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CONTENTS

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AN ELECTRICAL SIGNALING METHOD FOR GUIDING AERIAL AND MARINE CRAFT*

By

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It is evident that vessels have not had means for sufficiently accurate guiding of them in narrow channels, dangerous channels, and in fog. Largely for this reason, many vessels have been lost or delayed. For example: one hundred and sixteen vessels have been lost in Alaskan waters north of Ketchikan. Many vessels are held up for considerable periods of time at harbor entrances, for example, at New York harbor entrance, where the financial cost for delay may amount to as much as $500 per hour for one vessel. It is believed that recurrence of such losses may be prevented by the following method.

Install a signal-carrying conductor along the sides of the channel or under the channel and pick up the signals on the vessel. For example, when conductors are on each side of the channel, guide the vessel so that the signals from the starboard conductor are slightly louder than those from the port conductor. Also, when two conductors are under the channel, one for inbound and one for outbound, keep the inbound vessel in the course that gives loudest sound indicating the inbound guide. The under-channel guide would probably be more practical.

The ship receiving device may consist of a coil of wire on an iron core attached to the bottom of the ship with the core athwart-ship for receiving from a submarine signal wire or vertically to the side of the ship for receiving from a wire parallel to the channel. The winding of the coil may be connected to a pair of telephone receivers worn by the helmsman or navigating officer, or one pair of telephones for each of the officers.

Where conditions will permit, the signal may be the spoken word "In" for the inbound channel and "Out" for the outbound channel.

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* Received by the Editor, July 14, 1919. Presented before the Seattle Section of the Institute, November 5, 1919.

If desirable and conditions permit, different frequencies of alternating or pulsating current may be impressed in the guide conductors,—one frequency for inbound traffic and one for outbound. These signals may be picked up by both telephones and a signal-strength indicating device (as, for example, a sensitive ammeter or galvanometer in a circuit resonant to the frequency of the current impressed on the guide conductor).

With two or more such indicating devices, the relative strength of the fields of the inbound and outbound signals and the relative strength of fore-and-aft and athwart-ship fields may be ascertained. Also by controlling the strength of the signal in accordance with the distance from a given point, for example, by grounding a portion of the current thru suitable resistances at points at fixed distances from the source of supply, the strength of the signal would be dependent on the distance from that source. Such indications of strength of signal relative to the source of supply (for example, the dock) and relative to the inbound and outbound signal conductors and relative to the angle the ship makes with the signal conductor, offer means for a relatively high degree of accuracy in steering the vessel so as to keep clear from danger.

A further complexity of circuits may be provided which will afford sufficient accuracy in certain places, for example, the guide may consist of several conductors in one cable. The conductors would be of several suitable lengths and suitable speech currents would be impressed on them. For example, one conductor would carry a speech current which says periodically "One mile in," while the next in length would say "Two miles in" while the outbound signal wire in that vicinity might say "Nine miles out."

The ship's receiving circuits may be arranged fore and aft and athwart-ship in such manner as to indicate whether the ship is approaching the signal conductor, or leaving it, or is parallel to it, or at some angle to it.

Structural conditions of ships, channel conditions, and financial and political conditions have their bearings on what structural arrangements would be best to carry out the method.

For example, in New York harbor it would probably be entirely practicable to provide all possible refinements and strong accurate signals which could be followed by vessels equipped with the more simple inexpensive apparatus as well as those which might be equipped with more expensive and more highly accurate apparatus.

In the long passages in Alaska, it may be practicable and sufficient for the present to follow the Army cable lines. This may be made possible by picking up the telegraph signals and guide signals which might be supplied by the Army in intervals between telegraph signals. To do this is more difficult than would be the case if the cable were made for directing purposes, because the Army cable currents are weak and the cable is covered with a sheath containing iron. Also the resistance, inductance, and capacity of the long cables limit the quantity and kind of signals that may be impressed on them.

However, there are several methods which can be used as may be necessary to pick up the weak cable signals altho they are in an iron sheath.

For example, the pick-up circuit (which may be relatively small) may be lowered from the ship to near the bottom and maintained in the same relative position relative to the ship; also prescribed frequencies may be used on the cable and tuned receiver circuits and very weak currents may be amplified.

The receiving or pick-up circuit may include a coil virtually wound around more or less of the hull; one coil, for example, wound in a fore-and-aft plane and another in athwart-ship plane, or a coil or coils inside or above the hull depending on the practicability of these various arrangements.

Increasing the efficiency of the pick-up coil, increasing the current in the signal wire, and increasing the amplification all serve to increase the possible distance.

Only one signal conductor can serve, if necessary. For example, if vessels are to pass to starboard in a channel, two receiving circuits (port and starboard) may be used as indicated above, and the vessels steered so that the sound is always louder on the port side.

Portions of the guide conductor may be enclosed in iron for reducing the signal strength at desired points or for desired sections. Such an arrangement might prove desirable for certain of the conductors where several conductors were used; for example, one conductor might have the words "Port ninety" for a sharp turn and be in iron beyond the turn.

A first-rate, well-protected signal cable containing more than one conductor would probably cost a-dollar-a-foot, laid. Less expensive cables could be laid, however, depending on the depth of the water, the channel currents, and whether the bottom was soft or abrasive.

It may be desirable to arrange the incoming and outgoing guide conductors as a circuit instead of having a ground return for each, or it may be desirable to have a common metallic return conductor for both. The return conductor might be bare wire. Some conditions might permit the use of a bare wire conductor on shore on insulators with a return bare conductor circuit under water. The bare conductor might be of such low resistance that it would be the principal current path and so serve as a guide cheaper than where under-water insulation was used.

The signal current in the conductor along the channel may be like that in the antenna of a radio transmitter, and the radio receiving outfit on shipboard may be used to receive it, using a regular antenna or a coil. Also the coil might be rotatable on its axis so it could be turned to pick up the signal and then turn the boat so it would have the proper fore-and-aft position relative to the coil and therefore be headed right in the channel.

At this date it is hard to say what is the most practical arrangement to use to suit conditions. It may be best to go along the lines of making the best direction control apparatus irrespective of the radio apparatus and leave the radio apparatus free to handle other things, or it may be best to impress common radio frequencies on the signal conductor or load the antenna for lower frequency so that all vessels equipped with radio could tell when they were closest to the conductor by the strength of the receiving signal. The Alaska cable is probably not suitable for using radio frequencies.

However, the use of the common radio frequencies in the guide conductor might interfere with some stations which did not want to receive direction signals but did want to receive messages from distant stations, and it is easier to build underwater conductors for longer wave lengths. This indicates the use of the lower radio frequencies.

Fifteen thousand meters is about as long a wave length as any kind of a radio station receives at present. Therefore, we might go to a slightly longer wave length, that a ship's antenna could be loaded up to, and which a closed coil could be built for, and would be rotatable for getting the direction not only of this conductor but of radio stations. All such signals could be received on detectors, interrupted properly if sustained wave.

Suppose we take 20,000 meters, which corresponds to a frequency of 15,000 cycles. Fffteen thousand cycles is audible, but our ears do not pick it up well. Training might, however, make 15,000 cycles a practical frequency to hear.

Fifteen thousand meters probably could best be impressed on a submersed insulated wire about 3,000 meters or two miles long if the wire were grounded at the one end—probably the end near the transmitter generator. That frequency probably would do well in even longer wires or in a succession of wires one mile long, inductively or otherwise coupled at the ends; in which case the ship in passing over the points of coupling would note differences every mile which would be used as a measure of distance and further contribute relative to location.

All things considered, possibly the most practical form for common service would include a standard frequency for all ocean-going vessels and for all ports, of say 750 cycles, and enough current in the signal circuit so that the receiving circuit would not necessarily include anything but a rotatable coil on top of the pilot house, a fixed condenser, and a pair of telephone receivers with an indicating dial and coil-turning handle in the pilot-house.

Such a frequency is applicable to quite long wires, and indeed quite long wires might be required in some places. Furthermore, such a sinusoidal frequency and current can be fairly easily obtained from an alternator and maintained with very small percentage variation. Then, to such a receiving coil and condenser and receiver can be fairly easily maintained in comparatively constant adjustment.

Sinusoidal current and the frequency of 750 or 1,500 would serve to cut out some interference. Those frequencies are different from the commercial 60-cycle current, and the radio 500- and 1,000-cycle frequencies also seem to be sufficiently different from common motor and dynamo commutator and field frequencies. The average ear is probably most sensitive to about 750 cycles, but quite sensitive to 1,500 cycles.

Special vessels (for instance, ferries) which do not use regular channels probably should be provided with additional special frequencies. On the Alaskan cable route, special very low frequencies (maybe twenty cycles or less) would be more practical. It might be found that the longest Alaska cable run has a minimum impedence for a frequency of four cycles or less.

For airships and airplanes, the guide conductors probably could be established on existing pole lines and suitable frequencies used with certain dot and dash signals as for water craft; or, by use of amplifiers, speech signals might be impressed on the guide wires, using modulated direct current or suitable alternating current to which the airship guide receivers or other receivers were tuned.

There seems to be sufficient number of applicable forms, modifications, and combinations to provide a standard arrangement for each group wherein the service and service conditions have a sufficient number of common characteristics.

With the above descriptions and discussion, a brief description of one experiment is probably sufficient.

A 4,000 circular mil (0.02 sq. cm.) rubber-covered wire about 700 feet (214 m.) long was dropped over into the water along the side of a dock. One end of the wire was bare and in the water, the other end was brought up on the dock and connected to one side of the "break" on a buzzer. The other side of the "break" was connected to the water. Five dry cells were used to operate the buzzer. The wire along the dock under water and the ground return showed a bridge resistance of about 5,000 ohms. The predominant frequency produced by the buzzer corresponded to about 1,200 cycles. The rubber-covered wire in the water was intended to correspond to a short guide conductor in a channel, the center of the channel being along the dock.

The receiving device consisted of a wooden frame four feet (1.2 m.) square wound with two coils of number 28 double silk-covered wire* (*L* and *L′* in Figure 1). The coils were side by side separated by about 4 inches (10 cm.) each coil having a winding space cross section of about 0.5 inch (1.2 cm.) diameter. The coils were connected in series and had a resistance of about 1,000 ohms and inductance with telephones of about 10 henrys. There were about 1,000 turns. A variable air condenser of 0.005 microfarad maximum capacity (*C*) and a pair of 2,200-ohm telephones were connected in series with the total coil.

Wearing the telephones and carrying the condenser and coil (as shown in Figure 1) along the length of the dock with the coil vertical to the dock and its lower 4-foot (1.2 m.) side parallel to the signal conductor, the buzzer signals were sufficiently loud to be heard above the noise from riveters near the dock, the wind and induction from commutated circuits, and so on.

A tug, with steel hull and deck houses, was lying by the dock, its side being directly above the signal wire. The receiving apparatus was taken to the top of the pilot house, and the same results obtained.

The signals fell off as the coil was revolved away from parallelism to the guide conductor. No buzzer signals were heard when the plane of the vertical coil was at right angles to the conductor. Tipping the coil from vertical indicated on which side the conductor was located.

The signals could be tuned in or out by adjusting the condenser.

FIGURE 1

The above experiment can be easily duplicated or approximated, and indicates that a tug at least can be accurately guided by this method in a channel, which is deep enough for a tug. And the experiment, together with the previous descriptions, probably will indicate to those experienced in radio, telephone, or alternating current electrical engineering, that the method with suitable variations, somewhat as outlined, can be applied to various service conditions over comparatively great distances.

The cost of a suitable cable cannot be stated in general terms. Local conditions and the length of the channel may be such that the cable should be inexpensive both for first cost and maintenance. A five mile (8 km.) cable we have used for steering a vessel along the lines described, cost about $800 per mile; while on the other hand more profitable service might result by installing cable that would cost $10,000 per mile. In New York Harbor, the most suitable cable arrangement might cost a great deal and pay for itself in the first foggy month.

There are a wide variety of arrangements which can be made to suit the peculiarities of harbors, vessels, traffic, and so on. There seems to be a practicable solution for each peculiarity. For example, an unequipped foreign vessel may be served by the harbor pilot using receiving apparatus that he can carry with him, providing the signal cable current is made sufficient.

Sharp turns can not only be taken care of by the method previously mentioned, but also by shifting the cable from the true channel so the magnetic trail as indicated by the position of the receiver, will indicate the true channel.

FIGURE 2

With audio frequency apparatus, any interferences are due to current variations on the ship and, being of nearby origin, it is possible to neutralize such local disturbances by inserting a small coil in series with the main coil and bringing the small coil near and properly placed relative to the local source of disturbance so the disturbance picked up by the guide coil is neutralized without neutralizing the signal. By proper allowance for phase relations this may also be done by inductively coupling the neutralizing system to the guide coil. Sufficient current in the cable and selected frequency also serve to minimize disturbances.

It is also more or less apparent that if sufficient current is used in the cable, the vessel might be automatically guided. One or two schemes have been designed for this during the consideration of providing a suitable automatic device which will give the pilot a visual indication of where the ship is relative to the guide.

It will also be apparent that along these same lines a cable could be laid along a defense line and a submarine could ply back and forth under water along such a defense line and, not only be guided by the cable, but could handle messages to and from the cable. Also that automatic torpedoes or mines could be moved along such a cable by a control station. The control station could, for example, learn from airplanes where the enemy was going to cross the cable.

The receiving coil, coil supports, and the location of the coil may be such that the same coil frame can carry a smaller inductance coil for use as a radio compass. With this combination the coil arrangement can be used on the high seas to find the location of radio stations on ship or shore and thereby steer for the entrance of the channel. Having reached the entrance of the channel, the simple throwing of a switch is sufficient to change the equipment to pick up and follow the cable guide signals.

The first complete practical installation was made on the S. S. *Tourist* of the Kennedy Line, Navy Yard Route, using the United States Army submarine cable from Bainbridge Island to Pier 8 in Puget Sound Navy Yard.

Captain Barrington of the *Tourist* has repeatedly guided his vessel by sound over this cable; and on one or more occasions the results indicated that it was easier to guide the vessel over the cable by this sound method than by the buoys, even when the buoys could be seen at a considerable distance. This may be because the drift due to tide currents is more noticeable by the channel cable electrical signal method than when trying to keep in line with buoys.

The cable was loaned by courtesy of Colonel Lenoir of the United States Army Signal Corps and Lieutenant-Commander Luckel and Gunner Thomas of the 13th Naval District Communication Service. The use of Kennedy Line Vessels was obtained by courtesy of Captain Mitchell, Manager. The writer was assisted by Mr. Schoenborn, Mr. Rowe, Mr. Palmer, Dr. Lester, and other members of the 13th Naval District Radio Engineering Organization.

FIGURE 3

The cable is an ordinary submarine telegraph cable. The conductor is covered by insulation and a sheath of iron wires.

One end of the cable conductor was grounded at Fort Ward and the other was connected thru a key, ammeter, resistance and a 500-cycle generator to ground at Puget Sound Navy Yard Radio Laboratory. A 500-cycle generator, resistance, ammeter and key was also placed on Pier 8 for use at that point when more convenient. The morse signal "M A" was used as the guide signal.

From the standpoint of providing a wide margin of safety, the potential applied to the cable was limited at 40 volts. With this potential, the maximum cable current obtainable was seven-tenths of an ampere.

The receiving coil consisted of four coils of number 28* double silk covered wire connected in series, and in series with variable air condenser having a maximum capacity of 0.005 microfarad and the primary of a vacuum tube amplifier circuit. The system showed minimum impedance for 500 cycles when the capacity was about 0.004 microfarad. There are about 2,000 turns of wire in this total receiving coil and the coil is about four feet (1.2 meter) square.

Three steps of amplification were used to pick up the signal from the 28 watts or less in the cable which is about five miles (8 km.) long.

For convenience, the receiving coil and amplifiers were placed in the smoking room, under the pilot house and a pair of receiving telephones were connected for use of the pilot in the pilot house. Other telephone receivers were connected in series for use in the smoking room. With this arrangement it was necessary for the Captain to keep the vessel within about three hundred to six hundred feet (100 to 200 meters) of the cable to hear the signal.

As the pilot could not see the receiving coil, the coil was usually left vertical and fore and aft and the Captain swung the ship as necessary to hold maximum signal.

The receiving coil was turned and tipped for getting the location of the ship relative to the cable, as shown in the photographs. At times this was done when the vessel was being operated and the location signalled to the pilot. The coil is supported on pivots so it can be turned around a vertical axis or tipped around a horizontal axis. The loudest sound is heard when the coil is parallel to the cable and entirely on the same plane. The least or no sound is obtained when the coil is at right angles to that position.

In Figure 2 are shown the magnetic lines of force of the current in the cable. From their directions, the mode of operation of the system can be readily deduced. The actual receiving coil used on the *Tourist* swung out of its normal positions relative to its vertical and horizontal axes, is illustrated in Figure 3.

The harbor guide circuits should be so constructed, maintained, and operated, as to guarantee uniformity and reliability.

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* Diameter of number 28 wire = 0.0126 inch = 0.032 cm.

Therefore, their construction, maintenance, and operation should probably be defined by Federal law as soon as sufficient experimental and development service has been rendered to indicate just what complete arrangement or arrangements will render the maximum service. Too early definition by law might serve to handicap development.

Development by different private companies and by government departments would probably result in a number of different forms and installations which would later have to be standardized into certain lines of uniformity to render the best service.

Probably the method for development and application which would provide the most efficient service in the shortest period would be for some department of the government to provide a special organization for this work, under appropriations from Congress.

The business of this organization should be simultaneously to study the service requirements and carry on experiments and development with apparatus of government design, and such as might be purchased from private interests that might give their attention to this work. The development experiments should then be followed by the establishment of permanent standard guide circuits and by laws and international arrangements as necessary; probably leaving the supplying of suitable receiving apparatus to private concerns which might rent or sell them to the steamship companies, operating under various flags.

Radio compass stations are already being established. These can be used to guide vessels to the harbor entrances, where the guide signals could be picked up and followed thru narrow or crooked channels and past outbound vessels without seeing channel markings or the vessels and without having previously navigated that channel.

Since the writing of the above, several articles have appeared somewhat along the same lines. In those articles the matter of invention has recsived some attention. To make the above paper more nearly complete some remarks relative to patents probably should be added.

My files, in which the more basic inventions along this line are noted, have been in storage since 1914; however, it is my recollection that a patent was issued to Thomas A. Edison in 1878, which quite broadly covers the principle of intercommunication between a moving object (for example, a steam train) and a conductor along the line of travel.

Next in importance, probably, is the patent which was issued to Robert E. Owens in 1903 and of which the following is a brief extract:

> "No. 736,432, Apparatus for Ascertaining Position Relative to a Pre-arranged Guiding System. Robert E. Owens, Montreal, Canada. Filed March 11, 1902. Serial No. 97,799, issued August 18, 1903.
>
> "Claim 1. In apparatus for ascertaining position relative to a pre-arranged guiding system, a submerged electrical conductor located along the course to be followed by a vessel, a shore-circuit connected with and supplying the submerged conductor with a current adapted to create a magnetic field within which the vessel moves, and a double-coil indicating device carried by the vessel, adapted to be affected by said magnetic field, whereby the vessel's position relative to the submerged conductor may be ascertained."

SUMMARY: Inability to guide vessels accurately results in large losses of life and property. An arrangement by which vessels may be guided accurately will have a value corresponding to what it saves.

A signal-carrying conductor along the course of a vessel, and means capable of indicating the proximity and direction of the signal conductor are described and discussed, including various forms and combinations. Ocean-going vessels entering harbors are chiefly considered, the same principle being applicable to other craft and channels, air ships, and so on.

Experimental tests of the system are described in detail, with numerical data; and suggestions are made as to how the system may be further developed and applied.

STATIC ELIMINATION BY DIRECTIONAL RECEPTION*

By

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In the early days of radio communication, those disturbances which have been variously called "static," "atmospherics," "X's" and "strays" were either attributed to distant lightning, or more vaguely and correctly to "atmospheric electricity." While it is still true that our knowledge of static causes is far from satisfactory, we have at least progressed to the point where the distant thunder-shower has ceased to be considered an important source of static, and are now able to concentrate our attention on the higher levels of the atmosphere. Such disturbances as may exist at these levels are unquestionably electrical, so far as they concern our receiving circuits, and are due to a supply of electricity which in some way is generated in or supplied to the atmosphere. The normal electrification of our atmosphere, observed as a rather marked potential gradient in the lower and more accessible layers, accompanied by downward electrical currents and attended from time to time by high level auroral displays and magnetic storms, is undoubtedly due to ultra-terrestrial sources. According to Arrhenius[1] the sun is the ultimate cause of electrical phenomena in our atmosphere, and altho his original theory has suffered certain modifications and additions in the past fifteen years, it will well serve as an introduction to this paper.

The sun being an intensely heated body must in consequence have emitted electrons in such abundance as to have acquired a very large positive charge. This charge, estimated by Arrhenius as three billion volts, forms a powerful center of attraction for stray electrons and negative ions, which are gathered in even from space far beyond the confines of the solar system. An electron or a negative ion, moving in toward the sun under this

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force, will eventually reach the outer and cooler solar atmosphere, where it will form a nucleus for condensation. A droplet, perhaps consisting of iron or calcium, will grow around this nucleus until it attains a diameter of the order of a wave-length of visible light. At this point in its growth, the pressure of light upon its surface considerably exceeds the solar gravitational pull upon its mass, and the droplet moves away from the sun. Such of these minute particles as may reach the vicinity of the earth fall into our upper atmosphere, and as they carry with them their original electrical charges, they constitute an important source of electricity. There are, however, two other sources, also solar, but differing materially in their mechanism. One of these is the ionization produced by the shorter wave-lengths of the sun's light, as it impinges upon the gas atoms in the upper strata. The other consists of a direct emission of either electrons (Beta rays) or, according to Chapman[2], charged helium atoms (Alpha rays). This direct emission apparently does not take place all over the sun's surface, but jets out in streams, presumably most vigorously from sunspot areas, in consequence of the great thermal gradients and magnetic forces existing at such spots. When such a stream, which may be ten or more degrees wide, sweep across the earth, it makes itself evident as magnetic storms and intense aurora.

