VOLUME 7 DECEMBER, 1919 NUMBER 6

PROCEEDINGS
of
The Institute of Radio Engineers
(INCORPORATED)

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TECHNICAL PAPERS AND DISCUSSIONS

EDITED BY
ALFRED N. GOLDSMITH, Ph.D.

PUBLISHED EVERY TWO MONTHS BY
THE INSTITUTE OF RADIO ENGINEERS, INC.
THE COLLEGE OF THE CITY OF NEW YORK

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THE COLLEGE OF THE CITY OF NEW YORK

NEW YORK, N. Y.

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Corrections: On the following pages of the 1919 PROCEEDINGS, page 453, line 1 should read:

"decreases from *d* toward the point *n*"

Page 478, line 12 from bottom, change "affect" to "effect"

Page 488, lines 14 and 15 should read:

"because of the rate at which"

At the end of this number are the title page, page of general information, and table of contents pages for the entire Volume 7 (1919) of the PROCEEDINGS. These last may be suitably placed at the beginning of the volume for binding.

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LONG WAVE RECEPTION AND THE ELIMINATION OF STRAYS ON GROUND WIRES (SUBTERRANEAN AND SUBMARINE)*

By

Lieutenant-Commander A. Hoyt Taylor

(United States Naval Reserve Force)

Many of the properties of ground wires with respect to long wave reception have been touched upon in the previous paper which dealt mainly with short wave work (Proceedings of The Institute of Radio Engineers, volume 7, number 4, 1919). The purpose of this paper is to take up some of the special problems of long wave reception with ground wires, with special reference to the work done by the writer on the elimination of strays.

1. Optimum Wire Length for Long Waves

Number 12 rubber covered wire[1] was used for all of the earlier experiments on optimum wire length because it was found to hold its insulation for several weeks and was cheap and easy to handle. It is not recommended for permanent installations. It has already been shown in the previous paper that for 600 meters the optimum length for this wire was 125 feet (38.1 meters) each way, and that up to 1,125 meters this length seemed to be proportional to the wave length. It was therefore expected that a similar relation would hold for waves between 4,000 and 15,000 meters. For 12,000 meters the length was therefore expected to be 2,500 feet (763 meters). Since there was comparatively little arc work being done by stations south of Great Lakes, and since there were no arc stations north of Great Lakes, it was necessary in the work done there, to attempt optimum length experiments on stations either east or west of Great Lakes. At the laboratory on the bluff, it was not possible to lay wires in trenches for so great a distance, while at the station on the beach, it was only possible to lay a wire in one direction, using

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* Received by the Editor, March 7, 1919.

[1] Diameter of number 12 wire = 0.081 inch = 0.205 cm.

it against a ground. An attempt was made in two ways to determine whether or not optimum length existed for these long waves. First the signals from Lyons, France, on 15,000 meters were observed on a wire 3,000 feet (915 m.) long, running straight east into the lake, the outer end of the wire being sixty feet (18.3) under water. This wire was gradually pulled in and observations taken. It was a laborious and difficult matter to obtain satisfactory observations in this way, but those that were taken indicated that 2,650 feet (808 m.) gave the best signal for Lyons. The signals were too weak to get, with the amplification at that time available, any adequate measure which would indicate whether the ratio of signal to stray was better at this length than at others. About this time Doctor L. W. Austin reported that, as far as he could determine from the experiments made in the slightly brackish water of the Potomac at Anacostia, District of Columbia, there was no optimum wire length for long waves and that no proportionate increase in signal was observed after 2,000 feet (610 m.). In the Great Lakes experiments, all signals were compared with those received on a standard wire, 2,000 feet (610 m.) in length. In order to avoid the laborious process of hauling in the long wire, which occupied considerable time, the problem was attacked at Great Lakes on a different basis. Two wires, separated 50 or 60 feet (15 or 18 m.), running in the same direction were compared. They were both fixed in length, one being 2,000 feet (610 m.) and the other 1,750 feet (534 m.) long. For various wave lengths between 5,000 and 14,000 meters, the ratio of signals on the 2,000 foot (610 m.) wire to signals on the 1,750 foot (534 m.) wire was determined. These observations were insufficient in number to be at all conclusive, but the best ratio was obtained at 12,600 meters, Nauen's wave, indicating that 2,000 feet (610 m.) was not far from the optimum length for this wave. It is, of course, possible that the relation between optimum wire length and wave length is not exactly linear, and it is deemed that the data herein reported is not entirely satisfactory. The experiments on optimum length were continued later at the U. S. Naval Radio Station, Belmar, New Jersey, which was then the principal station and control center of the trans-Atlantic system and where the writer was stationed as trans-Atlantic Communication Officer. The Belmar experiments on wires laid in the inlet (salt water) in front of the radio station, showed that up to the length of 1,500 feet (458 m.) signals from Nauen on 12,600 meters continued to increase. It was impossible to obtain a greater distance than 1,500 feet (458 m.) without deviating too far from the proper direction. During the month of January, ice formed on the inlet and a piece of "packard cable," number 14 high tension[2], was laid on the surface of the ice for the purpose of determining the optimum length of Nauen's short wave, 6,300 meters. The signal strength rose rather rapidly until a thousand feet (305 m.) were used, after which it rose very slowly so that it was difficult to determine exactly where the optimum length lay. It was estimated to be 1,600 feet (488 m.). Similar experiments with a wire on the ice, using Lyons' spark wave of 5,300 meters, indicated an optimum length of 1,200 feet (366 m.) and showed also that the rise of signal strength was very gradual and that there was no practical advantage in using over 800 feet (344 m.) of wire for 5,000 meters and not over 1,000 feet (305 m.) for 6,000 meters. About this same time, January, 1918, lead covered cable on the surface of the ground was tested at Belmar. The sheath of the cable was grounded at a number of points, special care being taken to get a good ground at the receiving end. The core of the cable contained two number 18 copper wires[3], which were connected to the receiving set and used against a ground connection. The behavior of lead-covered cable showed at once that the most suitable length for long waves was decidedly different from that proper for ground wires or submerged wires. For instance, while 2,000 feet (610 m.) of underground wire was found very suitable for waves of 10,000 meters and upwards, it was found that a lead-covered cable 3,000 feet (915 m.) in length showed up best on wave lengths between 5,000 and 6,000 meters. A lead-covered cable 7,000 feet (2,135 m.) in length was then opened at a series of points 500 feet (153 m.) apart and observations were taken on Nauen's 6,300 meter wave, comparison being made in each case with the signals obtained on a fixed 2,000-foot (610 m.) ground wire. A curve was plotted from this data which showed a maximum at 3,000 feet (915 m.); the curve was, however, very flat. A little later experiments were undertaken with a ground wire buried seven feet (2.1 m.) deep, a number of pits having been dug for the installation of disconnecting switches. Observations were taken on signals on 9,500 meters from Stavanger, Norway, and on Nauen's 6,300 meter wave. The total length of ground wire available was 2,000 feet (610 m.). The observations were inconclusive, the Stavanger signals at 9,500 meters indicating a

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[2] Diameter of number 14 wire = 0.064 inch = 0.162 cm.

[3] Diameter of number 18 wire = 0.040 inch = 0.102 cm.

maximum when the full length of the wire was used, whereas measurements on Nauen indicated a linear rise proportionate to the length of the wire, that is to say, the Nauen observations indicated no optimum length inside of 2,000 feet (610 m.). It is regretted that the pressure of other work interrupted these interesting experiments at this point. A little later in the Spring, experiments were begun at the Naval Radio Station, Chatham, Massachusetts, by Gunner D. J. Burke, under the writer's direction, and some attempts were made there to discover whether there was such a thing as optimum wire length in fresh water, salt water, and in ground. The results were negative as far as salt water is concerned, and doubtful as far as fresh water and ground were concerned. During the summer a special station was erected at Belmar with a 2,000-foot (610 m.) sea wire, but no results were obtained with this wire indicating an optimum length. Altho an insufficient number of observations on long waves have been taken, it is quite evident that the optimum length does not exist in salt or brackish water and that if it exists in fresh water or for wires buried in the ground, the optimum is not at all sharp. The most positive indications of optimum length on long waves were obtained with surface cables laid either on the ground or on the ice. Theoretical considerations would indicate that for very long waves and correspondingly long wires, the resistance of the system is so high that it is much more perfectly aperiodic than is the case for short waves. Confirming this is the fact that a single ground wire may be so readily used for the reception of a number of different stations on different wave lengths without any interference whatever in the tuning, it being assumed, of course, that the local oscillations of the receiving bulbs are so adjusted as not to heterodyne against each other. It was frequently possible at Belmar to copy simultaneously on any of the ground wires or sea wires, Lyons on 15,000 meters, Carnarvon on 14,000 meters, Nauen on 12,600 meters, Rome on 11,000 meters and Nantes on 10,000 meters. This procedure, altho possible on short waves, does not work out well at all, because each wave requires, for best results, its particular optimum length.

2. RATIO OF SIGNALS TO STRAYS

In order for the ground wire system to be of practical value it must be able to show advantage in readability of signals not only over an ordinary aerial but over a properly designed receiving frame or closed loop, since the latter is more compact and easier of installation. The elimination of *actual static* is, of course, fairly complete on the ground wires, but the relative advantage of ground wires over rectangles, as far as the elimination of *all* strays was concerned, had to be made the subject of exhaustive tests. Early in January, 1918, the writer requested Ensign A. Crossley at Great Lakes to construct a rectangle 11 feet (3.36 m.) square, wound with 80 turns of number 13 double cotton-covered wire[4] spaced 0.5 inch (1.27 cm.) apart. This rectangle was compared for a considerable period of time with the 1,200 foot (366 m.) "packard cable" at the Great Lakes laboratory station on the bluff, the cable being buried four feet (1.22 m.) under the surface of the earth. The ground wires gave signals averaging three times as strong as those on the rectangle. The ground at that time was partly frozen. The following table is typical of the observations obtained at Great Lakes:

Station		Ground Wire	Rectangle	Ground Rect.
WGG	Tuckerton, New Jersey	5.5	4.7	1.17
NPL	San Diego, California	6.6	2.9	2.26
KET	Bolinas, California	2.2	1.3	1.70
NAA	Arlington, Virginia	1.5	2.8	0.54
NAD	Boston, Massachusetts	1.0	1.4	0.72
KIE	Heiia Point, Hawaii	0.4	0.3	1.33
NBA	Darien, Panama Canal Zone	1.3	0.9	1.45
NPC	Puget Sound, Washington	2.2	1.6	1.38
KSS	San Francisco, California	2.1	1.2	1.75
NPM	Pearl Harbor, Hawaii	1.5	0.7	2.13
NPG	San Francisco, California	1.0	0.7	1.44
WII	New Brunswick, New Jersey	15.0	7.4	2.02
POZ	Nauen, Germany	0.2	0.1	2.00
BZZ	Carnarvon, Wales	0.3	0.2	1.50
NPA	Cordova, Alaska	0.3	0.1	3.00
				Average—1.626

The average readability of signals at Great Lakes was 62.6 per cent. better on the ground wire than on the rectangle. About the time the frost penetrated well into the ground at Great Lakes, it had been noted that the strays became distinctly worse. The same thing was noticed on the sea wires at Belmar when the

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[4] Diameter of number 13 wire = 0.072 inch = 0.183 cm.

shallow inlet froze up so that the wires were partly covered with a three-inch sheet of ice. In order to get further evidence, wires were laid at Belmar on top of the ice and directly over the sea wires and the ratios of signals to strays on many trans-Atlantic stations were obtained in comparison with the signals on the sea wires frozen in the ice. The readability of signals, defining readability as the ratio of signals to strays, was twice as good on the sea wires under the ice, altho not as good as on the same wires without any ice over them. In the meantime hundreds of observations had been accumulated at Belmar comparing the ratio of signals to strays received on rectangles 77 feet (23.5 m.) long by 30 feet (9.2 m.) high, with 12 turns of number 10 copper wire[5] spaced 6 inches (15.2 cm.) apart, with those obtained on 1,200, 1,400, and 1,700-foot (366, 427, and 519 m.) sea wires and with those obtained on a 2,000-foot (610 m.) land wires buried 2 feet (61 cm.) deep. Many observations were also made on a 2,000-foot (610 m.) land wire buried 7 feet (2.14 m.) deep. This latter wire gave louder signals than the one buried 2 feet (61 cm.), but the same ratio of signals to strays. The general average showed that the signals obtained on rectangles and sea wires were of approximately the same intensity, but that the readability of the signals received on the sea wires was twice that received on the rectangles. On the other hand, the ground wires, altho giving signals four to five times as strong as the rectangle, showed no advantage whatever in readability. Similar experiments were carried out during the summer at the Naval Radio Station at Tuckerton, New Jersey, with the ground wires placed in extremely moist earth and where they showed a marked advantage over the rectangle, altho they proved to be not quite as good as the sea wires at Belmar. In the meantime a great many measurements had been made at Chatham, Massachusetts, on wires both in fresh and salt water. The fresh water wires showed tremendous signals but no better ratios or readability than rectangles. The sea wires on the other hand showed good readability, but owing to their being covered part of the time by a high tide to a depth of six feet (1.8 m.), they showed rather weak signals. It was attempted to remedy this by suspending them from floats, but owing to interference with traffic in the bay and to stormy weather conditions this was abandoned as being impracticable. It must be noted that the good results on long waves in the earlier experiments at Great Lakes were obtained with wires buried in wet sand and a little later with wires buried on the bluff at a

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[5] Diameter of number 10 wire = 0.102 inch = 0.259 cm.

sufficient depth to be near ground water level, in fact below it at a good many points. It is quite evident that the ground wire system possesses no advantage over the rectangle in the elimination of strays other than static, except when the ground wires are laid in a partially conducting medium. An attempt was made to confirm these results at the Naval Radio Station at Bar Harbor, Maine, and it was found that ground wires laid in the very rocky surface soil seemed to have even worse strays than those received on the rectangle. A sea wire, 1,100 feet (1,336 m.) long was placed in an inlet, but was found to be, even when floated on the surface, completely shielded from all trans-Atlantic signals, there being a cliff considerably over 100 feet (30.5 m.) high on one side and another cliff 80 feet (24.4 m.) high on the other. The waves apparently jumped this gap without influencing the wire floating on the surface of the water in the least, showing a rather interesting case of complete shielding. The effect of the freezing of the ground or of the water in which the wires were placed is evidently due to the change in conductivity thereby produced. Bearing these facts in mind an attempt was made at Belmar to use lead-covered cable in such a way as to imitate the properties of properly installed ground wires, without the necessity of burying them. These attempts met with a partial degree of success. A lead-covered cable showed stray ratios intermediate between those of the wires buried in dry soil and the sea wires. If, however, the sheath of the cable was frequently intercepted so that its electrical continuity was broken up, the signal rose greatly in intensity and the strays still more so, until the ratio of signals to strays was slightly worse than that obtainable upon wires buried in dry soil. If the conducting medium surrounding the wires is of too high a conductivity, good results will not be obtained, especially if the wire is lowered to any considerable distance below the surface. During the month of June, 1918, experiments were made ten miles (16 km.) off the coast at Belmar with an 800-foot (244 m.) wire trailed behind a small motor dory. The signals from trans-Atlantic stations decreased rapidly with the depth of the wire, so that at 15 feet (4.6 m.) below the surface, it was not possible to copy them with two stages of amplification. Of course, trans-Atlantic signals at that time of the year and at mid-day, when the test was conducted, were not very strong, nevertheless when the wire was within four feet (1.2 m.) of the surface, Carnarvon, Nauen, Nantes, and Rome were all copied without difficulty on this particular occasion.

3. METHODS OF ELIMINATING STRAYS FROM LONG WAVE RECEIVERS

It may be of interest to note here a few of the methods tried out at Belmar for the further suppression of strays on ground wires and particularly on sea wires, altho the principle was finally accepted that the strays had to be eliminated before entering the receiving circuit.

(a) Tuned telephone circuit. The use of group tuners or audio frequency tuners in the amplifier circuits was tried out and shown to have some slight advantage, but not enough to warrant its general adoption. The tendency of all such devices is to produce a ringing or blurred signal. These devices are very deceptive to the ear; they appear at first to produce a very great improvement, but when one tries to make copy it is discovered that the improvement is generally imaginary.

(b) Audio frequency balanced circuits. A device somewhat similar to the Fessenden interference preventer was next tried out. It consisted of two complete receiving circuits arranged in duplex thru a differential transformer which led to the amplifier. The idea here was to take advantage of the fact that several circuits could be tuned to one ground wire without mutual disturbances and by tuning one of the circuits, say to 14,000 meters and the other to 13,500 meters, and opposing the output of the receiving bulbs in the differential transformer, it might be possible to balance out strays on adjacent wave lengths without eliminating the signal. It was found, however, that this was not possible unless the signal as well as the strays was balanced out.

(c) Radio frequency balance. A radio frequency differential transformer was then tried out, the device consisting of two circuits tuned to nearby waves, the secondaries of the two tuners being coupled differentially to a tertiary circuit, the coupling being made very loose. Some improvement was obtained with this circuit, altho the adjustment was very critical in order to get exact opposition in phase and amplitude. It had one great advantage, namely, it was possible to differentiate very sharply between stations the wave lengths of which were very close together, but on the whole it was not considered to be of sufficient assistance in the elimination of strays to make it worth while.

(d) Radio frequency amplifiers. A three-stage radio frequency amplifier with tuned circuits and very loose coupling was next tried out. Again the results showed very high selectivity and a noticeable gain in readability, nevertheless the circuits were so difficult to handle that it was not considered to be satisfactory from an operating point of view, neither was the gain sufficient to make it seem worth while.

(e) Automatic recorders.

An automatic recorder of unusually good design, selectivity, and sensitiveness was then tried out. At first it seemed to promise great results, but after reading several thousand feet of tape and comparing it with the copy obtained by a good operator, it was found that the recorder was no more reliable than a good operator and if the speed was increased beyond thirty words a minute, the recorder was badly interfered with by strays. One difficulty was that rather excessive amplification was necessary in order to use this recorder on sea wires.

(f) The use of high pitched telephones. Some experiments of considerable interest were carried out with very high pitched telephones and these experiments did show a bona fide improvement in the ratio of signals to strays and the writer believes that there is a profitable field of investigation in this line, if telephones of high pitch can be manufactured with a sensibility that is comparable with that of standard telephones at a thousand cycles.

4. THE ELIMINATION OF STRAYS FROM LAND AND SEA WIRES

It was finally decided that the only way to do anything towards the further suppression of strays over and above that already obtained by the use of a good sea wire, was to apply the method of elimination ahead of the primary of the receiver. Considerable improvement in the ratio of signal to stray was obtained by placing a low resistance of value between 1 and 25 ohms across the primary of the receiving set. It will be remembered that the receiving sets were standard Navy long wave tuners and, therefore, had a series condenser, and that in ground wire work the tuning of the primary is dependent only upon the constants of the primary and not upon the length of the ground wire, the only exception being when exceedingly short ground wires are used. There is also probably some slight deviation from the rule when working with short waves around the optimum wire length. The placing of the shunt around the primary therefore did not in any way affect the tuning of it. The improvement in signal-to-stray ratio obtained by the use of the shunt is at the cost of considerable diminution in signal strength and is not therefore of very great value in improvement in readability except in special cases. It having been determined that the sea wires had twice as good a ratio of signal to stray as the rectangles, it seemed likely that one ought to be able to balance the strays from a rectangle against those from a sea wire and still have some signal left over. This was first attempted by coupling magnetically the primary of the receiving set by means of a differential radio frequency transformer to both sea wire and rectangle. The differential transformer had one secondary coil which was in series with the primary of a receiving set and it had two primary coils, one of which by means of a series condenser was tuned to a rectangle and the other tuned by means of another series condenser and suitable loading coils to one of the sea wires. See Figure 1. As a balancing arrangement the device worked perfectly, but altho signals even of very great intensity could be accurately balanced out, it was not possible to balance out strays. It should be noted that the planes of the rectangle pointed in the same direction as the sea wire, that is towards the European stations. The failure of the experiment was, at the time, laid to a lack of exact similarity in directive properties of the two component parts of the balanced system, but it is the present opinion of the writer that the failure was due to the fact that the rectangle constitutes a relatively feebly damped receiving system, while the sea wire is, especially for long waves, aperiodic. A similar attempt, shown in Figure 2, was made to balance a land wire against a sea wire and with the same results as far as this circuit is concerned. This is probably due to the fact that a land wire in dry soil is not so nearly aperiodic as a sea wire. If the land wire were laid in wet soil the experiment would also fail, because the ratio of

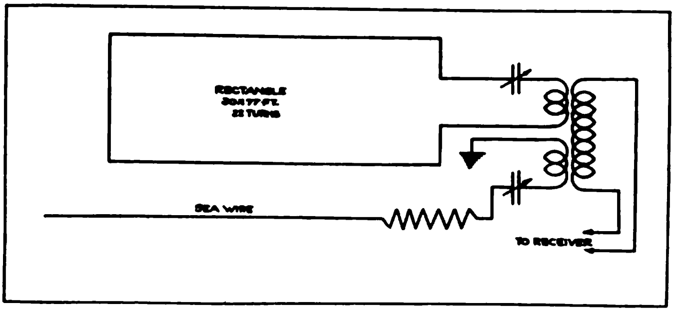

FIGURE 1

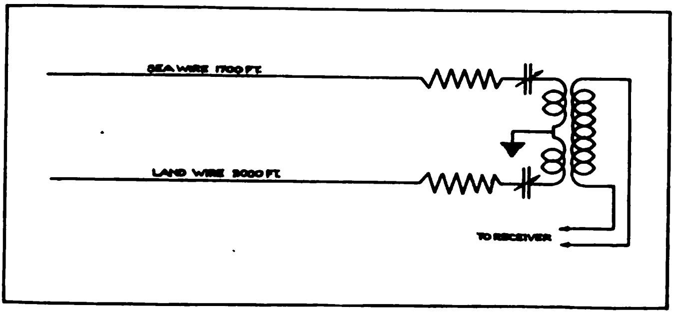

FIGURE 2

signal to stray would be too nearly the same for both sides of the system. The next attempt, shown in Figure 3, was to balance by means of a small potentiometer arrangement, a land wire against a sea wire. The resistance *R* was a slide wire rheostat, various values being tried from 50 to 2,000 ohms. The

