VOLUME 4 OCTOBER, 1916 NUMBER 5

PROCEEDINGS
of
The Institute of Radio Engineers
(INCORPORATED)

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TECHNICAL PAPERS AND DISCUSSIONS

EDITED BY
ALFRED N. GOLDSMITH, Ph.D.

PUBLISHED EVERY TWO MONTHS BY
THE INSTITUTE OF RADIO ENGINEERS, INC.
ONE HUNDRED AND ELEVEN BROADWAY
NEW YORK

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PHYSICAL ASPECTS OF RADIO TELEGRAPHY *

BY

JOHN L. HOGAN, JR.†

(CHIEF RESEARCH ENGINEER, NATIONAL ELECTRIC SIGNALING COMPANY)

Very soon after wire telegraphy was first accomplished, conditions were encountered in which the desirability of effecting electrical signaling without connecting wires became apparent. Islands were to be reached by telegraph, and rivers were to be crossed. It was difficult to keep cables in operation in some of these locations, and some means of eliminating the wire connection was therefore sought. As a result of this need, there arose a number of methods of telegraphing without wires, some of which were based on conduction, others on magnetic induction, and still others on electrostatic induction. It was not at all difficult to explain the operation of any of these; in the conduction system the numerous paths of current thru the earth or water could be traced by imaginary lines, and in the induction systems the lines of force could be visualized. The physical mechanism of the transmission was as clear to nearly all the workers in the telegraph art of that period as was the mechanism of the ordinary wire telegraphy.

When radio telegraphy was introduced, however, " wireless " became a mystery to most people. Communication between ships, and from ship to shore stations became common, and the attention of the public was attracted more strongly than it had been during the lives of the older systems. Scientific interest was aroused all over the world as a result of Marconi's first experiments. Scientists, engineers and laymen in all civilized countries attempted to duplicate the early apparatus and to secure similar effects. Not many of the experimenters understood the physics of what they were attempting, and this condition gave rise to a

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* Paper presented before the Pan-American Scientific Congress, at Washington, D. C., for The Institute of Radio Engineers, on January 4, 1916.

Presented at Baltimore, Md., under the joint auspices of the Baltimore Section, American Institute of Electrical Engineers and the Department of Engineering, Johns-Hopkins University, on February 11, 1916.

† Alternate to Second Pan-American Scientific Congress, for The Institute of Radio Engineers. Vice-President of The Institute of Radio Engineers, New York.

semi-technical and technical literature, a large part of which it is almost shocking to consider. Such conceptions as the operation of a coherer by the impinging of waves directly upon it, and the deflection of waves from the " ether " to the coherer by means of an elevated wire, were carried into the new longer-wave radio telegraph art from the old laboratory experiments with electromagnetic waves a few centimeters in length. Ideas of radiation from antennas, the production of waves by impulsive spark discharge, the role of the earth in transmission, and related matters were extremely vague.

Of course, the general rule of indefinite and erroneous ideas as to the physical mechanism of radio telegraphy was proven by a few notable exceptions. Some few earnest workers in the new art undoubtedly had good engineering and clear physical conceptions of radio telegraphy, even in the earliest days. Their writings during the few years near 1900, prove definitely that their ideas were clear; in fact, the records of that time are very fair indications of the mental attitudes of the numerous persons then interested in radio signaling.

The veil of mystery which covered radio workings almost completely was not in any way lessened by commercial operations during the years which followed practical applications of the new art. From about 1904 to 1909, the entire radio art fell into commercial disrepute in the United States, thru the illegitimate commercial operations of several notorious stock-selling agencies. This unfortunate condition undoubtedly had a great affect upon the development of radio technology, since it repelled earnest scientific investigators. It is probable that many of the engineering problems of radio telegraphy which have only been solved within the past three or four years, would have been overcome much earlier had not radio telegraphy been so violently exploited commercially.

Within the past five years, the realization has been growing that there is essentially no reason why radio telegraphy should be made a mystery. It is of course true that ultimate causes and ultimate effects are, and will probably remain, mysteries to all of us; nevertheless, we do secure and make use of knowledge concerning immediate causes and their effects. We collect information as to what actions produce certain results, and, by correlating these in quantitative systems, create our applications of the physical sciences.

Radio telegraphy is now, and has been for some little time, at that stage of its technical development where it can be considered to consist of a series of expected effects, resulting from a series of controllable causes. In other words, radio telegraphy is upon an engineering basis. Its instruments can be designed to meet various needs, and their operation can be predetermined with accuracy. The physical nature of these controllable causes is closely allied with that of the elements of all electrical systems; in fact, apparatus for radio telegraphy consists merely of varied aggregations of the same physical elements which are used in all branches of electrical engineering.

The scope of natural phenomena made use of in radio telegraphy, is, however, considerably greater than that which occurs in any single branch of ordinary engineering. The electrical actions of power transmission, the conversion of current frequencies, the peculiar conditions in transmission lines of distributed electrical constants, the free wave-motion effects of radiation, reflection, refraction, interference and absorption, the delicate engineering problems of small powers, such as occur in telephony, and the physics of sound generation and recording are by no means all of the important fundamental actions involved.

When the application to radio telegraphy of the physical elements using these principles is considered in greater detail, it is found that the units are merely those of every-day engineering. The inter-relations are perhaps peculiar to the conditions of radio signaling, but the elements are the same. Radio telegraphy is merely an additional practical system for the communication of intelligence, and, like all such systems, depends fundamentally upon only three parts; viz., a medium of transmission, a means to excite this medium, and a means for observing the excitation of the medium. For example: in ordinary speech, the vocal system sets into vibration, according to a conventional code called a language, a medium of transmission (which is, in this case, the atmosphere). The air vibrations, like other free waves, travel thru space in all directions, and are intercepted at the receiving point by an ear and auditory system which retranslate them into the language code. Thus intelligence may be transmitted in ordinary conversation, by the interaction of the three fundamental elements above set forth.

These three elements are present in all communication systems. In the wire telegraph, the battery and key are the exciting-source of the transmitter, the transmission medium is the hypothetical ether surrounding the line wire which guides the electromagnetic pulses to the receiver, and the final element is the telegraph sounder which magnetically observes the effects produced by the transmitter. Similarly, in the telephone, the currents over the line wire are an inseparable part of the electromagnetic disturbance produced by the combined action of the transmitting battery and modulating microphone; these voice-modulated disturbances and their accompanying currents are observed magnetically by the telephone receiver at the distant station.

In radio telegraphy, the three fundamental physical elements are also present. The medium of transmission is the same luminiferous ether which is assumed to carry light vibrations thru space. The transmitter may consist of any one of a large number of forms of apparatus which will serve to vibrate this ether of space according to some pre-arranged code. The receiver, likewise, may be any one of many types of instrument which will serve to detect ether vibrations and to produce appreciable effects, dependent in occurrence or vigor upon the intensity of the ether vibrations.

In the first transmitters for radio, a spark gap was connected across the secondary terminals of an induction coil. one side of the spark gap was connected to earth and the other side to an elevated insulated conductor as in Figure 1. Upon each inter-

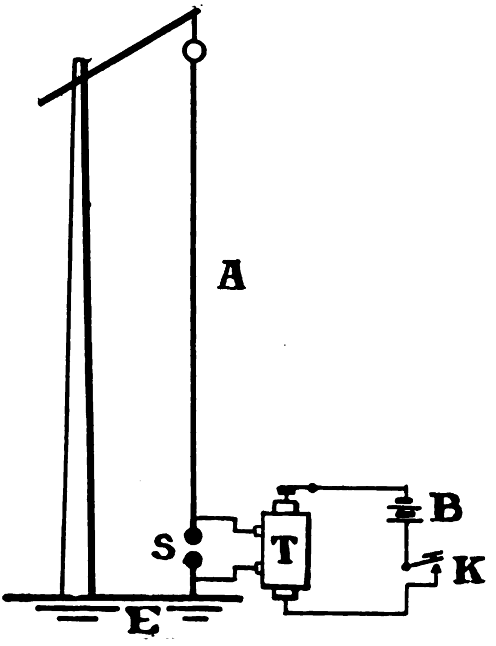

Figure 1

ruption of the coil's primary circuit, a surge of potential developed in the secondary and charged the elevated wire to a definite potential with respect to the earth, so storing in it a definite amount of energy depending upon the voltage and capacity of the system. If the spark gap was sufficiently narrow, the potential would reach a value more than high enough to rupture the air between the electrodes, and the energy which had been stored in the aerial wire would discharge across the spark gap in a rapidly damped oscillation. That is to say, during the instant of passing of the spark, an alternating current of very high frequency and having constantly decreasing maxima would exist in the aerial wire. The frequency of this alternating current is dependent upon the capacity and inductance of the antenna system; and it was soon found that by inserting lumped inductance at the base of the antenna, as in Figure 2, the frequency of oscillation could be reduced as far as desired. It was also found that if instead of charging the antenna and allowing it to discharge directly across a spark gap, a condenser in a separate circuit were charged and allowed to discharge thru an inductance, this inductance might be magnetically coupled to the antenna system, as

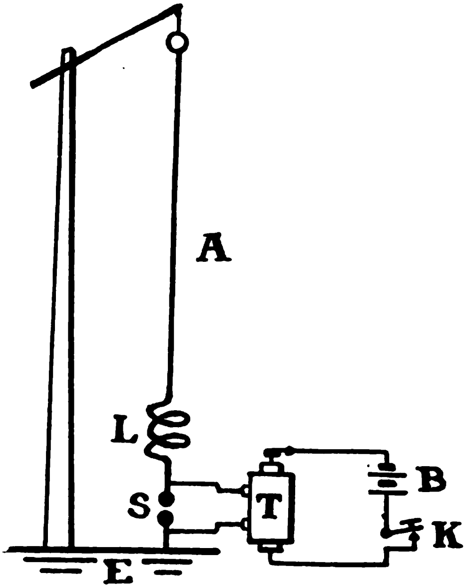

FIGURE 2

in Figure 3, and would, if the capacity and inductance relations were correctly adjusted, produce a more intense and less rapidly decadent high frequency current in the aerial wire.

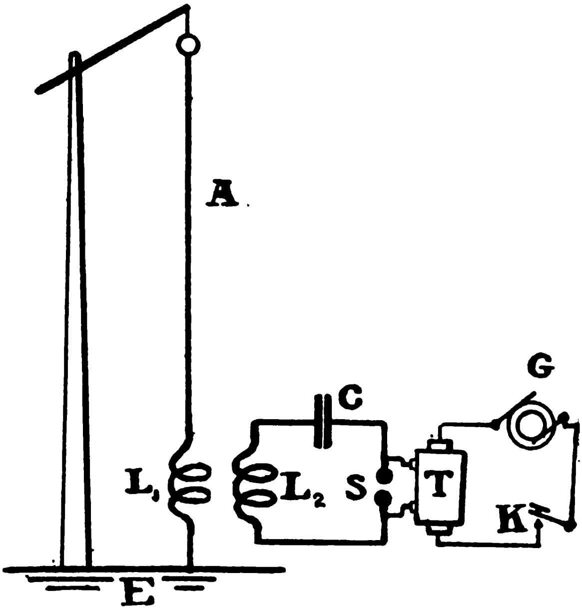

FIGURE 3

It was also found possible to generate high frequency alternating currents directly in the antenna system by making that conductor a part of the circuit supplied from a special high frequency (or so-called radio frequency)* alternator. This arrangement results in an absolutely uniform flow of high frequency current in the antenna system, so long as the alternator is connected and in operation. This is shown in Figure 4.

The effect of any alternating current in any conductor is to produce in the ether about it interlinked magnetic and static fields. These fields whirl, reverse, expand and contract according to the variations in direction and intensity of the current in the conductor. Figure 5 shows the wave field spreading from such a system. If the frequency of the current becomes high, (of "radio frequency"), say beyond 10,000 cycles of alternation per second, a large part of its energy is sent off into space as electromagnetic

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* Frequencies above 10,000 cycles per second are arbitrarily called "radio frequencies."

waves, which always have the same frequency as the current. If, as in a radio telegraph antenna, the conductor carrying the radio frequency current is partly or wholly vertical and has one end connected to earth, the electromagnetic waves which are sent off will have inseparably associated with them alternating

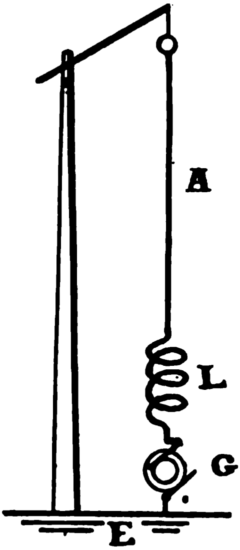

FIGURE 4

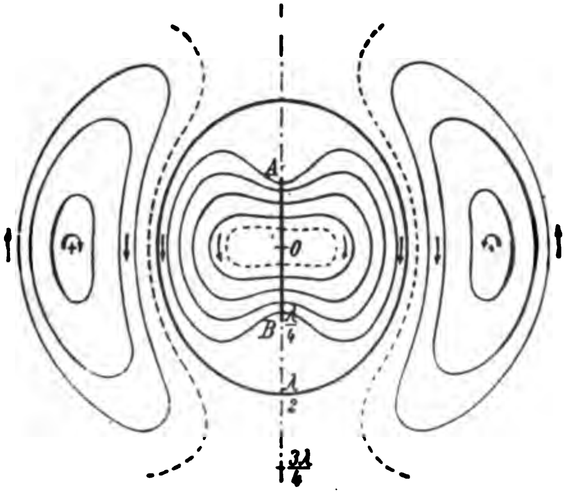

FIGURE 5

currents in the surface of the earth. The waves will spread in all directions from the transmitting aerial, but will always have their bases terminating upon the earth's surface, as in Figure 6.

It is a physical property of such travelling electro-magnetic waves that they set up alternating currents of their own frequency in any conductors upon which they impinge. If we project into the air an antenna system consisting of a number of wires, and connect the lower end of this aerial to the ground, (perhaps thru a suitable observing instrument, as in Figure 7), the electromagnetic waves which arrive at this structure will set up in it alternating currents. If these currents are sufficiently intense, their presence may be detected by the indication on a thermo-ammeter placed in series at the base of the aerial wires; if, as is common in radio receiving stations, their amplitude is quite small, some more delicate receiver will be necessary to indicate their presence. Obviously, if this receiver is of such form that it gives a visible or audible signal to show the time of beginning and cessation of the arrival of electromagnetic waves, it may be associated with a distant controllable transmitter for the purpose of communication. Any convenient code of signals may be used, for instance that devised for use on the Morse telegraph. To transmit actual messages, then, it is only necessary to set up short and long series of waves, corresponding to dots and dashes, and, at the receiver, to produce short and long effects in accordance with these short and long series of waves.

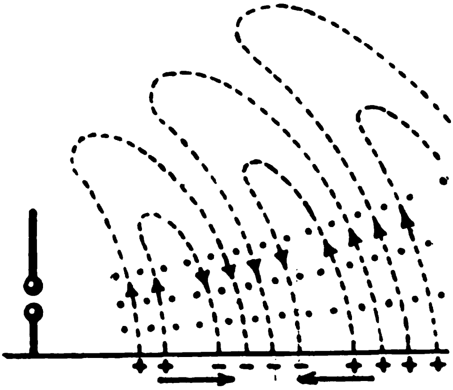

Figure 6

The receivers originally used were very crude, and usually consisted of imperfect contacts which were adjusted to be just on the point of closing. The strong voltage impulse set up in an aerial system by a powerful arriving wave was conveyed to the terminals of such a loose contact instrument, or coherer; and was usually enough to complete the closure of a battery and relay circuit also connected across the coherer terminals, as in Figure 8.

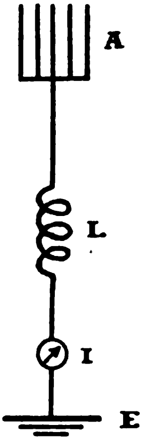

FIGURE 7

After the receipt of each signal this device required mechanical or other agitation, in order to break its internal circuit and prepare it to indicate another signal. In this type of apparatus the intensity of the first impulse received was of the greatest importance; and the operation was not aided in any way by waves received after the first strong disturbance. It was soon found that greater final sensitiveness could be secured by using thermal or electrolytic receivers, which rectified and added together the small effects produced by each individual wave of a signal, and gave a cumulative indication on some instrument such as a telephone. Practical firm-contact solid rectifiers were later discovered, which acted upon the cumulative and proportional principle and also produced indications by conversion of the radio frequency antenna currents into pulsating currents which could operate a telephone. Still later such vacuum tube rectifiers as the audion, which combines unidirectional conductivity and amplifying action and thus gives great sensitiveness, were developed. In connection with ordinary spark transmission all these receivers have proved useful; for operation with the continuous waves produced by direct operation of a radio frequency alternator other and more complicated forms of receiver have been devised.

Electromagnetic waves produced by radio telegraph transmitters are not the only disturbances which vibrate the medium of transmission which we call the ether. This same hypothetical body conveys those extremely rapid vibrations which produce the sensation of light, and those, somewhat lower in frequency, known as radiant heat. The range of vibration frequencies for these two classes of electromagnetic waves lies well above ten million per second, and hence they produce no appreciable direct effect upon radio telegraph receiving stations. The wave frequencies used in radio telegraphy are in general from one million down to as low as twenty thousand per second. Even within this range, however, there are natural ether waves, caused by various forms of electrical disturbances in nature, which produce unfortunately violent effects at radio telegraphic receivers. The natural atmospheric electrical disturbances may be divided into two main classes, those produced by "static" and those produced by "strays." Static effects appear, in general, as currents flowing between the aerial system and earth as a result of the discharge into the antenna of the electrification of dust and moisture particles drifting thru the atmosphere. Ordinarily these discharges create little or no difficulty in radio telegraphy, and they are

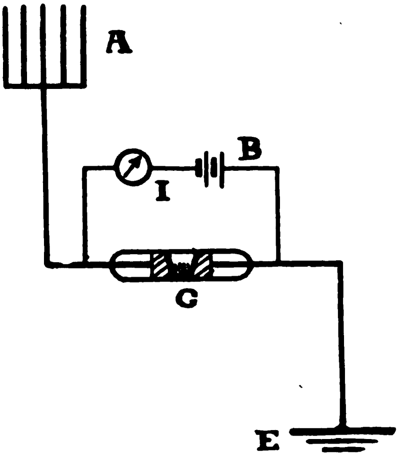

FIGURE 8

usually, not concerned with electromagnetic radiation, except when they are sufficiently violent to set up waves travelling outward from conductors in which they pass to earth. Strays, however, are looked upon as electromagnetic impulses, (often of great violence), which are set up in the ether by some distant and usually powerful electrical discharge; e.g., lightning. These heavy impulses ordinarily produce, in receiving aerials, damped alternating currents of the natural or tuned frequency of the aerial wire system.

In order to appreciate more fully the practical inter-linkage of these various physical characteristics, it is desirable to consider a little more closely what occurs during the operation of the several main types of transmitting and receiving apparatus.

In the plain aerial instrument of Figure 1, the total antenna resistance is very large; and as a result only a few electrical oscillations take place before the amplitude of the radio frequency current reaches a practical zero. A discharge of this sort is shown in Figure 9, in which antenna oscillating current is plotted against time. Assuming the aerial to be 250 ft. (76 meters) in height, the frequency of the oscillating current will be about 750,000 per second, and the length of the radiated wave about 400 meters. When series inductance is inserted, as in Figure 2, the wave length and persistence of the system are increased, and the discharge is more nearly that represented in Figure 10. Assuming the same aerial, and a loading inductance of 0.5 millihenry, the frequency is decreased to 330,000 per second, which makes the radiated wave length about 900 meters. If the coupled circuit of Figure 3 is used, the oscillating currents in the closed circuit *X* induce similar oscillating currents in the open circuit *Y*; these two condenser circuits are adjusted to have

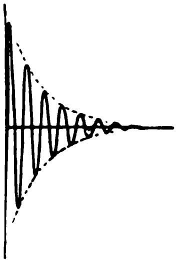

FIGURE 9

practically the same natural period of vibration. The antenna current in this case is still less strongly damped, and, when the spark gap circuit is properly designed, may be represented by the graph of Figure 11. It will be noted that the persistence of antenna current increases in each of the successive types, and that in Figure 11 the decrement (an indication of the rate of amplitude decrease with time) is comparatively small. For the sustained wave alternator sender of Figure 4, the radio frequency current has a constant amplitude, as shown in Figure 12, and the decrement is therefore zero. These four last figures, 9 to 12 inclusive, represent not only the amplitude variation with time of the current in the antenna, but also that of the electromagnetic wave in space. This wave upon reaching a receiving aerial sets up in it currents of identical frequency and (except in the case of sustained waves) a somewhat greater decrement, the latter depending upon the constants of the receiving apparatus.

