# AN ELECTRON TUBE TRANSMITTER OF COMPLETELY MODULATED WAVES

By Lewis M. Hull

The electric waves used in radio transmission are sometimes classified as undamped or continuous, and damped or interrupted waves. A more fundamental classification would separate radio-frequency waves into the two general types: Unmodulated, which are always continuous, and modulated, which may be continuous or discontinuous. Under the first group come the single frequency, sinusoidal oscillations which are obtained under certain operating conditions from a simple electron tube oscillator, and the constant amplitude but uniformly distorted waves of arc transmission, which can be resolved into the sum of a radio-frequency fundamental oscillation and a number of frequencies which are integral multiples thereof.

All modulated waves can be thought of as a single radio-frequency whose amplitude is a function of time which may be periodic, as in the case of a "sine-modulation" and spark transmission, or which may be irregular, as in the case of voice modulation (radio telephone), and which in any case can be expressed by the sum of a constant term, an audio-frequency fundamental and a series of audio-frequency harmonics. The audible response of a detector to modulated radio-frequency oscillations depends upon the degree of modulation. In the case of spark transmission this means that the response depends, to a certain degree, upon the maximum amplitude of the radio-frequency constituent, since the radio-frequency is always completely modulated; that is, periodically reduced to zero.

In order to utilize a radio-frequency oscillation of given power most effectively in a nonoscillating receiving system it must be completely modulated, the periodic reduction to zero occurring at a suitable audio frequency. Radio-frequency harmonics, manifested by distortions in the shape of the radio-frequency or carrier wave, limit the total power radiated by a transmitter at the

single frequency to which the receiver is tuned. Audio-frequency harmonics, manifested by distortions in the envelope of the radio-frequency oscillations from sinusoidal form, determine the response of any amplifying and rectifying detector.

There are two possible methods of operating an electron tube generating system so as to furnish a completely modulated output: (1) The use of a direct supply voltage in connection with a mechanical interrupter or "chopper," which periodically breaks the supply circuit, causing the antenna current to be reduced to zero; (2) the use of an alternating audio-frequency supply voltage. If the frequency of the supply voltage be $F$ and the peak value be $E_b$, then the plate is positive with respect to the filament $F$ times per second while the supply voltage rises from $O$ to $E_b$ volts, and negative $F$ times per second while the supply voltage falls from $O$ to $-E_b$ volts. The antenna current is maintained for a half cycle when the plate is positive and is reduced to zero a greater part of the half cycle when the plate is negative.

The first method requires a source of high direct voltage which may be inconvenient if high-power tubes are used. With the second method the whole system can be operated from any audio-frequency generator with suitable transformers for the high-voltage plate and the relatively low-voltage filament. The note produced by telephone receivers actuated by the rectified output from the transmitter corresponds to the frequency $F$. Consequently a desirable value for $F$ would be 800 cycles per second, since most audio-frequency receiving apparatus is designed for best operation at about that frequency. If no 800-cycle generator is available, a 500-cycle machine can be used.

No power is taken from the plate supply transformer when the plate is negative. Power is consumed by the tube while the plate voltage varies from zero to the peak value of the alternating voltage. When the tube is operated over such a wide range of plate voltages, the usual square relation between plate voltage and output power does not hold throughout the whole range, and the adjustment of transmitter circuits for maximum output can be obtained only by trial and not by calculation from theoretical considerations.

A transmitter of this description has been designed and built at this Bureau. The set fulfills the following requirements: (1) Use of a single, type "P" pliotron, with a 500-cycle, 150-volt alternator; (2) power output exceeding 200 watts in an antenna having 8 to 15 ohms resistance and a natural wave length below

200 m; (3) a readily adjustable range of wave lengths from 500 to 1000 m; (4) transmission of completely modulated waves, making possible their reception with crystal detectors; (5) sharply tuned waves in order to avoid excessive interference over long series of tests. The set has been used in fog-signalling and direction-finding experiments, and in transmission tests carried out as part of an investigation of wave propagation.

In designing the set the average power output in a given antenna was taken as the criterion of its merit as a transmitter of radio waves. The *form* in which the power is radiated determines to a large extent what type of receiving circuits should be employed to utilize this power effectively. However, if it be understood that an appropriate receiving circuit is to be used, the rms current output in an antenna of given radiation resistance at a given wave length determines the merit of any transmitter of modulated or unmodulated waves. (There is, of course, an exception to this statement in the case of radiotelephone signals, in which the interpretation of the signal depends upon the kind and degree of modulation.)

