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A NEW SYSTEM OF SHORT WAVE AMPLIFICATION*

By

Edwin H. Armstrong

(Columbia University, New York)

The problem of receiving weak signals of short wave length in a practical manner has become of great importance in recent years. This is especially true in connection with direction finding work where the receiver must respond to a very small fraction of the energy which can be picked up by a loop antenna.

The problem may be summed up in the following words:—to construct a receiver for undamped, modulated continuous, and damped oscillations which is substantially equally sensitive over a range of wave lengths from 50 to 600 meters, which is capable of rapid adjustment from one wave to another, and which does not distort or lose any characteristic note or tone inherent in the transmitter.

It is, of course, obvious that some form of amplification must be used, but a study of the various known methods soon convinces one that a satisfactory solution cannot be obtained by any direct method. In the interests of completeness, we will consider the three well-known direct means which might possibly be employed, and examine the limitations which apply to each. These three methods are:—

(1) Amplification of the audio frequency current after rectification;

(2) Amplification of the radio frequency current before rectification; and

(3) Application of the heterodyne principle to increase the efficiency of rectification.

Consider first the method of rectifying the radio frequency current and amplifying the resulting audio frequency current. Two limitations at once present themselves, one inherent in audio frequency amplifiers, and the other inherent in all known rectifiers. The limitation in the amplifier is the residual noise

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which makes it impractical to use effectively more than two stages of amplification. The second limitation lies in the characteristic of the detector or rectifier. All rectifiers have a characteristic such that the rectified or audio frequency current is roughly proportional to the square of the impressed radio frequency emf. Hence the efficiency of rectification becomes increasingly poorer the weaker the signal until a point is reached below which the detector practically ceases to respond.

The second method of attack on the problem is the amplification of the received radio frequency currents before rectification to a point where they can be efficiently dealt with by the detector. This method is ideal on long waves, and various methods of inductance, resistance, and capacity couplings have been successfully used, but when the attempt is made to use the same methods of coupling on wave lengths below 600 meters, it results in complete failure. This is because the low capacity reactance existing between the various elements of the tubes causes them, in effect, to act as a short circuit around the coupling means and thereby prevents the establishment of a difference of potential in the external plate circuit. It is, of course, possible to eliminate the short-circuiting by tuning with a parallel inductance but this introduces a complication of adjustment which is highly objectionable and the tuning of all circuits also leads to difficulty with undesirable internal oscillations.

The third method which might be used is the heterodyne method to increase the efficiency of rectification. Great increase in signal strength is possible by means of this method, particularly where the signal is very weak, but there are certain reasons why it cannot be effectively used in practice at the present time. The chief reason in receiving continuous waves of short wave length is the instability of the beat tone which makes operations below 600 meters unsatisfactory. This disadvantage does not apply to the reception of spark signals but here the loss of the clear tone and its individuality offsets much of the gain due to increased signal strength. In the case of telephony the distortion which always results likewise offsets the gain in strength. It is, of course, undeniable that there are many special cases where the use of the heterodyne on short wave lengths is of the greatest advantage but the foregoing remarks apply to the broad field of commercial working where the practical aspects of the case greatly reduce the value of the amplification obtained by this method.

In spite of the great difficulties involved in a direct solution, great success was obtained by Round in England and Latour in France in the production of radio frequency amplifiers to cover effectively a range from 300 to 800 meters. This result was accomplished only by the most painstaking and careful experiment and it represents some of the very finest radio work carried out during the war. Round secured his solution by constructing tubes having an extremely small capacity without increase in internal resistance above normal values and coupling the tubes by means of transformers wound with very fine wire to keep down the capacity and very high resistance to prevent oscillation at the resonant frequency of the system. The effect of the high ratio of inductance to capacity and the high resistance of the winding is to flatten the resonance curve of the system and widen the range of response. Latour solved the problem by the use of iron core transformers wound with very fine wire, the iron serving the double purpose of increasing the ratio of inductance to capacity and introducing resistance into the system. Both these factors widen the range of response.

It is the purpose of this paper to describe a method of reception evolved at the Division of Research and Inspection of the Signal Corps, American Expeditionary Force, which solves the problem by means of an expedient. This expedient consists in reducing the frequency of the incoming signal to some predetermined super-audible frequency which can be readily amplified, passing this current thru an amplifier, and then detecting or rectifying the amplified current. The transformation of the original radio frequency to the pre-determined value is best accomplished by means of the heterodyne and rectification, and the fundamental phenomena involved will be understood by reference to the diagram of Figure 1. Here *LC* represents the

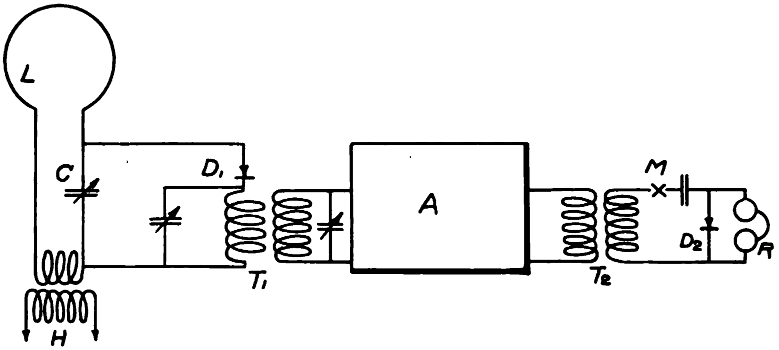

Figure 1

usual tuned receiving circuit, loop or otherwise, H a separate heterodyne, and D_1 a rectifier. A is a radio frequency amplifier designed to operate on some pre-determined frequency. This frequency may be any convenient frequency which is substantially above audibility. The amplifier is connected on its input side to the rectifier D_1, and on its output side to a second rectifier D_2 and a telephone or other receiver.

Suppose now that the frequency to be received is 3,000,000 cycles per second corresponding to a wave length of 100 meters and, for the sake of simplicity, that the incoming waves are undamped. Also, assume that the amplifier A has been designed for maximum efficiency at 100,000 cycles per second. The circuit LC is tuned to 3,000,000 cycles, and the heterodyne H is adjusted to either 3,100,000 or 2,900,000 cycles either of which will produce a beat frequency of 100,000 cycles per second. The combined currents of 3,000,000 and 3,100,000 (or 2,900,000) cycles are then rectified by the rectifier D_1 to produce in the primary of the transformer T_1 a direct current with a superimposed 100,000-cycle component. This 100,000-cycle current is then amplified to any desired degree by the amplifier A and detected or rectified by D_2. In order to get an audible tone where telephone reception is used some form of modulation or interruption must, of course, be employed in connection with this second rectification as the current in the output circuit of the amplifier is of a frequency above audibility. While this frequency is only 100,000 cycles and while it is therefore well within the range of practical heterodyning, its steadiness depends on the beats between 3,000,000 and 3,100,000 cycles per second and hence in any attempt to heterodyne it to audibility the same difficulties due to fluctuation would be encountered as in heterodyning the original radio frequency to audibility. However, the inability to use the heterodyne on the second rectification is not of great importance because the amplitude of the signal to be rectified is large and hence the difference (as far as signal strength in the telephone is concerned) between heterodyne and modulated reception is not great.

It is important to note here that the value of the heterodyne current in the first rectifier should always be kept at the optimum value in order to ensure the carrying out of the first rectification at the point of maximum efficiency. This adjustment, however, is not a critical one, and, once made, it is seldom necessary to change it. The amplifier A may be made selective and highly regenerative if so desired, and some very great increases in the selectivity of the system as a whole can be secured. Figure 2 illustrates the principle involved. This arrangement is substantially the same as Figure 1 except that the primary and secondary coils of the transformer T_1 are tuned by means of condensers as shown and the coupling between them is reduced to the proper value to insure sharp tuning. This system of connection has all the advantages of tuning to the differential frequency in the manner well known in the art and an additional one due to the fact that since it is above audibility the musical character of atmospheric disturbances so troublesome in audio frequency tuning, does not appear.

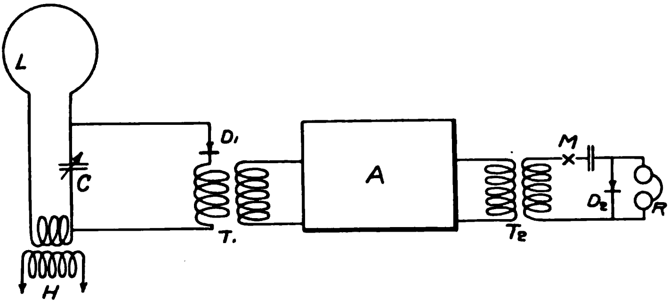

FIGURE 2

So far, the reception of undamped waves only has been considered, but this method of amplification is applicable also to the reception of damped wave telegraphy and to telephony with practically equal efficiency and without distortion of any characteristics of tone. It is somewhat difficult to understand this, particularly in the case of the reception of spark signals as in all previous experience the heterodyning of a spark signal has resulted in the loss of the note, whereas in the present case the individuality between stations is more marked even than on a crystal rectifier.

This is the most interesting point in the operation of the system and the reason will be understood from the following analysis:

In heterodyning, the efficiency of rectification of the signaling current depends on its phase relation with the local current. If the two currents are either in phase or 180° out of phase the efficiency of rectification is a maximum; if 90° out of phase a minimum. In ordinary heterodyning, the initial phase difference depends on the time of sparking at the transmitter and hence this initial phase difference will be different for each wave train. As the frequency of the two currents are substantially the same, and as the duration of a wave train is short compared to the time necessary to produce a complete beat at an audible frequency, this initial phase difference is maintained throughout the wave train. Hence the different wave trains are rectified with varying efficiency, the telephone current becomes irregular, and a rough or hissing tone results.

In the present method of heterodyning the beat frequency is high so that several beats per wave train are produced. As a consequence, the phase angle between the signaling and local currents varies thru several cycles and the initial phase difference becomes a matter of minor importance. The number of beats which actually occur in practice depends on the beat frequency, the damping of the incoming wave, and the damping of the receiving circuit. As the damping of the receiving circuit is almost invariably much less than the damping of the incoming wave, it is the determining factor. In any practical case, however, where the beat frequency is kept above 20,000 cycles per second, there is a sufficient number of beats to minimize the initial phase differences and maintain the characteristic tone.

The phenomena which occur in the reception of modulated continuous wave telegraphy and telephony are substantially a combination of those explained in the cases of undamped and damped wave reception. The adjustments are made in the same manner as for undamped waves and the only precaution necessary in the reception of telephony is to damp the amplifier circuits somewhat to prevent distortion of the speech by excessive resonance.

The general arrangement found most suitable for practical working is shown in Figure 3. Both rectifications are carried out by three-element vacuum tubes. The amplifier here shown is resistance coupled, although any form of coupling may be used. The tuned circuits L' and L'' are preferably adjusted to some frequency between 50,000 and 100,000 cycles. The circuit L' may be made regenerative if so desired, by any form of reactive coupling, but the practicability of this depends largely on the amount of time which is available for making adjustments.

In the diagram of Figure 3 only two stages of intermediate frequency amplification are shown, but at least four and preferably six should be used to get the maximum advantage of this method.

This is because the transformation of frequency is accomplished only by a certain loss so that something between one and two stages of amplification is required before this is overcome and it is possible to realize a gain. In this figure a separate heterodyne is shown, and it will generally be necessary to use it on account of the mistuning which is involved in the use of the self heterodyne This mistuning is considerable on 600 meters but on the shorter waves it is possible to use the self heterodyne method with equal efficiency as far as signal strength is concerned and a great gain in simplicity, as adjustments have been reduced to the minimum of a single one.

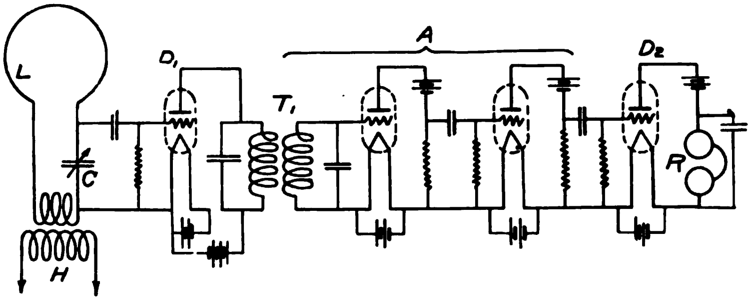

FIGURE 3

It may be observed here that this method is not limited to one transformation of frequency with one subsequent amplification. If the frequency to be received is 5,000,000 cycles this may be stepped down to 500,000 cycles, amplified, stepped down again to 50,000 cycles, re-amplified and detected. The great advantage of this method of amplification is that the tendency to oscillate due to the reaction between the output of the amplifier and the input is eliminated as the frequencies are widely different. The only reaction which can take place is in each individual amplifier. Hence, the process of extreme amplification is best carried out in stages of several frequencies, the amplification on each frequency being carried as far as possible without loss of stability. As soon as the limit of stable operation is approached, no further amplification should be attempted until the frequency has been changed.

The foregoing descriptions and explanations do not pretend to any save a most superficial treatment of the phenomena present in this method of reception. Lack of time has prevented a careful study and quantitative date only of the roughest sort has been obtained. Sufficient work has been done, however, to demonstrate the value of the method particularly in the case of modulated continuous wave telegraphy and telephony. In this field neither the amplification nor the selectivity can be equalled by any direct method.

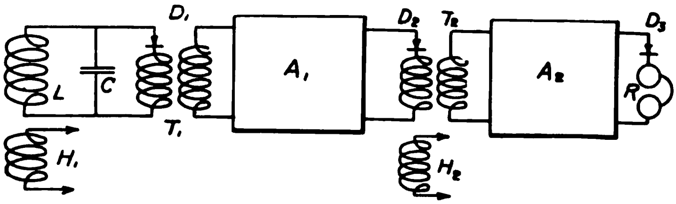

FIGURE 4

The practical results which have been obtained may perhaps be of interest. With a ten-turn, three-foot (1 meter) loop antenna and an amplifier consisting of six stages, resistence coupled, making a total of eight tubes, the night signals of ships working with the Florida and Gulf stations are loudly received. The night signals of amateur stations in the Middle West are regularly received as are also the signals of stations in the Gulf States. The general arrangement of the apparatus used is shown in Figures 5 and 6 which illustrate the scheme of connections of the frequency transformer and amplifier respectively. Four stages of amplification only are shown but six were actually used.

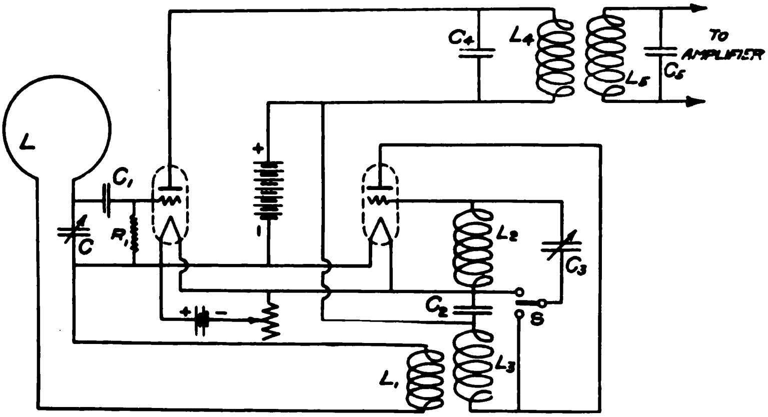

FIGURE 5

It is beyond question much more efficient to use some form of inductive coupling since the amplifier is intended to operate on only one frequency and the use of a resistance coupled amplifier is not recommended where one of the former type is available.

The new practice of this method involves the use of many known inventions, but in connection with the production of a superaudible frequency by heterodyning I wish to make due acknowledgment to the work of Meissner, Round, and Levy, which is now of record. The application of the principle to the reception of short waves is, I believe, new and it is for this reason that this paper is presented.

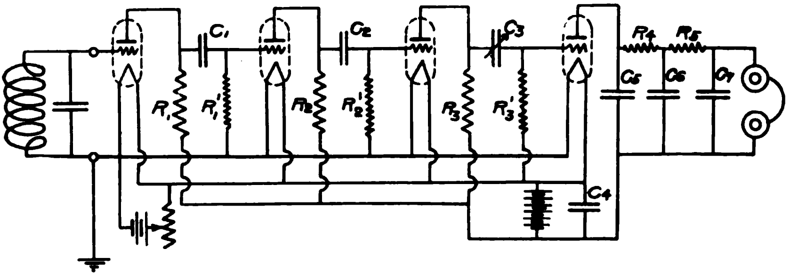

FIGURE 6

While the fundamental idea of this method of reception is relatively simple, the production of the present form of the apparatus was a task of the greatest difficulty for reasons known only too well to those familiar with multi-stage amplifiers; and to Lieutenant W. A. MacDonald, Master Signal Electricians J. Pressby and H. W. Lewis, and Sergeant H. Houck, all of the Division of Research and Inspection Signal Corps A. E. F., I wish to give full credit for its accomplishment.

Hartley Research Laboratory,
Columbia University, New York City.

SUMMARY: The various possible known methods of amplifying incoming signals of very short wave length (below 600 meters) are described and their limitations considered.

The new method then described consists (for continuous wave reception) of the following steps:—

1. Heterodyning, with the production of a beat frequency which is itself a *radio* frequency (for example, 100,000 cycles per second).
2. Rectification of the beat current.
3. Amplification at the beat radio frequency, preferably by a tuned amplifier.
4. Audio frequency modulation of the amplified current.
5. Rectification of the modulated current.

For reception of damped wave or radiophone signals, step 4 is omitted. It is shown that in this case the quality (characteristic tone) of the incoming signals is preserved.

brought to act on the second detector or else some form of chopper must be used. For very short waves of the order of 50 meters, it is possible to make a self-heterodyne of the first tube and thus avoid the extra adjustments and apparatus required by a separate local oscillator. In this case it is advisable to use as low a beat frequency as possible in order not to necessitate too much mistuning, and to design the amplifier circuits accordingly. The question, however, of selecting the proper super-audible beat frequency and the actions involved in the performance of these circuits are not as simple perhaps as Major Armstrong may have led some of us to believe. Upon closer inspection it is found that certain limitations must be imposed upon the design, especially in application to the reception of spark and telephone signals, and it appears likely that the system cannot be used to advantage at all radio frequencies.

The following paragraphs may be of particular interest in connection with the opinion held by some that the present amplifier will tend toward returning spark radio systems to the favor accorded them before the advantages of continuous waves were so fully appreciated and utilized.

GENERAL THEORETICAL CONSIDERATIONS

In the reception of *continuous waves* by the method under consideration the actions involved are relatively simple. The interference of the incoming signal oscillation with that produced locally results in a beat frequency which is almost truly sinusoidal and makes the design of the coupling transformers a very satisfactory proposition with the possibility of securing maximum amplification through sharp tuning and accurate resonance adjustments. In this case also, it is quite immaterial, as far as the operation of the amplifier is concerned, whether the super-audible beat frequency used is adjusted to something of the order of 100,000 or 200,000 cycles or whether it is set at a low value of say 15,000 cycles.

