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Volume 8 AUGUST, 1920 Number 4

CONTENTS

CORRECTION: In THE PROCEEDINGS OF THE INSTITUTE OF RADIO ENGINEERS for April, 1920; Volume 8, Number 2, page 165, the formula on line 3 should read:

$$C = \left(4\sqrt{a} + 0.885\frac{a}{h}\right)\left(1 + 0.015\frac{l}{b}\right)\cdot 10^{-6}$$

and in the Table 1, the seventh column of the second portion of the Table should be headed $\frac{l}{b}$

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TRANS-OCEANIC RADIO COMMUNICATION*

By

Ernst F. W. Alexanderson

(Chief Engineer, Radio Corporation of America, New York)

It has already become generally known that a new highway for world traffic has been opened up thru the development of trans-atlantic radio communication. It is now a matter of history that radio was largely used for communication between the United States and armies in Europe, and that the Great War was brought to a close by negotiations conducted by radio which led to the Armistice. Now, we are ready for an international commerce of unprecedented scope, but lack adequate means for communication.

The recent achievements of radio technique have become common knowledge, and the world has now turned to this new method of communication clamoring that it step in and save the day. This is a condition which places a serious responsibility upon radio engineers. Fortunately, the technique has emerged from the cloud of mystery that used to surround it, and we are in position to treat the problem coolly and scientifically like any other problem in electrical engineering. However, it must not be inferred that the task is an easy one, if the radio technique is to fulfill all the hopes which are placed on it.

It has been demonstrated during the war period that trans-oceanic communication has become thoroly reliable, every day in the year, and practically every hour in the day. Thus far, we can say, that the problem is solved. But a second question will be raised: What volume of traffic can be carried by the means at our disposal at the present time, and what is the relation of this radio traffic to the world traffic of to-day and to the world traffic of the future? The facts of the case are briefly the following:

Experience has shown that the wave lengths which are most suited for trans-oceanic communication lie between 12,000 and 17,000 meters. This "space in the ether" has already been taken

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* Received by the Editor, September 8, 1919. Presented before a joint meeting of The American Institute of Electrical Engineers and The Institute of Radio Engineers, New York, October 1, 1919.

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up by five first-class transmitting stations which, during the war period and up to the present time, have been in continuous service for trans-atlantic communication. Of these stations, two are in the United States, one in England, one in France and one in Germany. By extending the range of wave lengths down to 10,000 and up to 20,000 meters, and following the same system of intervals there would be room for about seven more stations or a total of twelve first class transmitting stations.

A first class station has such radiating power that its messages can be received in all parts of the world. This is one of the advantages of radio communication; but it implies that if such a station is to be used to full advantage it must have a "right of way" for its wave length over the whole world. Thus if we look at the matter pessimistically, without allowance for the improvements that further engineering developments are likely to bring, it would look as if the capacity of the world for first class radio stations would be about twelve. The rate of transmission at the present time from these stations is about twenty words a minute and it would thus be easy to figure out that the capacity of radio for handling any considerable portion of world communication would be totally inadequate.

The other side of the picture, which the radio engineer of the future must study carefully and closely, should indicate the technical possibilities for improving the situation. The tendency of present day developments points to the following means for expansion of radio traffic:

1. Increase in speed of transmission.
2. Improved selectivity based on the direction of the wave.
3. Improved selectivity making possible closer spacing of wave lengths.

As a basis of discussing the general situation it may be here stated as simple facts:

1. That signals have been transmitted and received at considerably more than 100 words a minute.
2. That signals have been received from Europe while an American high power station within comparatively short distance was radiating on the same wave length.
3. That it has proven practical to separate radio signals differing in wave length considerably less than 1 per cent.

Based on these facts, it is probable that the transmitting speed in the future will average 100 words a minute instead of 20 words a minute.

That the selectivity for direction of the waves will multiply

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by five the number of stations that may be operated on one wave length; and that the selectivity with reference to wave length will be improved so that the wave lengths of messages will be within 1 per cent. of each other, instead of 7 per cent., which is the spacing of the stations at present.

These prospects, taken in combination, give us an optimistic picture in which the possible capacity for trans-oceanic radio traffic of the world is 175 times as great as it is with the practice of to-day.

To claim that the traffic capacity could immediately be increased, nearly 200 times, would be an exaggeration, because the different improvements which have been made may partly conflict with the execution of each other if they are to be used simultaneously. This optimistic picture is, therefore, to be regarded as a goal—perhaps never to be reached, but it points the way for almost unlimited possibilities for progress by continued engineering efforts.

In order to avail ourselves of these improvements simultaneously, the transmitted wave must be a continuous wave which does not "spill over" with harmonics, decrements or variations, into the range of wave length assigned for other communication. When wave lengths are spaced 1 per cent. apart, each wave must be sufficiently pure so as to have no objectionable components outside the limits of one-half of one per cent. While rules to this effect should be rigidly enforced, it must be appreciated that there are certain fundamental limitations.

High Speed Signalling

Modern trans-oceanic radio signalling is conducted by means of continuous waves. It must be appreciated, however, that signalling by an absolutely continuous wave would be impossible, because the making of dots and dashes introduces increments and decrements in the radiation. It will be shown that a repetition of increments and decrements can be resolved into a group of closely adjacent continuous waves. This agrees with the well-known fact that the tuning of a wave with a decrement is known as a broad tuning. To illustrate this point we may take as a basis a signal at 100 words a minute (5 letters per word). If it is assumed that the increments and decrements in making the dots are not sharp interruptions but a continued variation by sine wave curves as indicated in Figure 1, it is found by analysis that such a wave may be resolved into a group of con-

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tinuous wave components within the limits of 40 cycles above and below the average. This is the theoretical minimum width of the band of wave lengths which are necessary to transmit 100 words per minute. If the dots are defined by sharper interruptions the wave becomes still "broader" and it would not be unreasonable to say that the minimum practical band of wave lengths for 100 words per minute is 100 cycles on each side of the fundamental. This would make possible a spacing of the waves 1 per cent. apart when using a wave length of approximately 15,000 meters. Messages at a higher rate of speed will occupy a correspondingly wider "space in ether."

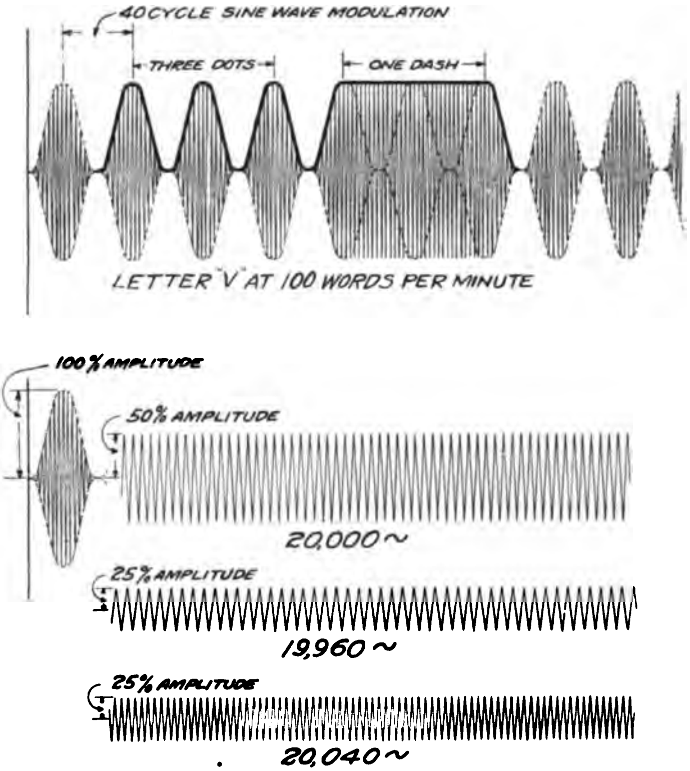

FIGURE 1—Method of Resolving Sine Wave Modulation Into Three Continuous Waves

As a conclusion from this analysis it may thus be said that an increase of the speed to 100 words a minute and increase of messages to a spacing 1 per cent. apart may be accomplished

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simultaneously, provided that waves are used of such a character and modulation that they contain no radiation except the one needed to accomplish the intended purpose.

DIRECTIVE RECEPTION

The second means for increasing radio traffic consists in improving the selectivity by taking advantage of the direction of the waves. The author's paper printed in the PROCEEDINGS OF THE INSTITUTE OF RADIO ENGINEERS, August, 1919, described a receiver referred to as the "barrage receiver" which was used to demonstrate directive reception. There are several other types of receiving devices, developed by the United States Navy and other investigators, which accomplish substantially the same purpose. The broad principle underlying all these directional receiving devices is the one discovered by Bellini and Tosi, and generally referred to under their names.

In the United States Navy's tests of the "barrage receiver," it was proven that it is possible to carry on simultaneous two-way communication on exactly the same wave length. If this method of directive reception is carried out consistently in a world system of communication, it may be assumed that transmitting stations operating on the same wave length may be located approximately as shown in the map in Figure 2—one in Europe, one on the American east coast, one on the American west coast, one in the Far East, and one in South America. The American receiving station for European signals in such a system should be located east of the American Atlantic trans-

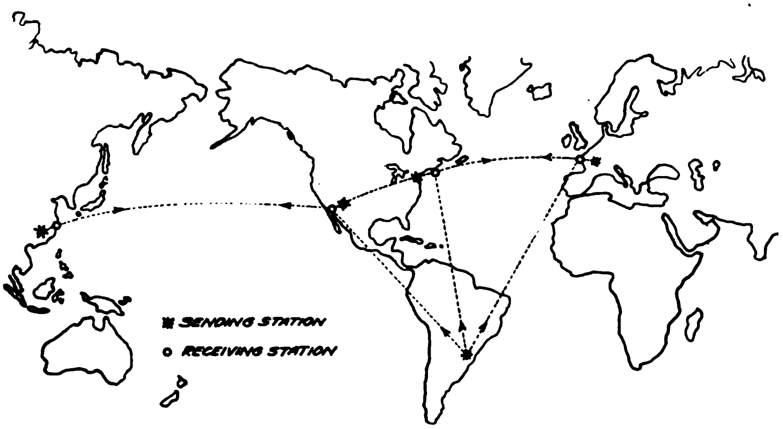

FIGURE 2—Proposed Simultaneous Radio Transmissions on the Same Wave Length

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mitting station, and in line with the Pacific transmitting station. Thus messages from the two American transmitting stations could both be simultaneously neutralized in the American receiving station by a "barrage receiver," while signals on the same wave length are received from Europe. Interference from the South American station may be neutralized by the use of a double barrage system, while the station in the Far East, tho it may not be exactly in line with the two others, would be sufficiently near the general direction so that, considering the great distance, it would not cause interference.

If this communication system is to be duplicated on a number of other wave lengths, the practical conclusion follows that the transmitting stations as well as receiving stations for each district should be grouped in centers, and these centers located relatively so as to make the directive neutralization as effective as possible. The neutralization of several transmitting stations simultaneously may not always work out as first designed. It has been shown by investigations of the Navy Department that the radio waves do not always follow straight lines and not always the same path. However, discrepancies from such origin may again be overcome by further extending the principle of neutralizing waves from several directions simultaneously.

CLOSER SPACING OF WAVE LENGTHS

The method of increasing traffic capacity by closer spacing of wave lengths has great possibilities. It has been shown that the selectivity with reference to wave length can be greatly increased by several successive tunings in either the radio, the audio or some intermediate circuit. It is thus entirely practical to receive either by ear or by photographic records, signals which are considerably less than 100 cycles apart. The theoretical limits for such selectivity in connection with high speed transmission are defined below. As illustrated in Figure 1, a high speed message is not a single continuous wave, but a band of wave lengths—100 words per minute occupying a space of about 200 cycles. Therefore the same degree of selectivity is not to be expected with a high speed signal if the interfering radiation is of considerable intensity.

Speaking in terms more familiar to practical radio operators it may be said that high speed telegraph signals assume to some degree the objectionable characteristics of a spark signal. As an illustration of this, Figure 3 shows the relative decrements in a continuous high speed telegraph wave and a spark wave,

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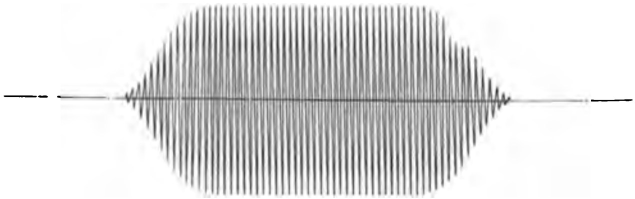
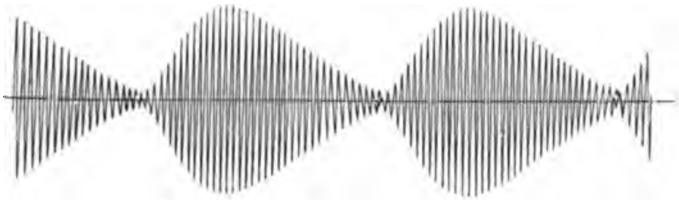


WAVE TRAIN SHOWING ACTUAL NUMBER OF RADIO CYCLES IN A DOT OF THE TELEGRAPH CODE TRANSMITTED AT THE RATE OF 500 WORDS PER MINUTE AT 15,000 METERS WAVE LENGTH



A Spark Wave at 400 Sparks Per Second

Figure 3—Decrement of High Speed Signal Compared with Spark Wave

showing that the increments and decrements of the continuous wave signal at 500 words per minute are about equal to a spark wave of 400 sparks per second. These illustrations apply to wave lengths of about 15,000 meters.

The Radio Transmitting System

Several types of radio transmitting systems are at present in use with a high degree of success. The descriptive matter in this paper will, however, be confined to the system for which the author is responsible, as represented by the Naval Radio Station at New Brunswick, New Jersey.

Generally speaking, any radio transmitting system consists of three essential elements:

1. The generator of radio frequency energy.
2. The modulating system, whereby the energy is controlled so as to produce the dots and dashes of the telegraph code or the modulations of the human voice.
3. The antenna or radiating system.

Generating System

There are four types of generating systems of radio frequency energy in use at the present time.

1. The spark or impulse generator.
2. The Poulsen arc generator.
3. The radio frequency alternator.
4. The vacuum tube oscillator.

The system which will be described is of the type employing a radio frequency alternator. The installation in New Bruns-

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wick contains a 50-kilowatt alternator shown in Figure 4 which was operated for some time for experimental purposes with radio telephony at a wave length of 8,000 meters, and later in transatlantic telegraph service at 9,300 meters.

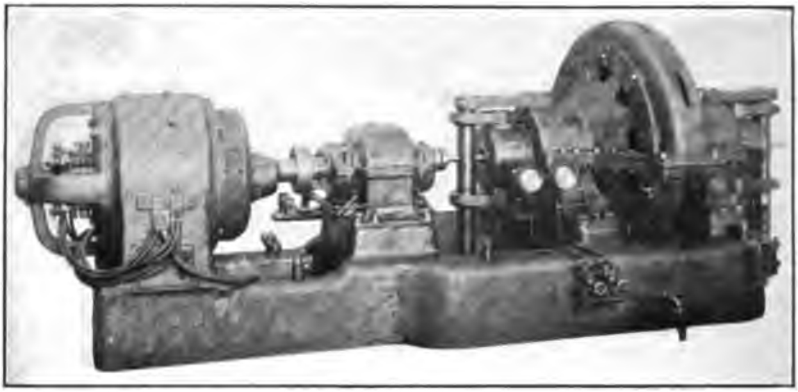

FIGURE 4—50-Kw. 50,000 Cycle Alternator

A larger equipment which has been in continuous service for the last year consists of a 200-kilowatt alternator shown on Figures 5, 6, and 7. Figure 5 shows the machine partly assem-

FIGURE 5—200-Kw. Radio Frequency Alternator

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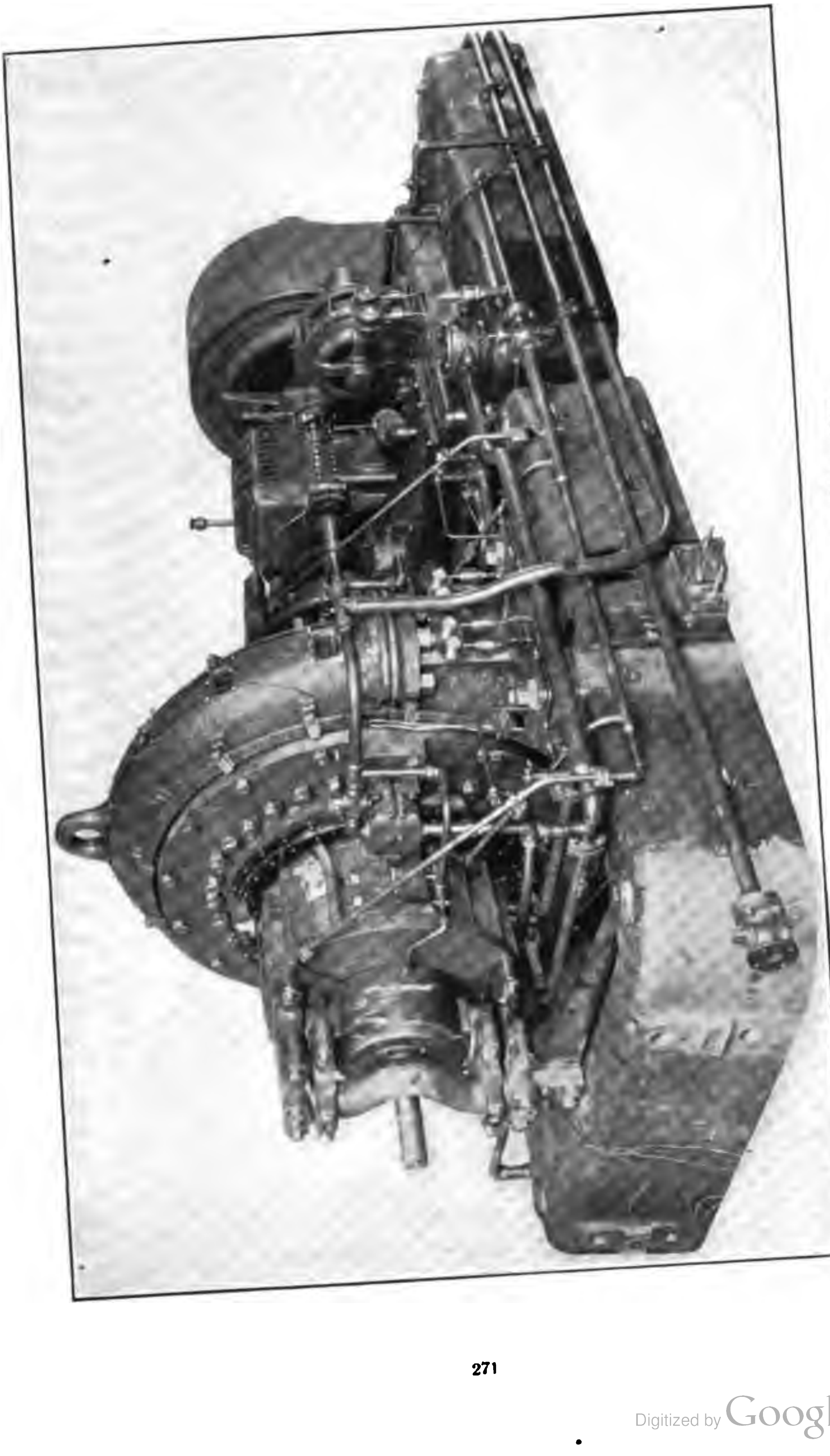

FIGURE 6—200-Kw. Radio Frequency Alternator

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bled, the rotor consisting of a solid steel disc. The spaces between the polar projections are filled with non-magnetic material so as to present a smooth surface and thereby reduce air friction to a minimum. The disc runs between the two laminated armatures, which are cooled by water pipes, as shown in the photograph. The armature winding which consists of wire wound back and forth in straight open slots, is divided in 64 sections, each section generating about 100 volts and 30 amperes. The current generated by these 64 windings is collected in the air-core transformer mounted on the top of the machine (Figure 7). This transformer has 64 independent primary windings corresponding to the armature windings. The single secondary winding of the transformer delivers the complete output of the alternator. This collecting transformer is thus to be considered as an integral part of the generating unit; and for all purposes of calculation, the characteristics of the generating unit, such as electromotive force and current, are given as delivered from this secondary winding. At full output the alternator delivers 100 amperes at an electromotive force of 2.000 volts. It can thus be seen that the alternator is designed for a load resistance of 20 ohms. However, the same machine might be adapted for any other load resistance by selecting a different number of turns in the secondary of the collecting transformer. The reason why this particular machine is designed for a high voltage and low current will be given later in discussion of the new type of antenna with which it is used.