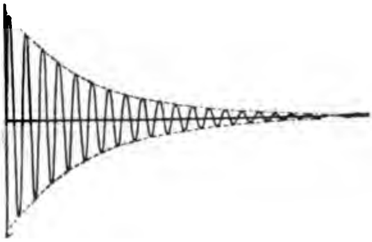

FIGURE 10

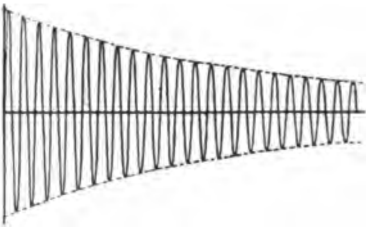

FIGURE 11

The illustrative receiver of Figure 7 is shown as comprising an antenna, an inductance coil, and a thermo-ammeter connected in series to earth. These elements form an oscillating electrical system having a definite resonant period dependent upon its capacity and inductance. The effective sharpness of resonance in the circuit will depend upon the persistence of the incoming wave and the resistance of the receiver as a whole. Greatest selectivity is secured when the receiver resistance and the decrement of the incoming waves are a minimum. Evidently the later types of transmitter, having a maximum persistence, give the greatest freedom from interference between stations. Receivers designed for continuous waves are in general least affected by impulsive disturbances; therefore the harmful effects of strays or atmospherics are minimized when this type of apparatus is used.

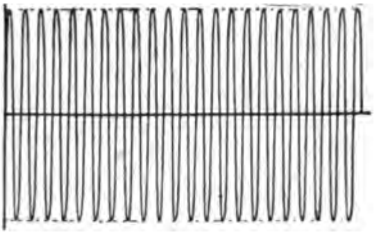
FIGURE 12

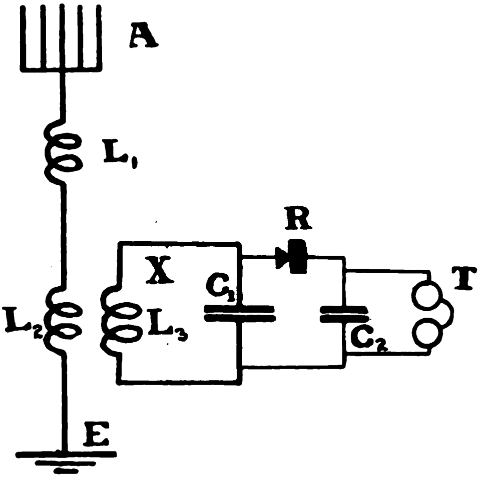

FIGURE 13

A modern form of receiver for grouped-wave operation is shown in Figure 13, and consists of an antenna and ground having connected between them suitable inductances to make the resonant period of the aerial system agree with that of the incoming wave. Magnetically linked to one of the antenna inductance coils is a secondary coil L_3. This secondary has connected across its terminals a condenser C_1, which permits the resonant period of the closed circuit X to be brought into accord with that of the incoming wave and the antenna system. The rapidly alternating potentials developed across the condenser C_1 are applied across the rectifying detector R and condenser C_2, and, because of the asymmetric resistance characteristic of the detector R, the condenser C_2 is charged in one direction during the receipt of a wave train. The charge which it takes is then discharged thru the telephone T and produces a movement of the diaphragm.

The operation of the entire transmitting system may become more clear by reference to Figure 14. Here the axis P shows the secondary potential of the power transformer at the transmitting station, plotted against time. Assuming a frequency of 500 cycles per second, which is common for spark telegraphy, the transmitting condenser is charged first in one direction and then

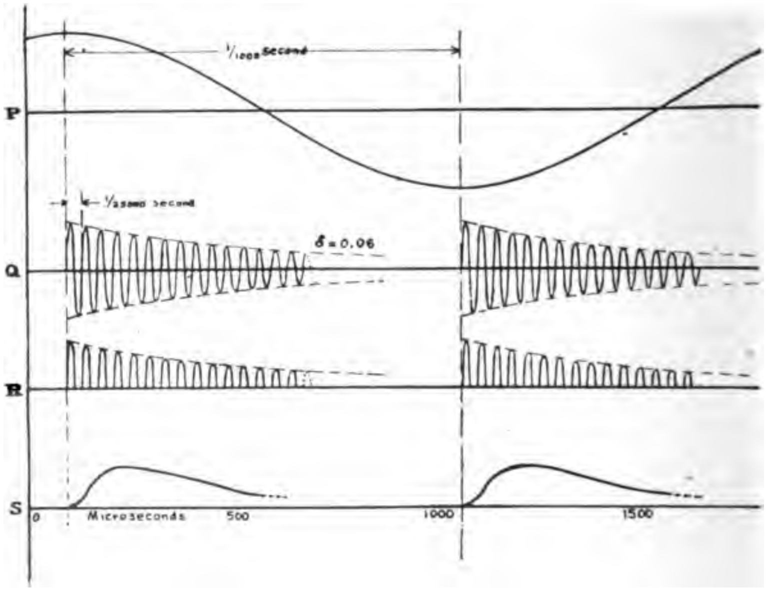

FIGURE 14

in the other, at intervals of 1/1000th of a second. At the instant of charge to maximum potential, indicated by the vertical lines, the condenser discharges across the spark gap (see Figure 3), with oscillations, as shown on the *Q* axis of Figure 14. These oscillating currents have a frequency dependent upon the capacity and inductance of the closed circuit *X*, and for this graph are assumed to oscillate at 25,000 cycles per second, corresponding to a 12,000 meter wave length. The wave train is quite persistent, consisting of some 30 oscillations before reaching a small value, and therefore lasts for about 0.00075 second. Such groups of oscillations follow each other at intervals of 1/1000th of a second; when repeated for each condenser discharge, they result in practically identical currents in the antenna circuit *Y*, practically identical waves in the ether between sender and receiver, and practically identical currents in the receiving antenna circuit and in the receiver's closed circuit *X*. This same graph, along the *Q* axis of Figure 14, represents the alternating voltage impressed across the detector *R* and condenser C_2; the current thru the rectifier is indicated by the half waves shown on the *R* axis of Figure 14. These charge the condenser which discharges thru the telephone in current pulses such as shown at *S*, one pulse for each group of waves. If the transmitting sparks occur one thousand times per second, one thousand current pulses pass thru the telephone windings in one second, and the telephone gives off a tone having a sound frequency of one thousand per second or corresponding approximately to the second *C* above middle *C* on the musical scale. By holding the sending key down for a short time, say one-twentieth of a second, fifty of these wave groups are sent out, a short tone is heard in the telephone receiver, and a Morse dot is signalled. By holding the key down approximately three times as long, one hundred and fifty trains are emitted, a longer tone is heard in the receiver, and a Morse dash is indicated. Thus short and long pressures of the key at the transmitting station may be translated, according to the Morse code, at the distant receiver.

The above explanation applies to any of the grouped-wave transmitters, and shows how a tone is produced at the receiving station. If the wave trains are uniformly spaced, and occur at a fairly high rate, the response of the telephones is musical; if the sparks are irregular in occurrence, hissing or scratching sounds will be produced in the telephone. Atmospheric impulses or irregular disturbances of any sort produce such irregular sounds; therefore, by making the spark rate high and definite, it is possible for the receiving operator to distinguish easily between the musical signal tone, carrying the message which he desires to interpret, and the interfering noises from strays. This method of reducing the disturbing effects of atmospheric has been found in practice to be most effective.

When sustained waves are emitted, as by the transmitter of Figure 4, the stream of current in the antenna is ordinarily constant and uniform during the times the key is held down. At the receiver there is consequently no tone-effect, such as that just described, unless an interrupter or its equivalent is placed in some one of the circuits. A rotary circuit breaker may be placed in series with the antenna at the transmitter, or at the receiver, and will produce an action indicated in Figure 15. In these graphs the sustained radio frequency current of 25,000 cycles per second, is shown along the axis *T*. At *U* it is shown broken up into groups succeeding each other at the rate of one thousand per second. This graph represents the potentials which are applied to the detector *R* in Figure 13, and which result in rectified potentials such as shown on axis *V*, and pulsating currents thru the telephone winding as shown on axis *W*. Morse signaling is effected by short and long pressures of the key, as before. This interrupter method of using sustained waves gives a pure note in receiving, but is not notably efficient. A somewhat analogous interrupter method of receiving sustained waves involves the use of a rapidly vibrating contact called a tikker, at the receiving station; this contactor replaces the rectifier *R*, in Figure 13, and operates quite sensitively. It does not produce a musical tone in the telephone, however, and so telegraphy in which it is used is unnecessarily subject to interruption because of atmospheric interference. One modification of this device varies its resistance, instead of actually opening the circuit; another, by relating properly the wave and interrupter frequencies, produces a whistling signal sound.

The most satisfactory method of receiving sustained waves does away with all interrupters and vibrating contacts, and produces pure musical signal tones by the interaction of two radio frequency alternating currents or potentials. The apparatus which is used in a preferred form of this heterodyne receiver is shown in Figure 16, where the left hand side represents the ordinary receiver as shown in Figure 13, having added to it, however, a generator of feeble radio frequency currents in the circuit *F*, *G*, *H*. It is a well known physical principle that the addition of sine waves of slightly different frequencies results in a composite wave of a mean frequency which varies in amplitude periodically at a rate equal to the numerical difference in the component frequencies. The musical beats noted in the tuning together of mandolin strings, and the flickering of synchronizing lamps in power generating stations, are familiar examples of beats occurring according to this principle. The

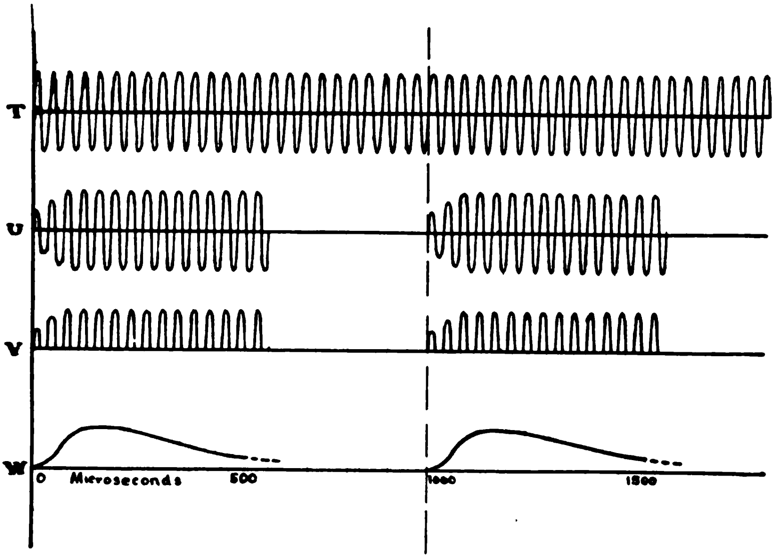

FIGURE 15

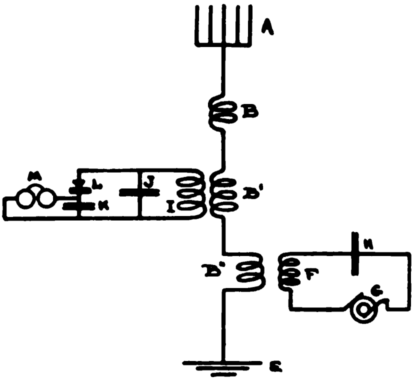

FIGURE 16

application to radio receivers becomes clear from a reference to Figure 17. Here the antenna current generated by the incoming sustained wave is indicated along the *A* axis. The current produced in the receiving antenna system by the local generator, having a slightly different frequency, is shown along the *B* axis. These currents add together algebraically, and, by their interference, produce beats at a rate equal to the difference between them, as shown along the *C* axis. If the incoming wave is of a frequency of 100,000 cycles per second and the locally generated current is of frequency 101,000, the beat frequency is one thousand cycles per second, the numerical difference of the components. Referring to Figure 18, the graph along the *C* axis may be taken to represent the potentials applied across the detector *L* of Figure 16; these are rectified as shown on the *D* axis, Figure 18, and result in current pulses at the rate of one thousand per second, passing thru the telephones, as shown by axis *E*. In this heterodyne receiver the response depends upon the interaction of two sustained radio frequency currents, and is its maximum when both of these are of zero decrement. The signal tone is purely musical, and may be varied in pitch to any point desired merely by altering slightly the frequency of the local oscillator. The circuits used are designed for maximum effect at the maximum persistence, since they depend for their action upon receipt of sustained waves. These three points co-operate to eliminate largely disturbances due to strays; and by taking advantage of

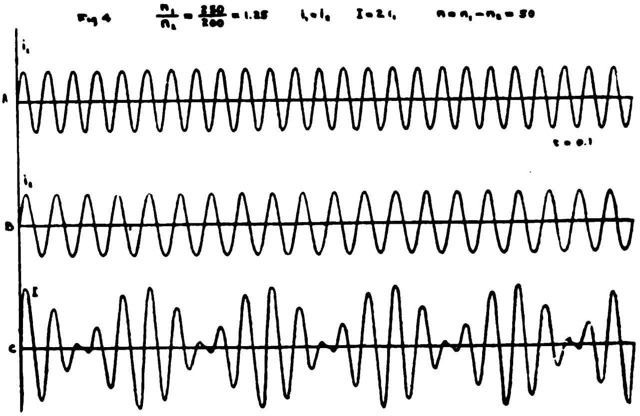

FIGURE 17

the three features it has been found possible to secure the maximum freedom from interruption by atmospherics.

Having considered the qualitative physical relations involved in practical radio telegraphy, some features of the quantitative study may now be outlined. Before this is done, however, it is desirable to determine what requirements must be met by radio in order to give commercial service. There are, of course, all degrees of "commercial" service; radio should be expected, however, to perform as well or better than could a wire telegraph or submarine cable interconnecting the points served by the radio stations. Operation of this character may be expected if the following main requirements are met:

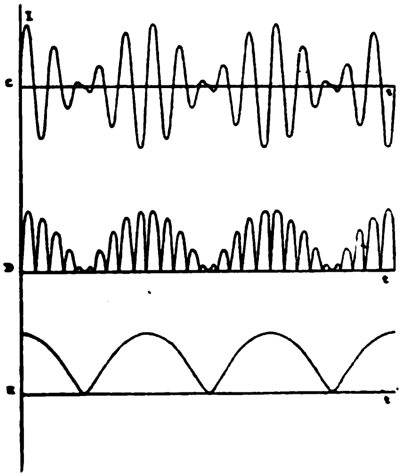

FIGURE 18

(1) The stations should be duplexed, so that messages may be sent in both directions at the same time, in order to save delays enforced by simplex sending.

(2) Spare transmitting and receiving apparatus should be installed, and the units should be so designed that twenty-four hours' service can be furnished per day of operation.

(3) The received signal should be musical, and of intensity sufficient to permit the operator to copy messages directly upon a typewriter, day or night, winter or summer.

Taking these up in order, it is evident that duplex transmission can be effected if the two senders operate on somewhat different wave lengths and if at each end of the link the transmitter and receiver use well separated antennas. Referring to Figure 19, if *A* and *B* represent transmitters at New York and San Juan, Porto Rico, 1,400 miles (2,200 km.) apart, *A* and *B* may be considered to send on wave lengths of 5,000 and 6,000 meters, respectively. If then, about fifteen miles from each of the transmitters, there is installed a receiving station, it will be possible for the receiver *A* near New York, to copy signals from the San Juan transmitter *a* on a wave length of 6,000 meters without interference from the local transmitter *A*. Simultaneously the Porto Rican receiving station *b*, will be able to read messages from New York *A* on 5,000 meters, without interference from *B*. By making *a* and *b* the operating stations, and controlling the transmitters at *A* and *B* by relays operated thru land lines from the operating to the power stations, genuine duplex transmission can be effected.

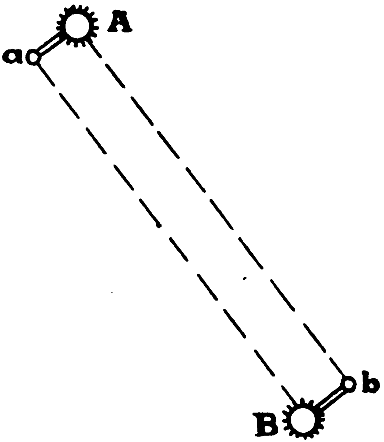

FIGURE 19

As to the second point, reliance must be placed entirely upon the designers of the apparatus to be used. No instrument should be installed which has not given evidence of its ability to perform satisfactorily over long periods, without requiring undue attention from experts.

Intensity of received signals, the third point above, is to be secured in several different ways. It has been demonstrated, however, that the use of very sensitive detectors or amplifiers cannot be depended upon, for the reason that atmospheric disturbances are magnified as much or more than the desired signals. In the absence of severe stray disturbances, it is possible to signal over long distances with small transmitted power, by using intensifying and extremely delicate receiving instruments. However, such apparatus is not satisfactory for commercial radio telegraphic service, in the present development of the art, for the reason that even moderate stray interference will overwhelm the sensitive receiving apparatus and make translation of messages impossible. It is therefore necessary to instal transmitters of sufficient power to produce an easily readable signal with receivers of moderate sensitiveness and rugged characteristics. Reduction of strays is then effected by taking advantage of persistence-selection and musical tone, as outlined above.

The numerical relations between the elements which govern certain of the above stated requirements have been the subject of many researches from almost the first years of radio telegraphic practice. A great many experiments have been made to interrelate the severable variables, and as a result there have been deduced some quite well verified relations between transmitted power, antenna height, wave length, distance, and audible intensity of received signals on various types of receiver. Such numerical data is, of course, an essential for the predetermination of station constants to meet specific requirements. Without going into great detail, it may be stated that if a current of 100 microamperes is set up in the receiving antenna by the incoming signal-carrying wave, a sufficiently loud response will be had, on the heterodyne receiver, to permit separation of the signals from severe atmospheric disturbances; altho it is true that occasionally, when lightning storms are near, strays will become so violent that 150 microamperes or perhaps even more would be desirable. Practical operation, in the absence of strays, can be carried on with perhaps one-tenth this antenna current, but the additional signal intensity should be available if really commercial service is to be secured. As a result of long trials made jointly by the United States Navy and the National Electric Signaling Company in 1910, 1911, 1913 and later,* the following expression has been quite well confirmed:

$$I_r = \frac{392\, I_s h_1 h_2}{\lambda d} \varepsilon^{-\frac{0.0474\, d}{\sqrt{\lambda}}}$$

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* Reported in "Some Quantitative Experiments in Long Distance Radio Telegraphy" by L. W. Austin, "Bulletin Bureau of Standards," Vol. 7, Number 3, 1911, page 315; and "Quantitative Results of Recent Radio Telegraphic Tests Between Arlington, Va., and U. S. S. *Salem*," by John L. Hogan, Jr., "Electrical World," January 21, 1913, page 1361.

where I_r equals receiving antenna current in microamperes (thru 25 ohms, a fair receiver effective resistance), I_s equals sending antenna current in amperes, h_1 and h_2 equal sending and receiving antenna effective heights in feet, λ equals wave length in meters, and d equals distance of transmission in kilometers. If h_1 and h_2 are expressed in meters, the 392 above should be replaced by 36.3. The constants 392 and 0.0474 are reasonably accurate for daylight transmission over sea water or almost perfect ground; for night time transmission signals are almost invariably louder than indicated by the mathematical expression.

It has been assumed that, with the best receiving apparatus obtainable, $I_r = 100$ will give commercial transmission under unfavorable conditions. On attempting to solve the equation for this value, it is at once seen that for any given distance several combinations of transmitter power, antenna height, and wave length are possible. The balance between height of sending aerial and power of sending equipment is one which the natural economy of location most determine; in some places it is less expensive to build a low aerial and use large power, while in others, the reverse is true. The received signal is also dependent upon the height of the receiving aerial, but the amount of interference from strays is increased when tall aerials are used. It is therefore preferred to restrict antenna heights at the receiving station. The wave lengths used should be in general the longest at which the proposed antennas operate efficiently, since this will give as a rule the minimum attenuation. Data on the most desirable and economical types of transmitting and receiving antennas are not available, but it is to be expected that practice in this direction will become more nearly standardized in the future.

It may be interesting to consider the types of installation which are necessary to fulfill the above stated physical conditions for practical radio telegraphy over distances of 2,000, 3,000, 4,000 and 5,000 kilometers. The following tabulation gives a group of numerical values of the computed physical constants for each of these distances, and represents what may be considered good engineering practice of the present day. The assumptions are based upon the use of rugged heterodyne receivers and sustained wave transmitters; the transmitting antenna power (and consequently the sending antenna current) would have to be largely increased if spark transmission or other types of receivers were used:

Distance in Kilometers	2000	3000	4000	5000
Distance in Statute Miles	1240	1860	2480	3100
Wave Length in Meters	4000	7000	10000	12000
Antenna Heights in Feet (=3.28 height in meters)				
Sender	450	700	850	1000
Receiver	300	400	450	500
Antenna Currents				
Receiving in Microamperes	100	100	100	100
Sending in Amperes	64	105	170	265
Sending Antenna Resistance in Ohms				
Radiation Component	1.9	1.5	1.07	1
Total	3.5	3	2.5	2.5
Sending Antenna Power in Kilowatts	14.5	33	72	175

The comparatively large powers which are necessary in order to transmit regularly over long distances thru strays should be particularly noted.* When the bad effects of atmospheric disturbances are reduced far beyond the point in commercial practice of the present day, it will be possible to signal at all times with perhaps one-tenth the transmitted power now used. This saving of transmitting cost will give radio telegraphy a further and tremendous advantage over wire or cable signaling, by reason of its economy; therefore the atmospheric disturbance problem is receiving the most serious attention of radio engineers all over the world.