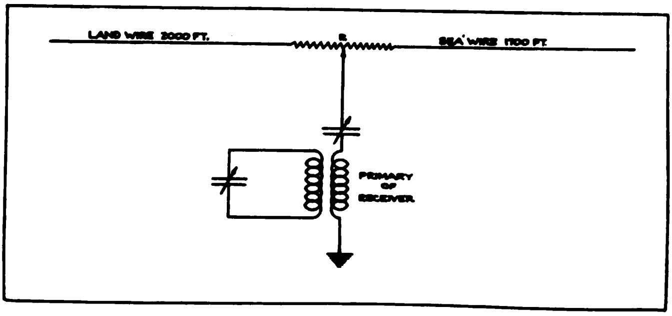

FIGURE 3

idea in the arrangement of Figure 3 was that the current from sea wire to ground would be opposed in phase from the current from land wire to ground and by suitably proportioning the two parts of the resistance *R*, the strays could be balanced out. Such, however, did not prove to be the case and it was recognized that the difficulty was due to the fact that the phase relationship of the current in the sea wire was not the same as for the current in the land wire. The final arrangement for the balance of the land wire against the sea wire is shown in Figure 4, where a phase-adjusting device, $L_1 C_1$, is put in series with either land wire or sea wire. It is not necessary to have this device in series with each collector. It was usually used in series with the land wire. It will be noted that the ratio of signal to stray on collector number 1, that is, the sea wire, has been further improved by the use of the resistance R_1, which shunts the end of that wire directly to ground. This circuit at once gave very satisfactory results and experiments were immediately continued to determine whether the balance of strays was dependent upon the length and nature of the land and sea wires. It was found that within the limits wherein observations were taken on sea wires, namely from 1,000 to 2,000 feet (305 to 610 m.), the length of the sea wire had but little influence, best results being obtained with 1,500 feet (458 m.) of sea wire. The length of the land wire was found to depend upon the wave length, in general, shorter lengths working better when shorter waves were to be balanced. The lead-covered cable was used as a land wire very successfully when the strays were made as bad as possible on the cable by intersecting the sheath, every two hundred feet (61 m.). It is desirable, of course, that the land wire have as bad a ratio as possible. Exceedingly satisfactory balances were obtained thruout the summer of 1918 on all wave length between 6,000 and 15,000 meters. No work was done on shorter wave lengths than 6,000 meters. The device was put into the hands of the operators on April 7, 1918, and either this circuit or the following circuit was used at Belmar from that time on for copying all trans-Atlantic signals. Encouraged by the success of this method of balancing two wires, attention was again given to the rectangle, since the rectangle showed just as

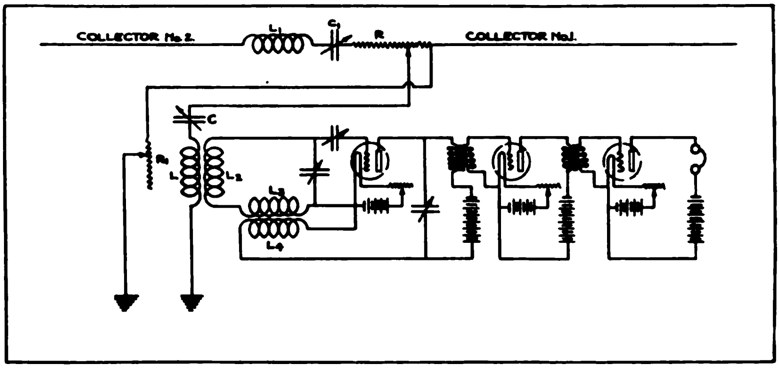

Figure 4

bad a ratio of signal to stray as the land wire and should have sufficiently similar directivity. The rectangle was therefore substituted for the land wire. The resistance *R* is sufficiently high to give the rectangle a very high decrement. The tuning is exceedingly flat. No marked success was obtained until the circuit shown in Figure 5 was adopted, that is, until the sea wire was shunted to earth thru a small resistance R_1. The exact functioning of this resistance is not understood, but its presence, especially in the balancing of a rectangle against a sea wire, is of the utmost importance. Figure 6 shows the design of a panel to be placed to the left of a standard Navy long wave receiver, this panel providing the necessary terminals for sea wire and either land wire or rectangle. It also contains the phase-adjusting device in series with the rectangle or land wire, the balance

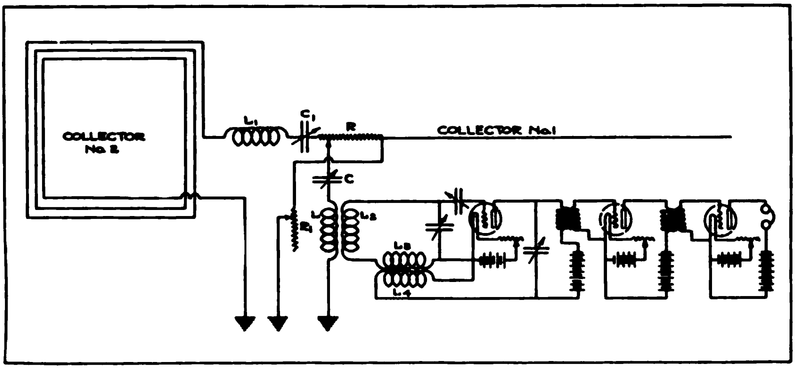

FIGURE 5

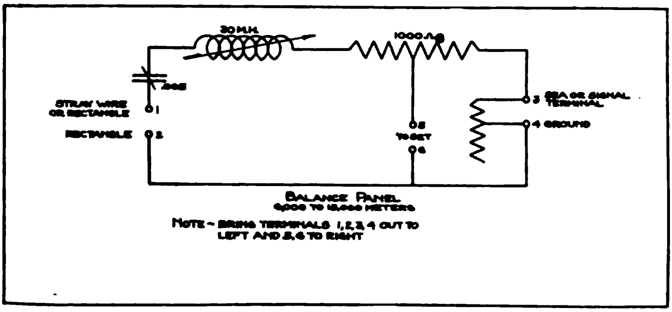

FIGURE 6

resistance, and the shunt to earth on the sea wire terminal. This circuit, Figure 5, is dependent also for its success upon the proper choice of the dimensions of the rectangle, since it is necessary to have a comparatively high resistance in series with it at all times. The rectangle must, therefore, be designed to have adequate collecting power. Naturally this depends upon the wave length. For 6,000 meters a rectangle 30 feet (9.2 m.) by 77 feet (23.5 m.) with 12 turns of number 10 wire[6] spaced 6 inches (15.2 cm.), was found satisfactory. For waves from 10,000 to 15,000 meters, a rectangle of the same dimensions but with double the number of turns was found best. The setting of the phase-adjusting condenser depends slightly on the depth of the water over a sea wire. As the tide came in it was found necessary to advance the phase slightly in the ground wire or rectangle, as the case might be.

5. METHODS OF ADJUSTING BALANCED SYSTEMS

The method of adjusting the balanced system is described as follows (reference Figures 4 or 5):

(a) The slider of the resistance R is pushed to the right until there is little or no resistance between the slider and collector number 1. The primary of the receiver is adjusted by variation of the inductance L and the capacity C until it is tuned to the incoming signal. The resistance R_1 is adjusted to the lowest value which is consistent with good audibility of signal. The secondary L_2 is adjusted in the usual manner as are also the amplifiers.

(b) The slider of the resistance R is pushed to the left so that little or no resistance lies between the capacity C and the primary. Without changing the primary adjustment, the loading coil L_1 and the capacity C_1 are adjusted so that the same signal is received from collector number 2.

(c) The slider of the resistance R is then moved back and forth until the best readability of signals is obtained, the normal position being nearer the end of collector number 1 than to the capacity C_1. In other words, the larger part of the resistance R will normally be in series with that collector which produces the worst strays.

(d) The condenser C_1 is now varied so as to shift the phase slightly in collector number 2. This adjustment is fairly broad, as on account of the resistance R, the tuning in the circuit involving collector number 2 is extremely broad, in fact the cir-

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[6] Diameter of number 10 wire = 0.102 inch = 0.259 cm.

cuit is almost, if not quite, aperiodic. After a few adjustments have been made, the balance of the circuit is extremely simple, reminding one forcibly of the method of balancing employed in the bridge method for comparison of inductance at audio frequencies, where variable resistances and one variable inductance are used and the other unknown inductance is fixed. The difficulty of balance is of exactly the same order, which means that after a very little experience, it is not difficult at all. In fact, after one or two days' training, this system was put into the hands of operators who had had comparatively little experience, men who had been thru the Naval Radio School at Harvard University and whose only practical experience was that which had been acquired in the course of duty at the Belmar station. From time to time slight corrections in the balance may be advisable, as the character of the strays changes. These corrections are, however, mostly in the phase-adjusting condenser C_1, and were thought to be due largely to the influence of the tide in shifting the phase of the signal in the sea wire.

6. CHARACTER OF STRAYS

The behavior of the balanced system is such as to lead to the conclusion that strays are very complex. Certain very sharp and violent strays were soon recognized, after experience with this set, to be of comparatively local origin, traceable to some storm within a radius of about one hundred miles (160 km.). It would frequently happen that it was possible to obtain trans-Atlantic copy when there were violent storms in the immediate vicinity of the station. The lightning flashes themselves would produce very brief and sharp crashes which also manifested themselves at times by discharges thru the lightning arrestors in series with ground wires. But these brief disturbances constituted only a small interruption in traffic. At other times, these local storms which could be seen or heard from the station, produced quite complete interruption. It was finally discovered that if the storm was approaching from a direction at right angles to the system, it produced far less interruption to traffic than when it approached parallel to the system. In other words, the system has a certain amount of what may be called a "focussing effect," the term being one to which I am indebted to Mr. E. F. W. Alexanderson. Referring to Figure 4, it is evident that if the two parts of the resistance R are so chosen as to balance a disturbance ten miles (16 km.) away, that is to s
a distance comparable with the linear extent of the sys

will not balance a disturbance a hundred miles (160 km.) away. Since the energy of the impulse varies as the inverse square of the distance from the centers of the respective collectors, number 1 and number 2, it must be evident that the adjustment of the slider of the resistance *R*, which equalizes impulses from a nearby point, will be very different from the adjustment which equalizes disturbances from a great distance. The greater the length of the two collectors, number 1 and number 2, the more pronounced will be this focussing effect. It can be utilized to great advantage in distant control work, where the interfering station is within a few hundred feet (about a hundred meters), but the balance obtained for eliminating such local interference is not the same as that which is utilized for the elimination of strays. All of the evidence collected during the summer of 1918 tends to show that the origin of the strays, while varying widely, is, except for those produced by local storms, at a very considerable distance, probably several hundred miles (over about 500 km.). Rarely did it happen that strays were bad at Belmar but what they were reported bad also at Sayville and Chatham. Bar Harbor, however, had entirely different receiving conditions, and on the whole was so remarkably free from strays as to be on an entirely different basis. The balanced system has, in view of the aforesaid focussing properties, a great value in handling local disturbances and nearby interferences, but this advantage cannot be utilized to its fullest extent at the same time that the stray balancing property is made use of. In the event of the necessity of simultaneously coping with bad strays and nearby interference, a compromise balance has to be effected.

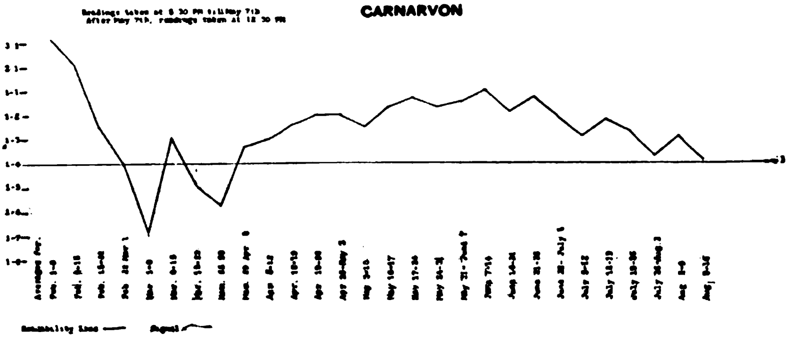
7. RATIO OF IMPROVEMENT

Multiplex reception of any number of stations on the same ground or sea wires is readily possible when using unbalanced reception, but with a balanced circuit it is necessary that each station be received on an independent pair of collectors. Six complete balanced circuits, some of the type shown in Figure 4 and some of the type shown in Figure 5, were therefore installed at Belmar and by the middle of April, 1918, all trans-Atlantic copy was made using the balanced system. Many observations were taken, showing the very great improvement in the readability of signals. These observations, in case of strays which are very heavy, are difficult to obtain. It has frequently been possible to get 95 per cent. copy using the balanced system on signals which, unbalanced, were not even audible on account of absolutely continuous strays. Strays which arrive in an almost continuous stream are handled most effectively by the balanced system. The following table, reported to the Bureau of Steam Engineering under date of July 27, 1918, is typical of the results obtained. Since hundreds of observations have shown the sea wires to produce twice as readable signals as rectangles within the limits of accuracy of audibility measurements, the last column showing the ratio of improvement over rectangle is obtained by multiplying by two the ratio of improvement over sea wires. Four cases are included in this table where unbalanced the signal was inaudible, giving a theoretical improvement in ratio of infinity, which, of course, simply means that it was not possible to obtain the audibility of the signal with the means at hand.

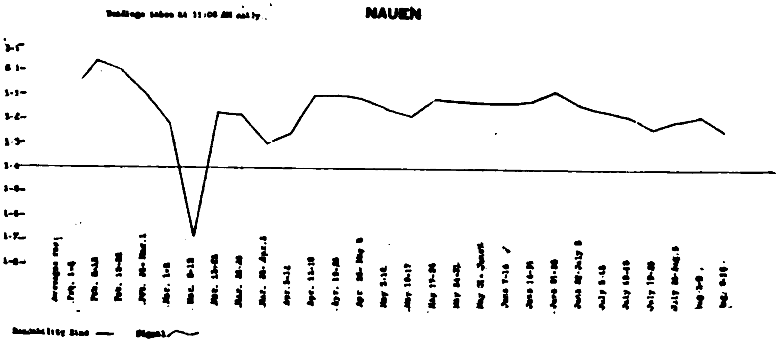
It is a little hard to say exactly what ratio of improvement is obtainable with the balanced system, the same depending so much on the character of the strays, but the writer believes that a ratio of improvement of 4.3-to-1 over the sea wires, that is to say, 8.6-to-1 over the rectangle, is a conservative estimate. As long as only one balanced set was in operation, much larger ratios of improvement were obtained. In fact the ratio of improvement averaged nearly twice as much. There was, however, an inevitable reaction when six sea wires were laid side by side within two hundred feet (61 m.), no one of the balanced circuits showing the degree of improvement that it showed when used alone. This is a very important point, and if new stations of this character were to be designed, it would be highly advisable, as recommended in one of the Belmar reports to the Bureau of Steam Engineering, to space the wires as far apart as possible. It was estimated in this report that two hundred feet (61 m.) between the different collecting systems would be a satisfactory spacing. At Belmar, the rectangles used in balanced work were entirely too close together, four rectangles being erected within a distance of three hundred feet (92 m.). When the Belmar system is compared with other systems on the basis of the work done in the summer of 1918, the important fact should be borne in mind that from four to six balanced circuits were in continuous operation in close proximity to each other during the entire summer. Further evidence of the improvement produced by the advent of balanced sets at Belmar in the early part of April is shown in curves numbers 1 to 5 inclusive. Curve 1 represents the signals from Carnarvon at 14,000 meters. The vertical

Date	Station	Time	Balanced		Unbalanced		Ratio of Improvement over	
July		P. M.	Strays	Signals	Strays	Signals	Sea Wires	Rectangle
22	Nauen	3:30	200	80	400	40	4	8
22	Carnarvon	3:30	300	100	600	20	10	20
23	Nauen	3:30	160	20	600	Inaudible	Infinity	
23	Carnarvon	3:40	Signals inaudible on balanced and unbalanced sets					
24	Nauen	3:30	120	20	——	Inaudible	Infinity	
24	Carnarvon	3:40	250	40	——	Inaudible	Infinity	
25	Carnarvon	3:30	200	25	——	Inaudible	Infinity	
25	Nauen	4:00	80	20	80	5	4	8
26	Carnarvon	3:30	120	20	300	10	5	10
26	Nauen	3:40	80	25	800	80	3	6
27	Nauen	3:30	160	40	200	30	2	4
27	Carnarvon	3:40	100	20	300	30	2	4

ordinates are readabilities, that is to say ratio of signals to strays, the base line representing an adverse ratio in favor of strays of 4-to-1, which the writer believes is the practical limit of readability. It will be seen that from February 22nd to March 29th, Carnarvon's signals were getting very bad, being unreadable a large part of the time, but with the advent of the balanced system, they quickly jumped above readability and remained so during the bad summer months. After May 7th, Carnarvon shifted his schedule to the afternoon, which also produced an improvement in his readability, nevertheless without the balanced system he was usually unreadable during the summer months. Curve 2 shows a similar graph for Nauen,

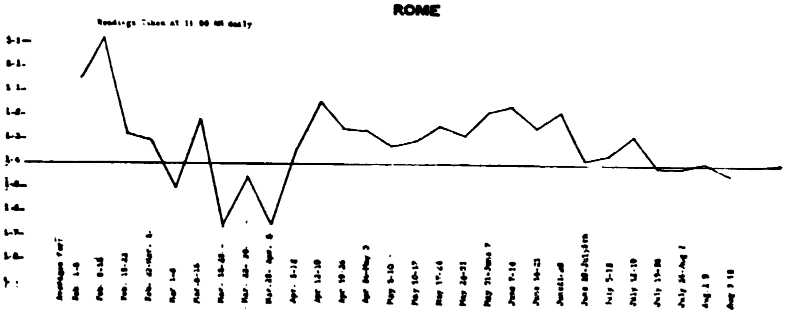


Curve 1

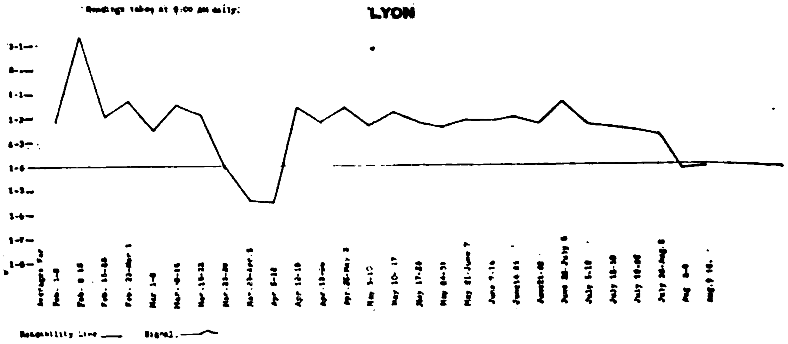


Curve 2

observations being taken on 12,600 meter wave. Curve 3 shows the improvement in Rome's signals on 11,000 meters after the first week in April, when the circuit was provided with a balanced system. The Lyons circuit was not provided with a balanced system on account of the lack of a large enough rectangle for 15,000 meters until the second week in April. Curve 4 shows the resulting improvement. Curve 5 shows data obtained on signals from Nantes on 10,000 meters, but does not antedate the balanced system as we had no schedule with Nantes during that period. It is felt that the results at Belmar would have been somewhat better if the bluff across the inlet had not shielded the sea wires considerably. That this was the case

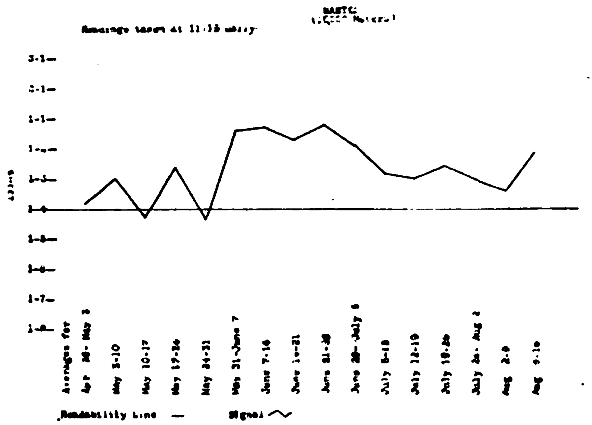


CURVE 3



CURVE 4

was demonstrated by experiments made with an 800-foot (244 m.) wire which was towed about further out in the inlet, receiving being done on board a small motor dory. The signals were noticeably stronger further away from the bluff.



CURVE 5

8. DIRECTIVITY

It is difficult to carry out accurate experiments on directivity of ground wires. Perhaps the most conclusive experiments at Belmar were those referred to in the preceeding paragraph, where the 800-foot (244 m.) wire trailed from a motor boat was swung about in different directions, maximum signals always being obtained when the wire pointed either toward or directly away from the European stations. Work done by Mr. H. H. Lyon at New London indicated some difference in the strength of signal when the wire pointed toward the station as compared to what it was when the wire pointed away from it. This was not confirmed at Belmar. It is believed that Mr. Lyon's results may have been influenced by shielding effects, which was certainly not the case at Belmar, as the work was carried on well out in the inlet and away from the shore. Concerning directivity, it has been noted that the directivity does not seem as sharp on very distant stations as it does on nearby stations. This is, of course, fully understandable. There are many routes by which a signal might reach a station from a transmitter at a great distance. The most striking case noted at Belmar was where signals from Cavite, Philippine Islands, 8,300 miles (13,-

280 km.) distant, were received with an intensity loud enough to be heard with the telephones on the table, altho the shortest great circle line from Belmar to Cavite, which passes up thru Hudson Bay, the Arctic Ocean and thru part of Siberia, strikes Belmar almost exactly at right angles to the wires which were used for reception. In agreement with the lack of directivity at times on long distance stations stand certain results obtained by the writer at the Naval Aircraft Radio Laboratory with very long wave direction finders. There are times, especially around sunset, when the signal may appear to come from a direction many degrees different from the true bearing of the station. Signals have been obtained from New Brunswick, distant less than 200 miles (320 km.), which showed a variation around sunset of 68° in fourteen minutes, returning to normal bearing after sunset, rather large deviations persisting, however, thruout the evening. This matter will be reported in the "Bulletin of the Bureau of Standards," and is fully explainable on the basis of the refraction and reflection theory. Evidently on very long waves coming from great distances there will be times when the resultant wave front really comes from a very different direction than the geographical bearing of the station. It may be confidently asserted, however, that the directivity of the ground wires is of the same nature as that of closed loops, and that either one of them will show peculiar directive properties on very long waves. As long as the ground wire and the rectangle are arranged to have the same line of directivity, the balanced system works satisfactorily.