The 200-kilowatt alternator when operated at the New Brunswick wave length of 13.600 meters runs at a speed of 2,170 r.p.m. It is driven by an induction motor thru a gear of a ratio of 2.97:1. When the radio frequency alternator is used as a source of radiation, the wave length is determined directly by the rotative speed of the machine. Thus, obviously, it is important that the rotative speed should be as nearly absolutely constant as it is possible to make it. An important accessory of the alternator set is therefore the speed regulator. The 50-kilowatt alternator set shown on Figure 3 is driven by a direct current motor whereas, the 200-kilowatt set is driven by an induction motor of the slip ring type. The 50-kilowatt set was equipped by a direct current motor because the problem of speed regulation of that type of motor is somewhat easier. Induction motors were, however, decided upon for the later types because alternating current power is more easily available in most localities.

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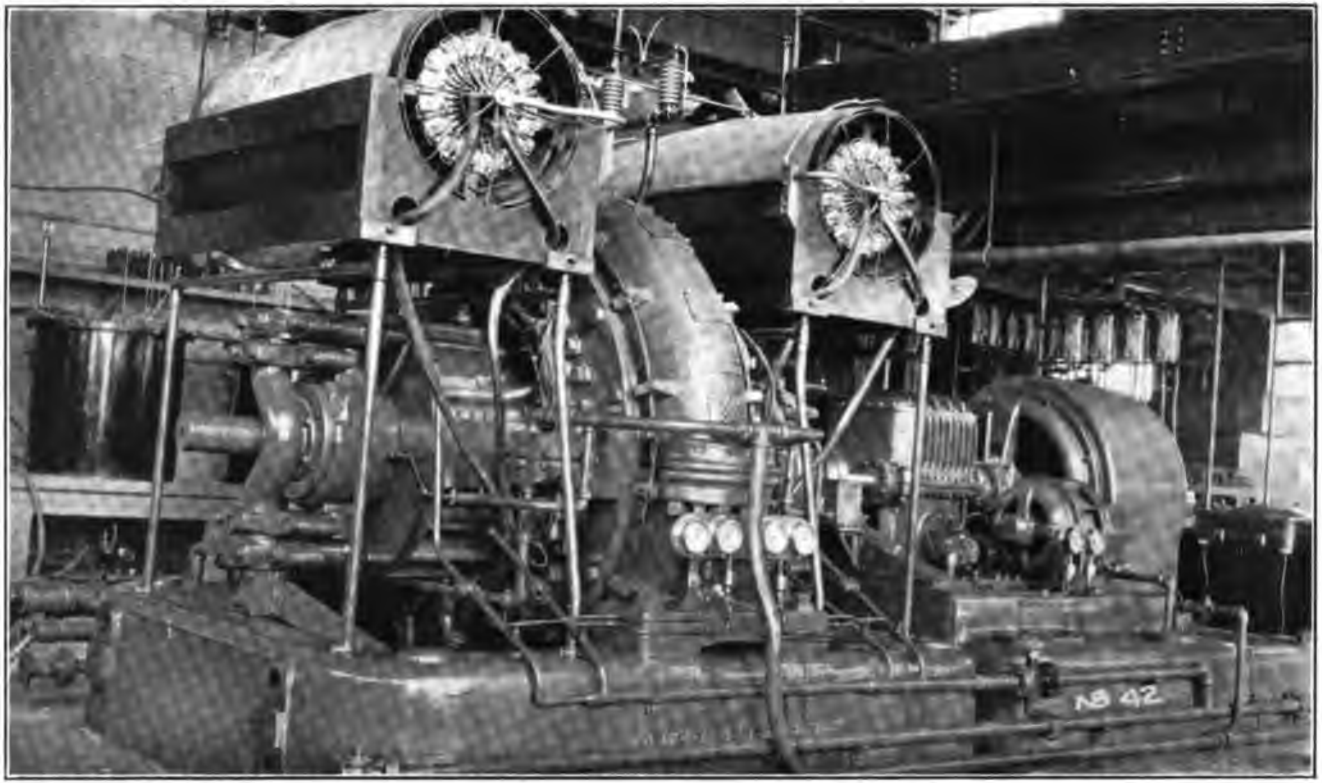

FIGURE 7—200-Kw. Alternator Set as Installed in the Naval Radio Station, New Brunswick, N. J.

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The speed regulator consists of a speed-determining element and a power-controlling element. The speed-determining element is a resonant radio frequency circuit fed by one of the 64 alternator windings which is set aside for that purpose. The oscillating energy of this radio frequency circuit is associated by magnetic couplings with a rectifying circuit in which the radio frequency energy is changed into direct current. This rectified current in turn, actuates the controlling magnet of a vibrating regulator of the type that is generally used for voltage regulation in power stations. When the driving motor is a direct current motor, it is easy to see how this vibrating regulator may be made to control the speed by regulating the voltage of the power supply to the motor. In order to accomplish the same object with an induction motor some new features have been introduced.

An ordinary induction motor is operated at constant potential. When the motor runs light, it draws from the line a magnetizing current which is almost wattless. Thus it operates at a low power factor. When the motor is fully loaded, it draws power at a high power factor—a motor of the type used having a power factor of 90 per cent.

When the New Brunswick station was adjusted for operation, it was found that a wave length was desired which required the induction motor to work at 19 per cent. slip. The rheostat in the secondary of the motor could easily be adjusted so that the motor would deliver the desired power with full load at 19 per cent. slip. However, inasmuch, as the output of the alternator varies continually with the making of dots and dashes of the telegraph code, the motor is alternately loaded and not loaded. The tendency would, therefore, be for the motor to speed up during the intervals. If the potential of the power supply to an induction motor is varied, the motor torque varies by the square of the voltage. It is furthermore easy to show, by the theory of the induction motor, that if a motor consumes power at 90 per cent. power factor at full load and the load is reduced to ¼ by the reduction of voltage to ½, the power factor will remain 90 per cent. In fact, it will always consume power at 90 per cent. power factor regardless of its load if the voltage supply is adjusted accordingly, so long as the secondary resistance remains constant and the speed remains constant.

Thus it may be said that the standard method of operating an induction motor is at constant potential and variable power

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factor. The method of operating the driving motor of the radio set may on the other hand be characterized as variable potential and constant power factor.

The problem which thus presented itself was to find means for varying the applied voltage in accordance with action of the speed determining element, and this has been done in the following way:

Between the motor and the power supply is introduced a choke coil with iron core, the permeability of which can be varied by saturation. The change in permeability is produced by a direct current which is controlled by a vibrating regulator. When the motor carries full load the iron core is saturated so that the choking effect is practically zero. At fractional load, the choking effect is automatically adjusted by the regulator so that the motor delivers at all times the power required to hold constant speed. The motor itself operates at all times at its maximum efficiency and power factor, but the power factor of the current drawn from the line varies with the load. Thus when the motor operates at ¼ load the power factor of the line is 45 per cent., while the power factor of the motor is 90 per cent. The circuits of the regulator are shown in Figure 8 and the photograph of the vibrator regulator in Figure 9.

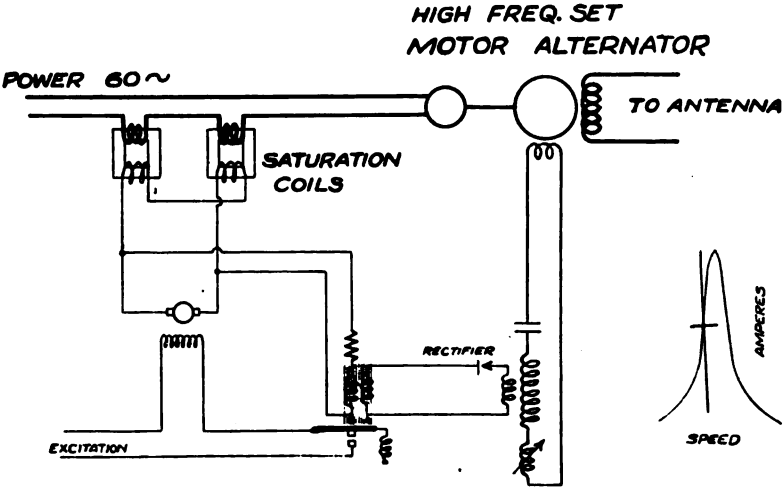

FIGURE 8—Speed Regulator Alternating Current Drive

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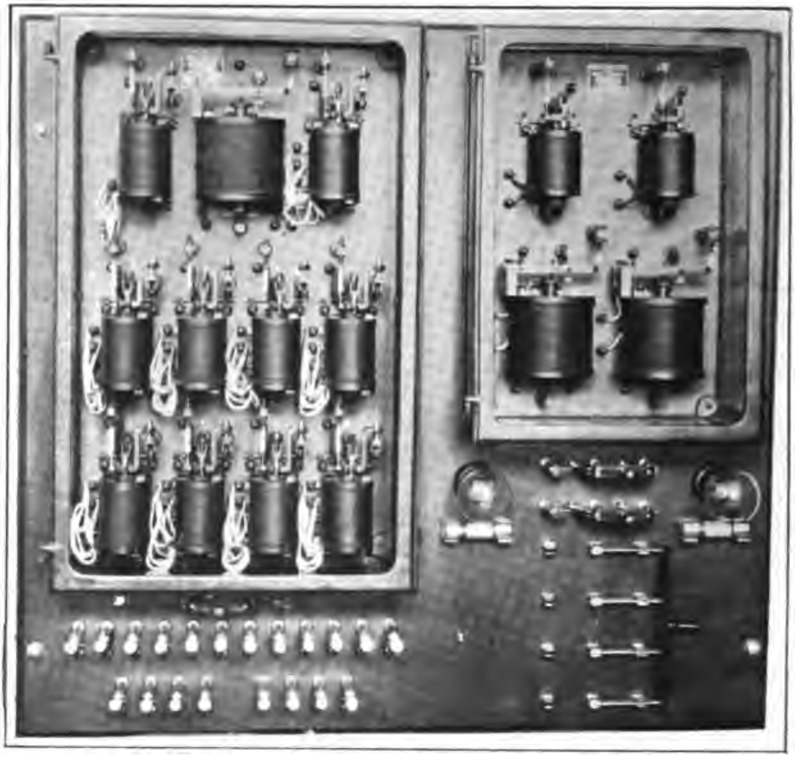

FIGURE 9—Combined Current and Voltage Regulators for Radio Frequency Alternator Control

MODULATING SYSTEM

The method of controlling radio frequency energy involves an apparatus which has become known as the "magnetic amplifier." This device is described in a paper by the author in the PROCEEDINGS OF THE INSTITUTE OF RADIO ENGINEERS, January, 1916, and therefore needs to be referred to only briefly. The magnetic amplifier is a device which is physically of the nature of an oil-cooled transformer. The iron core which is made of fine laminations, is designed in such a way that the magnetic permeability of the iron core can be varied by magnetic saturation. By a special combination of tuned circuits as shown in Figure 10, it has become possible to separate the controlling current from the radio frequency current so that a comparatively weak current of a few amperes controls as many hundreds of amperes in the antenna. When the transmitting station is used

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for telegraphy, the magnetic amplifier is controlled by the telegraph relays which are a part of the wire telegraph system. During the war service, the telegraph key was operated in the centralized operating room of the Naval Communication Department in Washington. When the station is used for telephony the controlling current is an amplified telephone current.

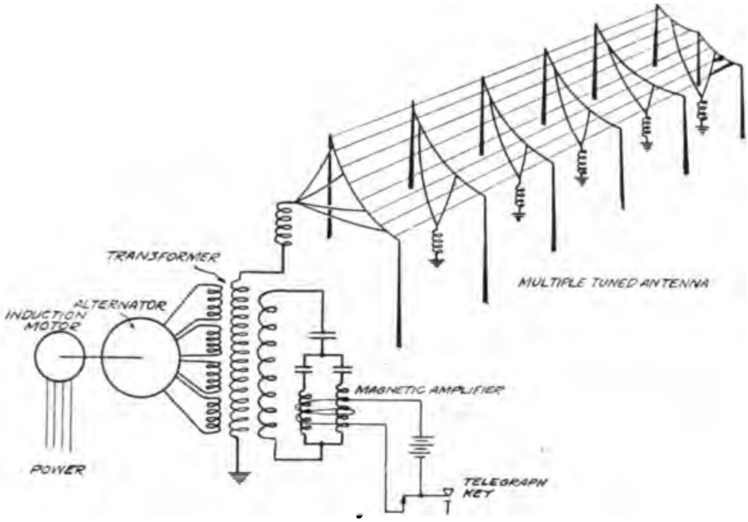

Figure 10

While the magnetic amplifier has proven to be a very satisfactory and reliable controlling device for ordinary telegraphy, its particular advantages are most prominent in high speed telegraphic transmission and telephonic transmission, on account of its instantaneous magnetic action without any arcing contacts. Figure 11 shows an oscillogram of radiation at 100 words per minute and a photographic record of reception at the same speed. Figure 12 shows the telephone modulation of the antenna current when Secretary Daniels was speaking over the telephone line from Washington, controlling the output from the New Brunswick station, thereby transmitting his voice to President Wilson's ship at sea.

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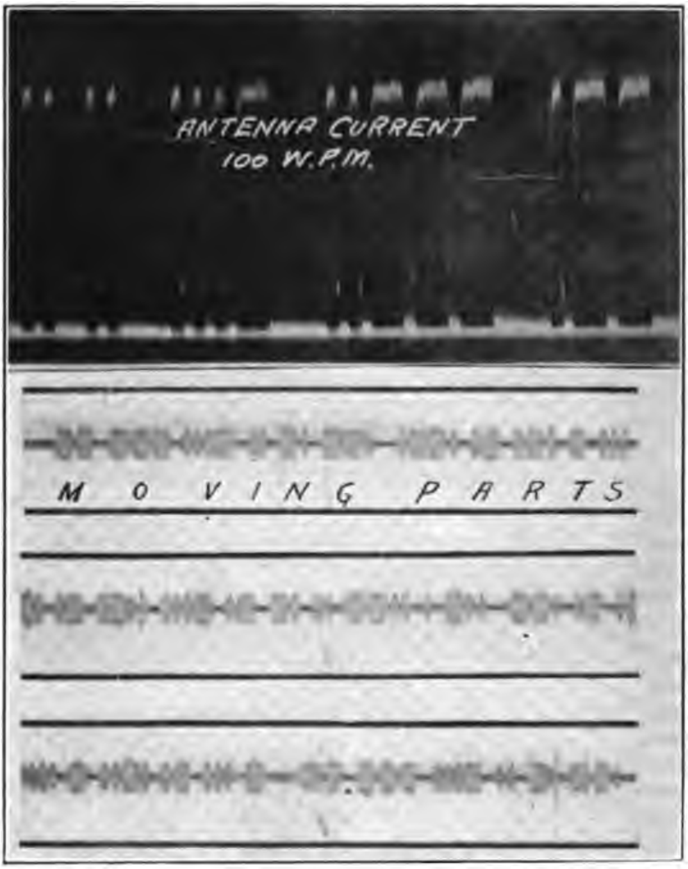

FIGURE 11—Oscillogram of Radiated Signal from New Brunswick; and Photograph of Received Signal from New Brunswick at 100 Words per Minute

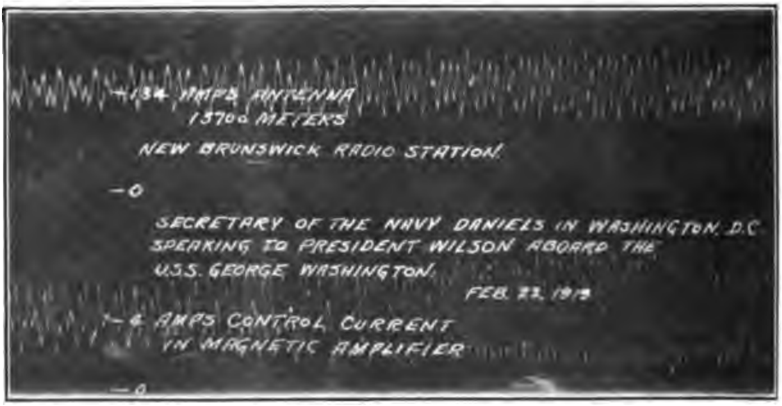

FIGURE 12

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THE MULTIPLE ANTENNA

The antenna of the New Brunswick station represents a new departure in the method of radiation. The old antenna structure was originally one of the horizontal Marconi antenna, 5,000 feet (1,500 meters) long, 600 feet (180 meters) wide, supported on towers 400 feet (120 meters) high. The original antenna had a resistance of 3.8 ohms.

The antenna as operated now has a resistance of 0.5 ohm, distributed approximately as follows:

Radiation resistance	0.07	ohm
Tuning coils and insulation	0.10	"
Ground resistance	0.33	"
Total multiple resistance	0.5	ohm

The reduction in total resistance of the antenna is due to the reduction of the ground resistance. While the old antenna had one tuning coil located in one end, the new antenna has six tuning coils as shown on Figure 10 and Figure 13.

THEORY OF THE MULTIPLE ANTENNA

The theory of the multiple antenna can be explained in several ways. Without going into details, an explanation will be presented, giving the point of view which has proven most useful for general discussion.