It may be that some of the methods which have already been devised and used in laboratories, but which are not yet applied commercially, will solve the problem of permitting continuous operation on small power. It may be that the methods which seem promising at the moment will be as great disappointments as have been a large number of others attempted in the past ten years. In whatever way this one remaining obstacle to the greatest economies in radio telegraphy may be overcome, the fact remains that at the present time radio communication may be depended upon for entirely commercial service over long distances; it is necessary only that the stations should be designed with a full engineering understanding of the large number of physical problems involved.

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* (See page 451 of this issue of the PROCEEDINGS for comparative data.—EDITOR.)

SUMMARY : The development of radio telegraphy, as a mysterious and little understood physical art, from well known inductive and conductive methods of telegraphy is briefly stated. It is shown that radio telegraphy is now subject to engineering treatment and consists of a series of expected effects resulting from a series of controllable causes. The large scope of natural phenomena involved is outlined, and the general physical basis of all communication systems stated. The fundamental operation of transmitters and receivers, from those first used to the most modern sustained-wave-heterodyne apparatus, is described. Difficulties produced by atmospheric disturbances, and their effects upon the requirements of commercial radio telegraphy are discussed. Following the qualitative considerations, some of the quantitative physical relations involved in practical radio telegraphy are outlined. Important constants for transmission over distances of 2,000, 3,000, 4,000, and 5,000 kilometers are given, and the paper concludes with a brief outline of future development.

ARLINGTON RADIO STATION

AND ITS ACTIVITIES IN THE GENERAL SCHEME OF NAVAL RADIO COMMUNICATION*

BY

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(SUPERINTENDENT OF THE UNITED STATES NAVAL RADIO TELEGRAPHIC SERVICE)

The naval radio station at Radio, Va., known and referred to generally as the Arlington radio station, was the first high power radio station constructed for the Navy Department, and was intended as the primary link in a chain of high-powered radio stations, whereby naval ships within the vicinity of our continental or insular coasts could always be reached directly or by relay.

Many sites were examined around Washington and in its vicinity before the present one was finally selected; and it may be mentioned here that the site of a radio station involves many considerations. First of all, the electrical conditions in the way of ground connections must be good, and the possibility of the absorption of electromagnetic waves by high mountains, land, or buildings in the immediate vicinity must be considered. It must have sufficient area on which can be erected towers and buildings; be near a source of power, if not self-sustaining; must be accessible by at least some of the ordinary means of communication, and as far as possible must be protected from assaults by possible enemies. If near the coast, it should be located sufficiently inland to insure safety from gun-fire from ships, and sufficiently distant not to be subjected to assault by raiding parties. It should preferably be near a base of supplies; and should have land wire, telephone or cable communication. One of the necessary considerations in the determination of a site near Washington was that it should be on government owned land.

All of the sites examined in the vicinity of Washington

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*Presented for the Washington Section of The Institute of Radio Engineers before a joint meeting of the American Institute of Electrical Engineers and The Institute of Radio Engineers, February 29, 1916.

were government owned; among others, these included ground near the Naval Observatory, sites on the grounds of the Soldiers' Home, and on ground near the site of the St. Elizabeth Hospital. All of these sites met with more or less objection from various outside interests. The site finally selected, being the present one, was formerly a part of the Government Reservation known as the Fort Myer Military Reservation, and the ground, 13.4 acres in extent, was transferred from the War to the Navy Department by act of Congress. A general view of the towers of the station after completion is shown in Figure 1.

FIGURE 1—Towers and Station, Arlington

The average elevation of the space on which the towers are built is about 190 feet (58 m.) above sea level. The view shows three skeleton steel towers, one 600 feet (183 m.) high from the ground, the other two each 450 feet (137 m.) high. The centers of the towers form an isosceles triangle, the base of the triangle being 350 feet (107 m.) long and the altitude 350 feet. Figure 2 shows one tower leg with its insulation switch and short-circuiting switch. The base of the triangle, the distance between the two shorter towers, runs approximately magnetic north and south, and this is shown in Figure 3, which shows also in general the outline of the ground occupied by the station and the approximate dimensions. Two hundred and seventy-five tons (25000 kg.) of steel were used in the construction of each of the smaller towers, and 500 tons (45,000 kg.) in the larger. These towers were supplied and erected by the Baltimore Bridge Co., and the steel was furnished by the Carnegie Steel Co.

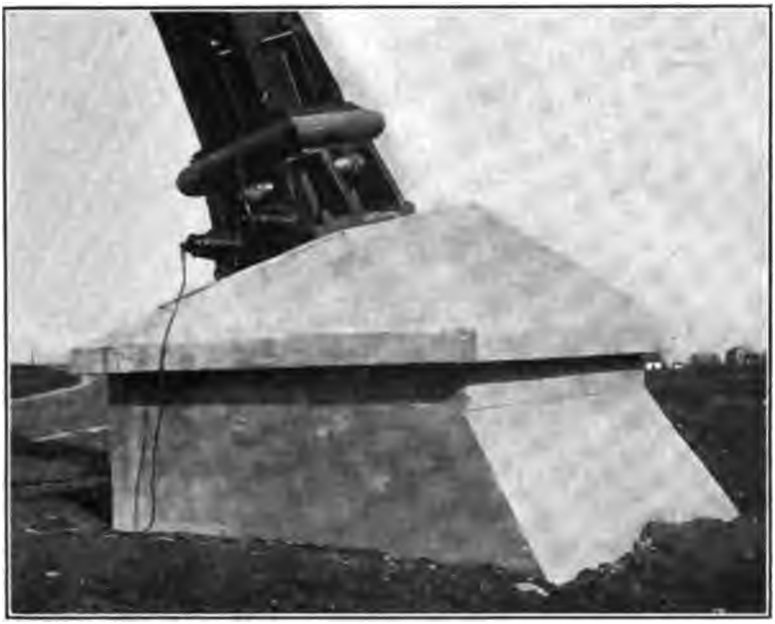


FIGURE 2—Base of Tower and Ground Switch, Arlington

The current as supplied is 3 phase, 25 cycle, 6,600 volts; and after entering the basement it is transformed to 220 volts.

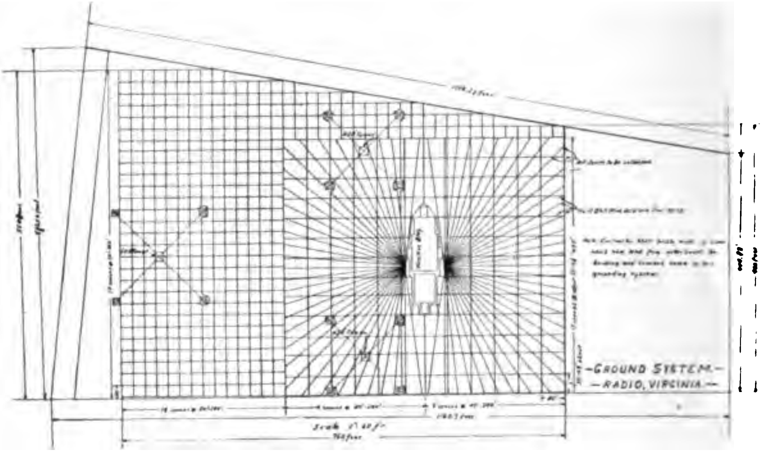
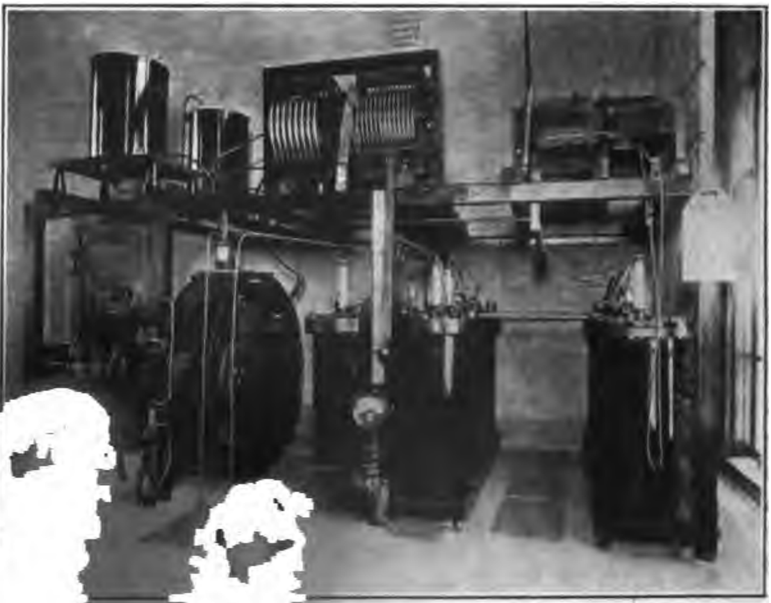


FIGURE 3

SPARK SET

The first set installed in the Arlington station was a spark set constructed on the Fessenden system, and a general view is shown in Figure 4. The main driving unit is a Westinghouse



100 K.W. Spark Set, Arlington

200 horse power, 220 volt, 25 cycle, 3 phase synchronous motor, 300 revolutions per minute, and is controlled by means of an oil switch with auto starter. On this motor shaft, and driven by it, is an 8 kilowatt, 110 volt direct current generator, which is used to excite the fields of both the 200 horse power driving motor and the driven 100 kilowatt generator, which furnishes the energy for the transmitting apparatus of the radio set.

The 100 kilowatt generator is a General Electric, 220 volt, 500 cycle machine, and is driven at 1,250 revolutions per minute thru a leather belt by the 200 horse power motor. On the generator shaft is the rotor, or moving portion of the synchronous rotary spark gap, as shown in Figure 5, which consists of a fiber wheel with a heavy brass ring on its outer circumference from which protrude 48 copper tractors about ten inches long. The bearing at this end of the generator is especially constructed with a large flange 70 inches (1.78 m.) in diameter which supports the casing for the rotor. The casing, which carries the stationary electrodes of the spark gap, is fitted so that it can be moved

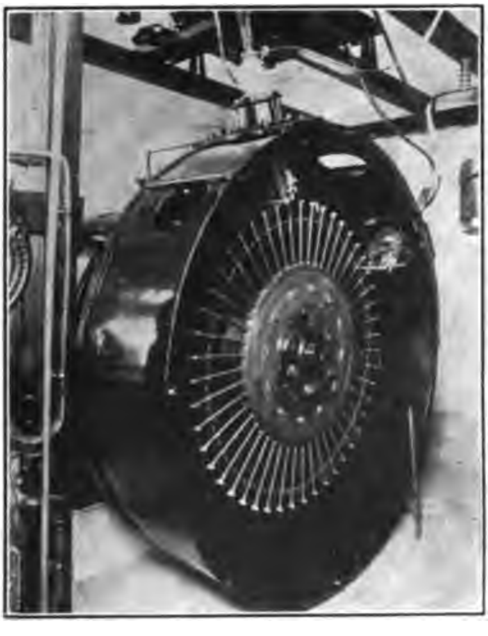


FIGURE 5—Rotary Gap of 100 K.W. Spark Set, Arlington

backward or forward by a worm gear. Provision is made to cool the stationary electrodes by running water thru them. The requirement that the stationary electrodes may be moved is very essential as any small changes in the variable factors which produce changes of wave length tend to cause the sine wave of the alternator to lead or lag, and it is necessary to move the electrodes so that the sparking will occur at the peak of the wave in the condenser charging current.

The main leads of the generator run to a panel on the switchboard, and after passing thru a circuit breaker carry current to the primary of the transformer. The wiring diagram is shown in Figure 6. One of these leads is broken by a large relay key,

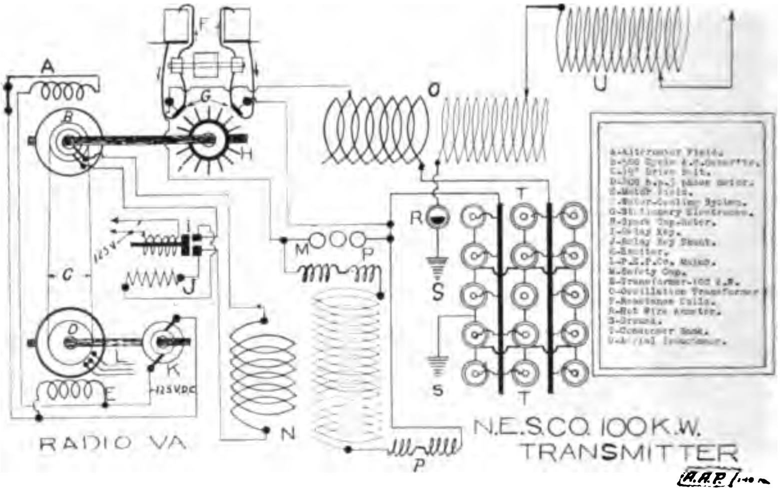


FIGURE 6

and shunted around the relay contacts is a large, variable current capacity, resistance grid which takes care of the considerable current in the primary from the time the circuit breaker is closed until the condensers are almost up to the point of discharge. When the key is closed and opened the greater part of the current is taken up by the grid, and this serves the double purpose of protecting the contacts from wear and of keeping the condensers constantly up to the sparking point ready for instant discharge. This relay key is operated by a small sending key in the operating room or at any other distant point.

The secondary leads carry current from the transformer at 25,000 volts to the stationary electrodes, and shunted across the electrodes is the closed circuit containing the condensers and primary inductance of the oscillation transformer in series.

The primary inductance is a special helix made of ten turns of one inch (2.54 cm.) copper tubing about four feet (1.2 m.) in diameter, fitted with suitable spring clips by means of which the leads can be clamped to any turn for varying the sending wave lengths.

The condensers were furnished by the National Electric Signaling Company, and are of the compressed air type. An open view of one of these condensers is shown in Figure 7. Each consists of a large metal cylindrical tank in which the plates (about 200) are suspended; one set being connected to the tank itself, and the other set connected by a rod thru an insulator running thru the center of the cover. A lead washer under the rim of the cover and a lead bushing around the insulator insures the tank being air tight. The plates are placed one-eighth inch (3.2 mm.) apart, and at that distance would not stand the high voltage were it not for the compressed air. After the plates have been properly placed and the condensers assembled, the air is compressed to a pressure of 250 pounds per square inch (17.6 kg. per square cm.), and a special treatment is given the plates to increase the dielectric strength between them. A safety gap is set on the outside of the tanks between the rod thru the insulator and a terminal on the tank cover, this gap being slightly longer than the distance between the plates. The primary current is then turned on intermittently, allowing the sparking to take place inside until the small particles of dust in the air are burned out, after which the spark will jump the safety gap. The latter is then lengthened and the operation continued until the safety gap is enlarged to one inch(2.54 cm.). In this operation, known as "burning out," the generator voltage must be reduced to as low value as possible. By this treatment a spark can be made to jump a one inch gap in air before it will jump the one-eighth inch gap in compressed air. Each condenser has a capacity of 0.036 μ f. (microfarad), 14 units being used in multiple series, (two sets of seven in parallel and two sets in series).

The secondary of the oscillation transformer is made up in the same manner as the primary but is of three-eighth inch (9.5 mm.) copper tubing and has twice the number of turns. One lead is taken off to a hot wire ammeter and from there to the ground and the other lead has a spring clip and can be connected to any turn of the loading coil or antenna inductance. The adjustment of the oscillation transformer is made as nearly correct as possible before the spark is turned on; then the loading coil, which has similar contacts, can be revolved while the spark is in operation so as to bring the antenna (and secondary circuit) into resonance with the primary. This is done by watching the reading of the hot wire ammeter and moving the loading coil until maximum antenna current is obtained.

Figure 7—Compressed Air Condenser

The primary of the oscillation transformer has a screw attachment by means of which the primary can be moved farther away or nearer to the secondary so to obtain the proper amount of coupling to ensure a sharp or pure wave.

The antenna lead is taken from the loading coil to a switch on short pole mast outside the building, the lead passing thru an electrose insulator fitted in a plate glass window one inch

(2.54 cm.) thick and five feet (1.58 m.) square. The switch on these masts is controlled by a lever and sprocket chains from the sound proof operating room. A view of this outside switch is shown in Figure 8.

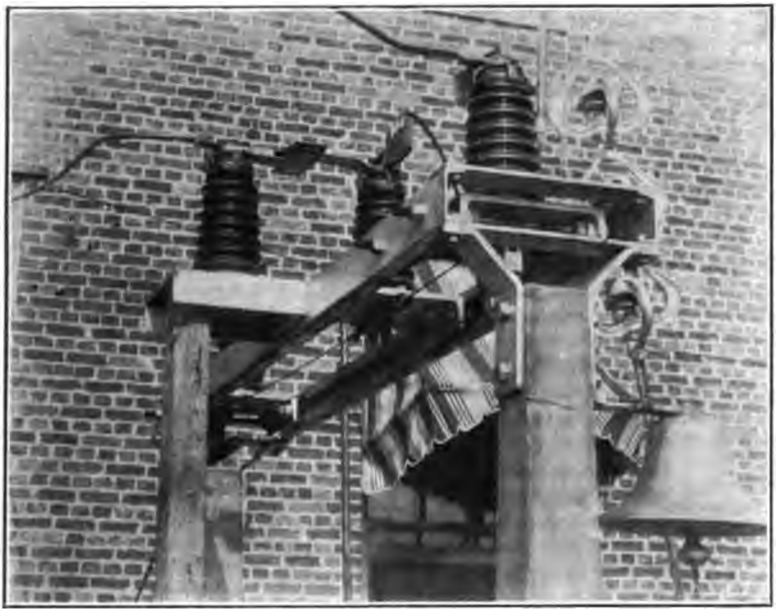


FIGURE 8—Antenna Switch, Arlington

The antenna is made up of three sections, 23 wires in each section, each wire consisting of 7 strands of number 20 phosphor bronze.* These wires are attached to spreaders made up of three inch (7.6 cm.) pipe, 88 feet (23.2 m.) long, reinforced by trusses; and the spreaders are attached to the towers by 10 electrose insulators between them and the towers. A general view of the construction of the antenna is shown in Figure 9. It is open at the highest end, at the 600 foot (183 m.) tower, and two sections are brought down to the 450 foot (137 m.) towers, and there joined to the main section by jumpers made up of 23 wires bunched in the form of a rope. The main section is what is known as a "T" antenna, and the vertical part ("rat tail") is taken from the middle. The 23 wires of the "rat tail" are brought down in the shape of a fan for 300 feet (92 m.) and

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* Diameter of number 20 wire = 0.032 inch = 0.081 cm.

then in the form of a large cage the rest of the way to the switch on the pole mast.

The above antenna arrangement gives a fundamental of 2,100 meters with a capacity of 0.0094 μ f., and can be readily swung over by means of a switch on the pole mast for use either in transmitting or receiving. In the latter case, it forms a very efficient arrangement for receiving long waves, as it is not necessary to insert an inductance of necessarily high resistance. For receiving shorter waves, a small antenna has been put in place at a height of 300 feet (92 m.) and is used also in transmitting with a 5 kilowatt transmitter which is installed for local work, such as that with Philadelphia, New York, and Norfolk.

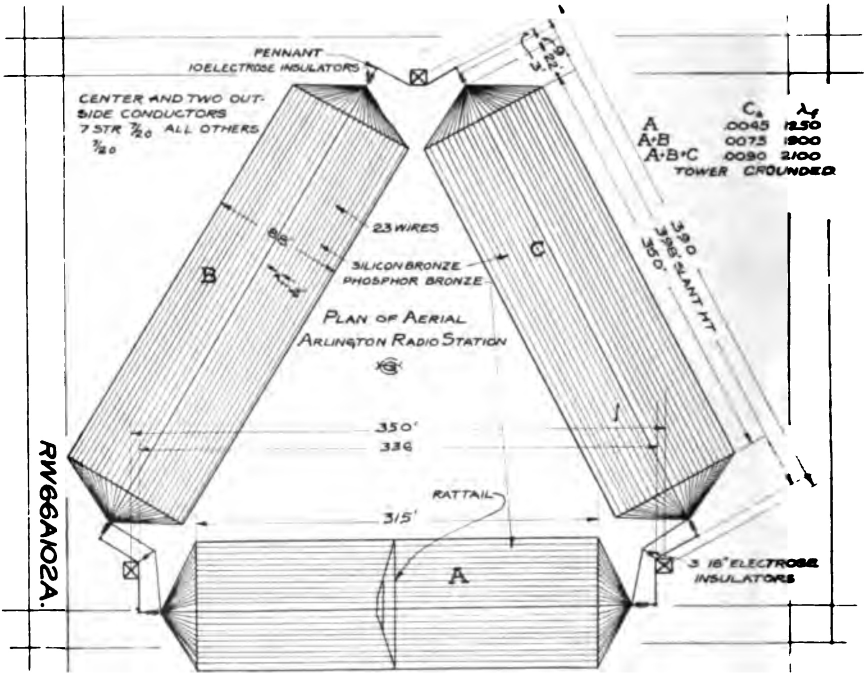

FIGURE 9

The ground connections consist of many lengths of wire buried in the ground at various depths, in the space near the towers, and laid in a checker-board pattern with soldered junction. A general plan of the ground wire connections is in Figure 3. Miles of this wire were laid making a large network; and finally wire leads are run down the slopes ending in a small stream that flows near by. The ground connection between the antenna and this network is thru a large copper strip 6 inches (15.2 cm.) wide and ¼ inch (6 mm.) thick run to the ground wires and permanently soldered to them.