The aurora, or Northern Lights, give us a certain illumination as to the manner in which these charged particles arrive and move in the upper levels of our atmosphere. Perhaps the most striking part of this phenomenon is the streaky or discontinuous structure of most aurora. It would appear as if, instead of a steady shower of charged particles, they arrived in clouds, these clouds being eventually drawn out into streaks or lines roughly parallel with the lines of force in the earth's magnetic field. This is exactly what we would expect of a charged particle in rapid motion, when it encountered a magnetic field. It would tend to spiral its way down a magnetic line of force, at least until it reached and penetrated the upper level of the atmosphere, whereupon it would begin to spend its energy in ionization, with light as one of the less objectionable by-products.

The writer is well aware that a theory is at the most tentative, and under suspicion of unsoundness, until it yields confident forecasts. Until such time as it may have been proven by this acid test, it is unwise to overburden a theory by speculative exterpolation. However, even at this risk, as well as the graver one of diversion from the subject matter of this paper, the writer cannot refrain from a speculation as to the possible connection of the auroral structure, above outlined, with certain facts as to the difference between east-and-west, and north-and-south radio communication. If, as would certainly appear from the visible aurora, east-and-west bound waves encountered a celestial hurdle, while north-and-south waves ran peacefully between the ionized filaments, the ease of north-and-south, and the comparative difficulty of east-and-west radio communication would be readily explained. One might go a step further, and attribute, at least at times, a sufficiently periodic spacing to these ionized clouds for the formation of a gigantic reflection grating, and thereby account for de Forest's[3] observation of the easy transmission of certain wave-lengths, and the high absorption of others. Certainly the visible aurora frequently has a very regular spacing, and it might be interesting to ascertain if it be of the right order to account for these effects.

But for the purposes of this paper it will be sufficient to assume only that the charged particles enter our atmosphere in a discontinuous manner. Charged clouds will be formed at some high level, probably drawn out so that their greatest length lies approximately north-and-south and, in a manner similar to that observed in a thunder-storm, there will be equalizing discharges between these clouds. At first, because of the low dielectric strength of the atmosphere at the higher levels, such discharges will occur at small potential differences, and hence will tend to be of small individual intensity but of frequent occurrence. As the charges sink toward the earth, they will reach denser air, and there the discharges will become of greater individual intensity but less frequent.

We recognize to-day two important, that is to say bothersome, varieties of static. One of these is the "click," consisting of rather widely separated but very strong disturbances, reminiscent of the discharges of that aptly-named apparatus, the static machine. The other is the "grinder," which runs the gamut of noise from a grating or grinding sound thru something resembling handfuls of gravel thrown against a window, with perhaps slushy or even hissing sounds at the other end of the scale. The clicks are most probably relatively low level discharges. This is supported by the fact that local thunder-storms give rise to clicks which can sometimes be identified with visible discharges between cloud and cloud, or cloud and ground. Grinders, however, would seem to have two possible origins. In the first place, they might arise from very high level discharges of considerable tho irregular frequency. The writer has succeeded in imitating, with a disconcerting fidelity, grinding static by the simple process of discharging a small condenser thru a series circuit of a wet string and a vacuum tube, replenishing the condenser from an influence machine. Grinding static might also arise from the summation of many distant clicks. There is some experimental evidence of the existence of these two varieties, either singly or mixed, and to this a later reference will be made. For the present, our principal interest is in the manner in which the static waves arrive at the receiving station. If we assume a more or less uniform distribution of discharges in the upper atmosphere, the condition of affairs with respect to the receiving station might be pictured somewhat as in Figure 1.

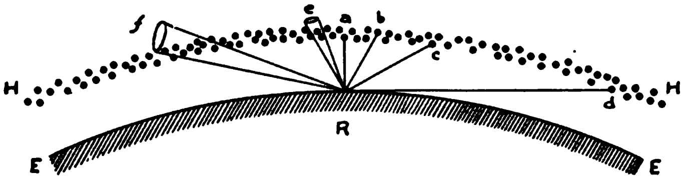


FIGURE 1

Here a discharge stratum, *H-H*, forms a portion of a sphere concentric with the earth's surface *E-E*. This stratum is not only above the receiving point *R*, but envelops this point in all directions, even to the horizon. It is at once apparent that individual discharges, as at *a*, *b*, and *c*, will set up waves or pulses which will arrive at the receiving station with intensities inversely proportional to their distances *a-R*, *b-R*, and *c-R*. This may be approximately expressed by saying that the intensities will vary as the sine of the vertical angle, save near the horizon. To state the law exactly would obviously require a knowledge of the height of the stratum *H-H* which we do not yet possess. However, it is apparent that the intensity on the horizon, as at *d*, is far from being zero, and is most probably between five and ten per cent of the zenith intensity. The maximum static intensity, tho by no means confined to the zenith, is evidently distinctly *above* the receiving point *R*. At first thought it would seem that the total amount of disturbance produced by static would be represented by the product of the individual intensity by the frequency. Inasmuch as the number of individual discharges included in a given small solid angle near the zenith, as at *e*, is much smaller than the number included in the same solid angle taken nearer the horizon, as at *f*, varying in fact approximately as the square of the cosine of the vertical angle, it would seem that the total effect should *increase* as we pass from the zenith to the horizon. In general, the writer finds this to be the fact, altho it not infrequently happens, particularly in the forenoon, that light static comes down from above, with very little from the horizon. This may be explained by considering such horizontal static as consisting of weak discharges at great distances from the receiver, and of so great frequency (because of the summation of so many individual discharges) as to blend into a distinctly "soft" disturbance. Bearing in mind that static acts upon a receiving circuit by pure impact, a not inapt analogy is that of a bell set into vibration by irregularly spaced impacts. For the same amount of energy in a given time, a bell will give the greatest response when the taps are individually strong and fairly well separated in time, rather than when the taps are weak but frequent. Furthermore, at least until such time as all reception is photographic, the psychology of the receiving operator must be borne in mind. There is doubtless an illy defined, but none the less existent frequency of maximum disturbance. For example, the writer finds irregularly spaced disturbances most troublesome when their mean frequency is about twice that of the signal element.

If the discharging clouds are drawn out in a north-and-south direction we should expect that the waves arising from such discharges would show a certain uniformity in their planes of polarization. Altho it would be absurd to think of the discharging clouds as accurately oriental linear oscillators, nevertheless there should be a certain preponderance in that direction.

The writer's theory of static might be summed up as follows: According to the assumed character and location of the discharging masses, static waves may be expected to come in on the receiving stations from all angles in altitude and azimuth, with a maximum individual intensity from above, and a maximum frequency in the neighborhood of the horizon. The total disturbing effect will in general come in from points nearer the horizon than the zenith, altho the altitude of the ring of maximum disturbance is indefinite. The individual planes of polarization may take all possible angles, but with a preponderance in a direction determined by the earth's magnetic field. Finally it would seem that the most probable static wave form was a single highly damped pulse, because of the low conductivity of the discharging masses.

According to the above theory, the problem of the elimination of static and the preservation of the signal consists simply of the reception of a wave-train originating at a definite point, and the exclusion of static pulses originating at all points in altitude and azimuth. In a broad sense, there are two solutions for this problem, one involving a separation of signal and static based upon their difference in wave form, and the other a separation based simply on sharply directional reception. It is quite clear that if we could restrict reception to a small solid angle including the distant station, there would be relatively little static included. To use an optical analogy, the problem is essentially like that of receiving monochromatic light signals in full daylight. A spectroscope or a filter screen would be one solution, and directive reception as by a telescope another, but best of all would be a combination of the two. In present day radio communication we have already highly developed the spectroscopic or filter separation of signal from static, as by sharply resonant circuits and beat reception. But altho we have had two practicable types of sharply directional receiving circuits for the past twelve years or more, very little use of these appears to have been made until quite recently.

In a paper entitled "Absorption and Reflection of Electrical Waves," read before the New England Wireless Society on December 7, 1912, the writer, after discussing the probable relation between ionization conditions in the upper atmosphere and electrical wave transmission, went into some detail of his early experiments to determine the nature of static. At his first experimental station, at Blue Hill Observatory, Milton, Massachusetts,[5] he conducted a long series of tests which apparently showed a relation between the wind velocity and the number of disturbances in a given time, which led to the conolusion that effect was a local one, possibly consisting of an actual discharge to the receiving aerial from electrified masses of air moving past the antenna wire. This theory was rudely upset by his further work in 1901, when comparison of tapes at Galilee and Brielle, New Jersey, about twenty miles (32 kilometers) apart, showed the same dots and dashes from static, day after day. It was clear from this that some static, at least, came from discharges at considerable distances from the receiving aerial. He then said:

"A little later, I surrounded a receiving aerial by a F raday cage[6] constructed with loading inductances to avoid shielding the aerial inside from the desired signal. This seemed to eliminate a small portion of the static—probably that portion due to direct discharge to the wire from the atmosphere—but had no observable effect upon the distant variety."

At this point, the writer wishes to call attention to the careless manner in which members of this Institute refer to the Faraday cage antenna shield as a "Dieckmann cage." Dieckmann, in 1912,[7] first published his description of an aperiodic shield or cage around an aerial, so designed as to permit the passage of signal waves, but to be opaque to static pulses. The writer has published, in a patent[6] filed six years before Dieckmann's date, this exact thing. Reference to Figure 2 will show the antenna wires *A*, *A*, surrounded by a cage, sectioned off into short elements which are connected together by impedances and grounded thru other impedances so that an aperiodic shield results. While he is inclined to agree with Weagant[12] that the device is of small utility as against the most bothersome varieties of static, it seems only fair that he, and not Dieckmann, should receive whatever credit is due for this invention. While the

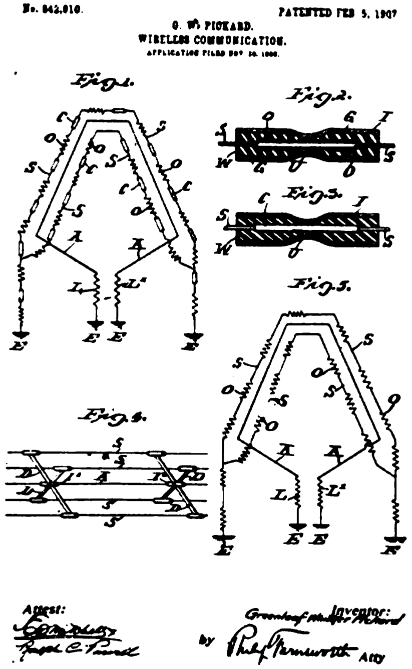


FIGURE 2

shielded antenna is open to attack from clicks and grinders, it is a complete solution of the hissing variety of static, due to a direct discharge to the aerial. Where a series condenser is employed in the antenna circuit, this is very apt to charge up to the limit of its dielectric strength, and then spill over, giving an excellent imitation of pistol shot static. This occurs most markedly during snow-storms; and, on shipboard, where the aerial is slung immediately over the funnels, the vessel manufactures this type of static in abundance, and delivers it effectively to the waiting antenna. Shielding is of distinct value in such cases.

FIGURE 3—Pre-Dieckmann Shield

Continuing his paper before the New England Wireless Society, the writer then describes his early work with directive aerials, particularly with the ungrounded coil or loop aerial.

Again, as with the Dieckmann cage, the writer must pause to correct a heresy. Altho it has been fashionable of late to attribute this invention to Messrs. Bellini and Tosi, it should be noted that these gentlemen first published an account of their work on November 14, 1907[13]. The writer began his development of the coil or loop aerial in 1902, and published an account of his work on June 15, 1907[13], almost exactly five months prior to Messrs. Bellini and Tosi. It is of interest in this connection to note that the writer, on September 13, 1907, demonstrated one of his coil aerials at Dorchester, Mass., to Lieutenant-Commander S. S. Robinson, detailed by the United States Navy for this purpose. This particular coil aerial is shown in Figure 5, and consisted of two turns of wire forming a square about nine meters (27.45 feet) on a side. Altho but two turns are shown,

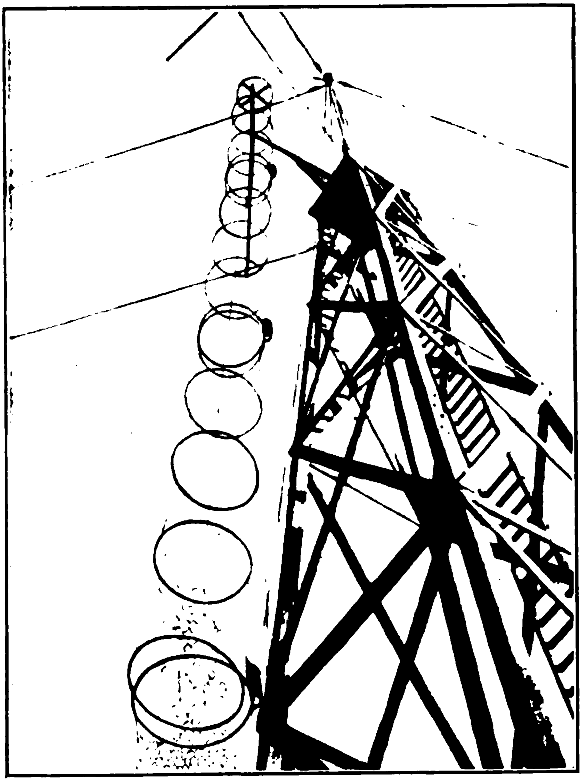


FIGURE 4—Pre-Dieckmann Shield

from one to ten turns were actually employed, depending of course upon the wave-length. Exceedingly accurate bearings of a number of distant stations were taken, some over sixty kilometers (38 miles) away from the loop, with a maximum error not greater than 2 degrees of arc.

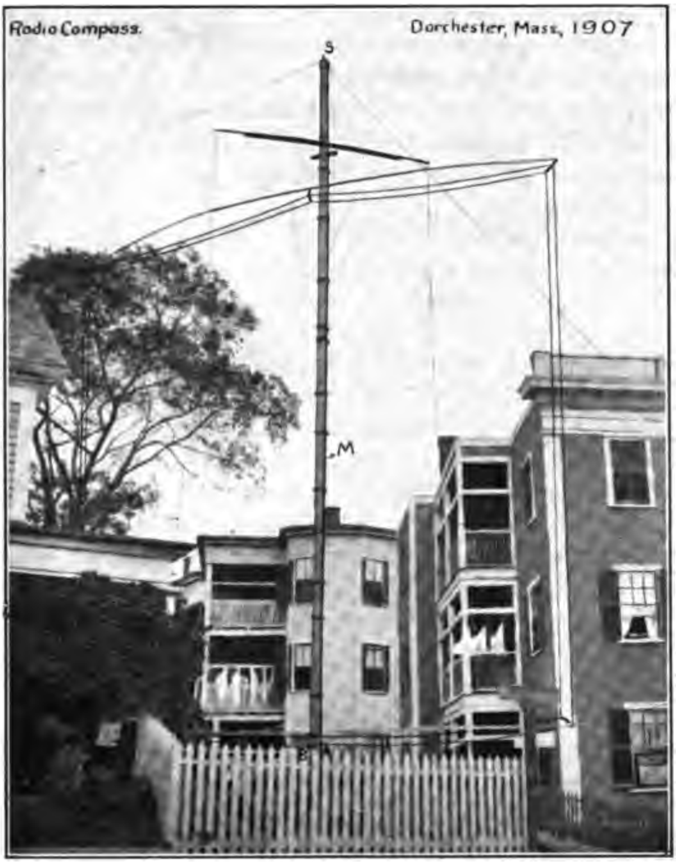


FIGURE 5

Further on in the 1912 paper, the writer said:

"But the worst summer static appears to be at a very considerable distance from the receiver, and I believe it originates at some of the higher levels already discussed in this paper; probably many miles over our heads. I also believe that static is simply a discharge from one high level cloud of ions to another similar cloud, very like what we see from cloud to cloud in a thunder-shower; that is, an equalizing discharge. Like lightning, static appears to be non-oscillatory, as may be readily found by experiment."

The writer does not claim novelty for the "static from above" theory. In fact, Airy[4] said in 1911:

"It was concluded that most of the disturbances were not due to local weather conditions, but to discharges taking place in the upper atmosphere, and at very great distances from both stations. He thought it would be eventually proved that these atmospherics were connected with magnetic disturbances, and that they had the same common origin—that is, the arrival of negatively charged electrons from the outer space into the earth's atmosphere."

The writer concluded his 1912 paper with the following up-to-date treatment of the static problem:

"I believe, as a result of considerable experimental work, that the real solution of the static problem lies in the use of sharply directional receiving antenna. Provided only that the static does not originate at the same point as the signal, good directional reception should eliminate most of it."

As already stated, there are two practical methods of obtaining sharply directional reception. In the first method, originally suggested by Elihu Thomson[8] in 1899, patented in England by S. G. Brown in the same year[9], more fully disclosed and patented in this country by Stone in 1902[10], elaborately worked out for two, three, and four collecting circuits by Braun in 1906,[11] and more recently used by Weagant[12], two or more separate collectors are employed, spaced apart a material fraction of a wave-length in the line of propagation, as shown in Figure 6. These collectors act upon a common secondary circuit in such wise that when the collectors are simultaneously affected by any disturbance, the current set up therein will arrive in phase at the center of the system, and there, by opposed windings, be placed 180° apart in phase in their effect upon the secondary. Because of this opposition, such currents will not affect the detector, and no signal will be produced. On the other hand, the signal wave, passing the collectors successively, will set up currents therein which will arrive at the center of the system in an out-of-phase relation, and such signal currents will add in their effect upon the secondary and affect the detector. This is very well shown in Figure 7, and clearly explained in the specification of the Stone patent of which Figure 7 is the drawing. The writer, in 1905, devised

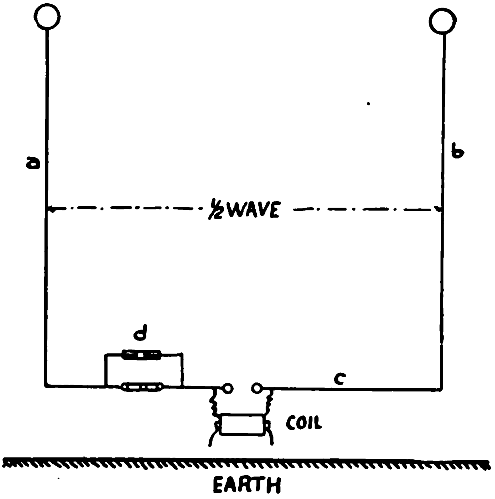


FIGURE 6

a system in which two aerials, tuned to the distant station and separated on centers by some thousands of meters (about a mile),

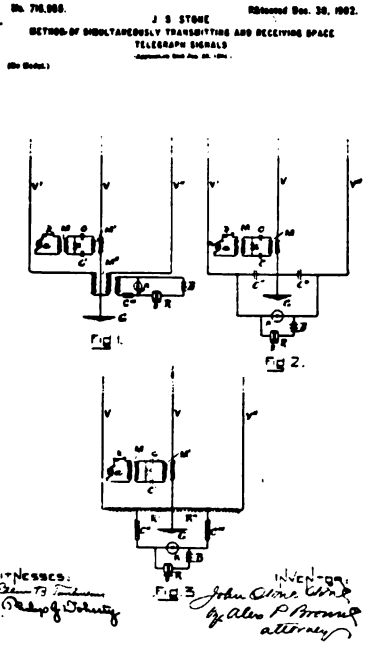


FIGURE 7

were connected to a common secondary by way of phase adjusting means, so that the currents were added in the secondary in such phase as to produce the maximum signal. This method was first published in a patent filed in 1907,[13] and is shown in Figure 8. The particular case discussed in this publication involved two large loop or coil aerials, arranged in an east-and-west plane for the purpose of trans-atlantic reception. These loop aerials consisted of long, low rectangles, and were tuned to the desired wave-length by inserted series capacity and inductance. With this system it is possible to so adjust the phase relations of the currents arriving at the secondary that interference or static arriving from any particular direction is cancelled out in the secondary, and does not affect the detector. A further advantage of this system, which has recently been pointed out by Weagant[14], is the fact that it has materially greater or sharper directional reception than any single type of collector. This is obvious when we consider the fact that the loop aerials M^2 and M^4 have simple cosine reception curves in the horizontal plane,

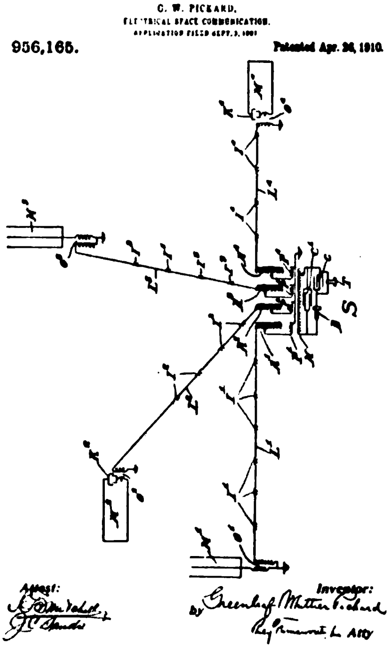


FIGURE 8

and that a pair of open or non-directive aerials, separated as are M^2 and M^4, in Figure 8, by a considerable fraction of a wavelength, with currents combined in a common secondary, have also a cosine curve characteristic. The combination of two loop aerials in the manner shown in Figure 8 has therefore a cosine square reception curve.

This same publication also states that combined loop and open aerials may be used at such points as M^2 and M^4. It is of interest to note the reception curve of this system, when one, two and three separate collectors of this form are employed. In Figure 8-A is shown in dotted line the reception curve of one collector. This is a cardioid, or heart-shaped figure, with maximum reception in the direction *O-A*. With two such collectors, the reception curve is shown in dot-and-dash line, and is markedly more sharply directional than the curve for one collector. A still further improvement results when three collectors are employed, this being shown in full line.