For this purpose the multiple antenna may be considered as an aggregate of several antennas of the ordinary vertical type, each having its own tuning coil. When regarded in this way, the multiple antenna in New Brunswick is equivalent to six independent radiators placed 1,000 feet (305 meters) apart. The ground resistance of each of the radiators is 2 ohms, the coil resistance 0.6 ohm, and the radiation 0.07 ohm; making a total resistance of 2.67 ohms. Each of these radiators has an aerial 1,000 feet (305 meters) long and 600 feet (153 meters) wide, mounted at an average height of 300 feet (91.5 meters). A total resistance of about 2.67 ohms is, as a matter of fact, the resistance to be expected from an antenna of such dimensions and ordinary design. If one individual antenna, such as described, is operated with a radiation of 100 amperes, the energy consumption of the antenna would be 26.7 kilowatts, and the radiation efficiency would be 0.07 ohm divided by 2.67 ohms, which is 2.6 per cent. If it is desired to increase the radiation from 100 amperes to 600 amperes, the energy consumption

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would be 36 times as great, that is, 960 kilowatts. There is, however, another way to produce a radiation equivalent to 600 amperes. If six separate antennas of the dimensions described were built and each operated with a radiation of 100 amperes, each antenna would emit a system of waves proportional to 100 amperes radiation. If all the waves emitted by the six antennas were in phase, the amplitude of the combined wave would be six times as great as the wave emitted by one antenna. Thus the amplitude of the combined wave would be equal to the amplitude of the wave emitted by one antenna when operated

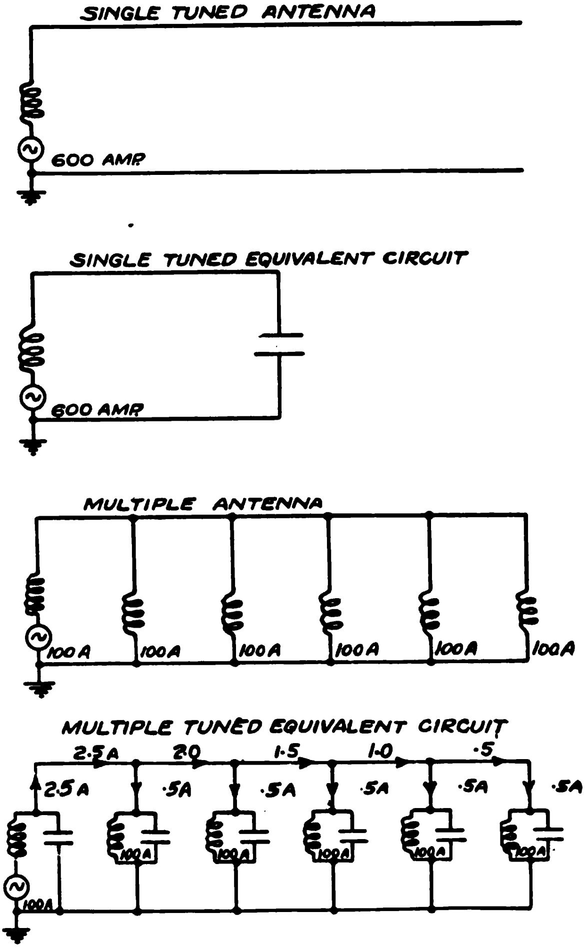

FIGURE 13

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at 600 amperes. The energy consumption required for operating one antenna was 26.7 kilowatts, thus it might offhand be concluded that the energy consumption required for operating the six antennas simultaneously would be 160 kilowatts. This conclusion is not exactly correct because there is an interaction between the radiating effects of the different antennas resulting in a somewhat higher energy consumption. This might be expressed as follows:

The radiation resistance which is 0.07 ohm is common for all six antennas, whereas the ground and coil resistance of 2.6 ohms belongs to the different antennas individually. Thus the combined circuit of the multiple antenna can be represented by the common radiating resistance of 0.07 ohm connected in series with a group of six multiple resistances of 2.6 ohms each, so that the total current of 600 amperes flows thru the 0.07 ohm radiation resistances, while 100 amperes flow thru each of the 2.6 ohm resistances, which represent the ground and coil resistance of the individual antennas. Hence the total energy consumption of the combined antenna is found to be 180 kilowatts, out of which 155 kilowatts is ground coil and insulation loss and 25 kilowatts radiation. The radiation efficiency of the multiple antenna is thus 14 per cent. against the radiation efficiency of 2.6 per cent. for the individual antenna. The above calculation is made for the present operating wave of 13,600 meters. If, on the other hand, the same calculation is made for the wave length of 8,000 meters, which has been found more efficient for telephonic transmission, it is found that the radiation efficiency is 30 per cent., the energy being distributed as follows:

Radiation resistance	0.2	ohm
Coil and insulation	0.07	"
Ground resistance	0.33	"
Total multiple resistance	0.6	ohm

For the sake of convenience in dealing with the radiation from a multiple antenna, it has become practice to indicate the total radiation from the multiple antenna as the sum of the currents measured in the six ground connections. The equivalent multiple resistance of the antenna is then determined by the equation $I^2 R =$ energy consumption, where I is the sum of the currents in the ground connection.

It has been assumed above that each of the individual antennas is operated so that the waves sent out by the same are not only of the same frequency, but exactly of the same phase.

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It remains to be shown how this is accomplished. Figure 13 shows the relation between the antenna and the multiple tuning coils and the alternator. As shown by the diagram, the alternator is connected in series with one of the six tuning coils. Arrows on the diagram indicate further how the oscillating currents and the energy currents are distributed. Six independent oscillating circuits are formed, the current in each ground connection corresponding to the charging current of the corresponding section of the aerial. If the antenna had been shock excited so that it continued to oscillate in the way indicated, no current would flow in the horizontal wires between the different sections of the antenna. However, in order to maintain continued oscillations a flow of energy must take place from the alternator, which is connected to one of the six tuning coils. When the antenna is operated with 100 amperes in each of the ground connections the energy consumption as shown above is 180 kilowatts, that is, each oscillating circuit consumes 30 kilowatts.

What actually takes place is the following: The tuning coil to which the alternator is connected transforms the energy of the alternator into a power supply at a potential of 60,000 volts, and each of the oscillating circuits draws energy from this power supply at that voltage. Thus the energy current consumed by each oscillating circuit is only 0.5 ampere. It can thus be seen that while the total oscillating current of the antenna is 600 amperes, the energy current which flows horizontally from the power source to the multiple oscillating circuits is only a total of 2.5 amperes. In other words the energy which is delivered by the first tuning coil in the form of 100 amperes at 1,800 volts is transformed by the first oscillating circuit and distributed as in a transmission line from which 0.5 ampere at 60,000 volts is drawn in five places. The analogy between the multiple antenna and a high tension power distribution system is thus apparent.

This point of view is a departure from the conventional theory of radiation; but it must be remembered that there was a time in the development of electric power technique when the introduction of the high tension multiple distribution system was a radical departure.

DIRECTIVE RADIATION

The multiple antenna as described in its simplest form is adjusted so that the radiation from each of the individual oscillators is in phase. If, however, the antenna dimensions are so

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chosen that the phase displacement of the travelling wave between the different radiators becomes an essential factor, it is possible to obtain directive radiation. The radiated wave will

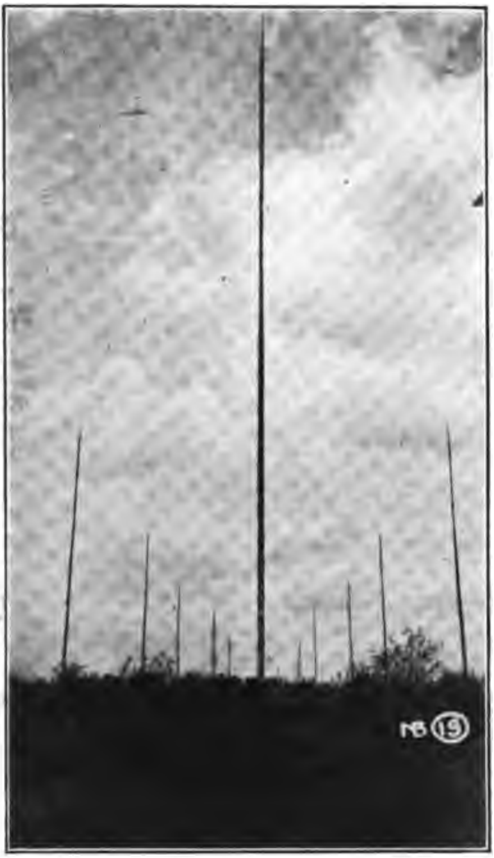

Figure 14—Perspective of Antenna

then not be a simple circular wave, but an interference pattern which may be treated like the corresponding phenomena in light and sound waves. Furthermore, the phase displacement of the oscillations of the individual radiators may be regulated by tuning. Thus a variety of interference patterns may be created, and analysis of these possibilities shows, that an efficient uni-directional radiation by such methods should be possible.

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Methods for unidirectional radiation have been established through the well-known work of Bellini and Tosi. Thru the courtesy of Mr. Bouthillon of the French Post Office, results of tests made in France have been placed at the disposal of the author, which show conclusively directive radiation by the Bellini and Tosi antenna.

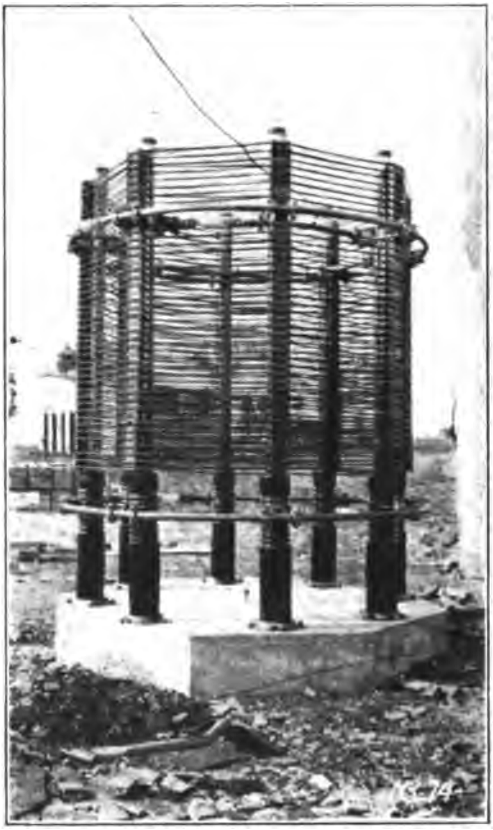

FIGURE 15—Outdoor Tuning Coil

With the dimensions of antennas used up to the present time, efficient directive radiation has not been practical. It has, however, been proven by various tests that the system of a central power source and a distribution system of energy to a large number of multiple radiators places at our disposal means for constructing radiators of dimensions of one wave length or more.

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The New Brunswick antenna (1,500 meters or 5,000 feet long) has a minimum wave length of 8,000 meters as a single antenna, whereas it can be operated as a multiple antenna at 2,000 meters wave length. A detailed analysis of the possibilities of multiple radiation would fall outside the scope of this paper, but the author is in position to predict with confidence that directive radiation on large scale will not only prove practical, but that it will be the most efficient method of radiation.

To add directive radiation to the proposed program for increasing the capacity of radio traffic would perhaps be premature until it has been demonstrated on a large scale. However, it deserves mention in order to show that new principles which may be utilized for still greater expansion of the radio technique have not yet been exhausted.

SUMMARY: The possible limitation in the number of long distance radio stations simultaneously in operation is considered. It is shown how high-speed transmission, improved directional selectivity, and better frequency selectivity would greatly increase the number of feasible co-existent stations,

The utilization of a wave length band as a result of high-speed transmission is discussed in connection with frequency selectivity.

The 200-kilowatt alternator station at New Brunswick is described, special mention being made of the constant speed regulation system for the induction motor drive, the functioning of the magnetic amplifier, and the operation of the multiple antenna. In this latter connection, the possibilities of effective directional radiation are considered.

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MEASUREMENT OF THE ELECTROMAGNETIC FIELD OF WAVES RECEIVED DURING TRANS-OCEANIC RADIO TRANSMISSION*

By

Giancarlo Vallauri

(Director of the Electrotechnical and Radiotelegraphic Institute of the Royal Italian Navy, Leghorn, Italy)

1

In the early part of August, 1919, the radio station at Annapolis, Maryland, in the United States (call signal "N S S") carried on experimental transmission lasting thru the 24 hours of the day. An occasion thereby arose for the Electrotechnical and Radiotelegraphic Institute of the Royal Navy to carry on quantitative measurements on the electromagnetic field of the arriving waves. The method chosen was a simple one of the substitution type, and was rendered easy of execution by the fact that the antenna at the Institute is a large radio goniometer. This goniometer consists of two entirely similar loop circuits of nearly triangular form, and so placed that one of them makes an angle with the geographic north of 36° or 216° (and therefore approximately NE and SW) and the other an angle of 126° or 306° and therefore approximately NW and SE). The area enclosed by each antenna is approximately 1,404 square meters (15,100 square feet).

The distance between Annapolis and Leghorn (measured along an arc of a great circle of the earth) is 6,917 kilometers (4,300 miles), and the azimuth of Annapolis relative to Leghorn is 298° 47′.

It follows that the northwest antenna is almost exactly placed for most favorable reception from Annapolis (with an approximate error of $306° - 299° = 7°$). Furthermore, the northeast antenna is in a very favorable position in order not to be influenced by the signals at all.

In connection with the reception, there was used an amplifier with eight vacuum tubes, having six stages of resistance amplifi-

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* Received by the Editor, September 15, 1919. Translated from the Italian by the Editor.

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cation and two stages of telephone transformer amplification. These last two stages were not used during the experiments. Since the inductance of each antenna is 255 microhenrys, and since the amplifier works conveniently with a circuit of much larger inductance, it was found desirable to insert the amplifier into a secondary oscillating circuit, coupled inductively with the antenna circuit.

2

The method of the measurements can be clearly gathered by an examination of the circuits of Figure 1. It consists in obtaining in the NW-SE antenna circuit the actual signal, and then switching over to the NE-SW antenna circuit and inducing in this new circuit (which is identical in all respects with the first except in direction) a locally regulable and measureable electromotive force. The frequency and amplitude of this local electromotive force can be so varied as to render it identical with that induced in the NW-SE antenna by the electro-magnetic wave coming from Annapolis.

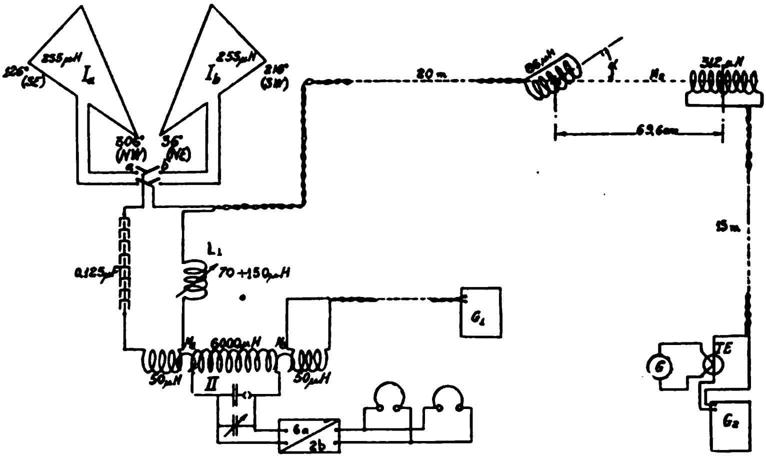

Figure 1—Measuring Circuits

The antenna consists, therefore, of one or other of the two loops (according as the switch *a b* is thrown to one side or the other), of the capacity shown which is made up of eight paper condensers each of one microfarad, connected in series, of the

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50-microhenry primary of the mutual inductance M_1 for coupling with the receiver, of the variometer L_1 which can be varied between 70 and 150 microhenrys for tuning, and finally of the secondary of the mutual inductance M_2 for coupling to the local oscillation generator G_2. This last secondary consists of 19 turns of diameter 12 centimeters (4.72 inches), and has an inductance of 86 microhenrys. The secondary circuit II, or receiving circuit, includes the 6,000-microhenry secondary of the mutual inductance M_1, a fixed condenser, and a variable air condenser across which the amplifier is connected. To produce beats in reception, the oscillations produced by the local heterodyne oscillator G_1 are introduced into the receiving circuit thru the mutual inductance M_3. To induce into the antenna circuit, when the switch is thrown to the side *b*, an electromotive force identical with that produced by the Annapolis signals in the NW loop, the oscillations produced by the generator G_2 are introduced into the antenna circuit thru the primary of the mutual inductance M_2. This primary consists of 50 turns of diameter 10 centimeters (3.94 inches), and has an inductance of 312 microhenrys. The current in the circuit of oscillator G_2 is measured by means of a thermo couple *TE* and a galvanometer *G*. The calibration of this galvanometer is given in Figure 2 which shows the relation between the reading *l* of the galvanometer and the current in milli-amperes passing thru the heater wire of the thermo couple. Each of the oscillators G_1 and G_2 is a vacuum tube generator with inductive coupling.

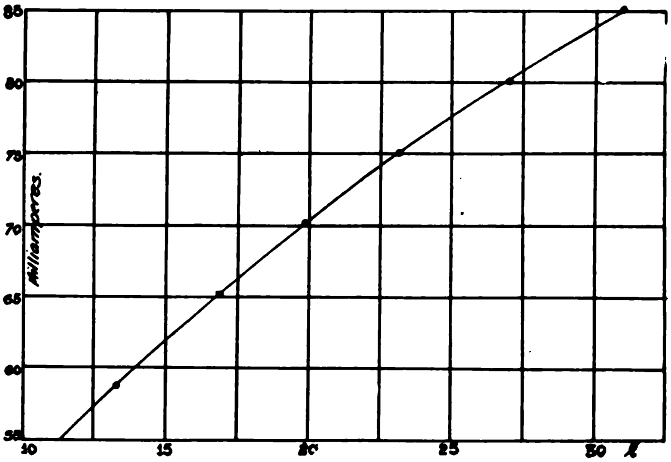

FIGURE 2—Calibration of Galvanometer

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Calling α the angle between the axis of the primary and secondary coils of the mutual inductance M_2, it is found that the value of mutual inductance when $\alpha=0$ (that is, when the primary and secondary inductances are coaxial) may be calculated from Havelock's formula, and is equal to 0.049 microhenrys. In view of the small dimensions of these two coils as compared with their distance apart (69.6 centimeters or 27.5 inches), we can correctly assume that

$$M_2=0.049 \cos \alpha$$

in microhenrys.

3

The following is the detailed method of carrying out the measurements. The switch is thrown to side *a* and the oscillator G_1 is started up, while the oscillator G_2 is not in operation. The quantities L_1, M_1, M_3, and the wave length λ_1 of the heterodyne oscillator G_1 are so regulated as to permit convenient reception of the signals. Then, leaving all other constants of the circuits unchanged, one changes over from the *first position* just described to the second position (for which the switch is thrown to side *b*) and the oscillator G_2 is started up. The mutual inductance M_2 is then roughly regulated so as to give approximately the same signal intensity as was obtained in the first position. By close regulation of λ_2, the wave length of the oscillations produced by G_2, there is finally obtained complete identity of the musical tone produced in the two positions. To check up the correctness of adjustment, a number of rapid transfers are made back and forth between the first and second positions. Then, keeping the note constant and leaving λ_2 unchanged, the intensity of the signal is regulated in such a way as to be equal in the two positions. This is accomplished in the second position by varying the angle α on which M_2 depends. When the angle α is 90°, the mutual inductance M_2 is zero and there is always an average sector or region in which the signal produced by G_2 diminishes to the disappearing point. Consequently, there can always be found two angular readings α_1 and α_2 on the two sides of such a sector for which the locally generated signals produced in the second position have the same intensity as the external or incoming signals in the first position. As a matter of fact, for each reading l of the galvanometer or rather for each deflection of G_2, four readings of α are taken, two for increasing signal intensity and two for diminishing signal intensity, and the averages of each of the two

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sets are taken as the values of a_1 and a_2. Then, by passing very rapidly from the second to the first position, it is possible to make sure that the identity of the two signals was really obtained.