There are no sound theoretical reasons why a transmitting system with sinusoidal supply voltage can not be adjusted to maximum current output using either a capacity coupled, direct

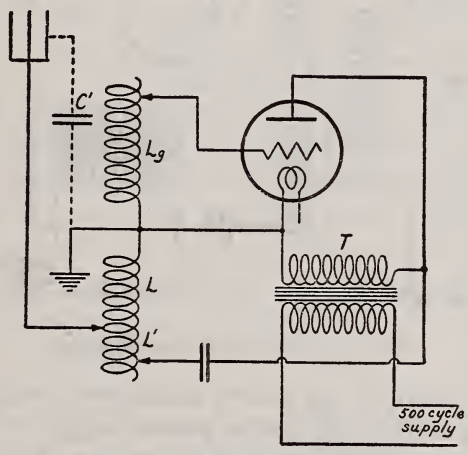


FIG. 1a.—*Direct-coupled circuit*

coupled, or inductively coupled generating circuit. However, it was found experimentally, with 500-cycle power supply, that any inductively coupled circuit, either with series or with parallel power supply was equally suitable and conveniently adjustable. Fig. 1, (*a*), (*b*), and (*c*) show the essential connections of three circuits which were found to be serviceable.

In all three figures $T$ is the 500-cycle supply transformer furnishing the alternating plate voltage and $C'$ is the total effective capacity of the oscillatory (antenna) circuit.

Fig. 1, (*a*) shows a direct-coupled circuit with parallel power supply. The secondary of the supply transformer, $T$, may furnish a sufficient choke for the radio-frequency plate current. In some transformers the distributed capacity of the secondary winding is so great as to by-pass the radio-frequency plate current, and a radio-frequency choke coil must be inserted in series with this winding. $C$ is a stopping condenser with negligible radio-frequency reactance; it should be noted that it is possible to approach 500-cycle resonance in the circuit formed by the secondary of the transformer, $T$, the condenser, $C$, and the plate coupling inductance, causing an alternating voltage to be applied between plate and filament much higher than the secondary voltage of the transformer. This condition may be disastrous for the tube if it is not taken into account in determining the transformer ratio.

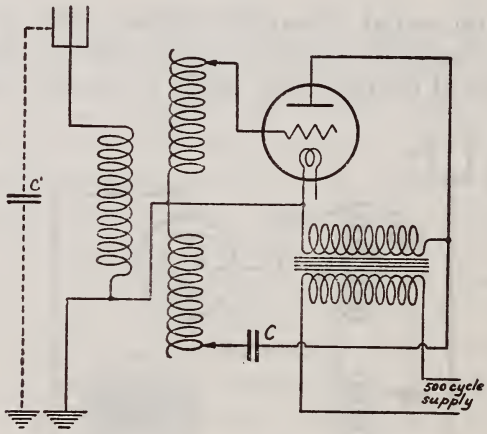


Fig. 1*b*.—*Inductively coupled circuit*

In Fig. 1, (*b*) and (*c*) are shown inductively coupled (Meissner) circuits with parallel and series power supply. In the case of series power supply the condenser $C$ acts as a by-pass condenser, and its 500-cycle reactance should be large, unless audio-frequency resonance is required to build up the supply voltage. In every case one side of the secondary of the supply transformer is grounded.

For convenience in shifting wave lengths and adjusting to maximum output the inductively coupled circuit with parallel power supply has been used extensively. It is found necessary, in any

case, with high effective values of supply voltage, to make the coupling of the antenna circuit with the plate circuit much greater than its coupling with the grid circuit, for maximum output. Since a certain minimum value of grid voltage must be fed back into the tube to sustain the oscillations, this necessitated the use, with the direct coupled system, of a large number of turns in the plate-filament circuit. In a transmitter used at relatively short wave lengths, only a few turns can be included in the antenna circuit, and the plate coupling must be supplied largely by mutual inductance between the antenna coil and the inductance $L'$ (Fig.