For receiving spark signals, however, and for telephony the situation is somewhat different. Special precautions must be taken in order to avoid distortion effects, and the selection of proper value of the super-audible beat frequency is important.

Figure 1 is supposed to represent trains of damped voltage oscillations such as are produced at the detector of a receiving circuit by a spark transmitter. The successive groups of oscillations recur at tonal frequencies, each group being the result of a discharge at the spark gap of the transmitter. The mathematical expression for such a train of oscillations may be written as follows:

$$[V+V_1 \sin(pt+\phi_1)+V_2 \sin(2pt+\phi_2)+V_3 \sin(3pt+\phi_3)+ \cdots V_n \sin(npt+\phi_n)] \sin \omega_1 t \qquad (1)$$

wherein the bracketed expression is the equation of the envelope curve bounding the amplitude of the radio frequency oscillations, expressed in the form of a Fourier's series, and the last term, $\sin \omega_1 t$, refers to the radio frequency oscillation of periodicity ω_1 which is to be considered as an oscillation modulated at audible frequency according to the envelope curve just mentioned.

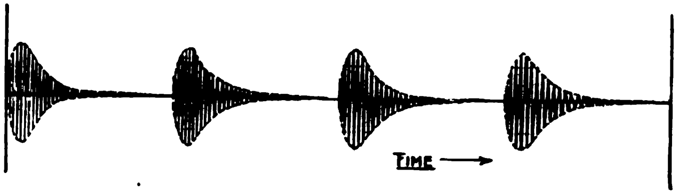

FIGURE 1

The envelope contains a fundamental frequency corresponding to p and all the harmonics $2p$, $3p$, $4p$, $\cdots$ np characteristic of the spark frequency and of the decrements of the transmitter and receiver. Thus, ordinarily the periodicity p would correspond to a 500- or 1000-cycle spark and the harmonics may run to the 10th or 20th before their amplitudes are small enough to make them negligible. V_1, V_2, V_3, $\cdots$ V_n designate respectively the amplitudes of the fundamental and the various harmonics. ϕ_1, ϕ_2, $\cdots$ ϕ_n and so on represent their phases.

The voltage produced by the local oscillation for heterodyning is

$$V' \cos(\omega_2 t+\theta) \qquad (2)$$

The total or resultant voltage acting on the first detector at every instant is therefore given by the sum of expressions (1) and (2). This can be written in the following form

$$\begin{aligned}
&V_1\Big[\cos\frac{(\omega_1-\omega_2-p)\,t+(\phi_1-\theta)}{2}\cos\frac{(\omega_1+\omega_2-p)\,t+(\phi_1+\theta)}{2}\\
&\qquad-\sin\frac{(\omega_1-\omega_2+p)\,t+(\phi_1-\theta)}{2}\sin\frac{(\omega_1+\omega_2+p)\,t+(\phi_1+\theta)}{2}\Big]\\
&+V_2\Big[\cos\frac{(\omega_1-\omega_2-2p)t+(\phi_2-\theta)}{2}\cos\frac{(\omega_1+\omega_2-2p)t+(\phi_2+\theta)}{2}\\
&\qquad-\sin\frac{(\omega_1-\omega_2+2p)\,t+(\phi_2-\theta)}{2}\sin\frac{(\omega_1+\omega_2+2p)\,t+(\phi_2+\theta)}{2}\Big]\\
&+V_3\Big[\cos\frac{(\omega_1-\omega_2-3p)\,t+(\phi_3-\theta)}{2}\cos\frac{(\omega_1+\omega_2-3p)\,t+(\phi_3+\theta)}{2}\\
&\qquad-\sin\frac{(\omega_1-\omega_2+3p)\,t+(\phi_3-\theta)}{2}\sin\frac{(\omega_1+\omega_2+3p)\,t+(\phi_3+\theta)}{2}\Big]\\
&+\\
&+V_n\Big[\cos\frac{(\omega_1-\omega_2-np)\,t+(\phi_n-\theta)}{2}\cos\frac{(\omega_1+\omega_2-np)\,t+(\phi_n+\theta)}{2}\\
&\qquad-\sin\frac{(\omega_1-\omega_2+np)\,t+(\theta_n-\theta)}{2}\sin\frac{(\omega_1+\omega_2+np)\,t+(\phi_n+\theta)}{2}\Big]\\
&+V\sin\omega_1 t \qquad\qquad (3)
\end{aligned}$$

In each of the bracketed terms four different frequencies appear, namely,

$$\frac{\omega_1-\omega_2-k\,p}{4\pi}$$

$$\frac{\omega_1-\omega_2+k\,p}{4\pi}$$

$$\frac{\omega_1+\omega_2-k\,p}{4\pi}$$

$$\frac{\omega_1+\omega_2+k\,p}{4\pi}$$

k having the different values 1, 2, 3, 4, · · · n corresponding to the 1st, 2nd, 3rd, 4th, or nth bracket involving the 1st, 2nd, 3rd, or nth harmonic.

The explicit values of these frequencies depend principally upon the values ω_1 and ω_2 of the incoming and local radio frequencies and also to an increasing extent upon the periodicities $k\,p$, of the audio harmonic spark frequencies, for the higher harmonics. Relatively the four frequencies concerned may be of the same or very different orders of magnitude, and the two cases presented hereby involve important practical considerations in the design and use of the amplifier. The two different conditions may be treated separately under the headings (1) Short Wave Reception and (2) Long Wave Reception.

SHORT WAVE RECEPTION

The wave lengths to be considered here are of the order of 50 or 100 meters, or shorter. In this case ω_1 and ω_2 are both very large and of the four frequencies mentioned above the two involving the differences $\omega_1 - \omega_2$ are considerably smaller than the two comprising the sums $\omega_1 + \omega_2$. Thus, the two trigonometric products which appear in each of the bracket terms of (3) indicate a radio frequency voltage of frequency

$$\frac{\omega_1 + \omega_2 \pm k\,p}{4\,\pi}$$

modulated by a considerably lower, tho still super-audible, frequency, in the present amplifier, of value

$$\frac{\omega_1 - \omega_2 \pm k\,p}{4\,\pi}$$

The form of such a voltage wave for one of the trigonometric products is shown in Figure 2.

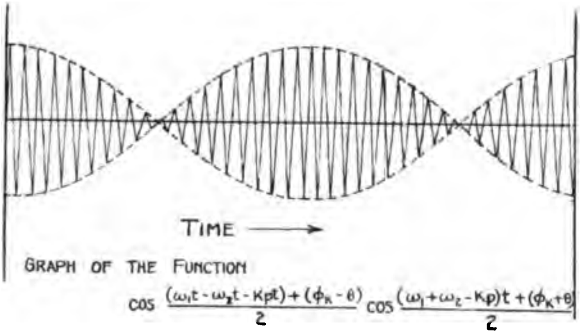

FIGURE 2

After rectification at the first detector tube the above frequencies are still essentially present and are impressed upon the amplifier proper. The frequencies $\frac{\omega_1 - \omega_2 \pm k\,p}{4\,\pi}$ are the heterodyne beat frequencies produced by interference of the local and signal voltages. The transformers of the amplifier are designed for frequencies of their order of magnitude and are not, therefore, affected by the radio frequencies $\frac{\omega_1 + \omega_2 \pm k\,p}{4\,\pi}$. No energy of these latter frequencies passes thru the amplifier. Neither does energy of the incoming signalling (radio) frequency ω_1 represented by the last term of (3), particularly if the transformers between stages of the amplifier are not broadly tuned. This is the normal way in which the amplifier works and is that described by Major Armstrong.

It is only the beat or difference frequencies

$$\frac{\omega_1-\omega_2-k\,p}{4\,\pi} \quad \text{and} \quad \frac{\omega_1-\omega_2+k\,p}{4\,\pi}$$

that have to be considered in designing the transformers and circuits. All of these frequencies lie in the neighborhood of the value

$$\frac{\omega_1-\omega_2}{4\,\pi}$$

which is the fundamental or basic beat frequency produced by the signal and local oscillations. They are greater and less than this value by the amounts

$$\pm\frac{p}{4\,\pi},\ \pm\frac{2\,p}{4\,\pi},\ \pm\frac{3\,p}{4\,\pi},\ \cdot\ \cdot\ \cdot\ \pm\frac{n\,p}{4\,\pi}$$

The transformers are fundamentally designed for the basic or mean frequency $(\omega_1-\omega_2)/4\,\pi$. This can be adjusted by regulating the local oscillation *but its proper value is by no means immaterial.* It is limited in the lower ranges by the fact that it must be above audibility, and thus about 20,000 cycles is as low as is permissible. The limitations in the other direction are those usually encountered in amplification of extremely high frequencies and a value of 5×10^6 cycles is about as high as can be used effectively.

The transformers should be as sharply tuned as possible to permit the building up of high voltages and avoid losses in resistance. A second requirement is that there shall be no distortion in the tonal quality of the received signal as it passes thru the transformers. This means that essentially all of the harmonics contained in the envelope curve of the arriving modulated oscillations must appear in the telephone current of the last detector. Thus, it is necessary to transmit equally thru the coupling transformers of the amplifier all of the frequencies.

$$\frac{\omega_1-\omega_2+k\,p}{4\,\pi} \quad \text{and} \quad \frac{\omega_1-\omega_2-k\,p}{4\,\pi}$$

and while designing the transformers for the basic frequency $(\omega_1-\omega_2)/4\,\pi$ the tuning must be broad enough so that the response is practically uniform over all the frequencies up to $n\,p/4\pi$ on either side of this basic value. A spark signal may contain appreciable harmonics up to the 10th or 20th which in a 500 cycle transmission of the usual type would mean that the amplifier transformers at the receiver would have to pass side frequencies up to 10,000 or 20,000 cycles above and below the basic frequency on which the design is based.

Laboratory experience has shown that it is difficult to build high frequency transformers tuned flatly enough to pass frequencies more than about 40 per cent above and below their best frequency. Even this value is accompanied by a marked loss of over-all efficiency because of the resistance effect, that must be introduced to broaden the tuning. It is obviously impracticable, therefore, to use transformers designed for a heterodyne frequency of 20,000 or 30,000 cycles, because a great many of the harmonic side frequencies that have to be transmitted to preserve the quality would be lost, and in order to get even a few of them the flat tuning required and the resistance inserted to secure it would mean low efficiency. It is much better in this case to work at a beat frequency of 100,000 cycles. The 10th harmonic in the spark signal under consideration, that is, 10,000 cycles, is then only off tune by 10 per cent which allows fairly good efficiency to be realized in the transformers. A beat frequency of 200,000 cycles would be even better.

There is another circumstance which favors the use of high beat frequencies, at least for the reception of short wave lengths, and that is that small changes in either the signal or the local oscillator frequencies such as might be caused by movements of the operator's hand or body in the neighborhood of one of the circuits, cause a much smaller percentage change in the beat frequency when this is high than when it is low, and the apparatus thereby becomes more nearly immune to such variations. At longer wave lengths, however, conditions are altered somewhat and there is an upper limit to the usable beat frequency.

The beat frequency can be produced with the local frequency (ω_2) either less or greater than the incoming frequency (ω_1). It is usually best, with short waves, to make ω_2 less than ω_1, because it is then more easily controlled and freer from variations of the type just mentioned.

Long Wave Reception

In the reception of long wave lengths a condition arises in which the incoming signal frequency is of the same order of magnitude as the heterodyne frequency for which the transformers are designed. Such is the case, for instance, when receiving a wave length of 3,000 meters with an amplifier tuned to the beat frequency of 100,000 cycles. When this condition exists, the incoming frequency, $\omega_1/2\pi$, represented by the last term of (3), passes thru the amplifier together with all the heterodyne frequencies

$$\frac{\omega_1-\omega_2-kp}{4\pi} \quad \text{and} \quad \frac{\omega_1-\omega_2+kp}{4\pi}$$

and interfering with all of them in their different amplitudes and phases produces a conglomeration of resultants which will be heard in the telephones, after rectification at the last detector, as a badly distorted, mushy signal like that usually heard when receiving spark signals on an ordinary oscillating receiver. This will always happen if the incoming signal frequency passes thru the amplifier. In order to avoid the effect, therefore, it is necessary to design the amplifier for heterodyne frequencies that lie wholly outside the range of wave lengths to be received. It is easy to accomplish this, as will readily be seen, when short wave lengths are involved but when waves of one or several thousand meters are to be handled the proper selection of the value of the heterodyne frequency requires careful consideration.

As an example, consider the case of a receiver to function on all wave lengths from 1,000 meters to 5,000 meters; that is, 300,000 cycles to 60,000 cycles. In order to avoid distortion of the kind just mentioned on certain wave lengths this whole band of frequencies is at once eliminated from use as heterodyne frequencies in the amplifier, and the range ought to be extended at least 10,000 cycles beyond this at both ends because the spark signal may contain appreciable harmonics up to this value and certain of the side frequencies of the incoming oscillation might therefore get directly through the amplifier and produce distortion. In the case under consideration, therefore, the amplifier ought to be designed for a frequency either less than 50,000 cycles or greater than 310,000 cycles.

The disadvantages in using low heterodyne frequencies (on the 50,000 cycle end in this case) have been pointed out above in discussing the reception of short waves. Broad transformer tuning with comparatively low efficiency is required to avoid the other kind of distortion due to elimination or at least the reduction of the higher harmonics. But in addition to this there must be considered the fact that static is always more pronounced at long wave lengths and an amplifier designed for low frequencies might therefore be expected to be more affected by these disturbances than one using higher frequencies.

For these reasons it appears very desirable to design the amplifier transformers for a beat frequency of the order of 350,000 or 400,000 cycles, that is, about 750 meters, in the case under consideration.

If spark or telephone signals were to be received on extremely long wave lengths such, for instance, as 15,000 meters (20,000 cycles) there is another consideration that would come in to limit the upper value of heterodyne frequency that could be used. This may best be explained by reference to the formula (3) above. High heterodyne frequencies of the order of 500,000 cycles cannot be used in this case because the sum of the signal and local frequencies $(\omega_1+\omega_2\pm k\,p)/4\pi$ (carrier frequencies) would come thru almost as well as the difference or desired beat frequencies, namely, $(\omega_1-\omega_2\pm k\,p)/4\pi$ (modulating frequencies) and very bad distortion would result. To take the figures given, f_1, would be 20,000 cycles and f_2 520,000 cycles. Their sum would be 540,000 and their difference 500,000, a variation of less than 10 per cent and both therefore conceivably within the working range of an amplifier transformer.

The type of distortion discussed above which is caused by the passage of the incoming frequency directly thru the amplifier and which results in a mushy, harsh signal can be confined to a rather narrow range of wave lengths by making the tuning of the amplifier transformers sharp. But this cannot be carried to extremes or, as has already been explained, it will then not be possible to pass the side frequencies. These will, in telephone transmissions, probably not exceed 2,000 cycles either side of the basic frequency but in spark signals may run to 10,000 cycles or so in extreme cases.

SHARPNESS OF TRANSFORMER TUNING

In order to get an idea of the sharpness of tuning desirable in the transformers under different conditions the curves of Figure 3 are given showing the variation of secondary transformer potential as function of the ratio f_2/f_1 that is the ratio of the frequency to which the transformer secondary is tuned to the varying impressed frequency. Curve "a" is for a broadly tuned transformer of decrement 0.8; curve "b" represents sharper tuning with a decrement of 0.2. It will be seen that in the first case a frequency change of 10 per cent from the best value will cause a reduction in signal of about 5 per cent. In the second case, a difference in frequency from the best value of only 2 per cent causes the same change in signal.

If the 5 per cent reduction in potential for the side frequencies is assumed to be as much as is allowable in order to avoid distortion, and if it is further assumed that as sharp tuning as is represented by the curve "b" with 0.2 decrement is to be usable and the harmonics or side frequencies to be passed are to run to 5,000 cycles then the basic heterodyne frequency for which the transformers must be set will have to be at least 250,000 cycles; and if 10,000 cycles either side of the basic frequency are to be passed the latter cannot be less than 500,000 cycles, which is about the upper practical limit. It turns out, therefore, that curve "b" corresponding to a decrement of 0.2 represents about as sharp tuning as can be used, and even then it is necessary to use the higher range of available heterodyne frequencies. It is to be noted that this tuning is by no means sharp as judged by the standards usually set for radio circuits.

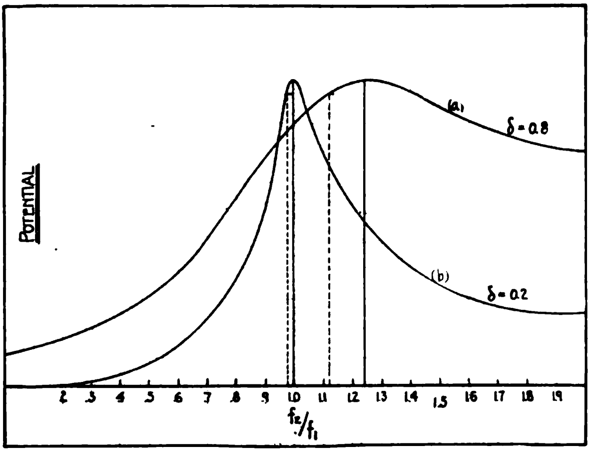

FIGURE 3

With such tuning, frequencies 15 per cent greater and 30 per cent less than that to which the transformer is tuned are only reduced in amplitude by one half, and considerable energy within these frequencies would get directly thru the amplifier and produce the distortion just mentioned with harsh signal. In figures, it may be expected, if the amplifier were tuned to 3,000 meters, that mushy signals would be obtained for all waves between 3,900 meters and 2,550 meters.

If low heterodyne frequencies are to be employed then the tuning must be broader and the resonance curve "a" applies. Here, the allowable reduction of 5 per cent in response occurs for a change of about 10 per cent in frequency from the optimum value which means that the latter must be set for at least 50,000 cycles if a side frequency of 5,000 cycles is to get thru sufficiently to prevent distortion. With such broad tuning, however, even frequencies of half the value for which the transformers are designed get thru directly with very little loss and distortion with the mushy, harsh type of signal may be expected over a wide range of wave lengths.

For purposes of design of the transformers it is possible from the above considerations to decide on the most suitable heterodyne frequency, the sharpness of tuning and the approximate decrement and to determine roughly the constants of the transformer from the relations

$$\delta = \frac{r_2}{2fL_2}$$

$$f = \frac{1}{2\pi\sqrt{L_2C_2}}$$

Still another point is involved here. In a pair of tuned coupled circuits such as must be used in the amplifier, the secondary and primary voltages are proportional inversely to the square root of the tuning capacities in the two circuits. That is

$$V_2 = \sigma V_1 \sqrt{\frac{C_1}{C_2}}$$

To get large secondary potentials, therefore, it is best to use small capacity and large inductance. Then, in order to keep the tuning or decrement to the desired value, the resistance must be increased, and these statements would hold without any qualification were the output of the vacuum tubes not definitely affected by the transformer load in their plate circuits.