4

In the second position (switch thrown to *b* and oscillator G_2 in operation), if the coupling between circuit I and the oscillator G_2 is exclusively due to M_2, the readings a_1 and a_2 must be symmetrical relative to 90°, or rather the two corresponding values of M_2 must be equal and of opposite sign. As a matter of fact, in spite of the use of screens and the considerable distance of separation between the various parts of the equipment, it is found that the oscillating circuit G_2 does have a certain mutual inductance M_o to the antenna circuit in the second position in addition to the mutual inductance M_2. If we take

$$M_2' = 0.049 \cos a_1$$

and

$$M_2'' = 0.049 \cos a_2$$

as the two values of M_2 corresponding to the two readings a_1 and a_2, we evidently have

$$M = M_2' + M_o = -(M_2'' + M_o)$$

from which

$$M_o = -\frac{M_2' + M_2''}{2}$$

$$M = \frac{M_2' - M_2''}{2} = \frac{0.049}{2}(\cos a_1 - \cos a_2),$$

in which M is the coefficient of total mutual inductance between the circuit G_2 and the circuit I in the second position. That the value M which is that used for the calculation of the induced electromotive force, does not depend on the direct coupling M_o is confirmed by the fact that the results of the measurements, given in the following table and relating to the tests of the same group, are in practical agreement with each other, altho it must be stated that they were attained by an intentional modification of the value of M_o. In order to carry out such modification, the inductance coil of the oscillator G_2 was changed in position, between one measurement and the next, in relation to the remainder of the circuit, or a similar change in position was given to both coils constituting the mutual inductance M_2 The corresponding variations in M_o are indicated by a shifting of the region of silence as indicated on the graduated circular scale of M_2 and particularly by variation of the value of $\frac{a_1 + a_2}{2}$.

The results of the measurements would have been invalidated if there had existed a direct coupling between the circuit G_2 and the secondary II, and to avoid any such defect, the two sets of apparatus in question were widely separated from each other. To check up this point, tests were made which showed that no matter how the equipment comprising the mutual inductance $M_1 M_3$ was placed relative to the remainder of the circuits, no change was produced in the readings α_1 and α_2 for a given reading of the galvanometer and a given signal intensity.

5

There is a danger, however, that the circuit of the heterodyne oscillator G_1 not only influences the secondary II thru the mutual inductance M_3, but also acts on the primary circuit, and that this action may be changed in amount between the first and the second position. As a matter of fact, the coupling M_3 is relatively close, because, in order to secure optimum heterodyne adjustment, it is found convenient to have an electromotive force induced into the secondary of a markedly greater amplitude than that produced by the signal. At any rate, it was possible to prove that such an objectionable influence was actually negligible by taking advantage of the short pause in transmission from Annapolis, and then noting that if the oscillations produced in G_1 and in G_2 remain unchanged and the set is switched from one loop to the other, the readings α_1 and α_2 are indeed somewhat altered, but the difference $(\cos\alpha_1 - \cos\alpha_2)$ remains unchanged.

One may finally consider the effect produced in the second position in the NE loop by the signals from Annapolis. This induced emf. is proportional to $\cos\beta' = \cos(299° - 216°) = \cos 83° = 0.12$, and it should be added to that induced from the oscillator G_2. It appears, however, more reasonable not to include this effect, since it is found that in the second position a slight variation in λ_2 does not cause any alteration in the note and since, in the same position, and with G_2 extinguished, even the greatest amplification obtainable does not permit one to hear any trace of the signals from Annapolis.

6

From the reading I of the galvanometer and α_1 and α_2 and the calibration of M_2, the effective value of the induced electromotive force can be calculated from:

$$E = \omega M I = 2.67\,(10)^{-3}\,(\cos\alpha_1 - \cos\alpha_2)\,I$$

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where $\lambda = 17{,}300$ m. $\omega = 109{,}000$

$$M = 49\,(10)^{-9}\,\frac{\cos\alpha_1 - \cos\alpha_2}{2}.$$

It is worth while mentioning that the identity of the note obtained from the signal of Annapolis in the first position and the signal from oscillator G_2 in the second position can also be secured at a frequency f_2 differing from f, which is that of the signal, provided that the frequency f_1 of G_1 satisfies the condition $f - f_1 = f_1 - f_2$. This can be readily avoided by noticing which way the note changes as λ_1 is changed in the first position and also when λ_2 is changed in the second position. In all these measurements, we arrange that $\lambda_1 < \lambda$ and $\lambda_2 > \lambda_1$, so as to have $\lambda = \lambda_2$.

Having obtained the effective value E of the electromotive force induced, we can obtain the magnetic field strength H of the incoming wave from Annapolis from the following equation:

$$H = \frac{E\,(10)^8}{\omega S \cos\beta} = 6.58\,(10)^{-5}\,E,$$

where S equals 14,040,000 square centimeters (15,100 square feet), this being the area covered by the receiving loop, and $\beta = 7^\circ$ is the angle between this plane and the horizontal direction of propagation of the incoming wave. The effective value H of the magnetic field is expressed as C. G. S. electromagnetic units. From this, there can be obtained the electric field intensity $F = vH$ where v is the velocity of light, and therefore

$$F = 3\,(10)^7 \cdot H \text{ volts per km.} = 1.97\,(10)^3 \cdot E \text{ volts per km.}$$

Carrying out the calculations in the manner indicated above, the following numerical table of result has been obtained. The observations were always carried out with two observers, each using one of the headband telephone receivers provided with the amplifier. Six different operators took part in these measurements. In the table given, *all* the results of the measurements carried out are given without any rejection whatsoever. The values may, therefore, be taken as a fair representation of the accuracy of the results from the point of view of accidental errors. As can be easily seen, with the method of measurement chosen it is by far preferable to take readings when the transmitting station makes a long dash rather than when it is transmitting signals.

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Observation	Group	Date	Time G.M.T.	α_1	α_2	$\cos\alpha_1 - \cos\alpha_2$	l Galvanom.	I_2 mA	E μV		H C.G.S.	F Volt/Km.	hI Amp. x Km.		Signals from NSS
													(Austin)	(Fuller)	
1	1	Aug. 6, 1919	14h 6m	71° 0	94° 0	0.3954	26.0	78.7	83	77	5.0.10−9	0.151	530	78	Long Dash
2			9	73° 5	93° 5	3450	27.2	80.3	74						"
3			12	71° 0	91° 5	3518	26.5	79.4	75						"
4	2	"	21h 38m	70° 5	93° 0	0.3861	14.0	60.0	62	53	3.5.10−9	0.104	360	82	"
5			42	69° 0	88° 0	3235	13.0	58.2	50						"
6			47	70° 0	88° 0	3071	12.5	57.2	47						"
7			51	69° 0	88° 0	3235	14.0	60.0	52						"
8			57	69° 0	90° 0	3584	12.5	57.2	55						"
9	3	Aug. 7, 1919	5h 50m	74° 5	84° 0	0.1627	18.0	67.0	29	34	2.2.10−9	0.067	230	33	Signaling
10			59	91° 0	105° 5	2497	13.0	58.2	39						"
11			6h 3m	94° 0	106° 0	2058	16.0	63.6	35						"
12			6	94° 0	104° 0	1721	16.0	63.6	29						"
13			8	96° 5	107° 0	1792	17.5	66.2	32						Long Dash
14			11	93° 0	107° 0	2401	16.9	65.0	42						"
15	4	"	7h 24m	94° 0	102° 0	0.1381	17.5	66.2	24	25	1.6.10−9	0.049	170	24	"
16			26	95° 5	101° 5	1036	17.8	66.6	18						"
17			28	93° 0	105° 5	2149	12.3	56.8	33						"
18			30	93° 5	102° 0	1469	15.0	61.8	24						"
19	5	"	9h 8m	91° 5	101° 0	0.1646	25.0	77.5	34	36	2.4.10−9	0.071	250	38	"
20			10	73° 2	86° 5	2280	18.8	68.4	42						"
21			13	74° 0	84° 0	1711	21.0	71.9	33						"
22			16	74° 0	84° 0	1711	22.0	73.4	34						"
23	6	"	11h 51m	72° 5	89° 5	0.2920	13.0	58.2	46	42	2.7.10−9	0.082	280	41	"
24			53	73° 5	87° 7	2439	12.0	56.3	37						"
25			57	73° 2	88° 0	2551	13.7	59.5	41						"
26			12h 1m	88° 5	104° 0	2681	13.8	59.7	43						"
27			4	73° 5	89° 2	2700	14.1	60.2	43						"
28	7	"	16h 23m	73° 7	85° 5	0.2021	17.6	66.3	36	39	2.5.10−9	0.076	260	38	"
29			26	72° 5	85° 0	2135	16.1	63.7	36						"
30			30	71° 7	88° 0	2791	11.3	54.8	41						"
31			32	71° 0	88° 0	2907	12.7	57.5	45						"

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It is easy to understand that the method might have been equally well carried out, using appropriate precautions, by the employment in the second position of an artificial antenna equivalent to, and in the place of, the NE-SW loop. However in this case the results of the comparison would have been less certain because atmospheric disturbances might have been missing in the second position. During the days on which the tests were carried on, these disturbances were very intense and did not appear to change on switching over from one antenna to the other.

7

The results of the measurements are not sufficiently numerous to permit drawing definite conclusions regarding the daily variation in the intensity of the signals received. For this purpose it would also be necessary to know the actual variations in antenna current at Annapolis during the experiments. The measurements of group 4 seem to confirm the "fading effect" of signals received from America during the morning hours, an effect which has been noticed at all the Italian stations which receive from North America.

The results obtained supply the quantitative material necessary either for verifying the various formulas enabling calculation of the range of a radio station or for providing the values of the minimum electromagnetic field intensity necessary with a given type of antenna to enable satisfactory reception. In this connection it may be stated that with an induced electromotive force of about forty microvolts, and therefore with a magnetic field of $2.6\ (10)^{-9}$ C. G. S. units and an electric field of 0.078 volts per kilometer, reception of messages using a eight-step amplifier was readily accomplished except during the periods of maximum atmospheric disturbance. As an example, during the afternoon of August 5th, the messages sent from Annapolis could be copied with perfect continuity at any time and were received with an intensity of six. (In this system, 4 = weak, 5 = somewhat weak, 6 = fair, 7 = good, 8 = strong, 8 = very strong. The normal signal strength is 6.)

Considering the formulas dealing with the calculation of the range of radio telegraphic stations, and particularly that of Austin* which can be put into the following form:

$$I_r = 377 \frac{h_r\, h\, I}{\lambda\, d\, R} \sqrt{\frac{\theta}{\sin \theta}}\ \varepsilon^{-0.0015 \frac{d}{\sqrt{\lambda}}}$$

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* Proceedings of The Institute of Radio Engineers, February, 1917 volume 5, number 1, page 25

we have $$F = \frac{R\,I_r}{h_r} = 377\,\frac{h\,I}{\lambda\,d}\sqrt{\frac{\theta}{\sin\theta}}\;\varepsilon^{-0.0015\frac{d}{\sqrt{\lambda}}}$$

where R is the resistance of the receiving antenna, h_r its effective height, I_r the current intensity at its base, h and I the corresponding effective height and current in the transmitting antenna, λ the wave length used, d the distance along a great circle between the two stations, and θ the angle subtended at the center of the earth by the arc joining the two stations. R is expressed in ohms, I and I_r in amperes, h, h_r, λ and d in kilometers, while the electric field F is expressed in volts per kilometer.

Starting from the unknown quantity $h\,I$ and taking $\lambda = 17.3$, $d = 6{,}917$, $\theta = 62^\circ\ 18.5'$, we have

$$h\,I = \frac{\lambda\,d}{377}\,F\sqrt{\frac{\sin\theta}{\theta}}\;\varepsilon^{0.0015\frac{d}{\sqrt{\lambda}}} = 3{,}500\,F \quad \text{amp. km.}$$

The values of $h\,I$ which are obtained in this way from Austin's formula, and which are given in the table, are evidently too large and actually about ten times larger than the true values. This indicates that for long distances Austin's formula gives values of the intensity of the electromagnetic field of the incoming wave which are much smaller than those actually found, or, in other words, that propagation of the waves is accomplished in a more favorable way than that indicated by the assumption on which the formula is based.

Very similar results are obtained by applying Dr. L. F. Fuller's formula ("Proc. American Institute of Electrical Engineers," volume 34, page 567, 1915):

$$I_r = 377\,\frac{h_r\,h\,I}{\lambda\,d\,R}\sqrt{\frac{\theta}{\sin\theta}}\;\varepsilon^{-0.0045\frac{d}{\lambda^{1.40}}},$$

whence $$h\,I = \frac{\lambda\,d}{377}\,F\sqrt{\frac{\sin\theta}{\theta}}\;\varepsilon^{-0.0045\frac{d}{\lambda^{1.40}}},$$

or, in this case, $h\,I = 500\,F$ approximately.

The values of hI thus obtained are about one-seventh as great as those given in the table. Knowing the effective values of hI for each group of observations in the table, there can be calculated for each of them the exponential coefficient to be substituted for 0.0045 in Fuller's formula to obtain agreement between the experimental results and the formula.†

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† The average value of the antenna current at Annapolis for the hours during which the seven groups of tests were carried on was 210 amperes. Taking the effective antenna height as 105 m. (320 feet), we have for $h\,I$ the value of 22.1 amp. km. These values have been obtained by courtesy of the United States Navy Department thru Captain S. W. Bryant, Acting Director of Naval Communications.

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It is hoped that the opportunity will arise to carry out much more numerous and definite measurements of this type which will require the use of several different stations, at different distances from each other, and employing various wave lengths.

Leghorn, August 22, 1919.

SUMMARY: A series of recent experiments is described on the determination of the electric and magnetic field intensities of the waves received at Leghorn, Italy, from the Annapolis, Maryland transmitting station.

A pair of large loops, respectively practically parallel and perpendicular to the incoming wave are used. The incoming signals are received by heterodyne oscillator and amplified. The substitution method is used for the measurements, whereby the incoming signal is compared to an artificial signal produced in the non-receptive loop by a local oscillator. A thermo-couple and galvanometer in the oscillator circuit, together with a calibrated mutual inductance for coupling to the non-receptive antenna, permit quantitative results. The necessary precautions and procedure are described.

Numerical results are given, and it is shown that the field strengths of the incoming waves are much greater than those calculated by the usual transmission formulas.

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DISCUSSION

Louis W. Austin (by letter): I am very glad that so eminent an experimenter as Professor Vallauri has entered the field of quantitative measurements in long distance transmission, in which I have been left so long practically to myself. For the further progress of transmission theory it is imperative that a large amount of quantitative data be gathered in different parts of the world, especially on signals coming from great distances. It has become increasingly plain that no single formula can represent the experimental facts correctly at all times. There are factors active in transmission which produce such variations in signals travelling more than two thousand miles (3,200 km.), that on certain days the signals produce current in the receiving antenna in Washington more than fifty times the strength produced on the weakest days. This is quite apart from all experimental errors and from the special fading periods lasting a few hours. It is possible that this region is particularly unfortunate in the matter of variations and very probably in other parts of the world the signals may be found more constant, but it is certain that the best that can be expected from a transmission formula is that it shall represent a fair average of the strength of the received signals throughout the year.

While Professor Vallauri's method of measurement is rather complicated, all the observations and necessary precautions appear to have been taken with the greatest care. The only improvement which I can suggest would be a further check on the calibration of the receiving system by sending with a small known antenna current from a portable antenna or loop at a distance of one or two wave lengths from the receiving station. At this distance and with the long wave length used, absorption would not be appreciable, and all the constants and the distance being known, the original calibration could be verified with considerable certainty.

From the several thousand long distance measurements which have been made by the Laboratory in Washington and at other points, I feel sure that the Navy formula will agree with the *average current for the year* received at Leghorn from Annapolis with an error not much greater than fifty per cent.

It is now believed that the attenuation over salt water of damped and undamped signals is not appreciably different, as the formula originally developed from spark observations seems to apply to undamped measurements.

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Fuller's formula for undamped waves ("Transactions of the American Institute of Electrical Engineers," volume 34, page 809, 1915), which gives a smaller attenuation than the Navy formula for long waves is probably in error on account of the assumption in the experimental work that the received telephone current, using a slipping contact tikker, is proportional to the power in the antenna, while, as a matter of fact, it is more nearly proportional to the received antenna current. At any rate it has not been found possible to make this formula represent the observations made in the Research Laboratory, altho at certain times it does appear that the longer wave lengths have a greater superiority over the shorter than would be represented by the Navy Formula.

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RADIO DIRECTION CHANGES AND VARIATIONS OF AUDIBILITY*

By

Carl Kinsley

(Major, Signal Corps, United States Army)

and

Albert Sobey

(Major, Signal Corps, United States Army)

Introduction

The development of methods for the determination of the point from which radio signals originate was actively carried on during 1918. The radiogoniometer measurements played an increasingly important role during the fall of last year. It seemed probable that the so-called radio compass might be called on to an extraordinary extent to assist in the projected operations of the spring of 1919.

There has been no opportunity, however, for an examination of the degree to which reliance could be placed upon that method of determining directions when the origin of the radio signals was known. During the winter and spring of 1919, we were fortunately able to carry on an extended series of measurements under the peculiarly favorable circumstances of widely separated stations operated by well-trained observers.

Discussion of Problem

There has been an extensive examination of the possible means by which the electromagnetic wave is bent around the earth without suffering the attenuation which would be present if the transmitting medium were homogeneous. The wave apparently follows the surface of the earth with but little of its energy being dissipated by a vertical expansion of the wave. This may be due to there being an upper permanently ionized region known as the Heaviside layer at an altitude of about 80

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* Received by the Editor, August 5, 1919.

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km. (50 miles), the lever at which the aurora is first observed, which acts as a conductor so that the wave spreads between it and the earth as tho they were two concentric conducting spheres with a dielectric between.

If this should not be the case, then the wave might be refracted around the earth without getting far from the earth's surface. Several possible causes for such a refraction have been suggested. Eccles shows how this might come about by slowly increasing ionization and Schwers considers that the hygrometric state may be such that the electromagnetic wave will be totally refracted downward and follow the curvature of the earth.

In any case, the wave passes thru regions where the moisture content is considerable, and where the ionization is partially dependent on the sun's light. Since the transmitting medium is not homogeneous, it is obviously possible that there should be some horizontal bending of the waves which might appreciably effect the radiogoniometric measurements.

It is desirable, therefore, to determine to what extent the electromagnetic waves, used for radio purposes, change their direction as measured by the radiogoniometer, and to obtain, if possible, the variations in audibility of the signals so as to note the relation existing, if any, between changes of audibility and changes of direction.

The causes for departure from the direct line of the transmission of radio signals as well as for their constantly changing audibility, may be expected to be explainable on a basis of changes in the uniformity of the transmitting medium. This will be considered at some length for the purpose of determining whether or not the physical conditions existing afford the necessary discontinuities to explain the variations observed.

Methods and Results of Radio Tests

In the measurements given in this paper, accurate quantitative methods were employed in the direction measurements.

Having in mind the different methods used by the English and French radio engineers in direction measurements, the following brief statement is given as it is believed that the method employed renders any considerable error impossible, altho the accuracy is much greater than that found to be necessary after the establishment of the fundamental facts of radio direction changes have been made.

Figure 1 gives a polar curve of audibility changes as the receiving loop is rotated. This curve is thoroly characteristic.

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The difference between its upper and lower parts is due to the design of the receiving loop, which was purposely constructed so as to indicate the absolute direction of the radio signals. It has been found from many tests that the minimums lie 90 degrees from the direction of the transmitting station—using normal daylight conditions. It is to be noted that this is true even tho the maximum vector does not lie along this direction. In the figure shown, a difference of about 10 degrees will be noted while the direction of the transmitting station as computed from the minimum values is in error by only 35 minutes.