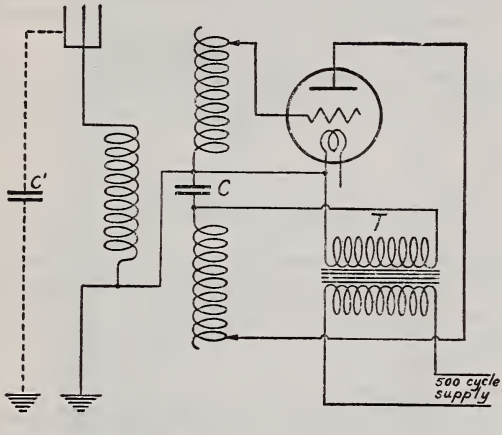


FIG. 1c.—*Inductively coupled circuit*

1, (*a*) ). If the Meissner circuit be used, the antenna coil can be made entirely separate from the coupling coils and can be placed around them, giving a higher mutual inductance per turn of the plate coupling coil than if the antenna, plate, and grid inductances were of the same coil. It was found also that the plate and grid coupling could be varied separately, or together, without changing appreciably the wave length of transmission; similarly, the wave length could be varied without changing the relative coupling values.

Fig. 2 is a diagram of connection of the final form of this transmitter as put into service at Windmill Point Light, Chesapeake Bay. Attention is called to Figs. 3 and 4, showing the set completely assembled. It should be stated in connection with these photographs that this particular set was assembled upon a panel designed for a different purpose and might have been constructed in much more compact form. Below are given the dimensions and details of construction of the various parts. The letters refer to Figs. 2, 3, and 4.

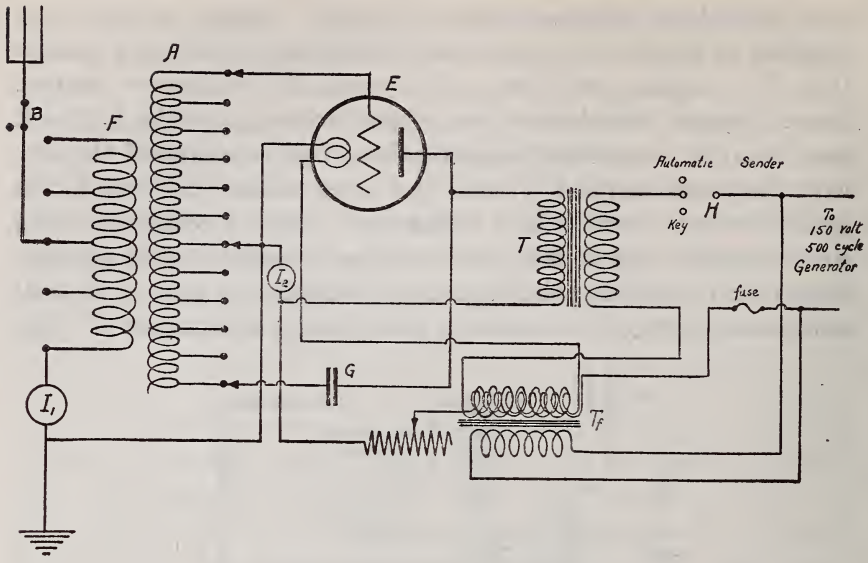


FIG. 2.—*Complete transmitter connections*

*A*, Plate and grid coupling coils; continuous coil wound on fiber tube 5½ inches in diameter; 80 turns No. 18 solid wire spaced one-eighth inch apart; end taps brought out every 5 turns on grid side and every 10 turns on plate side of coil.

*B*, Antenna switch.

*D*, Generator field rheostat.

E, Electron tube, type *P* pliotron.

*F*, Antenna coil; 30 turns, litzendraht, wound on fiber tube 6⅜ inches in diameter; taps brought out every 2 turns; mounted so as to slide over coupling coil in order to vary mutual inductance.

*G*, Stopping condenser; mica; $C = 0.004\ \mu f$.

*H*, Automatic sender, driven by direct-current motor, which is supplied from the field circuit alternator.

$I_1$, Antenna ammeter.

$I_2$, Filament ammeter.

*R*, Filament rheostat.

*T*, Supply transformer, 2 kva.; ratio of turns 40/1; full-load voltages 160/6500.

$T_f$, Filament transformer, special construction, shown in detail in Fig. 5. The main windings consist of 200 turns No. 16 d. c. c. wire on the primary side, connected across the 180-volt supply, and 120 turns No. 16 d. c. c. wire on secondary side, connected to filament circuit.