The receiving or operating room at the Arlington station was built to be sound proof and is constructed somewhat like a refrigerator with double doors and walls 20 inches (61 cm.) thick. Before the plastering was put on, the ceiling, walls, and floor were covered with ¾ inch (1.9 cm.) "linafelt" for sound proofing, and then a layer of chicken wire of ¼ inch (6 mm.) mesh was secured over the linafelt. The meshing was carefully electrically connected together, and then several strips of copper were soldered to it and taken to the ground connection outside the building to make a screen for the receivers so that any induction effects from the generator would be absorbed by the screen.

The room is ventilated by two small fan motors, 220 volt, 25 cycle, 3 phase and the air ducts have baffle plates lined with felt on the same principle as a muffler or Maxim silencing device so that the air is silent when it reaches the room. In the air duct is a radiator from the heating system to heat the air for the room in winter months.

5 KILOWATT SPARK SET

The second set installed in the Arlington Station was a 5 kilowatt spark set sonstructed on a system developed by the Wireless Improvement Company, and shown in Figure 10.

The motor generator of this set, which was especially designed for this station, consists of one 15 horse power, 3 phase, 25 cycle Wagner motor, one 10 horse power direct current, General Electric motor, and one 5 kilowatt, 500 cycle, Crocker Wheeler inductor type generator. These machines are directly connected on a common bed plate, with the alternator between the two motors. Three different makes of machines were necessary, so as to get symmetry, and the three machines when lined up are exactly the same height.

When driving from an outside source of power, the 15 horse power motor is used, and the direct current motor then becomes a generator, supplying current for the field of the generator, and is connected thru a station panel for direct current supply to other auxiliaries. In case of failure of the outside source of power, current is obtained from a Diehl, direct current generator driven by a 30 horse power Remington crude oil engine (Figure 11), which supplies current to the 10 horse power, direct current motor.

Both motors are controlled from the one panel, which is supplied with the set; arrangements being made on the board so that by throwing two switches, either alternating current or direct current supply can be used.

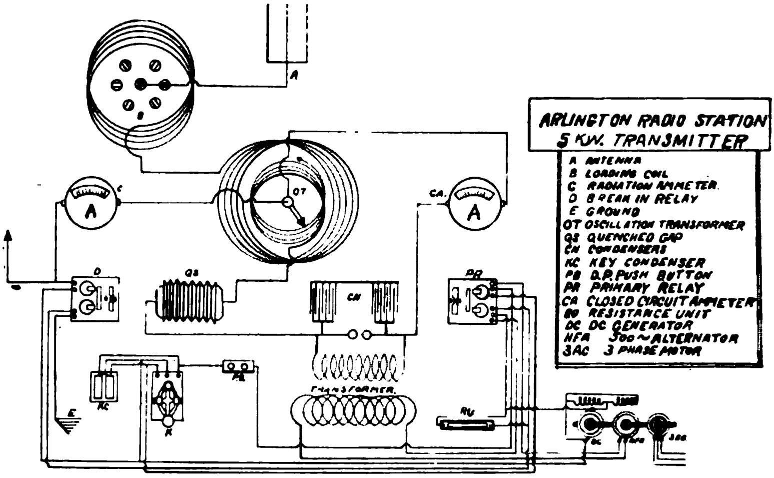

FIGURE 10

The whole set is mounted on two panels, one being for automatic control of the power end, while the other has all the radio apparatus on it. The control is accomplished by a push button, bringing the current to the starter and the set is started in about twelve seconds.

The transmitting apparatus, which is mounted on the other board, differs slightly from other quenched gap sets of the Navy, in that it has fixed secondary and continuously variable primary circuits.

The wiring plan is shown in Figure 10. The primary inductance is in the form of a helix made up of 26 turns of flat rib copper ¼ by 3/32 of an inch (6 by 2.4 mm.) built into a micarta frame. A spiral grooved shaft runs thru the center, carrying an arm on the end of which is a copper wheel, held against the ribbed copper by a spring. As the handle on the front of the board is turned, the arm swings around the helix, the wheel travelling on the ribs, while the arm is forced along the grooved shaft, in this way covering the length of the helix from zero to its maximum length. The capacity of the primary or closed circuit is made up of standard Leyden Jars of 0.002 μ f., 28 jars being used in a bank of series parallel, forming a total capacity of 0.014 μ f.

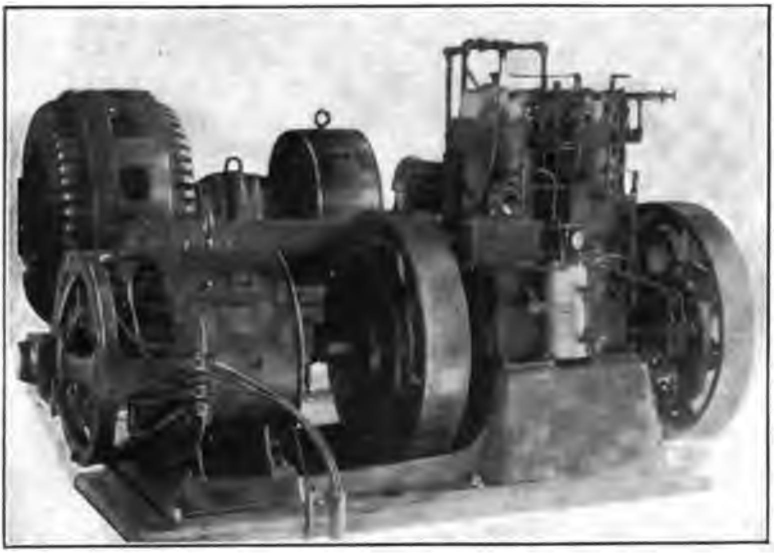

FIGURE 11—Oil Engine and Generators, 5 K.W. Spark Set, Arlington

The secondary helix is made up of same material as the primary, and is fitted on slides, fitting closely around the primary. This helix can be operated from the front of the board by a wheel which moves the helix backward and forward, to vary the coupling. In series with this and the antenna is the loading coil, made of the same material, and containing 48 turns. From certain predetermined places on this coil, leads are taken to the swinging switch on the front of the panel.

The set was originally intended for a range in wave length of 300 to 3,000 meters, but as only two wave lengths, 952 and 2,400 meters are used, the swinging arm in the primary helix has been changed and two points permanently fixed, so that the operator can change the wave in a few seconds to that desired.

From the center of the swinging switch at top of panel is taken the antenna lead, which is led thru a window in suitable insulation to a four wire antenna. Originally this antenna, consisting of four wires about four feet (1.2 m.) apart, was secured between the north and west towers, forming an inverted "L" under the north wing of the large antenna. This proved to be a very poor location, and other stations complained of weak signals, even when radiating 23 amperes. Apparently this small antenna was blanketed by the larger one above it. A stay was then rigged up between the north and south towers, and the vertical lead was suspended from it by suitable insulators. Then the free end was taken due east, away from the large antenna, the end being secured to a convenient tree by a stay and insulators. This proved a much better arrangement and is in use now.

This arrangement gives a natural period of about 900 meters, with a capacity of 0.00199 μ f. The antenna is somewhat on the style of an inverted "L," with the vertical 150 feet (46 m.) in length, and the horizontal 250 feet (76m.) in length. The end leads down slightly, so that it is not a true "L."

100 KILOWATT ARC SET

The third set installed at Arlington is a 100 kilowatt, Federal Telegraph Company, arc set, manufactured by the Federal Telegraph Company of Palo Alto, California, and shown in Figures 12 and 13.

This set consists of a motor-generator, arc chamber, magnet poles, magnet coils, inductances and necessary panels.

The motor-generator is manufactured by the General Electric Company, the motor being a 160 horse power, 3 phase, 25 cycle induction motor, and the generator for 500 volts direct current and 100 kilowatt, both mounted on a common base and direct connected. The motor shaft has an extension, whereby a pulley can be mounted and the set run by an engine or other driver by means of belting. The control for the motor is mounted on a panel and is controlled from a position near the arc by means of a small switch, which operates the contactors of the panel, starting the machine on low voltage and automatically bringing it up to full voltage as the starting current is reduced. This machine is brought up to speed in four seconds from the time the switch is closed. The wiring plan is shown in Figure 14.

There is a special pair of panels for the generator, these having been installed with a view to running two arcs and two generators at the same time, as experiments may be tried with machines in series and parallel. The generator leads are taken to these panels, a circuit breaker being in the line for safety, and from the panel they are taken to a small operating panel near the arc. Before going to this small panel the positive lead is connected to three inductive choke coils, while the negative passes to one coil. These coils are to choke back the oscillatory current generated by the arc, and localising the oscillations in the antenna and thus excluding them from the generator.

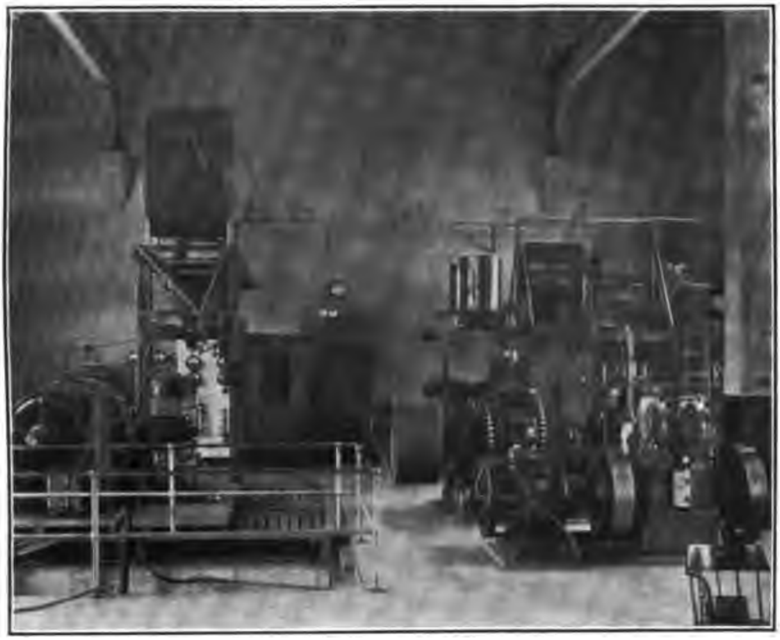

FIGURE 12—Arc and Spark Transmitters, Arlington

From the small panel, the positive lead runs direct to the copper electrode, which must always be positive. The negative lead is taken, thru a resistance, to the magnet coils, and then to the carbon, which must always be negative. If the polarity is reversed, the copper electrode would not last two minutes; for if the positive lead were taken to the carbon and the flame thus blown toward the copper, the arc would act like an acetylene torch, causing the metal in the electrode to boil; whereas if the opposite is the case, the flame is blown toward the carbon, which being rotated by a small motor, does not permit the formation of a crater on the carbon.

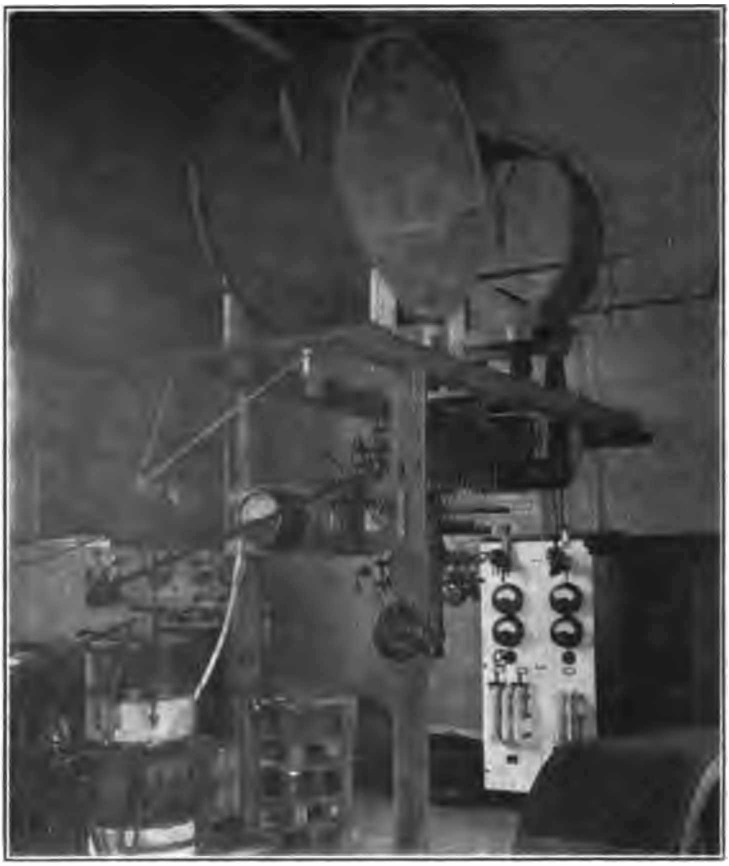

FIGURE 13—Arc Set, Arlington

The resistance in the negative lead is controlled by single pole, knife switches, and allows the arc to be struck on a low voltage. As the arc current increases, these switches are used to cut out portions of the resistance until full voltage is being used.

The arc chamber is water cooled thruout, as are the electrode holders also. Feeding into the chamber is a small flow of alcohol, which, when ignited by the arc, generates a gas, or conducting, ionized vapor, the action being to facilitate re-ignition of the arc after it has been blown out by the action of the electro-magnets.

p
v
c

h
w
iz
af

From the copper or positive electrode, a lead is taken to the helix, and thence to the antenna. In series with the helix, is a smaller helix of twelve turns, giving wave length change of about two hundred meters; and from each turn of this helix

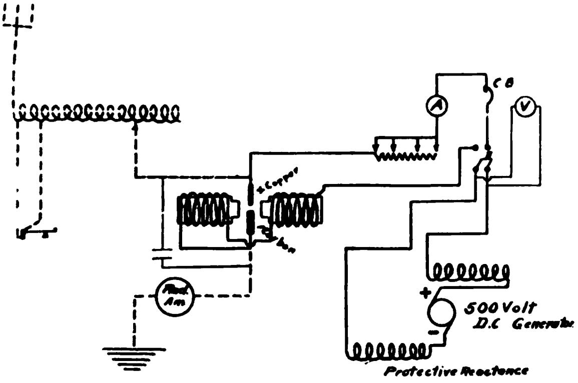

Figure 14

a lead is taken to a twelve point relay, which is operated by 110 volt direct current. The resulting action when the contacts are closed, (which happens when the hand key is released), is that the wave is shortened by the twelve turns of inductance being short-circuited. When the hand key is pressed, as in operating, the contacts are opened, thus lengthening the wave. Thus there are two distinct waves sent out, one when the key is pressed, of say 6,000 meters, and the other when the key is released, which would be about 5,900 meters.

From the negative electrode a lead is taken thru the hot wire ammeter, and then to ground.

The operation consists in first striking the arc at reduced voltage, and by means of a fine threaded screw arrangement, bringing the carbon back, thus lengthening the arc, at the same time increasing the voltage by cutting out resistance. This operation is repeated until full voltage is on, when the length of the arc is regulated by the radiation meter, there being a maximum setting, from which opening or closing the arc causes a drop in the antenna current.

Figures 15, 16, and 17 show a reproduction of the log of the Washington station for one day, February 1, 1916; and an examination of it will show the stations daily communicated with. They further show the character of the log required to be kept by every Naval shore radio station. In twelve months ending June 30, 1915, Arlington handled 78,921 messages. In January of this year, Arlington transmitted 2,737 messages and received 3,452, a total of 6,189 messages and an average of 200 per day.

INTERNATIONAL RADIO COMMUNICATION

In line with the general desire to promote closer business and social relations between the United States and countries of Latin America, as developed by the several Pan-American Scientific Congresses and particularly the last one recently held in Washington, preliminary steps have been taken to ensure an interlocking radio communicating system between the radio stations of the various countries of the western hemisphere.

The plan of communication has been developed by the Naval Radio Service and has been presented to representatives of the various countries thru the co-operation of the State Department, and it is expected there will shortly be an international committee appointed to meet in Washington to consider the suggestions advanced by the Naval Radio Service. This committee will be charged with the duty of preparing the necessary regulations to combine the radio services of all American republics into one homogeneous system for the transaction of government and commercial business, to arrange traffic regulation, to designate regular and alternate routes of transmission, to assign wave lengths to the various stations with a view to eliminating interference, to establish rates for the service rendered and in general to standardize and systematize the administration, operation, material, and personnel features of radio communication in the entire western hemisphere.

It is proposed to divide the territory embraced in the Pan-American republics into zones of radio communication with one control radio station for each zone, in a manner similar to that on which the Naval Radio Service is organized for the transaction of United States Government business.

These zone stations will receive and relay radiograms to their destination in accordance with the regulations provided. It is proposed to have one main station for the entire hemisphere, located in as nearly a central position, geographically, with reference to all American republics, as may be practicable. Such a main station should be capable of direct communication with central stations in each of the proposed zones, covering the territory of the interested governments, and Darien is suggested as this main station.

The plans drawn up provide for zone central stations at the following places tentatively; changes may later be found to be desirable.

Buenos Aires, Argentine
Para, Brazil
Guatemala
Guantanamo
Washington
Possibly Tela, Honduras

Each of these zone center stations will serve as a receiving and distributing station for the stations in their respective zones, and each will be capable of direct communication with the main station. In each country, preferably at the capital, there will be a central controlling and distributing station, which would be capable of direct communication with the appropriate zone center station and local stations of low power.

The diagram shown in Figure 18 represents graphically the ideas advanced, and it will be noticed that the scheme of communication covers the whole of the United States, Central and South America, and that the zones represent the United States, West Indies, Central America, Northern South America, and southern South America. From each of the zone stations, communication is possible to other distributing stations, and each of these distributing stations can communicate with local stations in various countries. Thus, a message from Washington to Paraguay in the vicinity of Concepcion could be routed via Darien (zone station), Buenos Aires (zone station), Ascuncion, Paraguay (distributing station), Concepcion and thence to its destination by land lines. A study of this scheme will show that any place in these countries that has telegraphic connection can be reached, and the whole system is mutually interlocked.

SOME REMARKS ABOUT NEW HIGH POWER STATIONS

The high power stations in course of construction at San Diego, Pearl Harbor, Cavite, and Guam are well under way, and Figures 19, 20, and 21 show a view of San Diego as it appeared in January, 1916. The steel towers, three in number, of the self-supporting type, are each to be 600 feet (183 m.) high in the form of a triangle, 1,100 feet (336 m.) along the base, each of the other sides being 1,000 feet (305 m.) between towers. The power input will be 200 kilowatt with 150 amperes in the antenna, this current being furnished by apparatus of the Poulsen system as developed by the Federal Telegraph Company. The power will be supplied with the following characteristics, viz.: 3 phase, 60 cycle, 11,000 volts. The station is located on a site specially selected and purchased for the purpose and which contains about 27 acres, being about twice the size of the Arlington reservation.

FIGURE 18

The station at Pearl Harbor, generally referred to as Honolulu, will have three steel, self-supporting towers, erected in the form of an equilateral triangle, 1,100 feet (336 m.) between each two towers. The system used is the Poulsen with 350 kilowatts input power, with 200 amperes in the antenna. Power is obtained from the Naval station plant, 3 phase, 60 cycle, 2,200 volts. The station is built on government property and is not limited in area.

Figure 19—Erection of Tower Leg,
San Diego

Figure 20—350 K. W. Station Buildings,
San Diego, Cal.

The station at Cavite, in the Philippines, will have three towers similar to those at Pearl Harbor, but only 1,000 feet (305 m.) between towers. Apparatus of the Poulsen system, with 350 kilowatts input power and 200 amperes in the antenna will be supplied. The power will be from a 250 volt, direct current, oil engine driven generator and storage battery. The towers are built on the station reservation and the area is practically not limited.

FIGURE 21—Tower Base, 350 K. W.
Station, San Diego

FIGURE 22—Station,
Arlington

FIGURE 23—Administration
Building, Arlington

The station on the Island of Guam will have two steel self-supporting towers, each 400 feet (122 m.) high, with a distance between towers of 700 feet (214 m.). Apparatus will be of the Poulsen system, with 35 kilowatts input and 30 amperes in the antenna. Power will be obtained from the Naval reservation site and will be 3 phase, 60 cycle, 2,200 volt. This station is erected on government property and has all space desired.

Details of the antennas have not yet been developed except that it is proposed to have the spreaders a permanent part of the towers, and each wire supported by independent insulators.

FIGURE 24—Superintendent's Office, Administration Building, Arlington

FIGURE 25—Accounting Room, Administration Building, Arlington

As each wire for the large station will weigh something over 300 pounds (136 kg.), some arrangement is desirable whereby it will be possible to handle but one wire at a time.

(Thru the courtesy of Capt. Bullard and Messrs. Pannill and Clark, the Editor is able to lay before the readers of THE PROCEEDINGS OF THE INSTITUTE OF RADIO ENGINEERS photographs of the administrative offices and a practically complete group of illustrations of the Naval radio stations of the Atlantic coast, Porto Rico, the Canal Zone, the Great Lakes, the Pacific Coast, and China. These illustrations, which are suitably labelled, give an admirable idea of the magnitude of this system.—EDITOR)

SUMMARY: The Arlington station of United States Naval Radio Service is described in detail. The towers, large antenna, ground, power supply, 100 kilowatt spark set, receiving room, 5 kilowatt spark set, small antenna, and 100 kilowatt arc set are fully considered as to design and operation. The traffic statistics of Arlington are given.

