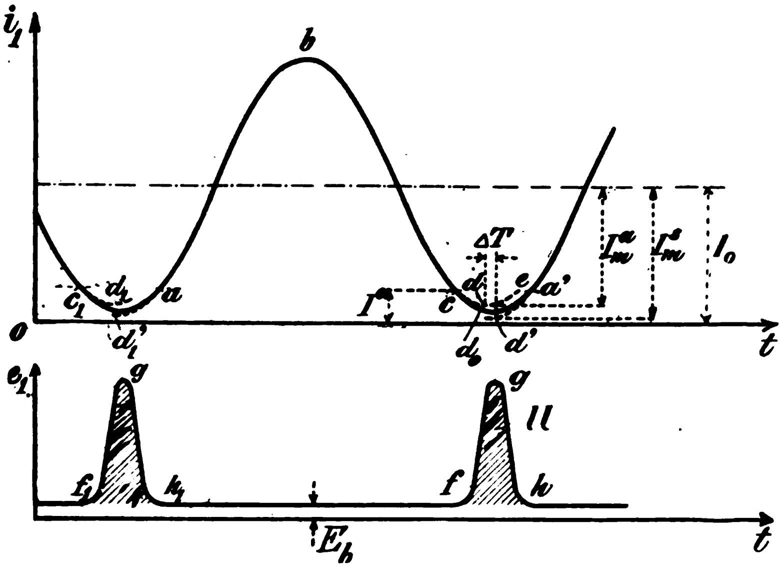

FIGURE 1—Diagram of arc current (i_1) and arc voltage (e_1) for oscillations of the first type (that is, oscillations without interruption of current thru arc)

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* PROCEEDINGS OF THE INSTITUTE OF RADIO ENGINEERS, volume 5, number 4, page 255. The nomenclature given on pages 315 and 316 of that paper applies also to the present paper.

† Received by the Editor, December 18, 1918.

constant and equal to E_b for currents greater than I^o. The part $a\,b\,c$ of the current curve can, therefore, be written in the form

$$I_o - i_1 = i_{10} = I_m^s\,\varepsilon^{-\kappa t} \cos(2\pi n t - \phi), \tag{1}$$

where I_m^s is the initial maximum amplitude of the current; while

$$\kappa = \frac{R}{2L}, \text{ and } 2\pi n\sqrt{LC} = 1.$$

At the point c of the current curve, the voltage commences to increase, and $f\,g\,h$ represents the peak; the corresponding part of the current curve is $c\,d_o\,a'$. We shall now determine the relation between the curves $f\,g\,h$ and $c\,d_o\,a'$.

For the arc voltage e_1 we have

$$-e_1 = L\frac{di}{dt} + Ri + \frac{1}{C}\int i\,dt, \tag{2}$$

i_1 being the arc current and L, R, and C the constants of the r.f. circuit.

If we put $i = i_{10} - i_1'$ where i_{10} is a current as determined by (1), then i_1' is the difference between this current and the actual arc current, that is, between the curves $c\,d\,e$ and $c\,d_o\,a'$ in Figure 1.

Substituting the above expression for i_1 in (2), we get the following equation:

$$e_1' = e_1 - E_b = L\frac{di_1'}{dt} + Ri_1' + \frac{1}{C}\int i_1'\,dt. \tag{3}$$

However, i_1' is so small that the last two terms may be neglected, and (3) may therefore be written

$$e_1' = e_1 - E_b = L\frac{di_1'}{dt} \tag{4}$$

or

$$i_1' = \frac{1}{L}\int_f^t e_1'\,dt = \frac{1}{L}\int_f^t (e_1 - E_b)\,dt. \tag{5}$$

At the point h, the arc voltage again reaches its normal value E_b, and at the corresponding point a' the current curve again begins to be represented by an equation of the form shown in (1). The maximum amplitude in the point d is reduced to I_m^s, and if the oscillations are to continue with the same intensity, the maximum amplitude at the point d' must be equal to I_m^a. The peak $f\,g\,h$ must, therefore, be such as to be able just to cause this increase in maximum amplitude from I_m^a to I_m^s, if the oscillations are to continue. If the peak is lower, the amplitude will decrease continually and the arc becomes "inactive" or non-oscillatory. If the peak is higher, the amplitude will increase, and eventually becomes greater than I_o, the oscillations then being of the second kind.

The area U of the peak such, that it is just possible to sustain the oscillations is, according to (5), determined by

$$U = \int_f^h (e_1 - E_b)\,dt = L i_{1h}', \tag{6}$$

where i_{1h}' is the greatest value of i_1' and corresponds to the point a' of the current curve. For oscillations of constant amplitude, this value i_{1h}' must very nearly be equal to $I_m^s - I_m^a = \delta I_m^s$, where the logarithmic decrement $\delta = \pi R \sqrt{\frac{C}{L}}$. Equation (6) may, therefore, be written

$$U = L\,\delta I_m^s = \pi R\sqrt{LC}\cdot I_m^s = \frac{\lambda R}{6\cdot 10^{10}}\cdot I_m^s. \tag{7}$$

This formula agrees with formula (59) of the former paper.

Formula (7) may easily be obtained in another way. During one complete period, the feeding current delivers an amount of energy A to the r.f. circuit, and to the arc, such that

$$A = \int_t^{t+\tau} I_o e_1\,dt = I_o E_b \tau + \int_f^h I_o (e_1 - E_b)\,dt = I_o E_b \tau + I_o U \tag{8}$$

The first term, $I_o E_b \tau$, represents the energy spent in the arc, while the second term, $I_o U$, is the energy delivered to the r.f. circuit.

Accordingly we have

$$I_o U = I^2 R\tau = \tfrac{1}{2} I_m^{s2} R\, 2\pi\sqrt{LC} = \pi R\sqrt{LC}\, I_m^{s2} \tag{9}$$

But I_m^s is very nearly equal to I_o, and (9) accordingly reduces to

$$U = \pi R\sqrt{LC}\cdot I_m^s$$

which was to be shown.

B. MAGNETIC FIELD OF THE POULSEN ARC

The experimental evidence given in the former paper showing that the arc in too weak a field behaves as shown by the sketch in Figure 19 of that paper, may, perhaps, be deemed somewhat meagre. In fact, the evidence consisted only of part *b* of Figure 17b. Some crater oscillograms and side views which will probably be more convincing are therefore given in Figure 2 of this paper. Parts *b*, *b′* correspond to a normal field, *c*, *c′* and *d*, *d′* to fields which are too weak. A comparison with Figure 19 of the first paper shows a complete agreement.

In parts *a*, *a′* of Figure 2 the magnetic field is too strong. The crater curve in this case, however (contrary to what is the case in parts *c* and *d* of Figure 17b of the former paper), consists only of a single curve for each period. It thus appears that the crater curve in strong fields does not always split up into a number of separate parts. This being so, there is some probability that the preliminary hypothesis relative to the behavior of the arc in excessively strong fields put forth in the former paper, and referred to in connection with Figure 18 II, is not altogether correct. The different parts of the crater curve corresponding to the time of one period may possibly be formed simultaneously, the arc consisting of separate parts which are forced outward in the same manner by the magnetic field. From the data at hand I have not yet been able to decide which of the two views is the correct one. To quote the former paper: "A full elucidation of these phenomena will, therefore, necessitate further investigation" (former citation, page 297).*

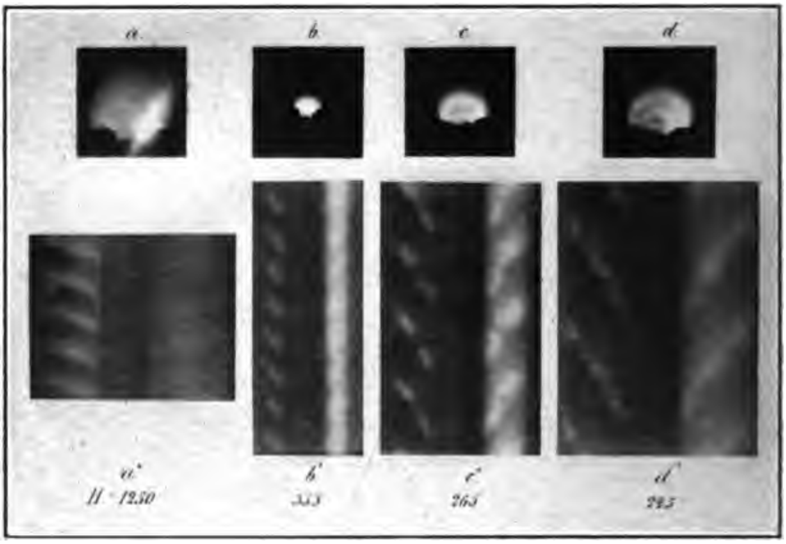

FIGURE 2—Side Views of Arc and Corresponding Crater Oscillograms
Anode to the left. $\lambda = 9{,}000$ m.; $R = 0$; $I_e = 20$ amperes
Parts *a*, *a′*—magnetic field too strong ($V_e = 120$ volts)
Parts *b*, *b′*—normal magnetic field ($V_o = 60$ volts)
Parts *c*, *c′*—magnetic field too weak ($V_o = 100$ volts)
Parts *d*, *d′*—magnetic field too weak ($V_o = 118$ volts)

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* In the bibliography given in my former paper I had unfortunately overlooked an important paper by G. Grandquist (Nova Acta Reg. Soc. Sc. Ups., Series IV, volume 1, 1907) dealing with the theory of the Duddell arc.