Owing to the fact that the 500-cycle voltage, when using a 2 kw alternator, dropped enough to decrease the filament current by as much as 15 per cent when the load was thrown on in the plate circuit, it was found necessary to include in the filament transformer a series compensating winding. This is rendered doubly imperative by the fact that when operating a tube at high plate voltage, the power output changes to a much greater extent with slight changes in emission than when operating at lower plate voltages. The system is always kept adjusted for maximum out-

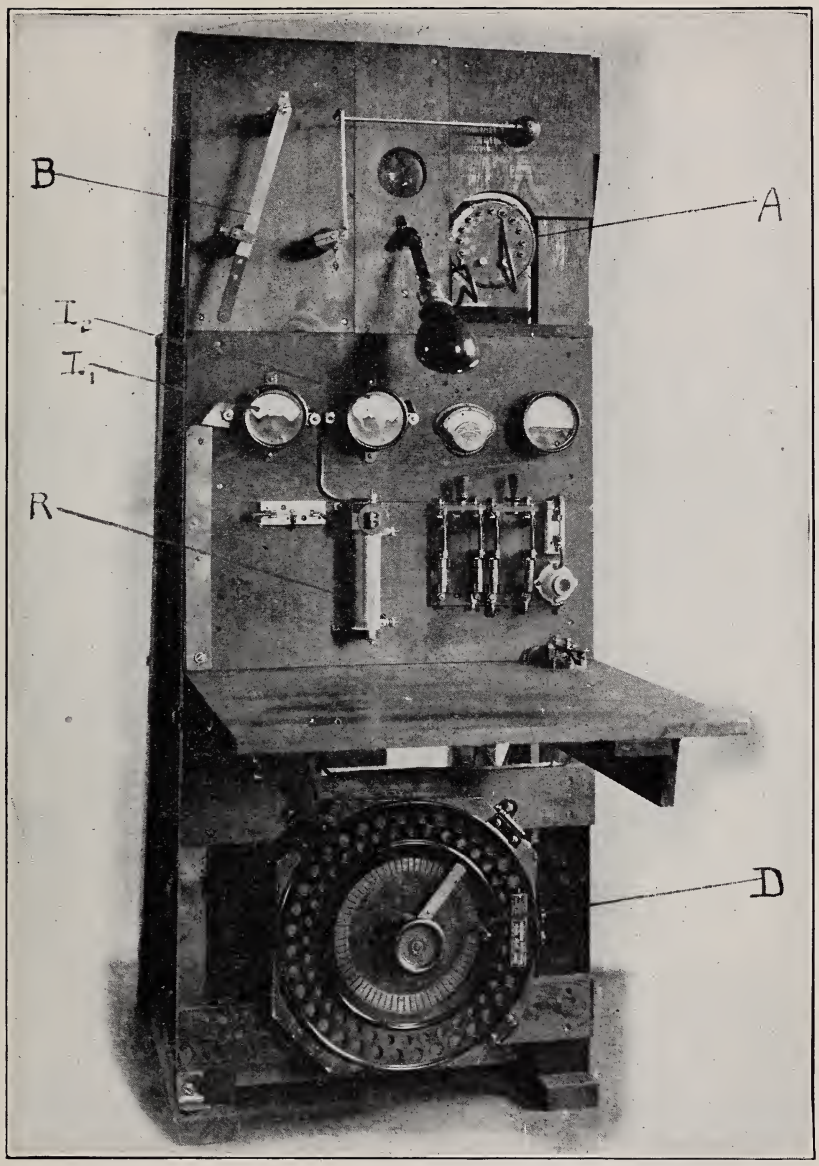


FIG. 3.—*Transmitter, front view*

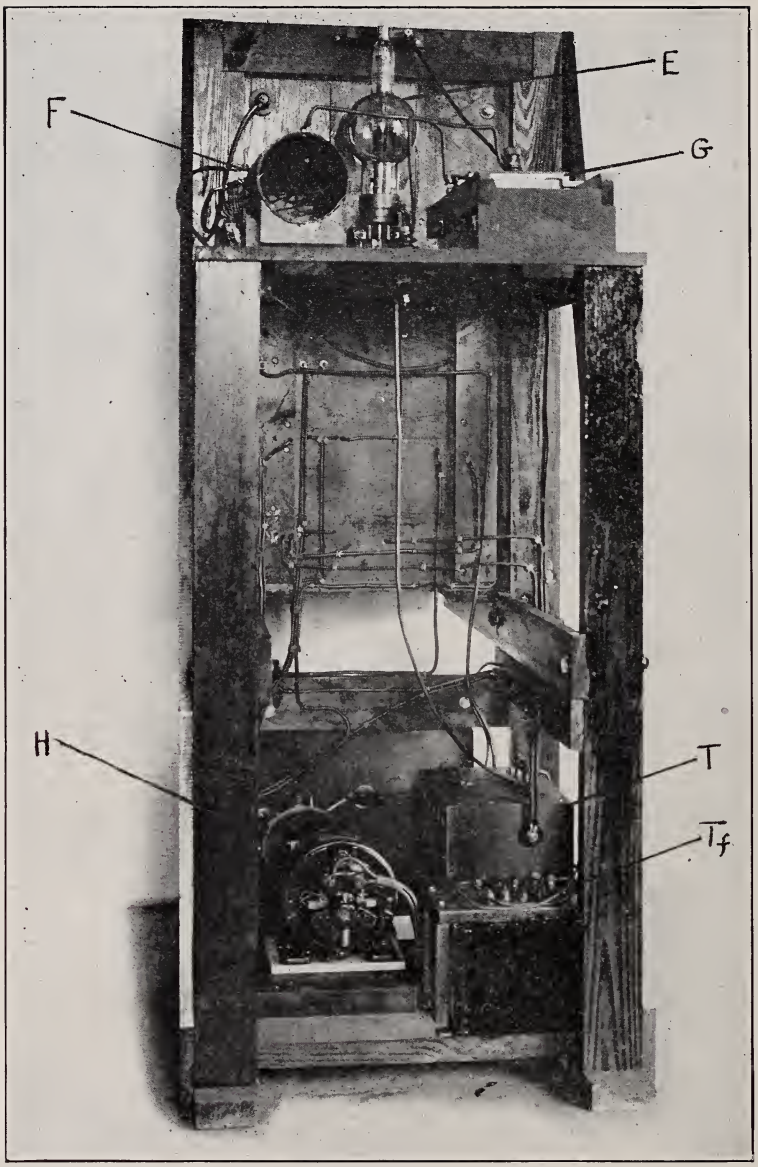


FIG. 4.—*Transmitter, rear view*

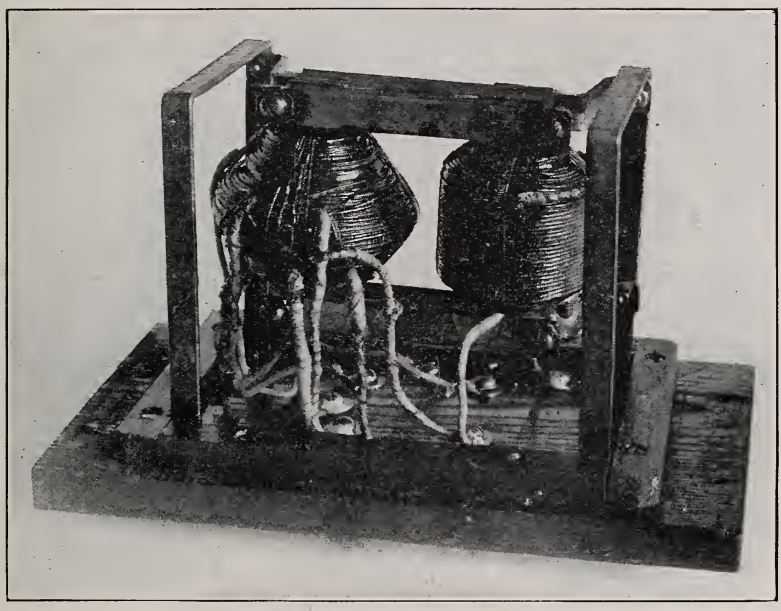

FIG. 5.—*Filament-circuit transformer*

put at the maximum safe filament current, $I$, rms[1] = 3.6 amperes, and even a slight decrease in this current decreases the power output considerably, and the current output to a corresponding extent. In order to be able to adjust this transformer to give suitable compensation for the drop in primary voltage, and still be able to use it at different values of generator voltage, when it is found desirable to transmit at reduced power, it is necessary to make the number of turns in the compensating winding adjustable. The compensating winding of the transformer shown in Fig. 5 is composed of 100 turns No. 16 d. c. c. wire, with a tap every 12 turns from 30 to 100. The filament rheostat makes it possible to adjust the filament current for any steady value of primary voltage on the transformer; the series compensating winding makes it possible so to adjust the transformer to the supply circuit that the filament current reaches a safe maximum when the load is thrown on. If sufficient power is available from the generator, it is advisable to overcompensate the transformer, making it possible to heat the filament at reduced current except when the key is pressed.