The question of Pan-American radio communication is considered and a comprehensive zone system is proposed and explained. The routing of a typical message is followed out.

The new high power stations at San Diego, Pearl Harbor, Cavite, and Guam are considered, with some details as to their equipment.

A series of illustrations of the Naval radio stations follow.

FIGURE 26—Chelsea, Mass.

FIGURE 27—Newport, R. I.

FIGURE 28—Sayville, N. Y.
(Station under Naval
Control)

FIGURE 29—Tuckerton, N. J.
(Station under Naval
Control)

FIGURE 30—Naval Radio Laboratory, Washington, D. C.

FIGURE 31—Washington,
D. C.

FIGURE 32—Charleston, S. C.

FIGURE 33—San Juan, Porto Rica

FIGURE 34—Darien, Canal Zone

FIGURE 35—Colon, Panama

FIGURE 36—Balboa, Canal Zone

FIGURE 37—Mare Island, Cal.

Figure 38—Great Lakes Station

Figure 39—Cordova, Alaska

Figure 40—Dutch Harbor, Alaska

Figure 41—North Head, Alaska

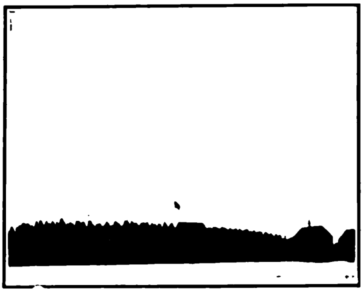

Figure 42—Kodiak, Alaska

Figure 43—Pekin, China

DISCUSSION

Charles J. Pannill: Few people outside of our own service fully appreciate the size and scope of the Naval Radio Service of which Arlington is the central station. The time is not distant when it will be very necessary for Arlington to be able to have three or four transmitting circuits and the receiving office to be able to take at least five messages, all of which transmitters and receivers will have to be in operation at the same time. This is not only practicable, but can be done with a very small outlay. In addition to the Government traffic for all departments handled by our service, we also handle a large volume of commercial traffic both in our ship-to-shore and point-to-point service, including our service in Alaska. The operation and control of the Sayville-Nauen and Eilvese-Tuckerton circuits are handled by our office, which is as well as the clearing house for all international ship-to-shore business in which American naval and merchant vessels are concerned. It is very gratifying to see such communication as that of Arlington working direct with Darien in day light and Darien working with a naval vessel a thousand miles (1,600 km.) south, thereby effecting communication nearly 3,000 miles (5,000 km.) over land and sea with a ship with only one relay. This is quite different from conditions at the time I entered radio, when communication between Fort Monroe and Ocean View, some four miles (6 km.) was considered wonderful. Captain Bullard has covered the subject so well that I cannot add anything further.

NOTES ON RADIATION FROM HORIZONTAL ANTENNAS[1]

By
Charles A. Culver
(Professor, Beloit College, Cambridge, Massachusetts)

Continuing the work done by the author,[2] Kiebitz, and others, we have recently carried out a series of experiments on the relative radiation efficiency of low horizontal antennas. These tests were conducted at the Cruft High Tension Laboratory, Harvard University, during the spring months of 1915.

A low antenna was erected on the plan shown in Figure 1. The mean height of *A B* was 3.7 meters; *C D*, 4 meters; *D E*, 1 meter. The wire composing the system was copper, 7 strands of number 22[3], and insulated from the ground. The particular dimensions chosen were determined by local physical conditions and hence have no special significance. The complete system *AE* had a capacity of 0.00738μf. The capacity of *CE* was 0.00313 μf., and of *CE* 0.00355 μf. The decrement of the complete system was approximately 0.3. The radiation resistance of *A B* was 10.6 ohms at 810 meters, and 8.4 ohms at 1,100 meters. Provision was made for utilizing *A E*, *A B* or *C E* as radiating units. The water system in the building served as a ground in a number of the tests, while in others a radial earth system was utilized. The latter consisted of a number of stranded

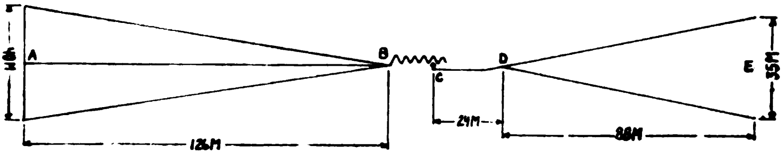

Figure 1 —Arrangement of Horrizontal Radiating System at Harvard University

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[1] Received by the Editor, February 2, 1916.
[2] "Physical Review," N. S., Vol. III, No. 4, April, 1914.
"Electrical World," Vol. 65, No. 12, March 20, 1915.
[3] Diameter of number 22 wire = 0.025 inch = 0.064 cm.

copper wires buried a few centimeters beneath the surface of the ground and extending radially more or less directly beneath the section *A B*. The natural period of the part *A B*, when utilizing the radial earth just referred to, was 740 meters; when using the water system as an earth the period was found to be 665 meters. Power was supplied to the radiating system from a 2-kilowatt air-core transformer operating at 500 cycles. A quenched gap and loose coupling was employed. *B C* represents the secondary of the coupling transformer.

Tests were carried out between the above described station at the Cruft Laboratory and the points shown in Figure 2.

On May seventh and eighth a series of comparative tests were conducted between Cambridge and a temporary receiving station erected at Plymouth. The antenna at the latter place consisted of two nearly vertical wires approximately 1 meter apart and 21.3 meters long. The pipes of a steam system served as earth. The receiving equipment comprised a loosely coupled audion with shunted receivers for determining the audibility.

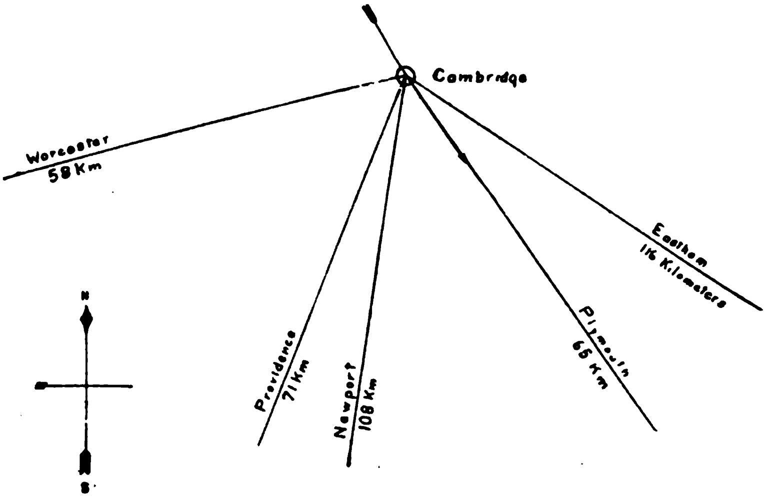

FIGURE 2—Relative Position of Stations. The arrow at the Harvard Station shows the direction of the horizontal radiating system.

At the Cruft Laboratory, the large vertical antenna was used as a standard of comparison for radiation. This will be referred to as the "standard antenna." It consisted of 16 nearly vertical wires having a mean height of 152 feet (46 m.). Its natural period was 370 meters when using the radial earth, and its capacity was 0.00208 μf. The radiation resistance was found to be 5.4 ohms at 890 meters, and 8.3 ohms at 644 meters.

The results of these tests appear in the following table. It will be noted that alternate readings were made between the standard antenna and the special type under test.

Table Showing Conditions and Results of Harvard-Plymouth Radiation Tests. Power: 1.9 kilowatts. Wave length: 800 meters.

Test Number	Radiating System	Antenna Current Amperes	Nature of "Earth" at Harvard	Audibility at Plymouth	Remarks
1	Standard	4.65	Radial	23+	7:30 P. M.
2	*AB* Figure 1	4.5	Radial	0	7:50 P. M.
3	Standard	4.65	Radial	24	8:30 P. M.
4	*AE* Figure 1	3.8	None	19+	8:45 P. M.
5	Standard	4.7	Radial	37+	9:30 A. M. Heavy rain during night.
6	*AB* Figure 1 Grounded At *A*	1.8	Radial	4+	9:50 A. M.
7	Standard	4.8	Radial	23+	10:30 A. M.
8	Standard	4.1	Water System	14+	10:45 A. M. Doubtful values owing to resonance conditions at *H*.

It was originally intended to make test number 8 a comparison of *A B* when using the water system as a ground; but owing to an error in arranging the schedule and inability to repeat the experiment, this comparison was omitted. However, in this connection, it should be mentioned that the Harvard station was heard on April tenth by 1*QC*, Eastham, Mass., when using the arrangement just indicated.

Several points of special interest are apparent in the above table. First it is evident that the horizontal system *A E* is comparable in radiating efficiency to the standard vertical antenna—at least this is true for a direction more or less in line with the plane of the horizontal antenna. When one considers the cost of erection and maintenance of a large vertical system such as that on the Cruft Laboratory, the comparison is even more striking.

A second point worthy of note is the result obtained when using a system made up of *A B* grounded at the end remote from the coupling transformer and the radial earth. The oscillation of this system gave rise to some radiation as will be seen by the audibility at Plymouth, tho it did not radiate appreciably when the end was not earthed. (See test number 4.) We propose to investigate this point further.

When one comes to investigate the radiation from a low horizontal antenna in directions other than that of its own plane, the results are found to be materially different. The following-described tests were arranged to secure data on this latter aspect of the question.

Qualitative tests were made between the Harvard station when using *A E* as a radiating system and a well equipped private station at Worcester, Mass. The Worcester station was unable to hear the Harvard signals.

Thru the courtesy of the United States naval authorities, a series of tests were carried out between the Harvard station and the United States naval station (*N A F*) at Narragansett Bay, Newport, R. I. This series of experiments was conducted on May thirteenth to nineteenth inclusive, between the hours of 8:30 and 8:45 A.M. Much interference was encountered, particularly on the last two days, but it was found possible to carry out several fairly satisfactory tests.

When radiating an 800-meter wave from the standard antenna at Harvard, the audibility at Newport was found to be 300 ohms. The Newport station was, however, unable to detect signals from the Harvard station when the latter radiated an 800-meter wave from the horizontal system *A E*.

With the kind coöperation of Professor Watson, it was possible to attempt a series of tests between the Harvard station and Brown University, Providence, R. I. For reasons which we have been unable to discover neither the radiation from the standard nor horizontal antennas could be detected at Providence.

It thus becomes apparent that the low horizontal antenna has a very low radiation efficiency in directions which make substantial angles with its own plane. In this connection, however, it is interesting to note that this system would respond to incident radiation from the directions in which it would not radiate. For example Arlington (*N A A*), could be heard at night with an audibility of 4 to 5. Many experiments made with the Harvard ground antenna, however, showed that it is comparatively inefficient as a receiving system in directions other than that of its own plane. This is in line with the results obtained by Mr. Riner and the author in previous experiments. Incidentally it might be of interest to note that last spring Mr. Riner, while experimenting at Madison, Wis., was able to hear the Arlington time signals and read the weather report when utilizing a ground antenna similar to the one described in our recent paper. Mr. Riner informs the author that his wires were supported about 2 feet (60 cm.) above the surface of the ground, and that a crystal detector was employed.

The Harvard experiments above described are more or less preliminary in character. Owing to local physical and electrical conditions it was impossible to determine the optimum wave length to be employed with an antenna of given length. It is more than probable that a materially higher efficiency would have resulted if it had been possible to adapt the wave to the electrical dimensions of the radiating system. The experiments show, however, that a low horizontal antenna may have for certain directions a radiation efficiency comparable with that of the conventional vertical systems; and also that the horizontal form, as is to be expected, probably has a decidedly asymmetrical radiation curve.

A series of experiments are now being arranged whereby it is hoped to be able to determine the polar radiation curve for a horizontal system placed within a few centimeters of the ground. It is also proposed to determine the optimum arrangement of the component parts of such a ground antenna when used as a radiating system.

In conclusion we wish to thank Professor G. W. Pierce of Harvard University, for his cordial and helpful coöperation in carrying out the investigation described in this paper.

Beloit College, January 1, 1916.

SUMMARY : Experiments on the radiation from various types of low horizontal antennas are described. A 2-kilowatt, 500-cycle quenched spark set is used at a wave length of 800 meters. The influence of the ground is investigated. Directional radiation is found, and also an apparent non-reciprocity between directions of non-radiation and those of non-reception.

A FEW EXPERIMENTS WITH GROUND ANTENNAS*

By

LEONARD F. FULLER

(CHIEF ELECTRICAL ENGINEER, FEDERAL TELEGRAPH COMPANY)

The experimental data described herein were taken early in 1912. Recent articles on ground antennas appearing in the PROCEEDINGS OF THE INSTITUTE OF RADIO ENGINEERS have again brought up the subject, and it is felt that a description of these rather incomplete experiments may be of interest inasmuch as they show polar curves of received current taken with a d'Arsonval galvanometer and crystal detector.

The work was carried on in all kinds of weather and frequent cross-checking of data showed no variation from this cause.

The topography of the country was rough with low hills and both transmitter and receiver were approximately 800 feet (250 m.) above sea level.

The transmitter consisted of a non-synchronous rotary gap, spark set, radiating 4 amperes in a flat-top antenna of ordinary design at a wave length of 1,000 meters and a high decrement.

The receiver was located 2,100 feet (640 m.) from the transmitter and was equipped with a silicon detector and galvanometer for the quantitative work in addition to the usual receiving apparatus. In the actual observations the detector was connected directly in the antenna circuit and no coupling was used. This gave the receiver a high decrement also.

It is to be regretted that only a little over half a wave length separated transmitter and receiver and also that the decrements were high thruout. The theoretical laws governing the performance of ground antennas were followed reasonably well by the experimental observations, however, and it is believed the above conditions did not seriously vitiate the observed results.

The ground antenna consisted of two number 16 B. & S. gauge,† rubber covered stranded copper wires, each 264 feet (80.5 m.) in length measured from the center of the house in which the receiving apparatus was located.

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*Received by the Editor May 15, 1916.

†Diameter of number 16 wire = 0.0508 inches = 0.129 cm.

These wires were laid flat on the earth with the far ends insulated therefrom.

In the FIRST TEST the two wires were kept diametrically opposite, i. e., 180° apart, and were rotated thruout 180°. Readings were made of their angular position and of the galvanometer deflection, the square root of which was proportional to the received current.

The observed readings were as follows:

TEST 1

Angle	Current
θ	I_R
0°	4.84
15°	4.57
30°	4.39
45°	3.55
60°	2.65
75°	1.54
90°	1.14
105°	1.54
120°	2.65
135°	3.55
150°	4.39
165°	4.57
180°	4.84

Wires 180° apart rotated thru 180°. Length of each antenna 264 feet (80.5 m.).
Outer ends ungrounded.

Plate 1 is a polar graph of these data, showing bi-lateral reception, a true cosine curve, with a maximum received current when the antenna lay in the plane of the arriving wave.

The equation of this curve is

$$I_R = K l \cos \theta$$

where I_R = received current,
l = length of each wire,
θ = angle between arriving wave and antenna,
K = a constant depending upon the units chosen for I_R and l.

In the SECOND TEST, the antennas were 90° apart and the resultant system shaped like a "V" was rotated thruout 180° with the base of the "V" as the center.

The observed readings were:—

TEST 2

Angle	Current
θ	I_R
0°	2.90
15°	3.80
30°	4.40
45°	4.85
60°	4.40
75°	3.80
90°	2.90
105°	2.49
120°	1.15
135°	0.00
150°	1.15
165°	2.49
180°	2.90

Wires 90° apart rotated thru 180°.

Length of each antenna 264 feet (80.5 m.).

Outer ends ungrounded.

At 0°, one wire was pointing toward the transmitter and the other at 90°.

Plate 2 is a polar graph of these data. It is somewhat similar to Plate 1, but rotated 45° with respect thereto. The main

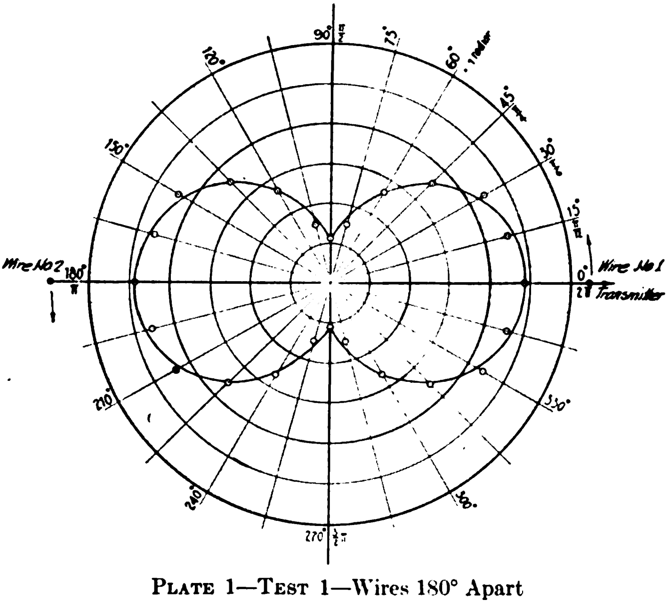

PLATE 1—TEST 1—Wires 180° Apart

point of interest is the excellent way in which the two halves of the ground antenna "buck" at 135° and 315°. No deflection of the galvanometer was visible at these angles.

The equation of this curve is

$$I_R = K\,l\,\cos\theta - K\,l\,\cos(\theta - 90°).$$

In the THIRD TEST one antenna was kept fixed, *pointing toward the transmitter,* and the other rotated.

The observed data were:—

TEST 3

Angle	Current
θ	I_R
0°	0.00
15°	0.00
30°	0.00
45°	0.00
60°	0.63
75°	1.66
90°	2.53
105°	3.05
120°	3.47
135°	3.61
150°	3.74
165°	3.96
180°	3.94

One wire fixed. Other rotated.
Length of each wire 264 feet (80.5 m.).
Outer ends ungrounded.

Plate 3 shows the polar graph, a cardioid in form. This is similar to curves obtainable with the Bellini-Tosi method under certain conditions.

The equation of this curve is approximately

$$I_R = K\,l\,(1 - \cos\theta).$$

TEST FOUR involved the use of one wire only. An earth connection was substituted for the other. In this way a Marconi directive antenna of extreme length for its height was obtained. The characteristic shown on Plate 4 is of the usual form for this type of antenna altho the zero received current at 90° and 180° is an extreme case of the usual reduction at these points, found in the commercial forms of this type of directive antenna.

The observed data were:—

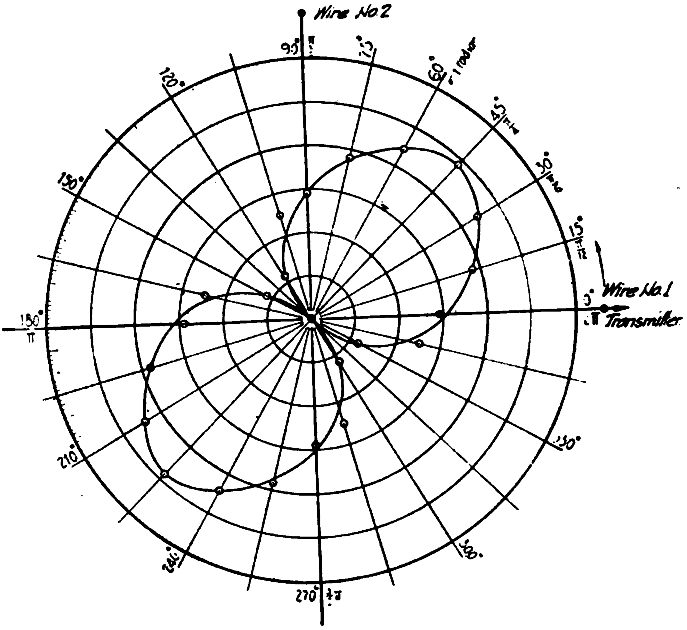

Plate 2—Test 2—Wires 90° Apart

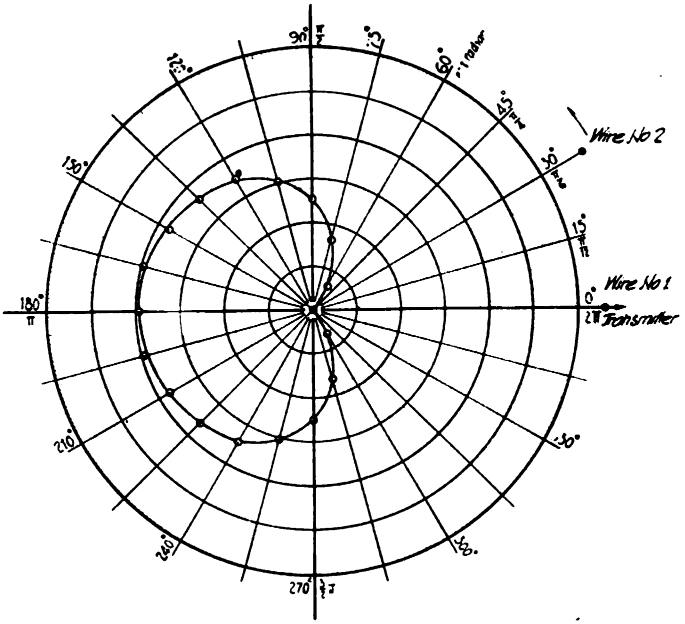

Plate 3—Test 3—One Wire Fixed, Other Rotated

TEST 4

Angle	Current
θ	I_R
0°	3.4
15°	3.2
30°	3.1
45°	2.49
60°	1.45
75°	0.78
90°	0.00
105°	0.78
120°	1.70
135°	3.07
150°	3.40
165°	3.55
180°	3.94

Single wire. One end grounded thru receiver. Other end rotated.