9. BALANCED SYSTEM WHERE SEA WIRES ARE NOT AVAILABLE

In this case the balanced system will not handle the strays well unless the ground wire is laid in moist ground so that it has a better stray ratio than the opposing collector. The opposing collector should be a rectangle, but might be a ground wire laid in dry soil, if such is available. The focussing property of the system might, however, be extremely valuable of itself, irrespective of the question of stray elimination. Results obtained at Tuckerton with the balanced system showed very favorable results on both points, altho the elimination of strays was not as good as that obtained at Belmar. When the set itself, which was placed 1,800 feet (549 m.) from the base of the Tuckerton tower, was shielded from direct influence of Tuckerton's radiation, remarkably excellent results in the way of eliminating interference from Tuckerton, were obtained. The experiments were never completed, owing to the fact that the writer was detached as trans-Atlantic Communication Officer, while the Tuckerton experiments were only just begun. The essential feature of the balanced system seemed to be two collectors which have fundamentally different ratios of signals to strays. The writer believes that it may be possible to construct a collector which will imitate the properties of sea wires and permit the balanced system to be installed almost anywhere. The experiments with lead-covered cable, while by no means successful in this regard, showed, however, very definite progress in the right direction. The balanced system herein outlined has the disadvantage of requiring special properties for one of the collectors, which so far have only been obtainable with sea wires and with wires laid in moist soil. It has the advantage, compared with some other systems, of requiring a comparatively small extent of territory for its installation, the total distance from the rear of one of the receiving rectangles to the outer end of the farthest sea wire at Belmar being 1,800 feet (549 m.). Trans-Atlantic work can be very satisfactorily carried on with a total distance from one end of the system to the other of 1,400 feet (427 m.)

SUMMARY

1. Ground wires show positive indication of optimum length only in the case of the lead-covered cable lying on the surface. It is highly probable that an optimum length also exists where the wires are laid in dry soil. There is a decided possibility of optimum length existing for wires in fresh water, but wires in salt water show no indications whatever of optimum length.

2. The optimum length, in any event, is much less sharply marked for long waves than for short ones.

3. Multiplex reception is possible on the same ground wire, water wire, or surface cable, it being possible to receive any number of long wave stations on different wave lengths simultaneously as long as the local oscillations are so adjusted that the sets do not heterodyne against each other within the range of audibility.

4. Wires laid in fresh water or in dry ground show the same ratio of signal to stray as a large rectangle. Lead-covered cable shows a better ratio of signal to stray than the rectangle, but the difference is not very great. The best ratio of signal to stray is obtained with wires laid in salt water; the next best ratio with wires laid in wet earth.

5. Wires in the earth have been laid as deep as seven feet

(2.1 m.) in dry ground without showing any diminution in signal strength, in fact the signal strength was greater than for wires buried two feet (62 cm.) deep. Wires may be laid in fresh water up to sixty feet (18.3 m.) and still receive excellent signals, but in salt water the signals fall off rapidly with the depth, satisfactory signals for trans-Atlantic work not being received below four feet (1.24 m.). From six to eighteen inches (15.2 to 45.7 cm.) is preferable for salt water.

6. Various experiments looking to the improvement of the receiver in the matter of eliminating strays have been described

7. A successful method of more or less completely eliminating strays before they reach the secondary of the receiver has been described in detail. Two types of balances have been utilized in trans-Atlantic work at Belmar. One depends upon the dissimilar properties of a land wire and a sea wire and the other upon the dissimilar properties of a sea wire and a rectangle.

8. The method of adjusting the Taylor balance system has been described.

9. The character of strays as handled by the Taylor system has been briefly discussed.

10. It has been pointed out that when a number of balanced circuits are operated in close proximity, the perfection of balance is somewhat impaired.

11. The ratio of improvement in readability is conservatively estimated to be 8.6-to-1 as compared to the rectangle, when six balanced circuits were used within a small radius at the same station.

12. Curves have been presented showing the marked improvement in receiving conditions at Belmar upon the advent of the balanced circuits.

13. The directivity of the balanced system has been discussed and is believed to be essentially the same as that of the receiving loop.

14. The advantage of the Taylor system in requiring a small area for its installation has been indicated and its possibilities outlined for stations where sea wires are not available.

15. The focussing effect of the system has been described and its value in connection with distant control work and the elimination of interference has been pointed out.

SUMMARY: The question of optimum length of (buried) ground wires for reception at a given wave length is discussed, and experimental data are given. The signal strength obtainable on such wires under various conditions is considered.

The signal-to-stray ratio on ground wires as compared to that on loop

receivers (rectangles) is found to be more advantageous, particularly under carefully chosen conditions.

After considering a number of methods of reducing strays which have already penetrated into the receiver circuits, there are described a number of more effective methods for reducing strays before their entrance into the receiver. Thus strays can be balanced out by using a sea wire and a land wire as opposing collectors, with an adjustable-phase differential coupling of some sort. The wiring of the arrangements used and the practical adjustment are given, together with some of the experimental results obtained therewith.

The distance of origin of strays (or interfering signals) can be adjusted for in balancing these out, so that an interesting "focussing effect" is obtainable wherein the effect of a stray (or signal) in the receiver depends on the distance to its source.

The ratio of improvement in readability of signals thru strays obtained by the above arrangement is given conservatively as 8.6-to-1.

Certain remarkable variations in directional effect sometimes obtained are then discussed.

AN OSCILLATION SOURCE FOR RADIO RECEIVER INVESTIGATIONS*

By

Julius Weinberger and Carl Dreher

(Research Department, Marconi Wireless Telegraph Company of America)

1. Introduction

The purpose of this paper is to describe a source of sustained oscillations for use in connection with radio receiver investigations, which has been found practical in the Research Department laboratories. A source was required that would reproduce the effects occurring in the reception of electric waves on an antenna, and which would also produce a minimum amount of mutual interference where several investigations were being carried on in the same room, along similar lines. The oscillating audion has been extensively used as such a source, as described by Austin[1] and Armstrong,[2] but the methods of these authors have some disadvantages when applied to our particular case. Firstly, the usual audion source gives rise to rather widespread electric and magnetic stray fields, even when the bulb is of the smallest available type (a receiving tube) and a minimum amount of power output is used, so that serious interference results when several investigations are being carried on in the same room on the same range of wave lengths. Secondly, in order to measure the energy input to the receiver, crystal detectors and galvanometers were used to indicate the received current; these require laborious calibration against a thermo-couple, which must be repeated if the crystal should get out of adjustment, and furthermore, the lower limit of current which can be thus measured is of considerably greater magnitude than that obtainable in long distance (e. g. trans-oceanic) reception. In the source which we shall describe, both of these difficulties have been avoided; by

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* Received by the Editor, March 29, 1919.

[1] Austin, Proceedings of The Institute of Radio Engineers, volume 5, page 239, 1917.

[2] Armstrong, Proceedings of The Institute of Radio Engineers, volume 5, page 145, 1917.

suitable construction stray fields have been greatly reduced, and, instead of measuring the *current* in the dummy receiving antenna, an *emf*. of known amplitude is introduced. This is exactly what happens when the set is used under operating conditions; assuming that there is practically no reaction of the current flowing in the receiving antenna upon the passing electromagnetic field. This is probably the case with the usual heavily loaded, high resistance receiving antenna circuit, the induced emf. being proportional only to the field strength and to the height of the antenna. The use of a known emf. instead of a known current has the advantage that one may obtain as small a known emf. as desired, by mutual inductance methods; the known current method, however, is limited by the sensitiveness of the detector-galvanometer system (which permits of a minimum current of only about 6 microamperes being measured, according to some recent results of Dr. Austin).

The main source of trouble, however, which we had to eliminate, was the stray field produced by the usual oscillation source. A circuit assembled out of ordinary types of coils and condensers, connected to a receiving audion so as to produce oscillations, gave rise to so strong a stray field that it was impossible for two investigations on the same range of wave lengths to be carried on within twenty feet of each other, without mutual interference from the oscillation sources. A number of experiments were therefore first made to determine the origin of the various fields surrounding the source.

2. PRELIMINARY EXPERIMENTS

The circuit used for the production of oscillations is shown in Figure 1. Here, L is a single coil, with a double tap brought out from its mid-point and connected to the plate battery of the tube, C is a variable condenser of about 0.001 microfarads maximum capacity, and the vacuum tube is electrically equivalent to one of the usual small receiving types. Now, in this circuit each element—coil, condenser, and tube—gives rise to a stray electric field, and the coil also to a magnetic field. When oscillations are produced in this circuit, the point to which the filament is connected generally remains at a constant, or earth potential—probably because of the high capacity between the storage batteries which light the filament and earth—and the plate and grid terminals of the loop LC oscillate at high, radio frequency potentials; thus any metallic bodies connected to the latter points (such as the plates of the variable conden rise to stray electric fields, and these cause extremely powerful signals in a receiving set when the source is within several feet of it.

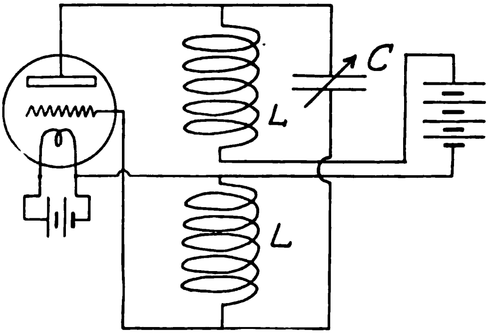

FIGURE 1

In order to study the exact manner in which the induction between the source and receiver took place, an elementary receiving set of the oscillating audion type was mounted on a board so that it could be moved about readily by the observer. A wiring diagram thereof is shown in Figure 2. The bulb was equivalent to the usual receiving type, L_1 and L_2 were single layer solenoids about 4 inches (10 cm.) in diameter having an inductance of 400 microhenrys each, C_1 a condenser of 0.0007 microfarads maximum capacity, C_2 was 0.005 microfarads, C_3 was 0.001 microfarads and R about 500,000 ohms. B_2 was a battery of 20 volts and T a pair of Baldwin receivers. All the

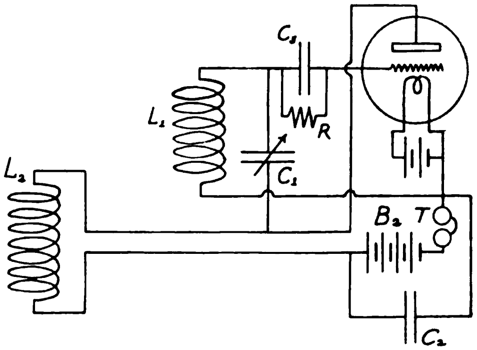

FIGURE 2

apparatus was fastened to a board except coil L_2, which was connected by a long pair of twisted leads to the rest of the receiving set so that it could be used as a search coil. The board containing the apparatus was usually placed at a sufficient distance from the source so that it was out of range of the effects of the fields therefrom, the search coil being used to pick up signals. When desired, the observer could handle the coil with a long wooden pole so as to eliminate effects due to electric fields picked up by his body.

The oscillator was set up as shown in Figure 1, the apparatus being the following: L, two single layer solenoids each about 4 inches (10 cm.) in diameter and each having an inductance of about 170 microhenrys, placed close together; C, a variable air condenser, of 0.0015 microfarads maximum capacity. A receiving tube was used, and the plate battery was 50 volts.

The search coil gave us a convenient means of distinguishing the kinds of fields around the oscillator, depending upon the following principle: If the coil is placed in a field which is purely magnetic, then a definite maximum and minimum signal is heard as the coil is revolved about its vertical axis, the maximum and minimum being 90 degrees apart. If the coil is placed in a field which is purely electric, then the signals remain of the same intensity all around, as the coil is revolved; inasmuch as the coil acts as a metal body upon which charges are induced. If both fields are present, then, as the coil is revolved, it is found that the maximum signal is not equally loud at two points 180 degrees apart. That is, if a maximum is obtained, and the coil then reversed, end for end, there is a distinct difference in loudness. This is because the emf. induced in the coil by the electric field has the same direction regardless of the reversal of the coil; but the emf. induced by the magnetic field is reversed relative to that induced by the electric field, when the coil is reversed. In other words, in one position of the coil the effects due to the two fields add, and in the other position they oppose. This phenomenon gives us a useful method of estimating the relative intensity of the two kinds of fields; we employed it to tell when we had only a magnetic field to deal with, or when both electric and magnetic fields were present.

(a) SHIELDING:

With the oscillator operating at a wave length of about 1,700 meters, it was found that just audible signals were obtainable within a radius of about 15 feet (4.6 meters); the signals were due to an electric field entirely. The entire oscillation source (including filament and plate batteries) was next placed in a copper covered wooden box; the latter had its cover and one side on hinges, so as to permit access to the apparatus, and copper covering was also placed around the edges of these parts. If the box was closed completely, a fairly perfect copper shield was obtained around the oscillator, except for small openings where the junction between the shields on the hinged doors and on the sides of the box was not quite perfect (due to unavoidable kinks in the copper sheet). The importance of not having *any* such imperfections in the shield was not appreciated until later. The shield was always connected to one terminal of the filament battery.

With the box closed, just audible signals, due mainly to a *magnetic* field, were found about five feet (1.5 meters) from the shield. By moving the search coil about, it was found that the field was especially strong along the little openings between the doors and sides of the box, and that the field was predominantly electric. These openings were not very large—varying from a fraction of a mm. to 2 mm. Undoubtedly, lines of electric force issued from these cracks. Along the sides of the box, only a moderate magnetic field was found (due to the oscillator coils); it may be noted that the thickness of the copper sheet was about 12 mils (0.305 mm.), and at this wave length, the magnetic field passed thru very well. When the doors of the box were opened wide, signals were audible at the same distance as when the oscillator was out in the open, and were due to the electric field of the oscillator.

Another more perfect shield was constructed, consisting of a brass cylinder, with top and bottom plates of close-fitting heavy brass sheet. With this, it was found that the electric field was perfectly shielded off, only the magnetic field remaining, as before. Apparently the problem of shielding a radio frequency *electric* field is easily solved by the use of a perfectly closed screen.

In attempts to reduce the stray *magnetic* field, the coils of the oscillator were first surrounded by close-fitting iron boxes; the output of the oscillator, however, was found to be decreased so considerably by this measure, that no definite conclusions could be drawn as to whether the diminished external magnetic field was due to magnetic shielding or to the diminished output. Hence, the entire oscillator, in its brass case, was placed inside of a large galvanized iron can, and a galvanized iron cover placed over it. The magnetic field came thru just as before. It may be concluded that galvanized iron does not act as a magnetic shield for weak radio frequency fields, either because skin effect causes eddy currents to flow in the galvanizing and the field is affected only by these eddy currents, or because of the low permeability of the iron for these fields. The latter is most probably the case, for, in connection with other work, we have noted that iron is a very poor shielding material for weak radio frequency magnetic or electric fields.

Another expedient for reducing the intensity of the magnetic field was the use of oscillator coils of small size and of the square or maxwellian cross-section type; with these, the magnetic field falls off in intensity very rapidly with the distance from the coil. Toroidal coils were also thought of, since these are generally supposed to have no external magnetic field.

(b) MULTILAYER COILS:

Two compact coils were built, each wound on a wooden form of the size shown in Figure 3. Each coil consisted of 80 turns of 7×7×number 38 litzendraht (diameter of number 38 wire = 0.101 mm.), wound in five layers of 16 turns each. The inductance of each coil was 260 microhenrys. These coils were substituted for the single layer coils in the oscillator circuit, and the oscillating current was found to be about the same as before.

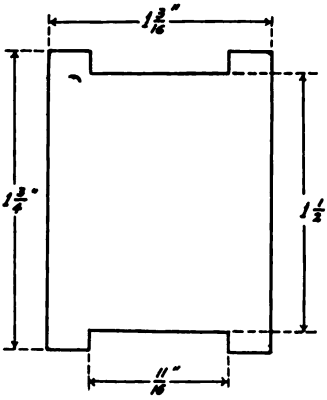

FIGURE 3

With the oscillator enclosed in its brass shield, just audible signals were obtained at a distance of less than a foot (30 cm.) from the shield; the effect, as determined by the search coil was due only to the magnetic field of the oscillator coils, the electric field being as usual completely shielded.

(c) Toroidal Coil

A toroidal coil was wound on a wooden form of the dimensions indicated in Figure 4. It had 187 turns of 7×7×number 38 litzendraht, with a double tap at the mid-point. From the first turn to the mid-point constituted one coil, and from the mid-point to the last turn constituted a second coil. The inductance of both coils in series was 200 microhenrys. This coil was used in place of the multi-layer coils, and the radio frequency oscillating current found to be approximately the same as before.

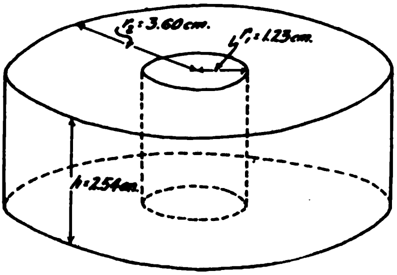

Figure 4

When the brass shield was closed, and the field investigated, much stronger signals were obtained than with the multi-layer coils. Rotating the search coil did not reveal any directional effects, the signals remaining of the same intensity as the coil was rotated. Such an effect could only be caused by an electric field.

However, we had already found that the shield screened off the electric field perfectly. We examined the field again, with the multi-layer and single layer-coils substituted for the toroidal coil and found no traces of an electric field—only of a magnetic field. Evidently the shield was still effective in cutting down the electric field.

Zenneck[3] describes a certain characteristic of toroidal coils

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[3] J. Zenneck, "Elektromagnetische Schwingungen und Drahtlose Telegraphie," pages 53, 54.

which probably accounts for the peculiar results obtained above. As long as the current in the coil is constant, a magnetic field is present only within the coil; that is, for direct currents the toroidal coil has no external magnetic field. As soon as the current varies, this internal magnetic field also varies, and according to Maxwell's theory, an electric field is induced, with lines of force orthogonal to the original magnetic lines of force thru the coil, and terminating on the shield. The displacement currents flowing to the shield set up a second magnetic field, which gets thru the shield. The search coil, however, cannot be affected by this magnetic field (which is of the same shape as that within the toroid), because the search coil would have to be linked with the toroid windings in order to have the magnetic lines induce voltages in it. This varying magnetic field in turn induces in the ether another electric field, and that part of the magnetic field which exists outside the shield of course gives rise to an electric field in this region. It is this secondary electric field which affects the search coil in the observed manner.

We conclude, therefore, that the most effective arrangement of the source can be obtained by the use of compact, multilayer coils of restricted magnetic field, with copper or brass shields surrounding those parts of the circuit which give rise to electric fields, the shield being connected to one terminal of the filament battery.

(d) EFFECTS OF BRINGING LEADS OUT THRU THE SHIELD

It will nearly always be necessary to bring leads out from points in the oscillating circuit, thru the shield; for example, it is inconvenient to keep the filament and plate batteries inside the shield, and it will also be necessary to bring out leads for coupling the oscillator to the receiver.

The filament and plate batteries were therefore located outside of the shield, connected by twisted leads, and the field was not found to be altered appreciably. It will be noted that the negative terminal of the plate battery is connected directly to the filament. If the plate battery were connected at any other point in the circuit, it would give rise to a strong stray electric field in case it were located outside the shield.

Next, a pair of twisted leads was brought out from point *B*, as shown in figure 5. Signals were immediately audible at a distance of 5 feet (1.5 meters) from these leads. Evidently a strong electric field was produced. But when the leads were brought out at point *A*, instead of *B*, the search coil had to be brought very close to them in order to hear anything, and a purely magnetic field was found. This residual magnetic field produced by a twisted pair of wires was undoubtedly due to incomplete opposition of the magnetic fields of the individual wires. In this connection it may be noted that when a small loop of perhaps one cm. in diameter was made by opening out the twisted pair, the increase in strength of the magnetic field of the wires was quite marked.

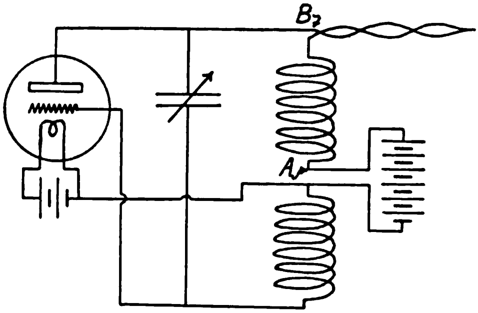

FIGURE 5

In may be concluded, therefore, that thoroly twisted leads may be brought out from a point in the oscillating circuit which is at constant (or ground) potential without materially increasing the existing external field. Such a point may be that immediately next to the filament, or, if the plate battery has its negative terminal connected to the filament battery, from the positive end of the plate battery. No leads should be brought out of the shield from other points in the circuit, or disturbing electric fields will be produced.

3. DESCRIPTION OF OSCILLATION SOURCE

Bearing in mind the conclusions from our preliminary experiments, the source described below was built. It is intended to give signals ranging from unit audibility to several thousand times audibility in a normal vacuum tube receiving set, over a wave length range from about 6,000 to 14,000 meters. It will be noticed that electric fields from the variable condenser, bulb and oscillating circuit inductance are shielded off; and that the energy from the oscillator enters the receiving set at only one point in the circuit of the latter, being controllable in amplitude thru purely magnetic coupling. The influence of stray magnetic fields from the oscillator is negligibly small compared to that which comes in thru the path desired.