SUMMARY: Continuing the discussion of sustained oscillations of the first or second type produced by Poulsen arcs, as given in his earlier paper in the PROCEEDINGS, the author derives an approximate value for the peak voltage required for the maintenance of such oscillations.

He then presents further experimental data on the nature of the arc in normal or too weak or strong magnetic fields. He also considers the question of the simultaneous versus sequential production of separate arcs during a period, when the arc takes place in a very strong field.

ELECTRICAL OSCILLATIONS IN ANTENNAS AND INDUCTANCE COILS*

By

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CONTENTS

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* Received by the Editor, April 18 and September 10, 1918

I. INTRODUCTION

In the following paper are outlined some results of the application of the theory of circuits having uniformly distributed electrical characteristics to the electrical oscillations in antennas and inductance coils. Experimental methods are also given for determining the constants of antennas and experimental results showing the effect of imperfect dielectrics upon antenna resistance.

The theory of circuits having uniformly distributed characteristics such as cables, telephone lines, and transmission lines has been applied to antennas by a number of authors. The results of the theory do not seem to have been clearly brought out, and in fact erroneous results have at times been derived and given prominence in the literature. As an illustration, in one article the conclusion has been drawn that the familiar method of determining the capacity and inductance of antennas by the insertion of two known loading coils leads to results which are in very great error. In the following treatment it is shown that this is not true and that the method is very valuable.

Another point concerning which there seems to be considerable uncertainty is that of the effective values of the capacity, inductance and resistance of antennas. In this paper expressions are obtained for these quantities giving the values which would be suitable for an artificial antenna to represent the actual antenna at a given frequency.

The theory is applied also to the case of inductance coils with distributed capacity in which case an explanation of a well-known experimental result is obtained.

Experimental methods are given for determining the constants of antennas, the first of which is the familiar method previously mentioned. It is shown that this method in reality gives values of capacity and inductance of the antenna close to the low frequency or static values and may be corrected so as to give these values very accurately. The second method concerns the determination of the effective values of the capacity, inductance, and resistance of the antenna.

In the portion which deals with the resistance of antennas, a series of experimental results are given which explain the linear rise in resistance of antennas as the wave length is increased. It is shown that this characteristic feature of antenna resistance curves is caused by the presence of imperfect dielectric such as trees, buildings, and so on, in the field of the antenna, which causes it to behave as an absorbing condenser.

II. CIRCUIT WITH UNIFORMLY DISTRIBUTED INDUCTANCE AND CAPACITY

The theory, generally applicable to all circuits with uniformly distributed inductance and capacity, will be developed for the case of two parallel wires. The wires (Figure 1) are of length l and of low resistance. The inductance per unit length

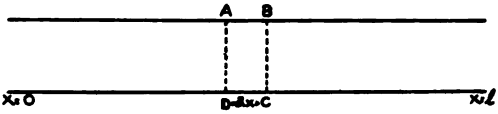

FIGURE 1

L_1 is defined by the flux of magnetic force between the wires per unit of length that there would be if a steady current of one ampere were flowing in opposite directions in the two wires. The capacity per unit length C_1 is defined by the charge that there would be on a unit length of one of the wires if a constant emf. of one volt were impressed between the wires. Further the quantity $L_0 = l L_1$ would be the total inductance of the circuit if the current flow were the same at all parts. This would be the case if a constant or slowly alternating voltage were applied at $x=0$ and the far end ($x=l$) short-circuited. The quantity $C_0 = l C_1$ would represent the total capacity between the wires if a constant or slowly alternating voltage were applied at $x=0$ and the far end were open.

Let us assume, without defining the condition of the circuit at $x=l$, that a sinusoidal emf. of periodicity $\omega = 2\pi f$ is impressed at $x=0$ giving rise to a current of instantaneous value i at A and a voltage between A and D equal to v. At B the current will be $i + \frac{\partial i}{\partial x} dx$ and the voltage from B to C will be $v + \frac{\partial v}{\partial x} dx$.

The voltage around the rectangle $ABCD$ will be equal to the rate of decrease of the induction thru the rectangle; hence

$$\left(v + \frac{\partial v}{\partial x}\right) d x - v = -\frac{\partial}{\partial t}(L_1 i \, d x)$$

$$\frac{\partial v}{\partial x} = -L_1 \frac{\partial i}{\partial t} \qquad (1)$$

Further the rate of increase of the charge q on the elementary length of wire AB will be equal to the excess in the current flowing in at A over that flowing out at B.

Hence

$$\frac{\partial q}{\partial t}=\frac{\partial}{\partial t}(C_1 v\,dx)=i-\left(i+\frac{\partial i}{\partial x}\,dx\right)$$

$$-\frac{\partial i}{\partial x}=C_1\frac{\partial v}{\partial t} \qquad (2)$$

These equations (1) and (2), determine the propagation of the current and voltage waves along the wires. In the case of sinusoidal waves, the expressions

$$v=\cos\omega t\,(A\cos\omega\sqrt{C_1L_1}\,x+B\sin\omega\sqrt{C_1L_1}\,x) \qquad (3)$$

$$i=\sin\omega t\sqrt{\frac{C_1}{L_1}}\,(A\sin\omega\sqrt{C_1L_1}\,x-B\cos\omega\sqrt{C_1L_1}\,x) \qquad (4)$$

are solutions of the above equations as may be verified by substitution. The quantities A and B are constants depending upon the terminal conditions. The velocity of propagation of the waves at high frequencies, is

$$V=\frac{1}{\sqrt{L_1C_1}}.$$

III. THE ANTENNA

1. REACTANCE OF THE AERIAL-GROUND PORTION

The aerial-ground portion of the antenna (*CD* in Figure 2) will be treated as a line with uniformly distributed inductance, capacity and resistance. As is common in the treatment of radio circuits, the resistance will be considered to be so low as not to affect the frequency of the oscillations or the distribution of current and voltage. The lead-in *BC* (Figure 2) will be

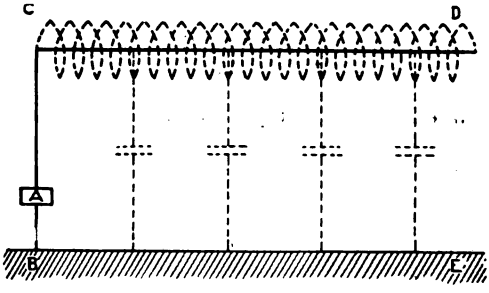

FIGURE 2—Antenna Represented as a Line with Uniform Distribution of Inductance and Capacity

considered to be free from inductance or capacity excepting as inductance coils or condensers are inserted (at A) to modify the oscillations.

Applying equations (3) and (4) to the aerial of the antenna and assuming that $x=0$ is the lead-in end while $x=l$ is the far end which is open, we may introduce the condition that the current is zero for $x=l$. From (4)

$$\frac{A}{B}=\cot \omega \sqrt{C_1 L_1}\, l \qquad (5)$$

Now the reactance of the aerial, which includes all of the antenna but the lead-in, is given by the current and voltage at $x=0$. These are, from (3), (4), and (5),

$$v_o=A \cos \omega t=B \cot \omega \sqrt{C_1 L_1}\, l \cos \omega t$$

$$i_o=-\sqrt{\frac{C_1}{L_1}}B \sin \omega t$$

The current leads the voltage when the cotangent is positive, and lags when the cotangent is negative. The reactance of the aerial, given by the ratio of the maximum values of v_o to i_o is

$$X=-\sqrt{\frac{L_1}{C_1}} \cot \omega \sqrt{C_1 L_1}\, l$$

or in terms of $C_o=l C_1$ and $L_o=l L_1$

$$X=-\sqrt{\frac{L_o}{C_o}} \cot \omega \sqrt{C_o L_o} \qquad (6)$$

or since $V=\frac{1}{\sqrt{L_1 C_1}}$

$$X=-L_1 V \cot \omega \sqrt{C_1 L_1}\, l$$

as given by J. S. Stone.[1]

At low frequencies the reactance is negative and hence the aerial behaves as a capacity. At the frequency $f=\frac{1}{4\sqrt{C_o L_o}}$ the reactance becomes zero and beyond this frequency is positive or inductive up to the frequency $f=\frac{1}{2\sqrt{C_o L_o}}$, at which the reactance becomes infinite. This variation of the aerial reactance with the frequency is shown by the cotangent curves in Figure 3.

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[1] Stone, J. S.; "Trans. Int. Elec. Congress," St. Louis, 3, p. 555; 1904.