Length 264 feet (80.5 m.).

Test Five involved observation of the effect of wire length upon received current. This current was found directly proportional to the wire length within the limits of the observations. The observed data follow:

TEST 5

Length	Current
l	I_R
56	0.95
106	1.93
156	3.12
206	4.11
264	4.85

Length (l) = length of each wire in feet.

Outer ends ungrounded.

Plate 5 shows these results in rectangular co-ordinates.

Test Six was a short comparison of ground and vertical antennas. The former were the data of Test 5. The latter consisted of a harp of four vertical wires, each 42 feet (13.8 m.) in length on approximately 10-inch (25.4 cm.) centers. These could be cut in or out at will.

The observed results follow:

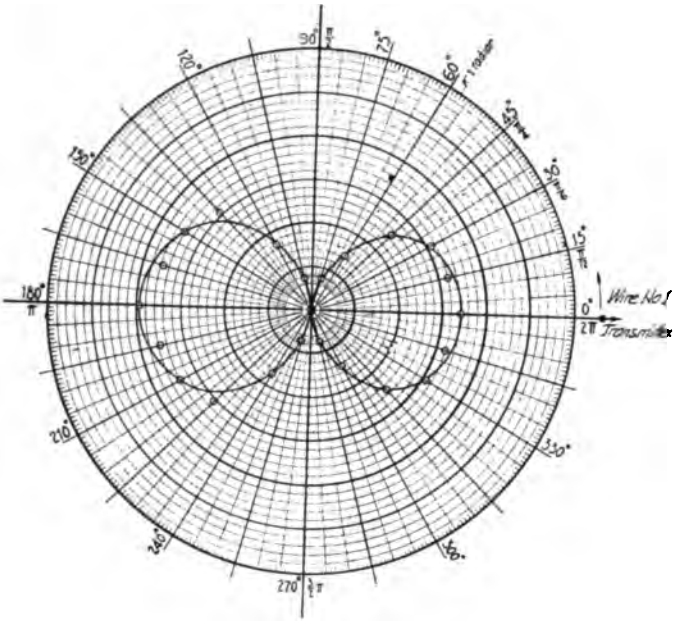

PLATE 4—TEST 4—Single Wire. One End Grounded Thru Receiver. Other Rotated

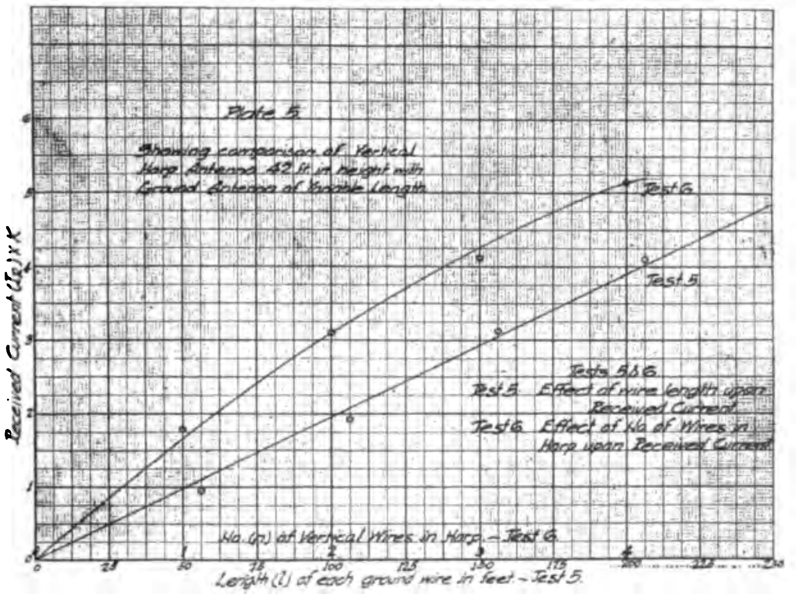

PLATE 5—TEST 5

TEST 6

Vertical Antenna	
Number of Wires	Current
n	I_R
1	1.78
2	3.10
3	4.12
4	5.15

These data are combined with those of Test 5, Plate 5, where the length (l) of each half of the ground antenna is compared with the equivalent number (n) of 42-foot (13.8 m.) vertical antennas required for the same received current.

Atmospheric disturbances were heavy and of about equal intensity on both the vertical and ground antennas.

At the date these data were taken neither continuous wave high powered plants nor oscillating tube receivers were available. Hence none of the present-day long distance reception was possible on the very small antennas used.

SUMMARY: **The polar energy distribution curves of various types of low antennas are given for of slightly less than the wave length from the transmitter. The measurements were made with silicon detector and galvanometer. The influence of wire length of receiver, and vertical vs. ground antennas, were studied.**

THE EFFECT OF THE SPARK ON THE OSCILLATIONS OF AN ELECTRIC CIRCUIT*

BY

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When a condenser is permitted to discharge thru a coil under such conditions as not to produce a spark or under such conditions that the resistance of the spark is completely negligible compared to the conductor resistance of the circuit, the phenomena observed accord well with the mathematical theory advanced in 1853 by Professor William Thompson, the late Lord Kelvin.[1] When, on the other hand, the discharge of the condenser is accompanied by the spark and the conditions are such that the conductor resistance of the circuit is negligible compared to the resistance of the spark, then the Thompson theory no longer applies, even approximately, and such oscillations as occur in the circuit are of a character, the mathematical theory of which, I had the honor to present to this Institute in 1914.[2]

The Thompson theory, which we may best describe as the logarithmic decrement theory, is therefore seen to be the mathematical theory of one extreme or limiting case of electrical oscillation. This extreme case I have shown to be characteristic of very low frequency oscillators. The theory which I presented to you last Spring and which may best be described as the linear decrement theory, is seen to be the mathematical theory of an equally extreme case of electrical oscillation—a case which I have shown to appertain particularly to very high frequency oscillators.

Tho most oscillating circuits used in radio telegraphy are of very high frequency, nevertheless, there are many in which the conductor resistance is by no means negligible compared to the resistance of the spark and such electric oscillators therefore fall into the class for which there is as yet no competent theory upon

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*Presidential Address presented before The Institute of Radio Engineers, New York, February 3, 1915.

[1] "Phil. Mag.," Series 4, Volume V, page 393.

[2] PROCEEDINGS OF THE INSTITUTE OF RADIO ENGINEERS, Volume 2, Number 4, page 307.

which reliable quantitative measurements may be based or from which reliable deductions may be made. It has seemed to me that it might therefore be desirable to carry the investigation of the effect of the spark upon the oscillations in an electric circuit further than was done in my latest paper and to consider the more general theory in which no limitation is placed upon the relative magnitude of the conductor and spark resistances. Such a general theory, of course, includes the logarithmic decrement theory and the linear decrement theory as special and oppositely extreme limiting cases.

It might well be expected that the deduction of this general theory would involve grave difficulties and that the resulting expressions deduced for the oscillatory charge, voltage, and current would be of considerable complexity. Neither of these sources of inconvenience has, however, been found to exist. The great simplicity both of deduction and result flows directly from the fact that the resistance of the spark is in general inversely proportional to the amplitude of the oscillating current flowing thru the spark, provided the oscillations be of radio frequencies and the spark gap electrodes be not composed of the so-called non-arcing materials. This fact was shown, in my before-mentioned paper, to be one of the necessary consequences of the experimentally observed linear mode of decay of the oscillations, noted when the spark resistance is the dominant resistance of the circuit.

As this paper is practically a second installment of my latest paper on this subject before the Institute, it is not necessary to repeat here the numerous collateral statements which it would otherwise be expedient to make by way of explanation, definition and limitation, and we may therefore proceed directly to the solution of the circuital equation:

$$0=\frac{1}{C}\int i\,d\,t+R\,i+L\frac{d\,i}{d\,t} \tag{1}$$

where C is the capacity of the condenser, i is the current at any moment, R is the total resistance of the circuit at that moment and L is the inductance of the circuit.

Let R_1 be the constant conductor-resistance of the circuit and R_2 be the spark resistance.

By dividing (1) thru by L, we may write the equation as:

$$0=\omega_o^2\int i\,d\,t+2\,(a_1+a_2)\,i+\frac{d\,i}{d\,t} \tag{2}$$

where $\omega_o^2=\frac{1}{C\,L},\ a_1=\frac{R_1}{2L}$ and $a_2=\frac{R_2}{2L}$

We know that the current is of the form $i = I \sin (\omega t + \psi)$ where ω and ψ are constant and I only is a function of t because the most careful resonance analysis of these oscillators fails to reveal the presence of a second frequency. If the spark introduced an oscillation of a second frequency, its presence could be detected even tho its amplitude were less than 1 per cent. of that of the principal or fundamental oscillation except in the case of extremely high damping. Furthermore, since the current must be zero when t is zero, if $t = 0$, be chosen as the time at which the oscillations begin, then

$$i = I \sin \omega t$$

It follows from what has been said above and from what was shown in my last paper, that

$$R_2 = \frac{d}{I}$$

where d is a constant.

Substituting these values for i and R_2 in the third term of the right hand number of (2) gives

$$-\frac{d}{L} \sin \omega t = \omega_o^2 \int i\,dt + 2\alpha_1 i + \frac{di}{dt} \tag{3}$$

We see immediately that the effect of the spark in the circuit is merely to introduce a simple harmonic counter electro-motive force $-\frac{d}{L} \sin \omega t$ into the circuit at the beginning of the oscillations and to maintain it there at constant amplitude $-\frac{d}{L}$ as long as the oscillations last.

The solution of (3) therefore resolves itself into the solution of two equations:

$$0 = \omega_o^2 \int i_1\,dt + 2\alpha_1 i_1 + \frac{di_1}{dt} \tag{4}$$

and

$$-\frac{d}{L} \sin \omega t = \omega_o^2 \int i_2\,dt + 2a_1 i_2 + \frac{di_2}{dt} \tag{5}$$

where $i_1 + i_2 = i$.

The complete solution of (4) with all constants determined by the conditions, $i_1 = 0$ and $\int i_1\,dt = Q_o$ at $t = 0$ is:

$$i_1 = I_1 \varepsilon^{-at} \sin \omega t \tag{6}$$

where

$$I_1 = Q_o \frac{\alpha^2 + \omega^2}{\omega} \equiv Q_o \frac{\omega_o^2}{\omega},$$

$$\alpha = \alpha_1$$

and

$$\omega^2 = \omega_o^2 - \alpha^2.$$

The solution of (5) is:

$$-I_2 \sin(\omega t+\theta)+I_3\, \varepsilon^{-\alpha_1 t} \sin(\omega t+\phi) \tag{7}$$

where $I_2=\dfrac{2\,\alpha_o\,\omega}{\alpha_1\sqrt{\alpha_1^2+4\,\omega^2}}$, $\theta=\tan^{-1}\dfrac{\alpha_1}{2\,\omega}$ and $\alpha_o=\dfrac{d}{2L}$.

I_3 and ϕ are determined by the conditions that at $t=0$, $i=0$ and $\int i_2\,dt=0$. These give:

$$I_3=\frac{2\,\alpha_o\sqrt{\alpha_1^2\,\omega^2+(\alpha_1^2+2\,\omega^2)^2}}{\alpha_1\,(\alpha_1^2+4\,\omega^2)}$$

and

$$\phi=\tan^{-1}\frac{\alpha_1\,\omega}{\alpha_1^2+2\,\omega^2}$$

The complete expression for the current is therefore:

$$i=Q_o\frac{\omega_o^2}{\omega}\,\varepsilon^{-\alpha_1 t}\sin\omega t-\frac{2\,\alpha_o\,\omega}{\alpha_1\sqrt{\alpha_1^2+4\,\omega^2}}\left\{\sin\left(\omega t+\tan^{-1}\frac{\alpha_1}{2\,\omega}\right)\right.$$

$$\left.-\frac{\sqrt{\alpha_1^2\,\omega^2+(\alpha_1^2+2\,\omega^2)^2}}{\omega\sqrt{\alpha_1^2+4\,\omega^2}}\,\varepsilon^{-\alpha_1 t}\sin\left(\omega t+\tan^{-1}\frac{\alpha_1\,\omega}{\alpha_1^2+2\,\omega^2}\right)\right\}\ \ldots \tag{8}$$

This expression might not, at first inspection, seem to support fully my earlier statement that the expressions for the oscillatory current voltage and charge are simple and convenient. When, however, this expression is examined in the light of the fact that the ratio $\dfrac{\omega_o}{\omega}$ is almost exactly unity for slightly or moderately damped oscillators, and is very nearly unity even in the case of very heavily damped oscillators and when further account is taken of the fact that the ratio $\dfrac{\alpha_1}{2\,\omega}$ is a very small quantity, even in the case of heavily damped oscillators, it is seen that the expression for the oscillatory current reduces to:

$$i=\left\{Q_o\,\omega_o\,\varepsilon^{-\alpha_1 t}-\frac{\alpha_o}{\alpha_1}\left(1-\varepsilon^{-\alpha_1 t}\right)\right\}\sin\omega_o t \tag{9}$$

In the limiting case of $\alpha_1=0$, or no damping except that due to the spark this expression reduces to

$$i=(Q_o\,\omega_o-\alpha_o t)\sin\omega_o t \tag{10}$$

which is the case of linear decrement treated in my first paper on the effect of the spark on the oscillations of an electric oscillator.

In the other limiting case, namely that in which α_o is negligible compared to α_1, the expression for the oscillatory current reduces to:

$$i=Q_o\frac{\omega_o^2}{\omega}\,\varepsilon^{-\alpha_1 t}\sin\omega t \tag{11}$$

which we immediately recognize as the well-known case of logarithmic decrement, first treated by Lord Kelvin and in which there is no damping due to the spark.

Before proceeding further with the specific subject of this paper, I shall call attention to the peculiar relations between ω_o, ω and a_1 which resulted in the marked simplification of the expression (9) for the oscillatory current.

If we define the logarithmic decrement per cycle of the oscillator in the absence of spark resistance as $\delta = \frac{\pi R}{L \omega}$, then the fact that $\frac{\omega_o}{\omega}$ is practically unity for all values of δ is exhibited in Table I.

TABLE I

$\delta =$	0.2	0.25	0.3	0.35	0.4	0.45	0.5
$\frac{\omega_o}{\omega} =$	1.00050	1.00078	1.00114	1.00155	1.00202	1.00257	1.00317

The fact that $\frac{a}{2\omega}$ and $\frac{a\omega}{a^2+2\omega^2}$ are both small compared to unity and practically equal to each other over a wide range of values of δ including even cases of high damping is exhibited in Table II.

TABLE II

$\delta =$	0.1	0.15	0.2	0.25	0.3	0.35	0.4	0.45	0.5
$\tan^{-1}\frac{a}{2\omega}$	.0080	.0120	.0160	0.020	0.0240	0.0280	0.0320	0.0360	0.040
	0° 27′	0° 41′	0° 54′	1° 9′	1° 22′	1° 35′	1° 49′	2° 3′	2° 17′
$\tan^{-1}\frac{a\omega}{a^2+2\omega^2}$	0.0080	0.0120	0.0160	0.020	0.0240	0.0280	0.0320	0.0360	0.040
	0° 27′	0° 41′	0° 54′	1° 9′	1° 22′	1° 36′	1° 50′	2° 4′	2° 18′

This digression is made and these tables are here introduced because the relations involved are of such universal application in the theory of oscillators and are capable of producing such marked simplifications of the mathematical expressions and computations therefrom, that it is well to have on record for convenient reference the numerical relations of these functions over a fairly wide range of values of the logarithmic decrement δ.

The expression for the quantity of electricity involved in the oscillations, when this expression is simplified in the same way as that for the current, becomes:

$$q = \left\{ \left(Q_o + \frac{a_o}{a_1 \omega_o} \right) \varepsilon^{-a_1 t} - \frac{a_o}{a_1 \omega_o} \right\} \cos \omega_o t \qquad (12)$$

The voltage is, of course, merely $v = \frac{q}{C}$, where C is the capacity of the condenser.

The expression for the current enables us to determine one for the resistance R_2 of the spark in terms of its initial resistance R_0 and time for, save in the very exceptional cases to which this theory does not apply, the resistance of the spark is inversely proportional to the amplitude of the current.

If we designate this amplitude by I, we have:

$$I = Q_o \, \omega_o \, \varepsilon^{-a_1 t} - \frac{a_o}{a_1}\left(1 - \varepsilon^{-a_1 t}\right) \tag{14}$$

and

$$R_2 = R_o \frac{I_o}{I} \tag{15}$$

where I_o is the initial amplitude of the current or $Q_o \, \omega_o$.

These expressions shed considerable light on the quenching of the oscillations of a wave train after a certain time T. In the logarithmic decrement theory there was no indication of the time of quenching, the current merely indefinitely diminished, and tho experience taught us that after a relatively definite time for any particular oscillator, the oscillations positively ceased and the circuit automatically opened at the spark gap, yet there was no recognition of this fact in that theory.

An important result of the fact that this theory which we have just developed, takes cognizance of the definite finite length of an oscillation train, is that it enables us to express in a Fourier's series any isochronous succession of similar damped oscillation trains, provided the oscillation trains do not overlap. The expression in a sine series is effected in this case, as in the case of the linear decrement theory.[3]

In determining the co-efficients of the series it is sufficient to take into consideration only the amplitude of the successive oscillation trains and not the instantaneous value of the oscillations, so that the series is of the form:

$$i = \sin \omega_o t \sum_{1}^{\infty} a_m \sin \frac{m \pi}{T_1} t \tag{16}$$

where T_1 is the periodic time of recurrence of the oscillation trains or the reciprocal of the group or spark frequency.

An examination of the expression (9) for the current shows that after a time

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[3] PROCEEDINGS OF THE INSTITUTE OF RADIO ENGINEERS, Volume 2, Number 4, page 318.

$$T_o = \frac{1}{a_1} \log_{\varepsilon} \left(Q_o \frac{a_1 \omega_o}{a_o} + 1 \right) \tag{17}$$

the amplitude of the current becomes zero and therefore by (15) the resistance of the spark gap becomes infinite. This time T_o, is obviously the time of the quenching of the oscillations.

If T is the time of a complete oscillation, then $\frac{T_o}{T}$ is evidently the number N of complete oscillations in an oscillation train, so that

$$N = \frac{\omega_o \log_{\varepsilon} \left(Q_o \frac{a_1 \omega_o}{a_o} + 1 \right)}{2 \pi a_1} \tag{18}$$

Concerning the condition of non-oscillatory discharge, evidently this occurs when $T_o = \frac{T}{2}$ so that the condition is reached

when $$\frac{a_1}{a_o} = \frac{\varepsilon^{\frac{\pi a_1}{\omega_o}} - 1}{I_o} \tag{19}$$

The first of the last two expressions shows that a_o, a_1, and ω_o remaining the same, the persistency of oscillations increases with the quantity of electricity discharged across the gap.

This expression (18) also shows that Q_o and $\frac{\omega_o}{a_1}$ remaining the same, the persistency of the oscillations decreases with the ratio $\frac{a_o}{a_1}$.

Similarly, the expression (19) shows that a circuit which is just aperiodic may become oscillatory thru an increase in the quantity of electricity discharged across the gap. This increase of Q_o of course means increase in the ratio $\frac{C}{L}$.

Table III shows the variation in the number of complete oscillations per oscillation train for varying values of $\frac{a_o}{a_1}$.

In this table the remaining quantities are taken as

$$Q_o = 10^{-15},\ \omega = \omega_o = 10^6 \text{ and } \delta = 0.2.$$

TABLE III

$\frac{a_o}{a_1} =$	0.1	0.5	1	2	3	4	5	6	7	8
$N =$	23.1	15.0	12.0	8.96	7.33	6.27	5.49	4.91	4.44	4.05

Figure 1 shows the decay of the amplitude of the oscillations of this same oscillator for various values of the ratio $\frac{a_o}{a_1}$. The outermost curve of this figure shows the decrescence of amplitude for the case of $\frac{a_o}{a_1}=0.1$, the next curve corresponds to the ratio $\frac{a_o}{a_1}=0.5$, etc., to the innermost curve which corresponds to a ratio $\frac{a_o}{a_1}=9.0$.

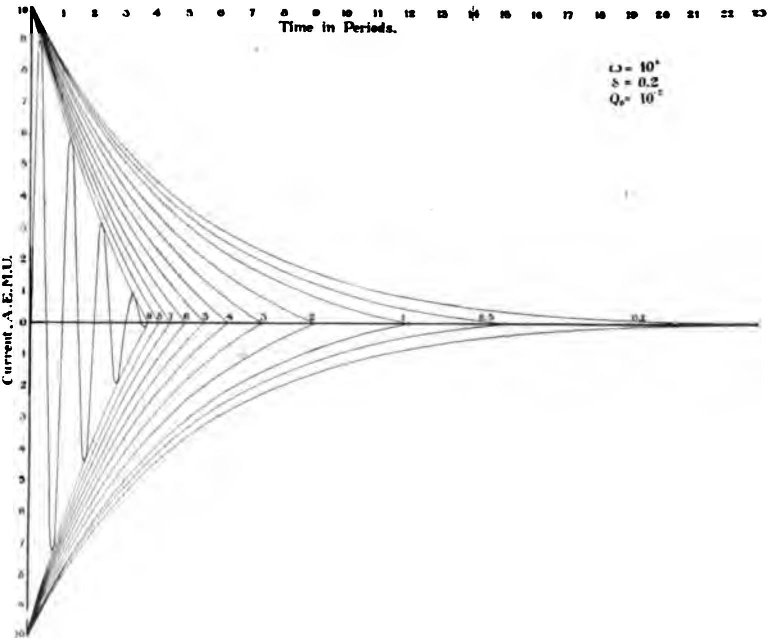

FIGURE 1

Table 4 shows the variations in the number of complete oscillations per oscillation train for varying values of the quantity Q_o of electricity involved in the oscillations. In this table the other constants of the oscillator involved are $\omega=\omega_o=10^6$, $\delta=0.2$ and $\frac{a_o}{a_1}=1$.