The wiring of the oscillator is shown in Figure 6, and photographs of it in Figures 7 and 8. Referring to Figure 6, the condenser C was of about 0.0007 *μf.* capacity at its maximum, coils L_1 and L_2 were portions of a single coil having a double tap brought out at one point of the winding,[4] B was the plate battery which might be varied from 20 to 80 volts in order to vary the output, R was a resistance of 12,000 ohms (a Ward Leonard resistance unit was used), and the coupler was one having coils of about 40 microhenrys each, with a maximum mutual inductance of about the same value. The purpose of the particular arrangement adopted for sending signals necessitates explanation. It will be noticed that the resistance R, of 12,000 ohms, is inserted in the grid side of the oscillating circuit, and is shunted by the primary of the coupler in series with the binding posts marked "Key." (These may have a sending key or automatic transmitting arrangement connected to them, outside the oscillation source.) When the key is open, the resistance R effectually prevents oscillations from occurring; when closed, the resistance is short circuited by the primary of the coupler, and oscillations occur thru it. This particular system was found to be the only one which gave clear signals when reception was

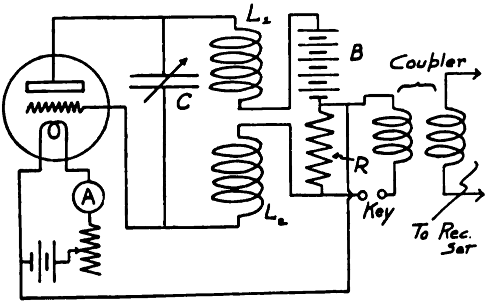

FIGURE 6

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[4] This coil was especially made to be as compact as possible. It consisted of 1,200 turns of number 28 S.S.C. wire (diameter of number 28 wire = 0.32 mm.) with the taps brought out at 300 turns, wound so as to have an inside diameter of 1.4 inches (3.56 cm.), an outside diameter of 2.6 inches (6.6 cm.) and a width of 0.6 inch (1.52 cm.). The total inductance was about 73 millihenrys, L_1 being 44 and L_2 5.3 millihenrys, respectively.

carried on by the heterodyne method; we had previously tried inserting the key in the plate battery leads and in other parts of the oscillation circuit, but the received signals always had a little variation in tone as the key was pressed or released. That is, as the oscillations were started and stopped, a slight variation in frequency to and from the normal oscillation frequency occurred, giving peculiar signals which were not clean-cut like the signals received from a radio frequency alternator or arc. It was found desirable not to interrupt the oscillation circuit completely, in sending, and the 12,000-ohm resistance cut into or out of circuit gave best results. In this connection, it may also be mentioned that good contact is very important in sending, with these small oscillating currents; the ordinary sending key when firmly operated in the manner customary with good operators, gave satisfactory signals. However, when an omnigraph was substituted for the key, so as to provide automatic transmission, the contacts were found to be insufficiently firm; hence, a telegraph relay (Western Union Company's type 3C signal relay) was used instead, which was itself operated by the omnigraph. The large contact points and firm pressure on the relay armature gave clean-cut signals; it was found desirable to connect the iron case of the relay magnet to the negative end of the filament to eliminate electrostatic induction from the interrupted direct current traversing the winding of the relay. Even this is not wholly satisfactory, however, and the best method of getting rid of clicks in the receiver from the relay direct current would undoubtedly call for thoro iron and copper shields completely around the magnets. We prefer to carry on tests with one man sending unknown material on a hand key, which has the double advantage of absence of direct current clicks and the reception by the other man of material unknown to him (one very soon becomes familiar with the material on some automatic transmitters).

Figure 7 shows the assembly of parts; individual units of commercial apparatus were merely assembled on a board. At the left, rear, is a filament ammeter, which is extremely necessary since the power output and frequency calibrations of the oscillator are correct only at one particular filament current; on the back of the ammeter is fastened a filament rheostat. At the right of the ammeter is the resistance unit *R* (shown better in the next figure); in front of it the variable condenser. The box-like affair in the middle is a wooden case covered with copper sheet, serving as a shield over the bulb and oscillating

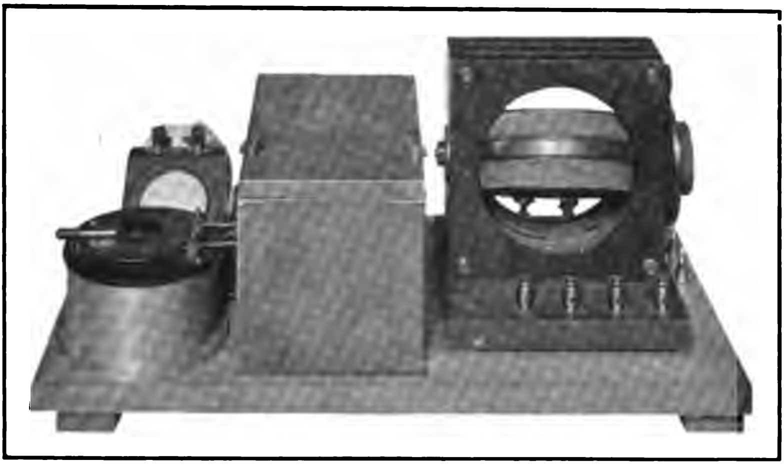

FIGURE 7

circuit inductance; in Figure 8 the latter elements are shown with the cover removed, resting on a copper plate over which the copper-covered box fits tightly (the copper on the box being brought around under its lower edges so as to make contact with the copper base plate). At the extreme right is the coupler between oscillator and receiving set. The oscillation circuit is connected to the *rotating* coil of the coupler, the receiving set

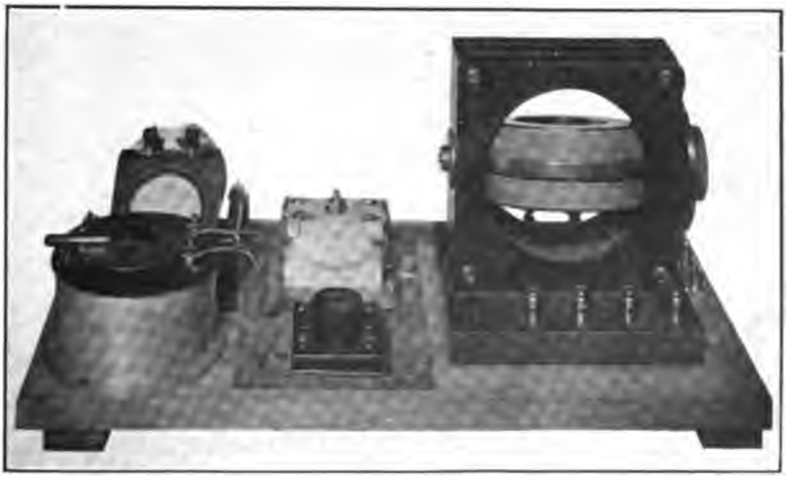

FIGURE 8

to the *fixed* coil. This is found necessary, since the coil which connects to the receiver is subject to some magnetic induction from the oscillation circuit inductance unless it is suitably placed with respect to the latter; by using the fixed coil of the coupler for the receiver connection and placing this so that its windings are at right angles to the magnetic field lines of the oscillation circuit inductance (which lies horizontally), this difficulty is avoided. The exact position is easily found by trial; the leads from the oscillating circuit to the coupler are short-circuited, the receiver connected by twisted pair leads 3 or 4 feet (1 meter) long to the stationary coupler coil and the entire coupler rotated until no signals are heard. Then there is no magnetic induction between the oscillating circuit and receiver, and any magnetic induction thereafter will be due to the field from the moving coil of the coupler (which is in the oscillating circuit). Usually we have found that the proper location of the coupler is as shown in the photographs.

The variable condenser we used had a metal case (brass or aluminum), but had its plates suspended from an insulating top; we found that it was necessary to complete the shield by putting a copper plate underneath this top, with a small hole cut where the shaft of the moving plates came thru. The metal scale was *insulated* from the moving plates, and we found that a considerable electric field leaked out thru the hole where the shaft came thru unless this scale was grounded to the rest of the condenser shield (it will be noted from the wiring diagram of the set that neither set of plates may be grounded); hence a small phosphor bronze brush was arranged to bear against the moving scale and connect it to the shield. With these precautions no appreciable electric field was found to emanate from the condenser. The two leads to the condenser were brought out thru the shield over the bulb and coil, and were very short; it was not found necessary to shield them, altho we had expected that it might be required. All shields were connected to the negative end of the filament.

4. RESULTS OBTAINED WITH OSCILLATION SOURCE

(a) CALIBRATION DATA

In Figures 9, 10, 11, and 12, there are given certain data relating to the constants of the oscillator. Figure 9 gives the mutual inductance between coils of the coupler for various settings. This was made on an inductance bridge at audio frequency.

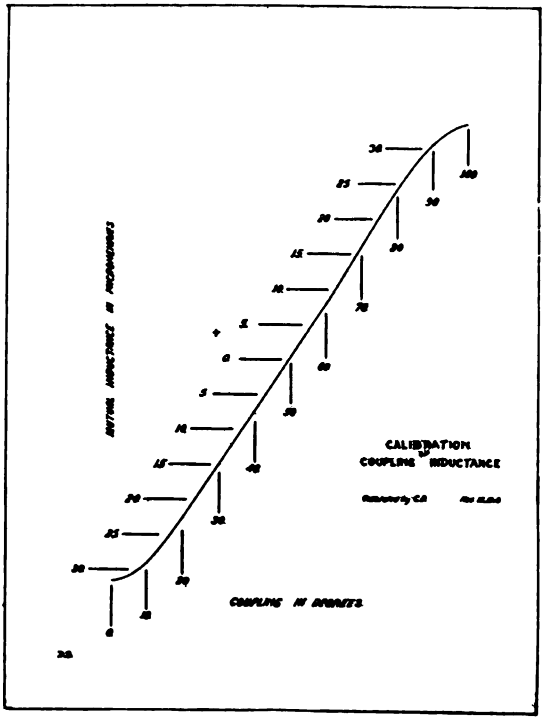

Figure 9

Figure 10 is the wave length calibration, which is correct only for the type of tube employed, operated at a filament current of 1.05 amperes; for other tubes and other filament currents this calibration (as well as the other calibrations given below) will vary slightly. However, when a given tube is always operated at the same filament current and plate battery, a calibration once made will remain the same for a long time. We have operated a tube day after day, at the same adjustments, and found absolutely no variation in the pitch of the *heterodyne signal* on a receiving set kept at constant adjustment. This calibration was made by receiving signals simultaneously from a large oscillator which had previously been calibrated by a wave meter and from our little oscillation source, on a crystal detector set. The interference between received currents due to the two sources gave rise to a beat tone in the receiver, and when zero beats were obtained the small oscillator was operating at the same wave length as the large one.

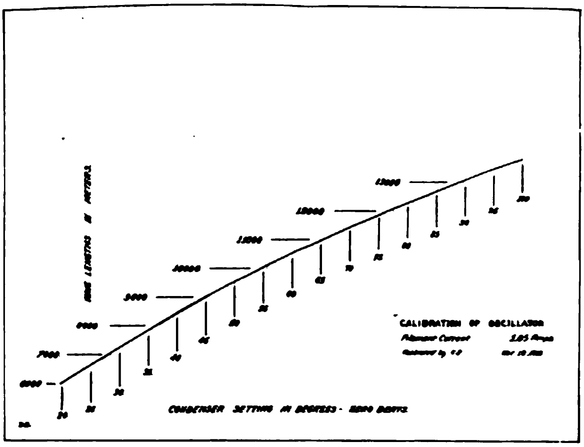

FIGURE 10

Figure 11 shows the radio frequency current in the oscillator circuit (that is, thru the primary of the coupler) with 20, 40, 60, and 80 volts plate battery. This was obtained by inserting a thermo-couple and galvanometer arrangement in series with the coupler primary as shown in Figure 13. The thermo-couple cannot be inserted directly in the circuit, since there is some

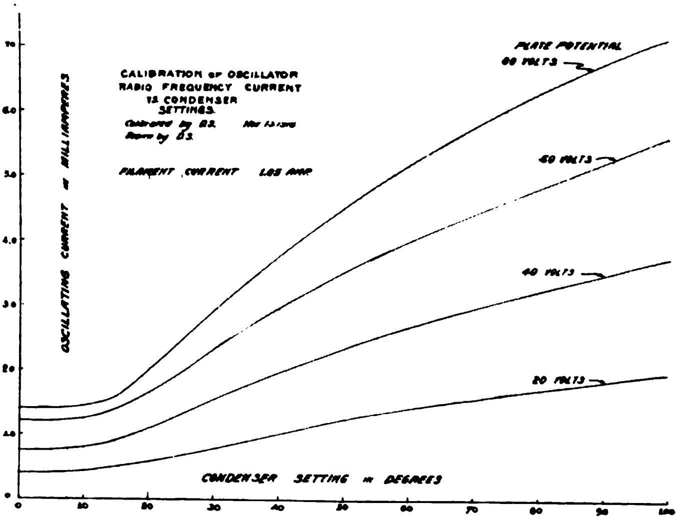

FIGURE 11

direct current flowing here; this direct current partially leaks thru the d. c. galvanometer and causes entirely erroneous deflections thereof. For example, reversing the circuit connections to the thermo-couple may cause different deflections, or even reversed deflections, to occur. Thermo-couples (even of the "heater" type), should never be connected directly in a circuit containing both direct and alternating currents; the arrangement shown in the figure is, however, free from this objection cited.

It will be seen that an inductance *L*, of impedance considerably higher than that of the thermo-couple heater, is shunted by a condenser in series with the heater. In our case *L* was 1 millihenry, *C* was 1 microfarad, the thermo-couple was one of R. W. Paul's vacuum types having a heater resistance of 0.8 ohms, and the galvanometer was a Leeds and Northrup suspension galvanometer (model 2285, 10 ohms coil resistance, 7 seconds period). The combination of thermo-couple and galvanometer alone had been previously calibrated at 60 cycles against electrodynamometer instruments.

Figure 12 shows the emf. induced in the stator of the coupler, at a wave length of 12,500 meters (this is the wave length of the station at Nauen, Germany) computed from the observed currents, mutual inductances, and frequencies.

$$e_2 = M\,\omega\,i_1$$

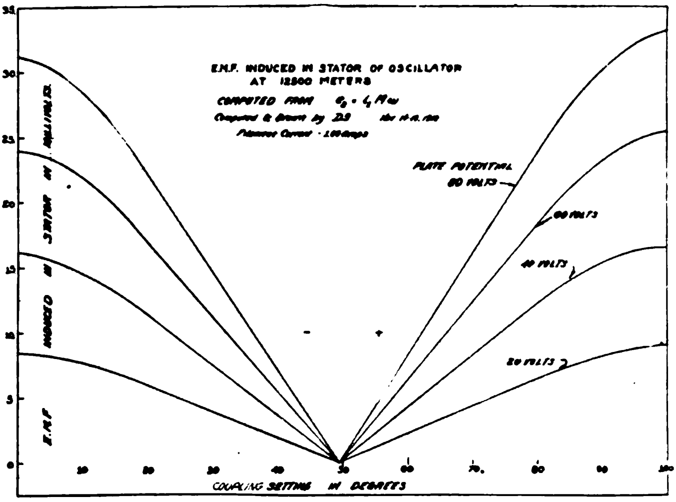

FIGURE 12

These values are given for various plate battery potentials. To find the voltages at wave lengths other than 12,500 meters, this equation may be used in connection with the curves previously given.

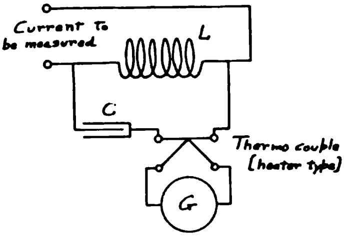

FIGURE 13

(b) AUDIBILITY OF SIGNALS COMPARED WITH MUTUAL INDUCTANCE BETWEEN COUPLER COILS

As a test of our assumption that the emf. induced in the stator of the coupler was proportional only to the mutual inductance between coils, the audibility of signals received by the heterodyne method on an experimental receiver was compared at various settings of the coupler. According to Dr. Austin's results, the audibility should be proportional to the emf. introduced into the receiver; and such proportionality was indeed found, the audibility being proportional to the mutual inductance, within limits of error in this class of measurement. In this connection, it may be observed that the customary method of measuring audibility in vacuum tube receivers, namely, putting two pairs of telephones in series and shunting one of them with the audibility meter, gives markedly incorrect results. If one observer listens in the unshunted pair of telephones, while the other is being shunted, the signals will be found to vary appreciably as the shunting resistance is varied. Obviously, the impedance of the output circuit of the tube is not maintained sufficiently constant by the extra pair of telephones. We found that to maintain the signals of the same intensity with or without a shunt on the telephone, it was necessary to add an inductance of about 10 to 15 henrys in addition to the customary extra pair of telephones, in the plate circuit of the tube. Such an inductance may be made of about 10,000 turns of fine copper wire on a silicon steel laminated core about

0.5 inch (1.25 cm.) in diameter and about 3 inches (7.62 cm.) long. A convenient method is to wind the wire on a hollow insulating tube, in which the core laminations may be slipped in and out and then, with the coil on an audio frequency inductance bridge, insert enough laminations to give the inductance desired. The current in the bridge should be as small as possible, so as to work the steel at a magnetizing force which falls in the region where the iron permeability is constant; the ordinary buzzer-driven inductance bridge is quite satisfactory in this respect.

It was also found that no signals were obtained at exactly the point of zero mutual inductance, on the coupler (49.5 scale divisions); this is an accurate check on the assumption that the induction between coupler coils was practically purely magnetic.

(c) OPERATION OF SET

In using the apparatus, it is first placed at a distance of about 3 feet (90 cm.) from the receiver under test, the filament current and plate potential being set at the calibration values. The coupler is then set at the point of zero mutual inductance, the receiver connected by thoroly twisted pair to the coupler stator, and one man transmits signals. If any are heard in the receiver they are due to a residual stray magnetic field which emanates from the oscillating circuit coil and gets thru the shield over this coil (a certain amount of the magnetic field is cut out by the shield, due to eddy currents, but some comes thru). The receiver or oscillator is then rotated about until no signals are heard. When this has been accomplished, the emf. desired is produced by suitable settings on the oscillator.

One use for this equipment might be the following: If it were desired to measure the emf. induced in a receiving antenna by a transmitting station, day after day, very accurate results could be obtained by having the secondary of the coupler connected in series with the receiving antenna (while reception was going on), and having one man send, by hand, material similar to that being transmitted by the station; while the second man adjusted the coupler setting until the signals were readable equally.[5] It is obvious that the results obtained would be independent of personal equations, of errors arising due to daily variation in receiver adjustments and stray intensity, all of

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[5] This idea is originally due to Messrs. R. A. Weagant and G. H. Clark, altho for a different purpose.

which enter into the present method of taking only audibility measurements.

We wish to express our indebtedness to Dr. Alfred N. Goldsmith for his valuable suggestions in connection with this work; and to Messrs. Sonkin and Ringel, of this Laboratory, for assistance with the experiments and calculations.

SUMMARY: A source of long-wave, sustained oscillations, for use in connection with investigations on radio receivers, and providing standard controllable signals of the same character as those due to actual radio signals, is considered. Heretofore, such sources have had the disadvantages that they necessitated the measurement of small "received currents," and also, that considerable interference was caused by stay electric and magnetic fields emanating from the elements composing the oscillation circuit. The latter makes it difficult to carry on numerous researches in the same room on the same range of wave length; while the former cannot be accomplished with present-day apparatus for the minute currents occurring in trans-oceanic reception. The source described provides an emf. of known magnitude, rather than a current, which is exactly what occurs under operating conditions. In order to devise methods of reducing the intensity of stray fields from the source, a number of preliminary experiments are made and suitable methods of shielding and construction of oscillator elements are determined. A practical source utilizing these principles is described and construction and calibration data given. Finally, the use of this type of source in connection with transmission measurements on long distance radio communication is proposed, to replace the ordinary audibility measurements.

ON THE DETECTING EFFICIENCY OF THE THERMIONIC DETECTOR*

By

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1. INTRODUCTION

Altho the thermionic detector, also known as the audion detector, is now used extensively in the reception of radio signals, I have not come across any publication which describes a satisfactory method of determining its detecting efficiency in absolute units. There has been no satisfactory way of expressing what constitutes a good detector. In the early stages of development of a new device the lack of quantitative expression is perhaps not so severely felt. But the thermionic tube or audion has now passed beyond these stages. The work that has been done on the device in this laboratory has reached a stage where the tube is designed to have definite electrical constants depending on the purpose for which it is supposed to be used and which are determined from equations giving the relation between these constants and the structural parameters of the tube, such as the structure of the grid, its position relative to the anode and cathode and so on. Definite expressions for efficiency have thus become a necessity.

The structural equations were formulated by the writer, on the basis of an extensive series of investigations, with a sufficiently high degree of accuracy to meet practical requirements.

It was, therefore, a comparatively simple matter, when the Signal Corps required tubes for field and airplane radio work, to design tubes having the electrical characteristics that were necessitated by such uses, for example, low power consumption and satisfactory operation over wide ranges of filament and plate battery voltages. And all that was necessary was to strengthen mechanically the structure of the tube to withstand the contemplated rough handling in the field and the vibration to which

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* Received by the Editor, April 9, 1919. Presented before THE INSTITUTE OF RADIO ENGINEERS, New York, May 7, 1919.

tubes are subjected on an airplane and to solve the problems of quantity production. It should be remarked that the tubes designed and manufactured before the war by the Western Electric Company and that have been used since 1914 as amplifying repeaters on long distance telephone lines, attained a higher degree of precision and uniformity of operation, than any tubes that were manufactured for war purposes. The reason for this is that on telephone lines the tube is usually inserted in the line at some intermediate place between the receiving and transmitting stations, the repeater stations being so arranged as to relay telephonic currents in both directions. It was therefore necessary for the tubes to have definite electrical constants to prevent their insertion in the line from causing an unbalance. Considering, furthermore, that on long lines several repeater stations are used and that sufficient distortion can be produced to make the transmitted speech unintelligible unless the tubes are properly designed and operated, it will become apparent that tubes to be used for relaying telephonic currents have to satisfy rather rigid test specifications. In radio telephony, on the other hand, the vacuum tube receiving sets, containing detector and amplifier tubes, are designed to transmit current only in one direction, and furthermore work directly into the telephone receiver. Requirements on such tubes need therefore not demand such close limits.

In the case in which the tube is used simply as a power amplifier, such as a telephone relay, methods of measuring the power amplification have been in use for many years. The most commonly used method consists in making a transmission test in which a current of about 800 cycles is amplified by the tube and attenuated by an artificial line of known attenuation constant. If the length of the line is adjusted to attenuate the current as much as it is amplified by the tube the degree of amplification can be computed from the constants of the line. This affords an extremely simple and rapid determination of the degree of amplification that a tube can give. (See Appendix.)