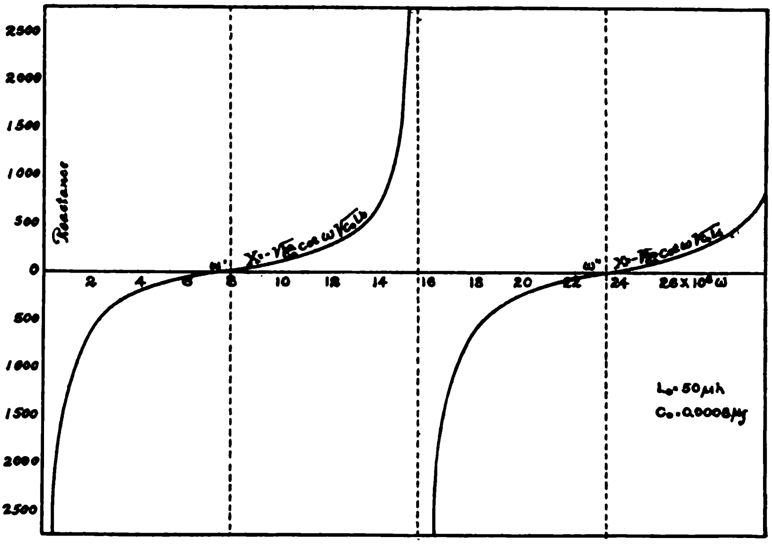

FIGURE 3—Variation of the Reactance of the Aerial of an Antenna with the Frequency

2. NATURAL FREQUENCIES OF OSCILLATION

Those frequencies at which the reactance of the aerial, as given by equation (6), becomes equal to zero are the natural frequencies of oscillation of the antenna (or frequencies of resonance) when the lead-in is of zero reactance. They are given in Figure 3 by the points of intersection of the cotangent curves with the axis of ordinates and by the equation

$$f=\frac{m}{4\sqrt{C_oL_o}};\quad m=1,\ 3,\ 5,\ \text{etc.}$$

The corresponding wave lengths are given by

$$\lambda=\frac{V}{f}=\frac{l}{f\sqrt{C_oL_o}}=\frac{4\,l}{m}$$

i. e., 4/1, 4/3, 4/5, 4/7, etc., times the length of the aerial. If, however, the lead-in has a reactance X_x, the natural frequencies of oscillation are determined by the condition that the total reactance of lead-in plus aerial shall be zero, that is:

$$X_x+X=0$$

provided the reactances are in series with the driving emf.

(a) LOADING COIL IN LEAD-IN. The most important practical case is that in which an inductance coil is inserted in the lead-in. If the coil has an inductance L its reactance $X_L = \omega L$. This is a positive reactance increasing linearly with the frequency and represented in Figure 4 by a solid line. Those frequencies at which the reactance of the coil is equal numerically but opposite in sign to the reactance of the aerial, are the natural frequencies of oscillation of the loaded antenna since the total reactance $X_L + X = 0$. Graphically these frequencies are determined by the intersection of the straight line $-X_L = -\omega L$ (shown by a dashed line in Figure 4) with the cotangent curves representing X. It is evident that the frequency is lowered by the insertion of the loading coil and that the higher natural frequencies of oscillation are no longer integral multiples of the lowest frequency.

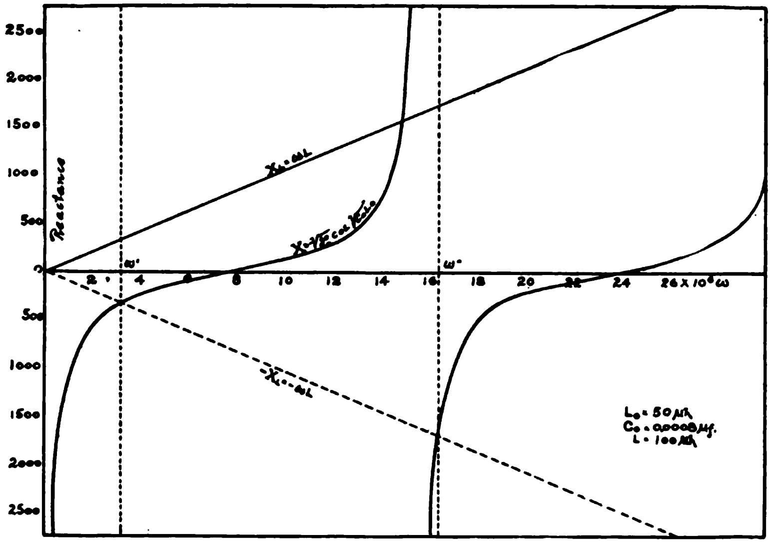

FIGURE 4—Curves of Aerial and Loading Coil Reactances

The condition $X_L + X = 0$ which determines the natural frequencies of oscillation leads to the equation

$$\omega L - \sqrt{\frac{L_0}{C_0}} \cot \omega \sqrt{C_0 L_0} = 0$$

or

$$\frac{\cot \omega \sqrt{C_0 L_0}}{\omega \sqrt{C_0 L_0}} = \frac{L}{L_0} \qquad (8)$$

This equation has been given by Guyau[2] and L. Cohen.[3] It determines the periodicity ω and hence the frequency and wave length of the possible natural modes of oscillation when the distributed capacity and inductance of the aerial and the inductance of the loading coil are known. This equation cannot, however, be solved directly; it may be solved graphically as shown in Figure 4 or a table may be prepared indirectly which gives the values of $\omega\sqrt{C_0 L_0}$ for different values of $\frac{L}{L_0}$, from which then ω, f or λ may be determined. The second column of Table I gives these values for the lowest natural frequency of oscillation, which is of major importance naturally.

(b) CONDENSER IN LEAD-IN. At times, in practice, a condenser is inserted in the lead-in. If the capacity of the condenser is C, its reactance is $X_c = -\frac{1}{\omega C}$. This reactance is shown in Figure 5 by the hyperbola drawn in solid line. The intersection

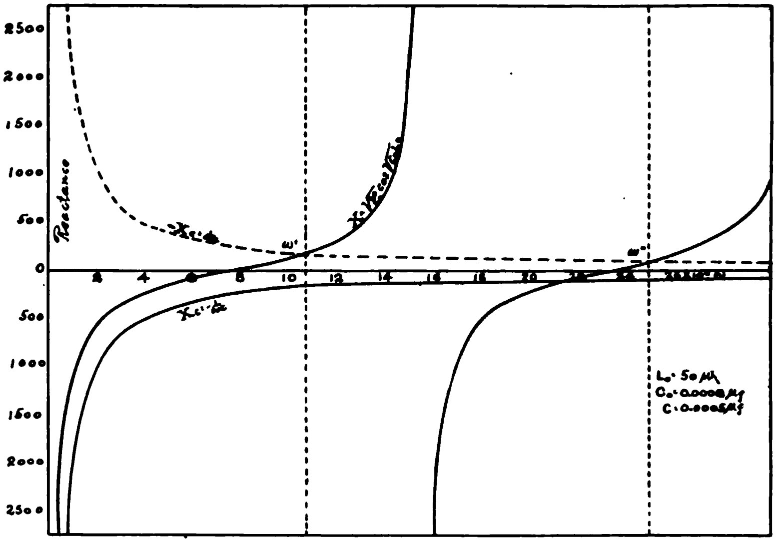

FIGURE 5—Curves of Aerial and Series Condenser Reactances

of the negative of this curve (drawn in dashed line) with the cotangent curves representing X gives the frequencies for which

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[2] Guyau, A.; "Lumière Electrique," 15, p. 13; 1911.
[3] Cohen, L.; "Electrical World," 65, p. 286; 1915.

TABLE I

DATA FOR LOADED ANTENNA CALCULATIONS

$\frac{L}{L_0}$	$\omega\sqrt{C_0L_0}$	$\frac{1}{\sqrt{\frac{L}{L_0}+\frac{1}{3}}}$	Difference, per cent	$\frac{L}{L_0}$	$\omega\sqrt{C_0L_0}$	$\frac{1}{\sqrt{\frac{L}{L_0}+\frac{1}{3}}}$	Difference, per cent
0.0	1.571	1.732	10.3	3.1	0.539	0.540	0.1
.1	1.429	1.519	6.3	3.2	.532	.532	.1
.2	1.314	1.369	4.2	3.3	.524	.525	.1
.3	1.220	1.257	3.0	3.4	.517	.518	.1
.4	1.142	1.168	2.3	3.5	.510	.511	.1
.5	1.077	1.095	1.7	3.6	.504	.504	.0
.6	1.021	1.035	1.4	3.7	.4977	.4979	.0
.7	.973	.984	1.1	3.8	.4916	.4919	.0
.8	.931	.939	.9	3.9	.4859	.4860	.0
.9	.894	.900	.7	4.0	.4801	.4804	.0
1.0	.860	.866	.7	4.5	.4548	.4549	.0
1.1	.831	.835	.5	5.0	.4330	.4330	.0
1.2	.804	.808	.5	5.5	.4141	....	....
1.3	.779	.782	.4	6.0	.3974	....	....
1.4	.757	.760	.4	6.5	.3826	....	....
1.5	.736	.739	.4	7.0	.3693	....	....
1.6	.717	.719	.3	7.5	.3574	....	....
1.7	.699	.701	.3	8.0	.3465	....	....
1.8	.683	.685	.3	8.5	.3366	....	....
1.9	.668	.689	.3	9.0	.3275	....	....
2.0	.653	.655	.3	9.5	.3189	....	....
2.1	.640	.641	.2	10.0	.3111	....	....
2.2	.627	.628	.2	11.0	.2972	....	....
2.3	.615	.616	.2	12.0	.2850	....	....
2.4	.604	.605	.2	13.0	.2741	....	....
2.5	.593	.594	.2	14.0	.2644	....	....
2.6	.583	.584	.2	15.0	.2556	....	....
2.7	.574	.574	.2	16.0	.2476	....	....
2.8	.564	.565	.1	17.0	.2402	....	....
2.9	.556	.556	.1	18.0	.2338	....	....
3.0	.547	.548	.1	19.0	.2277	....	....
				20.0	.2219	....	....