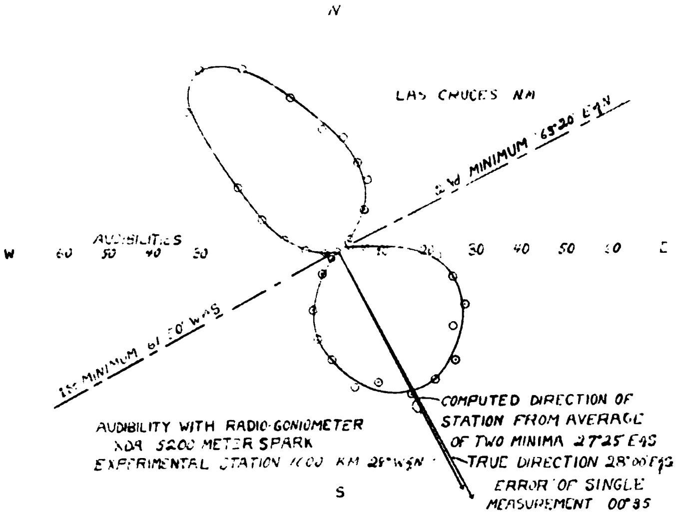

FIGURE 1

Figure 2 illustrates the method employed in determining the exact position of two of the minimums from which the directions plotted in Figure 4 are obtained. The particular points chosen were those showing the largest variations from the correct direction observed during the week of the test. These particular values were taken March 19th, upon which date no rain fell at Houlton, but at every other town listed in Maine. It will be noted that each minimum is obtained as the result of nine readings of audibility from which are plotted a medial line which intersects the curve of audibility at its correct minimum. It will be seen that an error larger than ¼ degree would be unlikely. Other illustrations are given in Figure 7.

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The audibility measurements thus need only be relative in order to give an exact quantative determination of the location of a minimum. We employed, therefore, the method of measurement involving the use of an audibility meter having an iron core inductive resistance in series with a high resistance telephone—2,000 ohms shunted by non-inductive resistances, the audibilities being computed by using the impedance of the telephone, not its resistance, in the usual equation. It was essential that the audibility measurements be made quickly so that an appreciable change of the direction would not occur during the time needed for making the nine readings. This time varied from three to seven minutes. If a change in minimum took place then the curve plotted was unsymmetrical and the medial line might be far from vertical. In the illustrations shown, the change in direction was of unusual rapidity, but the measurements were still sufficiently rapid to establish with certainty the position of the minimum. When the changes are too rapid to allow the use of the accurate method outlined then a method of disappearing points is used as illustrated in Figure 8.

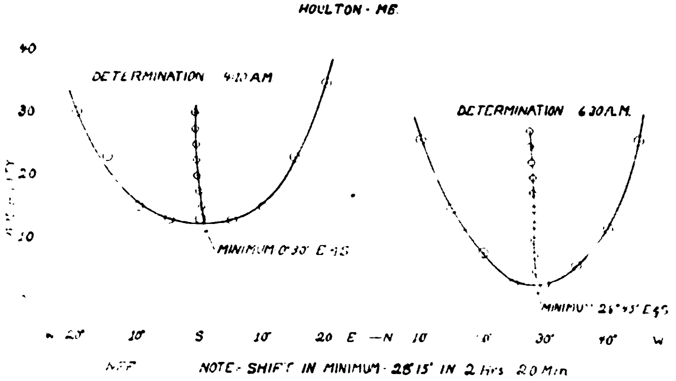

FIGURE 2

In Figures 3, 4, 5, and 6, the direction determinations are plotted radially and the time as the angles so that if the direction of the radio signals had not varied the plot would have shown merely a true circle.

The loop used at Houlton, Maine, for these measurements is as follows: sixty turns, number 26, B. and S. solid copper wire,* double cotton-covered, wound in one plane with horizontal

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* Diameter of number 26 wire = 0.06 inch = 0.15 cm.

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wires spaced 0.4 inch (1 cm.), and vertical wires 0.6 inch (1.5 cm.) apart. The outside dimensions of the loop are therefore, vertical dimensions 6 feet 5 inches (1.95 m.), and horizontal dimensions 9 feet 10 inches (3 m.). The loop was 7.5 inches (19 cm.) below ceiling and 9 inches (22.9 cm.) above floor, and having clearance of 6 inches (15.2 cm.) on one side and 12 inches (20.5 cm.) on the other, in a room on the lower floor of a small detached wooden house. The vertical axis about which the loop was turned was pivoted to floor and ceiling.

Figure 3 gives a series of direction determinations made as described above and each direction is the result of a computation from the accurately determined two minimums of a polar curve, each of which required nine audibility readings.

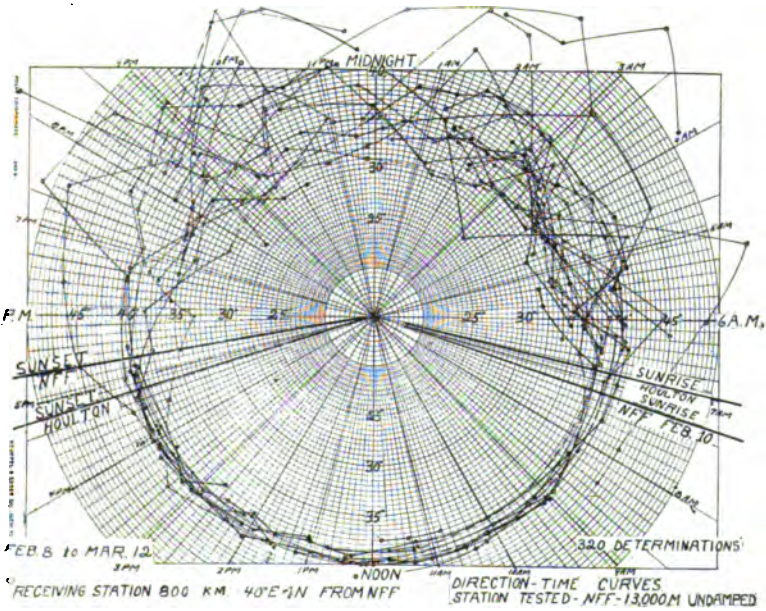

FIGURE 3

It will be noted that, during the sunlight hours, the direction measurements varied but little and the values could be used for determining the location of the transmitting station. During the night, however, the direction measurements showed extremely erratic values.

Figure 4 was obtained by the same methods as in Figure 3,

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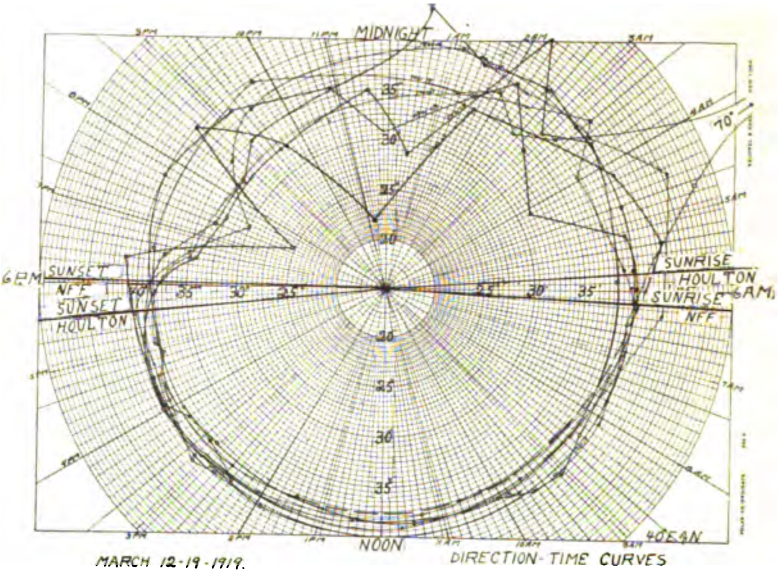
and all the measurements made during one week of continuous observation are shown. The particular case exhibiting the widest variation found during this week—4.10 A.M. to 6.30 A.M. in March 19th—has included in it the original data, a part of which is given in Figure 2 to show the accuracy of the measurements.



MARCH 12-19-1919.

DIRECTION-TIME CURVES
STATION TESTED-NFF-13,500 M. ARC.
RECEIVING STATION 800 KM. FROM NFF.

FIGURE 4

Figure 5 was obtained in the same way as in the case of the preceding figures, and it is to be noted that in the transmitting station, which also employed a machine generator, was located 12,000 kilometers (7,500 miles) from the experimental station, and most of that distance was over water. During the time when the whole path was in sunlight, the measurements showed no sudden changes in direction, altho there were a considerable number of observations taken on both sides of the mean.

Figure 6 is designed to show the directional measurements taken at widely separated places using radio transmission from the same station, which was a low frequency spark of 5,700 meters wave length. At McAllen, Texas, the receiving loop was of approximately similar design, but only thirty turns were employed. It is to be noted that the transmitting station was

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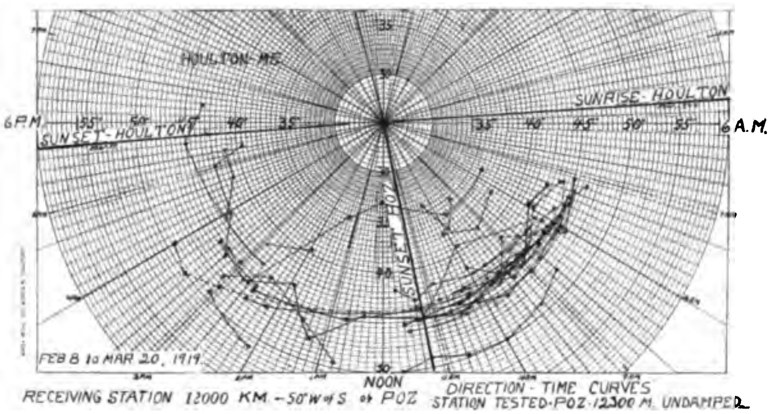

FIGURE 5

900 kilometers (560 miles) from one of the experimental stations, while in the case of Figures 3 and 4, the distance apart of the transmitting and receiving stations was approximately the same,

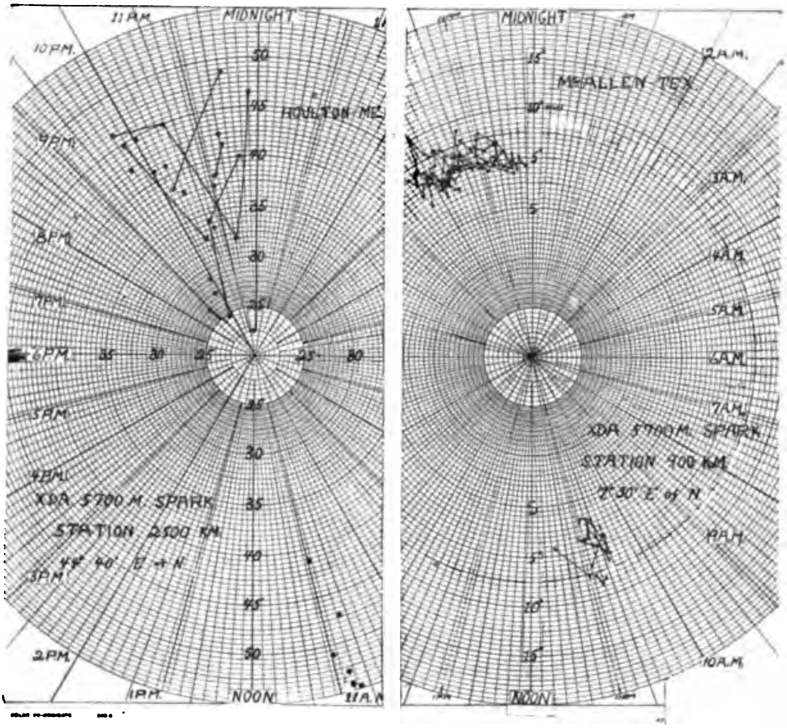

FIGURE 6

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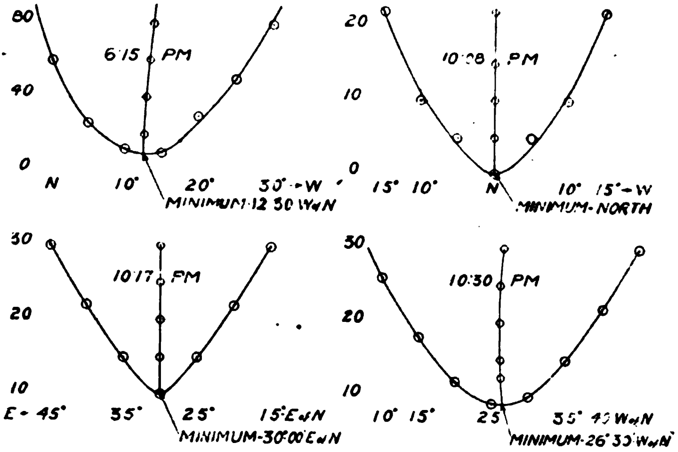
810 kilometers (406 miles). A more distant station, Houlton, Maine, 2,500 kilometers (1,560 miles) from the transmitting station, exhibits wide variations in direction during the night hours and considerable variation during the day time. The transmitting station is only operated for a limited time during the twenty-four hours, so no determination could be made as to whether or not there was a sharply defined change in the condition at sunrise, and sunset. It is not believed, however, that the large directional changes are due to the greater distances but rather to conditions relatively local.

It is to be noted that Figure 1 shows a complete audibility curve for this station, and the measurements obtained in that case indicate a true direction for the transmitting station. It will be seen from the observations taken at McAllen, Texas, that in general it was found at that point that the direction measurements seldom varied materially from the true direction of the station.

Figure 7 gives four of the minimums obtained at Houlton, Maine, in determining the variation of the direction of the radio signals sent by the Arlington, 2,500 meters wave length spark, on March 29th.

A considerable number of determinations were made on this station, and it was found that the direction very frequently differed from the true direction of the station.



NAA 2500M SPARK -- NOTE: SHIFT IN MINIMUM 56° 30 IN 13 MINUTES

FIGURE 7

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The complete measurements always involved the determination of both of the minimum curves, but only one of each pair is given in the illustration. It will be found that there can be no question as to the accuracy of the measurements, and the reality of the tremendous change in the measured direction. In spite of the large and rapid change, the method employed was sufficiently fast to insure a symmetry of the curves, and consequently the determination of the direction is reliable.

Figure 8 illustrates a curious change observed on March 2nd in the case of the same transmitting station used to obtain the results shown in Figures 3 and 4. There was a slight rain at Houlton on that day. In the course of these measurements, it was found that the direction was changing so rapidly that the audibility curve showing the minimum was no longer symmetrical, and consequently it became necessary to use a more rapid method of determining direction. The different methods of observation used are indicated in the drawing.

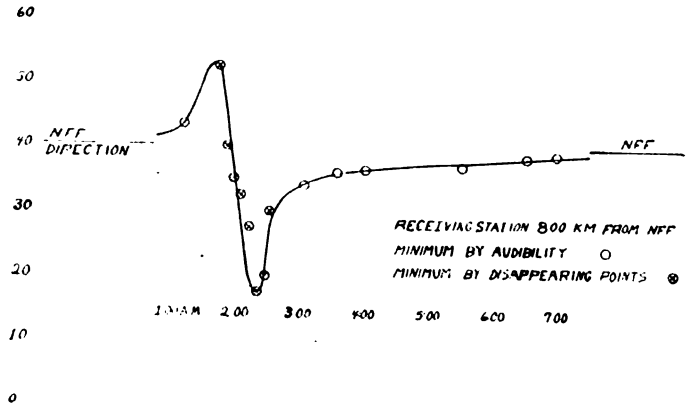

FIGURE 8

The rapid measurement of direction was accomplished with sufficient accuracy for most purposes by rotating the loop until the signal fades out or disappears. With a proper maximum audibility, it is generally possible to obtain, therefore, two pairs of disappearing points, giving an average from which the position of the loop for minimum audibility is determined. This method leaves a good deal to the judgment of the operator, and so one is inclined to place less reliance upon this method except for the particular case when he himself is the experimenter. It

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is believed, however, that good relative values may be obtained in this way, and that the results reported by any one operator would give reliable information with regard to the changes in audibility.

In the remaining figures are shown audibility measurements and directional measurements, in which the relative direction only was desired in order to determine whether or not the changes in audibility and the changes in direction have any relation to each other.

The directional measurements were therefore made by the disappearing point method, which has a very considerable advantage for this type of experiment, in that the time needed for making the directional measurements is only about 30 seconds, and so it is possible to obtain very sudden changes of direction, with greater relative accuracy.

Figure 9 illustrates the phenomenon often observed, and known as "swinging" of the audibility. The audibility measurements were made by the shunted telephone method, and so varied by steps of considerable magnitude. This is the cause of so many of the observations showing exactly the same audibility while a more accurate method would have distributed the values.

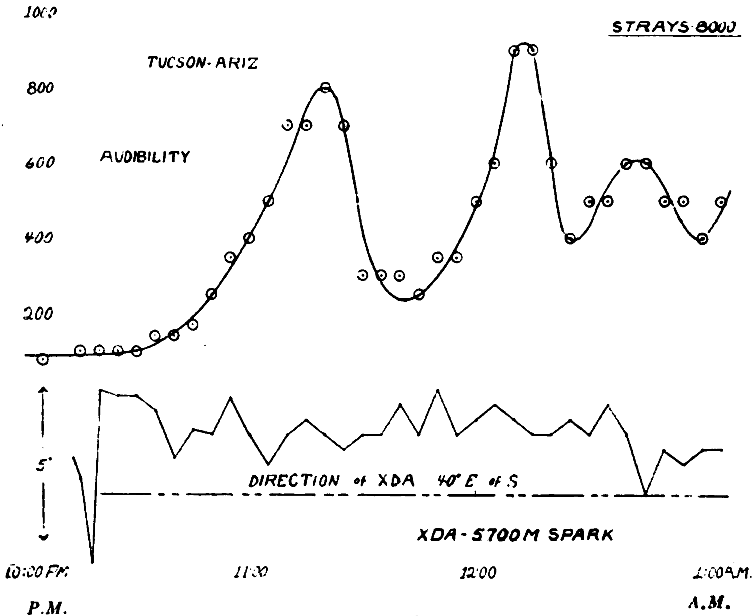

FIGURE 9

During the time covered by these observations, there was but little change in the direction measurements, and the only rapid change in direction noted occurred during the time that the audibility of the signal was constant. These observations were taken June 16th with heavy strays but with a clear sky.

It should be stated that the audibility measurements were made not with the use of the loop, but instead by using a vertical antenna which was located at more than 0.2 kilometer (610 feet) from the loop station; and it was proved by experiment that no interference existed between the two receiving stations, independently employed in making audibility measurements, and in determining by the loop the direction of the radio transmission.

In the following figures the same methods outlined above for determining audibility of the signals and the directional measurements, were employed.

Figure 10 is primarily intended to show that the same station may exhibit widely fluctuating values of audibility with negligible changes in direction, and also the converse of large and rapid changes in direction with inconsiderable changes in audibility. The data for these curves were obtained on June 4th. The weather was reported as hot, with the day partly overcast.