The detecting efficiency can, however, not be determined by such simple means, because here it is necessary to obtain a relation between the audio frequency power in the output of the detector and the radio frequency impressed on its input side. This determination is made difficult by the necessity of measuring the extremely small alternating currents involved in any attempt to carry out the experiments under conditions approaching those met with in practice. The currents to be measured in the output range from 10^{-8} to 10^{-6} ampere. The use of hot wire instruments is, therefore, entirely out of the question. To overcome this difficulty the telephone receiver has been resorted to as a measuring instrument. This means has been made use of in the so-called "audibility method," which is, however, subject to serious limitations as will be shown below. The unreliability of the audibility method makes it quite unsuitable for standardization purposes. In seeking to minimize the psychological and physiological influences attending measurements made by the audibility method, I devised the following method which it is the purpose of this paper to describe. This method which allows of relatively easy measurements and a good degree of accuracy, has been in use in this laboratory for two years for the purpose of standardizing detector tubes, and as a laboratory method has given very satisfactory results. It can be, and has in this laboratory been applied in the study of detection with heterodyne or regenerative circuits as well as in the case of straight detection of modulated waves.

2. THE PRINCIPLE OF THE METHOD can be gathered from the schematic diagram shown in Figure 1. Modulated high (radio) frequency oscillations can be impressed on the detector at *C*. The input voltages ranged from a few hundredths to a few tenths of a volt, and can be measured with the Duddell thermogalvanometer *G* and non-inductive resistance *r*. In order to measure the resulting audio frequency current in the telephone receiver *T*, which we shall call the detecting current, a generator *U* is used to produce an auxiliary tone of the same frequency as that of the detecting current. The current, i_1, from the gen-

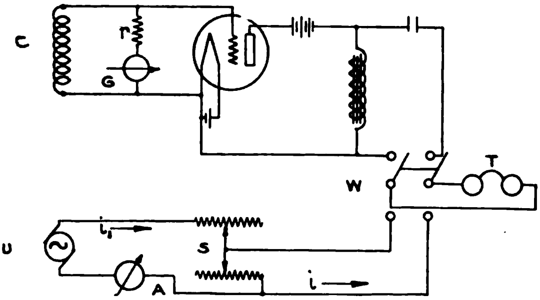

FIGURE 1

erator is so large that it can be easily measured with a thermocouple and milli-ammeter A, and can be attenuated by means of the shunt S, to a sufficient extent to make the branch current i equal to the detecting current. The current i can be computed in terms of the measured current i_1 and the constants of the shunt S, and this gives the detecting current when S is so adjusted as to make the note in the receiver of the same intensity for both positions of the switch W.

The shunt S is of the type commonly used in telephone measurements where it is known as a receiver shunt. It consists simply of shunt and series resistances so arranged in a box that when a telephone receiver of specified impedance is connected to one side the total impedance into which the generator works remains constant for all adjustments of the shunt. This nsures that the current i_1 remains constant for all values of i.

3. Detection Coefficient. In connection with the study of thermionic detectors two of the main problems encountered are (1) the direct measurement of the detection coefficient, and (2) the formulation of the relationship between the detection coefficient and structural and operating parameters of the tube and circuit. The latter is of importance in properly designing the tubes while the former is important in that it furnishes a means of measuring and expressing the degree of merit of the tube used as a radio detector.

The relation between plate current and applied voltages can be expressed by

$$I=f\left(\frac{E_B}{\mu}+E_c+\epsilon\right), \tag{1}$$

where E_B and E_c are the plate and grid potentials with respect to the filament and ϵ a constant. The form of the function f depends upon the constants of the tube and circuit. It is important to discriminate between the characteristic of the tube itself and that of the tube and circuit. When the tube is used simply as a power amplifier its characteristic can be expressed as[1]

$$I=a\left(\frac{E_B}{\mu}+E_c+\epsilon\right)^2, \tag{2}$$

that is, in terms of the tube constants which again bear definite relations to the structural parameters. This equation is a first order approximation and consequently needs modification be-

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[1] H. J. van der Bijl, "Phys. Rev.," 12, page 171, 1918; Proceedings of The Institute of Radio Engineers, volume 7, page 97, 1919.

fore it can be applied to the tube when used as a radio detector, because detecting action depends on second order quantities, being determined by current rectification in the grid circuit when the tube is used with a blocking condenser in the grid circuit, and by the second derivative of the plate current characteristic when operated without the blocking condenser. For the present we shall consider only the latter case.

When we are concerned with the direct measurement of the detection coefficient, it is not necessary to formulate the characteristic in terms of the tube constants, since it is always possible to express the characteristic of the tube and circuit in a convergent power series:

$$J = a_1 e + a_2 e^2 + a_3 e^3 + \cdot \qquad (3)$$

where J is the varying current in the output, e an alternating emf. impressed on the grid circuit, and $a_1, a_2 \cdot \cdot \cdot$ are functions of the tube and circuit constants.[2]

The only term that need be considered as effective in detecting is the second, since the series converges so rapidly that all terms of higher order than the second can be neglected. We can, therefore, express the detecting current i as

$$i = a\, e^2 \qquad (4)$$

The quantity a represents what is referred to as the detection coefficient.

4. Relation Between Detection Coefficient and the Operating Plate and Grid Voltages. If the detecting current, i, be measured as a function of the "effective grid voltage" $\left(\frac{E_B}{\mu} + E_c + \epsilon\right)$, the input voltage e remaining constant, it will be found that as the effective voltage is increased (by increasing either E_B or E_c) the detecting current at first increases, reaches a maximum, and then decreases. This effect has doubtless been noticed by most workers using audion detectors.

If the parabolic characteristic equation (2) were correct to a second order the detecting current would not show a maximum but remain constant. The cause of this maximum lies in the potential drop in the filament occasioned by the filament heating current. It can be explained as follows:

The effect of the potential drop in filament on the characteristic of a simple thermionic value has been given by W. Wil-

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[2] See J. R. Carson, Proceedings of The Institute of Radio Engineers, volume 7, page 187, 1919.

son of this laboratory[3] who finds that two characteristic equations are needed according as the potential difference V between the plate and (say) the negative end of the filament is less or greater than the potential drop E_f in the filament; thus

$$\left.\begin{aligned} I&=C\,V^{\frac{5}{2}} \text{ for } V<E_f. \\ I&=C\left[V^{\frac{5}{2}}-(V-E_f)^{\frac{5}{2}}\right] \text{ for } V>E_f. \end{aligned}\right\} \qquad (5)$$

In order to obtain an indication as to where the maximum of detecting current occurs, without making an attempt to express the actual value of the maximum quantitatively, we can apply these equations to the three-electrode tube by substituting the effective voltage $\left(\frac{E_B}{\mu}+E_c+\epsilon\right)$ for V:

$$I=C\left(\frac{E_B}{\mu}+E_c+\epsilon\right)^{\frac{5}{2}} \qquad (6)$$

$$I=C\left[\left(\frac{E_B}{\mu}+E_c+\epsilon\right)^{\frac{5}{2}}-\left(\frac{E_B}{\mu}+E_c+\epsilon-E_f\right)^{\frac{5}{2}}\right] \qquad (7)$$

If the current is plotted as a function of the effective voltage according to equation (6) for all values of effective voltage less than the potential drop in the filament and according to (7) for effective voltages greater than the filament drop, the resulting values form a smooth continuous curve closely approximating a parabola. The second derivative, however, shows a distinct maximum at an effective voltage equal to the potential drop in the filament. The effect can be made clear if we consider the simple case in which the tube works in a non-reactive output circuit of resistance R. In this case the detection coefficient can be expressed as[4]

$$a=-\frac{1}{2}\frac{\mu^2 R_o R_o'}{(R+R_o)^3}$$

where R_o is the a. c. plate resistance of the tube and R_o' its first derivative. R_o and R_o' can be evaluated from the characteristic of the tube by the formation of the derivatives

$$R_o=\frac{1}{\frac{\partial I}{\partial E_B}} \text{ and } R_o'=\frac{\partial R_o}{\partial E_B}.$$

This gives, putting $\frac{E_B}{\mu}+E_c+\epsilon=V_e$:

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[3] Paper read at the Philadelphia meeting of the American Physical Society, December, 1914.

[4] J. R. Carson, previous citation.

$$a=C'\left(\frac{R_o}{R+R_o}\right)^3 V_e^{\frac{1}{2}} \tag{8}$$

$$a=C'\left(\frac{R_o}{R+R_o}\right)^3 \left[V_e^{\frac{1}{2}}-(V_e-E_f)^{\frac{1}{2}}\right]. \tag{9}$$

according as V_e is less or greater than the potential drop E_f in the filament. It will be seen that for constant values of $\left(\frac{R_o}{R+R_o}\right)^3$, that is, when R is small compared with R_o, the coefficient a, which is a measure of the detecting current, increases with V_e according to equation (8) and decreases with V_e according to equation (9). The result is a curve like that shown in Figure 2. The simple rule, therefore, to obtain the best

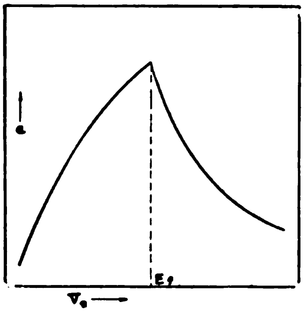

FIGURE 2

results when using a tube without a blocking condenser in the grid circuit, is to make

$$\frac{E_B}{\mu}+E_c+\epsilon=E_f. \tag{10}$$

Thus, supposing that $\mu=12$, $\epsilon=-0.5$, and $E_f=2.5$ volts, and the tube be operated without a grid battery, then the best plate voltage would be about 36 volts. An experimental curve is shown in Figure 3.

In determining the detection coefficient due regard must be taken of its dependence upon the applied d. c. plate and grid voltages.

5. INPUT SIGNAL WAVE. When measurements on the detection coefficient are made for the purpose of expressing the degree of merit of detectors it is necessary to specify the nature of the impressed radio frequency oscillations. The input volt-

age e may be characterized as the root-mean-square value of an unmodulated radio frequency voltage in which case a heterodyne local source of voltage or a regenerative circuit is needed to detect the oscillations; or it may be characterized as the root-mean-square of a modulated radio frequency voltage, which category would include spark signals.

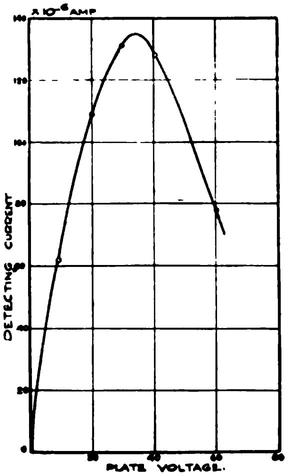

FIGURE 3

For the measurements under consideration, continuous unmodulated oscillations are unsuitable because the audio frequency response in the telephone receiver is determined mainly by the strength of the local auxiliary oscillations which is, in general, large compared with the strength of the received oscillations. Spark signals would be quite unsuitable, since here the character of the wave cannot be expressed in definite terms. The simplest and most easily reproduced type of wave is a radio frequency sinusoid modulated with an audio frequency sinusoid by means of a modulating device, such as the thermionic modulator, which enables the modulation to be controlled at will. This is the type of wave that was used in these measurements.

In order to specify fully the signal wave it is necessary to discuss briefly the process of modulation as effected by means of the thermionic vacuum tube. If we impress on the grid-filament circuit an emf.

$$e = e_1 \, sin \, pt + e_2 \, sin \, qt \qquad (11)$$

where $\frac{p}{2\pi}$ and $\frac{q}{2\pi}$ are radio and audio frequencies respectively, then the current established in the plate circuit ("output circuit") can be represented by the convergent power series (3). In general all terms of higher power than the second can be neglected, so that the current in the output can be represented by:

$$J = a_1 \, (e_1 \sin pt + e_2 \sin qt) + a_2 \, (e_1 \sin pt + e_2 \sin pt)^2$$

Let the output of the modulator be tuned to a frequency range $p \pm q$, so that currents of these frequencies only will be radiated. We can, therefore, in evaluating the above expression, drop all terms representing frequencies that fall outside of the range $p \pm q$, such as $\frac{2p}{2\pi}$, $\frac{q}{2\pi}$, and $\frac{2q}{2\pi}$. A simple trigonometrical transformation then gives for the radiated wave:

$$A \sin pt \, (1 + B \sin qt). \qquad (12)$$

where A and B are constants involving e_1 and e_2 and furthermore depend upon the constants of the modulator tube and circuit. This is a simple type of modulated wave and results from the curvature of the vacuum tube characteristic. Referring to Figure 4 which represents the plate current, grid voltage characteristic, if a radio frequency voltage $o\,a$ be superimposed on the negative d. c. grid voltage E_c, the output current will be proportional to $a\,b$. If E_c be reduced to E_c' or increased to E_c'', the output current will be increased to $a'b'$ or reduced to $a''b''$.

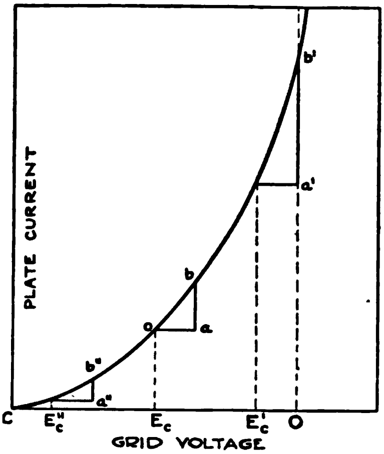

FIGURE 4

If this variation in E_c be effected by impressing a sinusoid of frequency $\frac{q}{2\pi}$ on the grid the output current will be given by equation (12) which represents a high frequency current the amplitude of which varies according to the low frequency $\frac{q}{2\pi}$. If the low frequency amplitude is equal to $E_c C$, the amplitude of the radio output wave will be reduced to zero whenever the low frequency input voltage attains its maximum negative value. In this case, B in equation (12) is unity and the wave can be said to be completely modulated.

It is very important in measurements relating to the detecting efficiency to insure that the input wave is completely modulated. The necessity for this can easily be seen from the following consideration.

If a voltage represented by (12) be impressed on the input of the detector, the detecting current can be obtained from:

$$i = a\,[A \sin pt\,(1 + B \sin qt)]^2$$

which on evaluating and dropping all terms representing inaudible frequencies gives for the detecting current which can be heard in the receiver:

$$a A^2 B \sin qt - \frac{a A^2 B^2}{4} \cos 2\,qt. \tag{13}$$

Its root-mean-square value is

$$X = a\sqrt{\frac{A^4 B^2}{2}\left(1 + \frac{B^2}{16}\right)} \tag{14}$$

The second term in the parenthesis represents a note of double the fundamental frequency and is generally weak enough to be neglected, so that we may write

$$X = \frac{a A^2 B}{\sqrt{2}} \tag{15}$$

The r.m.s. value Y of the modulated input represented by (12) can be evaluated by putting $p = n\,q$, since p is large compared with q. This gives

$$Y = \sqrt{\frac{A^2}{2}\left(1 + \frac{B^2}{2}\right)}. \tag{16}$$

Comparing (16) with (15) it is seen that for a constant value of the input Y, as measured by the Duddell galvanometer G (Figure 1), the response X in the telephone receiver depends upon B, that is, upon the extent to which the incoming wave is modulated. In order to obviate any error due to this effect it is necessary to make $B=1$ by completely modulating the test wave, which can then be specified by the expression

$$A \sin pt\,(1-\sin qt) \qquad (17)$$

It is to be remembered that a modulating device for which the power series (3) does not converge sufficiently rapidly to enable us to neglect terms of higher power than the second, will not produce a modulated wave as specified by (17). The characteristic of the thermionic vacuum tube, however, converges so rapidly that it satisfies (17) within the limits of experimental error. The wave used in the experiments described in this paper was a 300,000 cycle wave completely modulated by 800 cycles with a thermionic tube and can therefore be regarded as being characterized by expression (17). Complete modulation was secured by predetermining the negative grid voltage necessary to reduce the current to zero for the plate voltage used and then making the peak value of the audio frequency input voltage equal to $\frac{E_B}{\mu}-E_c$, where E_c is the constant grid battery voltage.

6. FUNCTION OF THE RECEIVER SHUNT. The receiver shunt furnishes a quick and simple means of measuring detecting currents. Its series and shunt resistances each consist of a number of separate non-inductive resistance units, so arranged that definite pairs are connected in circuit for each adjustment of the shunt, their values being so chosen that the total impedance into which the generator U works remains constant. The value of a constant impedance shunt becomes apparent when considering the measurements in the determination of the detecting current as a function of the input signal strength.

For convenience in representing the measurements, the relation between the generator current i_1, as measured by the ammeter A, and the detecting current i can be represented by the well known equation for current attenuation by a line or cable:

$$\frac{i_1}{i}=e^{ad} \qquad (18)$$

where e is the base of the natural logarithms, d is the length of cable of which a is the attenuation constant per unit length. The constant a is, of course, purely arbitrary. In conformity with practice among telephone engineers we shall make a equal to the attenuation constant of the so-called "standard number

19 gauge cable," namely, 0.109 per mile at a frequency of 800 cycles per second.* This reference cable has a capacity of 0.054 microfarad and a resistance of 88 ohms per mile at a frequency of 800 cycles per second. The current attenuation can then be expressed in miles, *d*, of the chosen standard cable of reference, the receiver shunt being calibrated in terms of two-mile steps. Length of cable forms a very convenient unit of measurement in cases where the telephone receiver is used as the measuring instrument. This unit has long been in use in telephone practice and I would urge its general adoption in measurements relating to radio detectors. The fact that the current ratio $\frac{i_1}{i}$ changes rapidly with the cable length *d* is not a disadvantage attending the use of this unit because small changes in current are not easily detected with a telephone receiver, which, on the other hand, gives sufficiently accurate readings since it is the instrument used in practice for giving us sense impressions of current. In fact, it is usually sufficient if the receiver shunt is calibrated in steps of two miles of standard cable. With a little practice such a calibration allows of an estimate to within one mile. It is to be understood that the relation between the length *d* of cable and the current ratio depends upon the chosen value of *a* which must be agreed upon. Wherever reference is made in the following to miles of cable the value of *a* will be understood to be 0.109. For convenience of reference the relation between *d* and $\frac{i_1}{i}$ for this reference cable is given in Table 1.

TABLE 1

Miles of Standard Cable d	Current Ratio $\frac{i_1}{i}$	Miles of Standard Cable d	Current Ratio $\frac{i_1}{i}$
5	1.72	50	232
10	2.97	60	689
15	5.13	70	2.05×10^3
20	8.85	80	6.08×10^3
30	26.3	90	1.82×10^4
40	78	100	5.35×10^4

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* 1 mile = 1.6 km.

7. Experimental Results. Since the detecting current i and input signal voltage e are connected by

$$i = a e^2 \tag{4}$$

we get by substitution in (18):

$$d = -2K \log_{10} e + C$$

where

$$\left.\begin{aligned} C &= K \log_{10} \frac{i_1}{a} \\ K &= \frac{2.3026}{a} = 21.13 \end{aligned}\right\} \tag{20}$$

The detection coefficient a can now be obtained in a simple way by successively applying different input voltages e to the tube and every time adjusting the receiver shunt S (Figure 1), so as to make the note in the receiver T of equal intensity for both positions of the switch W. The intercept C ($\log e = 0$) of the straight line (19) gives a in terms of the known values of K and i_1:

$$\log a = \log i_1 - \frac{C}{K} \tag{21}$$

The source of audio frequency which supplied the auxiliary note was used also to modulate the radio frequency. The circuit arrangement is shown in Figure 5. U represents the source of audio frequency current. What was actually used for this purpose in these experiments was a vacuum tube oscillator. The microphone generator shown in the diagram serves the purpose as well and has been used in portable vacuum tube testing sets. Its principal of operation is the same as that of an interrupter altho it is much superior, the interrupter being, on account of its unreliability and need of constant adjustment, practically useless for accurate measurements. The microphone generator which has long been used in telephone testing work, has the advantage that its circuit is never broken as in the case of the interrupter, the resistance of the carbon being merely varied harmonically by the effect of the flux in the coil on the diafram. It is therefore free from the usual troubles attending the use of an interrupter, such as sparking and consequent corroding of the contacts. It operates on about 3 to 5 volts d.c. The a.c. obtained from it is transmitted thru a filter F to give a pure note of 800 cycles. This and the radio frequency oscillations obtained from the vacuum tube oscillator O are both impressed on the input of the modulator M, the resulting modulated wave being impressed on the detector *D*. By means of the switch, *W*, the low frequency current can be transmitted either to the modulator or, thru the shunt *S*, to the telephone receiver *T*. Since the receiver had an impedance of

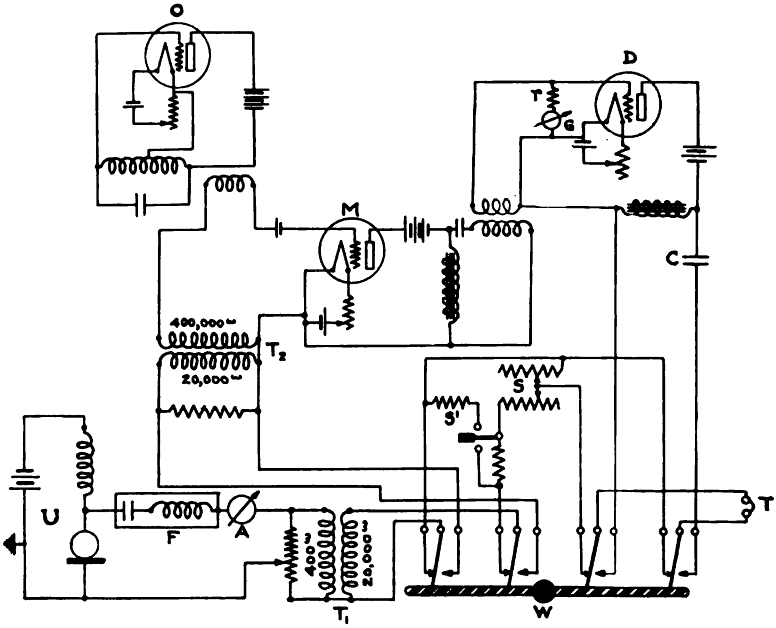

FIGURE 5

20,000 ohms the transformers T_1 and T_2 were inserted to insure that the generator *U* works into the same impedance for both positions of the switch *W*. If the audio frequency current is measured by *A* on the low side of the line a small correction might be needed for loss in the transformer T_1. However the audio frequency vacuum tube oscillator used in these experiments gave sufficient power to enable the current to be measured directly in the 20,000-ohm line. The receiver shunt *S* gave a maximum attenuation of 30 miles of standard cable $\left(\frac{i_1}{i} = 26.3\right)$. For higher attenuations extra shunts *S'*, each of 30 miles, could be added.