When tuned, the secondary of a transformer introduces an effective resistance into the primary equal to

$$\frac{M^2\omega^2}{r_2}$$

so that changing the resistance of the secondary to secure the decrement required to pass the side frequencies affects the load on the tube. What is desired is to get as high a potential V_1 across the transformer primary as possible. This requires the load impedance to be high as compared with the internal tube impedance. Increasing r_2 therefore militates against this and the best results can only be secured by careful adjustment of all of the factors, coupling, resistance, and inductance to the frequency involved.

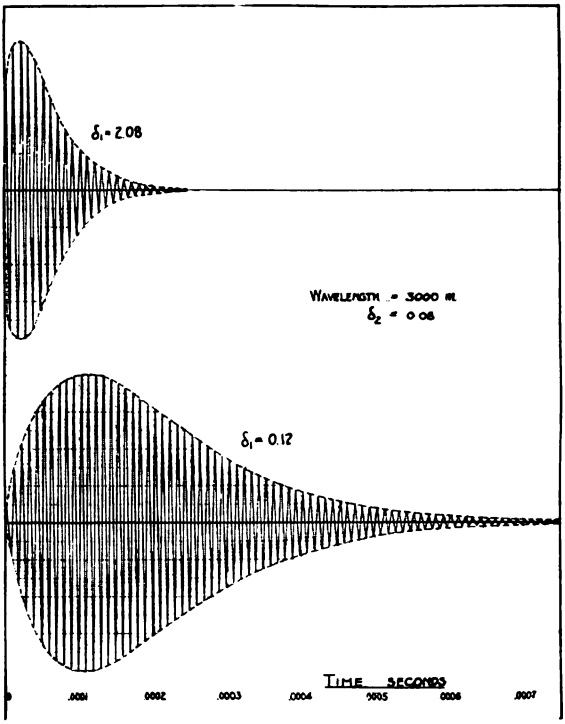

Figure 4

Effect of Transmitter Decrement and Atmospherics

It appears that this type of amplifier functions most effectively on incoming waves of low decrement and that atmospheric disturbances which are always highly damped or else actually dead beat may be eliminated to a very considerable degree.

Curve "b" of Figure 4 shows a train of oscillations in a receiving circuit such as would be produced by a spark transmitter operating at 3,000 meters wave length and decrement 0.12. The decrement of the receiver for this curve was taken as 0.08. Curve "a" is similar but drawn for an excitation of high decrement, 2.08, approximating a static disturbance of the same frequency as that to which the receiver is tuned, that is, 3,000 meters. These curves can both be represented by equations of the form of equation (1) in which the Fourier's series gives the equation of the envelope curve of the oscillations.

For the curve "b," that is, the case of smaller damping, the different amplitudes of the harmonics and of the constant term in the representative series are as follows:

$V = 7.86$
$V_1 = 12.23$
$V_2 = 5.92$
$V_3 = 3.72$
$V_4 = 2.09$
$V_5 = 1.56$
. . . . .
$V_{10} = 0.40$

For curve "a" with high decrement the constants are:

$V = 23.6$
$V_1 = 38.4$
$V_2 = 24.0$
$V_3 = 19.2$
$V_4 = 14.3$
$V_5 = 12.2$
$V_{10} = 6.3$
. . . . .
$V_{20} = 3.36$

The amplitudes of the fundamental and various harmonics in the two cases are plotted in Figure 5 assuming the fundamental to be 1,000 cycles as in the usual spark transmission. It is seen that the amplitudes in the highly damped signal fall off much less rapidly than those of the more lightly damped signal. This means that in the former case a great deal of the total energy is contained in the harmonics, and if these are not passed thru the amplifier there will not only be distortion but loss in volume of signal as well. The use of a feebly damped spark transmission with an amplifier tuned just sharply enough to pass the principal harmonics or side frequencies produced therefore gives a system which largely eliminates static disturbances.

In this respect the present arrangement is more effective than the ordinary radio frequency amplifier. In the latter the presence of strong signal oscillations at the detector, after having passed the amplifier, amplifies the static in the same way that a locally produced frequency would, so that when the receiver is tuned to the incoming signal very loud sounds are caused by the static. These diminish rapidly, however, as the receiver is detuned, because the signal energy then falls off and the ratio of this, the equivalent local oscillation amplitude, to the static amplitude being thus reduced there results a much greater than proportionate decrease in the endodyne amplification effect on the static, as has already been shown by Major Armstrong in another paper.[1] But in the new amplifier only the fundamental and the first few harmonics of the static impulse are amplified by these interactions and thus much of the energy of such disturbances is lost.

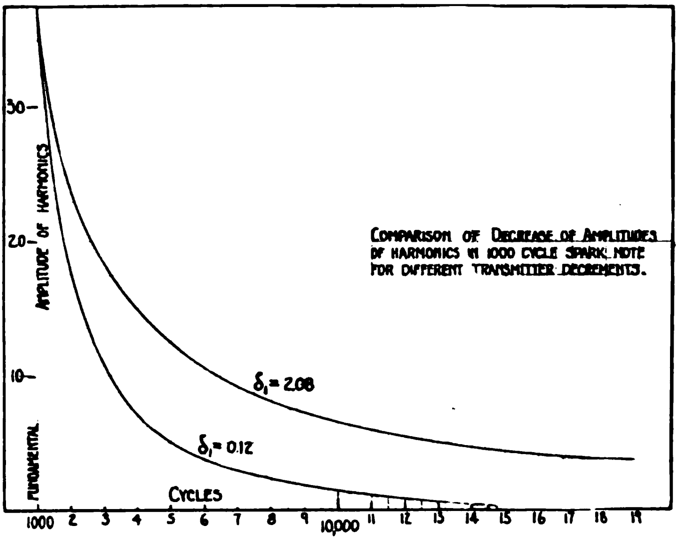

FIGURE 5

SUMMARY AND CONCLUSIONS

The above discussion has referred particularly to signals produced by spark transmitters, but the same general considerations are involved in telephone transmissions, except that in the latter the harmonic side frequencies to be considered will not generally exceed 2,000 cycles. The only point concerned in the case of sustained wave reception is that involving the passage of the incoming frequency directly thru the amplifier and this

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[1] E. H. Armstrong, PROCEEDINGS OF THE INSTITUTE OF RADIO ENGINEERS, April, 1917.

should be avoided with sustained waves for the same reasons that have been given to cover spark transmission.

Several practical considerations have been omitted from the discussion. Of these, one of the most important is the difficulty that is encountered in placing the circuits of a radio frequency amplifier with their transformers in a box in such a way that sharp tuning may be obtained and yet not have the whole or part of the system go over into oscillation. This involves careful adjustment of the various couplings and the resistances of the circuits and the proportions and arrangements are usually different for every wave length. It is suggested that an improvement might be made in this type of amplifier over the circuits that have been drawn by Major Armstrong, in which he uses air core tuned transformers in all of the stages of the amplifier, by the use of a tuned air core transformer behind the first detector tube feeding the first stage of the amplifier and with the stages following this coupled by means of carefully designed iron core transformers. The latter keep down stray field, and it has been found possible to build such transformers so as to get practically the maximum attainable amplification from the tube. By this arrangement the sharpness of tuning required in the amplifier is furnished by proper design of the first air core transformer, and the trouble experienced from coupling back, when several stages all tuned to the same frequency are employed, is reduced by the use of the iron core transformers which follow.

Two kinds of distortion are to be avoided. The first is caused by the passage of the incoming frequency directly thru the amplifier. The second is due to the more or less complete elimination of the harmonic side frequencies in passing thru the amplifier due to excessively sharp tuning. The type of amplifier in question is best suited to use on very short wave lengths, at least below 300 meters. At long wave lengths it is difficult to avoid distortion of the first of the two kinds mentioned, which, in the case of spark signals, results in a mushy, harsh note. Above 600 meters this type of distortion may be expected to occur over a hand of wave lengths from 15 per cent to 30 per cent above and below that for which the amplifier is designed.

As regards an estimate of the allowable sharpness of tuning in different cases it would appear that this lies approximately between the limits set by decrements corresponding to 0.2, as about the sharpest tuning allowable, to about 0.8 for the broadest tuning. The latter would not be allowable except perhaps for the reception of very short waves. These figures apply only to the case where several tuned transformers are used in cascade in the amplifier. If the arrangement using one air core transformer and the balance iron core broadly tuned instruments as just described be used, the tuning of the first air core transformer might be made considerably sharper than this, of the order usually found in ordinary receiving tuners.

In general, the basic frequency to be used in the design of the amplifier may be higher for long wave lengths than for short up to a certain point, the practical limit being in the neighborhood of 400,000 or 500,000 cycles for the reception of 6,000 meter spark signals. For very long waves the beat frequency cannot be made so high.

The analysis indicates that the amplifier can be made to be freer from interference from highly damped spark stations and static disturbances than the usual types.

There is one other point that has not been mentioned tho I know it has already occurred to Major Armstrong himself. That is the question of the extent of the loss, if any, in effecting the change of incoming signal frequency to the value for which the amplifier is built. An experiment made[2] at Camp Alfred Vail in which the signal received on a simple non-regenerative tube was compared with that obtained by Major Armstrong's arrangement using a separate heterodyne, a rectifying tube for the super-audio note, and a detector tube, indicated that about equal signals were obtained by each method. Apparently, the heterodyne amplification in the second case just about makes up for the loss which accompanies the change in frequency.

Radio Laboratories,
Camp Alfred Vail, New Jersey,
December 4, 1919.

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[2] By Mr. M. C. Batsel, Assistant Radio Engineer, Signal Corps, United States Army.

THE RELATION BETWEEN ATMOSPHERIC DISTURBANCES AND WAVE LENGTH IN RADIO RECEPTION*

By

Louis W. Austin

(United States Naval Radio Research Laboratory,
Washington. D. C.)

The fact that the atmospheric disturbances, commonly called "static" or "strays" by American operators, increase with the wave length to which the receiving system is tuned has been known qualitatively for a number of years. The object of the present experiments is to gain some degree of quantitative information on the subject.

Neglecting the lightning clicks and hissing disturbances which for the most part produce little interference with communication, we have in general to deal with the rumbling or grinding static which probably originates somewhere in the upper atmosphere, and which may perhaps be compared in its method of propagation to radio signals sent out from an airplane. Regardless of the orientation of the original oscillating body, the wave front spreads out in a more or less spherical form. When the wave strikes the earth the lines of force become grounded and travel off over the surface as tho transmitted from an antenna situated at some point roughly below the center of disturbance. Observations which will be described in another place, show that the wave front at 50 ft. (15 m.) from the ground is approximately vertical like that from a distant sending station. Of course there will be some disturbance centers nearly overhead, but these generally form only an insignificant portion of the whole.

It has frequently been thought that static is entirely aperiodic, and that it produces a pure shock effect on the antenna. This seems somewhat doubtful, since none of the aperiodic types of artificial static produced in the laboratory, even of the most violent kind, have ever been anywhere nearly so difficult to eliminate as the natural disturbances. It seems more probable that it consists of a great number of distinct disturbances coming

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* Received by the Editor, January 15, 1920. Presented before The Institute of Radio Engineers, New York, May 5, 1920.

from different sources and of widely varying wave lengths, thus producing a practically continuous disturbance spectrum, so that to whatever wave length the receiving apparatus is tuned, a corresponding static wave length is found.

According to observations made independently at a number of points on the North Atlantic Coast, the heavy afternoon and night summer static appears to come generally from the southwest, while the lighter static of the forenoon and that observed during the cooler portions of the year seems to be more evenly distributed in regard to points of the compass. It is also to be noted that this southwest static is usually more continuous than the other.

The following experiments have been carried on at the Naval Radio Laboratory at the Bureau of Standards, and the receiving apparatus used is that described in the Nauen-Eilvese experiments[1] and in an article on the measurement of radiotelegraphic signals.[2] The method of observation was as follows:

The Laboratory antenna and secondary receiving circuit containing an oscillating audion were set on the required wave lengths, the adjustments being made as described in the articles cited. The strength of the disturbances was measured by the shunted telephone method, and since the individual disturbances vary in intensity from second to second, it was necessary to adopt some arbitrary method of procedure in determining their audibility. After experimenting with different plans, it was decided to call the audibility of the disturbance, the setting of the audibility meter at which an average of three pulses of disturbance could be heard in the telephones in ten seconds. The observations were taken at about 10 a.m. and 3 p.m., the time consumed in each series for the range 3,000—18,000 meters amounting to less than 15 minutes. On account of the lack of a definite pitch in the atmospheric disturbances as heard in the telephones, the accuracy of observation is, of course, much less than in the measurement of received signals. For this reason, and on account of the irregularity of the phenomenon, the results are given in the form of curves rather than numerical tables. The work was begun in August, 1917, and since May, 1918, has been made a part of the daily routine of the laboratory. Of course it is impossible in an article of this kind to give more than a very small portion of the data accumulated. Therefore,

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[1] "Journal of the Franklin Institute," page 605, 1916.

[2] PROCEEDINGS OF THE INSTITUTE OF RADIO ENGINEERS, volume 5, page 239, 1917.

it has seemed best to pick out sample periods which are typical of the general conditions observed.

Figure 1 gives a series of observations extending from November 1 to November 14, 1917 taken at 3 p.m. The observations were taken every 1,000 meters between the wave lengths of 3,000 and 10,000 meters, and every 2,000 meters from 14,000 to 28,000 meters. These curves are typical of the variation in the disturbances with wave length during most of the year.

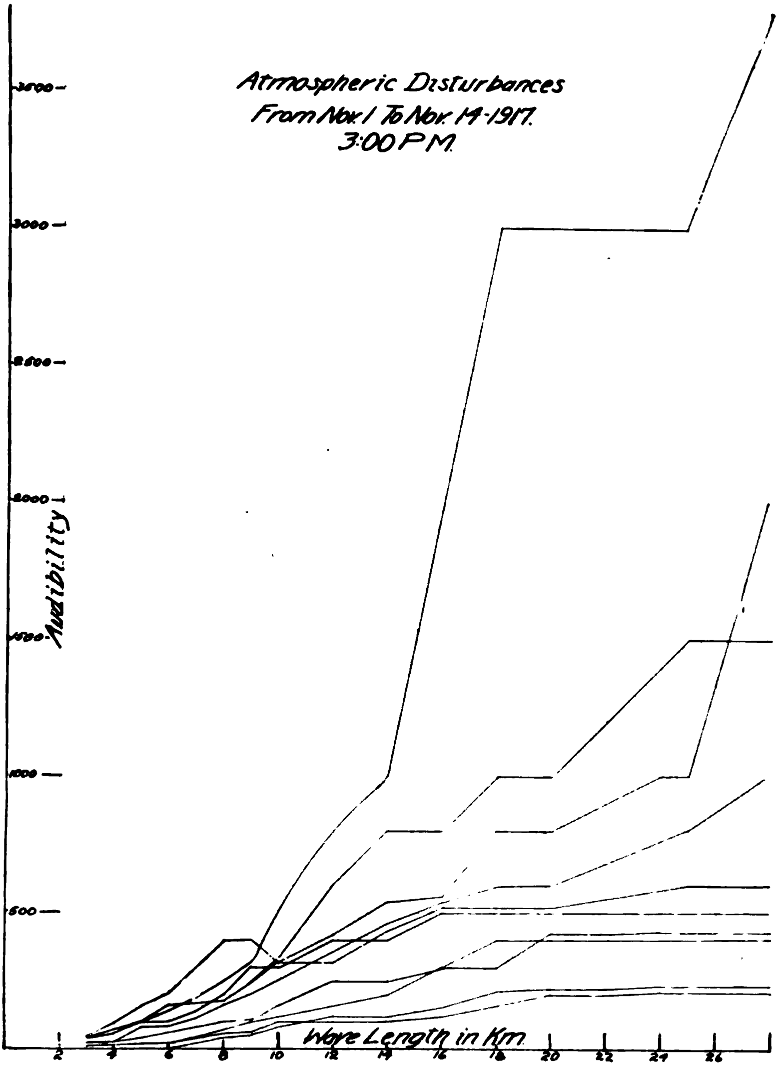

FIGURE 1

The forenoon observations are similar in form, tho somewhat lower in average audibility than during the afternoon, especially in summer. It is seen that, in general, there is a rapid, tho irregular rise in intensity with wave length and that occasionally, tho rarely, a maximum is found with a subsequent decline in intensity. In some cases, the rise extends only to a definite wave length, beyond which the intensity remains constant over a considerable range.

Figure 2 shows observations taken at 10 a.m. between December 1 and December 18, 1917, and covers the wave lengths between 3,000 and 16,000 meters, which is the range ordinarily employed in present-day long distance transmission. Figure 3, covering the period from August 16 to September 5, 1917, shows a time of unusually heavy afternoon summer disturbances. Disturbances of this character have hardly occurred at all during the summer of 1918 and 1919. The figure shows a much more rapid rise in intensity with wave length than is shown in Figures 1 and

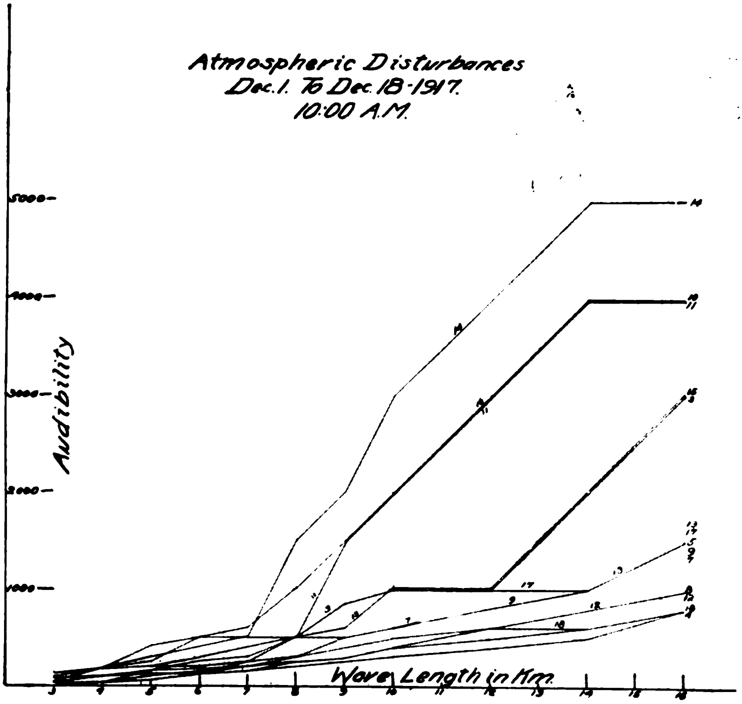

FIGURE 2

2, the intensity increasing often two or three times in an increase in wave length of 1,000 meters. The curves practically all run out nearly flat within the limits of the observations, after their initial rise.