There are shown also in this figure values for strays which

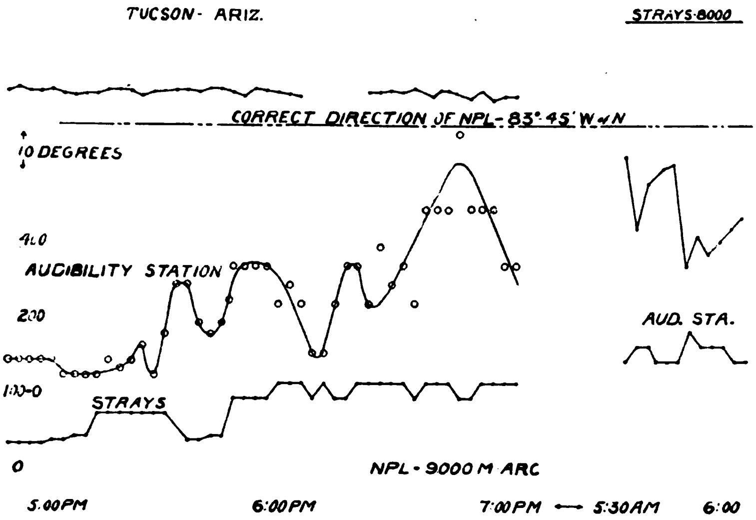

Figure 10

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in the first case were comparatively low, and in the second were extraordinarily high. It is believed, however, that the presence of high strays is no indication of excessive changes in audibility. This will be brought out in the following figure.

Figure 11 contrasts results obtained from two spark stations, namely, "XDA" using 5,800-meter wave, and "XAJ," using 960-meter wave. It is to be noted that a very considerable change in direction shown by "XDA" is accompanied by a large decrease in strays, but that there was little change in the audibility of the station.

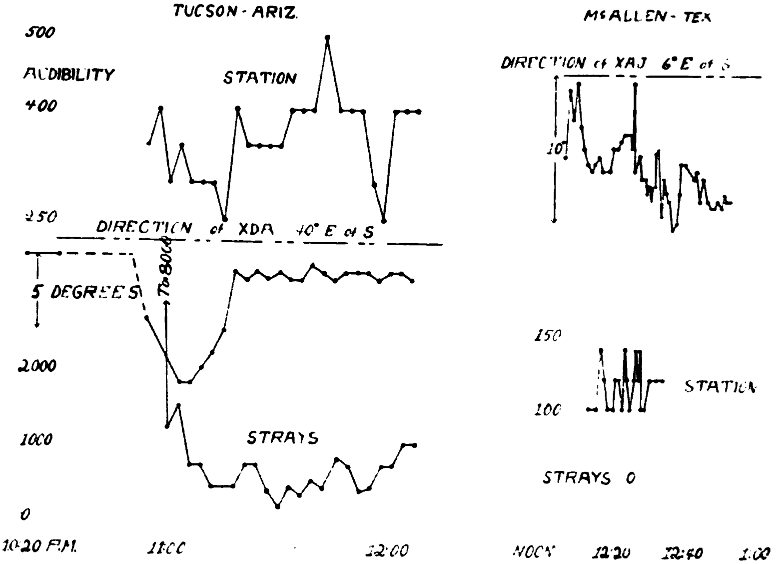

FIGURE 11

The results obtained from XAJ were taken between noon and one P.M., and exhibits much larger changes in direction than are normally found during the day time. It should be noted that, in this case, strays were absent and the audibility of the station was substantially constant.

The observations taken on XDA were made on May 22nd, at Tucson, Arizona. There was during the day time a rainfall of 0.34 of an inch (0.7 cm.). The station observations taken on XAJ were made upon the same date, May 22nd, at McAllen, Texas. There was no rainfall at that point.

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On the same day, at McAllen, observations were taken on XDA, which showed wide variations in direction, that were displaced by about one hour and a half from those observed at Tucson. The exact observations are not given, however, since a certain difficulty with the apparatus make the results less reliable than any of those reported in this paper. Simultaneous readings have been made at the three widely separated stations of Houlton, Maine, Tucson, Arizona, and McAllen, Texas, but the results are not yet ready for publication.

Figure 12 illustrates a very special case where the radiogoniometer loop exhibited no directional effect when rotated above a vertical axis. At the same time, on July 11th, the same transmitting station was observed at both Tucson, Arizona, and Houlton, Maine, and thruout the whole period at Tucson no direction could be obtained. The weather condition at Houlton, Maine, was overcast sky but no rain, while at Tucson, Arizona, there were bad static conditions, with lightning around the horizon but no precipitation of rain.

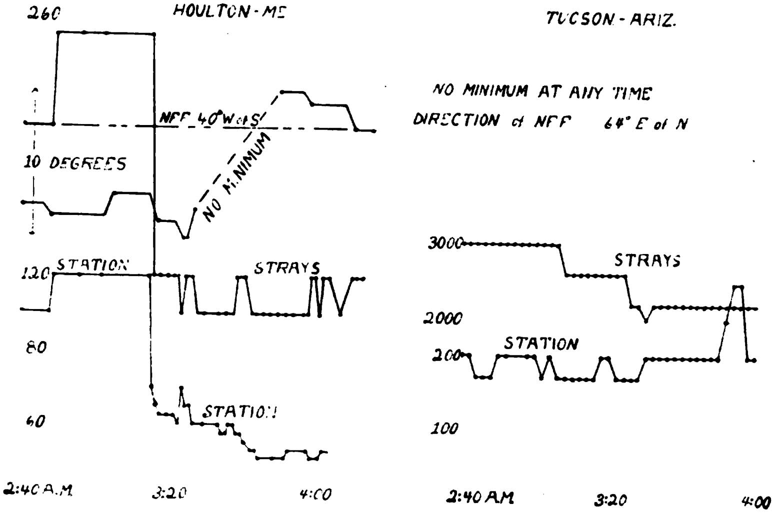

FIGURE 12

The observation at Houlton, Maine, showed uniform direction measurements somewhat displaced from normal, and with a broadening of the minimum. This means that the changes of audibility in the neighborhood of the minimum position of the

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loop, as the loop is rotating, were less rapid than normal and also with a maximum audibility of the usual value it would be found that the signals did not completely disappear when the loop was in the condition showing the minimum audibility; frequently it is necessary to determine the position of the loop for minimum by a single observation under these special conditions, since there is no complete disappearance of the signal as the loop approaches its position for minimum audibility.

When the special condition of "no minimum" is observed, the loop may be rotated about its vertical axis without any appreciable change in audubility. The explanation of this condition is given in a subsequent paragraph.

TABLES

No minimum audibility as radiogoniometer loop was rotated about a vertical axis.

Number 1

March 6th and 7th, 1919. Houlton, Maine.

1 A.M. to 7 A.M., March 7th, 1919, Sergeant Heinline.
1.15-1.28 A.M. NFF 36 degrees 90 minutes E. of S.
2.00-2.10 A.M.

Note.—Took readings on NFF and NSS and plotted curves for same. While reading NFF from 2 A.M. could find no minimum point; audibility being practically level at all points of the compass. Readings taken on NSS immediately after showed normal conditions for that station, while NFF continued flat.

2.10-2.24 A.M. NSS 42 degrees 30 minutes.
3.12-3.25 A.M. NFF 27 degrees 00 minutes.
3.27-3.36 A.M. NSS 43 degrees 45 minutes.
4.45-4.55 A.M. NFF 41 degrees 45 minutes.

Weather conditions were unsettled, March 6th, rain 0.20 inch (0.5 cm.); March 7th, rain 0.10 inch (0.25 cm.).

NFF is New Brunswick, New Jersey, employing a machine transmitter giving undamped waves at 13,500 meters.

NSS is Annapolis, Maryland, employing a large arc transmitter giving undamped waves of various lengths, and reported to have been 15,000 meters at this time.

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NUMBER 2

6 P.M., April 24th to 1 A.M., April 25th, 1919.

Sergeants Pfeiffer and McAllister

Glace Bay, "GB," with 8,000 *meter spark*

10.24 P.M. 12 degrees 30 minutes.
11.02 P.M. 12 degrees 30 minutes.
10.43 P.M. 12 degrees 30 minutes.
11.20 P.M. 12 degrees 30 minutes.

Arlington, "NAA," with 2,500 *meter spark*

11.30 P.M. *Note.*—NAA was tuned in on both of the loop receiving sets, but in neither case was it found possible to get definite disappearing points.

Mexico City, "XDA," with 5,700 *meter spark*

11.38 P.M. 27 degrees 30 minutes W of N.
11.59 P.M. 25 degrees 0 minutes.
11.49 P.M. 27 degrees 30 minutes W of N.
12.01 A.M. 42 degrees 30 minutes.
11.50 P.M. 29 degrees 0 minutes W of N.
12.25 A.M. No minimum.

Note.—Disappearing points began to spread, and in next minute no minimum points could be distinguished. This condition continued until 12.32 A.M., when it quickly changed and the following readings were taken.

12.34 A.M. 26 degrees 0 minutes.
12.52 A.M. 26 degrees 0 minutes W of N.

Weather conditions were unsettled, and traces of rain fell on the 24th and 25th about one-third of an inch.

Note.—In both number 1 and number 2 it is of importance to note that while certain stations gave *no minimum* reading when the radiogoniometer loop was rotated about its vertical axis, other stations gave good direction measurements.

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Number 3

July 11th, 1919, 1 to 8 A.M. Houlton, Maine.

Master Signal Electrician Pfeiffer

New Brunswick, New Jersey, "NFF," with 13,500 *meter undamped wave*

3.05 A.M. 35 degrees 30 minutes.

3.24 A.M. 32 degrees 30 minimum points much broader.

3.17 A.M. 33 degrees 45 minutes.

3.27 A.M. 34 degrees 30 minutes minimum points broad.

Note.—From 3.33 A.M. to 3.58 A.M., the minimum points were too broad for reading.

3.50 A.M. 42 degrees 30 minutes minimum points sharp.

3.59 A.M. 41 degrees 45 minutes normal.

Weather, overcast—light south breeze, cool, no rain.

Number 4

July 11th, 1919, 8 P.M. to 4 P.M. Tucson, Arizona.

Corporal Wm. F. Aufenanger

New Brunswick, New Jersey, "NFF," with 13,500 *meter undamped wave*

Note.—NFF heard from about 3.00 A.M. to end of watch, but was very weak. During transmitting periods neither Captain Ives nor operator could discern any disappearing points, as signals were faintly audible over entire 360 degrees. Weather and static conditions unusually bad, lightning continuously playing around horizon.

Number 5

July 13th, 1919, 1 to 8 A.M. Houlton, Maine.

Master Signal Electrician Pfeiffer

New Brunswick, New Jersey, "NFF," with 13,500 *meter undamped wave*

3.20 A.M. 43 degrees 30 minutes broad minimum.

4.02 A.M. 41 degrees 0 minutes sharper minimum.

3.57 A.M. 42 degrees 0 minutes broad minimum.

4.07 A.M. 44 degrees 0 minutes broad minimum.

4.29 A.M. No reading. *Note.*—Minimum points too broad reading.

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4.39 A.M. No reading. *Note.*—Minimum points hardly discernible, apparently being around due east and west.
4.47 A.M. No reading. *Note.*—Minimum points continually changing but very indefinite, now being around due north and south.
4.49 A.M. 55 degrees 0 minutes broad minimum.
4.57 A.M. 44 degrees 30 minutes sharp minimum.
4.52 A.M. 48 degrees 0 minutes slightly sharper.

Weather: Clear, cool, full moon.

It is particularly noted that all of the cases observed when no directional measurements could be made appeared during the night, and also in the large majority of them bad weather conditions prevailed.

Discussion of Results

It has been shown by the preceding figures that radio telegraphic signals of all kinds, including transmitters employing radio frequency alternators and arcs, giving undamped waves of 4,900 to 17,300 meters length, and various spark systems having damped waves from 960 to 5,700 meters wave length, suffer distortions whether transmission is over land or over water. Many observations have been taken which are not shown in the figures, covering a distance range from 65 kilometers (40 miles). (Annapolis, 17,300-meter arc received at Washington) to 12,000 kilometers (7,500 miles). (Funabashi, 3,800-meter spark, received at McAllen, Texas.) In all cases, neither the character of the transmitter, the wave length employed, nor the local conditions or terrain have been effective in preventing the distortion of the electromagnetic wave used in signaling.

It may be said, however, that the measurements made when the transmitter employs an undamped wave of great length show distortion more frequently, and, in general, of a larger amount than those found when a transmitting system using damped waves and a shorter wave length is employed. It will be seen for instance, that XDA, Chapultepec, Mexico, low frequency spark using 5,700 meter wave length is but seldom distorted when observed at McAllen, Texas, while the measurements made upon the same station at Houlton, Maine, show more frequent and greater divergence from the normal; but still not to the same extent as has been observed in the case of NFF, New Brunswick, New Jersey, radio frequency alternator using

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13,600-meter wave length received at the same station and over a much shorter distance.

It will be noted that the distortions found in the case of the long wave arcs during the daytime are of rare occurrence. It has not been possible to get any extended series of observations on short wave spark stations during the night. The ones taken, however, have shown but seldom any considerable distortion either by day or night. In the case of Tampico, Mexico, XAJ, spark system using 960-meter wave length shown in the figure, the distortion was very considerable, and was fully equal to that shown by the long wave arcs, taken, as was this, during the daylight hours. There does not seem to be any reason to believe that the short wave sparks may not, under unfavorable conditions, show distortion of the same magnitude as that given by other types of transmitters. In the case of Arlington, Virginia (NAA), using its 2,500-meter spark, there have been observed at Houlton, Maine, many distortions of large value and occasionally it was found that the loop receiver gave no directional indications. These distortions have been measured with great care, and the original data is given in one of the figures, showing a shift of 56 degrees 30 minutes in the angular direction of the signal wave within 13 minutes of lapsed time. There is also shown in the table a particular case where no directional reading could be obtained with a loop rotated about a vertical axis.

Other cases where no directional effect was observed are by no means rare, altho only a carefully kept watch would reveal all of them, since, as the illustrations show, the duration of this condition of no directional indication may persist for only a few minutes. During March and April, at Houlton, Maine, our records show this failure of the radiogoniometer on eleven different occasions. A good many other instances were recorded where there was a broadening of the minimum. The reason for this has been found in particular cases by other investigators to be caused by an apparent change in the wave front which may be corrected by a rotation of the loop about a horizontal as well as vertical axis. We do not know of any such examination when no directional effect at all is indicated by the radiogoniometer. All of the data obtained when no directional effect could be found show that two causes for the anomolous condition may exist.

First. Where the directional effect of the loop gradually disappears by a broadening of the minimum, but without any radical change in the directional indication: This would seem

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to show that at the receiver the resultant effect was just as tho the electromagnetic wave changed its direction of propagation from the horizontal to the vertical. Such a change in resultant direction would be shown by the establishment of disappearing points when the rotation is about a horizontal axis alone.

SECOND. At other times both before and after the disappearance of any minimum in the audibility, there has been found to be an extremely large and erratic change in the direction as indicated by the loop turned about the vertical axis. The data presented show particular illustrations of this condition. It would seem that the cause for the loss of directional effect must be of a radically different character from that in the first case. The explanation most probable is that at the receiver the electromagnetic wave is so modified as to produce a rotating field. When the two components of such a field have strictly quadrature relations, both with regard to time and with regard to direction, together with the same amplitude of oscillation, then the rotating field becomes purely circular and is the most simple case obtainable. It would be expected that this condition would persist only a very short time and would be preceded and followed by extremely erratic indications given by the direction of the loop. If this is the case then it would not be possible to obtain any directional effect by a rotation of the loop about the horizontal as well as the vertical axis. No experimental verification has been made in the case of long distance transmission, but such a condition has been observed by others in connection with radio experiments involving only a few hundred yards and employing very short waves.

The changes in audibility have also been obtained by an extended series of experiments, but the figures presented show only a few particular cases where it is desired to bring out the fact that large changes in directions are not necessarily accompanied by any considerable changes in the audibility of the signals and that even an entire loss of directional effect by the receiving loop may occur with no considerable change in the audibility of the signals.

The converse may also be true and it is shown that there may be very large changes in the audibility of the signals without any appreciable change in the direction.

In general, it may be said that the changes in audibility are of much more frequent occurrence and are proportionally much larger than the changes in direction. It seems, also, that the audibility changes follow a diurnal cycle as well as a seasonal

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cycle. Probably the underlying causes for the two changes are the same, but the directional changes only occur when the underlying cause produces a very special condition which does not have any considerable effect upon the energy absorption.

It might be expected, therefore, that most audibility variations would be produced by changes in the energy absorbed by the transmitting medium and more rarely by interference phenomena when the ionization causing absorption in general is so concentrated and segregated as to produce sharply defined conducting strata which would act as a reflector for the electromagnetic waves under conditions where the difference in path between a direct and reflected wave would be at most only a few half-wave lengths, and the angle would be small between the reflected and direct wave. The change in directional effect might be produced by the combination at the receiver of a direct and a reflected wave, but it would be necessary for the reflection to take place from a surface sufficiently removed in a horizontal direction from the receiver so that the reflected wave would have a very considerable horizontal component in order to cause the loop turning about a vertical axis to give an indication of a directional change.

In the second class of directional changes, it is assumed that there are two components, which have a quadrature relation both with respect to time and direction. This would require a reflected wave, as indicated above, from a surface at a considerable distance in a horizontal direction from the receiver, and at a distance which would make the reflected electromagnetic wave 90 degrees out of phase with the direct wave. If the distance were such that this phase difference was not 90 degrees, then the resultant wave at the receiver would show a direction depending upon the composition of the direct and reflected wave with respect to amplitude and direction. The phase combination of this reflected and direct wave might be almost anything, but would not affect the audibility of the signals as received by the loop, and so would not affect the general measurements upon which the direction indications depend.

We need now to examine with care the complex state existing in the atmosphere thru which the electromagnetic waves travel in order to determine the physical conditions upon which depend the observed phenomena of the direction changes and variations of audibility and strays.

The latest information that we have in regard to the conditions of the atmosphere shows that there are certain regions

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where there are discontinuities such as to make possible the formation of reflecting surfaces, assumed in our explanation of the observed phenomena. There are:

1. The Heaviside layer, assumed to be about 50 kilometers (30 miles) above the surface of the earth, and which has been discussed at considerable length by previous investigators.

There seems to be no doubt but that there would be a discontinuity and that it might very well happen that it would be much more pronounced during the night than during the daytime when the ionization produced by the sun's light might be expected to extend below the stratum of permanent ionization, diminishing rapidly as we proceed into the lower atmosphere. It might very well be that the greater transmitting distances observed during the night are obtained by the passage of the electromagnetic waves between the conducting surface of the earth and the conducting region of the Heaviside layer, which being a region of permanent ionization has a lower surface showing a sharp discontinuity, as soon as the ionization stops upon the disappearance of the sun and the ions present have rapidly recombined. There would, then, within this region below the Heaviside layer, be comparatively little free ionization and consequently but little absorption, allowing thus the transmission of radio signals over excessively long distances. During the daytime, the widely distributed ionization caused by the sunlight would result in large absorption of the energy, and this condition would be generally found to exist at all points. Irregularities in recombination at the disappearance of the sunlight might very well produce large regions in which the uniformity of the conducting layer is broken and where there persist for a time absorbing regions which would have considerable effect upon the audibility of the signals, and an erratic effect, as is usually observed in the case of the reception at night of radio signals.