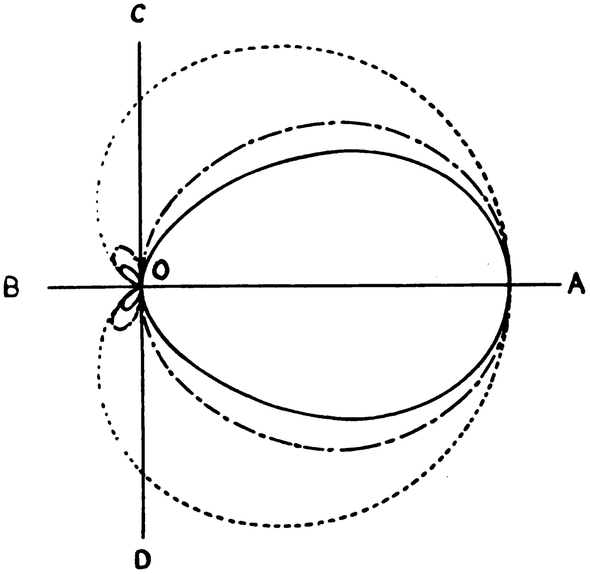


FIGURE 8-A

The second method of directional reception, devised by the writer[21], does not involve, even for long wave reception, such geographical dimensions as the systems shown in Figure 8. This second method consists simply of a closed tuned circuit or coil aerial, of dimensions small as compared with a wave-length. In its most effective form, consisting of a coil aerial combined with a so-called "open" aerial, this method gives true unilateral reception. The coil may be of quite small dimensions, particularly when it is employed simply as a radio compass. In Figure 9 is shown the first portable radio compass, which was employed by the writer in 1907-1908[16] for mapping out the wave-front around a transmitting station. This radio compass consisted of a three-turn loop, one meter (3.05 feet) in diameter, shunted by a variable air condenser and a crystal detector.

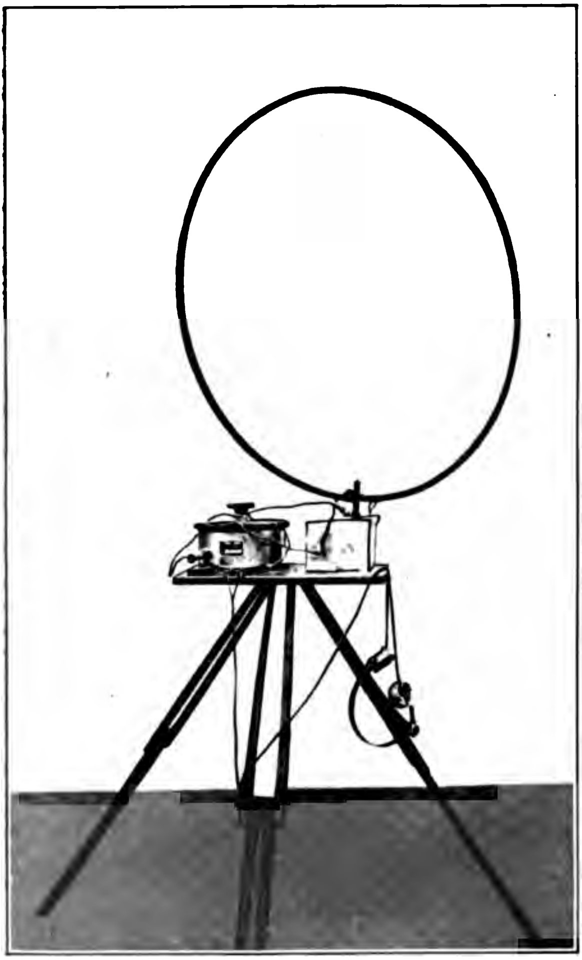


Figure 9

Heretofore, the reception characteristics of aerials have been studied principally, if not exclusively, in the horizontal plane. The writer is not aware of any publication dealing with the three-dimensional characteristics of aerials, altho for quite some time past, points of wave origin other than the horizon have been common, for example, static, and more recently transmitters on aircraft. Just why radio engineers have elected to live in a two-dimensional world is rather puzzling, and if this paper has no other effect than to add another dimension to their life the writer will feel fully repaid for his labor.

In Figure 10 is shown the now familiar reception curve of a vertical loop or coil antenna in the horizontal plane, consisting of a cosine curve drawn in polar co-ordinates. This is an ideal curve; actually a coil aerial gives a more or less distorted figure-of-eight, sometimes tending to an hour-glass shape, and usually more or less unsymmetrical. The reasons for this distortion have only recently been worked out in detail, and some of the more important causes of distortion will be explained later in this paper.

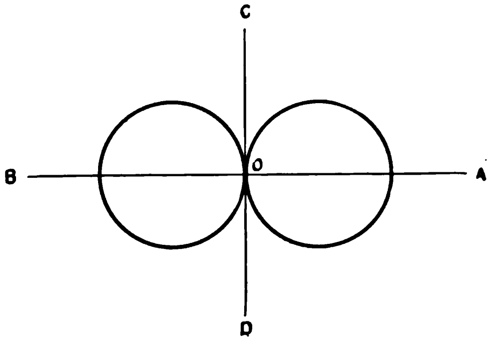


FIGURE 10

In a vertical plane, including the plane of the loop itself, reception is obviously symmetrical, and the reception curve in this plane is a circle, as shown in Figure 11. If the loop is near the ground, the lower half of the reception curve is normally without interest, because signals do not often originate from under foot, and hence is shown in dotted line.

If, however, a loop is placed aloft, as in aircraft work, the useful reception curve in this vertical plane is a full circle. Finally, the complete three-dimensional reception surface of the

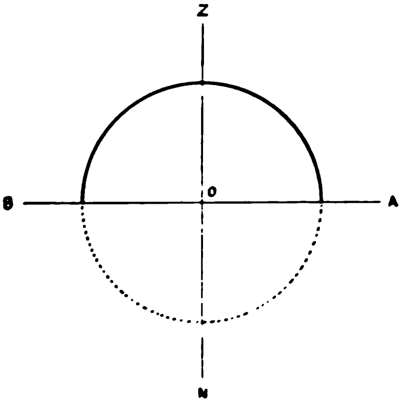


FIGURE 11

loop is a torus. This torus is shown in Figure 12, and differs from the conventional anchor ring or doughnut in that it has no hole in the center, this peculiarity making its representation somewhat difficult. The significance of this last figure is obvious —the loop receives more or less from all points in space, excepting only along a line passing normally thru its center. The further

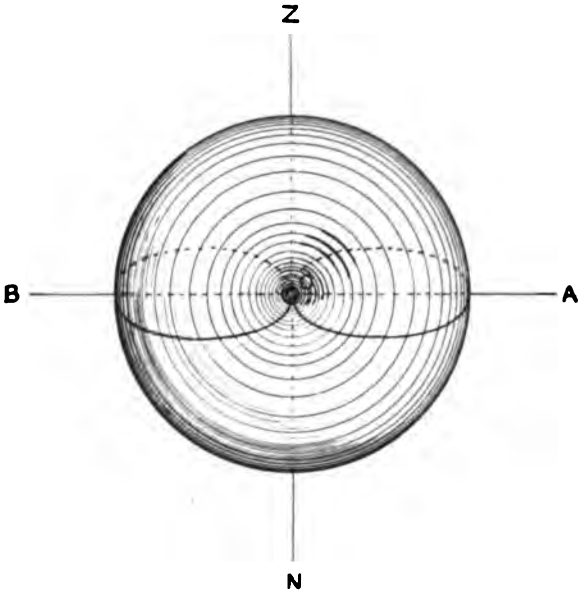


FIGURE 12

meaning of this figure is that maximum reception occurs only in all directions in the plane including the loop, and the significance of this fact is perhaps best brought out by Figure 13. This figure represents a plan of the hemisphere over the loop, just as if one were looking up at the zenith, and the shading indicates the amount of reception from different points in this hemisphere by a loop placed in an east-and-west vertical plane. The zone of maximum reception is a belt passing across the sky from east to west, reception decreasing to zero on the horizon at points north and south of the loop.

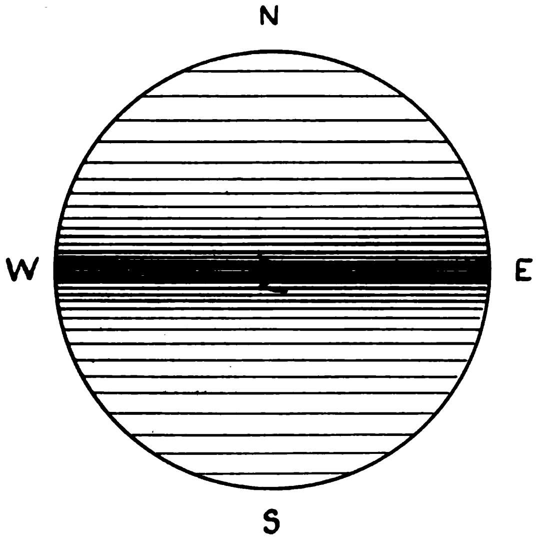


FIGURE 13

A so-called open antenna consisting of a vertical wire, short as compared with a wave-length, has in the horizontal plane a simple circle diagram, that is, it receives equally well from all points on its horizon. In any vertical plane passing thru the antenna, a quite different reception curve results, as reception is a maximum on the horizon, and decreases to zero at the zenith. The complete reception in any vertical plane passing thru the antenna is shown in Figure 14, and is, of course, the familiar cosine curve. The portion below the horizon is shown dotted in the figure; if the open antenna consisted of an ungrounded linear oscillator considerably removed from the earth, the lower portion of the curve would interest us. Actually, just as with the loop or coil aerial, and for similar reasons, this ideal curve usually suffers considerable distortion, partly because actual vertical aerials have an appreciable horizontal length in most cases, and partly because of unsymmetrical or electrically warped surroundings. The complete three-dimensional reception surface of the

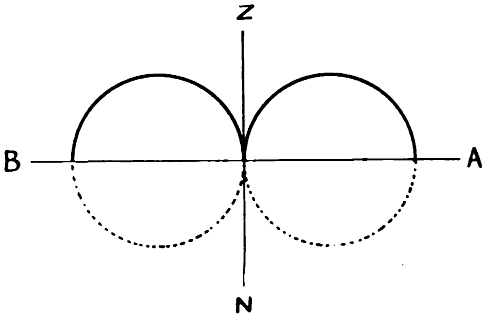


FIGURE 14

open antenna is therefore just like Figure 12 laid down flat, or, more exactly, laid down flat and half embedded in the ground if the open antenna is on the earth's surface. It will be seen from this that the loop and the open antenna have identical reception surfaces, but in planes 90° apart. Similarly to the loop, Figure 15 shows a plan of the hemisphere over an open antenna. In this

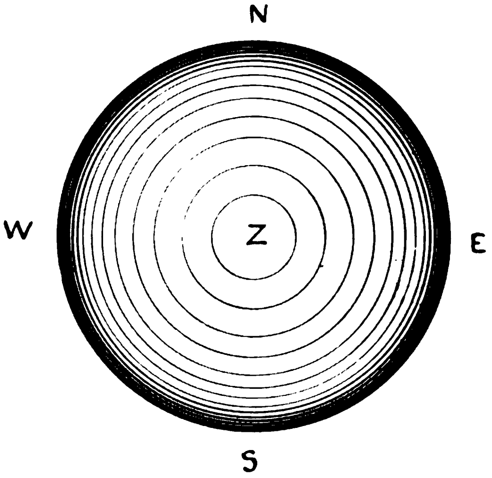


FIGURE 15

figure, the reception belt rings the horizon, and reception is zero from the zenith. If static came solely from above, an open antenna would make an ideal eliminator. Equally, if static came in on the receiving point with the same intensity from all points in altitude and azimuth, it would be difficult to account for the well-known freedom of the loop from static.[20] But if we assume that in general static is at its worst near the horizon rather than the zenith, a comparison of Figures 13 and 15 will show a reason for the relative immunity of the loop.

In Figure 16 is shown the method referred to above, which combines open antenna reception with loop or coil reception. A glance at the date of this drawing--June 10, 1907—will make it obvious that the combination of loop and open reception cannot be attributed to Messrs. Bellini and Tosi, often as this has been attempted of late. In this figure is shown the coupling of a loop and an open antenna to a common secondary, by way of phase-adjusting means, so that the currents in the loop and the

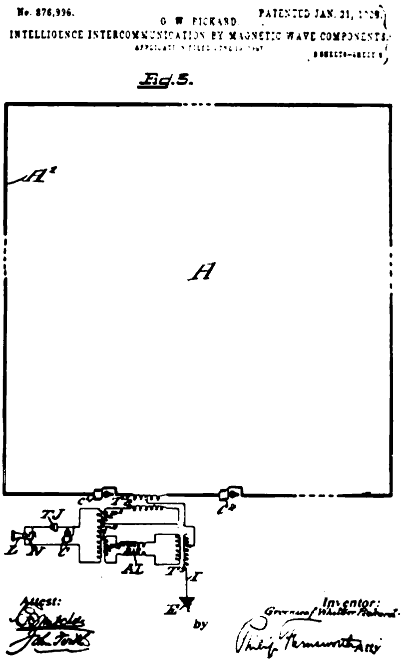


FIGURE 16

open antenna, normally 90° out of phase, are added in phase in the secondary circuit. If now, as by suitable dimensions of the loop or by coupling adjustment, or by both, the currents from the open antenna are made equal, in their effect upon the secondary, to those from the loop, the result of this addition, in a reception curve on the horizontal plane, is shown in Figure 17. Reception is at a maximum from the direction *O-A*, is zero from the direction *O-B*, and has intermediate values from other directions, the complete curve being a cardioid. Such a circuit, employed as a direction finder, gives the true bearing of the distant station, and does not, as with the simple loop, leave the direction indeterminate by 180°. In a vertical plane including the loop the reception curve is also a cardioid, as shown in Figure 18, with a maximum on the horizon at *A*, and zero on the horizon at *B*. Reception from the zenith, that is, along the line *O-Z*, being limited to the loop, has half the value of reception along the line *O-A*. In a vertical plane at right angles with the loop, that is to say, at right angles to the plane of Figure 18, the reception curve is that shown in Figure 19. In the center of this figure is shown the loop *L-L* and the open antenna *V-V*. A static source at *S-S*, in the vertical plane *C-Z-D-N*, is at an angle *A* with the vertical, and has an orientation or polarization angle *B*.

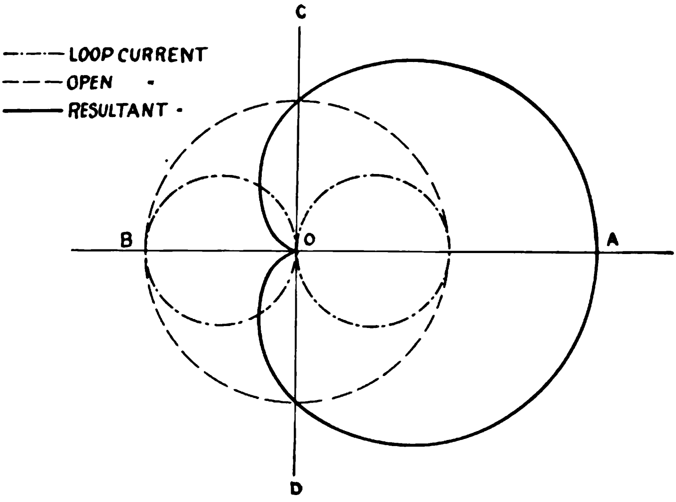


FIGURE 17

The current set up in the loop will be proportional to $\cos A \sin B$, while the current excited in the open antenna will be $\sin A \cos B$. The sum of these currents will be $\cos A \sin B + \sin A \cos B$; that is, for all possible orientations and vertical angles it will be a constant, so that the reception curve in the vertical plane normal to the loop will be, as shown in the figure, a circle.

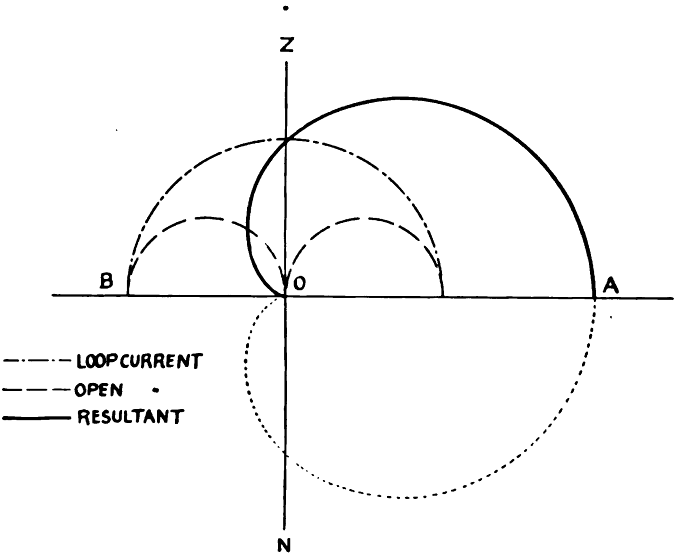
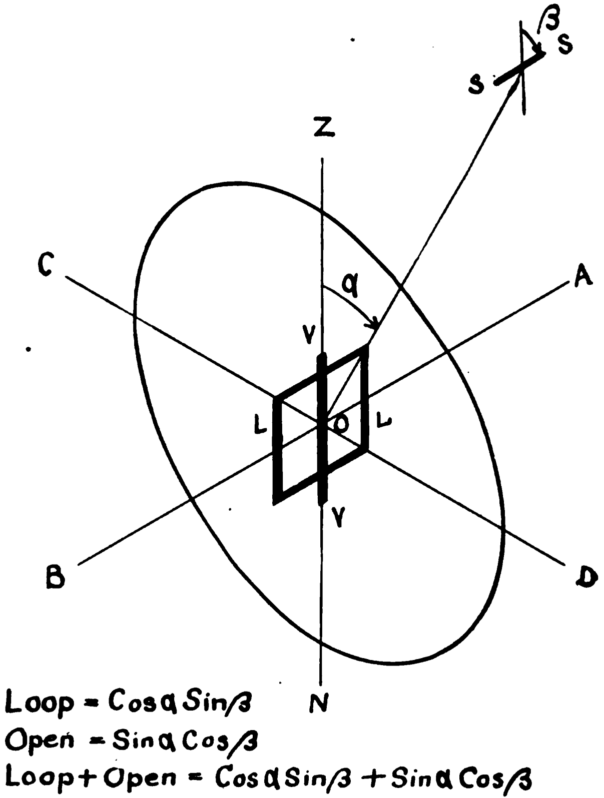


FIGURE 18

The complete three-dimensional reception surface is difficult to show in a two-dimensional figure or plan. Figure 20 shows its sections in three perpendicular planes. As will be apparent from this figure, the complete reception surface is a cardioid of revolution, which may be more simply described as an apple, with the pit at the origin *O*.

From a consideration of the three-dimensional unilateral reception of the combined open and loop antenna, as shown below in Figure 20, it will be obvious that static originating at points other than on the horizon in the direction of the distant transmitter will either be weakly received, or, if it happens to originate on the horizon at a point 180° from the transmitter, it will not be received at all. The circuit shown in Figure 16 is not at present, however, the best arrangement for this method of static reduction. As the effect of static on a receiving circuit is practically pure impact excitation, complex waves will be set up in the two coupled circuits—the loop and the open antenna—with the result that the just shown ideal diagrams of reception curves and surfaces are but roughly approximated. These diagrams are, of course, only true for undamped wave reception, or for static reception on substantially aperiodic circuits.



$$\text{Loop} = \cos\alpha\sin\beta$$
$$\text{Open} = \sin\alpha\cos\beta$$
$$\text{Loop} + \text{Open} = \cos\alpha\sin\beta + \sin\alpha\cos\beta$$

FIGURE 19

Shortly after America entered the war, the Wireless Specialty Apparatus Company equipped a radio station for Mr. Alessandro Fabbri, at Otter Cliffs, near Bar Harbor, Maine. When the station was completed, Mr Fabbri donated it to the Navy, and it was first used as a low power spark station. However, it was very shortly found that the location was an excellent one for trans-atlantic reception, and this eventually became its principal service, the station finally becoming the premier reception point in this country. The summer of 1917 having shown that altho the Otter Cliffs station had excellent signals, it also had overwhelming static on occasion, Mr. Fabbri invited the writer to install directional receiving circuits for static elimination, adapted to the requirements of trans-atlantic service. Within a few days after this request, the circuit shown in Figure 21 was installed, combining open antenna reception with loop or coil reception. This was immediately found successful in improving the signal-static ratio, and was at once placed in service. The loop *A* consisted of a solenoidal coil of four turns of number 16 Brown and Sharp gauge (1.3 mm. diameter) copper wire, with the turns spaced apart 30 cm. (12 inches). This loop was in the form of a long low rectangle, 30 meters (97.5 feet) long, and 6 meters (18.3 feet) high, the lower part of the loop being about 4 meters (12.2 feet) from the ground. The plane of this loop was approximately north-east by south-west, that is, it was in the great circle bearing of the more important European stations. This coil aerial was tuned to the desired wave-length by series inductance L_3 and capacity C, a fixed coil L_3 of 22 millihenrys

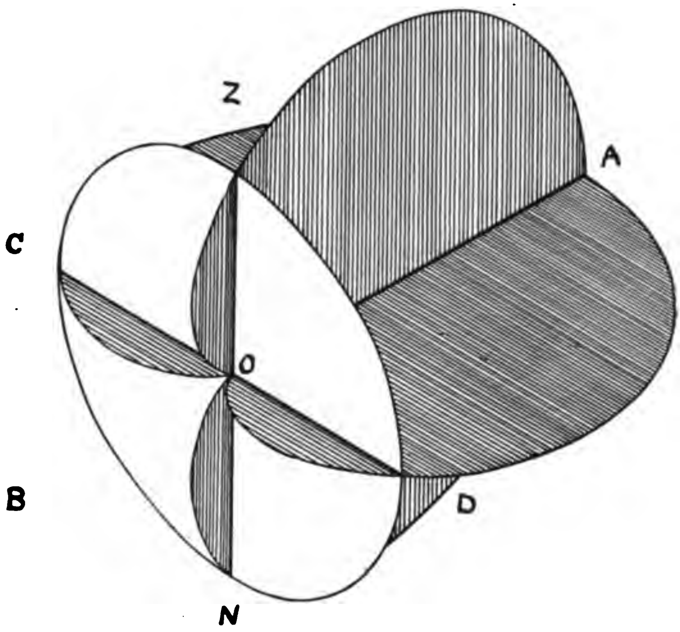


FIGURE 20

being used in most of the work. The open antenna of this combination consisted of the conductor of the loop itself and a connection to earth at *G* by way of a coupling coil L_1 of 22 millihenrys inductance, a variable inductance L_2 for tuning this open antenna circuit, and a variable resistance *R*, and was tuned to the same wave-length as the loop. The coils L_1 and L_3 were quite closely coupled together, and coil L_3 rather more loosely coupled to the secondary or detector circuit S. This secondary circuit, as shown in Figure 21, employed the static coupled audion circuit due to Lieutenant Eaton of the United States Navy.