TABLE IV

$Q_o =$	0.0001	0.0002	0.0003	0.0004	0.0005
$N =$	12.0	15.2	17.2	18.6	19.7

Figure 2 shows the decrescence of the amplitude of the oscillations of an oscillator having these constants, for varying values of Q_o.

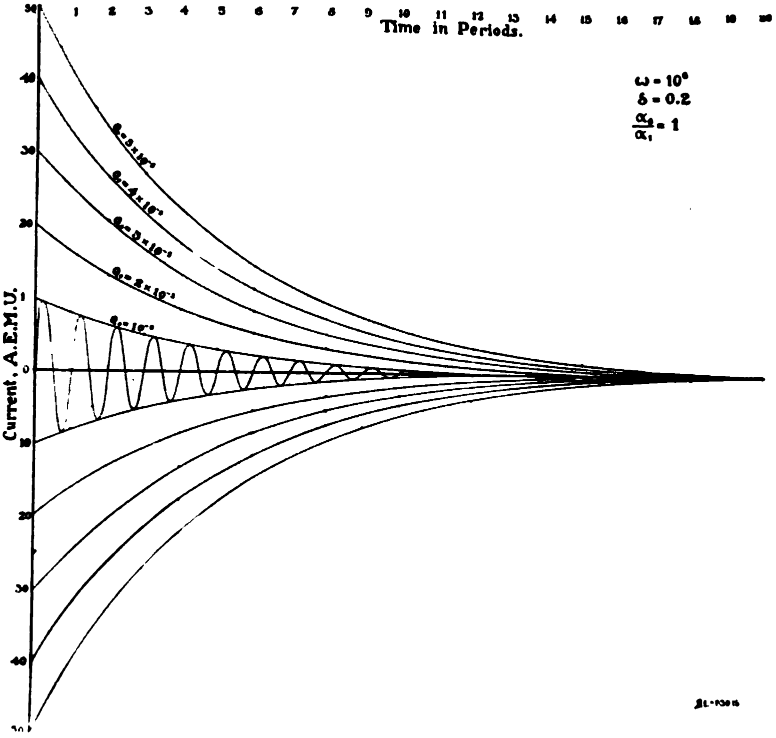

FIGURE 2

The increase of resistance of the spark with time for different values of $\frac{a_o}{a_1}$ and for different values of Q_o is exhibited in Figure 3. The curves marked 0.1, 0.5, 1, 2, etc., to 8, each represent the spark resistance for the corresponding ratio of $\frac{a_o}{a_1}$, the remaining constants of the oscillator being $Q_o = 10^{-5}$, $\omega = \omega_o = 10^6$ and $\delta = 0.2$. The curves marked $Q_o = 10^{-5}$, $Q_o = 2\times10^{-5}$, $Q_o = 3\times10^{-5}$, etc., represent the spark resistance for corresponding values of Q_o, the other constants being $\omega = \omega_o = 10^6$, $\frac{a_o}{a_1} = 1$ and $\delta = 0.2$.

In my earlier paper on the subject of the resistance of the spark, the mode of variation of the resistance of an arc with the instantaneous value of the current flowing thru it and the hysteretic lag in the resistance of an alternating current arc is

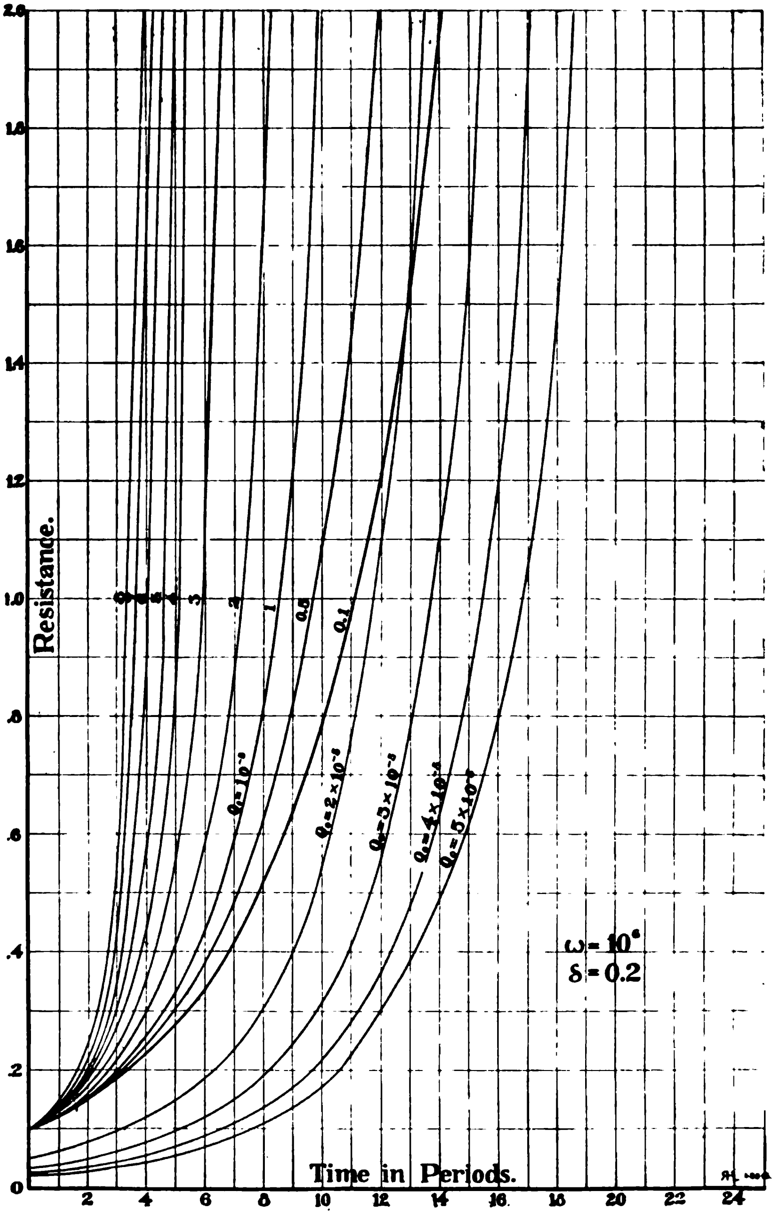

FIGURE 3

discussed.[4] The effect of these factors upon the shape of the curve of the instantaneous values of the voltage at the terminals of the arc is illustrated in Figure 8 of that paper. It is there shown that as the frequency of the alternating current is progressively increased, the instantaneous value of the resistance of the arc or spark becomes more and more nearly independent of the instantaneous value of the current and progressively tends to become more nearly inversely proportional to the amplitude of the alternating current so that when radio frequencies are reached, the simple law of inversed ratio to the amplitude of the current, in general, obtains.

In order to determine, in any particular case, to what extent, if any, there is a deviation in the resistance of the spark from the law of simple inverse ratio to amplitude of current, it is sufficient to examine the oscillators, by means of an extremely loosely coupled exploring resonant circuit, for the first odd harmonic. The relative magnitude of this odd harmonic, if such be found, to the fundamental oscillation will be an index of the departure, if any exists, from the law of simple inverse proportionality of the spark or arc resistance to the amplitude of the current.

Figure 4 of this paper shows how the peculiar dissymmetrical curve of instantaneous voltage across an alternating current arc may be synthetically constructed by the addition to the fundamental sine curve, of the two first odd harmonics. In this figure, curve 3 is the sine curve of the fundamental. Curve 4 is the sine curve of the first odd harmonic, curve 5 is the sine curve of the second odd harmonic, curve 6 is the cosine curve of the fundamental, curve 7 is the cosine curve of the first odd harmonic, the symmetrical curve 1 is the sum of curves 3, 4, and 5, and the dissymmetrical curve 2 is the sum of 3, 4, 5, 6, and 7.

Curve 1 corresponds very closely in shape to that of the voltage across an alternating current arc in which the instantaneous values of the resistance varies according to the well-known law

$$\rho = \frac{a}{i} + \frac{b}{i^2}, \tag{20}$$

which obtains for unidirectional arcs and for arcs in which the current varies so slowly as not to exhibit the effects of the hysteretic lag of resistance behind current variation.

In this expression, which is the same as that given on page 320 of my previous paper, ρ is the instantaneous value of the

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[4] PROCEEDINGS OF THE INSTITUTE OF RADIO ENGINEERS, Volume 2, Number 4, pages 320 to 322.

resistance of the arc or spark in question, *a* and *b* are constants and *i* is the current. This expression for the resistance of an arc or spark may be said to give its "static resistance."

Curve 2, on the other hand, corresponds very closely to the curve of the instantaneous voltage across an alternating current arc of ordinary lighting frequencies in which the effect of the resistance hysteresis is well defined.

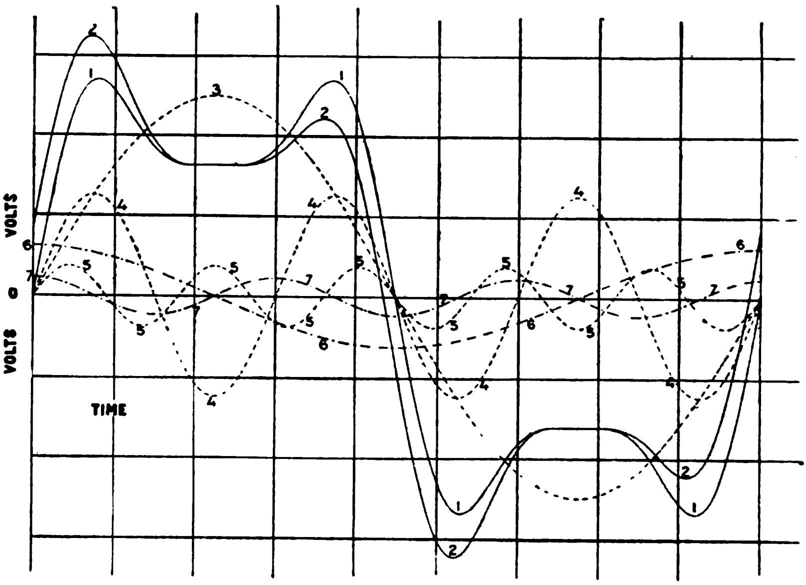

FIGURE 4

It will be noted that the two symmetrical peaks of curve 1, with the flat valley between them, are produced by the addition to the sine curve of the fundamental, of the sine curves of the first and second odd harmonics, while the dissymmetry of the peaks of curve 2 and the slight shift in phase of that curve is due, almost wholly, to the addition of the cosine curve of the fundamental. The diagram of Figure 4 illustrates well, therefore, how a resonant harmonic analysis of the oscillations of a circuit may be used to shed light on the degree to which, if at all, the resistance of the spark depends upon the instantaneous values of the current and therefore differs from the law of simple inverse proportionality to the amplitude of the current. It shows, moreover, that the degree to which the hysteresis of the spark or arc resistance is effective is not so easily determined.

Coming now to one of the practical applications of some of the considerations contained in my two papers on the resistance of the spark and its effect on the oscillations of electric circuits, it is to be noted that the quenching of a spark or arc is the same thing as the development of an infinite or practically infinite gap resistance. In the case of an alternating arc or spark, there are only two reasons why the resistance of the gap does not reach an infinite value every time the current passes thru a zero value, i.e., once for each alternation or reversal. The first reason is the resistance hysteresis and the second is that the current does not remain long enough at or near its zero value to overcome the effect of the resistance hysteresis and permit the gap to assume its "static resistance" in accordance with the expression (20).

The hysteretic lag of the resistance of an arc or spark behind the instantaneous value of current change may be minimized by anything that tends to cool the arc or spark gap quickly, or otherwise to extinguish the arc or spark. For this purpose air blasts and powerful magnetic fields across the gap have been successfully used. The characteristic structure now so well-known as the quenching gap, giving as it does the maximum mechanical opportunity for the conduction and radiation of the heat away from the spark as well as the sub-division of the spark into a number of small series sparks, is much used. The use of electrodes of such metals as silver and copper, which minimized the hysteretic lag of the resistance of the spark, and the use of hydrogenous vapor at the gap are common. But besides minimizing the hysteresis of the spark, it is customary in the quenched spark systems to cause two oscillations of approximately equal amplitude and differing from each other in frequency by a small percentage, to pass across the gap at each spark so that owing to the beats between these oscillations, the *amplitude* of the oscillating current across the gap will fall to zero after say about five oscillations or so have passed and the resistance of the gap thereby permitted to attain a practically infinite value in spite of such resistance hysteresis as the spark may have.

Up to the present time most effort has been exerted to the diminution of the resistance hysteresis of the spark, i. e., to the enhancing of the quenching action at the gap *per se*. But it is evident from the aspect of the subject as here presented that when great or rapid quenching is required as in the production of *impulsive excitation* or in the production of *sustained oscillations*, it is quite as important to provide time for the hysteresis of the arc or spark to expend itself and allow the gap to attain its "static resistance" as it is to minimize the resistance hysteresis at the gap. This can only be done by providing intervals of time when the current across the gap is zero or practically zero, these intervals being made long enough to permit the resistance at the gap to become sensibly infinite.

To accomplish this result we may have recourse to a combination of alternating currents or oscillations simultaneously flowing across the gap, these alternating currents or oscillations being so chosen that they will combine, together and with the supply current, to form intervals of zero current or substantially zero current across the gap.

By Fourier's theorem, it is evident that we can produce a combination of alternating currents, which will satisfy this requirement with as great a degree of approximation as we may wish. Thus the series:

$$i=I_o\left\{1+\frac{4}{\pi}\left(\sin\frac{2\pi}{T}t+\frac{1}{3}\sin\frac{6\pi}{T}t+\frac{1}{5}\sin\frac{10\pi}{T}t+\quad.\quad.\quad.\right)\right\} \quad (21)$$

is a function which alternately has the values $2I_o$ and 0, holding each of these values for successive intervals of time $\frac{T}{2}$. The degree of approximation to the desired result which may be obtained by this series when using four of the sine terms, is illustrated in Figure 5. In this diagram curve 1 is the sum of all the dotted sine curves, 2, 3, 4, and 5, taken about axial line I_o. These dotted curves may be taken to represent alternating or oscillating currents and the straight line I_o may be taken to represent a steady unidirectional charging current. It will be noted that for the first half of the period the resultant current represented by curve 1 is approximately $2I_o$ in value, and for the second half it is approximately zero. Such a combination of currents passing across a spark gap would cause it to quench once in each half period even were the fundamental alternating or oscillating current of radio frequency.

If it is desired to make the interval of time during which the current is approximately zero long compared to that during which it is at full strength, another series of alternating currents may be deduced by Fourier's theorem, but for practical purposes it would not be desirable or necessary to have resort to a Fourier's series, which would lead to the necessity of using too great a number of different alternating or oscillating component currents. One who is reasonably familiar with the practical working of Fourier's series can work out much simpler combinations of alternating or oscillating currents, which will give the desired intervals of approximately zero current with a sufficient degree of precision for

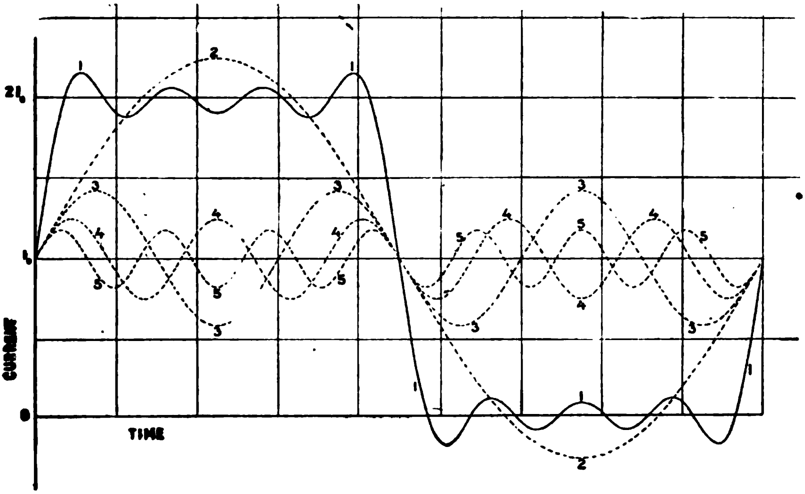

FIGURE 5

practical purposes. As an example, Figure 6 shows a case where the gap current illustrated by curve 3 is approximately zero 5/9*ths* of the half period. This result is accomplished by the

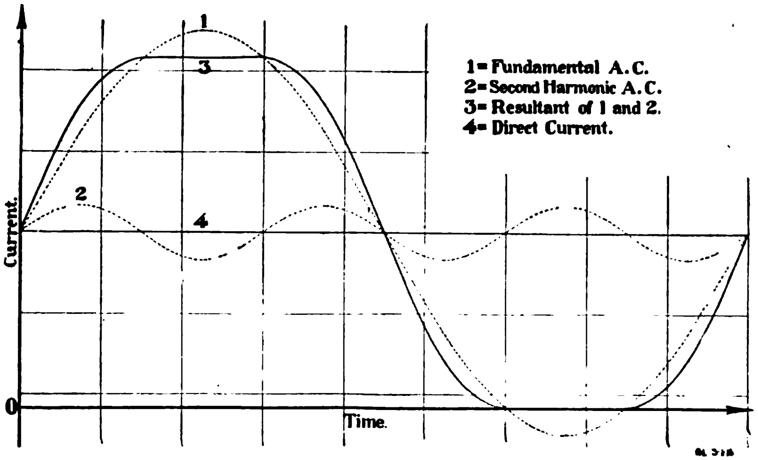

FIGURE 6

combination of a unidirectional charging current and two alternating or oscillating currents, the equation for the gap current being:

$$i = 0.86 + \sin \omega t + 0.135 \sin 3 \omega t \qquad (22)$$

Perhaps a better arrangement might be secured for some purposes by the use of three frequencies, the equation for the gap current then being approximately

$$i = 0.80 + \sin \omega t + 0.26 \sin 3 \omega t + 0.064 \sin 5 \omega t \qquad (23)$$

This case is illustrated in Figure 7 and it is seen that the gap current is approximately zero for two-thirds of the half period. Probably the easiest way to secure impulsive excitation, however, would be to employ a supply current not great enough, *per se*, to maintain an arc across the gap and then use a combination of oscillating or alternating currents whose sum would be zero over a considerable fraction of the time period of the fundamental. Such a combination is given approximately by the series:

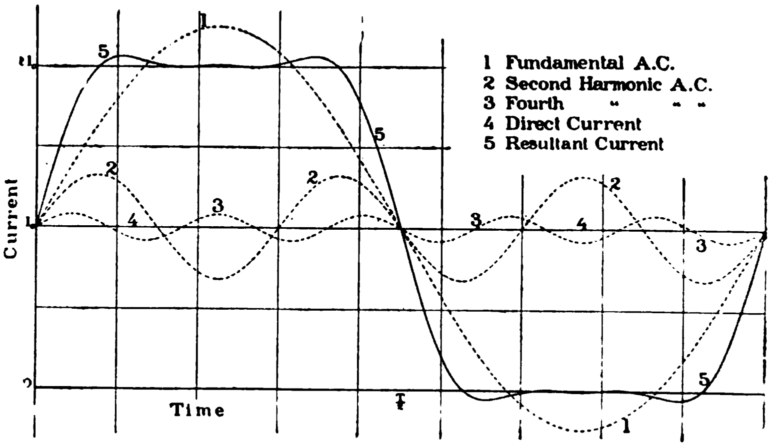

FIGURE 7

$$\sin \omega t + \sin 2 \omega t + \frac{1}{3} \sin 3 \omega t \qquad (24)$$

This series is approximately zero for about 4/11*ths* of the total period.

Several ways in which these combinations of gap currents may possibly be secured in the case where oscillating circuits are used and some suggestive modes of associating the oscillating circuits with the aerial are shown in Figures 8, 9, 10, 11 and 12, where S represents a quench gap which may have its quenching power enhanced, if necessary, by the use of hydrogenous vapor between its plates and by the use of a powerful magnetic field acting axially along the gap.