The possibility of reflection from these large ionized masses or from the Heaviside layer itself in such a way as to produce the interference phenomenon which is indicated in the figures and which has long been known to the radio engineer as a "swinging" and "fading" of the radio signals at night, has been examined in detail by a number of engineers, and their conclusions will be found in the literature on the subject. It does not seem to us that it would be possible to have an interference produced by these reflections at the receiver, since the number of half-wave-lengths' difference between the two paths necessary in

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order to account for the observed phenomena would be so great as to make any sharply defined interference pattern out of the question, considering the nature of the reflecting surfaces and the characteristics of the transmitting medium. This would also be even more evident in the case of the changes of direction, since the distance would be very considerably greater on account of the necessity for having the horizontal component needed to explain the observed angular displacement of the direction of the wave. We must therefore look further for a region possessing the characteristics needed to produce the phenomena recorded above.

2. The diurnal vertical convection is limited to from five hundred to one thousand meters (1,500 to 3,000 feet) above the surface of the earth, depending upon the season of the year and the condition of the weather.

There would be a discontinuity which would appear at about the place where the measurements of penetrating radiation have shown that the effect of the radioactive constituents of the earth disappears. It does not seem to us that this would be a sufficiently well defined discontinuity to account for the reflecting strata needed to account for the observed phenomena.

3. There is, during the summer, a region which is defined by the cumulous clouds at four or five kilometers (2.5 to 3.1 miles) above the earth. We do not believe that this discontinuity is sufficient to account for the results.

4. There is, at approximately an elevation of seven kilometers (4.4 miles), a region known as the alto stratus layer, which is present in both summer and winter. This layer is not sufficiently well defined, and the causes for the discontinuity are not such as to lead us to believe that the observed phenomena can be accounted for by any reflections at this altitude.

5. There is always found a sharp dividing line between the troposphere and the stratosphere (isothermal layer) which occurs at an average altitude of ten kilometers (6.2 miles). This is dependent somewhat upon the season and also the storm areas. It is found that changes as large as three kilometers (1.9 miles) may exist between the cyclonic and anti-cyclonic regions. At this sharply marked boundary there is undoubtedly a layer of cosmic dust which may very well be strongly radioactive and so one of the principal causes of a stratum of permanent ionization. This is also the region where the cirrus clouds usually form, and which is consistently their upper

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limit. It is the most sharply marked discontinuity of which we have any definite knowledge in the upper atmosphere.

It is probable that such a stratum is present during the night when there is little movement in the upper part of the troposphere and that this conducting layer forming the boundary between the troposphere and stratosphere, will act as an excellent reflector. The movement caused by a cyclonic disturbance will change, however, the inclination of this conducting layer. There may also be considerable regions in the part of the troposphere, bordering on its discontinuity which are strongly ionized, due to the upward drift of the negatively charged particles and water vapor which have been segregated in a sufficiently large quantity so as not to be immediately neutralized after the disappearance of sunlight. The cessation of the turmoil resulting from the convection currents caused by the sun's action will allow these ionized regions to assume a stratefied form which will act as excellent reflecting surfaces.

As soon as the sun reappears and convection currents are re-established, they both destroy the sharply defined conducting layer and cause a widely distributed ionization which absorbs much of the available energy. The result is a decrease in signal strength, but no considerable distortion in the direction of the transmission.

During the night the long distance transmission could take place between the earth and the Heaviside layer with the intermediate conducting stratum at approximately ten kilometers (6.2 miles) above the earth's surface playing but little part until some discontinuity caused it to act as a reflector. This conducting layer would also make possible abrupt local changes in energy due to absorption which would later, be equalized by a gradual distribution thru the conducting layer, which is of course not perfect, from the region lying between it and the Heaviside layer.

During the daytime, the greater ionization and its wide distribution below the Heaviside layer, as well as the constant occurrence of ionization below the stratosphere would both tend to absorb the energy of the electromagnetic wave, and so decrease the observed signal strength at the receiving station, while preventing the reflections necessary for the distortions observed during the night.

In the same way also the periodic change in audibility or "swinging" may be due to the movement of interposed conducting masses of air which absorb the energy of the wave. This

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would be particularly true when the periodic change occurs thru a considerable time. The interposition of a series of storm regions moving along the same direction would produce such changes in audibility. A test of this might be the determination of such variations with respect to a north-and-south line and an east-and-west line, since there is a decidedly greater storm movement along the east-and-west line.

There is consequently the condition necessary for reflection from the stratum which is approximately ten kilometers (6.2 miles) above the surface of the earth. The distance is such that it will permit the formation of interference patterns at the receiving station, since the number of half-waves would not be too large to make that possible. This might occur quite rapidly and be due to the interference of a direct and reflected wave when the reflecting surface is changing its position with a velocity often found in the movement of cloud masses. The entire disappearance of directional effect when due to the rotation of the electromagnetic field would also be easily possible when the reflection occurs from the ionized layer between the troposphere and stratosphere or from an ionized stratum below that boundary.

It would be expected that the changes in direction would occur, therefore, only when the discontinuity due to the stratification of the ionized gasses and particles became effective during the night hours, and that these changes in direction would be produced only by reflection and never to any appreciable extent by a refraction, so that changes of small amount might be expected to be of frequent occurrence, while changes of large amount requiring a reflection from a surface beyond the receiving station, so as to allow for the resultant direction caused by the combination of the reflected and direct waves to make a shift as great as the change of 56 degrees 30 minutes in thirteen minutes as shown, would be of much more infrequent occurrence than the audibility changes, continually observed, Also, the very special case where there is a complete disappearance of directional effect would not be produced except under very particular circumstances which might not be expected to occur except at rather infrequent intervals.

The results obtained have been quite disconcerting to those of us interested in making a quantative use of the directional characteristics of the loop, but it is believed that a knowledge of what may occur, altho but rarely, will be of material assistance in further work. It is possible also that our knowledge of the upper atmosphere may be greatly advanced by a systematic

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employment of radio frequency oscillations and the use of quantitative methods in radio measurements.

The observations from which the values plotted in the figures were obtained were taken by detachments of radio operators under the command of:

Captain James E. Ives, at Tucson, Arizona.
1st Lieutenant Alfred J. Main, at McAllen, Texas.
1st Lieutenant Arthur H. Boeder, at Houlton, Maine.

Many of the computations and the plotting of the figures was performed by 1st Lieutenant Lee Sutherlin.

The careful and interested co-operation of the officers and men engaged on this work, is most thoroly appreciated, and we take great pleasure in acknowledging our indebtedness to them.

SUMMARY: As a result of a large number of systematic measurements on direction of incoming signals, using loop reception, variations of considerable magnitude in the apparent direction and occurring within short periods of time are found. Their dependence on length and character of wave are studied.

There are certain possible theories of transmission proposed to account for the observed phenomena, notably reflection at the atmospheric "isothermal layer" (6.2 miles or 10 kilometers high), and the production of rotating fields at the receiving station.

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DISCUSSION

Lester L. Israel: It appears that all of the loops experimented with it in the preliminary work were of the same form as that described in the paper which gave an asymmetrical polar curve for its directional characteristic. Accordingly, I would suggest a possible source of error in the experiments, which would lead to a different explanation of the variations in wave direction from any so far advanced.

It is well known to those advanced in radio compass work, that it is necessary to have a loop with an accurately symmetrical polar curve for correctly locating the direction of radio waves. Now the spiral type coil has a particularly pronounced asymmetrical curve as the preliminary experiments given in the paper show.

With this type of coil, the angle of maximum or minimum signal is dependent not only on the resonance tuning of the loop but also on the relative amounts of energy picked up by the loop acting as a loop and acting as an open antenna. It seems to me that this ratio would depend not only upon the amount of capacity unbalance, but also upon the dip in the direction of wave propagation or even the so-called slant of the wave front.

A wave coming from *the east* with vertical wave front and propagating horizontally might create a minimum signal with the axis of the loop 5° *south of east*.

A wave coming from *the east* with a 45° slant of wave front, as by reflection from overlying clouds or ionized layers, or by high resistance ground (dry weather), might create a minimum signal with the axis of the loop 25° *south of east*.

What I am particularly trying to suggest is that the lateral deviation indicated by such an unbalanced coil may really be a vertical deviation of the wave. Some such other cause must exist to harmonize with the consistent results obtained by other observers working with perfectly balanced loops.

Carl Kinsley: Many direction measurements were made using balancing capacities, but that method of measurement was not satisfactory for the investigation which was the subject of this paper.

Here it was desirable to use a method for taking the data which would correctly give the variations in direction which frequently took place with extreme rapidity. Only the horizontal component of the change actually occurring was noted

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in the recorded observations. The desirability of getting also the vertical component was pointed out in the paper.

Altho most of the work was done with long waves, a particular case is shown where the wave length was under one-thousand meters and the direction variations were ten degrees within an hour and the time of observation was during daylight when long waves usually gave correct directions. The short wave stations did not transmit during the night at the time these observations were made and so it was impossible to get the mass of continuous observations which were obtained in the case of long waves.

It can be said in conclusion that the method of measurement correctly showed the variations in directions and the large variations noted were almost always of short duration and came most frequently from midnight to four A. M. It is not likely that a single observer would be ready to note them. Only by continuous measurements over long periods of time was it possible to obtain the results reported in this paper.

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NOTE ON RADIO FREQUENCY MEASUREMENTS*

By

CARL ENGLUND

(RESEARCH ENGINEER, WESTERN ELECTRIC COMPANY, NEW YORK)

Several articles on radio frequency measurements have lately appeared,[1] and, as considerable work of this kind has been carried out in the Western Electric Company's laboratories, it has seemed that a brief note, summarizing some of the results arrived at, might be of sufficient interest to warrant publication. This is the more so as bridge methods do not seem to be in general use elsewhere.

Alternating current bridges for radio frequencies have been in use in the Western Electric Engineering Laboratory for upwards of three years now, and a return to volt-ammeter methods of making measurements is unlikely. During this time, the laboratory measurements on coils, condensers, and circuits required for the radio apparatus manufactured by the Western Electric Company, have been made on these bridges. In addition the necessary measurements for the "multiplex telephone" development recently perfected have also been made in this manner. Naturally, for a great deal of the work, high accuracy has not been necessary nor desirable, but measurements to better than commercial accuracy have been frequent, and while the ideal bridge for commercial work, that is, one fitted with two terminals for connecting the unknown and appropriate dial handles for balancing to the requisite accuracy, is yet unborn (and, owing to the range in frequency and impedance to be covered is likely to remain unborn), this has not prevented the use of apparatus possessing a considerable convenience in the way of accuracy and rapidity with which measurements can be made. Lack of time and a feeling that such special apparatus, sometimes only used for the length of the job, might not have general interest, has so far prevented publication of the work done. Some general observations on an all-around bridge and the essentials for successful use of it may not be out of place

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* Received by the Editor, July 22, 1919.

[1] Dellinger, PROCEEDINGS OF THE INSTITUTE OF RADIO ENGINEERS, volume 7, page 27, February, 1919; "Bureau of Standards Circular," 74.

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here, however. Credit for the progress of bridge measurements is rather widely distributed among the past and present members of this laboratory, the radio frequency work being really an extension of the work by bridge methods begun some sixteen years ago when Dr. G. A. Campbell and his assistants introduced the shielded bridge, since so successfully used. At present the greatest trouble and chief source of error is in the standards used; it is possible to balance much more accurately than is justified by the standards available.

Any voltmeter-ammeter—or in other words deflection—method reduces to the reading of one scale. No greater accuracy is possible than that which the operator can attain by bisecting the smallest divisions with his eye. To expect more than 0.5 per cent accuracy for such an observation, near the top of the scale, would be optimistic, and a lesser degree of accuracy is usually attained. By balancing two deflecting instruments against one another in some manner, such as opposing two thermocouples, or winding two opposing windings on a dynamometer coil, we are enabled to use a more sensitive instrument and in effect have better than a single dial setting. But this is nothing more than a type of potentiometer work and with no standards of current or voltage available for alternating currents[2] as there are for direct currents (the Weston or Clark cell), it is logical to replace the unsteady balancing emf. by the drop across a known impedance and we then have the a.c. bridge. At once we reduce the balance to one of invariant (with time) circuit constants and free ourselves from the variations in current to which every radio frequency source is subject and, in addition, operate on very much smaller currents. Two milliamperes input is amply sufficient for any bridge measurement of low impedances (1,000 ohms, say). Another point is that no source of alternating current known at present is free from harmonics and the oscillating audion, the steadiest generator known, has them in plenty. This fact is not overlooked by a thermocouple, and tuning them out is difficult. The bridge balance can easily be made almost wholly immune to harmonics. Again, suppose a coil with ferric core is to be used in a receiving set. No thermocouple will operate on such small currents, and a measurement on larger currents gives incorrect results since the constants of the iron vary radically with the current used.

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[2] Alcutt, "Proc. Am. Inst. Elect. Engrs.," page 83, February 18, 1918, has proposed a method of establishing a secondary current standard applicable to alternating currents.

A bridge then becomes necessary. Only those who have had experience with such apparatus know what an advantage it is to be independent of a fluctuating source of radio frequency current.

Various types of bridges have been made and used in the laboratory here, and for special cases some have decided advantages. Thus, a capacity bridge for capacities only, and an inductance bridge for inductances only are very useful if expense can in some measure be disregarded. For all around work, the bridge later described has been most useful. Contrary to what might be supposed, radio frequency bridge measurements are not much more troublesome than measurements at audio frequencies. Up to something like 200,000 cycles, a bridge performs amazingly well. When 1,000,000 cycles is reached, trouble begins to be experienced, in measuring coils, due to the electromagnetic induction of the coil on detector circuits and the other bridge arms. This can be partly avoided by making the physical dimensions of the bridge small and spacing the generator, bridge, and detector. Shielding against electromagnetic induction has not proved very successful; but electrostatic shields, if made of material thicker than tin foil, leave nothing to be desired.

It is quite necessary, in general, that both generator and detector be either grounded at some point or completely enclosed in a grounded shield. With vacuum tube generators and detectors, if the negative end of the tube filaments (filaments usually in parallel) is grounded, no shielding becomes necessary. The generator inductance unit must be a toroidal coil, however; and since this will be a wood (in effect, air) core, the winding must be carefully done or an external magnetic field will be produced. This coil is easily subdivided into equal fractions, and with a switch may be thrown from "parallel aiding" to "series aiding" connections and thus greatly extend the frequency range. Two and three subdivisions have been used giving inductance ranges of 1 to ¼ and 1 to 1/9. Since the frequency should not vary as the bridge arms are altered at least two tubes are necessary for the generator. One tube oscillates freely, and the other tube, which is the power output tube, has the voltage thus produced impressed on its grid. With 150 volts plate battery and two "L" tubes, one should easily get an output of 10 milliamperes thru 1,000 ohms. By using more than two tubes, a generator may be made which has less pronounced harmonics but this is usually unnecessary. Figure 1 gives a generator circuit in use at present for the range 22,000 to 1,000,000 cycles.

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If no terminal of the bridge may be grounded, two transformers will be necessary, for input and output, respectively. This is the case for a bridge used to make measurements on telephone or telegraph circuits where the effective impedance measured is center grounded. For work at commoner radio frequencies the bridge may be grounded at one corner, and only one transformer is necessary. The circuit diagram shown in Figure 2 gives such a bridge. For all around work, it is best not to include any standards in the bridge itself; these are best mounted in separate boxes and used as occasion requires. If any standards are to be included, a three dial resistance box is best. There is no objection to including standards in the bridge if only low impedance measurements are to be made, but they become objectionable for high impedance measurements. No advantage will be gained by having several sets of ratio arms, and resistance ratio arms are wholly preferable, both for the ease of construction and the fact that their impedance is independent of the frequency. They should be exactly alike and need not be more than 500 ohms in value. If they are wound with number

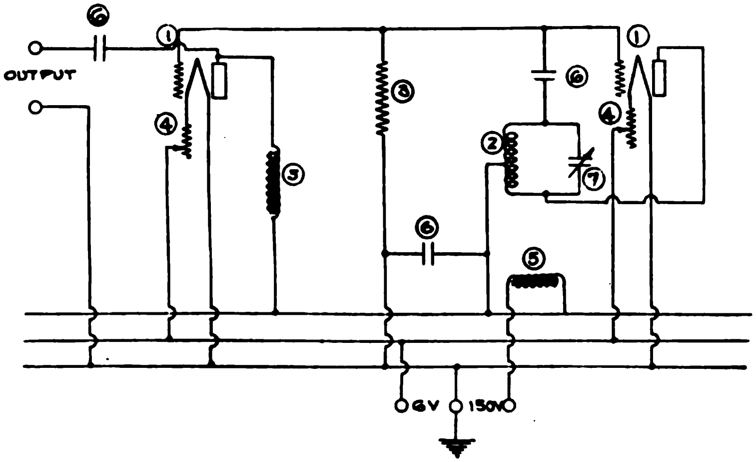

FIGURE 1—Radio Frequency Generator
① "E," "L," or "M"—Tubes
② Toroidal Inductance
③ 48,000 Ohms Grid Leak
④ 4-Ohm Rheostat
⑤ Radio Frequency Choke Coils
⑥ 1-Microfarad Paper Condenser
⑦ Tuning Condenser

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38 B. and S. gauge*, or smaller, "Advance" wire in a single layer in either "reversed loop" or Curtis fashion, and then given a 0.75 inch (1.9 cm.) spacing from the surrounding shield, they will perform satisfactorily. The circuit of Figure 2 has double shielded ratio arms, the inner shield is connected to the "A" corner of the bridge and the outer is grounded. The capacity between the two shields thus bridges the generator and is without effect on the balance.

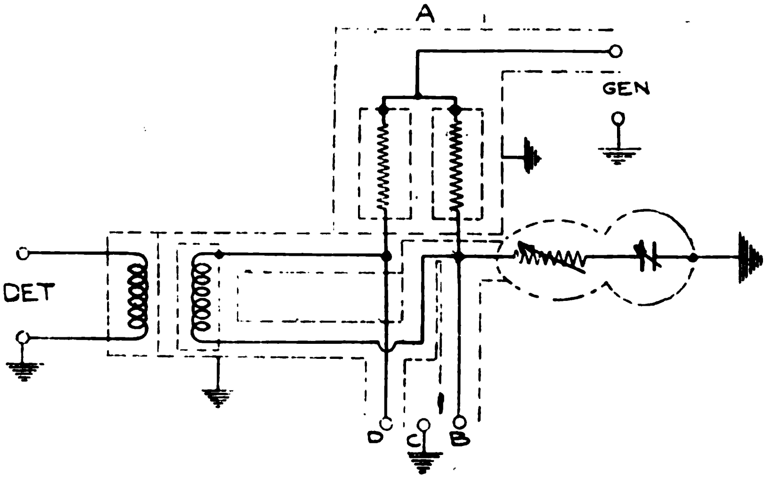

FIGURE 2—Utility Radio Frequency Bridge
(Shielding is dotted)

The output transformer is also double shielded, and preferably it contains a toroidal wood core and is mounted in an iron container. The distributed capacity between the primary winding and shield is without effect on the bridge balance since this balance implies that all parts of the primary winding and inner shields are at the same potential. The capacity between inner and outer shield is, in effect, in the "BC" arm of the bridge and a balancing condenser with either a variable low series, or a high shunt resistance, must be included in the "CD" arm to give the initial balance. For low impedance measurements this balancing member is unnecessary but it must be present when high impedance measurements are made. As a check on the bridge performance, we have usually included a switch so as to interchange the ratio arms and compare the two results. This

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* Diameter of number 38 wire = 0.004 inch = 0.01 cm.