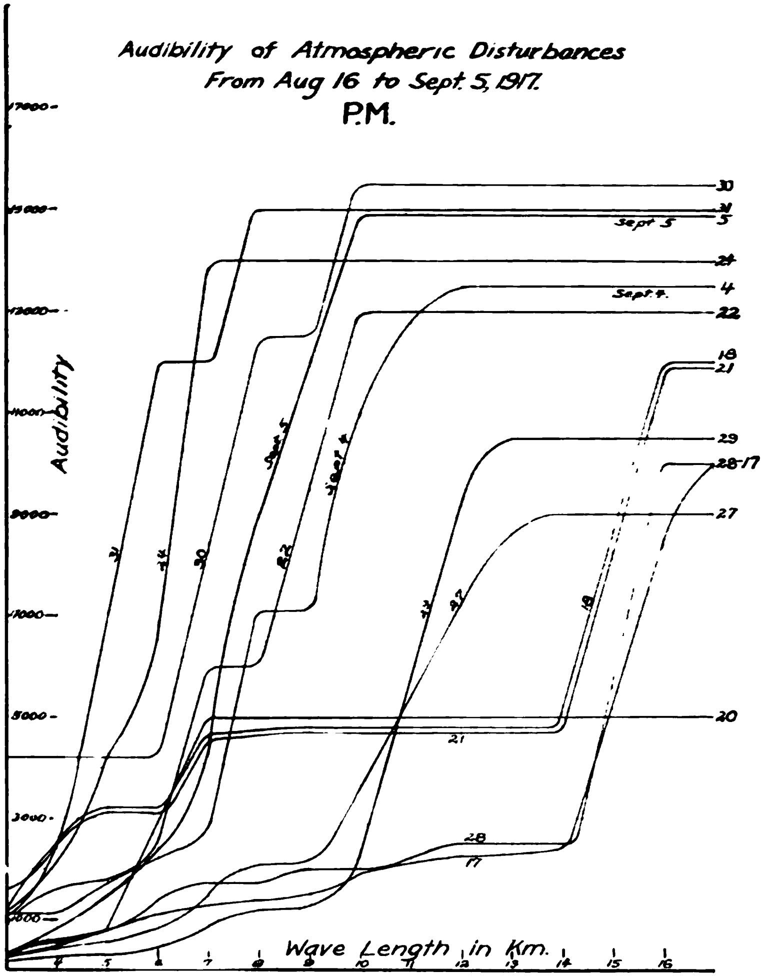

FIGURE 3

Figure 4 shows the forenoon observations covering the same period as Figure 3. The curves are quite distinct in character from the corresponding afternoon curves.

Figure 5 represents the static during the last half of August

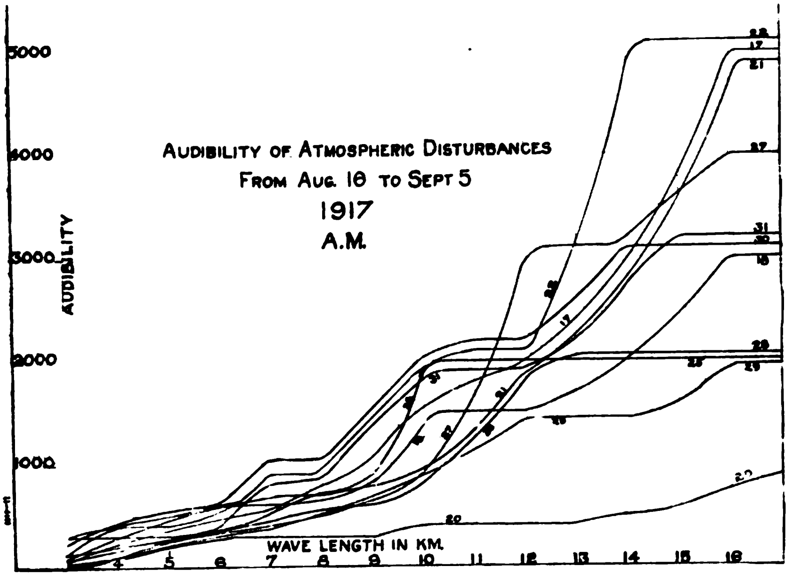

Figure 4

in 1919. The curves are evidently entirely different from those of the same period in 1917 (Figure 3) and correspond more nearly to the curves of Figures 1 and 2.

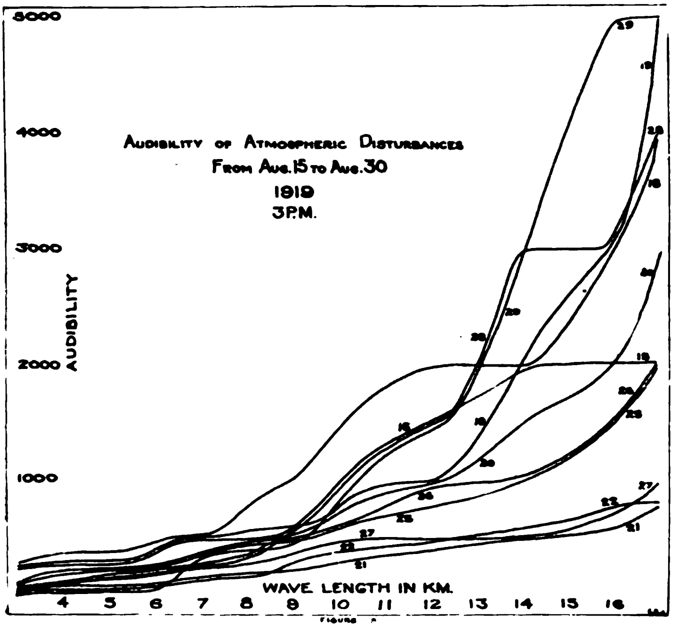

Figure 5

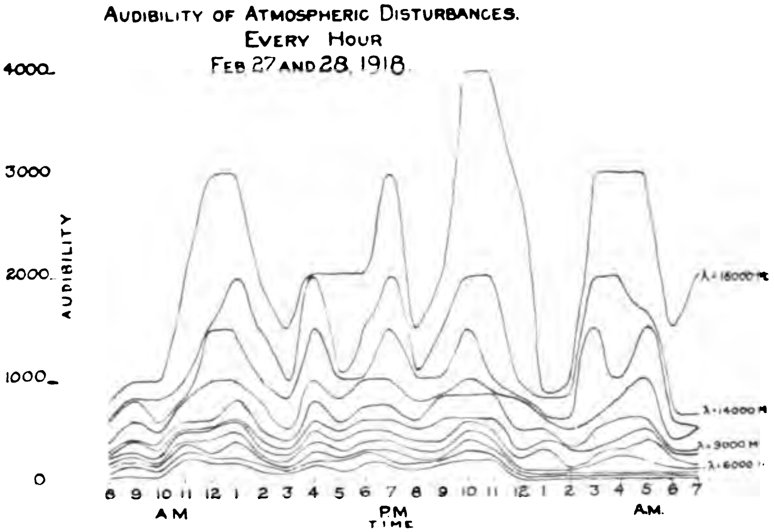

FIGURE 6

Sets of observations at the various wave lengths have been taken every hour for a period of 24 hours once a month during the last two years. Figure 6 shows the curves of a typical 24-hour test. It is seen that in general the maxima and minima of the different wave lengths correspond closely, altho there are many irregularities which may or may not have significance. There are always well marked minima at about half-past-one in the morning and at about daylight, and in addition there are always two or three other prominent minima present which shift position somewhat from day to day. There is little difference between winter and summer in the general appearance of the curves of daily variation.

1. Static increases rapidly with the wave length being on an average about twenty times as strong at 17,000 meters as at 3,000 meters. This increase is generally roughly proportional to the wave length.

2. There is at times especially during periods of unusually heavy afternoon summer static, a sudden increase at moderate wave lengths after which the intensity seems to remain nearly constant, so that the curve resembles a strongly damped resonance curve.

3. The strength of summer static varies greatly from year to year, the average during August, 1917 being about three times

as strong as that observed in the same month in 1918 and 1919. August, 1917 was also a month of exceptionally strong European signals.

U. S. Naval Radio Research Laboratory,
September, 1919.

SUMMARY: The apparent wave length of atmospheric disturbances at different times of the day and year is studied, and the results obtained are shown graphically and by description.

DISCUSSION

Greenleaf W. Pickard: Dr. Austin's paper is unquestionably a most valuable contribution to our knowledge of static disturbances. Altho in the past it has been generally recognized that static increased with the wave length setting of receivers, this paper has brought out two striking facts: first, that up to a certain wave length the increase in static intensity is nearly directly proportional to the wave length, and second, that after this critical wave length is passed, there is no further increase or even change in intensity.

But I do not find myself in agreement with the static theory briefly expressed in this paper. Instead of regarding static disturbances as a summation effect of many *oscillatory* discharges of different frequencies, I believe that the observed facts are better and more simply explained on the basis of *aperiodic* discharges. It is, of course, elementary that any imaginable wave form may be resolved by Fourier's theorem into a sine cosine series, and therefore might be built from a large number of suitably chosen undamped or feebly damped wave-trains. Actually, the various complex pulses known to us seldom or never have this genesis, and their resolution into a more or less infinite series of oscillation trains is merely a convenient mathematical analysis.

One of the simplest and best known aperiodic pulses is that caused by the discharge of a condenser through a circuit having a fixed ohmic resistance equal to or greater than $2\sqrt{L/C}$. In Figure 1 is shown a series of "resonance" curves for such pulses, when received on a feebly damped circuit corresponding to the ordinary receiving circuit. The full-line curve represents the usual i^2 readings in the wave-meter circuit, when acted upon by a condenser discharge in a neighboring circuit having twice the critical resistance. The broken line curve is that due to a just critically damped or non-oscillatory circuit, while the dot-and-dash and dotted line curves are due, respectively, to discharges in circuits having 0.5 and 0.25 the critical resistance, and hence oscillatory.

Dr. Austin employed an oscillating audion for his static measurements, and as he has pointed out[1] this detector responds in proportion to the first power of the received current. In Figure 2 is shown a plot of the first two curves of Figure 1,

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[1] Proceedings of The Institute of Radio Engineers, volume 4, page 252, 1916.

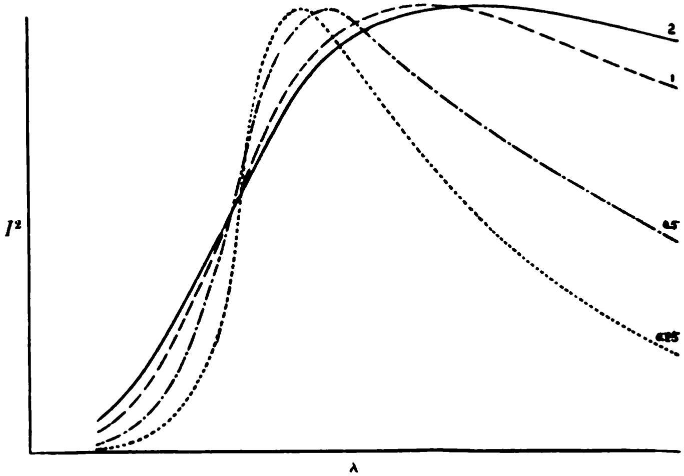

Figure 1

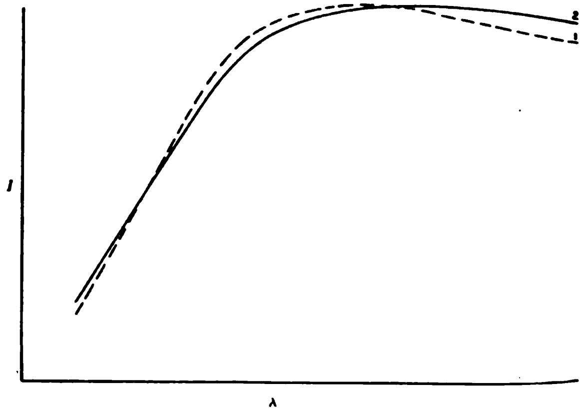

Figure 2

but with ordinates of current instead of current-squared. Their resemblance to the curves shown in the paper is striking.

It is altogether likely that if Dr. Austin had carried his measurements up to a wave length of 25,000 or 30,000 meters, he would have observed a decrease in the intensity of static. I have made a few comparative measurements of static intensity on these longer wave lengths, which show a clearly marked falling off in intensity above 25,000 meters.

I have found that the static measured by Dr. Austin on

August 27, 1917, may be well duplicated in the laboratory by a condenser discharge in a circuit tuned to about 16,000 meters, with sufficient ohmic resistance to give critical damping. This would indicate that the aperiodic "oscillator" responsible for the disturbance had a length of some eight or ten kilometers.

Frederick K. Vreeland: I have read with great interest Dr. Austin's paper, which furnishes an interesting confirmation of some of the conclusions regarding the nature of atmospheric strays derived by different means, and throws some illuminating side-lights on the subject.

Dr. Austin has said that the effect of strays on a receiving circuit tuned to variable frequency is analogous to that which would be produced by a continuous spectrum of waves of different frequencies. This is precisely the effect that is produced by an aperiodic transitory impulse, as has been well established by the analytical study of transients, and has been neatly illustrated, for certain special cases, by the experiments with artificial pulses described by Mr. Pickard.

Furthermore, the distribution of amplitudes among the wave lengths in this apparently continuous spectrum depends upon the decrement or rate of decay of the pulse. Thus, if we allow a given pulse to excite shock oscillations in a tuned circuit of small decrement, the energy of the oscillations increases with increasing wave length at a rate depending on the rate of decay of the pulse, and finally reaches a limiting value beyond which the change of energy is small.

Putting the matter rather crudely for the sake of simplicity, let us assume that the exciting pulse is relatively sluggish, that is, that its rate of decay is so slow that it persists over a period of several complete oscillations of the resonant circuit. It will be seen at a glance that the effect of the initial impulse in starting the first half wave of the oscillation will be partially neutralized by the smaller effect on the second half wave, the direction of which is reversed while the direction of the exciting pulse is unchanged. The oscillation will again be augmented in smaller degree during the period of the third half wave, and again diminished during the fourth, and so on until the exciting pulse has expended itself. It is thus evident that the effective value of a slowly decaying pulse is confined mainly to the initial impulse, the energy of the remainder of the pulse being ineffective.

If now, keeping the form of the exciting pulse unchanged, we increase the natural period of the oscillating circuit, it can be readily seen that the effect of the pulse in exciting shock oscillations will increase at an increasing rate with increasing wave length of the circuit, until a point is reached where the period of a half oscillation is sufficiently great to include practically the whole duration of the exciting pulse. The entire energy of the pulse is thus effective in exciting the shock oscillation, and the change in energy of this oscillation with a further increase in the wave length will be relatively small.

This is precisely what is shown in a general way by Dr. Austin's curves, showing the effects of atmospheric strays, and confirmed for special cases by Mr. Pickard's experiments with artificial pulses of known form. The curves show a rise at an increasing gradient up to a certain wave length, at which they suddenly flatten down and continue without further material increase. It thus appears that the results derived from theoretical study, considering the effect of a decaying aperiodic pulse, are borne out in a general way by the tests, within the limitations of the experiments. Dr. Austin's results are thus in accord with the conclusion, reached by other means, that atmospheric strays are largely of this character, as I have stated in former discussions.

A very interesting feature of Dr. Austin's curves, to my mind, is the manner in which the form of the curve varies under different conditions and at different times. It appears in a general way that the more intense strays produce a more rapidly rising curve, which reaches its flat portion at a smaller wave length. The height of this flat portion, however, is not fixed, but varies from time to time. One would naturally conclude from this that the most intense strays are as a rule the most abrupt, that is, their decrement is greatest, but that the relation between intensity and decrement varies from time to time. Thus, the curves for winter strays show a relatively gradual and continuous increase with increasing wave length, without reaching a maximum. The curves for the most violent summer strays, on the contrary, rise very rapidly and reach their critical value at a relatively short wave length, showing that these strays are very transitory, that is, they have a large decrement.

It would not be safe, however, to jump at any generalization regarding the relation between stray intensity and the form of the pulse. Anyone who has done serious work with strays knows better. On the contrary, Dr. Austin's curves, while indicating a rough general relation, also indicate certain notable exceptions. For example, some of the curves rise rapidly to the flat portion, continue horizontally over a considerable range of wave lengths, and then rise again abruptly at the longest wave lengths. In other curves this flat portion appears only as a relatively small jog in the curve. These discrepancies would seem to indicate that while the bulk of the strays observed are of short duration, there are some very powerful ones, the decrement of which is low, and which therefore affect the circuit chiefly at the longest wave lengths.

Here again we should guard against jumping at conclusions, for it is evident that an intense pulse may owe its intensity either to the intrinsic magnitude of the stray or to the proximity of its source. Thus, in some cases a very powerful stray may be of the same essential nature as other strays, which are usually weak, because their source is more distant.

Finally, we should bear clearly in mind the fact that Dr. Austin's observations do not relate to strays in general, but are limited to the most powerful strays occurring at any given time, in other words, those strays that are so exceptional that they occur only three times per second. It would be unsafe, therefore, to draw any conclusions regarding the great bulk of strays which produce the major part of the disturbance.

May we not venture to hope that Dr. Austin will continue and extend these very illuminating researches to include not only the exceptional strays, but all the strays which make up the complex effect? Such a statistical study, for which Dr. Austin has shown himself so admirably qualified, would doubtless throw much light on the subject, and would probably show curves of quite different form when the less intense and more frequent pulses are considered.

THE REDUCTION OF ATMOSPHERIC DISTURBANCES IN RADIO RECEPTION*

By

Louis W. Austin

(Head of the United States Naval Radio Research Laboratory at the Bureau of Standards, Washington, D. C.)

When the United States entered the war, it became highly desirable to establish radio communication with France sufficiently perfect to render the two countries independent of the cables, since these were at all times subject to danger of destruction by the enemy. For this reason great efforts were made by the Navy Department to improve apparatus and methods used in long distance radio work, and special efforts were directed toward the production of devices and circuits for the suppression of atmospheric disturbances, commonly known as static or strays, which it is well known form one of the chief obstacles to perfect radio reception. These disturbances are generally the strongest during the summer months in our latitude, and usually increase to a maximum in the late afternoon, that is, they are at their worst at a time of the year and time of day when the European signals are weakest at most of our receiving stations. Without attempting to discuss at length the origin of these disturbances, it may be mentioned that there are at least four types, all of which may arise from distinct causes. The most common type produces a rattling or grinding noise in the telephones. A second type, associated with snow or rain, gives a hissing noise. The third, due to lightning flashes, gives a sharp snap, while a fourth produces a noise somewhat like the first type but more crashing in character. This last seems in summer to be associated with thunder storm conditions, but it is also common, tho not usually as strong, in autumn and winter.