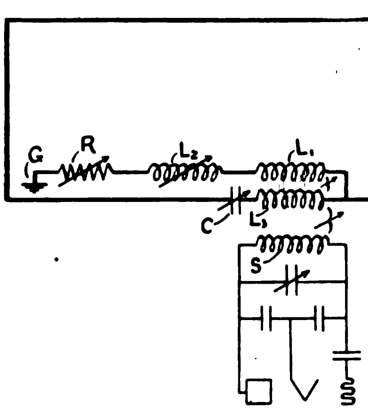


FIGURE 21

Two steps of audio frequency amplification were usually employed, in addition to the circuit shown, and the normal signal strengths from Rome, Lyons, and Carnarvon were above 1,000 times audibility. The resistance *R* was found to be an important element of the circuit, and in its absence the results were decidedly inferior. The amount of resistance required was surprisingly large, being about 3,000 ohms.

The operation of this circuit is substantially as follows: As it is a development of the circuit shown in Figure 16, and consists of a combination of a loop and an open antenna, with the currents added in phase in the secondary circuit, it has a reception surface which is essentially like the upper half of Figure 20, with a maximum reception only on the horizon in the direction of the distant transmitter. Static pulses from any direction other than that of the distant station itself are either received weakly or not at all if it happens to originate to the rear of the system.

Reaction between the open and closed circuits, with resultant complex wave formation, is prevented by the high damping of the open circuit, which with 3,000 ohms inserted is practically aperiodic. The reason why so large a resistance can be used in the open circuit and still have substantial equality of open and closed circuit current is due to the fact that a loop of the dimensions employed is much less effective than an open antenna of the same height at long wave-lengths. The currents from the open circuit, reduced to the same amplitude as those in the loop by the inserted resistance and degree of coupling, are shifted thru 90° in phase by the transfer from the open to the closed circuit by way of the coupling, between L_1 and L_3, and hence are added in phase in the loop circuit, and then transferred, by the coupling between L_3 and S, to the secondary circuit. It will be seen that the change in phase accomplished in the original circuit of Figure 16 by a phase adjuster in the form of a variable artificial line, is here done by the simple expedient of coupling together tuned circuits.

The performance of this circuit may be judged from a typical set of audibility meter readings taken by the writer, which are tabulated below:

Time A.M.	Station	Loop alone		Loop+Open	
		Signal	Static	Signal	Static
11.25	Nauen	2,500	800	400	60
11.35	"	5,000	1,500	3,000	800
11.45	"	3,000	1,000	400	120
11.50	"	5,000	1,500	——	——
12.00	"	3,000	1,500	——	——
P.M.					
2.35	"	1,000	1,000	250	60
2.40	"	——	——	1,000	200
3.10	Carnarvon	1,000	4,000	600	100
3.15	"	1,500	5,000	600	160
3.25	"	800	5,000	200	80
3.30	Nauen	1,000	5,000	250	80
3.35	"	1,000	4,000	600	160
3.37	Carnarvon	1.000	5,000	600	160
3.41	"	1,000	4,000	500	160
3.55	Nauen	1,000	5,000	300	80
4.00	"	600	2,000	300	60

The static intensities in the above table were taken in each instance over a period of five seconds, and no attention was paid to the clicks, which were of several times the intensity of the grinders. It will be noted that during the forenoon, with strong signals and weak static, the system had little effect. But during the afternoon, with weaker signals and much stronger static, the improvement in the ratio is rather striking. As a matter of fact, the circuit of Figure 21, during periods of severe static, enabled the solid, uninterrupted copying of stations which would on the ordinary circuits be so broken up as to be unreadable.

Continued use of this circuit at the Otter Cliffs station developed the fact that the earth connection of the open antenna was not attached symmetrically to the aerial, the result being that a certain amount of current in the open circuit was flowing directly thru the loop and coil L_3, of course 90° out of phase with the loop current. This tended to decrease the sharpness of the unilateral reception, and hence the degree of static elimination. As this effect is often present in the simple loop or coil aerial when used for direction finding, it may not be out of place to explain it briefly here.

Considering only the horizontal plane reception of a simple loop aerial, with a certain unbalanced capacity to ground (either by way of unbalanced leads or unsymmetrical construction of the loop itself), it is obvious that the system will act as a combination of loop and open antenna, with the currents added together, not in phase but in quadrature. As a result of this, the currents will add together irrespective of their direction, with the result that the ideal figure-of-eight reception curve degenerates into an hour-glass shaped figure, the breadth of the neck depending upon the amount of open antenna current. This degeneration is shown in four steps of increasing open antenna current in Figure 22. The remedy for this trouble is a simple one, and consists in balancing the loop to ground, as by a three-plate variable condenser, in the manner shown in Figure 23. By turning this loop thru 180° in its own plane, so that the terminals of the loop come out on top, a material advantage results in direction finding. As the points of highest potential are thus removed as far as possible from the earth, the loop is much less affected by surrounding grounded objects. Of course, this method is at its best with a single turn loop, altho improving a two-turn loop.

A simple loop may also suffer from open antenna current which is neither in phase with the loop current, nor in quadra-

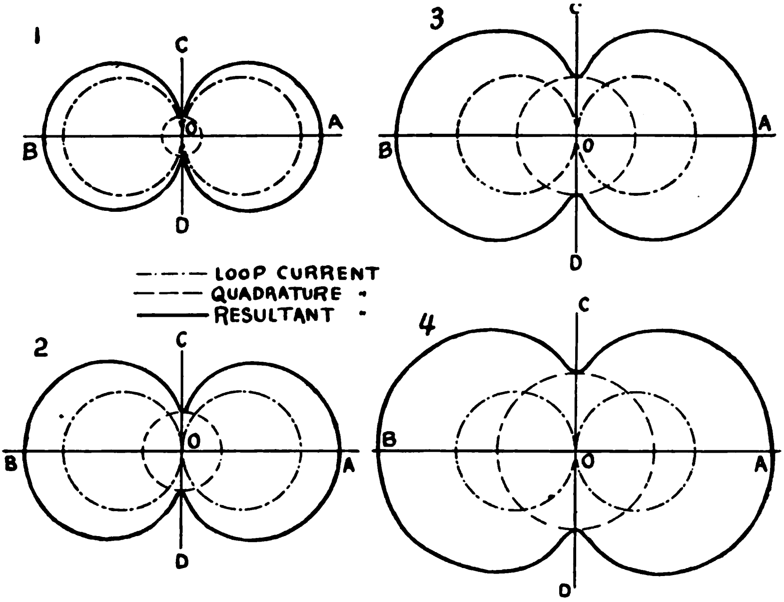


FIGURE 22

ture therewith. This sometimes happens in short wave working with loops of considerable inductance, that is, of considerable

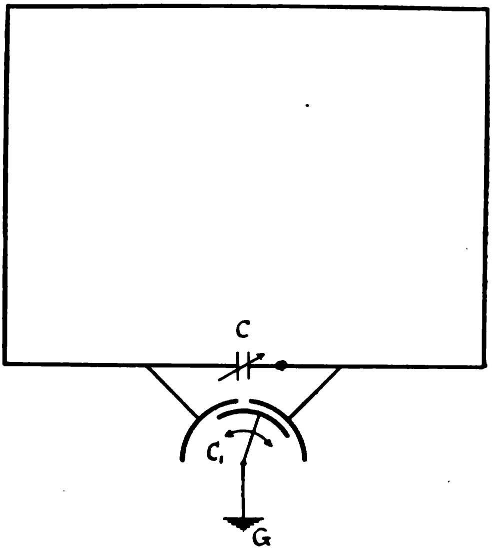


FIGURE 23

conductor length. It also happens with the circuit of Figure 21, because the two open antenna effects, one in phase and the other in quadrature, may be considered as one current. For graphical analysis, it is simpler to keep these currents separate, and this is done in Figure 24, which illustrates the evil effect of out-of-phase current. This is also an unbalance effect, and may be eliminated by suitable construction or by the three-plate condenser arrangement of Figure 23.

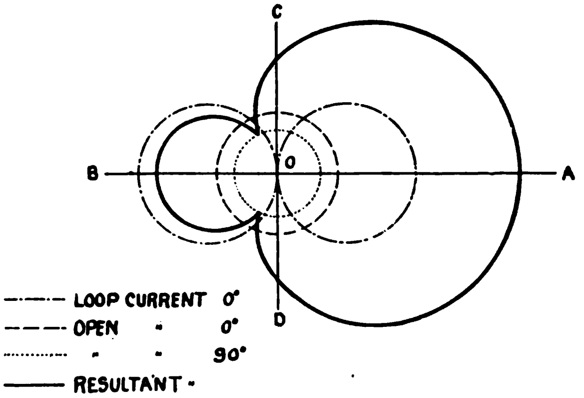


Figure 24

A more bothersome effect in simple loop working arises from a displacement current across the turns of the coil aerial, added to an open antenna current resulting from unbalance. Inasmuch as the displacement current across the turns of the coil gives a cosine characteristic like that of the loop itself, but displaced by 90°, the resultant characteristic of the system suffers distortion which is particularly noticeable at the minimum points at right angles to the loop. The writer had intended to treat this at some extent, but the interesting paper of Captain Blatterman[18], which issued after this paper was written, makes this unnecessary. It is sufficient to say that, with the exception of the displacement current effect (which can be obviated by using a pancake rather than a solenoidal coil aerial) proper balancing of the loop, either by construction or by the three-plate condenser, is all that is required.

An interesting modification of the circuit of Figure 21, due to a suggestion by Mr. J. A. Proctor, was tried out at Otter

Cliffs, and found to reduce the unbalanced open antenna effect. This circuit is shown in Figure 25, and differs only from the circuit of Figure 21 in that the ground connection from the right-hand end of coil L_3 is taken by way of a second loop, A_1, closely coupled with the main loop A. Unbalanced current in the loop A is opposed by current in the loop A_1, with the result that there is a certain cancellation of effect, and a sharpening of the directional action.

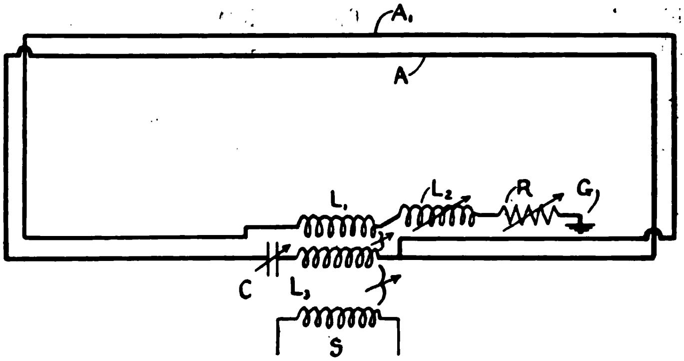


FIGURE 25

But the simplest solution, and the one that has given the best result from the combination of vertical open antenna and loop, is shown in Figure 26. This differs only from Figure 21 in that a separate open antenna is used, and the loop circuit remains entirely insulated. A typical performance of this

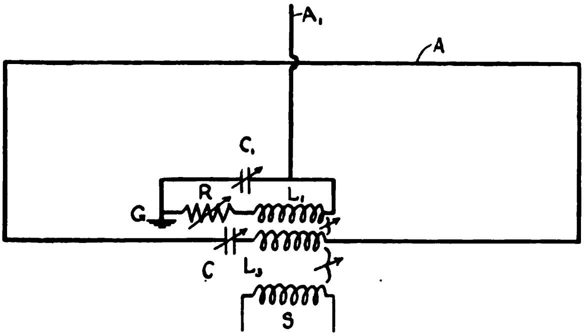


FIGURE 26

circuit (which had a loop of approximately the same dimensions as that of Figure 21) is given below:

Time P.M.	Station	Open alone		Loop alone		Loop+Open	
		Signal	Static	Signal	Static	Signal	Static
1.45	Nauen	2,000	4,000	300	600	300	60
1.54	Hanover	400	1,500	100	500	200	80
2.38	"	400	1,500	150	500	300	100
2.44	Nauen	800	6,000	200	500	300	80
3.10	"	200	800	300	800	400	80
3.18	Lyons	100	1,000	150	500	150	40
3.27	"	200	2,000	150	1,000	200	60
3.52	"	300	1,500	100	500	150	50
7.14	Carnarvon	300	1,500	150	600	150	80
7.28	"	400	4,000	300	1,000	400	100
7.40	"	400	3,000	200	800	300	100
8.26	Lyons	400	1,500	150	500	300	100
8.57	"	400	1,500	200	1,150	300	150
9.11	Carnarvon	100	800	100	800	150	60
9.20	Lyons	600	8,000	200	1,500	150	100
9.32	Carnarvon	?	8,000	?	1,000	150	100
9.37	Lyons	300	1,500	100	900	100	60

One of the striking things in the above tabulation is Carnarvon at 9.32 p. m. Neither on open antenna nor on loop, taken singly, could sufficient signal be heard to measure on the audibility meter. But on the combined loop and open antenna the signal was well above the static in intensity.

The adjustment of the combined loop and open antenna, in either of the forms shown, is quite critical, the best unilateral reception being when the loop and open antenna currents are equal. In Figure 27 is shown the result of combining different ratios of open and loop current. The uppermost reception curve is the horizontal plane characteristic of an open antenna, with no loop current. The second curve represents equal amounts of open and loop current, and is a cardioid.

The third figure represents the addition of two parts of loop current to one of open, while the fourth shows pure loop reception. It will be seen that the vector *O-A*, in the direction of the distant transmitter, increases uniformly as loop current is added to open current, until the ratio is one to one. Any further change in this ratio, increasing the proportion of loop current, decreased the vector *O-A*, the reception being only at a maximum when the ratio is unity. Similarly, the amount of reception from the direction *O-B* decreases steadily as loop current is added to open, being zero when the ratio is unity. Any further change, increasing the ratio of loop to open, results in increasing the amount of reception from *O-B*.

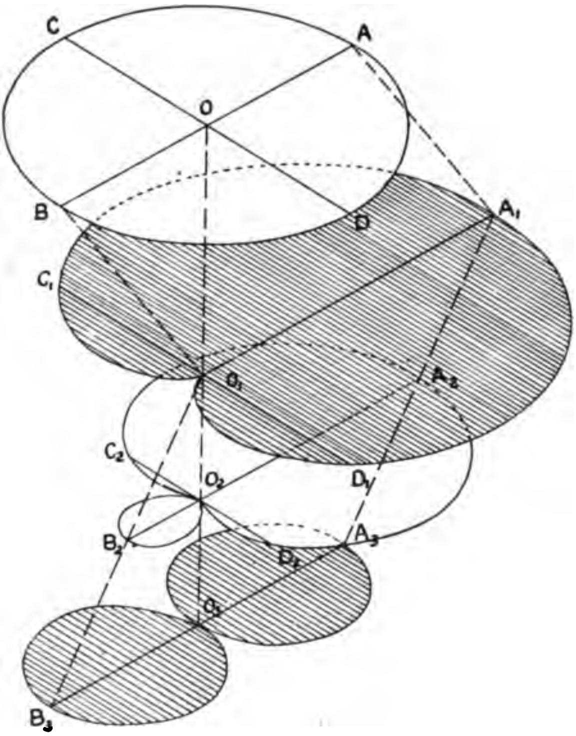


Figure 27

The writer here wishes to emphasize the fact that the results above tabulated are in no sense exceptional for his system of the combined loop aerial and open antenna, nor were they taken under "freak" conditions. These combined loop and open circuits have been in daily operation, summer and winter, over a period of nearly two years at Otter Cliffs, and have proven consistent performers. During the summer of 1918 the Otter Cliffs station circuits gave unbroken copying of the European stations at times when all other Atlantic coast receiving points were helpless. In fact, altho a large amount of interesting experimental work was done at various points on the Atlantic coast, it may now be definitely said that the above-described circuit, in the installation at Otter Cliffs, was the only static eliminator that played any part in our war use of trans-atlantic radio communication.

An interesting and as yet unexplained matter is the marked predominance, at least on the northern Atlantic coast, of static originating on the western or south-western horizon. In all probability, this direction of origin accounts for some of the elimination observed on the above circuits. The writer also has a certain amount of evidence which tends to show that this effect is confined to the immediate neighborhood of the coast, and that it vanishes a short distance inland.

As a result of the writer's study of the three-dimensional characteristics of various aerial combinations many novel and useful arrangements have resulted. While a detailed showing of these arrangements will be given in a later paper, a brief description of one of them may be of interest here. Examination of Figure 20 will show that if this figure is turned thru 90°, so that the vertical plane *C-Z-D-N* becomes the horizontal plane, a very favorable reception surface results. No energy would be received from the zenith, and but very little from the rest of the hemisphere, until the horizon was reached.

On the horizon, from static sources having all possible planes of polarization, there would be reception from all directions, but for signals from distant transmitters the predominant reception would be from the loop, so that signal reception would be directional.

In order to turn the reception surface of a circuit thru 90° one has only to turn the circuit itself thru this angle. In Figure 28 is shown the circuit of Figure 26, turned thru 90° in the plane of the loop. It is best to remove this circuit somewhat from the earth's surface, in order to prevent distortion of the open antenna characteristics. Ordinarily, if the lower part of the loop is elevated some five or six meters from the ground there will be no appreciable distortion.

In this connection it must be remembered that, over land at least, wave-fronts are not vertical, but are tilted forward in the direction of propagation. For example, at Otter Cliffs the writer found that waves arriving from European stations were inclined over 15° from the vertical. This tilting of the wave-front in and over poorly conducting soil is responsible for many curious effects; among others, it is the explanation of the action of the so-called underground aerials. When a tilted wave-front

Static Eliminator at Otter Cliffs with Four Stations for Simultaneous Reception of Trans-atlantic Schedules

Interior of Static Eliminator Station

passes the circuit of Figure 28, it is equivalent to tilting the horizon of this figure, with all that that implies as to the reception surface. Returning to Figure 20, it will be seen that if the plane *C-Z-D-N* be rotated slightly about *C-D* as an axis, one half of the reception surface will be more or less submerged, so that reception will be unilateral. In this manner, by swinging the circuit of Figure 28 thru a slight angle, it is possible to suppress practically entirely one side of the reception, and with the normal south-western static and trans-atlantic reception the circuit is free from disturbance.

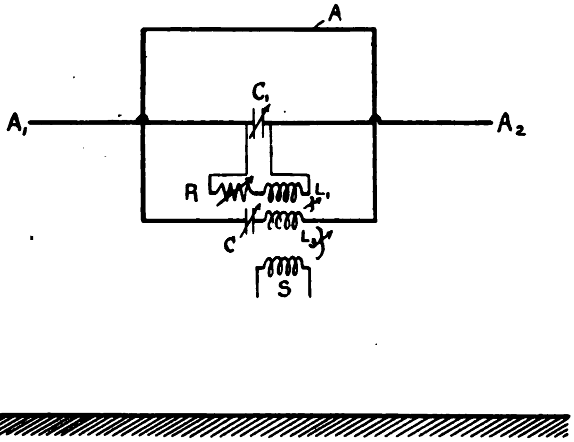


Figure 28

The writer gives below a typical extract from the performance log of this circuit. The loop *A* (Figure 28) consisted of seven turns of number 16 Brown and Sharp gauge copper wire (1.3 mm. diameter) spaced 10 cm. (4 inches) apart in a solenoidal coil, 30 meters (91.5 feet) long, 7 meters (21.4 feet) high and with the lower conductors of the loop about 4 meters (12.2 feet) above the ground. The open horizontal antenna A_1-A_2 consisted of a single wire 50 meters (153 feet) long, with a variable condenser C_1 inserted at its center. The coils L_1 and L_3 were of 20 millihenrys each, and the resistance *R* was 1000 ohms. Preliminary tests having indicated that the open antenna received materially less energy than the loop, the resistance *R* was removed from the open circuit, and placed in the loop. The secondary *S* was then coupled with L_1 instead of L_3, as shown in Figure 28, and the following readings were taken:

Time P.M.	Station	Loop alone		Loop+Open	
		Signal	Static	Signal	Static
2.45	Nauen	150	300	50	15
2.58	"	300	600	60	5
3.14	Lyons	100	500	30	8
3.28	Nauen	800	3,000	200	10
4.12	Carnarvon	100	500	40	5
4.25	"	100	600	60	8
4.32	Nauen	200	1,000	80	6
4.58	"	100	600	80	10

In conclusion, the writer wishes to acknowledge the valuable assistance and co-operation of Mr. J. A. Proctor, and the aid so freely given by Mr. Alessandro Fabbri, whose helpful enthusiasm and encouragement will long and gratefully be remembered.

SUMMARY: The author considers the possible origins of static and inclines toward a solar origin. He finds that static comes from all directions, with maximum intensity from above and maximum frequency from the horizon. The probable static wave form is a single highly damped pulse.

The author then describes his early work with loop directional receivers, his invention of the so-called "Dieckmann cage," and his early work in static elimination.

He gives the three-dimensional reception characteristics of linear antennas, loops, and various combinations of these.

The work carried on under his direction at the Otter Cliffs, Maine, receiving station is then described in detail. Highly successful loop-and-antenna combinations were used in static elimination, and these are discussed with numerical results.

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DISCUSSION

C. L. Farrand: Mr. Pickard states that a system comprising two loop antennas of Figure 8, United States Patent Specification, Number 956,165, will accomplish the elimination of static providing the currents of the two antennas are properly phased and opposed at the receiver. The reception curve of this system is of the form of a rotated lemniscate or figure of eight, with the points of minimum reception located in a vertical plane perpendicular to the direction of reception, assuming, as is usually the case, that the two antennas are on the line of communication. The system which Mr. Pickard, as he has shown us by the tabulated results of Figure 21, has used so successfully, comprising the earthed loop antenna, has a reception curve approximately of the form of a rotated cardioid, with the points of minimum reception located on the line of communication, in direction opposite to the distant station, and perpendicular to the plane of minimum reception of the two-loop arrangement. It is not apparent, therefore, by Mr. Pickard's explanation how these two systems, which he claims are embodied in his patents, accomplish the elimination of static by "directional reception."