The transmitter described in this paper was designed to operate at short wave lengths. The performance of such a system at short waves is limited by two factors, first, the electrostatic capacity between elements of the electron tube, which may provide a reactive shunt for the oscillatory circuit; second, the approximate linear relation between power output, resistance, and capacity. Consider any short portion of the wave train when the amplitude of the supply voltage may be considered constant so far as the radio-frequency oscillations are concerned. It has been shown[2] that the output power is given for any tube by

$$P_o = \frac{1}{R}\frac{L}{2C} f(P_o)$$

where $R$, $L$, and $C$ are the resistance, inductance, and capacity of the antenna and $f$ is a function which depends upon the characteristics of the tube and upon the plate and grid coupling. Over a certain range of operation the function $f$, which involves the oscillating grid voltage as dependent upon the antenna current and coupling, is found to be a direct linear function. Then the output power varies inversely with the antenna capacity and with the antenna resistance. Assuming constant $L$, since a change in $L$ involves a change in the function $f$, it is evident that if $C$ is

[1] rms=root mean square.

[2] B. S. Scientific Paper No. 355.

made small, as is the case at short wave lengths, $R$ must be increased, in order to obtain maximum output. It may be impossible to obtain maximum output from a tube in a given antenna of low resistance at short wave lengths, particularly in view of the fact that the total effective resistance decreases with increasing frequency.

The following table gives a record of the performance of the set at short wave lengths supplying an antenna having a capacity of approximately 0.004 $\mu$f and a resistance, at 500 m, of 10 ohms. In the column "Power output" it is assumed that this resistance remained constant from 600 to 420 m, which is not a particularly rash assumption, since the antenna was of such short natural period as to make the radiation resistance a small part of the total. The procedure of the test was to maintain a constant antenna capacity and change the wave length by varying the antenna inductance, adjusting the maximum output by changing the coupling.

| Wave length | Input | Rms filament current | Antenna current | Power in antenna | Overall efficiency transformer to antenna inclusive |
|---|---|---|---|---|---|
| | Watts | Amperes | Amperes | Watts | Per cent |
| 600 | 1000 | 3.5 | 5.1 | 286 | 35 |
| 525 | 1300 | 3.5 | 5.0 | 275 | 21 |
| 480 | 1120 | 3.5 | 4.0 | [a]176 | [a] 15.7 |
| 420 | 1100 | 3.5 | 2.9 | [a] 93 | [a] 8.5 |

[a] Approximate.

It should be noted that the power input and efficiency as computed include the power expended in the filament and filament transformer. The efficiency at 600 m from alternator output to antenna output is remarkably high for a tube system. No data are available on the efficiency of the tube alone, as ordinarily computed in terms of input to the plate and output in the antenna. It was impossible to adjust the coupling so as to obtain maximum output at the shorter wave lengths.

## TRANSMISSION AND RECEPTION TESTS

If the signals from this transmitter are to be received by heterodyne methods, the emitted radiation is a close approximation to an undamped wave as far as the radiation characteristics are concerned. Consider, for purposes of discussion, that the amplitude of the output current from the tube is proportional to the plate

voltage when the plate is positive. Then the antenna current will be of the form

$$I_a = I \sin \frac{\omega t}{K} \sin \omega t$$

for a half cycle and zero for the succeeding half cycle, $\omega$ being the angular frequency of the radio oscillations and $K = \frac{\omega}{2\pi F}$, the ratio of radio to audio frequency. The frequency components of the antenna radiation which are most effective in a tuned receiver are those to which the receiving antenna is resonant. Radio side frequencies or radio harmonics are effective to a smaller degree, depending, of course, upon their proximity to the fundamental or resonant frequency of the receiving circuit. Consequently, any radiating system is more effective, the greater the amount of energy radiated at a single frequency.

The modulated wave described above can be expressed as the difference between two radio frequencies

$$I_a = I/2 \left[ \cos\left(\frac{K-1}{K}\right)\omega t - \cos\left(\frac{K+1}{K}\right)\omega t \right]$$

which are separated by the slight fraction, $2/k$, of the radio-frequency. At 500 cycles and 600 m this amounts to $\frac{1}{500}$, and as far as any ordinary receiving circuit is concerned the energy can be said to be radiated at a single frequency.