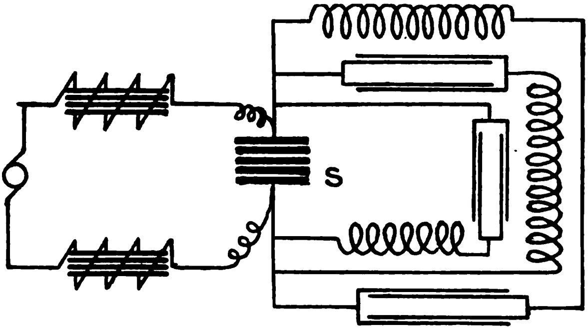

FIGURE 8

No attempt can be made here to go into a detailed discussion of the theory of operation of such circuits. Suffice it to point out that when there is more than one oscillating circuit shunted about a gap, the quenching of the spark after the initial surge has passed leaves the remaining circuits free to oscillate without the damping effect of the spark. If there be two oscillation circuits, these residual oscillations will have but a single frequency. If there be three oscillation circuits these oscillations will have three frequencies. If there are four there will be six frequencies, etc., the number of frequencies being given by the expression

$$N_1 \frac{N_1 - 1}{2} \qquad (25)$$

where N_1 is the number of branch oscillation circuits. Of course, if the aerial or radiating circuits be one of the oscillating circuits shunted about the gap, it tends to develop additional higher frequency component currents which are not, strictly speaking, harmonics, tho always of higher frequency than the main or fundamental natural frequency of the aerial. This phenomena may, in some instances, be of sufficient importance to modify, somewhat, the proportion of the other circuit or circuits shunted about the gap for the purpose of producing impulsive excitation of the aerial. These high frequencies can be suppressed to a very considerable degree by working the aerial at a frequency much below its fundamental natural frequency. Moreover, when the aerial is one of the oscillating circuits shunted about

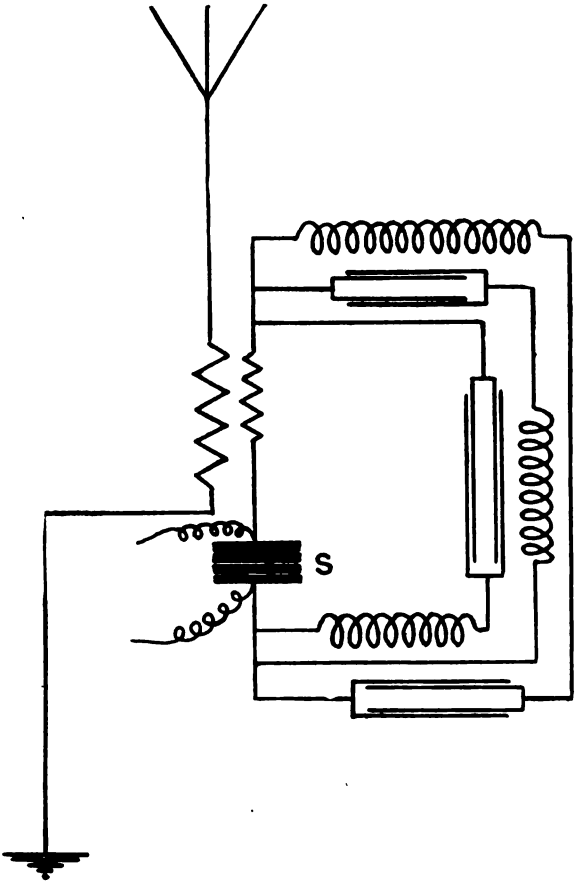

FIGURE 9

the gap, and a single wave length of radiation is desired, it will, in general, be necessary to employ but a single additional circuit shunted across the gap.

When two spark gaps are used in parallel as shown in Figure 12, the sparks occur alternately in the two gaps and if the gaps be shunted by similar oscillators, the oscillations developed in them will be opposite in phase. By this means, two trains of oscillations having any desired phase relation to each other

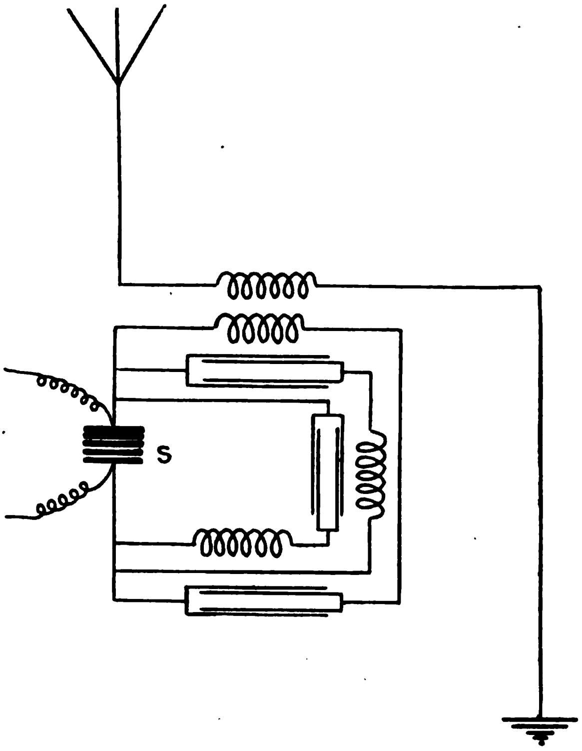

FIGURE 10

should be attainable. Furthermore, in this arrangement of parallel spark gaps, it should be possible to maintain the supply current extremely constant and to secure for a given power much higher frequencies of oscillation than with a single gap.

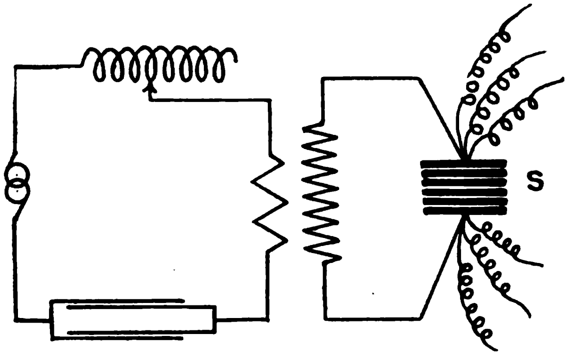

FIGURE 11

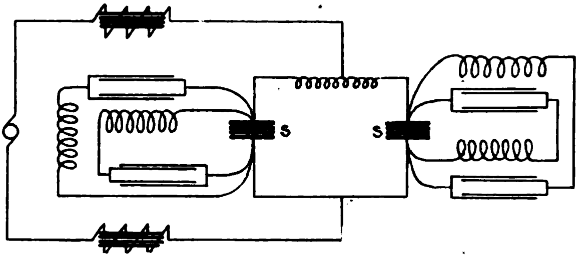

FIGURE 12

SUMMARY: The Thompson or "logarithmic decrement " theory of oscillatory circuits is contrasted with the linear decrement theory. Both are limiting cases of the more general theory which considers circuits containing both conductor and spark resistance. It is this last and most general theory which is fully developed in the present paper.

It is found that the effect of the spark is to introduce a simple harmonic counter E. M. F. of constant amplitude during the oscillations and having the same frequency as these oscillations. The mathematical expressions for the current and voltage, under practical working conditions, are found to be simple, and to reduce to the older expressions in the limiting cases.

The new theory gives the value of the spark resistance at any time and determines the quenching time. A new resonance analysis method of studying the law governing the dependence of spark or arc resistance on current is given.

A novel method of producing "quenching" in gaps is the following. There are shunted around the gaps several circuits of different frequencies so proportioned that the total current remains appreciably zero for a considerable portion of each cycle (of the fundamental frequency). The practical applications of this method to radio telegraphy are described in detail. Finally, a parallel spark gap method for obtaining oscillations of any desired phase difference is given.

DISCUSSION

J. Zenneck: We can speak of a "spark resistance" R only if we take the absorbed energy in the gap in the time dt as being $R\,I^2\,dt$. Here I is the instantaneous value of the current. The actual energy consumption in the gap can be studied by ascertaining the change of V, the terminal potential difference, with time. The energy consumption has the well-known value $I\,V\,dt$. Since we know by actual researches that the current in a condenser circuit is practically sinusoidal, a knowledge of the time-variation of V will readily give the energy absorbed.

Researches as to V have given the following results. There are two groups of metals (used for gaps) which are to be distinguished: (1) the copper group, consisting principally of copper and silver and (2) the magnesium group, which contains also calcium. The remaining metals lie between these extremes indicated by these groups, and, zinc and antimony lie near the magnesium group. With metals of the copper group, the gap potential follows a curve like that of Figure 1, while with the magnesium group it follows a curve like that of Figure 2. (D. Roschansky, "Annalen der Physik," 36, page 281, 1911.) The curves given hold even for the frequencies used in radio telegraphy. Whereas with the magnesium group the voltage is at

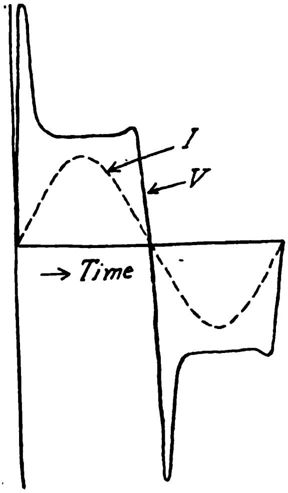

FIGURE 1

least approximately proportional to the current, with the copper group the gap voltage is similar to that of an arc at ordinary audio frequencies.

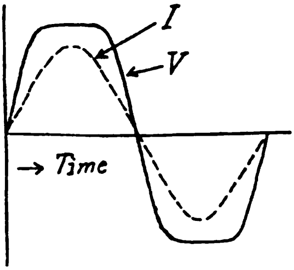

FIGURE 2

The foregoing principles lead to quite different types of decay of current amplitude in the two groups. For the magnesium group, the amplitude curve is one lying between an exponential curve (which corresponds to a constant spark resistance wherefor V would be proportional to I) and a straight line. According to conditions, the curve actually obtained will approach one or the other extreme. (See Figure 4). With the copper group, on the other hand, we found (carrying on a research with Braun tubes at the Physical Institute of Danzig) the amplitude curve to consist first, of a practically linear portion, which then suddenly fell off past a definite point. The oscillations are not actually quenched, but, as a careful examination of the photographs shows, simply fall off very rapidly.

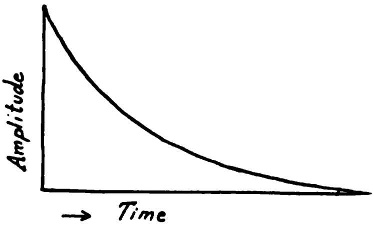

FIGURE 3

FIGURE 4

Ralph H. Langley: It was my privilege to perform those calculations which were necessary for the plotting of the curves shown in Figures 1, 2, and 3. In all, over 170 numeric solutions of the final equation were made. It is at once apparent that this work would have been very onerous, had the substitutions been made in the complete equation (8). It was found however that the work could be greatly simplified by a suitable simplification of the equation. Mr. Stone has given the form:

$$i = \left\{ Q_o \, \omega_o \, \varepsilon^{-a_1 t} - \frac{a_o}{a_1}\left(1 - \varepsilon^{-a_1 t}\right)\right\} sin \, \omega \, t \qquad (1)$$

but in order to justify this simplification, it was first necessary to compute the values of

$$\frac{\omega_o}{\omega}, \qquad tan^{-1}\frac{\alpha_1}{2\omega}, \qquad \text{and } tan^{-1}\frac{\alpha_1 \, \omega}{a_1^2 + 2\,\omega^2}$$

in order to demonstrate that these values might be neglected without seriously affecting the accuracy of the results. From the relations

$$\alpha_1 = \frac{\delta \, \omega}{2\pi} \quad \text{and} \quad \omega^2 = \omega_o^2 - \alpha_1^2$$

and assuming $\omega = 10^6$, and taking $\delta = 0.1$, 0.2, 0.3, 0.4, and 0.5 successively, the values which Mr. Stone has given on the fifth page of his paper were obtained.

The coefficient of ($sin \, \omega \, t$) in equation (1) gives the envelope curves which it was desired to plot. This expression was further simplified and thrown into a form suitable for numeric substitution as follows:

The amplitude
$$\begin{aligned} I &= Q_o \, \omega_o \, \varepsilon^{-a_1 t} - \frac{\alpha_o}{a_1}\left(1 - \varepsilon^{-a_1 t}\right) \\ &= \varepsilon^{-a_1 t}\left(Q_o \, \omega_o + \frac{\alpha_o}{a_1}\right) - \frac{\alpha_o}{a_1} \\ &= log^{-1}\left\{ log_\varepsilon \left\{ Q_o \, \omega_o + \frac{\alpha_o}{a_1}\right) - \alpha_1 t \right\} - \frac{\alpha_o}{a_1} \end{aligned}$$

since $-\alpha_1 t$ is the natural logarithm of the quantity ($\varepsilon^{-a_1 t}$).

One set of curves were obtained holding Q_o constant at 10^{-5}, and taking the ratio $\frac{\alpha_o}{a_1}$, which expresses the relative resistance of the spark gap at 0.1, 0.5, 1, 2, 3, 4, 5, 6, 7, 8, and 9 successively. Another set of curves was obtained holding $\frac{\alpha_o}{a_1}$ constant at 1 and taking the initial charge Q_o at 10^{-5}, 2×10^{-5}, 3×10^{-5} 4×10^{-5}, and 5×10^{-5} successively. In each case between 5 and 20 values of I were computed for increasing values of t. The logarithmic decrement δ was considered constant at 0.2 and the periodicity ω constant at 10^6. The values of t were obtained from $T=\frac{2\pi}{\omega}$ where T is the time in seconds elapsed at the end of one complete oscillation, and from $\alpha_1=\frac{10^5}{\pi}$ (from the assumptions). Whence $\alpha_1 t=\frac{2\pi}{\omega}\times\frac{10^5}{\pi}\times n=0.2$ at the end of the first oscillation, 0.4 at the end of the second, and so on, n being the number of complete oscillations considered.

The actual method then, was as follows: a table of Naperian or natural logarithms being used.* Go into the table with $\left(Q_o\omega_o+\frac{\alpha_o}{a_1}\right)$, take out $log_\varepsilon\left(Q_o\omega_o+\frac{\alpha_o}{a_1}\right)$. Subtract $\alpha_1 t$. Go into the tables with $\left\{log_\varepsilon\left(Q_o\omega_o+\frac{\alpha_o}{a_1}\right)-\alpha_1 t\right\}$ and take out $log_\varepsilon^{-1}\left\{log_\varepsilon\left(Q_o\omega_o+\frac{\alpha_o}{a_1}\right)-\alpha_1 t\right\}$. Subtract $\frac{\alpha_o}{a_1}$, and the result is I.

In order to determine how many oscillations would occur before I became equal to zero, in each of the various cases, the following equation was obtained:

$$\alpha_1 t=log_\varepsilon\left(1+\frac{Q_o\omega_o}{\frac{\alpha_o}{a_1}}\right)$$

from which we may calculate the value of t for $I=0$. These values have also been tabulated by Mr. Stone (seventh page of the paper).

In connection with Figure 6 which shows a method of producing shock excitation of an untuned antenna, by the use of a fundamental alternating current and a third harmonic alternating current superimposed on a direct current, the following observations may be made. Let the maximum value of the fundamental frequency current be unity. Then the maximum value of the third harmonic current should be 0.13397, which is the difference between the sin of 60° and the sin of 90°. It has

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*There are many equations used in radio calculations which may be very easily handled by means of a suitable table of Naperian or natural logarithms. For such a table the reader is referred to "Logarithmic Tables," by Professor George William Jones of Cornell University (Macmillan & Co., London), or to the "Mathematical Tables" published by the Smithsonian Institute, Washington, D. C.

been stated that this will not give a flat top to the resultant wave form, and that a second approximation for the amplitude of the third harmonic current should be made, in order that the current may be more nearly equal to zero during that part of the oscillation in which it is desired to have no activity.

The question here is, how great is the difference between the middle third of the fundamental frequency current, and the half oscillation of the third harmonic current? Computation shows that at no point is this difference greater than 0.00668, which is entirely negligible. No second approximation of the third harmonic current therefore seems necessary. Its amplitude should be 0.13397.

John Stone Stone: The question as to what may be strictly called the "resistance" of the arc or spark was not considered in my two papers. The inquiry therein made was merely as to the form of what might perhaps best be termed the effective resistance at the gap and its effect upon the oscillations.

Because of the purely utilitarian purpose of these papers, it was sufficient, as I pointed out in my first paper (see first paragraph, page 320, volume 2), to style the ratio $\frac{V}{i}$, of the instantaneous values of the voltage across the gap to the current traversing it, the resistance of the arc or spark. From this paragraph, to which I have referred, it will be seen that it was not the intention in these two papers to contend that all of this ratio $\frac{V}{i}$ is, strictly speaking, and in the last analysis, a true dissipative resistance. A consideration of what component of this ratio is an actual dissipative resistance, and what component may be regarded as a thermo-electric counter e. m. f., is interesting but was not considered germane.

Coming now to the law of decay of the oscillations between spark terminals of the two classes of metals mentioned by Dr. Zenneck, it is a fact that in the case of electrodes of the copper, silver group, if the frequency of the oscillations be not too high and if the conditions be such as to minimize the resistance hysteresis of the arc or spark, the gap voltage may cease to be proportional to the gap currents. Thus the gap voltage may depart from the shape of curve 4, Figure 8, of my first paper on this subject where I discussed this subject, and approach more nearly in shape to say curve 3, of that Figure. But the conditions which bring this phenomenon into prominence are perhaps somewhat exceptional; and even when this phenomenon is present, it is not likely sensibly to modify the law of subsidance of the oscillations in such cases as may be met with in radio practice for reasons which I hope to make clear.

The presence of such a deviation from the normal constancy in the ratio of the gap voltage to gap current, when it exists to any marked degree, is as I have shown (see Figure 4 of my present paper and the text relating thereto) easily detected; as, under such circumstances, the first odd harmonic of the fundamental will make its appearance and may be detected by a suitable resonant harmonic analysis of the oscillations in the oscillator. It is important to note that the magnitude of this phenomenon will be determined by the ratio of the amplitude of this first harmonic in the gap voltage to the amplitude of the fundamental in that voltage (see Figure 4). In any event, however, the effect of this phenomenon on the character of the oscillations is smaller than would at first seem possible because the power of this first odd harmonic component of the gap voltage to modify the character of the oscillations is proportional to its power of producing a current in the system and this is usually very small. Evidently, if it could produce no current in the system it would not modify the oscillations at all, and if the current which this component of the gap voltage can produce in the oscillator is a small fraction of that which the fundamental component of the gap voltage could produce in a circuit, the effect of the odd harmonic on the mode of oscillation of the circuit must be correspondingly small.

It may be shown that, in the case of an arc sustaining oscillations in an oscillator, the ratio of the amplitude or strength of the current which can be produced by the first odd harmonic in the gap voltage to that which can be produced in it by the fundamental of the gap voltage, is approximately $\frac{3}{8}\frac{a}{S}$ where a is the ratio of the amplitude of the first odd harmonic in the gap voltage to the amplitude of the fundamental in that voltage and S is the selectivity of the oscillator or $\sqrt{\frac{L}{C R^2}}$, L, C, and R being respectively the inductance, capacity, and resistance of the oscillator as a whole. Thus, if, in a given case of an arc sustaining oscillations in an oscillating circuit, the ratio of the amplitude of the first odd harmonic in the gap voltage to the amplitude of the fundamental in that voltage be one-third and the selectivity of the oscillator be 12.5, then the current which the first odd harmonic in the gap voltage will produce will be but 1 per cent. of that which can be produced by the fundamental of the gap voltage. In this example, however, the selectivity chosen was rather low and in radio practice the effect of the odd harmonic might be expected to be even much less than 1 per cent.

In the case where the oscillations are not sustained but consist of damped trains, this general proportion of effects must still obtain, but the resistance at the gap always becomes the dominant factor towards the extreme end of the train of oscillations as shown in curves 2 and 3 of Figure 4 of my first paper on this subject (see pages 312 and 313, volume 2) and in Figure 3 of my present paper. At the extreme end of the train, therefore, the odd harmonic in the gap voltage, when it exists to a marked degree has a chance to assert itself and to produce a modification of the mode of subsidance of the oscillation train. This is undoubtedly the reason for the sudden and interesting change in the law of the damping near the end of the oscillation train cited by Dr. Zenneck as having been observed at Danzig.

In this connection it is interesting to note that, as stated in my first paper on this subject (see first paragraph, page 313, volume 2), the experimental data upon which the present determination of the law of subsidance of the oscillations is based, is ambiguous as to the rate of subsidance at the extreme end of the oscillation train. But, as I there remarked, "the question of the extreme end of the train of oscillations is of minor importance, since by the time the amplitude of the oscillations has reached one-fifth its initial value, the energy of the remaining oscillations represents but 4 per cent. of the total energy of the train."

To sum up, the proportionality of the instantaneous values of the gap voltage to the gap current, may notably depart from constancy (thru the use of electrodes of the silver, copper group of metals and thru the minimization of the resistance hysteresis of the spark or arc), in any particular circuit, without sensibly modifying the frequency or mode of subsidance of the oscillations except perhaps near the end of a train of oscillations. Furthermore, the end of the train of oscillations is of relatively small importance because of the relatively small proportion of energy represented by these train ends. Tho the law of decrescence or subsidance which I have deduced depends for its rigid mathematical justification on the resistance at the gap being inversely proportional to the amplitude of the oscillatory current flowing across the gap, a notable departure from this proportionality in the instantaneous value of this resistance, due to the presence of a fairly strong third harmonic in the gap voltage curve, produces but slight deviation from the law except at the extreme end of the oscillation train and in the case of slightly damped oscillators, it is doubtful if an appreciable modification of the law can be produced.