It is to be assumed from Mr. Pickard's remarks that the two-loop arrangement of Figure 8 would function in a locality where the earthed loop of Figure 21 would not.

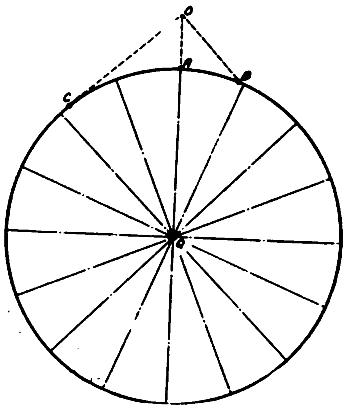
G. W. Pickard: That is approximately correct.

C. L. Farrand: A theory advanced to explain the effect of apparent vertical propagation of static is that the point of origin is at a great height, and that the horizontal components of the static so propagated are neutralized in propagation. Under this hypothesis assume circle $A B C$ to represent the earth's surface. Static originating at point Q, a relatively great height above the earth, would affect a station located at B as if propagated vertically, but the station located at A would be affected by a static signal of horizontal component $A B$ and vertical component $O B$ comprising the true direction $O A$. The station located at C would be affected by a static signal of purely horizontal direction, Thus static could be eliminated at station B, but stations A and B would be unfortunate in their locations.

A more reasonable hypothesis is that the point of origin of static is approximately at the center of the earth Q, and the radial propagation of static to the surface of the earth affects all stations in substantially the same manner. Thus not only would station *B* eliminate static but stations *A* and *C* would not be slighted.

The determination of direction, vertically upward or vertically downward, may be made by an arrangement similar to that shown by Mr. Pickard's Figure 28. Such tests were under way during the past summer and it is regretted that the shortness of the static season did not permit of their completion.

The hypothesis of vertical propagation has been objected to on the ground that a vertical antenna would accordingly eliminate static and that it is a well-known fact that the vertical antenna receives static very strongly. I might point out that very few antennas have been erected wherein the conductors were vertical or even approximated the vertical. The so-called vertical antenna generally has a considerable horizontal component, or has a flat top of its "L," "T" or umbrella, which horizontal component is responsible for its being affected by static. I have yet to see it proven that a simple vertical earthed antenna will not accomplish the elimination of static. The failure of the vertical earthed antenna may be attributed to the generation of static currents in the conducting earth, the earth in this case representing conductors perpendicular to the direction of propagation and in the path of vertically propagated static. Such is not the case, however, of the vertical unearthed symmetrical antenna, providing that the antenna is elevated sufficiently so that the effect of the earth is negligible. It is hoped that when more complete experimental corroboration can be obtained in various localities and under the many different conditions of service, that the subject matter suggested by the views set forth above may be presented more completely.



Harold H. Beverage: During the past two years, I have observed the static conditions to a considerable extent with a uni-directional receiver known as the "Barrage Receiver."*

When the barrage receiver was first set up at New Brunswick, New Jersey, we found that the signal-stray ratio was most favorable with the adjustments which balanced south-west signals. Furthermore, the signal-stray ratio with uni-directional reception was much better in comparison with the signal-stray ratio on a bi-directional loop than would be expected from a comparison of the horizontal plane intensity characteristics of the two receivers. If we consider that the horizontal plane intensity characteristics of the uni-directional receiver is a cardioid, we would expect the signal-stray ratio to improve in proportion to the reduction in area of the characteristic if the static were equally distributed in all directions.

The improvement to be expected on this assumption would be about 25 per cent. for uni-directional reception as compared with a bi-directional loop receiver. However, we found the improvement to average much more than 25 per cent, often being as much as 300 per cent and occasionally reaching 500 per cent or even more in the afternoon when the static was strong.

A barrage receiver was afterward installed at Otter Cliffs and the same phenomenon was noted there. Recent tests on Long Island have led to the same result. These observations apparently confirm Mr. Pickard's observation that the static is directional on the North Altantic coast with a maximum on the south-western horizon.

At Otter Cliffs, I have observed that, in general, the static in the morning is light and intermittent and does not usually show very great directivity. About 2:00 P.M., the static usually begins to increase rapidly in intensity and continuity, and at the same time begins to show directivity with a maximum in a general south-westerly direction. As Mr. Pickard mentioned, the European stations are roughly north-east from Otter Cliffs and may, therefore, be received with maximum intensity, at the same time preserving a balance on the south-west static. During the summer months, reception would often be impossible at Otter Cliffs with a bi-directional receiver due to strong static, but with uni-directional reception, interruptions are very rare.

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*Described in Mr. Alexanderson's paper, "Simultaneous Sending and Receiving," in August, 1919, PROCEEDINGS OF THE INSTITUTE OF RADIO ENGINEERS.

Mr. Pickard's uni-directional receivers at Otter Cliffs played a very large part in maintaining uninterrupted reception from Europe during the war, and he should be congratulated for his splendid contribution to radio communication.

Schenectady, New York,
November 15, 1919.

Greenleaf W. Pickard: Dr. Austin's Figure 9 indicates that he has been misinformed as to Otter Cliffs, as I was at this station during the latter half of August, 1918, and know from my own observation that such a circuit was not in use over this period.[1] Instead, the actual circuit then in use is shown in my recent paper,[2] this circuit having no such open-ended loop as is shown in Figure 9. I am also disappointed to find in this paper no actual comparison of all the various circuits under identical signal and static conditions, that is, side by side. Of course, I sympathize with Dr. Austin in the matter of the cumbersome Lakewood circuit, but I regret that in this instance Mahomet did not go to the mountain.

Dr. Austin agrees with me that a large portion of the static received on the north Atlantic coast comes from the southwest, and this fact suggests a possible connection between thunderstorms and static. A very popular theory of static causation is that its origin is in tropical, or at least southern lightning discharges, the waves resulting from these discharges being reflected back and forth between the earth and the Heaviside layer until they reach the receiving station. It must at once be admitted that this theory has a high degree of plausibility because of the circumstantial evidence in its favor. The seasonal variation in the number of thunderstorms in the United States, according to data collected by our Weather Bureau, may be fairly represented by the curve shown in Figure 1.

This curve shows a maximum in July, and a minimum in the winter months, and is certainly suggestive of static. Even when quantitatively considered, the resemblance is striking, as the ratio of maximum-to-minimum is about 300-to-1, which is also approximately true of static. There are occasional winter days with severe static, and it would be interesting to note these days, and compare them with Weather Bureau records of our southern states for the same days.

As thunderstorms are caused by upward convectional cur-

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[1] "Static Elimination by Directional Reception." Presented before The Institute of Radio Engineers, New York, November 5, 1919.

[2] Previous citation, Figure 25.

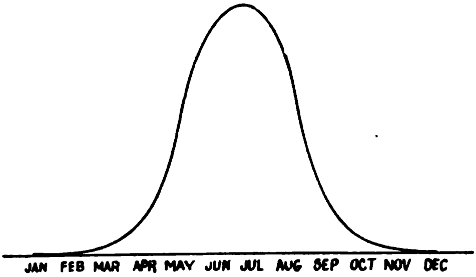

FIGURE 1—Seasonal Variation of Thunderstorms

rents in our atmosphere, they naturally exhibit a diurnal variation in frequency, reaching a maximum shortly after the lower air layers are most heated. Over land areas this will normally be in the afternoon, and we should expect the greatest number of thunderstorms to occur shortly after the greatest heat of the day. In Figure 2 is shown the diurnal variation of frequency of thunderstorms.

From midnight until about eight in the morning, the number of storms falls to a minimum. From then until about four in the afternoon, their frequency increases rapidly to a maximum, later falling off rapidly during the late afternoon and evening. This curve, also, is strongly suggestive of normal summer static,

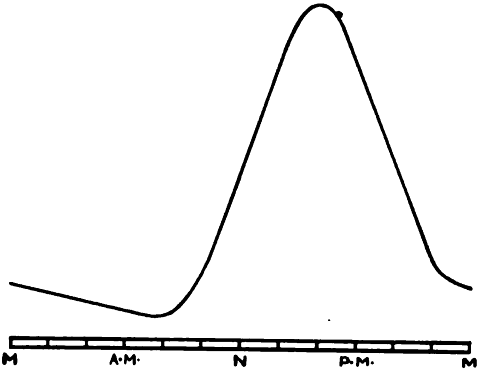

FIGURE 2—Diurnal Variation of Thunderstorms

altho I think the exceptions to the resemblance are more numerous here than with the seasonal curve of Figure 1. So far as trans-atlantic reception is concerned, the late afternoon decline in thunderstorms, if paralleled by static, would be more or less masked by the signal "fading" period. Still, the cumulative effect of these two figures is rather striking, and I do not think the average radio engineer or operator would have questioned these curves, if I had entitled them "Mean Seasonal and Diurnal Variation of Static."

I believe Mr. Marconi was the first to observe that static came from a definite direction. In 1906 he said:[3]

> When using horizontal receiving wires arranged as described in this note, I have often noticed that the natural electrical perturbations of the atmosphere or stray electric waves, which are generally prevalent during the summer, appear to proceed from certain definite directions which vary from time to time. Thus, on certain days, the receiving instruments when connected to wires which are oriented in such a way as to possess a maximum receptivity for electric waves coming from the south, will give strong indications of the presence of these natural electric waves, whilst on differently oriented wires the effects are at the same time weaker or imperceptible. On other days these natural electric waves may apparently come from other directions.
>
> It would be exceedingly interesting to investigate whether there exists any relation between the direction of origin of these waves and the known bearing or direction of distant terrestrial or celestial storms from whence these stray electric waves most probably originate. A considerable number of observations would be necessary to determine whether there exists any relation between the bearing of storm centers and the direction of origin of these natural electric waves. I propose to carry out some further investigations on the subject.

For the past thirteen years I have made directional determinations of static wave-fronts as received at points on the north Atlantic coast, and in general these measurements have indicated a southwestern origin, or, in the alternative, a corresponding plane of polarization for the static waves. During the discussion this evening, Mr. H. E. Campbell mentioned the interesting fact that directional determinations at Goat Island on the Pacific coast, gave a southeastern bearing for static. We are now in possession of cross-bearings, which apparently locate the static source somewhere in the vicinity of the Gulf of Mexico.

Figure 3 is a map of the United States, showing the distribution of thunderstorms during a ten-year period.

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[3] "On Methods whereby the Radiation of Electric Waves may be mainly Confined to Certain Directions, and whereby the Receptivity of a Receiver may be Restricted to Electric Waves Emanating from Certain Directions." Read before the Royal Society, March 22, 1906, and published in the "Proceedings," volume LXXVII, -A, pages 413-421. 1906.

There are here two maxima, one over the western coast of Florida, and the other in New Mexico. These two maxima lie southwest from our north Atlantic coast, and southeast from the Pacific, agreeably according to our static bearings.

Having now established at least a *prima facie* case for the connection between static and thunderstorms, we are warranted in examining the matter in greater detail. In the first place, my three previous figures in this discussion appear to rule out of consideration all thunderstorms outside of the United States. If, for example, we consider thunderstorms in Central and South America, it must be noted that as we travel toward the equator, the seasonal variation flattens out, and as we go south of the equator the curve reverses, for the simple reason that South America's summer is our winter, so that these storms cannot be held responsible for our static. In a similar manner, the diurnal variation, and also the cross-bearings I have mentioned above, appear to exclude European or Asiatic storms, because of the difference in longitude or time, as well as bearing. A glance at Figure 3 will show that our worst thunderstorm areas are spread over some two or three hours of longitude, and this should have the effect, so far as static is concerned, of broadening the diurnal maximum shown in Figure 2. Further, as these

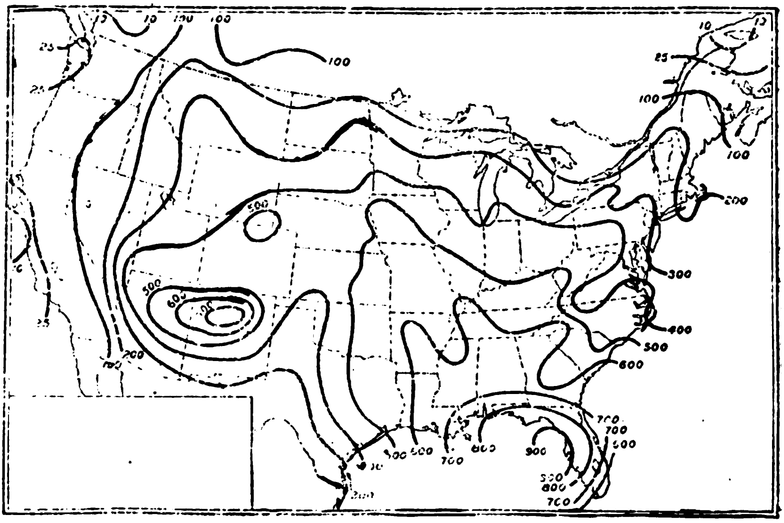

FIGURE 3—Total Number of Thunderstorms During the Ten-year Period, 1904-1913 (Alexander)

thunderstorm areas lie to our west, the effect should be to increase the static during the later afternoon and early evening, as compared with the curve of Figure 2.

Now, during a summer day with severe static, there may average some ten or more disturbances per second, some strong, and others weak, but all going to make up that disagreeable noise complex we call "grinders." Some idea of the number of these disturbances, as well as their varying amplitudes, may be obtained from Dr. Austin's Figure 10, on that portion of the record before my neutralizer system was connected This means from several hundred thousand to perhaps a million disturbances a day, and if each such disturbance is assumed to be due to a lightning discharge somewhere in the United States, the absurdity of the lightning theory is apparent, as a day with, say, half a million lightning strokes would be unique in the annals of meteorology.

Altho, for the reasons set forth above, I do not think that any considerable portion of static is directly due to distant lightning discharges, I am of the opinion that a thunderstorm may determine high level discharges, simply by reason of the disturbance created by its electrostatic field. It is not generally recognized that a thundercloud is not only a very highly charged body, but has a very appreciable electrostatic field many kilometers above itself, nor that thundercloud potentials, and the normal or fair weather potentials, are of entirely different orders of magnitude. My 1906 measurements[4] gave as an approximate thundercloud potential the rather large seeming value of two hundred million volts. C. T. R. Wilson's measurements[5] made by my method some ten years later, give even higher values.

For simplicity, I have first taken a spherical thundercloud, one kilometer (0.62 mile) in diameter and two kilometers (1.24 mile) above the surface of the earth, and charged to a potential of two hundred million volts.

In Figure 4 I have drawn the equipotentials around such a cloud, on the assumption that the conductivity of the atmosphere is negligible. It will be noted that the equipotential of one million volts against ground passes some twenty-odd kilometers (13 miles) above the cloud. Of course no actual thundercloud is spherical, and probably most of them are much

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[4] "The Potential of Lightning," "Electrical World," September 8, 1906, page 491.

[5] "Some Determinations of the Sign and Magnitude of Electric Discharges in Lightning-flashes," "Royal Society Proceedings," 92, pages 555-574, September 1, 1916.

larger, but I have used this spherical cloud by way of introduction, and for the reason that it is much easier to compute the equipotentials than with irregular flat clouds. Coming now to something more nearly approaching actuality, Figure 5 shows a thundercloud in the form of a disc one kilometer (0.62 mile) thick, six kilometers (4 miles) in diameter, and two kilometers (1.24 mile) above the ground.

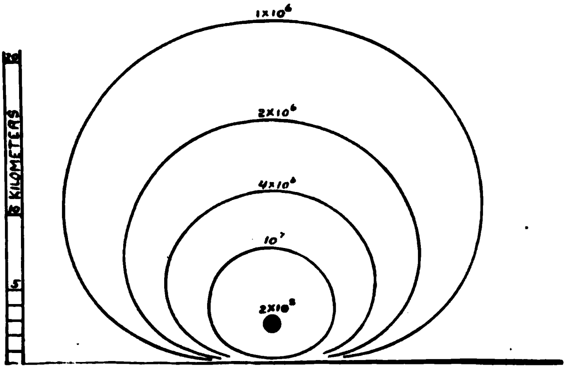

Figure 4—Equipotentials Around Thundercloud

With the charge on the cloud as before, the equipotential of one million volts passes over thirty kilometers (19 miles) above the cloud Actually, severe thunderstorms have cloud areas with mean diameters of over sixty kilometers (38 miles), and it is obvious that the electrostatic field over so extended a cloud area would be even more up-reaching. In fact, for very great heights above a cloud, that is, for distances which are large as compared with the radius and height of the cloud, the potential gradient, where R is the radius of the cloud in centimeters, V the potential of the cloud in volts, and X the distance above the cloud in centimeters, is given by the following simple formula:

$$R^2V/2\,X^3 \text{ volts per cm.}$$

Of course, it is futile to attempt to calculate these fields with any precision, as we have only an appromimate idea of the potential of the cloud. Further, atmospheric conductivity at the higher levels will modify, that is, flatten out, the upper portion of the field.

The normal or fair weather potential gradients in our atmosphere are quite low as compared with those around thunderclouds, and already have been explored up to about nine kilometers (5.6 miles).[6] A normal potential gradient near the ground is about one volt per centimeter, which decreases logarithmically to about one-thirtieth of a volt per centimeter at a level of nine kilometers (5.6 miles). The atmospheric conductivity, which is about 10^{-4} electrostatic units at the ground level, increases reciprocally with the decrease in potential gradient, at least up to nine kilometers (5.6 miles), and it may fairly be assumed that the entire potential acting across our atmosphere is only of the order of two or three hundred thousand volts. This potential is of course the one responsible for the normal downward electrical currents in our atmosphere, which under normal fair weather conditions are sensibly constant over large areas. It will be at once apparent that a thundercloud, with its enormous charge and field, will profoundly modify these normal conditions, and may bring about a state of affairs somewhat as in Figure 6.

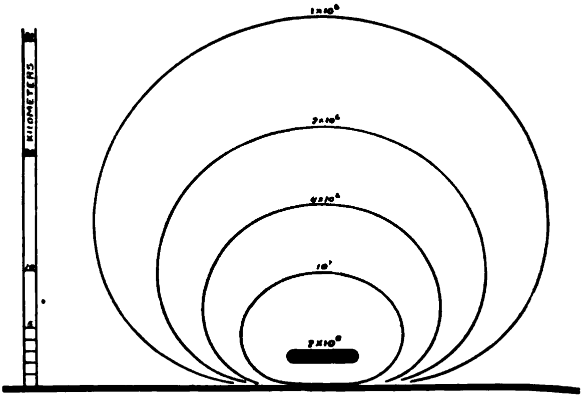

Figure 5—Equipotentials Around Thundercloud

At the left and right of this figure (which is not to scale) are the normal equipotential lines, shown dotted, with the normal or fair weather downward currents indicated by the vertical full lines at *A* and *C*. Over the thundercloud *T*, the equipotentials are crowded together, greatly increasing the potential gradient over the cloud, and as a result a much heavier downward current exists at *B*. This depletes the high level charge,

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[6] Wigand and Everling, "Deutsch. Phys. Gesell., Verh.," 16, 5, pages 232-244, March 15, 1914.

at an altitude perhaps fifty or a hundred kilometers (30 to 60 miles) over the cloud, lowering its potential with respect to the normal charge as above *A* and *C*, with the final result that equalizing lateral disharges, as at *D* and *E*, flow in to restore balance. It is my theory that these equalizing discharges are the origin of static, or at least that portion of the total static which is caused by the thundercloud. Of course, for a thundercloud at any considerable distance from the receiving station, the apparent bearing of the static will be that of the cloud itself, but for stations in the south, as at Florida and New Mexico, the bearing will be indeterminate in azimuth, and a considerable portion would apparently come from overhead.

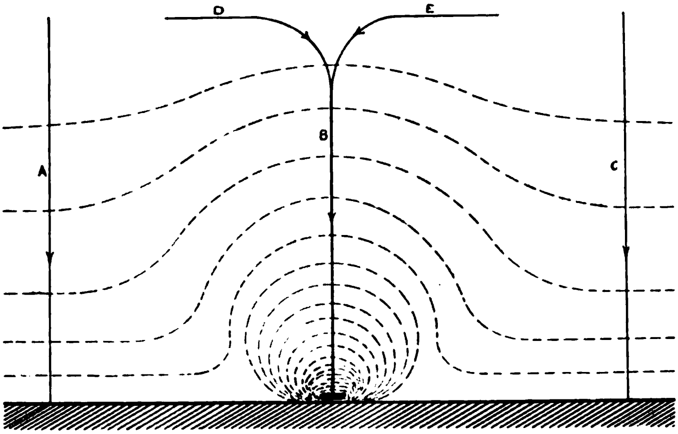

FIGURE 6—Equipotentials and Currents Above Thundercloud

In considering this theory, it may be well to bear in mind that a thunderstorm may be electrically a thunderstorm, even if there is neither cloud, rain nor lightning. Such "electric" storms, accompanied by dry and dusty winds, are observed in fine weather on our western plains, with every evidence of high electrification. Wire fences and other insulated metal objects give shocks when touched, and at night a corona or brush discharge—a St. Elmo's fire—appears at times on pointed objects. It is possible that during the entire thunderstorm season there is a practically constant high potential layer, a few kilometers (a mile or more) above the earth, distributed more or less uniformly over our southern states, and this may determine high level static. On the other hand, it is a rare summer day that does not see a thunderstorm somewhere on our Gulf coast, and one such storm might easily, according to my theory, account for that day's southwestern static.

Louis W. Austin (by letter): I am sorry if I was misinformed in regard to which of the circuits was used at Otter Cliffs during the latter half of August, 1918. I understood that the interwound loop was introduced late in July. The error is of less importance, however, since we know now that the two circuits in question as well as the simple antenna and loop combination all act in the same way, the main differences being in the convenience of adjustment.

It would of course have been more satisfactory to have had all the four systems compared under identical conditions, but the circumstances of war made many things inadvisable which would otherwise naturally have been done. As is pointed out in the paper, the conditions at Belmar, Lakewood, and Washington were considered to be very fairly comparable. Mr. Pickard's theory of the origin of static seems to be plausible tho it is perhaps difficult to understand how electrical disturbances can be produced without visible manifestations, of such magnitude that their waves are more powerful than those of the highest power stations, while a brilliant lightning flash hardly produces a disturbance twenty miles (32 km.) away.