The logarithmically modulated wave trains radiated from a spark transmitter are emitted at an infinite number of radio-frequencies, the broadness of the emission curve being determined by the damping of the wave trains. Thus from the standpoint of the transmitter, the power is radiated at a much smaller band of wave lengths from the tube transmitter than from a spark transmitter of equal power.

In substantiation of these statements the following tests are cited:

Signals from this set, which supplied 5 amperes rms, antenna current to an antenna approximately 50 feet high in Washington were copied at a distance of 100 miles by using an antenna 60 feet high, with an audibility of 10 000, using an autodyne receiving circuit with a two-step audio-frequency amplifier. Signals from this set working under the same conditions were received through heavy interference by using a 6-foot coil aerial and a similar detector and amplifier at a distance of 225 miles.

On the other hand, this type of modulated radio frequency is not suited for reception with a simple nonoscillating detector.

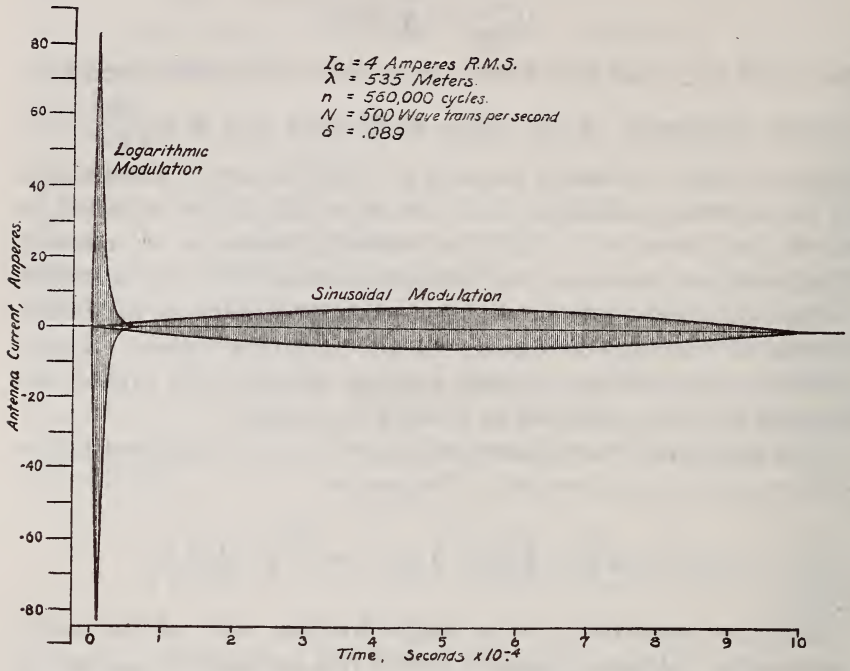


FIG. 6.—*Comparison of wave trains from spark and tube transmitters*

The voltages induced in a receiving antenna by a logarithmically modulated wave will give a response on the output side of the detector greater than that induced by a sinusoidally modulated wave train radiated from antennas in which the rms antenna current is the same, provided always that we confine our attention to short wave lengths. The truth of this statement has been proven experimentally by direct comparison of two such transmitters. It is beyond the scope of the present paper to discuss quantitatively the effects of sinusoidally and logarithmically modulated wave trains upon receiving antenna with rectifier and phones. However, a possible reason for such a behavior is suggested by the accompanying diagram, Fig. 6, upon which are plotted *to the same scale* the envelopes of spark and sinusoidally modulated wave trains emitted by two transmitters operating at 500 cycles and supplying the same antenna with the same rms antenna current. Although the logarithmically modulated wave train persists only about one-twelfth as long as the sinusoidally modulated wave train, yet it rises to a peak value over 13 times

as great. In order to give some idea of their relative number of radio-frequency oscillations per cycle the vertical lines have been so spaced that each one represents a complete radio-frequency cycle.