The early attempts to improve the signal static ratio[1] lay

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*Received by the Editor, October 30, 1919. Presented before The Institute of Radio Engineers, New York, April 7, 1920.

[1] According to Commander A. H. Taylor, a readable signal is generally obtained if the audibility of the static is not greater than four times that of the signal; that is to say, if the signal-static ratio is better than 25 percent. From our experience this is generally true, but it is evident that this must depend on the continuity of the static. Sometimes a ratio of 50 percent is hardly

largely in the direction of improvements in the secondary receiving circuit such as limiting the response of the detector to strong disturbances, using tuned and sometimes balanced audio frequency circuits, circuits in which an oscillating and non-oscillating audion were balanced against each other and their audio frequencies united in the telephones thru a differential telephone transformer, and many other unsuccessful devices in which numerous modifications of the secondary circuit were tried.[2]

As far as our knowledge now goes, the most successful method of static reduction employing the ordinary antenna alone, makes use of an exceedingly stiff primary circuit combined with a very stiff tuned audio frequency telephone circuit, using also sometimes a tuned audio amplifier. A good form of antenna circuit is shown in Figure 1.

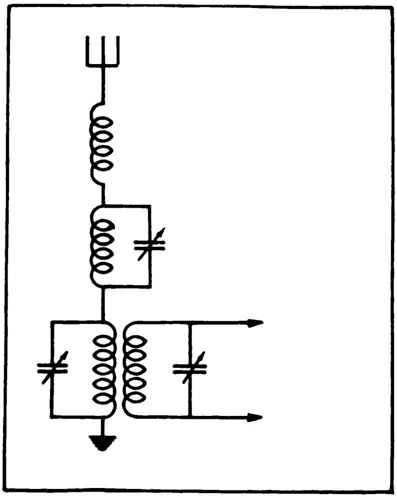

FIGURE 1

The closed loop or coil antennas and the underground and underwater antennas, which were considered very promising static reducers at one time, have not in their simple forms been

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readable while at other times 18 to 20 percent can be read. In these estimates it is assumed that the static audibility is the reading of the audibility meter at which the static can be heard three times in ten seconds.

[2] It must not be forgotten that the oscillating audion in comparison with the older types of detectors is itself the best static reducer known. (See "Quantitative Experiments with the Audion," "Washington Academy Journal," IV, page 84, 1916.)

found of much value at Washington in improving the ratio of signal to static. In oscillating audion reception of continuous waves, if the ratio signal over static is taken as unity for a good receiving antenna of the ordinary type, the ratio for a loop will be about two, while a good underground antenna in moist earth or fresh water will generally give a ratio of from two to three in the case of ordinary disturbances, but it should be noted that the buried antenna is entirely protected from true static induction, which, in the case of thunder clouds directly or nearly overhead, may produce severe disturbances in the telephones.

By the spring of 1918, four circuits had been developed, three in the Navy Department and one outside, which showed a substantial improvement in reception thru the atmospheric disturbances. In order to obtain information in regard to their relative merits, comparative reading tests were carried on during that summer on signals from some of the high power European stations. The receiving stations were:

The Marconi Experimental Station at Lakewood, New Jersey
(Weagant system)
The Marconi Station Under Naval Charge at Belmar, New Jersey
(Taylor system)
The Experimental Station of the Naval Radio Research Laboratory on the Anacostia River at Washington, D. C.
(Laboratory system)
The Naval Station at Otter Cliffs, Maine
(Otter Cliffs system)

The first three stations could be quite fairly compared since they all lie in a region where the conditions of reception are similar, altho conditions at Washington are slightly less favorable than at the other two. The comparison of Otter Cliffs with the other stations is of less value in respect to the excellence of the systems employed, on account of the differences in distance and climate in the two regions.

LAKEWOOD

The receiving station at Lakewood, New Jersey, employed a system developed by Mr. Weagant[3] (see Figure 2). The antenna consisted of two single-turn loops supported on telegraph poles extending for a distance of three miles (5 km.) each way from the receiving station. The loops lay in the direction of propagation of the incoming waves from the European stations, and had

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[3] PROCEEDINGS OF THE INSTITUTE OF RADIO ENGINEERS, volume 7, page 207, 1919.

a height of about 18 feet (5.5 m.) between wires at their outer ends, which decreased to 3 feet (0.92 m.) at the station. They were tuned by means of variable capacities and inductances, a part of the latter being inserted in the line at a distance from the station. The loops ended in the station in the two primaries of a large Bellini-Tosi goniometer and acted in opposition on the goniometer secondary. This last formed a part of an intermediate circuit which was in turn coupled to the usual secondary receiving circuit. Tho the loops were connected in opposition, the difference in phase due to their length resulted in a marked strengthening of the signal. At the same time the static was greatly reduced. According to Mr. Weagant, this reduction in static was due to the fact that static comes from above and thus acts in an equal and opposite sense on the two loops. This explanation seems very improbable, since if it were true, any antenna consisting of a vertical wire would be free from static.

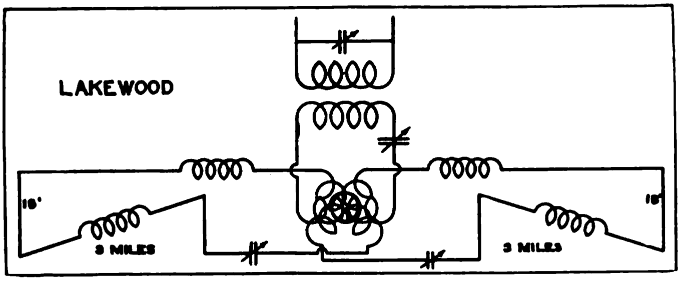

FIGURE 2

BELMAR

At Belmar the resistance balance system of Commander A. H. Taylor[4] was employed. The most recent type of circuit is shown in Figure 3. For the Nauen reception, the loop antenna *L* had 16 turns and was 75 feet (22.9 m.) long and 45 feet (13.7 m.) high. *W* was a well-insulated water wire about 1,500 feet (458 m.) long lying just below the surface in salt water. The signal in the water wire was exceedingly weak compared with that in the loop. The variable resistance *R′* served to increase the natural difference in signal static ratio of the loop and water wire, while *R* was a resistance with sliding contact used to obtain a

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[4] Proceedings of The Institute of Radio Engineers, volume 7, page 559, 1919.

balance between the static of the loop and that of the water wire. By this arrangement the signal static ratio of the combined system was rendered much better than that of the loop or wire alone. On account of the resistances employed, the signals were generally very weak so that considerable amplification was necessary. Five similar systems of loops and water wires were used for receiving various stations.

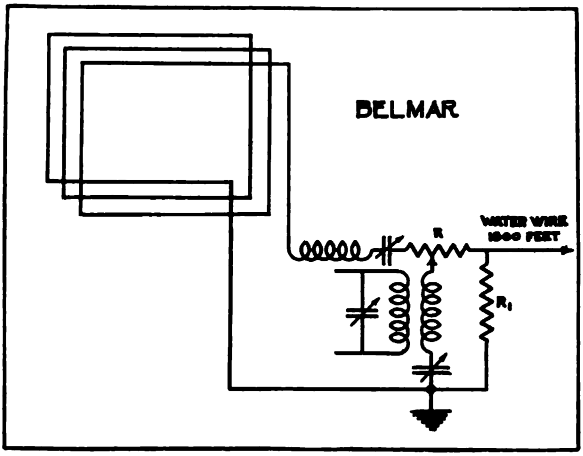

FIGURE 3

THE RADIO LABORATORY'S RIVER STATION

This station is situated on the Anacostia Flats a little below the Washington Navy Yard. The circuits are shown in Figures 4 to 8. The loop used during most of the summer of 1918 was 90 feet (28 m.) long and 30 feet (9.2 m.) high with 8 turns. This was later replaced by a higher and shorter loop in which the number of turns could be varied by switches. The well-insulated water wire 1,000 to 2,000 feet (305 to 610 m.) long lay in the brackish Anacostia River not far from the bank, while the surface wire lay along the top of the retaining wall. The condensers C_1, C_2, C_3, and C_4 (Figure 4) acted as coupling condensers controlling the energy flow from the loop and from the two wires. The antenna tuning was practically all done with the condenser C. In this circuit it was intended to take advantage of the difference in signal-static ratio of the water and surface wires discovered in the work at Piney Point in 1917, and also of the difference in this ratio on the loop and water wire. A considerable improvement in the action of the circuit was brought about by shunting a 30 millihenry inductance across the condensers C_1 and C_2 between the loop and water wire.[5] The theory of this circuit in regard to the reduction of static is not yet fully understood. While it may depend in part on the difference in

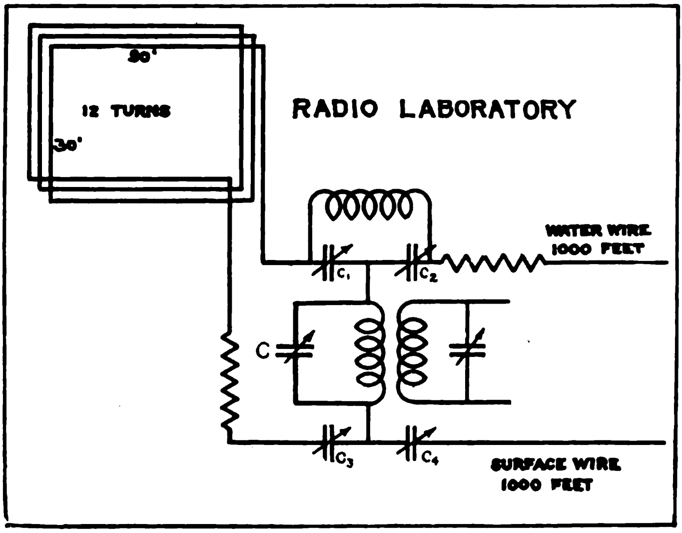

FIGURE 4

static-signal ratio in the surface and water wires, the main effect is apparently due to the combination of the loop with a water or ground wire, as very good results are obtained with the surface wire removed (see Figure 5), and almost as good results with the water wire replaced by the surface wire. The circuit is extremely unidirectional, being much stronger for signals coming from the direction of the extended wire than from the opposite direction. (Note: The experiments indicate that a great improvement may be expected in all loop reception by attaching a wire lying on the ground to the loop, in the manner indicated. For waves less than one thousand meters in length, this wire would need to have a length of only one hundred or two hundred feet (30.5 to 61 m.).) This unidirectional character of the circuit is probably an important factor in the reduction of static in European reception, as experience has shown that in this part of the country at least

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[5] This was introduced about September 1, 1918, and accounts in part for the improved work after that date. (See Table 1).

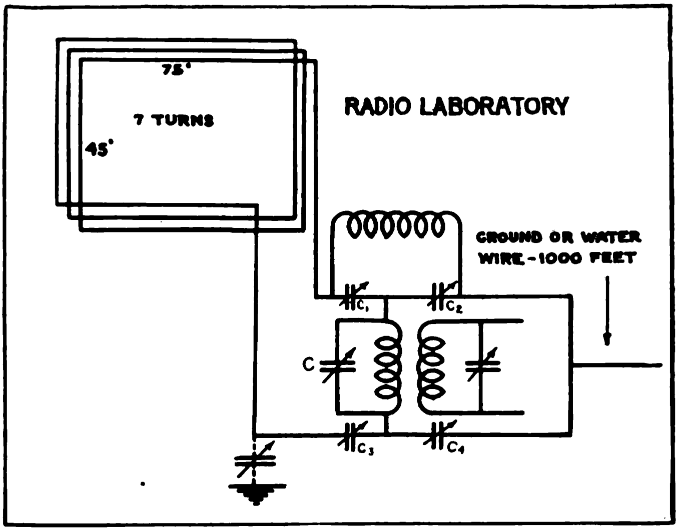

FIGURE 5

a large part of the first type of static (the most frequent kind) comes from the southwest, a direction almost exactly opposite to that of the European stations. It is also observed in confirmation of this idea, that using a water wire extending to the south-

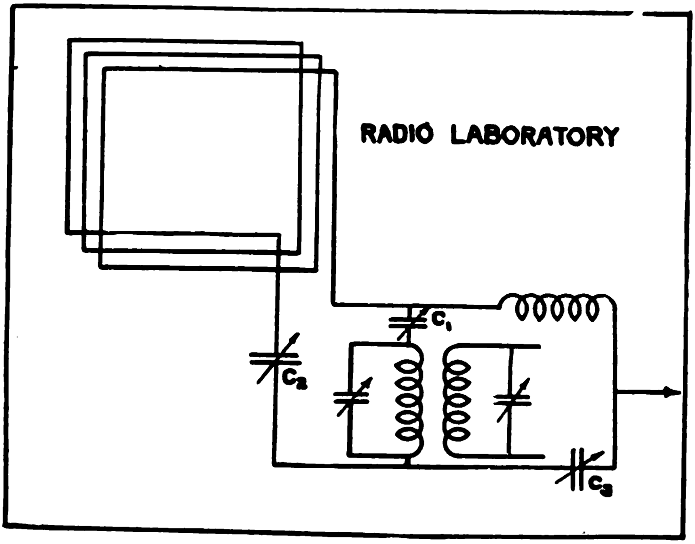

FIGURE 6

west for reception from that direction, the static reduction is less satisfactory than in the European reception.

Since the completion of the 1918 tests, a number of modifications and simplifications have been made in the laboratory circuits, Figures 6 to 8, which are for the most part due to Mr.

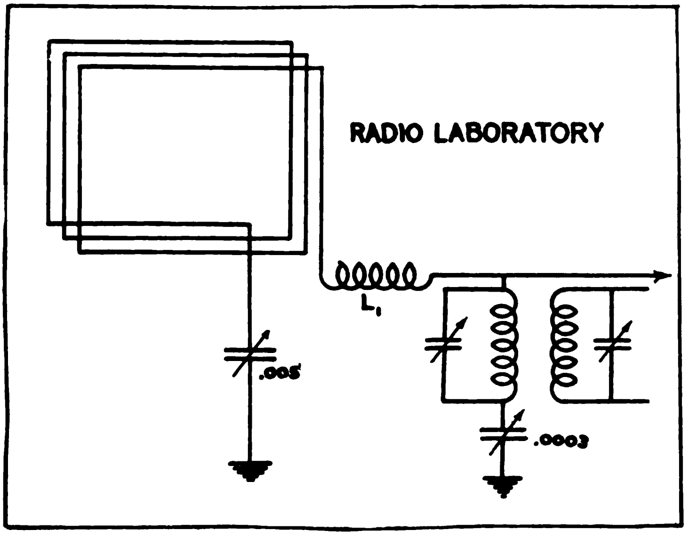

Figure 7

Clausing, of this laboratory. The circuits appear to be quite as efficient as the original form. They all represent various applications of condenser control to the balancing of loops and ground or water wires.

Otter Cliffs

The circuit shown in Figure 9 has been used at Otter Cliffs since the middle of the summer of 1918. It consisted essentially of an ordinary tuned loop of 3 turns, 125 feet (38 m.) long and 25 feet (7.6 m.) high with 20-inch (51-cm.) spacing, interwound with an open end untuned loop of 3 turns connected to ground thru an inductance of 30 millihenrys and a variable resistance of from 5,000 to 60,000 ohms. The closed loop was coupled both to the open loop and to the secondary circuit, and the reduction in static was accomplished by the adjustments of the two couplings and the variation in the grounding resistance. The interwinding of the loops produced a close condenser coupling between them in addition to a distributed inductive coupling. The circuits formed a combination which was evidently highly unidirectional, and probably there was also some differential action due to differences in decrement on the signal and static as in the loops and water wires at Belmar and Washington.

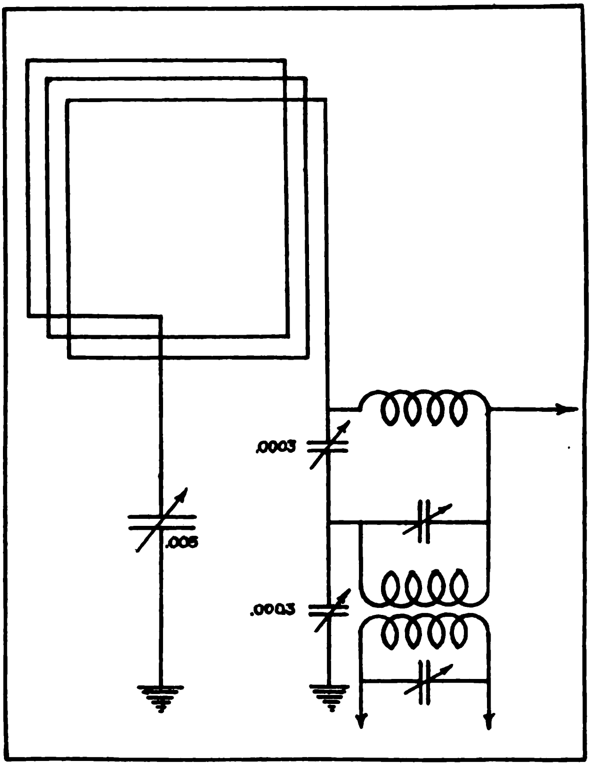

FIGURE 8

The situation of Otter Cliffs near Bar Harbor was much more favorable for European reception than that of the other stations described. To begin with, the distance from the sending stations was less by more than 500 miles (800 km.) and this alone, according to the Navy Transmission Formula, insures about double the strength of signal. In addition, the climatic conditions are such that the signals are less variable than in the more southern regions of the country and the atmospheric disturbances are probably in general less severe.