H. H. Beverage: Dr. Austin's classification of the types of static appears to me to be very comprehensive. My experience has been that the first type or grinder type occurs most frequently in the afternoon during the summer months, and is easily balanced for European reception as it almost always comes from a southwesterly direction. I have experimented with very directional antennas, and find that an antenna directive towards the northeast receives very little grinder static, while an antenna directive towards the southwest receives very strong grinder static, often ten to forty times as strong as on a northeast directive antenna of the same dimensions. The second or hiss type static seldom interferes with reception because of its slow variation, which does not produce a disturbance in the radio circuits. The third or click type static does not interfere seriously because of its intermittent character. The click type can usually be traced to direct lightning discharges somewhere in the vicinity of the receiving station.

The fourth type, which sounds something like grinders, but "more crashing in character," is the most serious static remaining after balancing the grinders. The fourth type occurs occasionally in winter, and is particularly bad during the spring months. It shows practically no directivity and cannot be balanced to an appreciable extent by directive receivers, only in so far as the area of the intensity characteristic can be narrowed down towards the ideal form, the search light beam.

At times, there is some evidence that the static of the fourth type is more or less local like the click type static. On Long Island, for instance, during periods when the static of the fourth class was very strong, I have noticed that Belmar would ask for a repeat on a word which was received comparatively free from static on Long Island, while on the other hand, a word almost completely smothered with static on Long Island would be received easily at Belmar. At other times, the same word would be smothered with static at both places simultaneously. It is possible, of course, that static of the third and fourth types existed simultaneously and it was the third or click type that produced the local effects. It is difficult to distinguish between the last two types, as they both produce the same electrical effect except that the fourth type is much more continuous and frequent.

Another experience which may or may not have a bearing on the origin of static was observed in the spring of 1919 on the United States Steamship "George Washington." Radiophone tests were made two or three times daily between New Brunswick and the "George Washington." Two trips were made over and back, and in each case, reception on the "George Washington" was extremely poor in the vicinity of the western edge of the Gulf Stream because of weak signals and very strong static. The New Brunswick radiophone was usually received very well up to three or four hundred miles (500 to 650 km.) and was then practically lost for a distance of about 200 miles (300 km.) when the ship was near the western edge of the Gulf Stream. Beyond this point, New Brunswick radiophone was received again consistently, up to about a thousand miles (1,600 km.), and intermittently, clear to Brest harbor, depending upon atmospheric conditions. In at least one instance, when the static was very bad and the ship was in the Gulf Stream, Otter Cliffs reported no static. European signals were always received much better just outside of New York harbor than in the vicinity of the Gulf Stream. No conclusions can be drawn from so few observations, but this experience may have some bearing on the local nature of some types of static.

C. A. Hoxie: The statement in Dr. Austin's paper that the greater portion of the static disturbances come from the southwest brings to my mind several records I obtained by means of my photographic recorder during the latter part of last August.

At that time, I was not particularly interested as to what direction the major part of these disturbances came from, the main object being to get a record that would show definitely what difference, if any, would be caused by turning the loop, other things being kept the same.

In order to do this two similar galvanometers were installed in one recording instrument and each placed in a position so as to record separately on the same piece of tape as it moved slowly thru the machine, the point of exposure being exactly in line across the tape so it could be readily seen whether or not the recorded impulses were simultaneous. The tape traveled at about 3 inches (7.5 cm.) per second.

Two separate loops, each 15 feet (4.6 m.) square having 25 turns of wire spaced two inches (5.08 cm.) apart were used. The loops were mounted on platforms separated by about 40 feet (12.2 m.) and equipped with wheels so that they could be quickly and easily revolved horizontally to any desired position.

The receiving sets were located midway between the loops, each loop being connected with a receiving set and one of the galvanometers, each receiving set being carefully tuned to the same wave length, approximately 15,000 meters, and adjusted so that the amplification of each and the sensitivity of the galvanometers were practically the same. Three stages of amplification were used, one stage of the resistance type and a two-stage "SE-1,000" Navy type amplifier. Special care was taken to guard against any interference due to tube noises, and so on.

Under these conditions, several records were made and interesting results obtained.

As might be expected when both loops were in the same position, both records were the same. Examination of records of 1, 2, 3, and 4 will show this. Records 5, 6, 7, 8, and 9 show that impulses that affect one loop do not necessarily affect the other if placed at a different angle.

An inspection of 6, 7, and 8 brings out two interesting points. 1st:—Considerably more static was recorded from the loop located extending NE-SW than from the loop placed E and W. 2nd:—Quite strong impulses were recorded on each of the two loops that were not recorded on the other.

An inspection of record 9 shows that much more static was recorded on the loop placed NE-SW than the one placed NW-SE.

In order more definitely to determine whether the greater portion of static came from some general direction and also to get some idea of the relative strength, it was decided to use only one loop. This was done to eliminate the chance of the amplification of one set being larger, or the sensitivity of one galvanometer being more than the other.

The procedure was as follows. The loop was placed, say, in a north and south position and a half minute record made (approximately 5 feet (1.5 m.) of tape); it was then quickly moved to NE-SW position and another half minute record made, then to E and W, and lastly to SE-NW.

Several of these tests were made on different days and showed very conclusively that the static effect was greatest when the loop was in a NE-SW position and the least when in a NW-SE position. Also that the static effect was greater when the loop was turned east-and-west than when it was in a north-and-south position.

Special care was taken during each test that no change was made in tuning, amplification, or the galvanometer adjustment.

The vibrating reed of the recorder is not aperiodic, but is tuned to 2,000 cycles. It was adjusted so as to reach full amplitude with 3 cycles, requiring the same time to come to rest, so that an impulse of oscillation lasting 0.0015 second would give full amplitude coming to rest 0.0015 second later, the total elapsed time being only 0.003 second, and representing 0.01 inch (0.025 cm.) on the tape.

Keeping in mind the above statement that not more than 0.01 inch (0.025 cm.) in the tape is required for the building up and damping after the cessation of an impulse, it is evident that if any more space is taken up it must be due to the impulse persisting longer than the 0.0015 second necessary for reaching full amplitude; or if less space than 0.01 inch (0.025 cm.) is taken up on the tape, the duration of the impulse was evidently less than 0.0015 second.

Records 10, 11, 12, and 13 are the results of one test and show very nicely the relative values of static with the loop in each of the four positions.

Records 14, 15, 16, and 17 show results of one other of the numerous tests made.

Only a few records of the many made are shown here, but I believe they can be considered typical of the whole.

A. S. Blatterman: Some observations on the direction of static have been made by the Signal Corps. In 1918, observations made at the Radio Laboratories, Camp Alfred Vail, New Jersey, showed that there were certain periods when the direction of the disturbances was ill defined or even impossible to determine altogether. Most of the time, however, it was easy to swing a loop and find a marked direction, and when this was possible the direction indicated was always southwest-northeast. This agrees with statements made in the paper, and with observations of Mr. Hoxie and others who have just discussed the paper.

During the summer of 1919, I made some similar observations on the directivity of static, while in the Army, at El Paso, Texas. These observations were made on a five-foot (1.53 m.) square loop, with a non-oscillating receiver, on wave lengths from 400 to 1,000 meters. During a period of ten days, during which time the weather at El Paso was continuously clear, it was impossible to find any directional effect at all.

Since El Paso is right on the border between Texas and New Mexico, and therefore quite close to the southwest thunderstorm center described by Mr. Pickard, the above observations give support to his theory. A receiver located at the origin of the static would not be expected to show direction on these disturbances.

Bowden Washington: I am curious to know the fundamental reasons for attempting to balance ground wires, water wires, and so on, against loops. It is, of course, realized, that the signal-static ratio in these two devices will probably be different and there is the possibility of balancing out the static and having some signal left, but I cannot but feel that it is starting under a difficulty.

If the static is to be balanced out, the phase should be the same, or rather it will be preferable to have it the same so as to eliminate phase-changing devices. The damping of the two circuits should be similar so that the envelopes will be similar. It is, of course, realized that when trying to balance two dissimilar energy receiving systems, it is possible by varying the constants of the circuits and by changing some phase-shifting device finally to accomplish this result; but all systems which consist of an effort to balance two dissimilar energy collectors appear to be starting under a handicap. It will certainly seem less difficult to obtain a balance between two similar devices in which the damping, receptive ability, and so on, are equal in the first place and in which the phase of the desired wave is different.

I should like to make a few remarks on the method of comparison between these various devices. I realize that to a certain extent the Navy had to use such locations and materials as were available and that research work had to be made secondary to the handling of traffic. However, I cannot but believe that comparisons made between apparatus situated in widely different localities, over somewhat different distances of transmission and with different personnel are almost valueless. It can almost be said without exaggeration that the personnel factor alone must constitute the biggest variable. It seems to me that the one true test is when the various devices to be tested are in the same locality, at the same time, receiving from the same transmitter, and, if recorders cannot be used, that the personnel should be interchanged so frequently as to reduce this variable. The reason I am bringing this point out is that it has been my experience with the Navy Department that it frequently commits this error, that in making a test to determine the ratio between two dependent variables, they take very little account of what is going on with a dozen or more dependent variables all of which are inter-related.

For instance, the writer witnessed a "range test" of transmitters in which the transmitters were operated from two different craft on different days with different receiving antennas and different operators—in one case a mineral rectifier was used for reception, while in the other a three-electrode valve. A direct comparison was made between the ranges obtained during these two tests.

I cannot but feel that in an art as new as radio engineering, in which we do not know the relations between a great many variable factors, it is most important to make every effort to keep constant, or I might say, keep equal, every variable factor, except the one directly on test.

S. M. Kintner (by letter): Dr. Austin's extremely interesting paper gives facts that should serve to convince even the most skeptical that long distance radio communication has been demonstrated. How many of the ocean cables can show continuous operation for practically 99 per cent of the time? Yet that is the result indicated for radio by Dr. Austin as having been accomplished. None of those familiar with radio operations doubt for one instant the ability of radio to render such service; yet few, if any, of the cable interests are willing to make any admissions regarding the capabilities of radio as a competing means. This is perhaps not strange;—it is but human nature. None are so blind as those who have eyes but will not see. When we look back on other great developments that have paralleled existing means of accomplishing substantially the same results, we are impressed with the similarity of the reception accorded them by the existing means and that given the radio art by the cable interests. It is also a rather significant fact that these new arts were not developed by those already in the business, but by entirely new interests. For instance, the early electric light companies were not promoted by the gas companies. The electric street cars were not developed by the old horse car operators. The automobile taxi-cab companies were not started by horse-drawn cab owners. The telephone even was not considered of much commercial utility by the existing telegraph companies, when it was first introduced to the public.

It is not strange then that human nature should again display the same characteristics and cause those now operating cables to close their eyes to the possibilities and capabilities of the greatest competitor they have ever had and refuse to see the radio art in its true importance. It is to such people that Dr. Austin's paper should be most instructive.

In the second paragraph of the paper and in a footnote referring thereto, reference is made to the oscillating audion. It is rather unfortunate that this should not have been described as the heterodyne receiver. The oscillating audion *per se* is of value in accomplishing the result described only when operating in the heterodyne arrangement of which it is but one form.

The general data supplied is most opportune and of great interest to the radio art.

Frederick K. Vreeland: These questions concerning the origin and direction of propagation of strays that have been raised by Mr. Pickard and other members are very interesting, and I say by all means let us learn all we can about them. But in the last analysis, this knowledge will not give us the final answer to the problem of stray elimination.

The practical question that interests the radio engineer is not the origin of the strays, but what do they do when they strike our collecting circuit, and how can we prevent them from doing it.

Dr. Austin has mentioned the four generally-accepted classes of strays, describing them according to the sounds which they produce in the receiver. We can all recognize them by these sounds, but if we wish to handle them intelligently we must know, in addition, what kind of currents they produce in the collecting circuit. It may be well, therefore, to review briefly our knowledge of this subject.

Taking the simplest case first, the frying and sizzling disturbances accompanying rain or snow are static, properly so called, and are due to potential differences existing in the neighborhood of the receiver. If we put a direct current microammeter in the antenna circuit, it will show a deflection, sometimes positive, sometimes negative, and sometimes reversing. This current may sometimes reach a surprisingly large value, but it produces little effect on the detector since the detector responds only to the changes in the current. Since these changes are relatively slight and not very rapid, the disturbing effect on the receiver is small.

Strays caused by nearby lightning discharges, on the other hand, induce enormous surges in the antenna. When the lightning flash occurs the induced charge on the antenna is suddenly released, producing shock oscillations of great intensity. These oscillations may jump the safety gap, but they produce comparatively little interruption of the reception since they are of short duration and far between.

The class of "grinders" are as a rule noisy, but really not as bad as they sound. They consist in rapidly recurring impulses of relatively small amplitude but following each other in quick succession. While they are so noisy as to produce serious interference with the reception, they are not so difficult to eliminate as some other strays. It is just as easy to eliminate one hundred stray impulses per second as it is to eliminate one, tho the hundred make a far louder noise. This is why some stray-reducing systems appear to a superficial observer to produce an extraordinary effect in taking out the noise of these grinding strays while failing utterly to conquer the apparently inconspicuous but much more troublesome clicks and crashes. One does not need to use an apparatus six miles (10 km.) long to conquer these grinders. That can be done in a little box two feet (60 cm.) on the side that stands on the operating table.

The really vital problem of stray elimination, therefore, reduces to the question of handling the so-called clicks and crashes. These are characterized by their very sudden impulsive nature and short duration. They are either aperiodic or very strongly damped, and because of their extreme abruptness and transitory character, they have an extraordinary power of exciting shock oscillations.

The vital problem of stray elimination, therefore, reduces to the prevention of such shock oscillations or making them innocuous in affecting the receiver.

I think it must be obvious to us all that a directional system alone cannot give the final solution of the problem, for however effective it may be in eliminating strays coming from a given direction, there will always remain a residuum coming from other directions, and this is sufficient to cause serious disturbance.

A balancing system, such as those described by Dr. Austin, to be fully effective must balance the shock oscillations in the two collectors, not only in magnitude but also in phase, in frequency, and in decrement.

Obviously if the two effects are not of the same amplitude, they will not balance.

Clearly, also, if they are not in phase, they will not cancel each other.

If they have not the same frequency, there will be certain intervals when they will be out of phase and hence will not balance.

If they have not the same decrement, there will be certain intervals when they will have different amplitudes and so will not balance. To secure perfect coincidence in all these four respects is not easy, and requires more than the simple balanced circuits described in Dr. Austin's Paper.

There are, however, simpler means of doing away with the disturbing effects of these sharp impulsive strays. This is not the time nor the place to explain how it may be done. That is another story.

Louis W. Austin (by letter): Of course Mr. Vreeland is right in remarking that balanced systems cannot afford a complete solution of the static problem since frequently local non-directional static is capable of producing considerable trouble. Then, too, there are cases when directional static comes from more than one center at once, as recently observed in Porto Rico; but in general, at least along the Atlantic Coast of the Northern United States, the directive systems are very effective especially in reception from Europe.

I cannot agree with him in regard to static being always a pure shock phenomenon, as recent experiments which will be published later indicate that often static pulses do not appear simultaneously on the different wave lengths, showing that the static has definite wave lengths of its own forming probably in some cases a continuous spectrum.

Of course we shall all be delighted if Mr. Vreeland is able to furnish a simple device to be connected to any receiving system which will entirely solve the problem.

QUANTITATIVE EXPERIMENTS WITH COIL ANTENNAS IN RADIO TELEGRAPHY*

By

Louis W. Austin

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Washington, D.C.)

The use of large inductance coils for sending, receiving, and direction determination was first proposed by the late Professor Braun[1], who carried out experiments at Strassburg on signals from the Eiffel Tower, and gave the general theory of a coil used as an antenna.[2]

Received current measurements, such as the laboratory made some years ago for the verification of the theory of transmission between ordinary antennas, have now been made for closed coils. According to the theory, a rectangular vertical coil of N turns, height H, and length L, is equivalent to two vertical antennas of effective height NH at a distance apart L, with their respective currents in opposite phase. Taking into account the phase difference due to the difference in path, either in sending to a point p, or in receiving from p, the effect will be the same as that of one antenna of height NH multiplied by the phase difference $2\pi \frac{L}{\lambda} \cos\theta$, where θ is the angle between the plane of the coil and the direction of p.[3]

Now the expression for the received current in a receiving antenna, with an antenna sending sustained waves, is, disregarding absorption:[4]

$$I_r = 120\pi \frac{I_s h_s h_r}{\lambda d R} \qquad (1)$$

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† Dr. Dellinger, of the Bureau of Standards, has published coil formulas in practical units with slightly different constants in a confidential report for the Signal Corps, "Radio Transmission Formulas," July, 1917.

[1] F. Braun, "Jahrbuch d. Drahtlosen Telegraphie," 8, pages 1 and 132, 1914.

[2] Mr. Kolster, of the Bureau of Standards, has developed an excellent direction finder on this principle.

[3] Zenneck, "Wireless Telegraphy," 1915, page 234 and note 307, page 425.

[4] Zenneck, "Wireless Telegraphy," 1915, page 248, and "Bureau of Standards Bulletin," 11, page 70, 1914, Scientific paper 226

where I_s is the sending antenna current, h_s the effective height of the sending antenna, h_r that of the receiving antenna, λ the wave length, d the distance, and R the receiving antenna resistance, expressed in amperes, ohms, and meters. Now if either or both of the antennas is replaced by a coil, we must replace its height by $NH \cdot 2\pi\frac{L}{\lambda}\cos\theta$ where NH is the height of the coil times the number of turns, and we find for a

Coil Sending and Antenna Receiving

$$I_r = 120\pi \cdot \frac{I_s N_s H_s}{\lambda d} \cdot 2\pi\frac{L_s}{\lambda}\cos\theta_s \cdot \frac{h_r}{R}$$

$$= 2369 \cdot \frac{I_s N_s H_s L_s h_r}{\lambda^2 d R} \cdot \cos\theta_s \qquad (2)$$

In the same way for an

Antenna Sending and Coil Receiving

$$I_r = 2369 \cdot \frac{I_s h_s N_r H_r L_r}{\lambda^2 d R}\cos\theta_r \qquad (3)$$

and for

Coil Sending and Coil Receiving

$$I_r = 14880 \cdot \frac{I_s N_s H_s L_s N_r H_r L_r}{\lambda^3 d R} \cdot \cos\theta_s \cos\theta_r. \qquad (4)$$

The effective height h of an ordinary antenna equivalent to any coil NH may be expressed if $\theta = 0$, by

$$h = 2\pi\frac{NHL}{\lambda} = 2\pi \cdot \frac{area \times turns}{\lambda} \qquad (5)$$

The equations show that, other things being equal, if an antenna be used, both for sending and receiving, the received current falls off as the wave length, while if one coil be used, it falls off as the square of the wave length, and with two coils as the cube of the wave length.

The value of the constant in the equation for a sending coil requires some consideration. The value given assumes that as the radiated field grounds itself, it takes the form of a field formed by the coil and its image as in the case of an antenna. This is probably true, at least for a coil the dimensions of which are large compared with its distance from the ground. In the case of reception, this question does not enter in.

Signals from Arlington have been measured at the laboratory on two coils. One was a crossed coil direction finder mounted on the roof of one of the buildings, having 56 closely wound turns, a height of 1.82 meters (5.97 ft.) and a length measured between the planes of the front and back vertical sections of 1.29 meters (4.23 ft.). The second coil, supported from masts, had 7 turns 80 cm. (2.62 ft.) apart and measured 21.6×24.4 meters (71×80 ft.), θ being 42°. The results are shown in Tables 1 and 2.

TABLE 1

Arlington Arc Received at Laboratory on Direction Finder.

λ meters	Received Current		Difference	%Difference
	amp. obs.	calc.		
6,000	$208.0 \cdot 10^{-6}$	$157.5 \cdot 10^{-6}$	50.5	24%
7,500	128.1	100.8	27.3	21%
10,000	67.5	56.7	10.8	16%
$I_s = 100$ amp.	$N = 56$		$L = 1.29$ m.	$\theta = 0°$
$h_s = 71$ m.	$H = 1.82$ m.		$R = 50$ ohms	$d = 7{,}800$ m.

TABLE 2

Arlington Arc Received at Laboratory on Large Coil.

λ meters	Received Current		Difference	%Difference
	amp. obs.	calc.		
4,000	$8.78 \cdot 10^{-3}$	$7.38 \cdot 10^{-3}$	1.40	16%
6,000	3.71	3.28	0.43	12%
7,500	2.26	2.10	0.16	7%
10,000	1.23	1.18	0.05	4%
$I_s = 100$ amp.	$N = 7$		$L = 24.4$ m.	$\theta = 42°$
$h_s = 71$ m.	$H = 21.6$ m.		$R = 50$ ohms	$d = 7{,}800$m.

Table 3 shows the current received on an antenna at Arlington from the large coil at the laboratory excited by a coupled bulb circuit. The received currents in all three cases were measured with shunted detectors and galvanometers,[5] calibrated and tested for proportionality between deflection and current squared in each experiment.

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[5] "Journal Wash. Acad.," 8, page 569, 1918.

TABLE 3

Large Coil at Laboratory Received on Antenna at Arlington.

λ meters	Received Current amp. obs.	Received Current amp. calc.	Difference	% Difference
2,800	$147.8 \cdot 10^{-6}$	$150.8 \cdot 10^{-6}$	-3.0	2%
4,890	50.5	49.5	$+1.0$	2%
$I_s = 1$ amp.	$N = 7$		$L = 24.4$ m.	$\theta = 42°$
$h_r = 71$ m.	$H = 21.6$ m.		$R = 50$ ohms.	$d = 7{,}800$ m.

In each of the tables, for the sake of comparison, the results are reduced to a common value of sending current and a common receiving resistance.

The observed values in Tables 1 and 2 are seen to be uniformly larger than the calculated. This is supposed to be due to an action of the coil as an antenna since an increase in the length of the leads increases this difference. The reason for the increased error at the shorter wave lengths is not yet clear.[6] The agreement of observed and calculated values in the case of the coil sending (Table 3) is all that could be desired. From this, sending from a coil and receiving on an antenna, seems to offer the most accurate method for determining antenna effective height.