$X_c + X = 0$, and hence the natural frequencies of oscillation of the antenna. The frequencies are increased (the wave length decreased) by the insertion of the condenser and the oscillations of higher frequencies are not integral multiples of the lowest.

The condition $X_c + X = 0$ is expressed by the equation

$$-\frac{\tan \omega \sqrt{C_o L_o}}{\omega \sqrt{C_o L_o}} = \frac{C}{C_o} \tag{9}$$

which has been given by Guyau. Equation (9) may be solved graphically as above or a table similar to Table I may be prepared giving $\omega \sqrt{C_o L_o}$ for different values of $\frac{C}{C_o}$. More complicated circuits may be solved in a similar manner.

3. Effective Resistance, Inductance, and Capacity

In the following, the most important practical case of a loading coil in the lead-in and the natural oscillation of lowest frequency will alone be considered. The problem is to replace the antenna of Figure 6 (a) which has a loading coil L in the lead-in and an aerial with distributed characteristics by a circuit Figure 6 (b) consisting of the inductance L in series with lumped resistance R_e, inductance L_e, capacity C_e, which are equivalent to the aerial. It is necessary, however, to state how these effective values are to be defined.

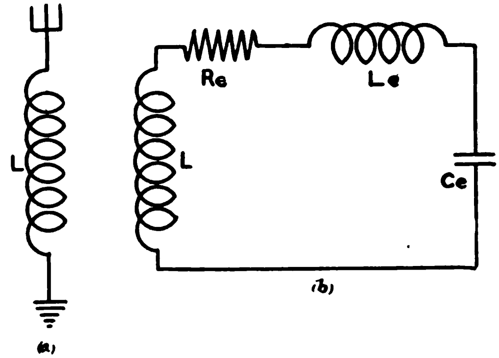

FIGURE 6

In practice the quantities which are of importance in an antenna are the resonant wave length or frequency and the current at the current maximum. The quantities L_e and C_e are, therefore, defined as those which will give the circuit (b) the same resonant frequency as the antenna in (a). Further the three quantities L_e, C_e, and R_e must be such that the current in (b) will be the same as the maximum in the antenna for the same applied emf. whether undamped or damped with any decrement. These conditions determine L_e, C_e, and R_e uniquely at any given frequency, and are the proper values for an artificial antenna which is to represent an actual antenna at a particular frequency. In the two circuits the corresponding maxima of magnetic energies and electrostatic energies and the dissipation of energy will be the same.

Zenneck[4] has shown how these effective values of inductance capacity and resistance can be computed when the current and voltage distributions are known. Thus, if at any point x on the oscillator, the current i and the voltage v are given by

$$i = I\,f(x)\,;\,v = V\,\phi\,(x)$$

where I is the value of the current at the current loop and V the maximum voltage, then the differential equation of the oscillation is

$$\frac{\partial I}{\partial t}\int R_1 f(x)^2\,dx + \frac{\partial^2 I}{\partial t^2}\int L_1 f(x)^2\,dx + \frac{1}{\dfrac{\{\int C_1 \phi(x)\,dx\}^2}{\int C_1\,\phi\,(x)^2\,dx}} = 0$$

where the integrals are taken over the whole oscillator. If we write

$$R_e = \int R_1 f\,(x)^2\,dx \qquad (10)$$

$$L_e = \int L_1 f\,(x)^2\,dx \qquad (11)$$

$$C_e = \frac{\{\int C_1\,\phi\,(x)\,dx\}^2}{\int C_1\,\phi\,(x)^2\,dx} \qquad (12)$$

the equation becomes

$$R_e\frac{\partial I}{\partial t} + L_e\frac{\partial^2 I}{\partial t^2} + \frac{I}{C_e} = 0$$

which is the differential equation of oscillation of a simple circuit with lumped resistance, inductance, and capacity of values R_e, L_e, and C_e and in which the current is the same as the maximum in the distributed case. In order to evaluate these quantities, it is necessary only to determine $f\,(x)$ and $\phi\,(x)$; that is, the functions which specify the distribution of current and voltage on the oscillator. In this connection it will be assumed that the resistance is not of importance in determining these distributions.

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[4] Zenneck, "Wireless Telegraphy" (Translated by A. E. Seelig), Note 40, p. 410.

At the far end of the aerial the current is zero, that is for $x=l$; $i_l=0$. From equations (3) and (4) for $x=l$

$$v_l=\cos\omega t\,(A\cos\omega\sqrt{C_1L_1}\,l+B\sin\omega\sqrt{C_1L_1}\,l)$$

$$i_l=\sin\omega t\sqrt{\frac{C_1}{L_1}}\,(A\sin\omega\sqrt{C_1L_1}\,l-B\cos\omega\sqrt{C_1L_1}\,l)$$

and since $i_l=0$

$$A\sin\omega\sqrt{C_1L_1}\,l=B\cos\omega\sqrt{C_1L_1}\,l$$

From (3) then we obtain

$$v=v_l\cos(\omega\sqrt{C_1L_1}\,l-\omega\sqrt{C_1L_1}\,x)$$

Hence $\phi(x)=\cos(\omega\sqrt{C_1L_1}\,l-\omega\sqrt{C_1L_1}\,x)$

Now for $x=0$ from (4) we obtain

$$i_o=-B\sqrt{\frac{C_1}{L_1}}\sin\omega t=-A\sqrt{\frac{C_1}{L_1}}\tan\omega\sqrt{C_1L_1}\,l\sin\omega t$$

whence $$i=i_o\frac{\sin(\omega\sqrt{C_1L_1}\,l-\omega\sqrt{C_1L_1}\,x)}{\sin\omega\sqrt{C_1L_1}\,l}$$

and $$f(x)=\frac{\sin(\omega\sqrt{C_1L_1}\,l-\omega\sqrt{C_1L_1}\,x)}{\sin\omega\sqrt{C_1L_1}\,l}$$

We can now evaluate the expressions (10), (11), and (12). From (10)

$$\begin{aligned}R_e&=\int_o^l R_1\frac{\sin^2(\omega\sqrt{C_1L_1}\,l-\omega\sqrt{C_1L_1}\,x)\,dx}{\sin^2\omega\sqrt{C_1L_1}\,l}\\&=\frac{R_1}{\sin^2\omega\sqrt{C_1L_1}\,l}\left[\frac{l}{2}-\frac{\sin 2\omega\sqrt{C_1L_1}\,l}{4\omega\sqrt{C_1L_1}}\right]\\&=\frac{R_o}{2}\left[\frac{1}{\sin^2\omega\sqrt{C_oL_o}}-\frac{\cot\omega\sqrt{C_oL_o}}{\omega\sqrt{C_oL_o}}\right]\end{aligned}\tag{13}$$

and from (11) which contains the same form of integral

$$L_e=\frac{L_o}{2}\left[\frac{1}{\sin^2\omega\sqrt{C_oL_o}}-\frac{\cot\omega\sqrt{C_oL_o}}{\omega\sqrt{C_oL_o}}\right]\tag{14}$$

and from (12)

$$\begin{aligned}C_e&=\frac{\left\{\int_o^l C_1\cos(\omega\sqrt{C_1L_1}\,l-\omega\sqrt{C_1L_1}\,x)\,dx\right\}^2}{\int_o^l C_1\cos^2(\omega\sqrt{C_1L_1}\,l-\omega\sqrt{C_1L_1}\,x)\,dx}\\&=\frac{C_1^2\dfrac{\sin^2\omega\sqrt{C_1L_1}\,l}{(\omega\sqrt{C_1L_1})^2}}{C_1\left(\dfrac{l}{2}+\dfrac{\sin 2\omega\sqrt{C_1L_1}\,l}{4\omega\sqrt{C_1L_1}}\right)}\\&=\frac{C_o}{\left[\dfrac{\omega\sqrt{C_oL_o}\cot\omega\sqrt{C_oL_o}}{2}+\dfrac{\omega^2L_oC_o}{2\sin^2\omega\sqrt{C_oL_o}}\right]}\end{aligned}\tag{15}$$

The expressions (14) and (15) should lead to the same value for the reactance X of the aerial as obtained before. It is readily shown that

$$X = \omega L_e - \frac{1}{\omega C_e} = -\sqrt{\frac{L_o}{C_o}} \cot \omega \sqrt{C_o L_o}$$

agreeing with equation (6).