To insure complete modulation of the wave impressed on the detector the modulator *M* can be made to measure its own input voltage according to the principle of the vacuum tube voltmeter of R. A. Heising[5]. If E_B and μ are the plate-filament voltage and amplification constant of the modulator, the negative grid voltage necessary to reduce the current in the plate circuit to zero is $\frac{E_B}{\mu}$. Complete modulation can then be obtained by applying a constant negative grid voltage $E_c = \frac{E_B}{2\mu}$ and making the peak value of the audio frequency input voltage e_1 also equal to $\frac{E_B}{2\mu}$. This can be done by first adjusting the negative grid voltage to a value $\frac{E_B}{\mu} + \frac{E_B}{2\mu}$ and then applying the low frequency a. c. and adjusting it until a current meter in the output circuit of M just begins to show a deflection. The peak value of the a. c. input is then equal to $\frac{E_B}{2\mu}$. The radio frequency can be measured in the same way and should be weaker than the audio frequency. For operating the modulator E_c must of course be finally adjusted to its proper value.

The accuracy with which the linear relation given by equation (19) holds is shown in Figure 6 in which the crosses and circles represent observations made by two different observers on different days. The close agreement of the slope, 42.2, of

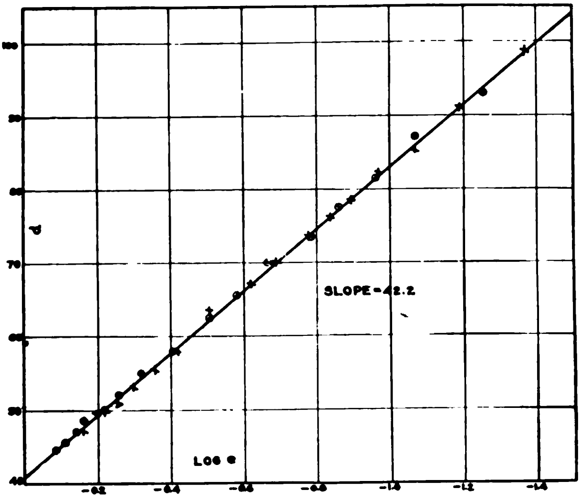

FIGURE 6

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[5] R. A. Heising, U. S. Patent 1,232,919.

this line with the theoretical value, $2\,K=42.26$, verifies equation (4). In measurements of this kind, where the intensities of two notes are compared, the influence of extraneous noises is small, almost negligible compared with their influence on measurements by the audibility method. The error in the observations was due largely to the fact that the detecting current contains a weak harmonic component (see equation 14) which to some observers seems to have a somewhat disturbing influence. If necessary this harmonic could easily be filtered out by the insertion of an appropriate inductance in series with the condenser C in the output of the detector.

The current i_1 as measured by the meter A, inserted in the 20,000-ohm line, was 3.10×10^{-3} ampere and the intercept for $e=1$ of the line shown in Figure 6 is 40.8. Hence the detection coefficient $a=36.2\times 10^{-6}$ amp./(volt)^2.

Table 2 gives the results obtained by a number of different observers, the observations being made on three successive days.

TABLE 2

Observer	Slope $2\,K$	Intercept C	Detection Coefficient Amp./(volt)^2
A	42.6	39.9	41.6×10^{-6}
A	42.6	40.0	41.0×10^{-6}
A	41.0	41.1	31.0×10^{-6}
B	42.7	39.7	42.8×10^{-6}
B	42.0	41.4	33.5×10^{-6}
B	42.1	41.4	33.7×10^{-6}
C	42.2	41.7	32.9×10^{-6}
D	41.4	41.4	31.0×10^{-6}
E	41.6	41.0	33.1×10^{-6}
Mean	42.0	40.8	35.6×10^{-6}

The input signal voltages concerned in these measurements are the root-mean-square values of the completely modulated wave. If it is necessary to express them in peak values they must be multiplied by $4/\sqrt{3}$ instead of by $\sqrt{2}$ as in the case of an unmodulated wave. This can be seen by making B equal to unity in equation (16) and noting that the peak value of the wave is $2\,A$ (equation 12).

8. DETECTING EFFICIENCY. The detection coefficient *a*, which gives a measure of the audible component of the current in the output of the detector, is not sufficient for expressing the figure of merit of the device, because it depends on the type of telephone receiver used. The impedance of the receiver must be so chosen as to give maximum response and the effect expressed in terms of the power dissipated in the receiver, which must, of course, be computed from its resistance.

When the thermionic detector is used without a blocking condenser in the grid circuit, as was the case in these experiments, the most efficient operation is obtained when the grid is kept sufficiently negative so as not to take current. The power consumption in the input circuit is then practically zero. The response in the output circuit depends on the potential difference established between filament and grid and not necessarily upon the power consumption in the input circuit. The detecting efficiency can, therefore, not be expressed as the ratio of audio frequency output power to radio frequency input power. The same reasoning applies to a consideration of the power loss in the input coil and condenser when using the customary input resonant circuit obtained by replacing the resistance and galvanometer *G* (Figure 1) by a condenser. Obviously if the power loss is a minimum the input voltage, and therefore also the detecting current, is a maximum.

This consideration furnishes an answer to the question as to whether the audion detector can amplify, that is, can give more audio frequency power in the output than radio frequency power expended in the input. Since the tube is a potential operated device the answer to this question must be in the affirmative. All that is necessary to verify this experimentally, is to impress a convenient voltage on the input of the tube, let us say by an arrangement such as shown in Figure 1. Practically all the input power consumption takes place in the resistance *r* and can be made as small as we please by making *r* sufficiently large and adjusting the input coupling so as to keep the input voltage constant. In this respect the thermionic detector differs from other types of detectors such as the Fleming valve and crystal detectors. Detection by these devices depends upon rectification of the incoming current. They can, therefore, never give more audio frequency power than the radio frequency power consumed in the input, in fact, they can never give as much. The audion, on the other hand, at least when operated without a grid condenser, does not detect by virtue of rectification of the incoming current.

The incoming current is not rectified at all and detection takes place solely by virtue of the curvature of the plate current characteristic, which makes possible an unsymmetrical release of energy supplied by the plate battery.

In view of these considerations it is best to express the detecting efficiency in terms of the relation of output audio frequency power to input radio frequency voltage. It is, therefore, given by

$$\delta = a^2 t \tag{22}$$

where a is the detection coefficient and t the resistance of the telephone receiver.

The receiver used in these experiments had an impedance of 20,000 ohms and a resistance of 6,400 ohms at 800 cycles per second. Hence, taking the mean value of a given in Table 2, the detecting efficiency is

$$\delta = 8.1 \times 10^{-6} \text{ watt}/(\text{volt})^4$$

The tube on which these measurements were made was one of the Western Electric type, V. T. 1 (Figure 7-a), that was specially designed for airplane radio telephone service and used by the United States Signal Corps for this purpose. This type

FIGURE 7a

FIGURE 7b

of tube does not give as high an efficiency as some of the pre-war tubes, but it was designed to operate on low power consumption, its operating plate voltage being about 20 volts and the power consumed in heating its filament 2.2 to 3.5 watts.

Figure 7-b shows a pre-war type of Western Electric tube which has been in use in this laboratory since the early part of 1916. While this tube has a higher detecting efficiency than that shown in Figure 7-a, the power consumed in its filament is about twice as much and it operates on a plate battery of 30 volts. Another type of pre-war tube is shown in Figure 7-c. This tube has an amplification constant of 40, and can be used as a voltage amplifier or detector.

Figure 7c

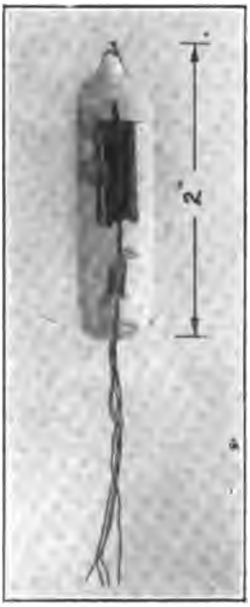

Figure 7d

Smaller types of detector and amplifier tubes have since been developed which require only a few tenths of a watt for heating the filament. Such a tube is shown in Figure 7-d. With a filament voltage of 1 volt, filament current of 0.18 ampere and a plate voltage of 10 volts, this tube has a detecting efficiency of 4.3×10^{-6} watt/(volt)^4. The filament can be operated on one dry cell, its operating voltage ranging from 1.0 to 1.5 volts.

The detecting efficiency of this tube is therefore about one-half that of the V. T. 1 tube. The actual effect on the ear due to this difference is not large. A ratio of two in the power corresponds to a difference of about three standard cable miles. A difference of one standard cable mile is hardly noticeable unless the comparison be made directly. For this reason also the detection coefficients given in Table 2 should be regarded as showing very small variations. The more correct measure, as far as the ear is concerned, is the detection coefficient expressed on the logarithmic scale, that is, the values of the intercept C given in the third column of Table 2, and which are expressed in miles of standard cable.

An idea can be obtained regarding the intensity of the sound produced when power of the order given by these tubes is dissipated in the receiver, by noting that the power dissipation necessary in this receiver to give the least audible signal is about 3×10^{-12} watt. From the above value of the detecting coefficient the input voltage necessary to give the least audible signal is therefore about 0.025 volt.

9. **Comparison of Detectors.** The constancy with which vacuum tubes can now be made to operate as detectors brings the testing of detector tubes by means of comparison circuits within commercial possibility. Comparison methods have a practical advantage in that they do not necessitate such accurate calibration of the quantities involved. Once the detecting efficiency of a tube has been determined the tube can be used as a standard of comparison to obtain the efficiency of any other tube by the simple circuit shown in Figure 8. The input voltage

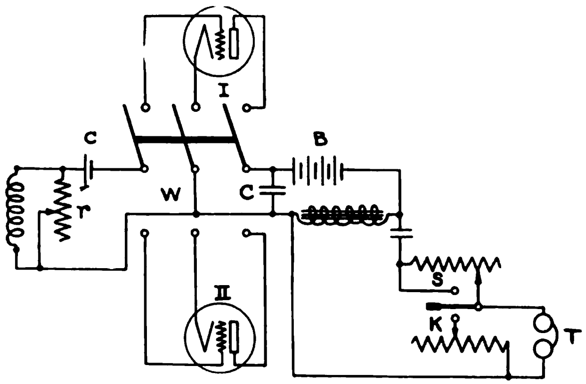

Figure 8

can be adjusted to any desired value by adjusting r, and need not be known accurately in this case, it being sufficient to know that it lies within the range of voltages encountered in practice. By means of the switch W either detector can be inserted in the circuit and the receiver shunt S adjusted until the note in the receiver T is of equal intensity for both positions of the switch W.

C is a radio frequency leak. By means of the key K the shunt can be thrown into or out of circuit according as the switch W connects the tube of higher efficiency or the other. If i_1 and i_2 be the detecting currents obtained from the tubes 1 and 2, and a_1 and a_2 their detection coefficients, then since the input voltage is the same for both

$$log \frac{i_1}{i_2} = log \frac{a_1}{a_2} = \frac{d_1 - d_2}{K} = \frac{d}{K}$$

where d is the adjustment of the shunt in units depending on the units of K. As before we can express d in miles of standard cable by making $K = 21.13$. The detecting efficiency can then be obtained from

$$\delta_2 = \left(\frac{a_2}{a_1}\right)^2 \delta_1 \tag{23}$$

10. MODIFIED AUDIBILITY METHOD. The audibility or "shunted telephone" method has been frequently applied in attempts to measure the strength of received signals in long distance radio communication and has also been used in obtaining an idea of the sensitiveness of detectors. This method consists in shunting the telephone receiver connected in the output of the detector and determining the value of the shunt necessary to reduce the current in the receiver to such an extent that dot and dash signals can just barely be differentiated. The ratio of the total current in the receiver and shunt, that is, the detecting current, to the current in the receiver alone, measures the "audibility" and can be computed from the resistance of the shunt and the impedance of the telephone receiver. When we consider the possibility of accurate measurements, this method is open to serious objections. In the first place it is liable to considerable error because the measurement of least audible signals is made difficult by the influence of extraneous noises, such as room noises and static. It furthermore depends to an appreciable extent upon the condition of the observer, so that the current necessary to give least audible signals will vary from time to time even with the same observer. These disad-

vantages make this method quite unreliable for purposes of determining detecting efficiency.

Secondly, the way in which the audibility method is ordinarily used does not make provision for the change in effective impedance when the shunt resistance is varied. This would give misleading results, since the detecting current, that is, the audible component of the current in the output circuit of the detector tube, depends upon the relative values of the internal output impedance of the tube and the impedance into which the tube works. It is therefore necessary in all measurements of this kind to adjust these impedances properly and keep them constant thruout the measurements. If the audibility method is to be used the "audibility box" should be so designed that any variation in the shunt resistance is accompanied by an addition or subtraction of an equivalent resistance so as to keep the total impedance of the circuit constant. This could be done with the scheme that will now be described.

The audibility measurements given here were made with the object of determining the possible error to which measurements would be subject when the audibility method is used, for example, for the determination of the strength of incoming signals. The fact that the current necessary to give least audible signals has different values for different observers, and is therefore incapable of objective determination does not of itself rule out the audibility method for the measurement of signal strength, since the detector set could first be calibrated by determining the audibility for known input signals and then used by the same observer to make the final measurements. Hence, assuming that extraneous noises could be effectively cut out, the possibility of adapting this method to such measurements would depend upon the extent to which the observer's conception of least audible signal remains constant during the time that elapses between his calibration of the set and the making of his final measurements. It is hardly necessary to say that the whole set must remain unchanged, especially the tube and the telephone receiver.

The circuit by which the variability of least audible signal was studied is shown in Figure 9. This circuit allows of audibility measurements under constant circuit conditions. The tube used was the same one on which the above measurements were made. It was a Western Electric "standard" the detecting efficiency of which had not changed to any noticeable extent in the course of seven months during which time it was in frequent use. Any variability of the least audible signal as determined by this set was due entirely to the observers.

The input signal wave was, as before, a completely modulated wave and could be measured with the Duddell galvanometer G. In order to keep the impedance of the output circuit constant the receiver shunt described above was used to shunt down the current in the telephone receiver. The choke coil, L, was inserted

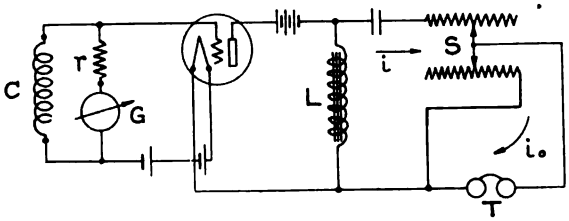

FIGURE 9

to keep the impedance of the tube constant. This was necessary because, altho the *impedance* of the circuit remains constant for all adjustments of the shunt, its d. c. *resistance* varies and if the coil L were omitted the variation in resistance would result in a variation of the d. c. potential difference between plate and filament with a consequent variation in the tube impedance.

The use of the receiver shunt makes it possible to express the "audibility" in a simple way. If i be the detecting current and i_0 the least audible signal current in the receiver the audibility $\frac{i}{i_0}$ can be expressed in miles d of cable by equation (19) where the intercept C $(e = 1)$ is now given by:

$$C = K\,(log\,a - log\,i_0) \qquad (24)$$

and gives a measure of the audibility efficiency in miles/(volt).[2]

The simple linear relation (19) makes it possible to obtain the audibility efficiency as the average of a large number of observations. A number of such observations plotted against the logarithm of the corresponding input voltages are shown in Figure 10. Altho the individual points vary considerably from the average they are nevertheless grouped evenly about the straight line, the slope of which, namely, 41, is quite close to the theoretical value, 42.26. In no case was there any difficulty in verifying the linear relation.

The slope of the line depends only upon the attenuation constant of the shunt and the simple quadratic relation (4).

The intercept, on the other hand, is influenced also by the detection coefficient, a, of the tube itself and by what constitutes the least audible signal current, i_o, for the particular telephone receiver used and for the observer at the particular time of making the measurements. The detection coefficient and the attenuation factor K certainly do not vary enough to be noticed. Any variation in the intercept C will, therefore, be due to the least audible current. Hence a number of separate determinations of C could be used to give an indication of the accuracy of the audibility method. Now, the least audible current depends firstly upon sensitiveness of the telephone receiver. By using the same receiver thruout the measurement any variation due to this factor can be regarded as negligibly small compared with the much more disturbing variation in conception of least audible signal on the part of the observers. Since this conception varies with different observers as well as with the same observer at different times, measurements were performed by four different observers over a period of eight days. The results are shown in Table 3 and were obtained from curves such as shown in Figure 10. They therefore give the average of over 350 observations. The fourth column gives the audibility efficiency in miles/(volt)^2, (log $e = 0$). The corresponding audibilities expressed in current ratio, determined from Table 1, are given in the adjacent column. The last column gives the input voltage (r.m.s.) necessary to give a detecting current equal to the least audible signal current ($d = 0$).

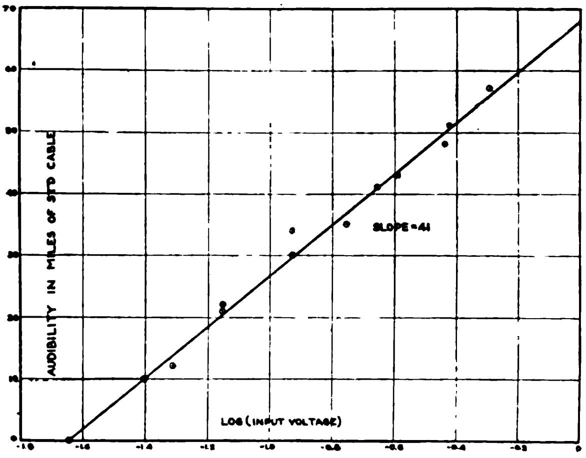

FIGURE 10

TABLE 3

Observer	Time	Slope 2 K	Audibility Efficiency, C		Input for Least Audible Current (Volts)
			Miles / (Volt)^2	i / i_0' (Volt)^2	
A	1st day A.M.	42.7	60.9	760	.037
	2nd " A.M.	41.4	61.6	820	.036
	2nd " P.M.	45.0	64.6	1140	.038
	3rd " A.M.	44.2	62.8	940	.030
	5th " A.M.	39.5	60.1	700	.033
	5th " P.M.	44.6	65.7	1280	.028
	6th " A.M.	43.7	68.6	1720	.025
	6th " P.M.	43.1	68.9	1800	.022
	7th " A.M.	40.8	67.6	1550	.023
	8th " A.M.	42.3	69.8	1980	....
	Mean:	42.7	65.0	1260	.030
B	2nd day A.M.	40.4	62.4	900	.028
	2nd " P.M.	43.0	65.8	1300	.030
	3rd " A.M.	38.0	61.6	820	.024
	5th " A.M.	41.5	64.1	1080	.028
	5th " P.M.	41.1	63.7	1040	.028
	6th " A.M.	42.1	64.0	1070	.030
	6th " P.M.	42.4	65.5	1250	.028
	7th " P.M.	43.2	68.1	1640	.026
	8th " A.M.	41.4	64.5	1130	.028
	Mean:	41.5	64.4	1130	.028
C	3rd day A.M.	43.6	66.6	1400	.024
	5th " A.M.	40.8	65.6	1260	.025
	5th " P.M.	43.3	65.4	1240	.031
	6th " P.M.	46.0	66.2	1340	.037
	7th " P.M.	41.2	67.8	1580	.023
	8th " A.M.	43.0	66.5	1380	.029
	Mean:	43.0	66.4	1360	.028
D	7th day A.M.	44.0	77.2	4840	.018
	7th " P.M.	44.0	73.5	3140	.021
	Mean:	44.0	75.4	4000	.020

It will be seen from these observations that the audibility varies quite considerably with different observers, and even with the same observer at different times. It must be remarked that these measurements were not performed under ideal conditions as regards freedom from noise, outside noises from the city streets being sometimes distinctly noticeable. Ideal conditions are, however, not practicable and the value of such measurements could reasonably be expected to be determined to a great extent by the accuracy with which they can be made under normal conditions. It is possible that the wide discrepancy in the reported error attending audibility measurements

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[6] See L. W. Austin, PROCEEDINGS OF THE INSTITUTE OF RADIO ENGINEERS August, 1917, page 239, and the discussion by J. Mauradian, page 248.

(the error ranging from about 20 per cent to several hundred per cent)[6] is due to the varying noise conditions under which the measurements were performed.

11. APPLICATION TO DETERMINATION OF SIGNAL STRENGTH. When considering the practical problem of measuring the strength of received signals, the audibility method has the one advantage that it does not require an auxiliary source of audio frequency. Its inaccuracy, however, would hardly recommend it for such measurements. The method described in the first part of this paper has the advantage of greater accuracy, especially when considering the influence of static disturbances. The constancy of the tube makes it possible to determine the efficiency of the set beforehand. From the observed detecting current the received input voltage can then be obtained, from which the received power can be calculated when the constants of the input circuit are known. For accurate measurements it would, of course, be necessary to consider the form of the incoming wave. When measuring weak signals received on long distance communication, the heterodyne method could be used. By putting the detecting current $i=b\,e\,e'$, instead of equation (4), where e is the signal voltage and e' the local input voltage, a simple linear relation can be obtained similar to equation (19). The local voltage e' could be made sufficiently large to enable it to be measured with the detector itself in the manner explained above (section 7) in connection with the measurement of the voltages impressed on the input of the modulator.