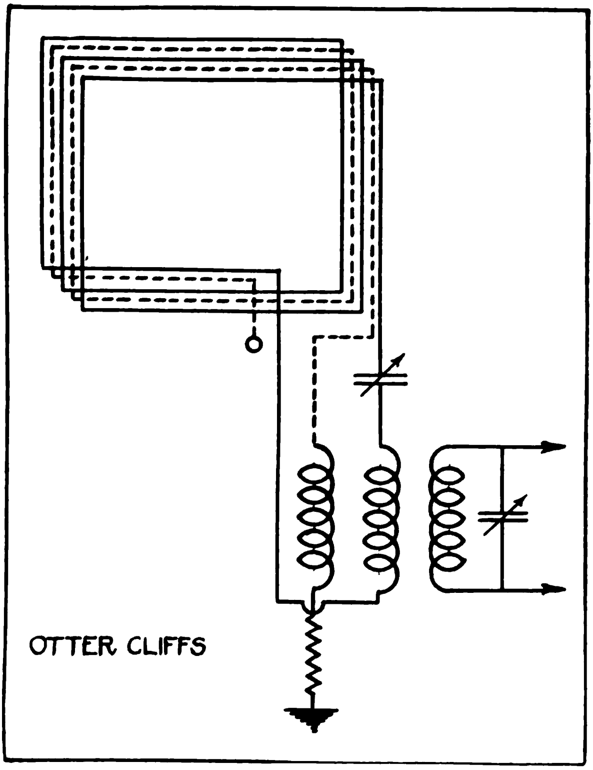

FIGURE 9

COMPARATIVE READING TESTS

During the last half of August and the whole of September, 1918, reading tests were carried on between the four stations mainly on the regular traffic from Nauen and Carnarvon. Belmar and Otter Cliffs, with their five receiving loops, were able to read simultaneously at any time during the twenty-four hours and took complete copy. Lakewood kept a twenty-four hour watch, switching from one station to another at intervals. The laboratory station was kept on this work during the afternoon, which was the most difficult time on account of the fading of the signals and the strength of the static, copy being taken from each of the two sending stations at frequent intervals. Carnarvon, being weaker, was more difficult to receive than Nauen, and therefore gave a more severe test of the static reducing qualities of the different receiving systems. On account of these different methods of carrying out the test at the different stations, it was somewhat difficult to arrange a plan for numerical comparison. As the afternoon was the most difficult receiving time and the only time during which all the stations received, it was finally decided to assume arbitrarily that reception during all hours from six at night to twelve o'clock noon would have been perfect. Then from the data[6] forwarded to this laboratory, calculations were made of the number of hours between twelve noon and six P. M., during which each station could have probably been received. Adding this to the eighteen hours of assumed perfect reception and dividing by twenty-four, we get the percentage of reception for the day. Table I gives the reception percentages for the four receiving stations for the August and September tests.

TABLE 1

Average Percentage of Reception

August 15-31

Receiving Station	Nauen Sending	Carnarvon Sending
Otter Cliffs	100 percent	98 percent
Lakewood	99 “	96 “
Laboratory Station	94 “	91 “
Belmar	94 “	81 “
	September 1-30	
Otter Cliffs	100 percent	100 percent
Lakewood	100 “	98 “
Laboratory Station	100 “	98 “
Belmar	99 “	91 “

The improvement in the work of the laboratory station in September is in part due to changes in the circuit and in part to the general improvement in receiving conditions. It is believed that Table 1 gives a fair estimate of the static reducing qualities of the circuits used at Lakewood, Belmar, and the Laboratory Station. As has been explained, the good work of Otter Cliffs

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[6] No reports on Otter Cliffs reception were sent directly to the laboratory. The rating given is based on statements of the officers who examined the copy sent in by Lakewood and Otter Cliffs.

is largely due to its situation; and it is not to be assumed that the circuit used there, tho an excellent static reducer, is really superior to the other circuits.

In estimating the value of the work on static reduction, it should be understood that with an ordinary antenna or even with a simple loop or underground or underwater antenna there are in most years, few if any days between June 15 and September 15 when a station like Nauen, to say nothing of weaker stations like Carnarvon, could be read at Washington thruout the twenty-four hours. Six or seven hours per day would probably be fair reception average for this time and even during the most favorable parts of the year there are many periods when reception is found impossible with the older methods.

OTHER TESTS OF THE CIRCUITS

Besides the comparative reading tests much work has been done at the Laboratory (River Station) in the endeavor to determine the actual amount of improvement produced by the various circuits. On account of the lack of space no attempt was made to set up a Weagant circuit.

The Taylor circuit has been extensively tested but has never given results comparable to those at Belmar probably because the proper decrement relation between the loop and water wire is only obtained in the water of high conductivity. (The water at Belmar is salt while that at the River Station is only moderately brackish.)

The Otter Cliffs circuit works well at the River Station but gives generally only about half the improvement in signal-static ratio produced by the Laboratory circuit. It has the great advantage however that it can be installed anywhere where a simple loop can be erected.

Table 2 shows some examples of improvement in signal-static ratio obtained with the Laboratory circuits under various static conditions. In the observations shown it appears that the improvement is greater the worse the original ratio. This is in part due to the tendency of the strong static to cover the signal and reduce its observed audibility. An extreme case of this is seen in the 3:00 P. M. observation of July 7th where the signal on the simple loop, tho evidently of some strength, is entirely inaudible thru the static. On the Laboratory circuit it was entirely readable. In other cases where the static is probably part of the fourth type, as on July 22nd, the improvement is slight.

Figure 10 reproduces a section of photographic recorder tape taken at Otter Cliffs in receiving from Lyons. It shows the effect on the readability of connecting and disconnecting the static reducing circuit.

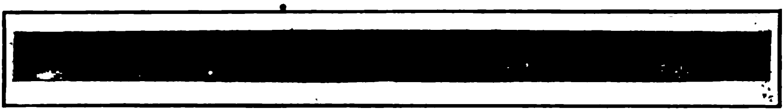

FIGURE 10

TABLE 2

EXAMPLES OF STATIC REDUCTION AT LABORATORY RIVER STATION

July 7, 1919

Lyons Sending

	Signal Audibility	Static Audibility	Ratio	Time
Simple Loop	6	4,000	0.0015	2:30 P. M.
Laboratory Circuit	36	150	0.24 (Readable)	2:30 P. M.
Simple Loop	Not heard thru static			3:00 P. M.
Laboratory Circuit	9	31	0.29 (Readable)	3:00 P. M.

July 11, 1919

San Diego Sending

Simple Loop	300	2,200	0.136	10:30 A. M.
Laboratory Circuit	58	245	0.236 (Readable)	10:30 A. M.
Simple Loop	140	1,200	0.117	11:40 A. M.
Laboratory Circuit	19	60	0.316 (Readable)	11:40 A. M.

Nauen Sending

Simple Loop	170	900	0.189	12:45 P. M.
Laboratory Circuit	80	250	0.320 (Readable)	12:45 P. M.
Simple Loop	12	1,200	0.01	2:00 P. M.
Laboratory Circuit	70	185	0.378 (Readable)	2:00 P. M.

July 22, 1919
Nauen Sending

Simple Loop	800	3,000	0.27	11:00 A. M.
Laboratory Circuit	40	80	0.50	11:00 A. M.

While the Weagant and Laboratory circuits showed the best records in the 1918 test, the Weagant adjustments were, according to last accounts, extremely difficult to make and the space required for the long loops (6 miles of 9.6 km.) was something of an objection. The Taylor and Laboratory circuits, tho very much smaller, require from 1,000 to 2,000 feet (305 to 610 m.), which precludes installation on shipboard and at some land stations. The Otter Cliffs circuit, on account of its compactness and simplicity, tho not the most efficient, has the widest application of the four.

The theoretical explanations of the static reducing qualities of the circuits are exceedingly incomplete. All the Navy circuits are very unidirectional and this undoubtedly explains some of their success in European reception, since in this part of the world, most of the first type of static (the most troublesome in summer) comes from the southwest. The balancing of the two directive systems of different decrements may also play a part and it is quite possible that we are also making use of factors not as yet recognized. At any rate the similarity of behavior toward the different types of static (easily eliminating the first type and having difficulty with the fourth) indicates that some of the important factors are common.

In conclusion, we may say of the four types of static enumerated at the beginning of this article: the first type, which is by far the most troublesome and common especially in summer, is found to be almost entirely eliminated by the new circuits. The second and third types in general cause little trouble. The fourth type, which causes most of the difficulty in reception now remaining, is reduced to a certain extent by all the systems, the Otter Cliffs circuit being perhaps the best of the Navy circuits in this regard. Mr. Weagant has recently reported in the paper already cited that he has obtained considerable success in its elimination.

The reduction in static described has naturally resulted in a marked improvement in European reception. Receiving at Washington with a simple loop or water wire, a high power transmitting station in Western Europe with an antenna current of approximately 300 amperes is unreadable for about 2,000 hours during the year. With any of the four static reducing systems, however, this time of unreadability can be reduced to less than 100 hours, or less than five percent of the time formerly lost.*

SUMMARY: The atmospheric disturbances of radio reception on the Atlantic Coast of the United States are classified as to type, effect, and probable origin. The static reducing systems of the Marconi Company (Weagant system), and of the Navy (Austin, Taylor, and Otter Cliffs systems) are described; and relative performance data of these are given. The improvement in reliability of reception to be obtained by the use of these systems is considered.

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*Thru an error, the discussion on the above paper has already appeared in the October, 1920, issue of the PROCEEDINGS, volume 8, number 5, beginning page 398. The readers of this paper are accordingly referred to the above citation.

THE MAGNETIC BEHAVIOR OF IRON IN ALTERNATING FIELDS OF FREQUENCIES BETWEEN 100,000 AND 1,500,000 CYCLES*

By

Leon T. Wilson

(Research Engineer, American Radio and Research Corporation,
Medford Hillside, Massachusetts)

PREFACE

This paper describes measurements of magnetization and core loss in iron, made by the author while a Lieutenant at the Signal Corps Radio Laboratories, Camp Alfred Vail, New Jersey.

The purpose of the work was a determination of the value of a sample of 0.002-inch (0.05 mm.) mild steel ribbon for use in transformers for radio frequencies.

The method employed in this investigation is not original. It has been described by Alexanderson in his paper on the "Magnetic Properties of Iron at Frequencies up to 200,000 Cycles."[1] However it is the belief of the author that the data obtained at the higher frequencies is new and also that the radio frequency voltmeter, as developed and described in this paper, is new and original.

The author wishes to express his thanks to the Officers of the Signal Corps Laboratories who so kindly secured permission for the release of the Signal Corps data and photographs for use in this paper. Especial thanks are due Lieutenant Donald G. Little for his generous and valuable assistance in the calculations. The enlisted men who built and arranged the apparatus assisted greatly by their thoroness and by their interest in the investigation.

The author desires to thank especially Professor L. P. Wheeler of the Physics Department, Yale University, for his criticism of this paper and suggestions for its improvement, and Professor C. F. Scott and Professor H. V. Bozell of the Electrical Engineering Department, Yale University, for their aid in the preparation thereof.

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*Received by the Editor, December 15, 1919.

[1] "Proceedings American Institute of Electrical Engineers," November, 1911.

INTRODUCTION

The measurements herein described are of two kinds:

Measurements of Magnetization.
Measurements of Core Loss.

METHOD AND THEORY

(a) MEASUREMENTS OF MAGNETIZATION.—These measurements consisted in observing simultaneously the current thru and the voltage across a toroidal winding containing the iron under test, at various frequencies and flux densities. These readings furnish data from which both H_{max} and B_{max} may be calculated.

H_{max} is given by the well-known relation

$$H_{max} = \sqrt{2}\frac{(0.4\,\pi\,n\,I)}{l}, \qquad (1)$$

where $\frac{n\,I}{l}$ is the effective ampere-turns per centimeter length of the magnetic circuit.

B_{max} is given by the relation $B_{max} = \frac{E_{effect.}}{4.44 f n\, 10^{-8} A}$, (2)

where E is the effective value of the voltage induced in the winding by the changing flux in the iron, f is the frequency in cycles per second, n is the number of turns on the sample, and A is the cross-section area of the magnetic path in square centimeters.

It should be noted that the foregoing equations assume respectively a sine wave of current and a sine wave of emf. or flux. In the calculations this condition of simultaneous sine waves of current and flux has been assumed, altho the assumption is an approximation because of magnetic hysteresis.

(b) MEASUREMENTS OF CORE LOSS.—The core loss was measured by means of a voltmeter and an ammeter. Since for power measurements these instruments require the current and voltage to be in phase, a method which would satisfy this requirement had to be employed. The principle of the method is as follows:

A variable condenser and a variable inductance are added in series with the test sample. The voltmeter is connected across the combination. The inductance coil is set at its minimum value and the condenser is varied until the voltmeter reads a minimum for a given current in the circuit. The current and voltage are now in phase and their product equals the power consumed by the group.

To find the power consumed in the test sample alone, another reading is necessary. The test sample is either removed or short-circuited. This time the inductance coil is varied for minimum voltage across the combination. The product of the voltage so obtained and the current gives the power consumed by the auxiliary apparatus. The difference between the two measurements is the power expended in the test sample.

DESCRIPTION OF APPARATUS

ARRANGEMENT—The complete arrangement of apparatus is shown in Figure 1. The corresponding diagram of connections is given in Figure 2. The same nomenclature is used on both the photograph and the drawing.[2]

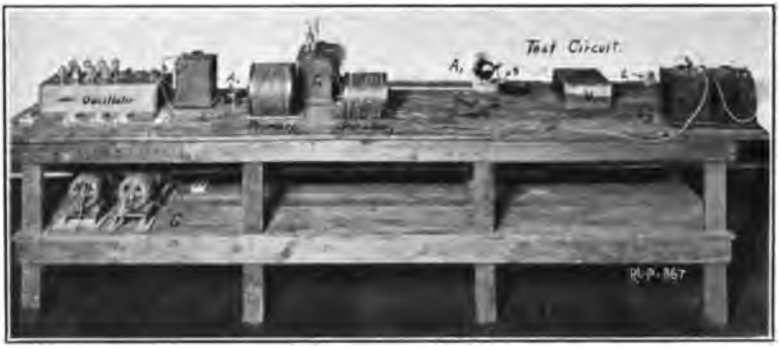

FIGURE 1

SOURCE OF POWER—The vacuum tube oscillator (1) shown at the extreme left in Figure 1 served as the radio frequency source of power. It consisted of 8 tubes arranged in pairs. A diagram of connections for one pair only is given.

The oscillator tubes used in this investigation were small ones designed for about 3 watts output. However as much as 7 watts per tube was developed in the test sample.

THE TEST CIRCUIT[3]—The arrangement of this circuit is shown in Figure 2. It will be noted that this circuit is entirely separate and distinct from the oscillator. This arrangement was made to secure greater flexibility and to provide a means for obtaining a coupling best suited for the efficient operation of the oscillator.

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[2] Details of the oscillator are recorded in the Appendix.

[3] Details of this circuit are recorded in the Appendix.

Energy was supplied to the test circuit thru the air-core transformer as shown. To reduce the losses to a minimum the transformer was wound with litzendraht wire.

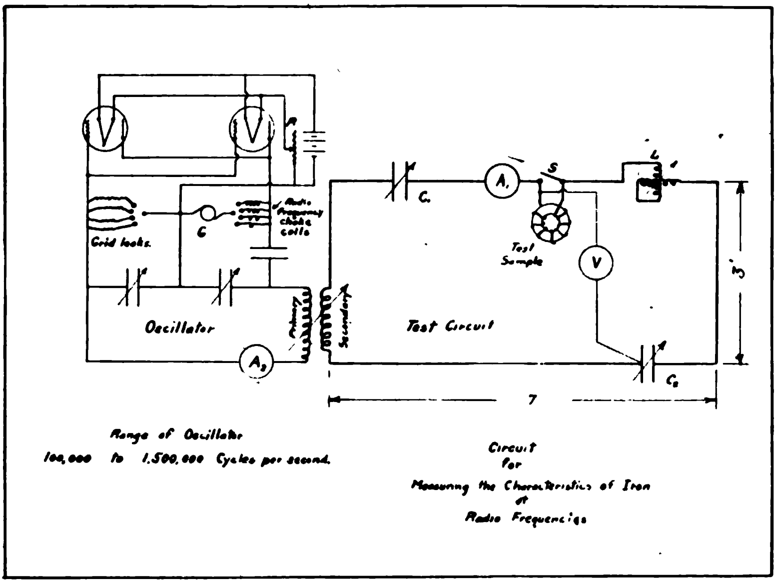

FIGURE 2

From Figure 2 it will be seen that the test circuit is considerably spread out. This was done to reduce the capacity of the sides of the circuit for one another, thereby securing a more nearly uniform current thruout the entire circuit. However, to insure measuring the current actually flowing thru the test sample an additional precaution was taken in placing the ammeter directly alongside of the sample.

The spreading out of the test circuit further served to prevent large electromotive forces from being induced in this circuit by stray fields from the oscillator and also to reduce the mutual inductance between parts of the test circuit.

THE TEST SAMPLE—The core of the test sample consisted of 20 doughnut-shaped laminations. These were punched from a mild steel ribbon[4] (annealed and enameled). The laminations were insulated from one another by thin paper in addition to their coating of enamel.

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[4] An analysis of this steel is recorded in the Appendix.

The outside diameter of the laminations was 2.75 inches (6.99 cm.) and the inside diameter 1.25 inches (3.18 cm.). The actual thickness of metal in each lamination was measured from an average of 7 samples to be .0341 cm. (.0134 inch).

As each lamination was itself a complete magnetic circuit, the core of the test sample had no air gap. This method of construction also eliminated the necessity of paying attention to the direction in which the steel was rolled.

The winding of the sample consisted of 2[illegible] turns of litzendraht wire[1] evenly spaced around the core. The winding was separated from the core by a thin layer of paper.

MEASURING INSTRUMENTS

(a) FREQUENCY.—The frequency of the oscillations in the test circuit was measured by means of a resonant circuit of known constants calibrated in wave lengths. This circuit contained a sensitive current indicator so that very little energy was required to operate it. This meter was checked against primary standards of known accuracy so that its calibration was easily accurate to 1 per cent.

(b) CURRENT.—The current thru the sample was measured with radio frequency hot wire instruments. These meters were frequently checked by comparison with D.C. standards. Four meters of different ranges were used in order to obtain good scale deflections for all values of current. By these precautions a probable accuracy of 2 per cent was obtained.

(c) VOLTAGE.—The voltage across the sample was measured by a thermo-couple galvanometer at radio frequencies. The development of this meter was undertaken with the purpose to secure (1) a voltmeter which would be reasonably sensitive as compared with audio frequency instruments and (2) one which could be calibrated with direct current and be used at radio frequencies without further calibration or correction.

The use of a thermo-couple and galvanometer appeared to be about the only way of satisfying these requirements as to sensitivity. For this purpose the instruments chosen from those at hand were a Western Electric thermo-couple of crossed wire type[2] and a Paul unipivot galvanometer. This combination gave full scale deflection with [illegible] volts across the heater of the thermo-couple, which had about [illegible] ohms resistance. The current taken by

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[1] Made of eleven strands of number 38 Brown and Sharpe gauge enameled copper wire.

[2] Diameter of heater wire = [illegible] inch = [illegible] cm.

the combination is seen to be very small—less than 3 milliamperes for full scale deflection.

To test the instrument for use at radio frequencies the circuit shown in Figure 4 was employed. This circuit corresponds to the one in which the voltmeter was intended to be used. The meter was connected to measure the voltage drop across the resistance *A B*.

It was found that the meter continued to show a reading when *A B* was short circuited. This reading was about one-third full scale deflection and increased as the meter was moved nearer the side of the circuit marked *L*.