It is not to be inferred from this diagram that the trains of voltage waves applied to the rectifier in a receiving circuit have an envelope precisely similar to the exponential envelope shown here for the wave train transmitted from the spark set. Nor should the assumption be made that diaphragms of the receiving telephones when acted upon by a strong voltage impulse lasting for one ten-thousandth of a second are distorted a proportionately greater amount than when acted upon by a weak impulse lasting for one-thousandth of a second. Undoubtedly, however, the voltage impacts acting upon the telephones are very much the more intense, though lasting for a shorter time, with the wave train of higher peak value, and it is possible that this is the correct explanation of the louder signal furnished by the logarithmically modulated wave train with simple rectifying detector. If the same power be radiated at long wave lengths, it is quite possible for the peak value of the logarithmically modulated wave trains to be so reduced in magnitude that the average value of their square (which is the measure of the output voltage of the detector) is equal to or even less than similar values for the sinusoidally modulated waves. It is likely also that if the wave lengths of transmission be sufficiently increased, the same results in receiving the signals with a rectifying detector can be obtained with the tube transmitter as with a similar spark transmitter.

In Fig. 7 are shown current-time curves of the actual output current in an antenna excited by the tube transmitter described above. These curves were obtained with a cathode-ray oscillograph in the following manner: Vertical deflections of the cathode beam were made proportional to the instantaneous antenna current by passing this current through suitable deflecting coils placed near the tube. Horizontal deflections were made proportional to the 500-cycle voltage by connecting the electrostatic deflection plates across the supply line.

By making a suitable adjustment of the phase of the deflecting voltage with respect to the radio-frequency wave train, it was thus possible to obtain a figure on the screen showing these oscillations throughout an audio-frequency half cycle, whose ordinates were proportional to the instantaneous antenna current, and

whose abscissæ were proportional to sine $(2\pi \times 500t)$. Those photographs were carefully developed to scale, making the abscissæ proportional to the time in seconds, as shown in Fig. 7.

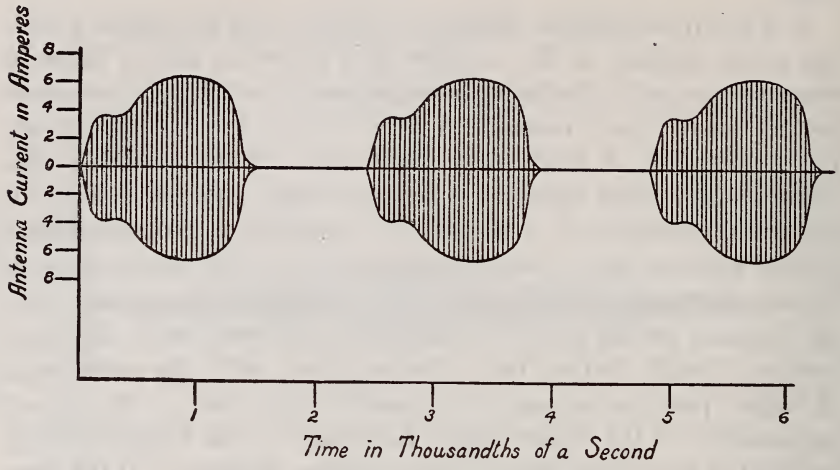


FIG. 7.—*Oscillograms of antenna current*

In copying the figures it was impossible to draw in the radio-frequency oscillations, so separate vertical lines are included, each to represent 15 complete radio-frequency cycles.

It can be seen that in actual practice the envelope of the antenna current is far from sinusoidal. Also, the wave train persists with the damping of the antenna after the tube has ceased to supply power. It was found that a decrease in either plate voltage or filament emission—that is, in power supplied to the antenna—resulted in a contraction of the peak on the latter half of the wave train; an increased emission from the filament, or closer coupling between the antenna and the plate circuit resulted in an increase in height of this peak without a corresponding increase in amplitude of the first group of oscillations. In no case was it possible to adjust the tube circuit so as to obtain maximum antenna current at the peak value of the supply voltage or approach more closely a sinusoidal envelope.

In summarizing the foregoing discussion the following essential points appear: (1) It has been found that an electron tube transmitter operated wholly from an alternating-current source can be made to compare favorably in operating efficiency with a similar transmitter operated from a direct-current source; (2) it possesses the advantage of not requiring a high-voltage generator or battery; (3) the added advantage over a continuous wave

transmitter is that the signals may be received over a limited distance with a nonoscillating detector.

Most of the experimental work, the results of which are described in this paper, was performed by H. A. Snow of this Bureau, to whom credit is also due for several unique features of design and construction.

WASHINGTON, February 2, 1920.