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is convenient but not absolutely necessary. It must be borne in mind that, at radio frequencies, the geometry of the layout must be considered and if a coil is being measured when so placed that its magnetic field generates considerable emf's. in the bridge network, trouble will result, The mutual inductance between primary and secondary in the transformer should be large in order to overwhelm small mutual impedances between bridge arms, detector, generator, and so on, and at the same time not exceed such values that the secondary may be fairly sharply resonant when tuned. For a range like 20,000 to a million cycles, a single transformer is somewhat unsatisfactory but normally preferable to any other arrangement since transformer coils (air core) with many taps are objectionable and two independent transformers, with switch gear, means too much apparatus. Except for such measurements as are, in effect, a severe test of the bridge, one transformer has been found good enough.

The balance is always observed by using an auxiliary source, and producing a beat note in an ordinary telephone. A good detector will be obtained if one detector and two amplifier tubes are used. This, if designed to give maximum amplification, will give excessive and selective low frequency amplification (since the transformers become anti-resonant), which is undesirable. Less amplification over a greater frequency range is to be preferred. When the ear tires of one note another may then be used or the operator may select any frequency best suited to his ear. Only primary (or secondary) batteries have proved successful as sources of filament and plate current for the detector and amplifier tubes and to save dry battery renewals high "μ" tubes may be used instead of ordinary amplifier tubes and give the same amplification. Overloading is then easier, however. A noisy detector circuit usually means that either the plate or filament battery has run down or developed a bad connection. The greatest trouble likely to be encountered is that of false balances due to overloading the detector tube. Large harmonics or too large input of the auxiliary source will give false balances. It is not hard to guard against when this is recognized. The detector may be made to oscillate and thus act itself as an auxiliary source, but it is much better to separate the detector and oscillator functions and have a separate oscillator to give the beat note. The input from the auxiliary source is varied by moving the oscillator about on the table. Figure 3 shows a detector circuit.

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The range from 5,000 to 15,000 cycles, when covered by using a beat note in the telephone receiver, gives trouble, as the harmonics of both generator and auxiliary oscillator are not far enough apart, and the operator easily gets "lost" in a jumble of notes.

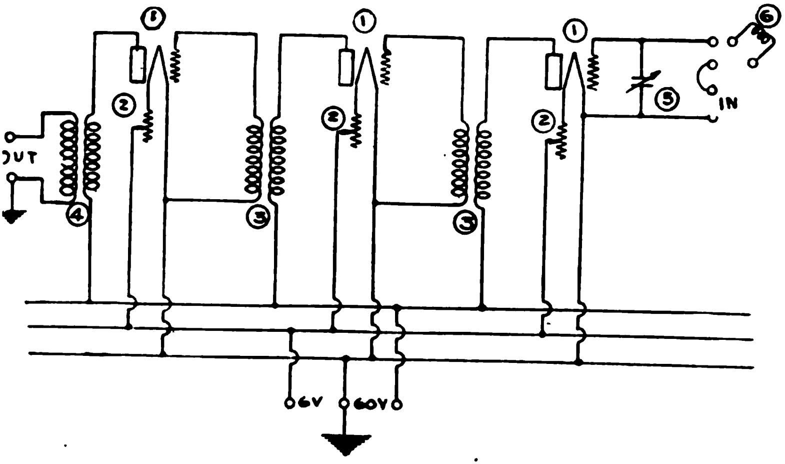

FIGURE 3—Detector Amplifier

① "D" or "V" Tubes
② 4-Ohm Rheostats
③ 61 A Retardation Coils Used as 1:1 Transformers
④ 201-A Transformer 400,000 to 20,000 Ohms (Use High Impedance Telephone)
⑤ Variable Condenser
⑥ Auxiliary Tuning Coils

Since most observers' ears are reasonably sensitive well over 10,000 cycles it has been found practicable to construct special telephone receivers and listen direct up to 10,000 cycles. Above this frequency, the beat method is used.

As stated, the limitations encountered are those of the stand-

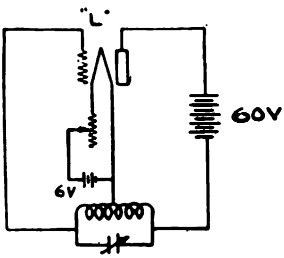

FIGURE 4—Heterodyne Oscillator

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ards used. Settings giving a balance of one part in 10,000 are not difficult, but in the absence of standards mean nothing. Air condensers with negligible dielectric losses, calibrated at low frequencies; and carefully wound resistance units of number 38 or finer "Advance" wire*, and adjusted with direct current, have been so far used as the basis of all work. Coils are tuned with such a condenser and measured as a pure resistance. Frequency determinations are made by balancing a calculated coil, of negligible shunt capacity, with the standard condenser against a resistance in the bridge. Condenser measurements are usually made by tuning the condenser with a variable inductance, whose other properties are unimportant, and substituting the standard condenser and retuning. Direct balance of the unknown condenser against the standard is possible but the first method makes the balance a low impedance measurement which is usually an advantage. In determining the resistance of coils and condensers, a standard resistance may have some reactance without introducing any error. The so-called "shunt" capacity of coils is determined by successively balancing the coil with the standard condenser at two frequencies. The capacity then follows from the formula[3]

$$C_o = \frac{C_1 - \frac{\omega_2^2}{\omega_1^2} C_2}{\frac{\omega_2^2}{\omega_1^2} - 1}$$

Absolute frequency determinations should be made by bridging the gap from an audio frequency (determinable with a standard tuning fork or siren) and the desired radio frequency, by means of an oscillator of pronounced harmonics of high order.

It is expected that further results of this work will be published at a later time, which will throw additional light on the advantages of bridge methods as compared with deflection methods.

Research Laboratories of the American
Telephone and Telegraph Company and
Western Electric Company, Incorporated.

SUMMARY: After discussing the need for a radio frequency bridge of general utility, the bridge method is critically compared with indicating, null, and potentiometer methods.

Certain precautions in the shielding and coil construction of such bridges are considered; and the specific form of bridge used by the author is described in detail. Beat note with amplification and telephone indicator of balance point are used. Some applications of the bridge are then given.

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* Diameter of number 38 wire = 0.004 inch = 0.01 cm.

[3] Weinberger, PROCEEDINGS OF THE INSTITUTE OF RADIO ENGINEERS volume 5, page 361, 1917.

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NOTE ON THE INPUT IMPEDANCE OF VACUUM TUBES AT RADIO FREQUENCY*

By

Julius Weinberger

(Research Engineer, Radio Corporation of America, New York)

In the various papers which have been published on the behavior of vacuum tubes with three internal elements, one frequently finds the statement that the input impedance (the impedance of the grid-to-filament path) of the tube is infinite when the grid is maintained at a negative potential with respect to the negative end of the filament. That is, it is assumed that since the d.c. characteristic of grid potential against grid current shows that no current will flow between grid and filament when the grid is negative (in a high vacuum tube), the behavior with alternating, or radio frequency voltages, will be the same. While at audio frequencies this path may act as practically an infinite impedance, I have found that at radio frequencies conditions are quite different.

In tubes, as they are now built, there exists considerable capacitive coupling between the grid-to-filament path and the plate-to-filament path; this coupling is sufficiently strong at radio frequencies to cause the apparent input impedance of the tube to be a function of the character of its output circuit. For example, I have noted that if there is a resistance in the output circuit (as when the tube is used in a resistance coupled amplifier), the input impedance will depend on the value of the output resistance. If the output circuit consists of an inductance, the input impedance will act as a negative resistance, which will reduce the resistance of the input circuit (for example, the secondary circuit of a receiving set to which the tube may be connected as a detector) or even give rise to oscillations.

Output Circuit Containing Resistance

In order to investigate the nature of these effects experimentally, the set-up shown in Figure 1 was made. A sustained wave oscillator operating at a wave length of 6,000 meters was

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located at a considerable distance from the set-up, and a pair of leads brought out to a single loop of wire, which was in turn, coupled to a second single loop. The coil *L* (about 9 millihenrys) and condenser *C* served as a receiving circuit to which the tube was connected. Loosely coupled to *L* was a circuit containing a coil, variable condenser, crystal detector, and portable galvanometer (the latter having a sensitivity of 0.1 microampere per scale division—one scale division equal to 2 mm.).

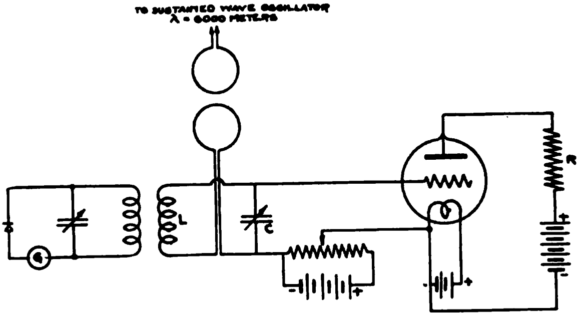

FIGURE 1—Experimental Set-Up

In series with the grid of the vacuum tube was placed a battery and potentiometer which served to maintain the grid at a negative potential with respect to the filament. The resistances *R* in the output circuit of the tube were of the deposited tungsten film type made by the General Electric Company.

In order to study the operation of the tube, the procedure was as follows: The tube was connected to *LC*, with various resistances in its output circuit, and the deflection of *G* noted for each case. A negative potential of 0.8 volt was maintained on the grid; the radio frequency voltage across *C* was always considerably less than this and no grid rectification was therefore possible.

After completion of the observations, the grid lead of the tube was disconnected from *C*, and the filament extinguished; then various resistances of the tungsten film type were shunted across *C* and the galvanometer deflections again noted. A curve of these is given in Figure 2. In all cases, the circuit *L C* was kept tuned to resonance by adjusting *C*.

The equivalent resistance of the tube and its associated output circuit could therefore be read off from the curve of Figure 2 by finding the resistance corresponding to a given galvanometer deflection.

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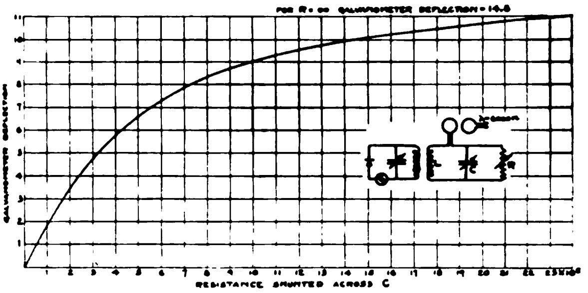

FIGURE 2

EXPERIMENTAL RESULTS

The results of these experiments are given in Table 1. It will be noted that as the output resistance is varied from zero to 5 megohms the apparent input resistance varies from infinity down to a minimum of 50,000 ohms and then up to 170,000 ohms. That this is sometimes equivalent to a considerable increase in effective resistance of the circuit *L C* is evident from the fact that a resistance of 2 megohms in the output circuit of the tube had the effect of apparently quadrupling the resistance of *L C*.

TABLE 1

Tube: Western Electric Company's Type D.
Plate Battery: 56 Volt; Filament Current: 1 ampere.
Grid Potential: 0.8 Volt Negative.
Wave Length: 6,000 Meters.
$L = 9.7$ millihenrys. $C = 0.001$ microfarad.

Resistance in Plate Circuit of Tube, ohms	Galvanometer Deflections Scale Divisions	Effective Input Resistance (Indicated by Galvanometer Deflection) ohms
0	14.8	Infinite
45,000	2.4	130,000
100,000	1.0	60,000
850,000	0.8	50,000
1,450,000	1.0	60,000
5,000,000	3.0	170,000

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It is possible to explain the above results on the basis of the following theory:

For radio frequency, at least, a tube with resistance in its output circuit has an effective input resistance which is equal to the total plate circuit resistance divided by the voltage amplification given by the tube for the particular output resistance in question.

By "total plate circuit resistance" is meant the sum of the internal resistance of the tube and the output resistance; by "voltage amplification for a particular output resistance" is meant the ratio of the voltage obtainable across the output resistance to that impressed on the input terminals of the tube. The latter is measureable on a modified Miller bridge, as shown in Figure 3. The theory of the regular Miller bridge for measuring the amplification factor of a vacuum tube has been published.[1] This modification permits the measurement of the ratio of the voltage across the output resistance R to that impressed across the grid and filament. The operation of the apparatus of Figure 3 will be obvious from the diagram.

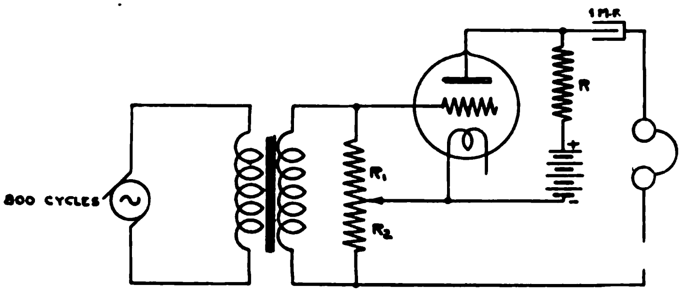

FIGURE 3—Modified Miller Bridge for Measurement of Voltage Amplification

In order to test this theory it was necessary to determine the total plate circuit resistance with various output resistances. This was done as follows: With a plate battery of 54 volts and the usual negative grid potential of 0.8 volt, a number of tungsten film resistances were successively inserted in the plate circuit. With each resistance the variation in plate current was observed on a sensitive d. c. galvanometer when the plate battery potential was increased and decreased slightly from the value of 54 volts (a variation of one or two volts was made).

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[1] John M. Miller, PROCEEDINGS OF THE INSTITUTE OF RADIO ENGINEERS, volume 6, page 141, 1918.

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The variation in battery potential divided by the corresponding changes in current gave the total plate circuit resistance. The values are tabulated in the second column of Table 2. In the third column are given the values of effective input resistance, corresponding to the output resistances of the first column, which have been taken from Table 1. In the fourth column are given the ratios of columns 2 and 3. These ratios correspond approximately to the voltage amplification values for the resistances of column 1, which are given in the last column.

TABLE 2

Resistance Inserted in Plate Circuit ohms	Total Plate Circuit Resistance (Measured) ohms	Effective Input Resistance (From Table 1) ohms	Ratio of Total Plate Circuit Resistance to Effective Input Resistance	Voltage Amplification for Resistance of Column 1 (Measured)
0	....	∞	0	0
45,000	220,000	130,000	1.7	1.8
100,000	325,000	60,000	5.4	5.2
850,000	1,050,000	50,000	21.0	23.5
1,450,000	1,860,000	60,000	31.0	28.9
5,000,000	5,450,000	170,000	31.2	31.0

GENERAL NOTES

The tube used for the above tests was a Western Electric Company's Type D. Similar behavior, at the wave length used, was observed with a Western Electric Company's Type J, and a General Electric Company's Type G tube.

Lack of time prevented the carrying out of extended experiments with inductive and capacitive output circuits and at other wave lengths. However, it was noted that an inductance in the output circuit of about 15 millihenrys caused a *diminution* of resistance of the circuit $L\,C$ to about one-fourth its value. That is, the effective input impedance of the tube was that of a negative resistance. On the other hand, shunting a resistance in the plate circuit by a condenser of 0.001 microfarad, caused the effective input impedance (which previously had been a low

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resistance) apparently to become an infinite resistance. That is, a capacitive output circuit produces neither a positive nor negative resistance effect at the input terminals.

Research Department of the
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SUMMARY: It is shown experimentally that the input impedance of a three-element vacuum tube at radio frequency is not infinite, as heretofore supposed, but that because of the capacitive coupling between input and output circuits within the tube itself, the input impedance greatly depends on the character of the output circuit. Experiments with resistance in the output circuit are given and a theory is advanced to explain the results observed. The general effect of inductive and capacitive output circuits is mentioned.

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DISCUSSION

Lewis M. Hull (by letter): Mr. Weinberger's paper shows his appreciation of the importance of a matter which will, in the future, surely figure largely in the intelligent design of all electron tube receiving apparatus. However, I wish to comment on his method of measuring the input impedance. It seems that the effect upon the current thru L (Figure 1), which is what is indicated indirectly by the galvanometer deflection, of connecting a pure resistance across the condenser C, is intended to replace entirely the effect of the input impedance of the tube that in a similar connection, or at least the resistance component of that impedance. Apparently it is assumed that the input impedance is a pure resistance; the statement that "the circuit LC was kept tuned to resonance" does not refute this, since the addition of a parallel resistance would detune the circuit. Attention is therefore called to two points in this connection. (In this discussion C_1 = capacity between grid and filament, isolated; C_2, grid and plate; and C_3, filament and plate.)

(1) This method does not indicate the total impedance of the tube, as may be deduced from the observed result: "with the external plate circuit resistance equal to zero the effective input resistance is infinite." The input impedance under these conditions is really C_1+C_2. Taking average values for a "D" tube and socket ($C_1 = 12\,\mu\mu$f.; $C_2 = 18\,\mu\mu$f.), this makes the impedance at 6,000 meters, 106,000 ohms, which is less than two of the resistance values given in Table 1. This impedance, being wholly reactive, and representing a detuning of the capacity C by only 3 per cent., would, of course, give a deflection of the galvanometer closely equal to the limiting resonance value, attained when R is infinite.

(2) Likewise the galvanometer deflection obtained with the tube connected across C, translated in terms of the R in Figure 2, does not indicate the resistance component of the input impedance. It has been shown ("Dependance of the Input Impedance of a Three-electrode Vacuum Tube Upon the Load in the Plate Circuit," Scientific Paper of the Bureau of Standards, Number 351) that the input impedance of a tube having a pure resistance load in the plate circuit can be represented by a resistance in series with a capacity. Over a wide range of radio frequencies, both the resistance and capacitive components of the impedance are important. At the wave lengths employed by Mr. Weinberger, the input capacity is given by

$$C_g = C_1 + C_2\left[1 + \frac{\mu R_p}{R_o + R_p}\right]$$

which becomes C_1+C_2 when R_p is short-circuited. The fraction in the brackets is, of course, the over-all voltage amplification. Thus it would seem that the phenomena in the measuring circuit are more complicated than is implied by Mr. Weinberger's discussion. If a certain reading be obtained at resonance in the *LC* circuit, for a given value of the resistance *R*, it must be apparent that for a series combination of resistance and capacity giving exactly the same deflection, *R* does not necessarily represent either the effective resistance or the total impedance, particularly in view of the fact that the capacity-reactive component of this impedance is usually larger than the resistance component.

Julius Weinberger (communicated): Mr. Hull's discussion brings out a number of points which are quite correct. Dr. Miller has, no doubt, covered the theory of operation of a vacuum tube in the admirable paper cited by Mr. Hull, in a much more thoro manner than the foregoing note of mine. However, the data given in this note was taken about a year before Dr. Miller's paper appeared and was written up at that time, but owing to other questions involved, publication could not be permitted until recently.

It is possible that the method employed in these experiments will prove useful to investigators who are limited in the amount of apparatus at their disposal. Dr. Miller's method, using a capacity bridge at 1,000 cycles, is possibly more accurate in its determination of the various capacities which enter into this phenomenon; but even Dr. Miller states in his paper that the dielectric losses in the tube capacities exert an important effect on the input impedance, and this in itself would indicate that a radio frequency measurement is preferable (since it cannot be assumed that the dielectric losses at radio frequencies can be computed from audio frequency observations). Moreover, the determination of the capacity component of the input impedance is quite possible with the radio frequency method by computation from the observed amount of detuning on the variable condenser. When a tube is connected to the secondary circuit of a receiving set, the resistance component is all that is important since the capacity component (which may just as correctly be assumed as being in parallel with the resistance, as in series) is then compensated for by the detuning of the variable condenser. The radio frequency method here shown then indicates directly what happens in the receiving circuit.

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