It is of interest to investigate the values of these quantities at very low frequencies ($\omega \doteq 0$), frequently called the static values, and those corresponding to the natural frequency of the unloaded antenna or the so-called fundamental of the antenna. Substituting $\omega = 0$ in (13), (14), and (15) and evaluating the indeterminant which enters in the first two cases we obtain for the low frequency values

$$R_e = \frac{R_o}{3}$$

$$L_e = \frac{L_o}{3}$$

$$C_e = C_o \tag{16}$$

At low frequencies, the current is a maximum at the lead-in end of the aerial and falls off linearly to zero at the far end. The effective resistance and inductance are one-third of the values which would obtain if the current were the same thruout. The voltage is, however, the same at all points and hence the effective capacity is the capacity per unit length times the length or C_o.

At the fundamental of the antenna, the reactance X of equation (6) becomes equal to zero and hence $\omega \sqrt{C_o L_o} = \frac{\pi}{2}$. Substituting this value in (13), (14), and (15)

$$\left. \begin{aligned} R_e &= \frac{R_o}{2} \\ L_e &= \frac{L_o}{2} \\ C_e &= \frac{8}{\pi^2} C_o \end{aligned} \right\} \tag{17}$$

Hence in going from low frequencies up to that of the fundamental of the antenna, the resistance (neglecting radiation and skin effect) and the inductance (neglecting skin effect) increase by fifty per cent., the capacity, however, decreases by about twenty per cent. The incorrect values $\frac{2}{\pi} L_o$ and $\frac{2}{\pi} C_o$ have been frequently given and commonly used as the values of the effective inductance and capacity of the antenna at its fundamental. These lead also to the incorrect value $L_e = \frac{L_o}{2}$ for the low frequency inductance[5].

The values for other frequencies may be obtained by substitution in (13), (14), (15). If the value L of the loading coil in the lead-in is given, the quantity $\omega\sqrt{C_o L_o}$ is directly obtained from Table 1.

4. EQUIVALENT CIRCUIT WITH LUMPED CONSTANTS

Insofar as the frequency or wave length is concerned, the aerial of the antenna may be considered to have constant values of inductance and capacity and the values of frequency or wave length for different loading coils may be computed with slight error using the simple formula applicable to circuits with lumped inductance and capacity. The values of inductance and capacity ascribed to the aerial are the static or low frequency, that is, $\frac{L_o}{3}$ for the inductance and C_o for the capacity. The total inductance in case the loading coil has a value L will be $L + \frac{L_o}{3}$ and the frequency is given by

$$f = \frac{1}{2\pi\sqrt{\left(L + \frac{L_o}{3}\right)C_o}} \tag{18}$$

or the wave length in meters by

$$\lambda = 1884\sqrt{\left(L + \frac{L_o}{3}\right)C_o} \tag{19}$$

where the inductance is expressed in microhenrys and the capacity in microfarads. The accuracy with which this formula gives the wave length can be determined by comparison with the exact formula (8). In the second column of Table I are given

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[5] These values are given by J. H. Morecroft in "Proc. I. R. E." 5, p. 389, 1917. It may be shown that they lead to correct values for the reactance of the aerial and hence to correct values of frequency as was verified by the experiments. They are not, however, the values which would be correct for an artificial antenna in which the current must equal the maximum in the actual antenna and in which the energies must also be equal to those in the antenna. The resistance values given by Prof. Morecroft agree with these requirements and with the values obtained here.

Values for the effective inductance and capacity in agreement with those of equation (17) above have been given by G. W. O. Howe, "Yearbook of Wireless Telegraphy and Telephony," page 699, 1917.

the values of $\omega\sqrt{C_0L_0}$ for different values of L_0 as computed by formula (8). Formula (18) may be written in the form

$$\omega\sqrt{L_0C_0}=\frac{1}{\sqrt{\frac{L}{L_0}+\frac{1}{3}}}$$

so that the values of $\omega\sqrt{C_0L_0}$, which are proportional to the frequency, may readily be computed from this formula also. These values are given in the third column of Table I and the per cent. difference in the fourth column. It is seen that formula (18) gives values for the frequency which are correct to less than a per cent., excepting when very close to the fundamental of the antenna, i. e., for very small values of L. Under these conditions the simple formula leads to values of the frequency which are too high. Hence to the degree of accuracy shown, which is amply sufficient in most practical cases, *the aerial can be represented by its static inductance* $\frac{L_0}{3}$ *with its static capacity* C_0 *in series, and the frequency of oscillation with a loading coil* L *in the lead-in can be computed by the ordinary formula applicable to circuits with lumped constants.*

In an article by L. Cohen,[6] which has been copied in several other publications, it was stated that the use of the simple wave length formula would lead to very large errors when applied to the antenna with distributed constants. The large errors found by Cohen are due to his having used the value L_0 for the inductance of the aerial, instead of $\frac{L_0}{3}$, in applying the simple formula.

IV. THE INDUCTANCE COIL

The transmission line theory can also be applied to the treatment of the effects of distributed capacity in inductance coils. In Figure 7 (a) is represented a single layer solenoid connected to a variable condenser C. A and B are the terminals of the coil, D the middle, and the condensers drawn in dotted lines are supposed to represent the capacities between the different parts of the coil. In Figure 7 (b) the same coil is represented as a line with uniformly distributed inductance and capacity. These assumptions are admittedly rough, but are somewhat justified by the known similarity of the oscillations in long solenoids to those in a simple antenna.

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[6] See foot-note 3.

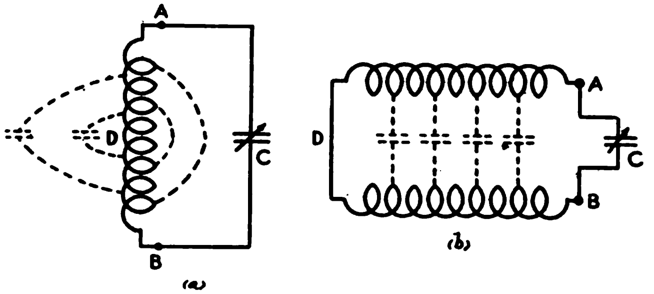

FIGURE 7—Inductance Coil Represented as a Line with Uniform Distribution of Inductance and Capacity

1. REACTANCE OF THE COIL

Using the same notation as before, an expression for the reactance of the coil, regarded from the terminals $A\,B\,(x=0)$, will be determined considering the line as closed at the far end $D\,(x=l)$. Equations (3) and (4) will again be applied, taking account of the new terminal condition, that is, for $x=l$; $v=0$. Hence

$$A \cos \omega \sqrt{C_1 L_1}\, l = -B \sin \omega \sqrt{C_1 L_1}\, l$$

and for $x=0$

$$v_o = A \cos \omega t = -B \tan \omega \sqrt{C_1 L_1}\, l \cos \omega t$$

$$i_o = -\sqrt{\frac{C_1}{L_1}}\, B \sin \omega t$$

which gives for the reactance of the coil regarded from the terminals $A\,B$,

$$X' = \sqrt{\frac{L_1}{C_1}} \tan \omega \sqrt{C_1 L_1}\, l$$

or

$$X' = \sqrt{\frac{L_o}{C_o}} \tan \omega \sqrt{C_o L_o} \qquad (20)$$

2. NATURAL FREQUENCIES OF OSCILLATION

At low frequencies, the reactance of the coil is very small and positive, but increases with increasing frequency and becomes infinite when $\omega \sqrt{C_o L_o} = \frac{\pi}{2}$. This represents the lowest frequency of natural oscillation of the coil when the terminals are open. Above this frequency the reactance is highly negative, approaching zero at the frequency $\omega \sqrt{C_o L_o} = \pi$. In this range of frequencies, the coil behaves as a condenser and would require an inductance across the terminals to form a resonant circuit. At the frequency $\omega\sqrt{C_0L_0}=\pi$ the coil will oscillate with its terminals short-circuited. As the frequency is still further increased the reactance again becomes increasingly positive.

(a) CONDENSER ACROSS THE TERMINALS. The natural frequencies of oscillation of the coil when connected to a condenser C are given by the condition that the total reactance of the circuit shall be zero.

$$X'+X_c=0$$

From this we have

$$\sqrt{\frac{L_0}{C_0}}\tan\omega\sqrt{C_0L_0}=\frac{1}{\omega C}$$

or

$$\frac{\cot\omega\sqrt{C_0L_0}}{\omega\sqrt{C_0L_0}}=\frac{C}{C_0} \tag{21}$$

This expression is the same as (8) obtained in the case of the loaded antenna, excepting that $\frac{C}{C_0}$ occurs on the right-hand side instead of $\frac{L}{L_0}$, and shows that the frequency is decreased and wave length increased by increasing the capacity across the coil in a manner entirely similar to the decrease in frequency produced by inserting loading coils in the antenna lead-in.

3. EQUIVALENT CIRCUIT WITH LUMPED CONSTANTS

It is of interest to investigate the effective values of inductance and capacity of the coil at very low frequencies. Expanding the tangent in equation (20) into a series we find

$$X'=\omega L_0\left(1+\frac{\omega^2C_0L_0}{3}+\ .\ .\ .\ .\right)$$

and neglecting higher power terms this may be written

$$X'=\frac{(\omega L_0)\left(-\frac{3}{\omega C_0}\right)}{\omega L_0-\frac{3}{\omega C_0}}$$

This is the reactance of an inductance L_0 in parallel with a capacity $\frac{C_0}{3}$ which shows that at low frequencies the coil may be regarded as an inductance L_0 with a capacity $\frac{C_0}{3}$ across the terminals and, therefore, in parallel with the external condenser

C. Since at low frequencies the current is uniform thruout the whole coil, it is self evident that its inductance should be L_o.