This phenomenon was apparently due to either the action of electrostatic forces on the sensitive needle of the micro-ammeter or to a displacement current flowing from the line *A B* to the line *L* thru the capacity existing between the micro-ammeter and the line *L*. This capacity is represented by the dotted condenser C_1. C_1 is shown connected to the terminal *G* because that is the terminal to which were grounded the metal top, internal shields, and the metal framework of the meter.

By further experiment without the thermo-couple but with the meter subjected to the same electrostatic forces as it had been with the thermo-couple, the action of these forces on the needle was found to be negligible. Therefore only the second explanation will be further considered. In this case the current is considered to flow from *L* thru C_1 to *G*, to the heater, from where it divides and flows to *A* and *B*. This current causes the thermo-couple to function in its normal manner, thus giving a deflection of the micro-ammeter.

Based on this reasoning a shield of copper foil was built around the instrument. It was made in the form of a box completely enclosing the meter, thermo-couple, and multiplier except for an opening in the top thru which the instrument might be read. This shield was electrically connected to *B* as shown in Figure 4 (b). With such an arrangement, the meter read the desired zero when *A* and *B* were at the same potential. However, when *A* and *B* were not at the same potential, two different deflections were obtained, depending on which way the voltmeter leads were connected to *A* and *B*. That is, on the reversal of its leads the meter gave an entirely different reading. On further experiment this difference in readings was found to increase with the amount of multiplier resistance.

These observations may be explained by the aid of Figures 4(b), 4-[illegible] and 4-[illegible]. In Figures 4-[illegible] and 4-[illegible], R_m represents the multiplier resistance, [illegible] and [illegible] represent respectively the heater and [illegible] resistances of the thermocouple. Figure 4-[illegible] assumes that the heater and [illegible] have [illegible] their respective [illegible]. A [illegible] this assumption [illegible]. Figure 4-[illegible] [illegible] equivalent

[illegible]

[illegible] Figure 4-[illegible] shows [illegible]meter [illegible] may readily [illegible] that [illegible] alternating between A and B [illegible] meter reading [illegible]. It may further be seen that when R_m [illegible] and the meter may be [illegible] reversal. This conclusion was checked experimentally. By the same reasoning, it is clear that the voltmeter would read the same on reversal if R_m were split in half and each half connected in either lead to the thermo-couple. Altho such an arrangement satisfies the condition that the meter reading should not change on the reversal of its leads, it is seen on further consideration that the deflection for a given potential is a function of the frequency because the impedance of C_2 changes with the frequency.

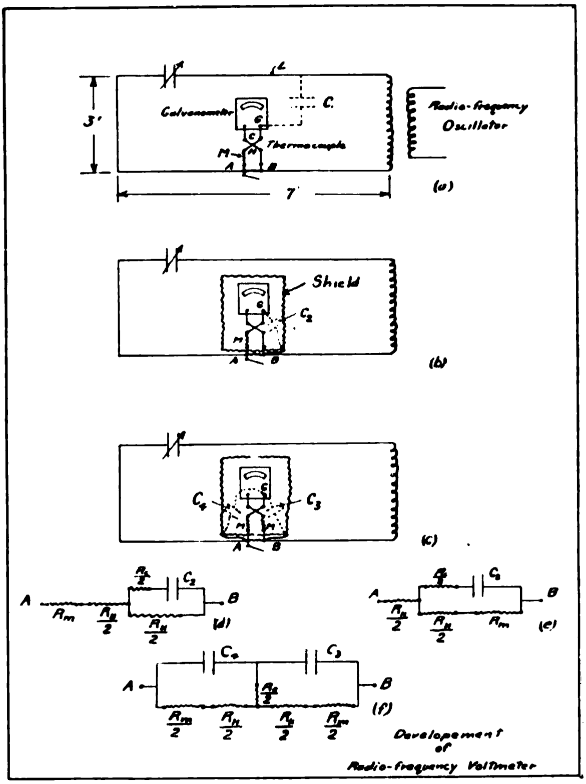

FIGURE 4

To overcome this latter difficulty the micro-ammeter was arranged to have the same capacity to both *A* and *B*. This was accomplished by splitting the original shield into two equal parts which were connected respectively to *A* and *B* as shown in Figure 4(c).

This circuit becomes a balanced a. c. bridge when $C_3 = C_4$.

and when the resistances are balanced. In practice C_3 was made equal to C_4 by a symmetrical placing of the meter with respect to the two halves of the shield. The resistances were balanced by splitting R_m and connecting the halves as already described.

In Figure 4 f) both the inductance and capacity between turns of the multiplier have been neglected. These factors must be small in order that the meter may be calibrated on d. c. and used at radio frequencies without further calibration or correction.

The inductance was made small by means of the bifilar winding.

The capacity between turns was reduced by means of a multi-pancake winding. Each half of the multiplier was wound on a cylindrical spool about 3 inches (7.62 cm.) long and 1 inch (2.54 cm.) in diameter. Each spool had 10 slots. Each slot contained about 4 feet of "prima-prima" wire (diameter 0.0015 inch) (0.0038 cm.) and resistance equal to 128 ohms per foot (or 420 ohms per meter). The spools were previously boiled in paraffin to eliminate moisture.

Altho the multiplier was found satisfactory, it is appreciated that much better windings might have been used. The foregoing method of winding was used because it was simple and required little labor, as the spools were already on hand.

The final test of the voltmeter for accuracy was performed as follows: A given value of current was sent thru a small diameter resistance wire at 3 different frequencies and the corresponding potentials across the wire were measured. The three frequencies were 0 or d. c.; 100,000; and 800,000 cycles. The resistance wire used was 4 feet (122 cm.) of number 40 "Therlo" having a resistance of about 120 ohms.[6] This wire was stretched out straight in air to permit a comparatively high value of current. The small sized wire was used to prevent errors due to skin effect.

The readings of the voltmeter on d.c. and 100,000 cycles were identical and the reading at 800,000 cycles was 1 percent. higher. At this high frequency, the ammeter was changed to the other end of the wire to eliminate errors due to stray displacement currents. However, the reading in this case was identical with the previous one. A part of this 1 percent. discrepancy at 800,000 cycles is accounted for by considering the inductance of the wire. From its calculated value an increase of voltage drop of 0.6 of 1 percent. would be expected.

The voltmeter in its final form is shown in Figure 3.

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[6] Diameter of number 40 wire = 0.00315 inch = 0.0080 cm.

PROCEDURE

MEASUREMENT OF MAGNETIZATION—Before each set of observations, careful adjustments were made of both the oscillator and test circuits in order that the current thru the test sample might approximate a sine wave as nearly as possible. These adjustments of course had to be consistent with a good transfer of energy into the test circuit.

The sharpness of the tuning of both the test circuit with the oscillator and the wave meter with the test circuit was used as a measure of the approximation to a sine wave of current in so far as that approximation is affected by the degree of coupling. That is, this method served to show whether or not the coupling between the circuits was too close, in which case the "double hump" would be present.

The oscillator was first tuned to approximately the desired frequency. Then the test circuit was tuned by means of the condenser C_1. The coupling between the test circuit and the oscillator was next adjusted for sharp tuning and good input to the test circuit. As the oscillator was now working under approximately final conditions, its grid leak and choke coils could now be varied for maximum output.

All these adjustments reacted upon one another so that several trials by the "cut and try" method had to be made.

The test sample heated considerably during the measurements. To save time two samples were used: one, for the preliminary adjustments, and the one to be tested, for the final adjustments. The one under test was immersed in an oil bath but even so, readings had to be taken quickly to avoid changes in the characteristics of the iron due to its rise in temperature.

The measurements of magnetization consisted in varying the current thru the sample by means of the plate voltage applied to the vacuum tubes, and observing the current thru the sample and the voltage across its terminals. The complete set of observations are shown in Figure 5.

MEASUREMENTS OF CORE LOSS—With some additions the same preliminary tuning was done in these measurements as in the foregoing ones. The inductance L was set at its minimum value, and the condenser C_2 was varied until the voltmeter V read a minimum for a given current. Changing C_2 of course detunes the test circuit which must be retuned by C_1. After several trials by the "cut and try" method the minimum reading of V was secured with the test circuit properly tuned.

The current thru the sample was next varied as previously described and readings were taken of the current and voltage. On the completion of these observations, the sample was short circuited and the circuit was retuned by increasing L, to replace the inductance of the sample. The correct setting of L was determined by the minimum reading of the voltmeter V. Another set of readings was now taken at the same current values as used in the previous set. The complete observations are given graphically in Figure 6.

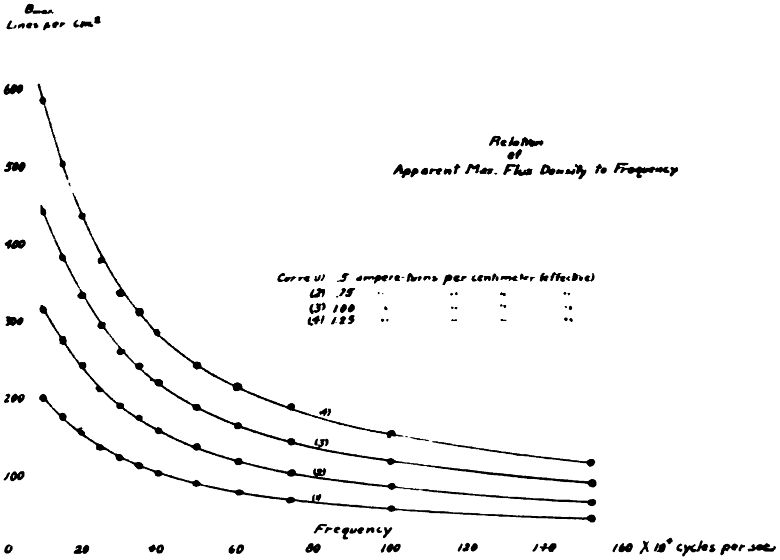

FIGURE 5

DATA AND ERRORS

The accuracy of the instruments (wavemeters, ammeters, and voltmeters) has already been considered. There remains for further consideration the accuracy of the method itself, with possible corrections for certain known errors.

The measurements are shown to be quite consistent by Figures 5 and 6, especially as each point on any one of the four curves represents a new tuning and adjustment of the circuits.

Altho consistent results were secured over the greater part of the range of current values, it was difficult to get consistent readings above 1.5 ampere turns per centimeter. This lack of consistency was not due to the method however, but was due to the changing characteristics of the iron itself, as caused by heating. Both the permeability and resistivity of the iron increase with the temperature which causes a corresponding increase in the apparent permeability. Altho Figures 5 and 6 show consistency in the measurements, they do not show that the results may not be all too large or all too small; that is, they fail to show the presence or absence of consistent errors.

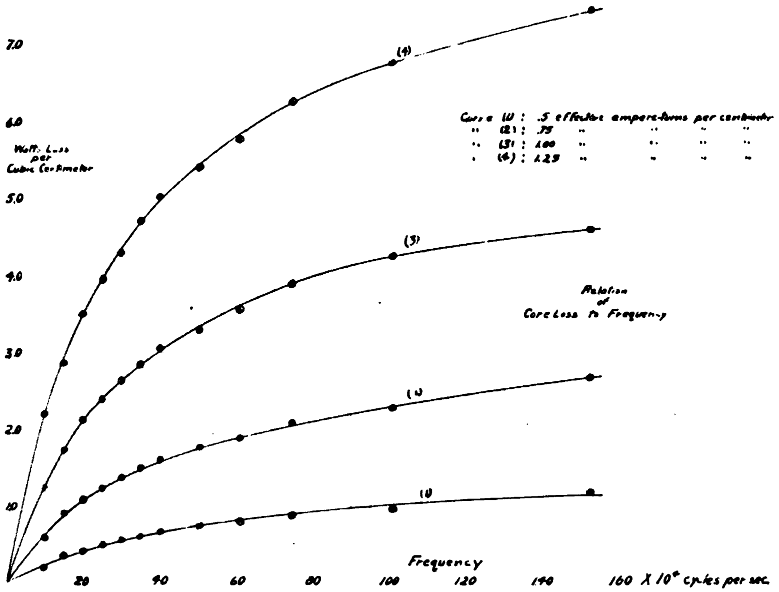

Figure 6

Among the consistent errors here considered are (1) those due to harmonics, (2) those due to the resistance of the winding on the test sample (the losses in this resistance are included in the losses in the test sample as measured), (3) those due to the leakage reactance of the winding on the test sample (the voltage induced in this reactance is included in the voltage measured across the sample), and (4) those errors due to the current taken by the voltmeter.

The following test made at one particular frequency shows at least for this one frequency that the second and third harmonics were very small in magnitude. A wavemeter was coupled with the test circuit and the fundamental wave length was measured. From this measurement the wave lengths of the second and third harmonics were determined.

The wavemeter was set accordingly to test for these two harmonics. No record of this test was made, but as the writer remembers only one of these harmonics was detected and the deflection of the current indicator was very slight. To get even this much indication the wave meter had to be coupled much more closely than it had been for the fundamental. No tests were made for higher harmonics. The foregoing test, coupled with the well-known fact that the harmonics generated by vacuum tube oscillators under average conditions are very small in magnitude, indicates that errors from this source may be neglected.

To find the magnitude of the resistance and leakage reactance of the winding of the test sample, an identical sample was constructed with a core of wood. The voltage across its terminals was measured at different frequencies and currents. These measurements are shown in Figure 7, with the impedance of the sample plotted against frequency. The resistance of the winding is shown to be negligible since the curve of total impedance goes very nearly thru the origin which would be the case if the impedance consisted of reactance alone, since the reactance is proportional to the frequency. The resistance would be expected to be small because litzendraht wire was used in the winding on the sample.

The reactance of the winding is not negligible, especially at the higher frequencies, where the iron is less effective. Here it produces an error of 10 to 15 percent.

Corrections have, therefore, been made in the measurements of magnetization. The corrected values were used for Figure 5.

In making these corrections the phase angle between the voltage induced by the flux in the iron and the voltage induced by the leakage flux was taken into account.

The true leakage reactance of the test sample probably differs somewhat from that measured by means of the dummy sample. However, as the correction is but a small percentage of the value corrected, considerable error in the correction may be entirely neglected.

It might possibly have been better to have used a test sample with a secondary winding and to have measured the voltage induced in this secondary. In this case the reactance drop could be neglected since the voltmeter current is so small. However on the basis of Alexanderson's experience, his method was considered sufficiently accurate and was, therefore, used, but, from the writer's experience, at the higher frequencies especially, the use of the secondary winding is recommended.

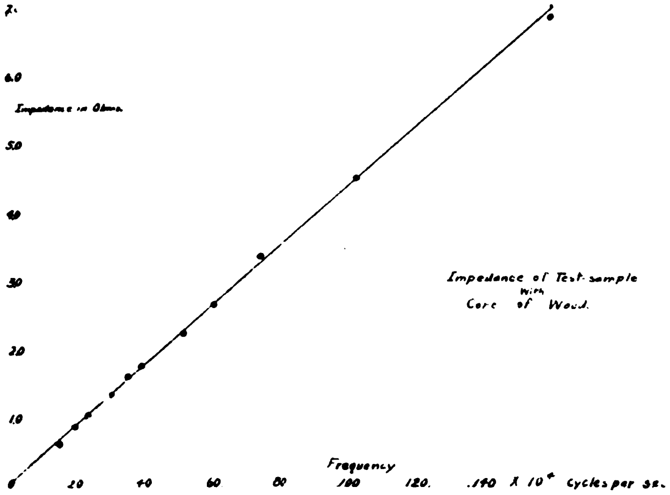

FIGURE 7

In considering the error due to the current taken by the voltmeter, there are two currents to be taken into account. The one is that current flowing thru the heater of the thermocouple, in phase with the voltage being measured. The other is the displacement current flowing between the halves of the shield around the instrument, 90 degrees out of phase with the voltage being measured.

The first current causes the largest error where this current is the greatest percentage of the current thru the sample, which is the case where the voltmeter was used without a multiplier (no multiplier was used for potentials below 3.5 volts), and where the voltage being measured is the highest for a given current thru the sample. Therefore, the maximum error, considering the heater current alone, occurs at the highest frequency, as may be seen from Figure 5, and at the lowest currents used. This maximum error is approximately 2.5 percent. At the lowest frequency the error is about 0.7 percent. Altho this error is appreciable, since it is small and occurs only at the smallest currents used, it has been neglected.

The error due to the displacement current is a maximum at the highest frequencies, since the impedance of the condenser formed by the shields is inversely proportional to the frequency; and at the highest currents, since the voltage across the sample per unit current is here the greatest. From the capacity between the shields, which was found to be about 75 micro-micro-farads,[7] the error calculated for the highest frequency and highest current (Figure 5) was found to be 2.7 percent. As this error, altho appreciable, is the maximum error and occurs only at the extreme limits of frequency and currents used, it has been neglected. Below 750,000 cycles the error is everywhere less than 1 percent, which is entirely negligible.

The error due to the total voltmeter current is a maximum at the highest frequency and lowest current and is equal to about 3.5 percent.

Since the errors due to the current thru the voltmeter are appreciable only at the extreme limits of the measurements, where the accuracy of the results as a whole is the least, these errors have been neglected.

It is the belief of the writer that the accuracy of the results as a whole compares favorably with the accuracy that might be obtained at frequencies of 60 cycles.

CONCLUSIONS

It will be remembered that equations 1 and 2 are based on the assumption of simultaneous sine waves of both the current and flux in the sample, which assumption, of course, holds only over the straight part of the saturation curve. From Figure 8, which shows the radio frequency saturation curves, it may be seen that the iron was not nearly saturated, even at the highest values of magnetization and highest frequency. The assumption in equations 1 and 2, therefore, appears to be justified.

From the curves shown in Figures 8 and 9 data was taken for the curves plotted in Figures 5, 6, and 10, which show, respectively, the variation of losses, apparent flux density, and permeability with frequency.

To calculate the depth of penetration of the magnetism into the iron the following relation has been used by Alexanderson and others:

$$l_p = \frac{1}{2}\frac{\mu_a}{\mu}t \qquad (3)$$

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[7] Measured by the Measurements Group of the Signal Corps Laboratories.