12. PRACTICAL APPLICATIONS. When it is necessary to test a large number of detector tubes, the circuit shown in Figure 5 is somewhat impracticable, because such a circuit requires careful adjustment of the operating parameters, such as the input radio frequency voltage impressed on the detector, the audio frequency current delivered by the generator U, and so on. The procedure that was adopted and found more practicable was to use this circuit to standardize, by means of the method explained above, carefully selected tubes the detecting efficiency of which was found to remain constant. These tubes were then used as comparison standards to test the factory product by means of a circuit like that shown in Figure 8. The tubes could then be compared with the standard under the actual circuit conditions under which they may be required to operate in practice. Figure 11 shows a comparison test circuit designed to test detectors which are intended for use in conjunction with

an amplifier. The circuit is arranged in a box, shown in Figure 12, with terminals for connecting the batteries and jacks for measuring the filament and plate voltages. It was necessary to secure a simple means of producing constant modulated radio frequency oscillations to serve as the source of input voltage. Ordinarily this would require a radio frequency oscillator, an audio frequency oscillator and a modulator. To avoid using such a cumbersome and rather impracticable arrangement the oscillator tube, *O* (Figure 11) was made to produce modulated high frequency oscillations directly with the aid of a microphone generator, *U*. The carbon button of this generator was inserted directly in the oscillating circuit, L_1 C_1, as shown in the diagram. The microphone causes an audio frequency variation of the resistance of the oscillating circuit and thus serves to modulate the radio frequency oscillations. The modulation produced by this means is not complete, but complete modulation is not necessary when *comparing* detectors. The audio frequency component in the output of the detector is amplified by the tube, *A*. C_2 is a high frequency leak and *r* a high resistance acting as a grid leak to prevent the grid from building up a charge. The difference in detecting efficiency of the two tubes can be measured by means of the shunt, *S*, in the manner explained in section 9, and can, as shown in the measurements described above, be most conveniently expressed

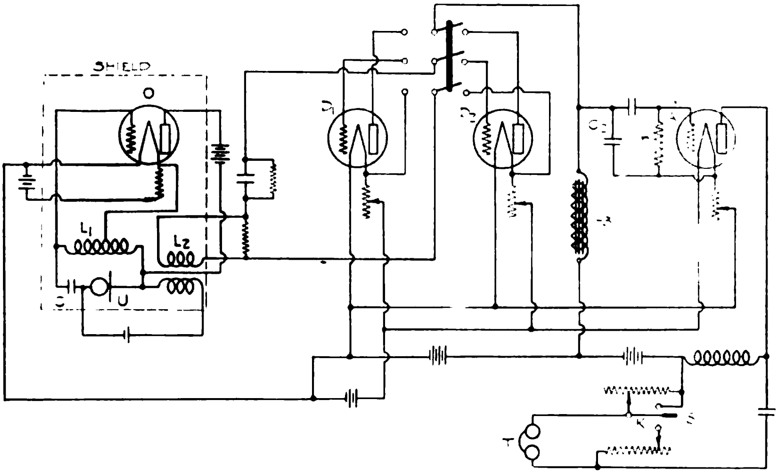

Figure 11

in the logarithmic scale. The shunt used in these test sets had a constant $K = 21.13$, thus giving the difference in detecting efficiency in miles of standard number 19 gauge cable.

FIGURE 12

APPENDIX

At the beginning of this paper mention was made of a simple method of measuring the amplification of audion tubes. Altho there is nothing new in this method which has been in use in this laboratory for many years, it is not generally known and may, therefore, be briefly described here. The circuit arrangement whereby the amplification can be measured is shown in Figure 13. Audio frequency currents are supplied by the generator, *U*, and are passed thru the filter to obtain a pure note of, say, 800 cycles per second. By operating the switch, *W*, this current can be transmitted either directly to the telephone receiver, *T*, or thru the tube and a receiver shunt, *S*. By adjusting the shunt until the note heard in the receiver is of the same intensity for both positions of the switch, *W*, the current amplification given by the tube is equal to the attenuation produced by the shunt, and is given by equation (18), or

$$d = K \, log \frac{i_2}{i_1}$$

where i is the current in the receiver and i_2 the current before being attenuated by the shunt. The reading, *d*, of the shunt usually gives the amplification in miles of standard cable. The actual current ratio can, as before, be obtained from Table 1. The power amplification, which is a more desirable expression, and means more than current amplification, can be obtained from the above equation by dividing the factor K by 2.

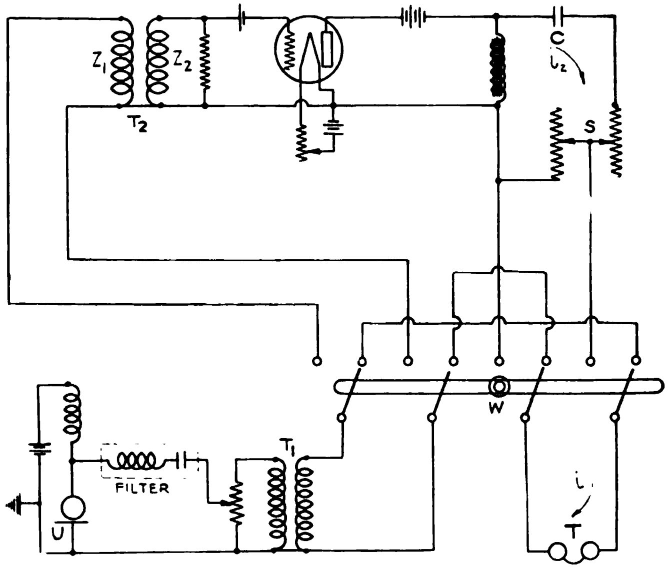

Figure 13

The generator, U, can be of any type that gives constant audio frequency current. In Figure 13 it takes the form of a microphone generator. On account of its compactness, this is a desirable source of audio frequency currents, when the test set is to be small, compact, and portable. A portable Western Electric test set (made for the United States Signal Corps) is shown in Figure 14.

Care must be taken, when using this method that the current in the secondary of the transformer, T_1, is the same when connected to the input of the tube as when connected to the telephone receiver. For this purpose the impedance, Z_1, of the transformer, T_2, is made equal to the impedance of the receiver. The secondary of transformer, T_2, is wound to have as high an impedance as possible, to impress the maximum possible voltage on the grid circuit of the tube. When, as in

FIGURE 14

this case, the receiver has an impedance equal to the plate resistance of the tube, it can be connected directly to the output circuit of the tube, as shown in the diagram, the receiver shunt being so designed that when placed between the tube and the receiver, the total impedance of the output circuit remains constant for all adjustments of the shunt. If the impedance of the receiver is very different from the plate resistance a transformer of the proper impedance ratio must be inserted in the output circuit.

In conclusion I wish to acknowledge the assistance of Mr. R. H. Wilson in carrying out the experiments described above.

Research Laboratory of the
American Telephone and Telegraph Company and
Western Electric Company, Incorporated,
New York City.

March, 1919.

SUMMARY: There is described a method of determining the detecting efficiency of vacuum tubes by feeding them with radio frequency current modulated at audio frequency. The theory of the method is given.

In connection with such measurement, the use of a receiver shunt calibrated in terms of miles of "standard number 19 gauge cable" is advocated.

For producing the radio frequency current for such measurement, a tube oscillator was employed. The audio frequency modulation was obtained either by a second tube or by a microphone howler. The apparatus is described in detail, and illustrated. Experimental data are given.

A method for comparing the detecting efficiencies of a standard tube and of a tube under test is also described, and the apparatus is shown.

In an Appendix, a simple method of measuring tube amplification is [illegible]ed.

DISCUSSION

John M. Miller: In connection with the method which has just been described for measuring the detecting efficiency of a three-electrode vacuum tube, it may be of interest to outline the method which has been independently developed at the Bureau of Standards for making these measurements. The general requirements of such a method are somewhat obvious, that is, a relation must be established between the radio frequency input to the detector and the audio frequency output. In order to obtain a source of completely modulated radio frequency for calibrating detector tubes, we have made use of the arrangement shown on the left of Figure 1. In the plate circuit of the oscillator tube which supplies the modulated radio frequency emf. to the detector tube there is an audio frequency voltage furnished by an alternator which is in series with the customary d. c. battery. The peak value of the alternating voltage is adjusted to equality with the d. c. voltage so that the total plate voltage varies from zero to a maximum value of twice that of the d. c. battery. A calibration of the output of the oscillator tube with respect to the plate voltage shows a linear relationship between output current and plate voltage thruout the range of voltage used, so that under the action of

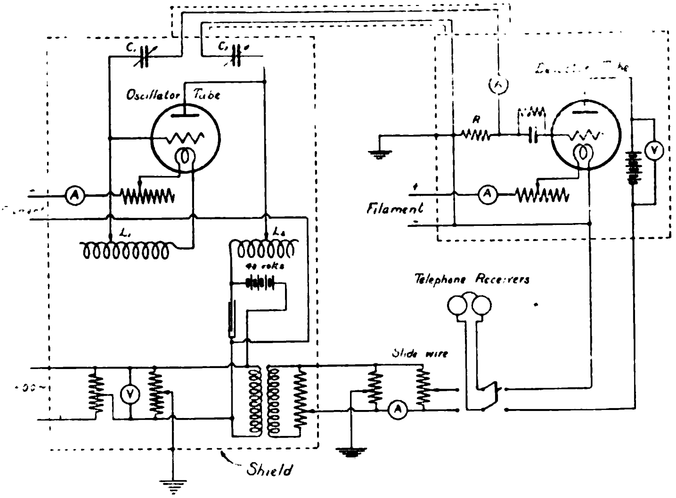

FIGURE 1

the combined a. c. and d. c. voltages the output current will be completely modulated with a sinusoidal envelope. A known emf. of this modulated radio frequency is supplied to the input of the detector tube, by measuring with a vacuum thermocouple the current thru a known resistance across which the input terminals of the detecting tube are connected, in a manner exactly similar to that described by Dr. van der Bijl. The method of measuring the audio frequency output of the detector tube is somewhat different in that we measure the audio frequency voltage acting on the telephone receivers. This is done by throwing the receivers back and forth from the output circuit of the tube to a potentiometer device (slide wire in Figure 1) which is supplied current from the same alternator from which the alternating voltage in the oscillating tube circuit is obtained ensuring the same pitch. The potentiometer voltage is adjusted until equality in sound intensity is obtained. The potentiometer current and setting then give the audio frequency voltage acting on the receivers. This method involves no changes in the electrical characteristics of the plate circuit of the detector tube. Since it likewise permits a continuous variation of the voltage acting on the telephones, it therefore furnishes the data to answer Mr. Ballantine's question as to the accuracy of such an intensity comparison.

We find that audio frequency emfs. can be compared in this way to about one-half of one per cent. when the mean of a number of observations is used.

There is one point in connection with the use of the constant impedance receiver shunt which can possibly introduce a slight error in some measurements. My idea of this device is that when the shunt is varied, the impedance, as measured from the input terminals of the shunt, is constant, but its angle varies. Thus, in one position, when the receivers are unshunted, the impedance can be represented by a vector which makes an angle of about 70° from that which would represent a pure resistance, assuming the values for the receiver impedance and resistance given in the paper. As the shunt is varied, the angle decreases, the modulus remaining constant. In case the shunt is used in the plate circuit of a vacuum tube, it will be in series with a pure resistance. The total circuit impedance will be given by the vector sum of these separate impedances and will, therefore, vary as the shunt is changed.

H. J. van der Bijl: Dr. Miller assumes a large angle for his receiver (82°). Generally receivers have angles considerably smaller that this value. If you calculate the shunt and series resistances of the receiver shunt, assuming that the receiver connected to it has an angle of 40°–50°, you will find that for current attenuations greater than that corresponding to about 6 miles (9.6 km.) of standard cable, the effect of the angle is negligible. This is because for large attenuation the series resistance is large and the effective angle therefore small. In this case we can, therefore, neglect the effect of the angle, which makes the computation of the necessary resistances very simple. If, on the other hand, the angle of the receiver is large, it must be taken into consideration and this has been done in the receiver shunts used in my experiments. In this case the problem is that of an inductive circuit with varying angle. The computation is somewhat tedious and therefore we generally determine the resistances graphically.

I was interested to hear about the experiments made by Dr. Miller at the Bureau of Standards, using this method. I could not quite gather from what he said whether he had made marked improvements on it; I understand that he made measurements which gave an accuracy of one-half of one per cent. I do not exactly know what that means.

I am very glad to hear that this method has been found to allow of such accuracy by Dr. Miller in the comparatively short time. Altho I disclosed my method of measuring detecting efficiency to the Signal Corps about two years ago, it was only about six or eight months ago that I acquainted the Bureau of Standards with the details of it.

HARMONIC OSCILLATIONS IN DIRECTLY EXCITED ANTENNAS USED IN RADIO TELEGRAPHY*

BY

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INTRODUCTION

Direct excitation, originated by Hertz, in his classic experiments, and subsequently used by G. Marconi in the first radio telegraphic stations, has meanwhile been practically wholly eliminated in modern stations of any importance, since the advantages afforded by indirect excitation by means of electromagnetically coupled circuits have come to be appreciated. Investigators in radio telegraphy have consequently never made a very careful examination into the oscillations produced in antennas by the more primitive method; and while they did become aware of the complex nature of the emitted waves, they confined themselves in most instances to the observation or calculation of the length of the first harmonic, without determining the amplitude; (rightly considering the harmonic oscillation to be merely an undesired source of loss, inasmuch as the energy radiated thereby was practically in no instance utilized for the transmission of signals, and contributed not towards the efficiency of such transmission, but towards increasing the losses inherent in the entire system).

From a theoretical point of view, moreover, the problem could be considered as having been completely solved by the well-known equation for the propagation of currents in circuits having distributed inductance and capacity, the general integral of which has been given in a sufficiently simple form by K. W. Wagner, in a classic treatise by that author, who also interpreted from a practical point of view, in the same volume,[1] the most important results obtained with reference to aerial and underground lines.

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* Received by the Editor, November 12, 1918. Translated from the Italian and edited by the Editor.

[1] "Elektromagnetische Ausgleichsvorgänge." 1908.

Using as a model a conductor or line of considerable inductance and capacity, the same author carried out experiments relative to the transient phenomena, following sudden changes of current and potential, and demonstrated that the actual phenomena were exactly in agreement with the theoretical conclusions arrived at with regard to the same[2]. The effects produced were shown in a number of oscillograms. Wagner's artificial line, however, applied only to low voltage experiments, in which the making and breaking of the circuits occurs without any material sparking. The circuit resistance and the damping being consequently practically constant, the phenomena may be considered to be correctly represented by the theoretical formulas, containing the heat losses and ohmic drops, while radiation need not be considered as of any importance.

On the other hand, the antennas used in radio telegraphy are very different in this respect, inasmuch as the radiated energy in some cases is about as large as the energy dissipated by the ohmic resistances. Among these latter resistances (at least whenever the excitation is accomplished by means of devices utilizing disruptive discharges), the most important one in many cases is that of the spark, which also gives rise to a damping factor, which is rather indefinite and exceedingly variable.

We have recently constructed at the Electrical Engineering Institute of the Royal Polytechnic School an artificial line for high voltages (which line can also be operated as a powerful Hertzian oscillator, or as a radio telegraphic antenna of low radiation resistance) and we have available means for generating radio frequency currents. It was decided to investigate the operation of this apparatus with oscillations directly excited by means of spark discharges of the principal types still used in radio telegraphic stations. Such spark discharges had been recently used by me in other research work concerning excess voltages and the protective systems.[3]

GENERAL EXPERIMENTAL ARRANGEMENT

For these measurements, the antenna was composed of two large solenoids of copper wire, 3 millimeters (0.12 inch) in diameter and 170 centimeters, (67 inches) long, each of the solenoids having 240 turns 36 centimeters (14.2 inches) in diameter, with an ohmic resistance of 2.7 ohms and an inductance of 0.004 henry.

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[2] "Elektrotechnische Zeitschrift," 1911, page 899.

[3] "L'Elettrotecnica," 1918, "Conferenza sperimentale alla A. E. I."

This artificial antenna is shown in Figure 1. *A* is the 42- or 150-cycle alternator, *T* the transformer, *M* the Marconi synchronous rotary gap, *a* an alternative fixed gap, *b* coupling coil to the wave meter, and *L* and *C* the artificial antenna. The constants are indicated in the diagram.

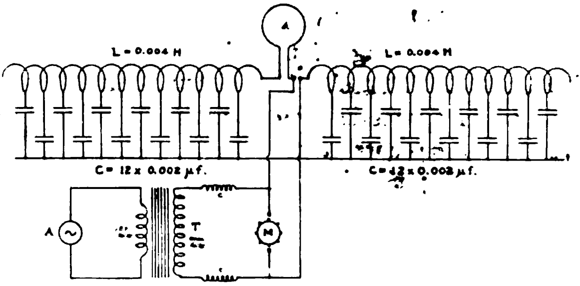

FIGURE 1—Artificial Antenna and Exciting System

The capacity of each section of the antenna was supplied by 12 Moscicki condensers having a total capacity of about 0.026 microfarad, one of the terminals of each condenser bank being grounded while the other was connected to its solenoid at distances of 20 turns from each other. With this arrangement, the fundamental wave length is about 11,000 meters, when the two sections are symmetrically excited at their connecting point; the surge impedance at this wave length proved to be 395 ohms, and the damping constant 330.

The antenna was sometimes excited by means of a large induction coil, with hammer break or turbine interrupter, or else with a Wehnelt interrupter, and with a spark gap having brass or zinc spherical terminals. At other times, excitation was accomplished by means of a 5-kilowatt transformer of commercial type, fed with 42-cycle alternating current from the city supply or from a small 150-cycle alternating current generator with rotating field. Keyed to the shaft of this latter alternator was a synchronous rotary spark gap of the Marconi type, with adjustable fixed terminals, controlled as to exact position by means of a worm gear attachment. In place of the rotary gap, the transformer may be connected to an ordinary spark gap having brass balls, or else to a Boas multi-section spark gap provided with tungsten electrodes, powerfully cooled, and of the type used in radio transmission by Wien's quenched spark system.

For measuring wave length, there was used a Marconi standard wave meter, provided with four fixed capacities and one variable capacity, and with a range of wave lengths from 400 to 6,000 meters. Shorter and longer waves could be measured in the usual way, with added capacity and inductance.

A diagram of the wave meter used is given in Figure 2. L_1 is the inductance, T_1 and T_2 the telephone terminals, H the crystal detector, C the variable condenser, C_1 and C_2 terminals for an external larger condenser, K_1 and K_2 keys; L_2 and L_3 extra inductances which would change the wave length by the same percentage (different in each instrument), R a resistance of 3 ohms, *ab* terminals for decrement measurement, and *cd* terminals for thermocouple. With K_1 to left and K_2 to left (normal settings), L_2 is in circuit. Throwing K_1 to right cuts L_2 out of circuit, while throwing K_2 to right and K_2 to left puts L_3 into the circuit.

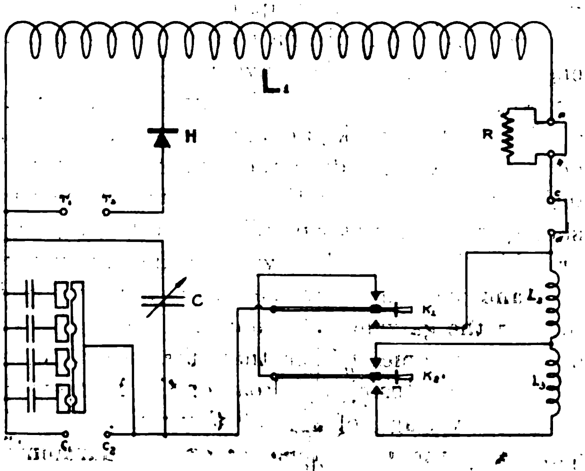

FIGURE 2—Wavemeter Used in Measurements

The wave meter is provided with two supplementary inductances, which could be switched into or cut out of the circuit by means of suitable keys, thus increasing or decreasing the frequency by 3.7 per cent. By means of a thermocouple and a precision galvanometer, two points of the resonance curve, symmetrical with respect to the resonance point, can thus be quickly determined, and the data thus obtained are sufficient for determining the total damping of the combined primary and secondary. For determining the primary and the secondary decrements separately, a supplementary resistance is included in the wave meter, and furnished with terminal clamps and a short-circuiting bar, by the removal of which bar the total resistance in the circuit is increased by a known amount, while the total damping is increased by an amount dependent on the wave length, and calculable in advance.

Using this method, only a few readings of the wave meter, kept in one position, are necessary to determine the primary current amplitude, containing, however, a factor of proportionality which depends only on the coupling coefficient to the wave meter.

If the position of the wave meter remains unchanged during a series of measurements at different wave lengths (or if, in case the meter has to be moved to a second position, by means of some separate measurements, the relative degrees of sensitiveness in both positions are determined by comparison), it becomes possible to determine quickly the amplitudes of the primary current and of all the harmonic currents in the range of wave lengths covered by the wave meter.

There were connected into the artificial antenna (double solenoid) close to the spark gap, and at a suitable distance from the solenoids (so as to reduce their direct influence), a couple of rectangular turns, similar to the inductances of the wave meter.

By sliding the wave meter parallel to itself along a supporting board or table, I succeeded in varying the coupling coefficient between it and the "antenna" circuit within very wide limits, and in having the galvanometer indicate perceptible deflections even for the harmonics higher than the twentieth, when the antenna was excited using the Boas or the Marconi discharger at a maximum voltage of several thousand. When using a brass spark gap, the measurements on the harmonics became comparatively unreliable; indeed the spark length had to be increased, with the result that the spark became rather unstable; or else the coupling had to be made so close as to cause distortion of the resonance curve. I refrained for the same reason from making a quantitative determination of the harmonics higher than the eighteenth. However, when using the Marconi gap, which operated more regularly, the presence of such harmonics was plainly indicated by the wave meter. Another wave meter having a small inductance, and constructed at our Institute, permitted measurements of shorter waves when the amplitude was reduced to a few per cent. of that of the fundamental wave. However, the determination of the new factors thus introduced was unreliable.

According to Wagner's theory, subsequently developed by Petersen[4], and recently re-investigated by Brylinski[5], the discharge of a line of length l, originally charged to the uniform potential E, and accidentally grounded at one end while the other end remains insulated, will be an oscillating phenomenon, equivalent to the superposition of two waves of rectangular form or profile, of a height $\frac{E}{2}$ and a length $4l$, moving in opposite directions with a velocity $\frac{1}{\sqrt{L_1C_1}}$ in which fraction L_1 and C_1 represent the inductance and the capacity per unit of length. The moving double wave would maintain its initial amplitude for an indefinite time if there were no ohmic resistance in the line, and in the absence of leakage, radiation, and any other factor causing loss of energy. If any of these factors occur, the travelling wave will become attenuated in course of time, and the decrement, calculated for the duration of a cycle, will remain constant if the ratio of the ohmic resistance to the inductance likewise remains constant. An increase in the resistance will therefore result in a more rapid decrease in the amplitude of the travelling wave, and will reduce its total duration, leading up to the new electrical conditions of the system.