Table 4 gives the effective heights of antennas which for sending or receiving are equivalent to coils of various area turns, calculated from Equation 5.

When I wrote this paper, I supposed that Messrs. R. A. Fessenden and G. W. Pickard used only single turn loops in their early experiments, but I have recently been informed that Professor Fessenden proposed multiple turn loops in his German patent number 225226, dated January 14, 1907, while Mr. Pickard demonstrated the use of a direction finder of this type to the Navy in the same year, and published his work in the "Electrical Review," June 15, 1907, and October 3, 1908. That these early experiments did not result in the general use of receiving coils was due entirely to the lack of sensitive re-

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[6] In experiments of this kind incorrect results may be obtained if observations are made too near the natural wave length of the coil, as in this case the current distribution is no longer uniform on account of the effect of the distributed capacity

ceiving apparatus at that time, while their present success is due to audion amplifiers, the introduction of which practically coincided with the appearance of Professor Braun's paper.

TABLE 4

Comparison of Coils and Antennas

λ (meters)	Equivalent Effective Antenna Height (meters)				
	10	20	30	40	50
	Coil-Area × Turns (meters)				
200	319	——	——	——	——
500	796	1,592	2,388	——	——
1,000	1,592	3,184	4,776	6,370	——
2,000	3,185	6,370	9,552	12,740	15,920
3,000	4,776	9,552	14,280	19,100	23,880
5,000	7,960	15,920	23,880	31,840	39,800
7,000	11,140	22,280	33,450	44,580	55,760
10,000	15,920	31,840	47,760	63,700	79,600
12,000	19,110	38,220	57,330	76,440	95,520
15,000	23,880	47,760	71,640	95,520	119,400
20,000	31,840	63,780	95,520	127,400	159,200

The observations in this paper have been taken for the most part by W. F. Grimes, Chief Electrician (Radio), assistant in the laboratory.

United States Naval Radio Laboratory,
Washington, D. C.
April, 1919

SUMMARY: After deriving formulas for received current in loop receivers or antennas (transmission being from other loops or antennas), these formulas are compared with a series of observations at various wave lengths. Good agreement is found with theory, and the residual discrepancy is partly explained.

DISCUSSION

J. H. Dellinger (by letter): The difference in the values of the constants of the transmission formulas as given by Austin and by me ("Bureau of Standards Scientific Paper," number 354) require a word of explanation, especially since the equations have been printed side by side in the "Radio Review," without comment.

The Austin antenna-to-antenna formula as given in his later papers, except for the attenuation term, is identical with the purely theoretical formula for the Hertzian oscillator, the ground being supposed to be a perfect conductor so that the antenna and its image form a hypothetical oscillator of a length equal to twice the height of the antenna to its center of capacity. My antenna-to-antenna formula is the theoretical formula for the Hertzian oscillator having its length the actual height of the antenna above the ground. In other words, Austin assumes a perfect image below the antenna and I assume no image. The truth is somewhere between the two.

There is no question that my formulas are the more nearly correct for any case where the radiating structure is away from the ground, as an airplane antenna of any type, or a condenser antenna (as described in my paper) or a coil antenna raised well off the ground.

For an antenna on very good conducting ground or on a ship in salt water there is probably a considerable image effect. In practice, on account of the partial effect of the earth conductivity, the presence of metal towers and so on, the image effect is partly lost, so that the equivalent oscillator is generally less than twice the antenna height. This is taken account of by Austin by defining h_s not as the actual but as the effective height of the antenna, that is, half the length of the oscillator which will produce the same radiated field as the antenna at a distance. It is found in many cases that the effective height is about half the total height and seldom approaches the full value. For the convenience of those using the formulas I have taken h as the full antenna height, since this is the simplest procedure and leads to results in agreement with experiment.

Dr. Austin agrees with me in the foregoing explanations.

George S. Davis (by letter): While it is true that the early experiments referred to by Dr. Austin did not immediately result in the general use of coil aerials, still I do not think that this was due entirely to the lack of sensitive receiving apparatus at that time but rather to the incredulity with which the announcement was received that one could determine by the use of a coil aerial the bearing or direction of the distant transmitter. I was in charge of the radio station at the Brooklyn Navy Yard during 1907 when this announcement was made and my recollection is that we treated it in much the same manner as we did announcements to the effect that someone had entirely overcome or eliminated static.

Of course, audion amplifiers have added materially to the utility of the coil aerial, but the fact remains that coil aerials are useful without audion amplifiers and could have been brought into universal use in 1907 had the announcement been given due credence or had Mr. Pickard at that time possessed the means to push it, or had the necessities later brought about by the war compelled the various governments, including our own, to adopt it for submarine detection and other purposes at that time.

Perhaps one of the most controlling factors contributing to the general use of the coil aerial was the absolute necessity of detecting the location of enemy transmitting stations at the front and on submarines, and to these necessities I think is due the general adoption of the coil aerial as much as to the audion amplifiers.

As distinguished from the necessities of the war, our problems and necessities in 1907 were altogether different and there were other problems remaining unsolved which at the time probably seemed more important to the "powers that be" than the problem of determining direction, altho in the light of what we know now, it is hard to understand why we in the United States Navy did not more vigorously follow up the results demonstrated to (then) Lieutenant Robison in 1907 by Mr. Pickard in the matter of coil aerials.

I also recall that during a visit to Brant Rock, Massachusetts, in 1910, Professor Fessenden was then conducting experiments which I understood were direction-finding experiments from his station at Plymouth, and he at that time urged upon Mr. Musgrave of the United Fruit Company the adoption of an antenna structure in the United Fruit Company's system of stations which would, as he explained, be directional both as to transmission and reception and would thus not only reduce interference but result in having to use less power for communication over a given distance. I do not recall whether the arrangement used by Professor Fessenden was that proposed in his

German patent mentioned by Dr. Austin, but, as this patent was first published in 1910 instead of January 14, 1907, as stated by Dr. Austin, it is possible that the arrangement used was that shown in the Fessenden patent. As I recall it, Fessenden was reported to have secured fairly good directional results in 1910, but here again the so-called direction-finding aerials did not come in general use, due not to any lack of sensitive receivers, but to the lack of demand for such aerials on the part of commercial interests in radio at this time and the apparent lack of necessity in Government service which was then perhaps the largest field for radio apparatus. Even after the Braun 1914 publication, when we had amplifiers, coil aerials did not come into immediate general use, due again to lack of demand, and it was not until 1915-16 when the absolute need for direction-finding stations was demonstrated through war operations that coil or direction-finding aerials were generally introduced. In fact, it seems that the English radio authorities did not give radio direction-finding aerials or apparatus much thought until after the battle with the Germans near the Falkland Islands, when it was generally reported that the Germans had located the English fleet through means of a radio direction-finding apparatus. In any event, it is notable that, after this fight, the adoption of radio direction-finding apparatus was more intensive than ever before.

In conclusion, it seems to me that, altho the audion amplifiers have contributed to the success of the coil aerials as demonstrated by Pickard in 1907, it was the necessities of war which brought them into general use, and pointed the way generally for their commercial adoption.

A DISCUSSION ON "ELECTRICAL OSCILLATIONS IN ANTENNAS AND INDUCTION COILS"* BY JOHN M. MILLER

By
August Hund
(University of California, Berkeley, California)

Dr. Miller's interesting paper[1] on "Electrical Oscillations in Antennas and Inductance Coils" in the June, 1919, Proceedings of The Institute of Radio Engineers is undoubtedly a paper of importance to the radio engineer, since there exists quite a confusion with respect to the proper determination of the various antenna constants and the different types for each constant. Altho this subject has been treated successfully in the earliest days of the art of radio engineering, changes have occurred with respect to the design of antennas and their excitation. Long horizontal antennas are now used more often and sometimes excited by means of sustained sinusoidal waves on account of the successful devolopment of suitable ferric and non-ferric radio sources.

Professor Morecroft's investigations[2] on an artificial antenna, operated at commercial frequencies, was therefore a timely contribution, since he demonstrated—in a most scholarly way—the distribution of the net impedance and confirmed the resonance current as well as the proper oscillation constant of an actual antenna by means of an artifical closed circuit.

The purpose of the following discussion is to give formulas for the calculation of the correct effective antenna constants for any coil-loading whatever for the condition of a long horizontal antenna excited by a sinusoidal radio frequency electromotive force if the electromagnetic field is under consideration. The results are compared with the formulas giving only the apparent effective constants. Such a comparison will then lead to a method by which the static constants as well as the correct effective antenna constants can be determined, and by which the effective coefficient of the loading inductance can be cal-

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*Received by the Editor, August 1, 1919.

[1] Volume 7, page 308 to page 311.

[2] "Some Experiments With Long Electrical Conductors," Proceedings of The Institute of Radio Engineers, December, 1917, volume 5, page 389 to page 411.

culated also. The deductions make use of the distributions indicated in the figure and the radio equation for the horizontal aerial.

The formulas for the correct antenna constants for the elecmagnetic point of view are

$$\left.\begin{aligned}
C_{e1}' &= \frac{8\lambda'}{\pi\lambda}\,\frac{\sin^2 90\frac{\lambda}{\lambda'}}{\pi\frac{\lambda}{\lambda'}+\sin 180\left(1-\frac{\lambda}{\lambda'}\right)}\,C_A = A_1 C_A \\
L_{e1}' &= \frac{\lambda'}{2\pi\lambda}\,\frac{\pi\frac{\lambda}{\lambda'}-\sin 180\left(1-\frac{\lambda}{\lambda'}\right)}{\sin^2 90\frac{\lambda}{\lambda'}}\,L_A = B_1 L_A \\
r_e' &= B_1\, r_A
\end{aligned}\right\} \quad (1)$$

while for the apparent effective constants they are

$$\left.\begin{aligned}
C_{e2}' &= \frac{2\lambda'}{\pi\lambda}\sin 90\frac{\lambda}{\lambda'}\,C_A = A_2 C_A \\
L_{e2}' &= \frac{2\lambda'}{\pi\lambda}\,\frac{\left(1-\cos 90\frac{\lambda}{\lambda'}\right)}{\sin 90\frac{\lambda}{\lambda'}}\,L_A = B_2 L_A
\end{aligned}\right\} \quad (2)$$

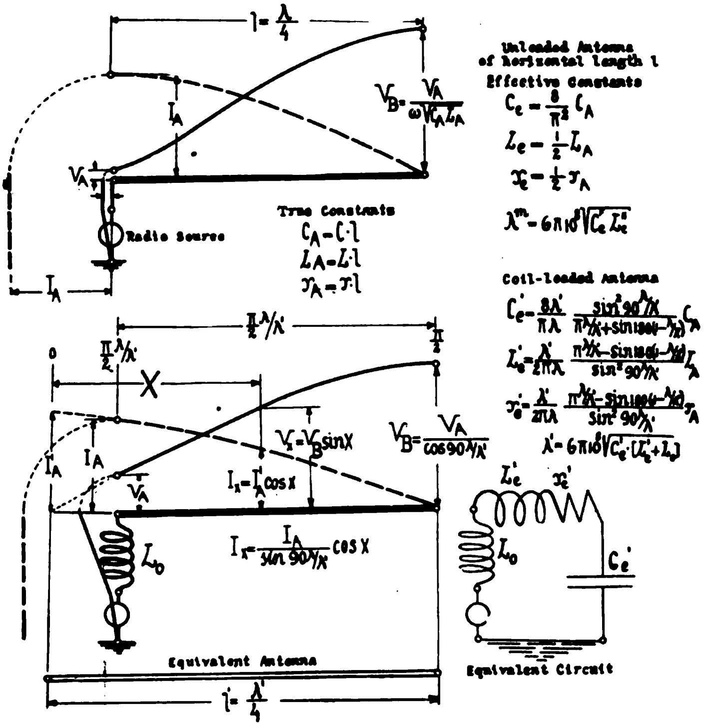
if λ and λ' denote the natural fundamental wave lengths for the unloaded and the coil-loaded antenna system, respectively. The quantities C_A, L_A, and r_A represent the static or true antenna constants for which the potential, as well as the current are, for all points of the horizontal length l, of unchanged amplitude and same phase. Any low frequency method will then give the values

$$C_A,$$
$$\frac{L_A}{3}$$
$$\frac{r_A}{3}$$

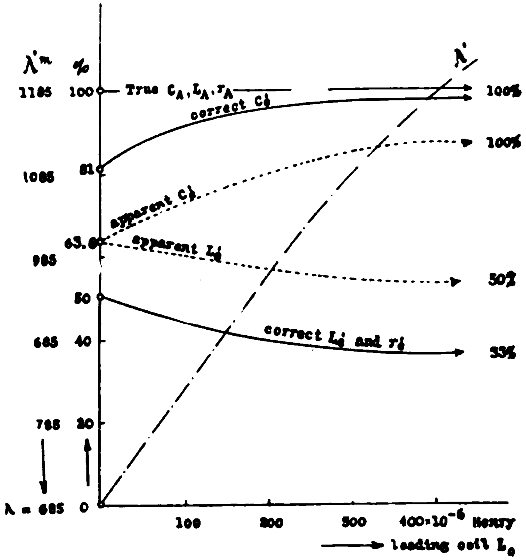
since then the effective antenna potential is practically constant along the aerial and the effective current decreases almost linearly to its zero value at the open end of the aerial.

The correct values, C_{e_1}', L_{e_1}' and r_e', for the effective capacity, inductance and resistance of the antenna will, for an inserted loading inductance L_o, confirm the oscillation constant

$$C_{e_1}'\left[L_{e_1}'+L_o\right]$$



$l = \frac{\lambda}{4}$
$V_B = \frac{V_A}{\omega\sqrt{C_A L_A}}$
I_A
V_A
Radio Source
True Constants
$C_A = C \cdot l$
$L_A = L \cdot l$
$r_A = r \cdot l$
Unloaded Antenna
of horizontal length l
Effective Constants
$C_e = \frac{8}{\pi^2} C_A$
$L_e = \frac{1}{2} L_A$
$r_e = \frac{1}{2} r_A$
$\lambda^m = 6\pi 10^8 \sqrt{C_e L_e}$
Coil-loaded Antenna
$C_e' = \frac{8\lambda'}{\pi\lambda} \frac{\sin^2 90\lambda/\lambda'}{\pi\lambda/\lambda' + \sin 180(\lambda/\lambda')} C_A$
$L_e' = \frac{\lambda'}{2\pi\lambda} \frac{\pi\lambda/\lambda' - \sin 180(\lambda/\lambda')}{\sin^2 90\lambda/\lambda'} L_A$
$r_e' = \frac{\lambda'}{2\pi\lambda} \frac{\pi\lambda/\lambda' - \sin 180(\lambda/\lambda')}{\sin^2 90\lambda/\lambda'} r_A$
$\lambda' = 6\pi 10^8 \sqrt{C_e' \cdot [L_e' + L_o]}$
$\frac{\pi}{2}\lambda/\lambda'$
0
$\frac{\pi}{2}\lambda/\lambda'$
$\frac{\pi}{2}$
X
$V_x = V_B \sin X$
$V_B = \frac{V_A}{\cos 90\lambda/\lambda'}$
I_A
I_A
V_A
$I_x = I_A' \cos X$
$I_x = \frac{I_A}{\sin 90\lambda/\lambda'} \cos X$
L_o
L_e'
r_e'
L_o
C_e'
Equivalent Antenna
Equivalent Circuit
$l' = \frac{\lambda'}{4}$



λ'^m
%
1185
1085
985
885
785
685
100
81
63.6
60
40
20
0
$\lambda = 685$
λ'
True C_A, L_A, r_A
100%
correct C_e'
100%
apparent C_e'
apparent L_e'
50%
correct L_e' and r_e'
33%
100
200
300
$400 \cdot 10^{-6}$ Henry
loading coil L_o

of the antenna as well as the surge impedance

$$\sqrt{\frac{L_{e_1}' + L_0}{C_{e_1}'}}$$

since the artificial antenna made up of these constants will produce the same resonance current for both damped and undamped sinusoids. That means, the correct effective constants will verify the generalized impedance

$$Z = r_e' + n\left[L_{e_1}' + L_0\right] + \frac{1}{C_{e_1}'} = 0$$

for the generalized angular velocity $n = a \pm j\,\omega$, since the constants are based on the derivations

$$\left.\begin{aligned}
C_{e_1}' &= \frac{\left[\displaystyle\int_{\frac{\pi}{2}\left(1-\frac{\lambda}{\lambda'}\right)}^{\frac{\pi}{2}} C \sin x \, dx\right]^2}{\displaystyle\int_{\frac{\pi}{2}\left(1-\frac{\lambda}{\lambda'}\right)}^{\frac{\pi}{2}} C \sin^2 x \, dx} \\
L_{e_1}' &= \int_{\frac{\pi}{2}\left(1-\frac{\lambda}{\lambda'}\right)}^{\frac{\pi}{2}} L \frac{\cos^2 x}{\sin^2 \frac{\pi}{2}\frac{\lambda}{\lambda'}} \, dx \\
r_e' &= \int_{\frac{\pi}{2}\left(1-\frac{\lambda}{\lambda'}\right)}^{\frac{\pi}{2}} r \frac{\cos^2 x}{\sin^2 \frac{\pi}{2}\frac{\lambda}{\lambda'}} \, dx
\end{aligned}\right\}$$

for which the integrations are to be taken over the effective electrical length $\frac{\pi}{2}\frac{\lambda}{\lambda'}$ corresponding to the actual line length l of the horizontal antenna.

The apparent effective values of formulas (2) confirm, however, only the proper oscillation constant, but generally not the surge impedance, altho a sinusoidal resonance current, flowing in the artificial antenna, would produce the correct effective value as measured at the interference point of the actual antenna, since for such an excitation the resonance current is practically determined by the effective resistance of the combination. The deductions for the apparent effective values are found by means of the derivations for the average values of the antenna potential and antenna current at a certain moment and the relations

$$\begin{pmatrix}\text{Electric Charge}\\ \text{on Antenna}\end{pmatrix} = (\text{Average Voltage}) \text{ times } (\text{Static Capacity})$$

$$\begin{pmatrix}\text{Magnetic Flux}\\ \text{about Antenna}\end{pmatrix} = (\text{Average Current}) \quad \text{times} \quad \begin{pmatrix}\text{Static In-}\\ \text{ductance}\end{pmatrix}$$

From the figure, it is evident that the correct effective antenna constants vary within the limits

$$\left.\begin{array}{r}C_{e_1}{}' = [81\% \text{ to } 100\%] \text{ static value}\\ L_{e_1}{}' = [50\% \text{ to } 33\%] \text{ static value}\\ r_e{}' = [50\% \text{ to } 33\%] \text{ static value}\end{array}\right\} \begin{array}{l}\text{from unloaded to}\\ \text{coil-loaded state}\end{array}$$

The limit for the unloaded condition confirms Dr. Miller's results, which are readily found from formulas (1) by equating λ' to λ.

The other limit is based on the fact that for a large loading inductance the effective potential varies but little along the antenna and the current decreases almost linearly towards the open end, for which distributions

$$C_{e_1}{}' = \frac{\left[\int_o^l C\,dx\right]^2}{\int_o^l C\,dx} = lC = C_A = \text{static value}$$

$$L_{e_1}{}' = \int_o^l L\left(1-\frac{x}{l}\right)^2 dx = \frac{1}{3}lL = \frac{1}{3}L_A = 0.33 \text{ static value}$$

$$r_e{}' = \int_o^l r\left(1-\frac{x}{l}\right)^2 dx = 0.33 \text{ static value}$$

If now the oscillation constants for the correct and apparent effective values are compared, one has

$$C_{e_1}{}'\,[L_{e_1}{}' + L_o] = C_{e_2}{}'\,[L_{e_2}{}' + L_o]$$

or

$$A_1 C_A\,[B_1 L_A + L_o] = A_2 C_A\,[B_2 L_A + L_o]$$

where

$$A_1 = \frac{8\lambda'}{\pi\lambda}\,\frac{\sin^2 90\frac{\lambda}{\lambda'}}{\pi\frac{\lambda}{\lambda'} + \sin 180\left[1-\frac{\lambda}{\lambda'}\right]}$$

$$B_1 = \frac{\lambda'}{2\pi\lambda}\,\frac{\pi\frac{\lambda}{\lambda'} - \sin 180\left[1-\frac{\lambda}{\lambda'}\right]}{\sin^2 90\frac{\lambda}{\lambda'}}$$

$$A_2 = \frac{2\lambda'}{\pi\lambda}\sin 90\frac{\lambda}{\lambda'}$$

$$B_2 = \frac{2\lambda'}{\pi\lambda}\,\frac{\left[1-\cos 90\frac{\lambda}{\lambda'}\right]}{\sin 90\frac{\lambda}{\lambda'}}$$

The static self-inductance L_A of the antenna can therefore be calculated from the formula

$$L_A{}^H = \frac{A_1 - A_2}{A_2 B_2 - A_1 B_1} \cdot L_o{}^H$$

If for the unloaded antenna $\lambda = 685$ m., and, for the same antenna with an inserted loading and inductance, $L_o = 0.000246$ henry, the resonance wave length $\lambda' = 1{,}015$ m., is measured, the correct effective constants become

$$\left.\begin{aligned} C_{e_1}{}' &= 0.967\, C_A \\ L_{e_1} &= 0.393 L_A \end{aligned}\right\} \quad \text{hence} \quad \left\{\begin{aligned} A_1 &= 0.967 \\ B_1 &= 0.393 \end{aligned}\right.$$

The apparent effective values lead to

$$\left.\begin{aligned} C_{e_2}{}' &= 0.826\, C_A \\ L_{e_2}{}' &= 0.56\, L_A \end{aligned}\right\} \quad \text{hence} \quad \left\{\begin{aligned} A_2 &= 0.826 \\ B_2 &= 0.56 \end{aligned}\right.$$

The static value of the inductance is then

$$L_A = \frac{0.967 - 0.826}{0.826 \times 0.56 - 0.967 \times 0.393}\, 0.000246 = 0.000413 \text{ henry}$$

The static line capacity can be calculated from the expression

$$C_A{}^F = \frac{\lambda^2}{144 \times 10^{16}\, L_A{}^H}$$

since for the unloaded antenna

$$\begin{aligned} \lambda &= 6\,\pi \times 10^8 \sqrt{C_e{}^F \cdot L_e{}^H} = 6\,\pi \times 10^8 \sqrt{\left[\frac{8}{\pi^2} C_A\right] \frac{L_A}{2}} \\ &= 12 \times 10^8 \sqrt{C_A\, L_A} \end{aligned}$$

where λ is expressed in meters.