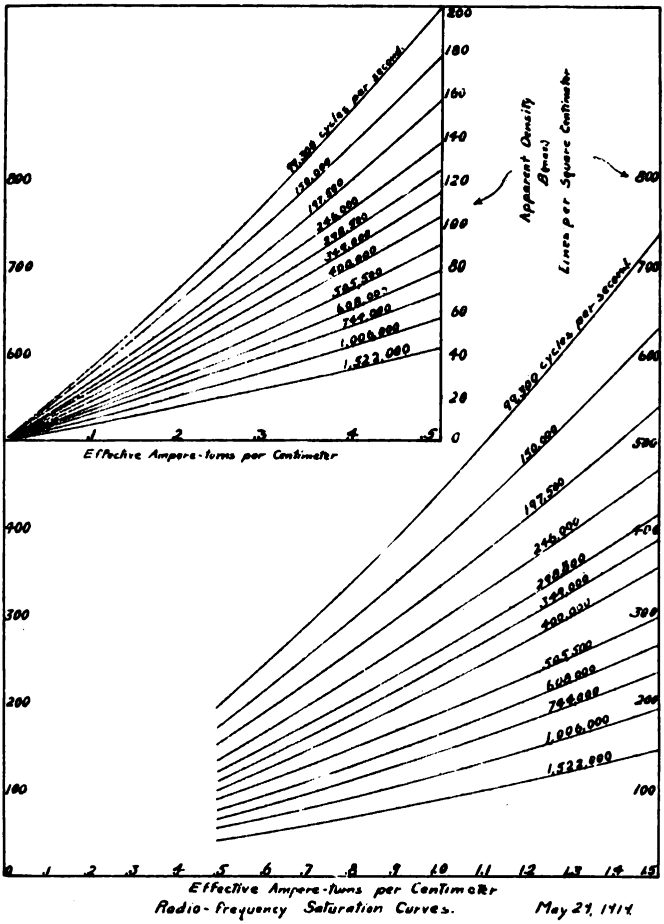
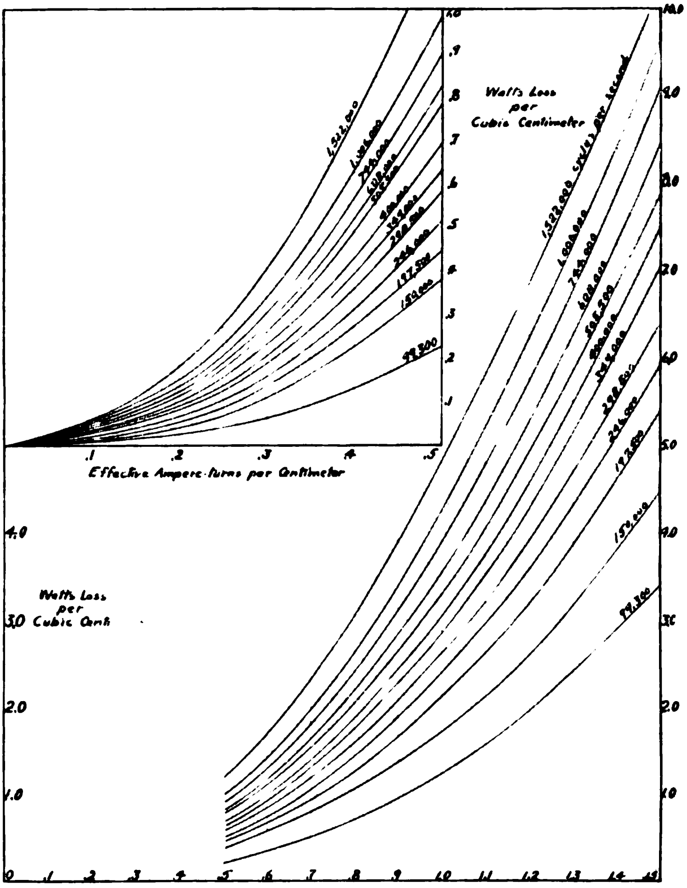


FIGURE 8

where l_p is the depth of penetration, μ_a is the apparent permeability, μ is the true permeability and t is the thickness of each lamination. In this equation the true permeability is considered to remain unchanged at radio frequencies and the apparent permeability is considered to be less than the true permeability for the reason that only a part of the iron is effective. The effective thickness of iron on this basis is equal to $\frac{\mu_a}{\mu}t$. The factor $\frac{1}{2}$ enters equation (3) because the magnetism penetrates both surfaces of the lamination.



Core Loss.

May 29, 1919

FIGURE 9

For μ, a value of 2,250 was assumed, there being no information at hand as to the true value and this being the value used by Alexanderson for thin iron. The depth of penetration as thus calculated is plotted in curve 2, Figure 11.

For comparison the value of penetration was calculated according to Steinmetz's formula:

$$l_p = \frac{3570}{\sqrt{\lambda \mu f}} \tag{4}$$

where λ is the electric conductivity of the iron, μ is the true permeability, and f is the frequency in cycles per second. Here

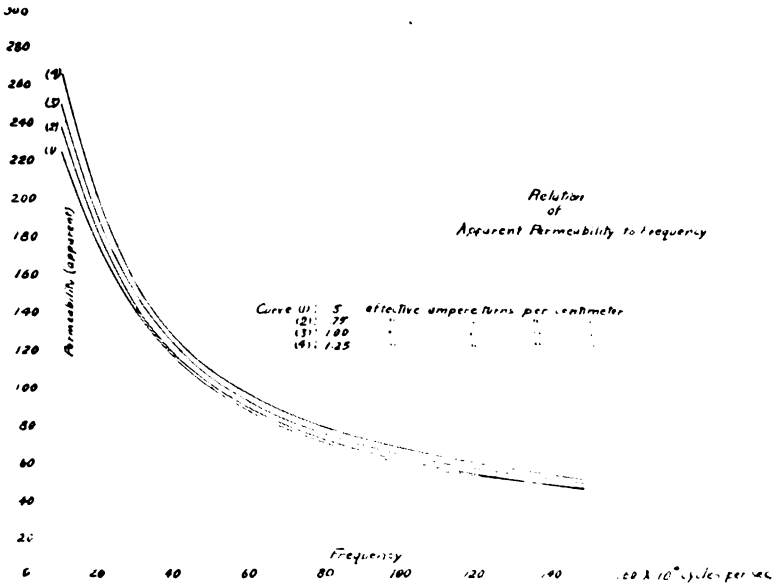


FIGURE 10

again μ was assumed to be 2,250. λ was measured to be $0.67\ (10)^5$. The calculated depth of penetration is plotted in Figure 11.

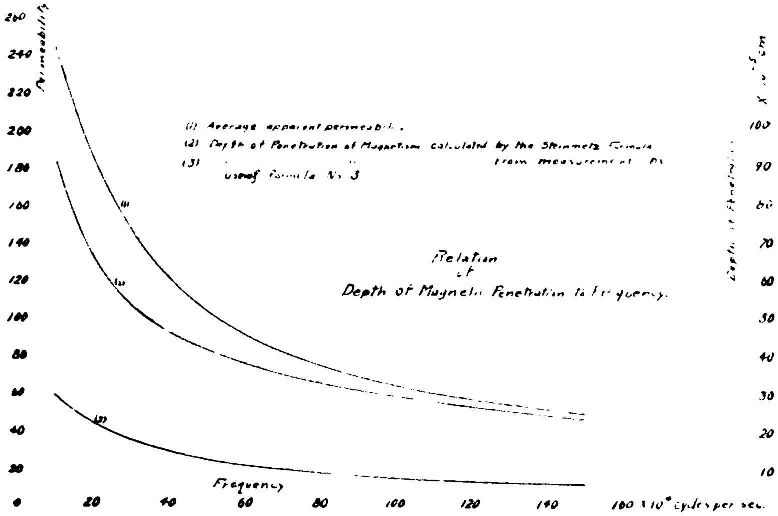


FIGURE 11

This value is seen to be about triple that obtained by the use of equation (3). Alexanderson found a similar discrepancy in the same direction but less in magnitude, and offered as a possible explanation that additional skin effect was caused by the slight gap between laminations in the sample used. This explanation cannot be applied in the present case where each lamination formed a complete magnetic circuit.

The present comparison of equations (3) and (4) is, of course, crude since the value of μ was not measured and ρ was measured from only a single sample about 0.5 inch (1.27 cm.) wide and 2 feet (61 cm.) long (in the direction of rolling). However, it is unlikely that errors in these two factors would account for the entire discrepancy, in which case there must be some other explanation. What this explanation may be the writer is not prepared to state.

At the values of frequency and current where this investigation overlaps that of Alexanderson, a comparison of results shows that about 25 percent (very approximately) higher flux density and core loss in the present investigation.

Assuming that the apparent permeability is inversely proportional to the thickness of laminations, an increase of flux density of about 40 percent would be expected, since Alexanderson used iron 0.0076 cm. (0.003 inch) thick while the writer used iron 0.0054 cm. (0.002 inch) thick. The results, however, are essentially in agreement.

The following observations may be of interest. They were made during the calculation of the corrections made in the magnetization measurements for the leakage reactance of the winding on the sample. The power factor of the sample was involved in these calculations. The power factor was seen to increase with the ampere turns to a marked degree at the lower frequencies, but to a very small degree at the higher frequencies. Also the power factor increases with the frequency and approaches a value of approximately 0.7 at a million cycles. It is interesting to compare this latter observation with Steinmetz's statement: "The lag of the apparent permeability represents an energy component of emf. of self induction due to the magnetic flux, which increases with increasing frequency and ultimately becomes equal to the reactive component."

Since the curves of the depth of penetration show that such a minute depth of iron is actually magnetized, the need for thin iron is strongly emphasized. Also since the depth of penetration increases with the electrical resistivity of the iron, this quantity should be large.

As it is a well-known fact that iron does not lose its permeability at radio frequencies and since there is a growing need for the use of iron at these frequencies, the problem of securing satisfactory iron becomes important. This problem appears to resolve itself into a metallurgical or chemical one: namely that of producing extremely thin iron of high resistivity.

The development and testing of such iron would be a very interesting problem for future research.

The development of formulas for the calculation of flux densities and losses at various frequencies and magnetizing forces and for different kinds and thicknesses of iron also offers a most interesting and practical field for future research.

For such investigation the standardization of the dimensions of the test sample is desirable.

SUMMARY: Mild steel ribbon, 0.002 inch (0.05 mm.) in thickness, was tested at various radio frequencies between 100,000 and 1,500,000 cycles per second for the relation between ampere turns per centimeter and flux density, and for core loss in watts per cubic centimeter at the various frequencies. A vacuum tube oscillator supplied the necessary current for magnetizing the ring samples of steel. The method of measurement required the development of a precision radio frequency voltmeter, which is described in detail. All the results obtained are shown in graphic form.

APPENDIX

THE OSCILLATOR

(1) Filament Battery Potential, 10 volts.

(2) Filament Rheostat Resistance, 2 ohms.

(3) Grid Leak Resistance, 1,000 to 30,000 ohms in 1,000-ohm steps.

(4) The grid and plate condensers were approximately equal in their capacities, which ranged from 0 to 30,000 $\mu\mu$f. each by means of 6 Dubilier mica condensers of 5,000 $\mu\mu$f. each.

(5) Range of hot-wire ammeter A_2, 0 to 15 amperes.

(6) The primary of the oscillation transformer consisted of 24 turns of litzendraht wire (size: 32 strands of number 38 wire) wound on 6.75 inches (17.1 cm) of bakelite cylinder 8.25 inches (2.1 cm.) long and 10 inches (25.4 cm) in diameter. Taps were brought out for each turn.

(7) Source of plate current. The source of plate current was two Westinghouse motor generator sets shown in Figure 1. For small values of power one of these was used alone. For

high values the machines were connected in series, in which case a voltage of 900 or 1,000 volts was impressed on the tubes.

(8) The vacuum tubes used were Signal Corps type, VT 12. This type of tube was used because of its ability to stand overloading. These tubes will operate with their plates white hot without gas appearing.

THE TEST CIRCUIT

(1) The secondary of the oscillation transformer consisted of 24 turns of litzendraht wire (size: 32 strands of number 38 wire) wound on 6.75 inches (17.1 cm.) of a bakelite cylinder 8.25 inches (21.0 cm.) long and 8.5 inches (21.6 cm.) in diameter. Taps were brought out for each turn.

(2) Condenser C_1, 500 to 25,000 $\mu\mu$f.

(3) Range of hot-wire ammeter A, $0-0.3$ amperes, $0-0.6$ amperes, $0-1.0$ amperes, and $0-3.0$ amperes.

(4) The Variometer L.

(a) The first variometer used consisted of a stationary cylinder 1.37 inches (3.49 cm.) long and 3.06 inches (7.73 cm.) in diameter wound with 20 turns of litzendraht wire (size: 32 strands of number 38 wire) and a rotating cylinder 1.37 inches (3.49 cm.) long and 2.18 inches (5.56 cm.) in diameter wound with 20 turns of the same size litzendraht as the stationary coil. The two coils were connected in series and the impedance of the variometer was varied by rotating the secondary with respect to the primary.

(b) A second variometer having a smaller minimum impedance than the first consisted of an outer and stationary cylinder 0.75 inch (1.91 cm.) in length and 5.0 inches (12.7 cm.) in diameter wound with 8 turns of litzendraht wire (size as before). The inner rotating cylinder was 0.75 inch (1.91 cm) long and 4.25 inches (10.8 cm) in diameter. It was wound with 10 turns of litzendraht wire (size as before).

(c) For the highest frequencies where the inductance of the test samples become very small this latter variometer was changed to 3 turns on the stationary coil and 5 turns on the secondary.

(5) Condenser C_2, 3,000 to 100,000 $\mu\mu$f.

(6) Voltmeter V Ranges: 1.0 to 3.4 volts (no multiplier), 3.0 to 10.5 volts low range of multiplier, 8 to 27 volts middle range of multiplier, and 17 to 60 volts high range of multiplier.

TEST SAMPLE

ANALYSIS OF STEEL—An analysis of steel similar to that used for the test sample is as follows:

	Percent.
Carbon	0.09
Silicon	0.025
Molybdenum	0.006
Phosphorus	0.004
Titanium	Trace
Chromium	Trace
Vanadium	None
Nickel	None

This analysis was made by Professor Frank W. Durkee, Tufts College, Massachusetts, for the American Radio and Research Corporation, Medford Hillside, Massachusetts. Thanks are due Dr. V. Bush for the use of this material.

DISCUSSION

N. W. McLachlan (by letter): In the preface to Mr. Wilson's paper, it is stated that the data are new. The actual numerical values for a certain thickness of iron and a certain range of frequency are undoubtedly new, but no new facts have come to light regarding the behavior of iron at high frequencies. From the absence of references in the paper, one would conclude that no investigations had been conducted on the behavior of iron at radio frequencies since Mr. Alexanderson's brilliant experiments of 1911. This, however, is not the case. The "Year Book of Wireless Telegraphy," for 1918, contains a complete résumé of work on iron at radio frequencies under undamped oscillations, up to October, 1917, together with a list of 45 references. Since this article was written, work on the same subject has been published in France and in Germany. In the "Journal of the Institution of Electrical Engineers" for April, 1916, a paper is published giving details of experiments on iron of different quality and thickness up to frequencies of 10^6 cycles per second. At that time the thinnest material available in England was 0.25 millimeter (0.01 inch).

Mr. Wilson's results are probably quite accurate enough for most practical purposes, for it is seldom, if ever, that iron is used in practice under the same conditions as those which hold in the laboratory. I am, however, not prepared to agree with the statement in which he claims the same order of accuracy at frequencies of a million as at 60 cycles per second. A calibration of hot wire ammeters by direct current is no guide to their behavior at radio frequencies. The current measurements could have been carried out to a high degree of accuracy by using an iron-cored current transformer[1] and a thermo-ammeter. It is possible to calibrate accurately the current transformer at radio frequencies by using a separate heater, thermo-junction and a sensitive direct current galvanometer.[2] I have built current transformers with errors less than 1 percent at frequencies from 10^5 to 10^6 cycles per second.

Mr. Wilson has found the usual discrepancy between the calculated and experimental values of the depth of penetration of magnetization, or as it is frequently termed, the "equivalent depth of uniform magnetization." The reason for the difference is probably due to the fact that the resultant magnetizing force operative on the iron decreases from the skin to the centre of the

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[1] "Electrician," December 22, 1916; "Wireless World," July, 1917.

[2] "Proceedings of the Royal Society of London," 1914.

plate. Thus the flux density, as is well known, decreases from the skin to the centre, since the so-called "true" permeability of iron varies with the flux density. It follows, therefore, that the "true" permeability varies from the skin to the centre. Moreover, the propagation of the flux waves within the iron, and the shape thereof, is quite different from that contemplated in the mathematical analysis, in which the permeability is assumed constant thruout the plate. Even when the phase displacement due to hysteresis is taken into account (with constant permeability), the discrepancy is still large. When the variation in permeability is considered, the variable hysteresis loss at different depths complicates the problem still further.

The question of a sinusoidal current wave giving rise to a sinusoidal voltage wave is a point which can be settled only experimentally. At low frequencies there is considerable distortion of the voltage wave form, and at high flux densities the wave is very peaked.[3] In this respect it would be extremely interesting to see exactly what does happen at high frequencies. Such an investigation could be conducted by using an apparatus similar to that developed by the French military authorities and known as the Dufour cathode ray oscillagraph. This instrument has been used to record oscillations of 7.5×10^5 cycles per second, generated by triodes.

Leon T. Wilson (by letter): In Dr. N. W. McLachlan's discussion, it is stated that "the actual numerical values for a certain thickness of iron and a certain range of frequency are undoubtedly new, but no new facts have come to light regarding the behavior of iron at high frequencies." This interpretation of my statement, that the *data* are new, is the correct and only one which I thought would be made. The chief novelty consists in the voltmeter employed and not in the data obtained, which are offered only as being of some possible general interest.

From the absence of any, except the necessary references in my paper, Dr. McLachlan would draw the conclusion that no investigations had been conducted on the subject since the experiments of Mr. Alexanderson in 1911. My paper, as may be seen from the first sentence of the preface, is not intended to be a historical résumé of all work previously done on the subject. The need for such a résumé was so well fulfilled by Dr. McLachlan's own paper contained in the "Year Book of Wireless Teleg-

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[3] "Journal of the Institution of Electrical Engineers," June, 1915.

raphy," for 1918, that I considered it entirely unnecessary even to attempt to add anything further.

Objection is made, and not without grounds, to my statement that the accuracy of the results as a whole compares favorably with the accuracy that might be obtained at frequencies of 60 cycles. Here I had in mind the accuracy of measurements as they are very generally made at 60 cycles, and not that accuracy which it is possible to obtain in the laboratory under the best conditions. That is, the statement should not be interpreted as claiming a high degree of accuracy.

Dr. McLachlan has made some interesting comments concerning current measurements, using an iron-cored transformer and thermo-ammeter. The use of such a refinement in the current measurement in the present investigation, without having gone to similar refinements thruout, which would have been rather difficult in view of the changes in the properties of the iron with changes in temperature, reminds one of the old adage about "straining at a gnat and swallowing a camel."

Dr. McLachlan's explanation of the usual discrepancy between the calculated and experimental values of the depth of penetration is constructive and of general interest. The reason for bringing out this point in the paper was to show that the discrepancy could not be explained as due to the presence of an air gap in the test sample.