Analytically, the rectangular double wave of discharge may be represented by two series of infinitely extended sinusoidal waves of lengths equal to $\frac{4l}{1}, \frac{4l}{3}, \frac{4l}{5}$, and of amplitudes $\frac{2E}{\pi}, \frac{2E}{3\pi}, \frac{2E}{5\pi}$, travelling in opposite directions and with equal velocities. Therefore, if the damping were eliminated, the amplitudes of the successive harmonics (as compared to that of the fundamental wave) would decrease in an inverse arithmetic progression of odd numbers. Consequently no wave corresponding to an even harmonic could be produced, because of the well-known property of functions symmetrical in their successive half-periods. In the special case considered, however, it would not be allowable to assume beforehand that there are no such waves corresponding to even harmonics present inasmuch as the amplitude of the various waves will in-

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[4] "Archiv für Elektrotechnik," volume 1, page 233; "Elektrotechnische Zeitschrift," 1913, page 167.

[5] "Revue Générale de l'Electricité," 1918, page 43.

evitably decrease in *geometrical* progression with increasing lapse of time and distance covered, even assuming that the insulation is perfect and the leakage zero. Consequently there will be an alteration in the form of the composite wave in the course of the successive half-periods, and the straight line which gave the outline of the positive and negative maxima of the rectangular wave at the beginning, will be replaced by other (logarithmic) curves. The less pronounced the asymmetry of the half waves (resulting from the damping) proves to be, the less will be the amplitudes of the even harmonics, and the more closely will those of the odd harmonics approach the amplitudes theoretically determined for the rectangular wave.

In Wagner's experiments, conducted with the previously mentioned low voltage line, the decrease of the wave was practically entirely due to the ohmic resistance of the coils, and since the resistance was rather limited $\left(\frac{R}{2L}=12.8\right)$, the decrease in wave amplitude did not amount to more than 15 per cent. after passing over the full length of the line. In the case of the antenna used by me for my research, the decrement was about 25 times as large because of higher ohmic resistance. However, since the natural period of oscillation is 250 times less, the wave should approximate more closely to the rectangular form in this case. Yet, since the antenna had to be excited directly by means of high voltage spark gaps, an additional damping factor was introduced by the spark; and this factor varied with the spark length of the latter, the current thru the gap, and the type of discharger used. For these reasons, the effects produced could not be theoretically predetermined, or at best only qualitatively. This induced me to undertake this modest quantitative research.

RESULTS OF EXPERIMENTS

Of the many experiments made, only a few will be described in this paper, but they will be sufficient to show the general nature of the influence produced by various types of discharger and different operating conditions.

In Table 1, for example, are given two sets of measurements, taken using the Marconi spark gap with 5,000 volts effective, or 7,000 volts maximum, across it. In the first case, the stationary terminals were set to a small spacing of 0.5 mm. (0.02

inch) from the moving electrodes, while in the second case a greater separation of 2 mm. (0.08 inch) was used.

The wave lengths are given in the first column, as determined by the wave meter, without making any corrections for such slight errors as were found because of the irregular distribution of the effective capacity, which would partly explain the discrepancy in the values of the frequency of the successive harmonics as compared to exact multiple values of the fundamental frequency.

In the second column have been entered the numerical ratios of these frequencies (which are inversely proportional to the wave length); and this leaves no room for doubt as regards the absence of odd harmonics and the presence of some even harmonics (and the existence of some other harmonics of an intermediate order), inasmuch as the same results were obtained in many different series of experiments, made under different conditions, and verified by means of various wave meters. The comparison between the actual discharge wave and the typical rectangular wave is simplified, by multiplying the frequency of some of the harmonics by the amplitude of the corresponding current as determined by calculation. In the typical rectangular wave, the resulting product should be constant for the odd harmonics, while for the even harmonics it should reduce to zero.

In the following columns of the table have been entered the logarithmic decrement of the antenna circuit *per complete period*, and the product of the amplitudes of the primary currents (calculated for each of the harmonics in accordance with the formula of Bjerknes) multiplied by the ratio of corresponding frequency to that of the fundamental wave. All the previous data are given for two different settings of the spark gap, namely with large and small sparking distances between electrodes.

The fact that the changes in the decrement are not perfectly regular, is presumably to be attributed partly to unavoidable errors of measurement and partly to the variable resistance of the spark. Moreover, these same factors also influence unfavorably the exact determination of the amplitudes; and therefore the calculated figures show discrepancies between different groups of experiments that are not wholly negligible. Their average is important in this research, since it shows in the most compact form the general character of the phenomenon.

The above remarks likewise apply to the data in Table 2, which represent the results of the measurements taken with the spark gap having spherical electrodes, and with the Boas spark gap with tungsten electrodes. In both these gaps the spark passes between stationary electrodes, but in consequence of the different composition and arrangement of the terminals, the sparks in the two cases have very different persistencies, which fact is plainly evidenced by the difference between the respective decrements, in turn producing different wave forms.

TABLE I

EXPERIMENTS CONDUCTED WITH THE MARCONI SPARK GAP

		Short Gap		Long Gap	
λ	$\frac{\lambda_1}{\lambda}$	δ	If	δ	If
10,800	1.0	0.300	100	0.440	100
3,530	3.1	0.074	45	0.200	63
2,020	5.3	0.054	36	0.184	61
1,320	8.2	0.054	40	0.172	74
960	11.2	0.056	44	0.160	81
750	14.4	0.056	40	0.144	63
610	17.7	0.058	45	0.120	57
Average Values		0.058	42	0.164	66

TABLE III

EXPERIMENTS CONDUCTED WITH THE BRASS SPARK GAP AND WITH THE BOAS GAP

		Brass Gap		Boas Gap	
λ	$\frac{\lambda_1}{\lambda}$	δ	If	δ	If
10,600	1.0	0.170	100	0.82	100
3,500	3.0	0.166	65	0.26	75
1,920	5.5	0.124	80	0.24	74
1,290	8.2	0.100	95	0.20	109
945	11.2	.....	...	0.18	119
745	14.2	.....	...	0.16	135
612	17.3	.....	...	....	
Average Values		0.130	80	0.21	102

By reason of the increasing irregularity of the phenomenon, at the higher harmonic frequencies the decrements and the amplitudes ascertained with the gaps described are less reliable, and some of them have accordingly been omitted in the Table.

However, a comparison of the results obtained appears to justify the following conclusions:

In radio telegraphic antennas, directly excited by means of an ordinary metallic electrode gap fed from a high voltage source of continuous or alternating electromotive force, the discharge wave has a complex form, which depends on the original potential distribution and on the decrements which arise from the dissipation of energy. Among the sources of loss, the resistance of the spark is of very material importance. The spark resistance depends on the nature and arrangement of the electrodes, by which the ratios of the amplitudes of the upper harmonics to that of fundamental waves are materially modified. The travelling wave has rather the form of Figure 3b than of Figure 3a.

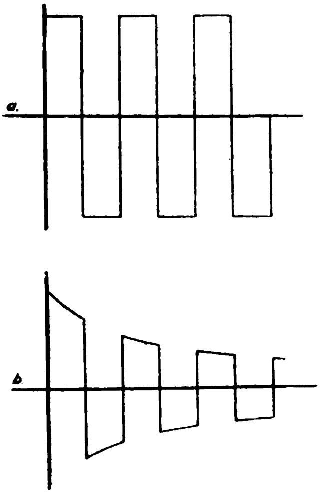

FIGURE 3

The relative amplitudes and decrements, and the frequencies of each of the harmonics can be satisfactorily determined by means of the wave meter which, while it does not afford means for the determination of their relative phases, nevertheless allows us to make a useful comparison of the actual harmonics with the corresponding components of the rectangular wave which would theoretically be produced in the case of a uniform original distribution of potential, and with zero damping.

Measurements thus taken on an antenna of low radiating capability made it possible to prove the presence of such harmonics up to, and even beyond the twentieth, and to determine the amplitude and the decrement of each as far as the eighteenth for some types of dischargers. The frequencies found are partly those of the odd harmonics, and partly of the even harmonics (or harmonics of an intermediate order) which latter are due to the dissymmetry of the waves produced during successive semi-periods.

The decrement measured generally diminishes as the frequency increases, but at a rate which is less than proportional to the reciprocal of the latter, and the damping factor therefore apparently increases with an increase in the frequency. The relative amplitude decreases in proportion as the frequency increases, but the product of the two factors which, in the case of the rectangular wave, should remain constant for the odd harmonics, and zero for the even harmonics, actually is slightly variable for the types of gap in which the spark ceases after a few oscillations, while it gradually increases in the other types of gap which produce a more persistent spark. In spark gaps of any given type, the average value of the said product will therefore increase with increase in distance between the electrodes and resulting increase of the damping.

The foregoing experiments are chiefly related to the form of the discharge wave as found at the base of the radio telegraphic antenna, or at the center of the Hertzian oscillator, and where—if the damping is zero—the potential node should be, as well as the common anti-node of all the stationary-wave currents corresponding to the fundamental oscillation and the upper harmonics.

The form of the wave is modified, however, from point to point along the antenna by the relative differences of phase of the harmonics, which directly influence the current and potential variations, as theoretically indicated.

In the case of the antenna herein described, and with the wave meter coupled to one of the ends thereof, the experiments showed with certainty the presence of the odd and even harmonics, as found in the center, and also showed the presence of even harmonics of a lower order, namely second and fourth, as well as some of higher order, which were missing in the center. However, I have not carried out a quantitative investigation of these latter, the interpretation of the results of which would have been a laborious task, particularly in view of the different coupling coefficients relating to the measurement of each of the harmonic currents in the circuit.

SUMMARY: Using a symmetrically excited artificial antenna consisting of two long coils with a spark gap between them, the author measures the frequencies, decrements, and the relative amplitudes of the fundamental current and of each of the harmonics. It is found that the theoretical rectangular wave, travelling along the antenna, is modified in form, particularly if the spark is fairly persistent. Numerical data are given.

RE-ENFORCED HARMONICS IN HIGH POWER ARC TRANSMITTERS*

BY

F. A. KOLSTER

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(A Discussion of a Paper by Luigi Lombardi, on "Harmonic Oscillations in Directly Excited Antennas")

In reading over Professor Lombardi's interesting paper, I am reminded of some experiments which I had occasion to make at the San Francisco transmitting station of the Federal Telegraph Company in the fall of 1914, for the purpose of determining the cause of extraordinary interference produced by this arc station at a wave length much shorter than the fundamental wave transmitted.

High power arc transmitting stations as equipped by the Federal Company consist of a directly excited antenna system; that is to say, the arc is placed directly in the antenna and the length of the wave emitted is determined entirely by the constants of the antenna system. Now it is well known that the antenna circuit is one having several degrees of freedom and when excited directly will therefore emit waves of shorter length than the fundamental, but of much less intensity. In fact, it is not expected that the intensity of these shorter secondary waves would be sufficient to produce any serious interference.

The arc generator produces in any oscillating circuit oscillations which contain to a greater or lesser degree all even and odd harmonics of the fundamental oscillation. If the oscillating circuit which is supplied by the arc generator is one of several degrees of freedom, then it is possible, as will be seen later, to obtain a marked re-enforcement of at least one of the arc harmonics.

Let us consider the theoretical cotangent character reactance curve of the ordinary antenna as shown in Figure 1. Points of zero reactance are obtained at ωf corresponding to the fundamental wave length of the antenna, at $\frac{\omega f}{3}$ at $\frac{\omega f}{5}$ and so on.

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* Received by the Editor, April 1, 1919.

When a loading coil is inserted in the antenna, the zero reactance points are obtained at ω_o, corresponding to the fundamental or main transmitted wave, at ω_1, at ω_2, and so on. One would expect, therefore, to obtain re-enforcement of arc harmonics corresponding in frequency to ω_1, ω_2, and so on.

Experimental observations obtained at the South San Francisco stations of the Federal Company confirmed the above predictions as well as could be expected.

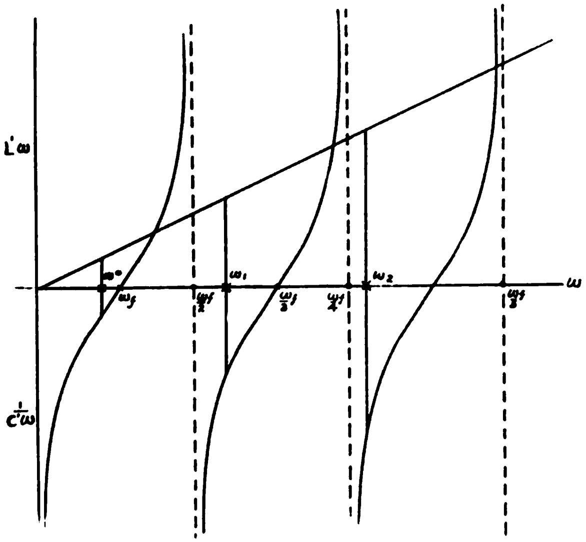

FIGURE 1

From measurements made upon the South San Francisco antenna, the reactance of the antenna was found to be fairly well expressed by the following equation:

Reactance = 230 cotangent $(107\,\omega \times 10^{-6})$

This is plotted in Figure 2, together with the reactance of the loading coil inserted in the antenna and it is seen that two points of zero total reactance are obtained, one at ω corresponding to 7,200 meters and another at ω corresponding to about 1,100 meters. The wave lengths corresponding to the odd and even harmonics of the arc are as follows:

7,200 = fundamental
3,600
2,400
1,800
1,440
1,200
1.028
900

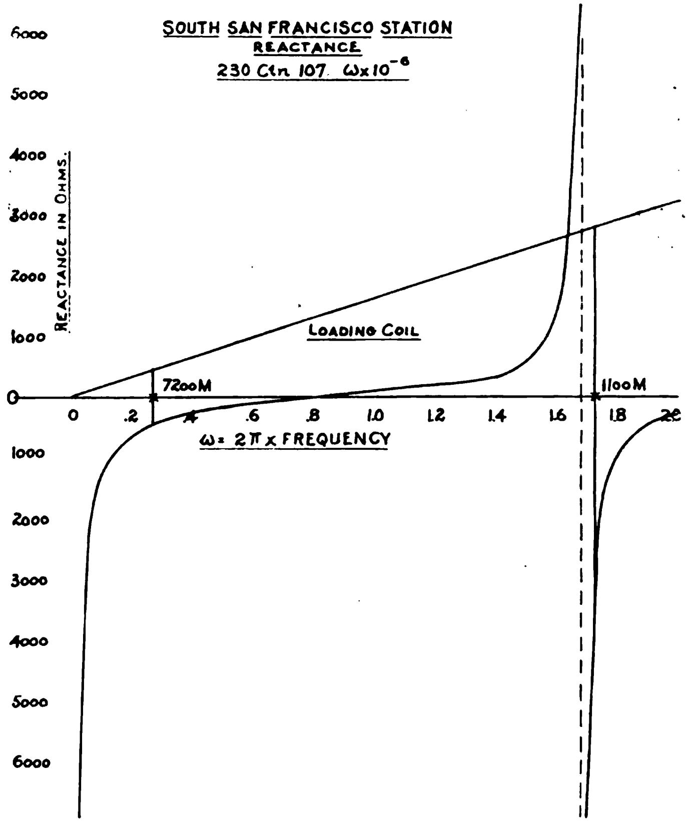

Figure 2

The extraordinary interference experienced occurred between 1,000 and 1,200 meters, and tests made at the transmitter showed that considerable energy existed in the antenna in this range, in fact, it was possible to light up three tungsten lamps connected in series with a circuit tuned to approximately 1,100 and coupled to the antenna circuit as shown in Figure 3. Furthermore, a wavemeter containing a hot wire indicating instrument coupled very loosely to the antenna circuit gave full deflection at about 1,100 meters whereas at other wave lengths corresponding to arc harmonics no deflection whatever could be obtained. In other words, due to the characteristics of the antenna system a marked re-enforcement of the 5th or 6th arc harmonic occurred and the energy radiated at this wave length was sufficient to cause serious interference at short wave receiving stations located at a considerable distance away.

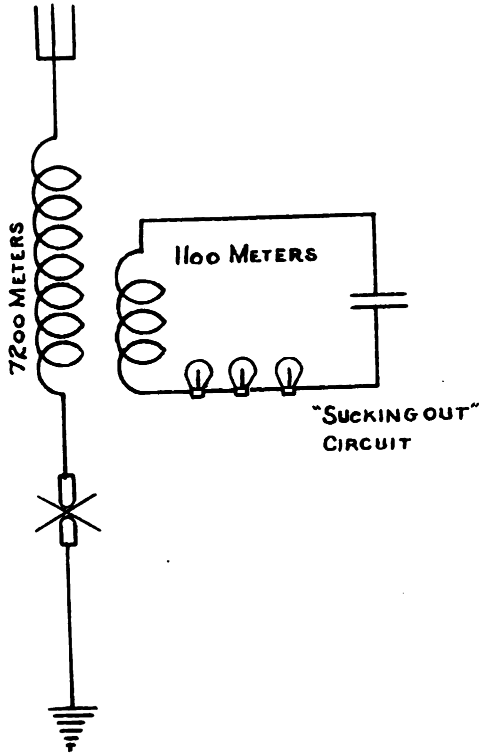

Figure 3

It is believed that a "sucking out" circuit, as shown in Figure 3, will materially reduce such interference and as high power arc stations multiply in number it is probable that some means will have to be devised to reduce the disturbing effects of these re-enforced arc harmonics.

SUMMARY: A Poulsen arc in the antenna will give rise to a series of non-harmonic oscillations of shorter wave length, some of which may cause troublesome interference with nearby short-wave receiving stations. The effect is explained, and a method of reducing such interference by the use of a suitably tuned absorbing circuit coupled to the transmitting antenna is given.

FURTHER DISCUSSION* ON

"ELECTRICAL OSCILLATIONS IN ANTENNAS AND INDUCTION COILS" BY JOHN M. MILLER

By

JOHN H. MORECROFT

I was glad to see an article by Dr. Miller on the subject of oscillations in coils and antennas because of my own interest in the subject, and also because of the able manner in which Dr. Miller handles material of this kind. The paper is well worth studying.

I was somewhat startled, however, to find out from the author that I was in error in some of the material presented in my paper in the PROCEEDINGS OF THE INSTITUTE OF RADIO ENGINEERS for December, 1917, especially as I had at the time I wrote my paper thought along similar lines as does Dr. Miller in his treatment of the subject; this is shown by my treatment of the antenna resistance.

As to what the effective inductance and capacity of an antenna are when it is oscillating in its fundamental mode is, it seems to me, a matter of viewpoint. Dr. Miller concedes that my treatment leads to correct predictions of the behavior of the antenna and I concede the same to him; it is a question, therefore, as to which treatment is the more logical.

From the author's deductions we must conclude that at quarter wave length oscillations

$$L_e = \frac{L_0}{2} \tag{1}$$

and

$$C_e = \frac{8}{\pi^2} C_0 \tag{2}$$

The value of L really comes from a consideration of the magnetic energy in the antenna keeping the current in the artificial antenna the same as the maximum value it had in the actual antenna, and then selecting the capacity of suitable value to give the artificial antenna the same natural period as the actual antenna. This method of procedure will, as the author states, give an artificial antenna having the same natural frequency, magnetic energy, and electrostatic energy, as the actual antenna, keeping the current in the artificial antenna the same as the maximum current in the actual antenna.

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* Received by the Editor, June 26, 1919.

But suppose he had attacked the problem from the viewpoint of electrostatic energy instead of electromagnetic energy, and that he had obtained the constants of his artificial antenna to satisfy these conditions (which are just as fundamental and reasonable as those he did satisfy); same natural frequency, same magnetic energy, same electrostatic energy and the same voltage across the condenser of the artificial as the maximum voltage in the actual antenna. He would then have obtained the relations

$$L_e = \frac{8}{\pi^2} L_o \tag{3}$$

and

$$C_e = \frac{C_o}{2} \tag{4}$$

Now equations (3) and (4) are just as correct as are (1) and (2) and moreover the artificial antenna built with the constants given in (3) and (4) would duplicate the actual antenna just as well as the one built according to the relations given in (1) and (2).

I had these two possibilities in mind when writing in my original article "as the electrostatic energy is a function of the potential curve and the magnetic energy is the same function of the current curve, and both these curves have the same shape, it is logical, *and so on.*" Needless to say, I still consider it logical, and after reading this discussion I am sure Dr. Miller will see my reasons for so thinking.

When applying the theory of uniform lines to coils I think a very large error is made at once, which vitiates very largely any conclusions reached. The L and C of the coil, per centimeter length, are by no means uniform, a necessary condition in the theory of uniform lines; in a long solenoid the L per centimeter near the center of the coil is nearly twice as great as the L per centimeter at the ends, a fact which follows from elementary theory, and one which has been verified in our laboratory by measuring the wave length of a high frequency wave traveling along such a solenoid. The wave length is much shorter in the center of the coil than it is near the ends. What the capacity per centimeter of a solenoid is has never been measured, I think, but it is undoubtedly greater in the center of the coil than near the ends.

The conclusions he reaches from his equation (22) that even at its natural frequency the L of the coil may be regarded as equal to the low frequency value of L is valuable in so far as it enables one better to predict the behavior of the coil, but it should be kept in mind that really the value of L of the coil, when defined as does the author in the first part of his paper in terms of magnetic energy and maximum current in the coil at the high frequency, is very much less than it is at the low frequency.

One point on which I differ very materially with the author is the question of the reactance of a coil and condenser, connected in parallel, and excited by a frequency the same as the natural frequency of the circuit. The author gives the reactance as infinity at this frequency, whereas it is actually zero. When the impressed frequency is slightly higher than resonant frequency there is a high capacitive reaction and at a frequency slightly lower than resonant frequency there is a high inductive reaction, but at the resonant frequency the reactance of the circuit is zero. The resistance of the circuit becomes infinite at this frequency, if the coil and condenser have no resistance, but for any value of coil resistance, the reactance of the combination is zero at resonant frequency.