Now the similarity between equations (21) and (8) shows that, just as accurately as in the similar case of the loaded antenna, the frequency of oscillation of a coil with *any capacity C* across the terminals is given by the formula

$$f=\frac{1}{2\pi\sqrt{L_o\left(C+\frac{C_o}{3}\right)}} \tag{22}$$

This, however, is *also* the expression for the frequency of a coil of pure inductance L_o with a capacity $\frac{C_o}{3}$ across its terminals and which is in parallel with an external capacity C. Therefore, insofar as frequency relations are concerned, *an inductance coil with distributed capacity is closely equivalent at any frequency to a pure inductance, equal to the low frequency inductance (neglecting skin effect), with a constant capacity across its terminals.* This is a well-known result of experiment[7] at least in the case of single layer solenoids which, considering the changes in current and voltage distribution in the coil with changing frequency, is not otherwise self-evident.

V. ANTENNA MEASUREMENTS

1. DETERMINATION OF STATIC CAPACITY AND INDUCTANCE

In applying formula (8) to calculate the frequency of a loaded antenna, a knowledge of the quantities L_o and C_o is required. In applying formula (18), $\frac{L_o}{3}$ and C_o are required. Hence either formula may be used if the static capacity and inductance values are known. We will call these values simply the capacity C_a and inductance L_a of the antenna. Hence $C_a=C_o$, $L_a=\frac{L_o}{3}$ and the wave length from (19) is given by

$$\lambda=1884\sqrt{(L+L_a)\,C_a} \tag{23}$$

where inductance is expressed in microhenrys and capacity in microfarads as before.

The capacity and inductance of the antenna are then readily determined experimentally by the familiar method of inserting,

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[7] G. W. O. Howe; "Proc. Phys. Soc.," London, 24, p. 251, 1912.
F. A. Kolster; "Proc. Inst. Radio Engrs.," 1, p. 19, 1913.
J. C. Hubbard; "Phys. Rev., 9, p. 529," 1917.

one after the other, two loading coils of known values L_1 and L_2 in the lead-in, and determining the frequency of oscillation or wave length for each. From the observed wave lengths λ_1 and λ_2 and known values of the inserted inductances, the inductance of the antenna is given by

$$L_a = \frac{L_1 \lambda_2^2 - L_2 \lambda_1^2}{\lambda_1^2 - \lambda_2^2} \tag{24}$$

and the capacity of the antenna from either

$$\left.\begin{aligned} \lambda_1 &= 1884\sqrt{(L_1 + L_a)\,C_a} \\ \lambda_2 &= 1884\sqrt{(L_2 + L_a)\,C_a} \end{aligned}\right\} \tag{25}$$

using preferably, the equation corresponding to the larger valued coil. This assumes that formula (23) holds exactly.

As an example let us assume that the antenna has $L_o = 50$ microhenrys and $C_o = 0.001$ microfarad, and that we insert two coils of 50 and 150 microhenrys and determine the wave lengths experimentally. We know from formula (8) and Table I that the wave lengths would be found to be 491 and 771 meters. From the observed wave lengths and known inductances, the value of L_a would be found by (24) to be

$$L_a = 17.8 \text{ microhenrys}$$

and from (25)

$$C_a = 0.00099_9 \text{ microfarad.}$$

C_a is very close to the assumed value of C_o but L_a differs by seven per cent. from $\frac{L_o}{3}$. This accuracy would ordinarily be sufficient. We can, however, by a second approximation, derive from the experimental data a more accurate value of L_a. For, the observed value of L_a furnishes rough values of $\frac{L_1}{L_o}$ and $\frac{L_2}{L_o}$ which in this example come out 0.96 and 2.88, respectively. But Table I gives the per cent. error of formula (23) for different values of $\frac{L}{L_o}$ and shows that this formula gives a 0.7 per cent. shorter wave length than 491 meters (or 488 meters) for $\frac{L}{L_o} = 0.96$ but no appreciable difference for $\frac{L}{L_o} = 2.88$. Recomputing L_a using 488 and 771 meters gives

$$L_a = 0.0168,$$

which is practically identical with the assumed $\frac{L_o}{3}$.

2. Determination of Effective Resistance, Inductance, and Capacity

When a source of undamped oscillations in a primary circuit induces current in a secondary tuned circuit, the current in the secondary, for a given emf. depends only upon the resistance of the secondary circuit. When damped oscillations are supplied by the source in the primary, the current in the secondary, for a given emf. and primary decrement, depends upon the decrement of the secondary, i. e., upon the resistance and ratio of capacity to inductance. The higher the decrement of the primary circuit relative to the decrement of the secondary, the more strongly does the current in the secondary depend upon its own decrement. This is evident from the expression for the current I in the secondary circuit

$$I^2=\frac{NE_o^2}{4fR^2\delta'\left(1+\frac{\delta'}{\delta}\right)}$$

where δ' is the decrement of the primary, δ that of the secondary, R the resistance of the secondary, f the frequency, E_o the maximum value of the emf. impressed on the secondary, and N the wave train frequency.

These facts suggest a method of determining the effective resistance, inductance, and capacity of an antenna at a given frequency in which all of the measurements are made at one frequency, and which does not require any alteration of the antenna circuit whatsoever. The experimental circuits are arranged as shown in Figure 8, where S represents a coil in the primary circuit which may be thrown either into the circuit of

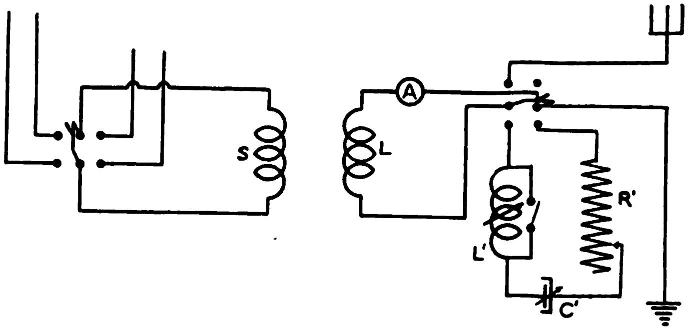

Figure 8—Circuits for Determining the Effective Resistance, Inductance, and Capacity of an Antenna

a source of undamped or of damped oscillations. The coil L is the loading coil of the antenna which may be thrown over to the measuring circuit containing a variable inductance L', a variable condenser C', and variable resistance R'. The condenser C' should be resistance-free and shielded, the shielded terminal being connected to the ground side. First the undamped source is tuned to the antenna, and then the $L'C'$ circuit tuned to the source. The resistance R' is then varied until the current is the same in the two positions. The resistance of the $L'C'$ circuit is then equal to R_e, the effective resistance of the aerial-ground portion of the antenna and $L'C' = L_eC_e$. Next the damped source is tuned to the antenna and the change in current noted when the connection is thrown over to the $L'C'$ circuit. If the current increases, the value of C' is greater than C_e, and vice versa. By varying both L' and C', keeping the tuning and R' unchanged, the current may be adjusted to the same value in both positions. Then since $L'C' = L_eC_e$ and $\frac{C'}{L'} = \frac{C_e}{L_e}$, the value of C' gives C_e and that of L' gives L_e. Large changes in the variometer setting may result in appreciable changes in its resistance, so that the measurement should be repeated after the approximate values have been found. To eliminate the resistance of the variometer in determining R_e, the variometer is short-circuited and, using undamped oscillations, the resonance current is adjusted to equality in the two positions by varying R'. Then $R' = R_e$. The measurement requires steady sources of feebly damped and strongly damped current. The former is readily obtained by using a vacuum tube generator. A resonance transformer and magnesium spark gap operating at a low spark frequency serves very satisfactorily for the latter source or a single source of which the damping can be varied will suffice. An accuracy of one per cent. is not difficult to obtain.

3. THE EFFECT OF IMPERFECT DIELECTRICS UPON THE RESISTANCE OF AN ANTENNA

The typical curve of the variation of the resistance of an antenna with the wave length of the oscillation is shown in Figure 10 (b). It has two characteristic features, a rapid decrease in resistance with increasing wave length in the region of the shorter waves and an apparent linear increase in resistance with increasing wave length at long waves. The decrease in resistance at short waves is ascribed mainly to the decrease in the power radiated in the form of electro-magnetic waves. This so-called radiation resistance should by theory decrease in inverse ratio with the square of the wave length. Skin effect and the change in distribution of current along the antenna would likewise produce resistance variations such that the resistance would decrease with increasing wave length. It has been difficult, however, to account for the observed linear increase in resistance at the longer waves. Austin[8] pointed out the similarity in the linear increase in resistance of an antenna at long wave lengths with the behavior of an absorbing condenser and concluded that dielectric absorption was a probable explanation of the phenomenon.[9]

The fact that in the curves which he had obtained for ship stations, the rise in resistance was less marked than for land stations, led him to believe that the absorption was probably caused by the ground acting as an imperfect dielectric. Austin stated that if we consider the ground as a dielectric rather than a conductor and consider it as a portion of the total dielectric lying between the antenna regarded as the upper plate of a condenser, and a ground water regarded as a lower plate, we reach a very probable explanation of many antenna resistance curves. The measurements carried out by the author verify Austin's hypothesis that the effect is caused by dielectric absorption; but do not confirm the supposition that the absorbing dielectric in question is the ground. Figure 9 shows the values of the equivalent resistance obtained at telephone frequencies for a small flat-top antenna at the Bureau of Standards. This antenna runs from a building to a tree and has a capacity of 650 micro-microfarads (0.00065 microfarad). The measurements were made at wave lengths varying from 100,000 to 750,000 meters, the equivalent resistance increasing linearly from 1,000 to 9,000 ohms. This is the order of magnitude which would be expected from Austin's measurements at radio frequencies upon an antenna for which the rise in resistance was particularly marked.

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[8] L. W. Austin; "Bulletin, Bureau of Standards," 12, p. 465, 1915. "Jahrbuch d. drahtl. Tel.," 9, p. 498, 1915.

[9] In a perfect condenser, or one which shows no energy loss, the phase of the current I in 90° in advance of the electromotive force E. In an imperfect condenser, the power loss, however caused, is given by $IE \sin \theta$ where θ is the phase difference or the angle by which the current lags from quadrature. An equivalent power loss is occasioned by a resistance (ρ) in series with a perfect condenser when this equivalent resistance satisfies the relation $\tan \theta = C p \rho$ where C is the capacity and $p = 2\pi$ times the frequency. It is characteristic of a condenser with an absorbing dielectric that the phase difference θ is, roughly, independent of the frequency, and hence the equivalent resistance must vary inversely as the frequency or directly as the wave length.

It seemed impossible, however, to ascribe this absorption to the ground acting as an imperfect dielectric. As shown by the above data, the effect persists at telephone frequencies while the calculations of True [10] and Reich,[11] based upon the measurements of conductivity and dielectric constant of the ground as given by Zenneck,[12] show that even for so high a frequency as would correspond to a wave length of a 1,000 meters, the magnitude of the conduction current in the ground exceeds by a hundred times that of the displacement current. Further, the absence of absorption in the ground was also shown by measurements at telephone frequencies upon a guard plate condenser with part air and part clay between the plates. This condenser behaved as a perfect condenser with a series resistance that was independent of the frequency. Only when the clay was exceedingly dry and particularly when it was loosely packed, was there any indication of absorption.

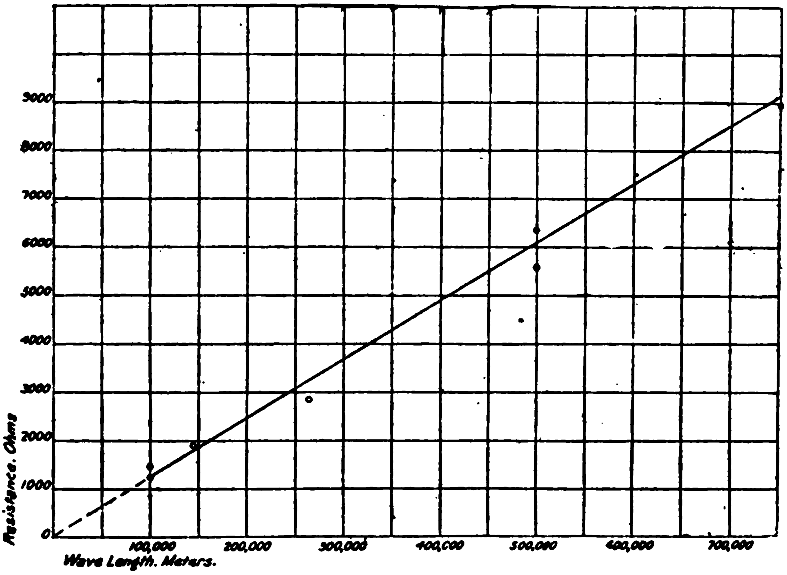

FIGURE 9—Equivalent Resistance of an Antenna at Telephone Frequencies

The observed large effect upon the absorption of variable air condensers brought about by the poor dielectric properties

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[10] H. True; "Jahrb. d. drahtl. Tel.," 5, p. 125; 1911-12.
[11] M. Reich; "Jahrb. d. drahtl. Tel.," 5, pp. 176, 253; 1911-12.
[12] J. Zenneck; "Ann. d. Phys.," 23, p. 859; 1907.

of small amounts of insulators in the electric field suggested to the author that the absorption in antennas is likewise caused by the presence of poor dielectrics in the field of the antenna. Accordingly, an experimental antenna was built in which the bad effects of poor dielectrics in the neighborhood were carefully avoided, but in which any absorption that might be caused by the ground would be considerably magnified. The main capacity of the antenna consisted of six parallel wires at a distance of about 0.3 of a meter (1 foot) above the surface of the ground and located at a considerable distance from the nearest building or tree. The antenna was supported by four wooden posts, but was insulated from them by double porcelain insulators spaced about a meter (3 feet) apart. A single lead, similarly insulated, ran to the building in which the measurements were made. The earth connection was made to the water pipes of the building. The proximity of the antenna wires to the ground should reduce the lateral spread of the electrostatic field and hence the displacement thru the wooden posts or other poor dielectrics, while the amount of ground between the antenna wires and ground water should be proportionately increased. The double-spaced insulators also served to reduce the capacity thru the supports. The capacity of the antenna was 850 micro-microfarads. The resulting resistance curve, for measurements made just within the window of the building, is shown in curve A of Figure 10. The rise in resistance even at 12,000 meters is very small, and probably caused by the lead wire to the building. The result was also verified at telephone frequencies where the absorption was barely detectable (less than 60 ohms at 3,000 cycles).

Curve B of the same figure shows the effect produced by adding a small capacity thru the wooden supports. Wires were run from the insulated portion of the antenna to porcelain insulators on three of the stakes, the total capacity being increased by only 40 micro-microfarads or less than 5 per cent. The effect of adding this small imperfect condenser is very marked. The linear increase in resistance becomes pronounced, and *brings with it an increase in the resistance of the antenna at all wave lengths.*

The effect of running the lead wires to an antenna inside of a building was also investigated. Curve C of Figure 11 shows the results upon the above described antenna under the same conditions as those obtaining for curve A of Figure 10 (reproduced in dash lines in Figure 11), excepting that the measurements were made within the room at a distance of about 5 meters

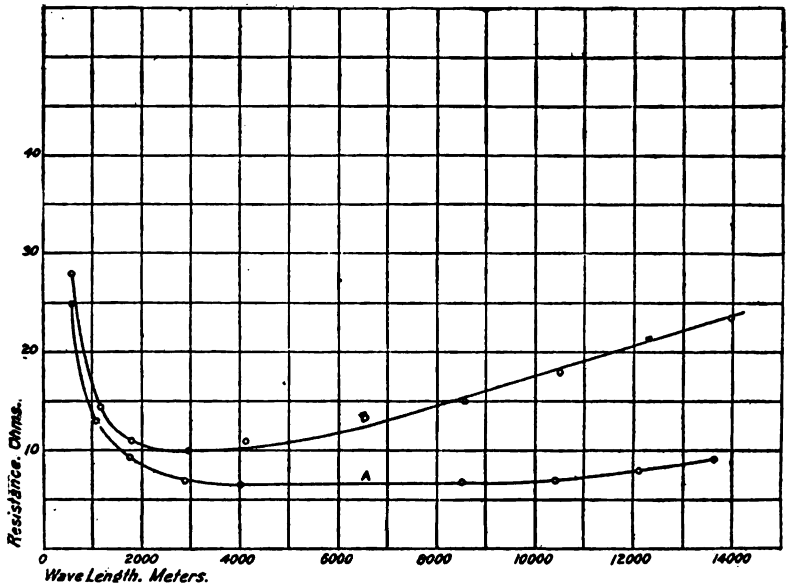

FIGURE 10—A, Resistance Curve for Antenna with Extremely Small Absorption; B, Effect of Adding Small Imperfect Capacity Through the Wooden Supports

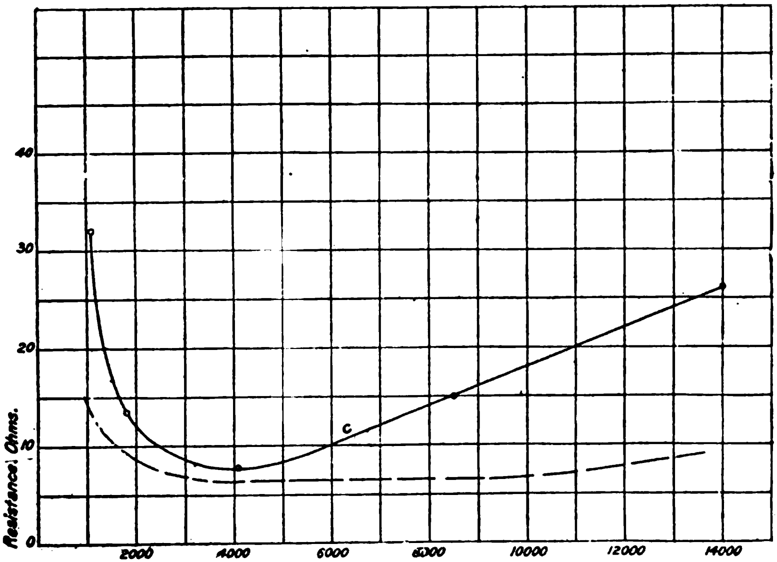

FIGURE 11—C, Absorption Effect Produced by the Portion of the Leads to an Antenna Inside of a Building

(16 feet) from the window. The increase in capacity in this case was 60 micro-microfarads. Curves D and E of Figure 12 were obtained for antennas completely within the building, the former having a capacity of 290 micro-microfarads, the latter having double the capacity. In this figure, the scale of resistance has been doubled. It is of interest to note that the equivalent series resistance in the case of the smaller capacity is approximately double that for the capacity of twice the size, which is the requisite condition for absorbing condensers with the same phase difference. Measurements, at telephone frequencies, were also made upon an antenna consisting of three wires stretched vertically along the outside of a brick building at a distance of 0.4 of a meter (1 foot) from the wall. The phase difference of the condenser was about 15 minutes, corresponding to an equivalent resistance of about 35 ohms at 10,000 meters for the capacity of 800 micro-microfarads. The phase difference is about the same as that obtained in the case of antennas within the building.

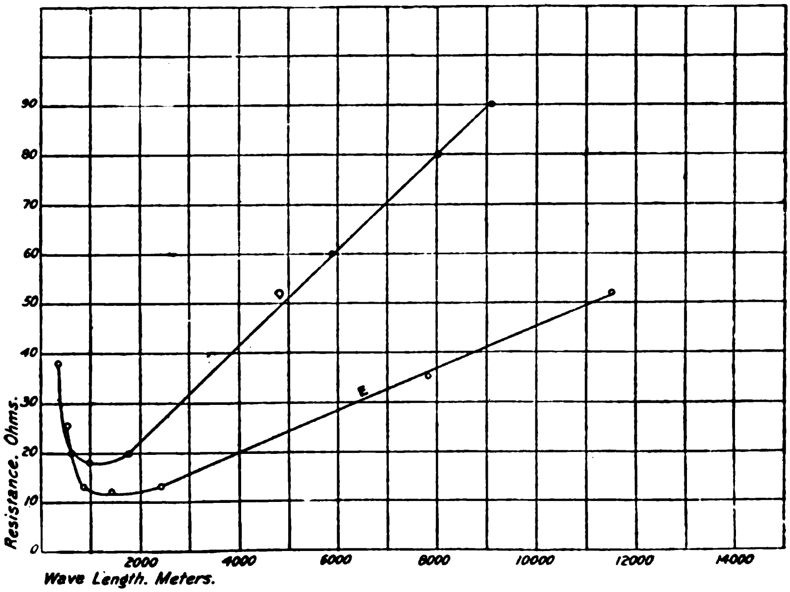

FIGURE 12—Resistance Curves for Antennas Completely Within a Building. The Capacity for E is Twice That for D

Finally the effect of a tree upon the absorption of an antenna was investigated. An antenna consisting of two parallel wires was strung from a building to a tree 20 meters (66 feet) distant at an average height of about 5 meters (16 feet) from the ground. The antenna terminated in a section of about 6 meters (20 feet) of wire which ran from limb to limb of the tree, but was insulated from it by porcelain insulators. At a distance of about 2 meters (6 feet) from the tree double porcelain insulators were interposed in each antenna wire, so that measurements could be made with the section in the tree included or excluded. Curve F of Figure 13 was obtained for the latter case, while curve G shows the enormous absorption produced by including the portion of the antenna in the tree. The capacity was increased from 390 to 540 micro-microfarads, and the phase difference of the condenser with the portion of the tree included was roughly 2 degrees. The measurements were made in the winter when the tree was free from foliage.

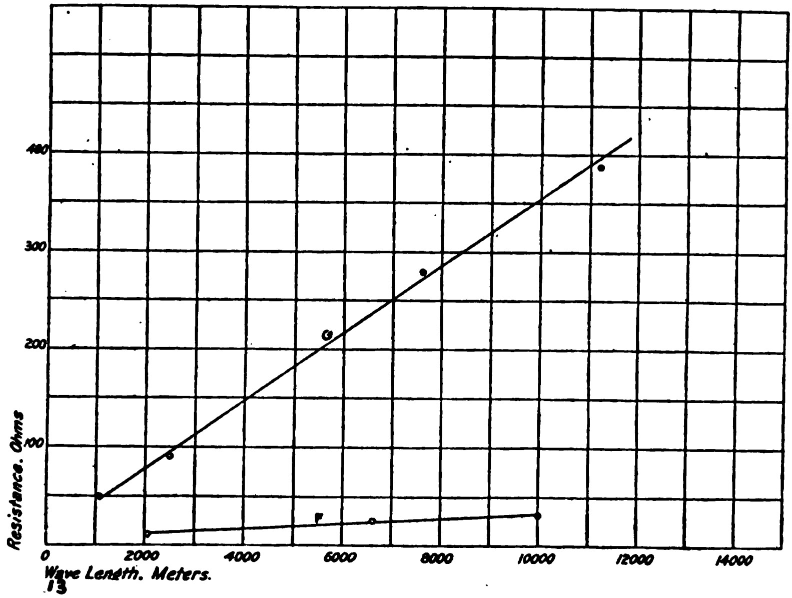

FIGURE 13—Curve G Shows the Enormous Absorption Caused by a Tree. Curve F Is the Same Antenna with Portion in Tree Excluded

From the above it is evident that in the design of an antenna it is a matter of importance to keep the dielectric absorption of the antenna, regarded as a condenser, as low as possible in order to minimize the waste of energy in the antenna and so improve its efficiency as a radiator. There is a possibility of greatly improving upon the design of existing antennas in this respect. The requirement is that the capacity thru wooden masts, trees, buildings, insulators, and so on, must be extremely small in comparison to the capacity of the antenna thru unobstructed air.

SUMMARY: After considering the theory of circuits having uniformly distributed constants, the author shows graphically the frequency-variation of reactance of such circuits and, after further analysis, those of inductance-loaded and capacity-loaded antennas as well.

The calculation of the effective constants of the antenna at radio frequencies in terms of their corresponding values at audio frequencies follows. Very simple relations are found, differing from those frequently given in the radio literature. The equivalent circuits of loaded and unloaded antennas are given, together with practical measuring methods for determining the effective constants at radio frequencies.

The frequency-variation of effective resistance of an antenna is then considered. Measurements are described and curves given which indicate that antenna resistance is largely due to imperfect dielectrics in the field of the antenna, and emphasis is placed on the necessity of avoiding such dielectrics in regions of strong antenna field.

FURTHER DISCUSSION ON "ON THE ELECTRICAL OPERATION AND MECHANICAL DESIGN OF AN IMPULSE EXCITATION MULTI-SPARK GROUP RADIO TRANSMITTER" BY BOWDEN WASHINGTON

By

SAMUEL COHEN

The paper by Mr. Bowden Washington in the December' 1918, PROCEEDINGS OF THE INSTITUTE OF RADIO ENGINEERS contained some very interesting information regarding impact excitation transmitter and especially gaps that gave most suitable results for this kind of work.

The writer has conducted a number of experiments on impact excitation transmitter, and the data obtained verifies to a great extent the results of Ensign Washington. In reference to the tungsten electrode gap, the writer found that altho the gap functioned most regularly with a stiffer circuit, yet the tone emitted by the same was very poor. The tone corresponded very much to that of escaping whistling steam. This was obtained when operating the gap in open air. The tone effect was considerably improved by immersing the electrodes in alcohol and having the discharge take place therein. This improved considerably the general operating characteristics of the gap and it was possible to run it at much lower potential. Copper and tungsten electrodes in alcohol showed favorable results.

A type of gap which gave most satisfactory results for impact excitation work is a combination of copper and amalgamated copper. The results obtained were far better than the ones obtained with the use of the tungsten-tungsten and tungsten-copper electrodes. The type of gap operating in alcohol was compared with the Chaffee gap of copper aluminum electrodes under identical condition, and it was found that the copper-amalgamated copper electrodes proved much better both in efficiency and in note effect. It was also found that it can be used with a much stiffer circuit without affecting its operating qualities. The potential across the gap was somewhat lower than the Chaffee gap.

The only present disadvantage that the copper-amalgamated copper gap possesses is that the mercury on one of the electrodes becomes carbonized from the alcohol and thereby changing the operating characteristics. It takes about six to ten hours of continuous use before a sufficient carbonization takes place on the electrode to change the operating characteristics of the gap. The spacing of the electrodes was in the order of 0.013 inch (0.032 cm). The gap discharging surface was 3 inches (7.62 cm.) in diameter.

The tungsten-tungsten electrode gap immersed in alcohol seems to give excellent results for radio telephony. Some of the results thus far obtained were very satisfactory, and further experiments are to be conducted in this direction. The gap is very constant and regular in its operation and it works very satisfactorily on potentials of 100 volts direct current. The use of alcohol as the discharge medium is important, as the gap functions very poorly without it and requires a much higher operating potential.