Hence

$$C_A = \frac{685^2}{144 \times 10^{16} \times 413 \times 10^{-16}} = 0.00079 \text{ microfarad.}$$

The correct effective antenna constants are therefore

$$\begin{aligned} C_{e_1}{}' &= 0.967 \times 0.00079 = 0.000764 \text{ microfarad} \\ L_{e_1}{}' &= 0.393 \times 0.000413 = 0.0001625 \text{ henry} \end{aligned}$$

If these values are inserted in the Thomson formula

$$\begin{aligned} \lambda' &= 6\,\pi \times 10^8 \sqrt{C_{e1}{}' \left[L_{e1}{}' + L_o\right]} \\ &= 6 \times 10^8\, \pi \sqrt{\frac{0.764}{10^9} \left[0.0001625 + 0.000246\right]} \\ &= 1{,}050 \text{ m. approximately,} \end{aligned}$$

a value is obtained which differs about 3.35 per cent from the measured wave length, $\lambda' = 1{,}015$ m. This discrepancy is probably due to the fact that the inserted loading inductance has been calibrated with an audio current.

Moreover, according to the above considerations the effective loading self induction L_o can be calculated from the formula

$$L_o{}^H = \frac{A_2 B_2 - A_1 B_1}{A_1 - A_2} L_A{}^H$$

Applying this result, for instance, to one of Professor Morecroft's investigations, where the static inductance of the aerial is $L_A = 0.375$ henry, the fundamental frequency $f = 100.5$ cycles per second for the unloaded antenna, and $f' = 60.2$ cycles per second for the same antenna but for an inserted inductance at the ground side, gives

$$\frac{\lambda}{\lambda'} = \frac{f'}{f} = 0.599 \qquad A_1 = 0.982 \qquad A_2 = 0.860$$

$$B_1 = 0.377 \qquad B_2 = 0.5415$$

hence

$$L_o = \frac{0.860 \times 0.541 - 0.982 \times 0.377}{0.982 - 0.860} 0.375 = 0.295 \text{ henry},$$

which is in very close approximation the measured value $L_o = 0.292$ henry in Professor Morecroft's experiments.

SUMMARY: Formulas for the correct and the effective inductance, capacity, and resistance of an antenna are given. The relation of the values given to the corresponding static values is studied. The results obtained are shown to agree closely with the experimentally determined values for a coil-loaded antenna.

FURTHER DISCUSSION ON

"THE USE OF GROUND WIRES AT REMOTE CONTROL STATIONS"

BY

LIEUTENANT-COMMANDER A. HOYT TAYLOR AND LIEUTENANT A. CROSSLEY

Ellery W. Stone (by letter): The above paper and Mr. Taylor's preceding papers on the use of ground and water wires have been of great interest to me, particularly because of the account of the elimination of interference from local transmitters at control stations. In this connection, a description of the conditions which obtained at the Naval Radio Station at San Diego, Cal., during my tour of duty there as District Communication Superintendent, may prove of interest.

As at all naval district center stations, the San Diego station consisted of a receiving and control station and a transmitting station, separated from each other by some 15 miles (24 km.). The control station, at which were also located the administration offices, was situated on Point Loma, a bluff some 500 feet (150 m.) high, overlooking the ocean. The transmitting station was located at Chollas Heights, some distance inland, at about the same elevation. At the control station, three receiving circuits were in operation which controlled respectively a high power arc (200 kw.), a low power arc (30 kw.), and a spark set (10 kw.). In addition, a fourth receiving circuit was in constant use for the interception of dispatches from German stations on both sides of the Atlantic. Altho considerable ingenuity was employed to eliminate the troublesome interference from our own transmitters as well as that from two other local military stations, Fort Rosecrans and the Naval Air Station, it was never found possible to eradicate it completely so long as elevated receiving antennas were employed.

Due to the success of Mr. Taylor's work at Great Lakes and other stations, experiments were carried on at the Naval Air Station on North Island, which is located in San Diego Bay, to see if the adoption of water wires would not eliminate this difficulty. The results, even at the start, were so gratifying that it was found possible to remove the control station to North Island, about five miles (8 km.) nearer our transmitters at Chollas Heights, and to obtain satisfactory, simultaneous operation of all circuits. It is a pleasure, therefore, to testify as to the value of Mr. Taylor's contribution to the advancement of the art.

In his first and third papers, Mr. Taylor accounts for the operation of the buried antennas in the induction of potentials within the wire by the horizontal component of the tilted electrostatic wave front. This does not explain the operation of the submarine antenna, however, for the wave front is perpendicular to the equatorial plane when passing over sea water *and has a zero horizontal component.* Since the most satisfactory operation of the buried antenna was always obtained when it was surrounded with a medium of good conductivity, such as moist soil or water (fresh or salt), in which case there would be very little tilting of the wave front—if any, it appears desirable to suggest a different explanation for the action of antennas of this type.

According to the usually accepted theory of wave propagation, the electrostatic strains from the transmitting antenna to earth become detached at the quarter wave length point and move over the surface of the earth, the static potentials at the earth's surface causing currents to flow in the ground which are accompanied by a magnetic field at right angles to the vertical static lines of force and to the horizontal earth currents.

It must be understood that in the consideration of the phenomenon of wave propagation it is not correct to differentiate between the three forces involved, that is, static, kinetic (conductive), and magnetic, to the extent of saying that the actual *propagation* depends upon either one or two to the exclusion of the remainder. On the contrary, all three are involved, and in the case of reception by the elevated, grounded antenna, all three are used.

With the buried antenna, however, despite the *presence* of the three forces of propagation, the shielding effect of the conductive layer above the wire eliminates any action of the electrostatic space strains, and as a result we appear to make use only of the earth currents and their accompanying electromagnetic field. We may consider that potentials are induced in the antenna wire by the magnetic field surrounding the earth currents and by electrostatic induction from the earth currents. This static induction takes place by virtue of the insulation between the two circuits, the earth and the wire, and is not to be confused with the static space strains above the earth's surface. The latter are made use of in reception by the loop antenna but not with buried wires. Since the earth currents are greatest in media of high conductivity, there will be a maximum magnetic and static induction of potentials with consequent greatest signal strength.

The explanation advanced above is of course not counter to Mr. Taylor's explanations concerning the shielding effect against strays and so on.

San Francisco, California,
July 12, 1920.

ELECTROSTATICALLY COUPLED CIRCUITS*

By

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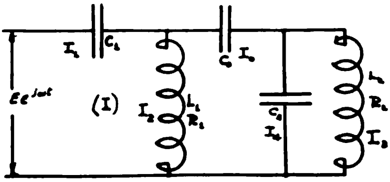
In radio frequency current work, coupled circuits in one form or another are generally employed; coupling between circuits may be either magnetic, direct, electrostatic, or any combination of the above types of coupling.

The magnetic type of coupling has been discussed extensively by a number of authors, and some attention has also been given to the theory of direct coupling, but very little consideration, if any, has been given to the subject of electrostatic coupling.

It is the purpose of this paper to discuss briefly the theory of electrostatic coupling from the point of view of energy transfer and sharpness of tuning, and compare results with these obtained in magnetic coupled circuits.

Electrostatic coupling is commonly understood to mean the electrical linking of two independent circuits by means of a condenser as shown in the diagram, and the term is used here in this sense. In the figures, C_1, L_1, and C_2, L_2 constitute the primary and secondary circuits respectively and C_o the coupling condenser.

To begin with it is desirable to ascertain the oscillation frequency constant of the system, which can be most readily done by determining the frequency for which the reactance of the system vanishes.



Electrostatically Coupled Circuit

* Received by the Editor, July 15, 1919.

The reactance of C_2 and L_2 in parallel is,

$$\frac{1}{Z_2} = \frac{1}{L_2 j\omega} + C_2 j\omega = \frac{1 - L_2 C_2 \omega^2}{L_2 j\omega},$$

$$Z_2 = \frac{L_2 j\omega}{1 - L_2 C_2 \omega^2},$$

Adding the reactance of C_o in series, we have

$$Z' = Z_o + Z_2 = \frac{1}{C_o j\omega} + \frac{L_2 j\omega}{1 - L_2 C_2 \omega^2}$$

$$= \frac{1 - L_2 C_2 \omega^2 - L_2 C_o \omega^2}{C_o j\omega (1 - L_2 C_2 \omega^2)}$$

Adding the reactance L_1 in parallel,

$$\frac{1}{Z_1} = \frac{1}{L_1 j\omega} + \frac{1}{Z'} = \frac{1}{L_1 j\omega} + \frac{C_o j\omega (1 - L_2 C_2 \omega^2)}{1 - L_2 C_2 \omega^2 - L_2 C_o \omega^2}$$

$$= \frac{1 - L_2 C_2 \omega^2 - L_2 C_o \omega^2 - L_1 C_o \omega^2 (1 - L_2 C_2 \omega^2)}{L_1 j\omega (1 - L_2 C_2 \omega^2 - L_2 C_o \omega^2)}$$

and

$$Z_1 = \frac{L_1 j\omega (1 - L_2 C_2 \omega^2 - L_2 C_o \omega^2)}{1 - L_2 C_2 \omega^2 - L_2 C_o \omega^2 - L_1 C_o \omega^2 (1 - L_2 C_2 \omega^2)}$$

Adding the reactances of C_1 in series, we get the total reactance of the system,

$$Z_t = \frac{1}{C_1 j\omega} + \frac{L_1 j\omega (1 - L_2 C_2 \omega^2 - L_2 C_o \omega^2)}{1 - L_2 C_2 \omega^2 - L_2 C_o \omega^2 - L_1 C_o \omega^2 + L_1 L_2 C_o C_2 \omega^4}$$

$$Z_t = \frac{\begin{array}{c} 1 - L_2 C_2 \omega^2 - L_2 C_o \omega^2 - L_1 C_o \omega^2 + L_1 L_2 C_o C_2 \omega^4 - \\ L_1 C_1 \omega^2 + L_1 L_2 C_1 C_2 \omega^4 + L_1 L_2 C_1 C_o \omega^4 \end{array}}{C_1 j\omega (1 - L_2 C_2 \omega^2 - L_2 C_o \omega^2 - L_1 C_o \omega^2 + L_1 L_2 C_o C_2 \omega^4)}. \qquad (1)$$

Putting the numerator of equation (1) equal to zero and solving for ω, we get,

$$\omega^2 = \frac{\begin{array}{l} (L_2 C_2 + L_2 C_o + L_1 C_1 + L_1 C_o) \pm \\ \sqrt{(L_2 C_2 + L_2 C_o + L_1 C_1 + L_1 C_o)^2 - 4 L_1 L_2 (C_o C_2 + C_1 C_2 + C_1 C_o)} \end{array}}{2 L_1 L_2 (C_o C_2 + C_1 C_2 + C_1 C_o)}. \qquad (2)$$

When the circuits are syntonised, $L_1 C_1 = L_2 C_2$, the above equation reduces to,

$$\omega^2 = \frac{\left(2 + \frac{C_o}{C_1} + \frac{C_o}{C_2}\right) \pm \left(\frac{C_o}{C_1} + \frac{C_o}{C_2}\right)}{2LC\left(1 + \frac{C_o}{C_1} + \frac{C_o}{C_2}\right)}. \qquad (3)$$

The expression for ω^2 given by equation (3) gives the value of ω for which the reactance of the system is zero. There are two values of ω for the condition of vanishing reactances, and the system has accordingly two natural frequencies of oscillations which are as follows:

$$\left.\begin{aligned} f_1 &= \frac{1}{2\pi\sqrt{LC}}, \\ f_2 &= \frac{1}{2\pi\sqrt{LC\left(1+\frac{C_o}{C_1}+\frac{C_o}{C_2}\right)}}. \end{aligned}\right\} \qquad (4)$$

It will be shown further on that even for tight coupling to get the maximum energy transfer to the secondary circuits, C_o is very small in comparison with C_1 or C_2, $\frac{C_o}{C}$ is of the order of $\frac{1}{200}$ or less, and the difference between the two frequencies is accordingly very small indeed for all degrees of coupling, so that for practical purposes the system may be considered as a single frequency system.

We shall now consider the current distribution in the circuits so as to determine the current amplitude in the secondary circuit and sharpness of tuning, and compare the results with those of a magnetic coupled system.

Refering to the diagram above, we have the following equations for the current distribution in the circuits:

$$\left.\begin{aligned} &\frac{1}{C_1 j\omega} I_1 + (L_1 j\omega + R_1) I_2 = E, \\ &\frac{1}{C_1 j\omega} I_1 + \frac{1}{C_o j\omega} I_o + (L_2 j\omega + R_2) I_3 = E, \\ &\frac{1}{C_1 j\omega} I_1 + \frac{1}{C_o j\omega} I_o + \frac{1}{C_2 j\omega} I_4 = E. \end{aligned}\right\} \qquad (5)$$

Also the supplementary relations,

$$\left.\begin{aligned} I_o &= I_3 + I_4, \\ I_1 &= I_2 + I_o = I_2 + I_3 + I_4. \end{aligned}\right\} \qquad (6)$$

Substituting the values of I_o and I_1 from (6) into (5), we get,

$$\left.\begin{aligned} &\left(\frac{1}{C_1 j\omega} + L_1 j\omega + R_1\right) I_2 + \frac{1}{C_1 j\omega} I_3 + \frac{1}{C_1 j\omega} I_4 = E, \\ &\frac{1}{C_1 j\omega} I_2 + \left(\frac{1}{C_1 j\omega} + \frac{1}{C_o j\omega} + L_2 j\omega + R_2\right) I_3 + \\ &\qquad\qquad\qquad \left(\frac{1}{C_1 j\omega} + \frac{1}{C_o j\omega}\right) I_4 = E, \\ &\frac{1}{C_1 j\omega} I_2 + \left(\frac{1}{C_1 j\omega} + \frac{1}{C_o j\omega}\right) I_3 + \left(\frac{1}{C_1 j\omega} + \right. \\ &\qquad\qquad\qquad \left. \frac{1}{C_o j\omega} + \frac{1}{C_2 j\omega}\right) I_4 = E. \end{aligned}\right\} \qquad (7)$$

Eliminating I_2 from equations (7), we get the following:

$$\left\{\frac{1}{C_1^2\omega^2}+\left(\frac{1}{C_1 j\omega}+L_1 j\omega+R_1\right)\left(\frac{1}{C_1 j\omega}+L_2 j\omega+R_2+\frac{1}{C_o j\omega}\right)\right\}I_3$$
$$+\left\{\frac{1}{C_1^2\omega^2}+\left(\frac{1}{C_1 j\omega}+\frac{1}{C_o j\omega}\right)\left(\frac{1}{C_1 j\omega}+L_1 j\omega+R_1\right)\right\}I_4$$
$$=E\,(L_1 j\omega+R_1)\,(L_2 j\omega+R_2)\;I_3-\frac{1}{C_2 j\omega}\,I_4=0 \qquad (8)$$

In the first equation of (8) we may, to a high degree of approximation, neglect the terms $\frac{1}{C_1 j\omega}+L_2 j\omega+R_2$ in comparison with the term $\frac{1}{C_o j\omega}$ in the factor of coefficient of I_3. The terms neglected are very small indeed in comparison with $\frac{1}{C_o j\omega}$ so no appreciable error is introduced thereby and the subsequent work is very much simplified by it. With the assumption indicated above, and multiplying thruout by $C_1 j\omega$ the first equation (8) takes the form,

$$\left\{-\frac{1}{C_1 j\omega}+\frac{1-L_1C_1\omega^2}{C_o j\omega}+R_1\frac{C_1}{C_o}\right\}I_3+\left\{-\frac{1}{C_1 j\omega}+\frac{1-L_1C_1\omega^2}{C_1 j\omega}+\right.$$
$$\left.\frac{1-L_1C_1\omega^2}{C_o j\omega}+R_1\frac{C_1}{C_o}\right\}I_4=E\,(-L_1C_1\omega^2+R_1C_1 j\omega) \qquad (9)$$

From the second equation of (8), we have

$$I_3=\frac{I_4}{-L_2C_2\omega^2+R_2C_2 j\omega} \qquad (10)$$

Introducing the value of I_3 from (10) into (9) and simplifying, we obtain the following:

$$\left\{\left(-\frac{1}{C_1 j\,\omega}+\frac{1-L_1 C_1 \omega^2}{C_o j\,\omega}+R_1\frac{C_1}{C_o}\right)(1-L_2 C_2 \omega^2+R_2 C_2 j\,\omega)+\frac{1-L_1 C_1\omega^2}{C_1 j\,\omega}(-L_2 C_2\omega^2+R_2 C_2 j\,\omega)\right\}I_4=$$
$$E\,(-L_1 C_1\omega^2+R_1 C_1 j\,\omega)\,(-L_2 C_2 j\,\omega+R_2 C_2 j\,\omega), \qquad (11)$$

and

$$I_4=\frac{E\left\{(-L_1 C_1\omega^2+R_1 C_1 j\,\omega)\,(-L_2 C_2\omega^2+R_2 C_2 j\,\omega)\right.}{\left(-\frac{1}{C_1 j\,\omega}+\frac{1-L_1 C_1\omega^2}{C_o j\,\omega}+R_1\frac{C_1}{C_o}\right)\left(1-L_2 C_2\omega^2+R_2 C_2 j\,\omega\right)+\frac{1-L_1 C_1\omega^2}{C_1 j\,\omega}(-L_2 C_2\omega^2+R_2 C_2 j\,\omega)} \qquad (12)$$

The current in the inductance coil of the secondary circuit is,

$$I_3=\frac{E\,(-L_1 C_1\omega^2+R_1 C_1 j\,\omega)}{\left(-\frac{1}{C_1 j\,\omega}+\frac{1-L_1 C_1\omega^2}{C_o j\,\omega}+R_1\frac{C_1}{C_o}\right)(1-L_2 C_2\omega^2+R_2 C_2 j\,\omega)+\frac{1-L_1 C_1\omega^2}{C_1 j\,\omega}(-L_2 C_2\omega^2+R_2 C_2 j\,\omega)}. \qquad (13)$$

For resonance condition, $L_1 C_1\omega^2=L_2 C_2\omega^2=1$, equations (12) and (13) reduce to,

$$\left.\begin{aligned} I_4&=\frac{E\,(-1+R_1 C_1 j\omega)\,(-1+R_2 C_2 j\omega)}{\left(-\frac{1}{C_1 j\,\omega}+R_1\frac{C_1}{C_o}\right)R_2 C_2 j\,\omega},\\ I_3&=\frac{E\,(-1+R_1 C_1 j\,\omega)}{\left(-\frac{1}{C_1 j\,\omega}+R_1\frac{C_1}{C_o}\right)R_2 C_2 j\,\omega}.\end{aligned}\right\} \qquad (14)$$

In practical radio circuits, $R_1 C_1 j\,\omega$ and $R_2 C_2 j\,\phi\,\omega$ are of the order of magnitude of 0.01 or 0.02, and hence may be neglected in comparison with unity, so we finally have for the currents in the secondary circuit at resonance condition,

$$\left.\begin{aligned} I_4 &= \frac{E}{R_1 R_2 \frac{C_1 C^2}{C_o} j\omega - R_2 \frac{C_2}{C_1}}, \\ I_3 &= \frac{-E}{R_1 R_2 \frac{C_1 C_2}{C_o} j\omega - R_2 \frac{C_2}{C_1}}. \end{aligned}\right\} \qquad (15)$$

The absolute values of the currents are,

$$\left.\begin{aligned} \bar{I}_4 &= \frac{E}{\sqrt{\left(R_1 R_2 \frac{C_1 C_2 \omega}{C_o}\right)^2 + \left(R_2 \frac{C_2}{C_1}\right)^2}}, \\ \bar{I}_3 &= \frac{-E}{\sqrt{\left(R_1 R_2 \frac{C_1 C_2 \omega}{C_o}\right)^2 + \left(R_2 \frac{C_2}{C_1}\right)^2}}. \end{aligned}\right\} \qquad (16)$$

MAGNETICALLY COUPLED CIRCUITS. For magnetic coupling we have the following well-known expression for the current in the secondary circuit:

$$I_2 = \frac{E M j\omega}{\left(L_1 j\omega + \frac{1}{C_1 j\omega} + R_1\right)\left(L_2 j\omega + \frac{1}{C_2 j\omega} + R_2\right) + M^2 \omega^2}. \qquad (17)$$

where M is the mutual inductance between the circuits and E is the amplitude of impressed emf. on primary circuit.
Equation (17) may be put in the following form:

$$I_2 = \frac{E M j\omega}{\left(\frac{1 - L_1 C_1 \omega^2}{C_1 j\omega} + R_1\right)\left(\frac{1 - L_2 C_2 \omega^2}{C_2 j\omega} + R_2\right) + M^2 \omega^2}. \qquad (18)$$

For resonance conditions, $L_1 C_1 \omega^2 = L_2 C_2 \omega^2 = 1$, equation (18) reduces to,

$$I_2 = \frac{E M j\omega}{R_1 R_2 + M^2 \omega^2}. \qquad (19)$$

The current in the secondary circuit is a maximum when $M^2 \omega^2 = R_1 R_2$, and in that case

$$I_2 = \frac{E}{2\sqrt{R_1 R_2}}. \qquad (20)$$

The relative merits of the two types of coupling, from the standpoint of secondary current and sharpness of tuning, can be best shown by a numerical example using the data of practical radio circuits and comparing results obtained by substituting in equations (16) and (20); and equations (13) and (18).

Example:

$R_1 = R_2 = 25$ ohms,
$C_1 = C_2 = 0.001$ microfarad,
$C_0 = 0.000005$ microfarad,
$\omega = 3 \times 10^5$.

By (16), resonance current, electrostatic coupling,

$$I = \frac{E}{\sqrt{(37.5)^2 + (25)^2}} = \frac{E}{45} \text{ approximately.}$$

By (20), resonance current, magnetic coupling,

$$I = \frac{E}{50}.$$

The current amplitudes are of the same order of magnitude in both cases.

SHARPNESS OF TUNING. The following table, giving the calculated values of the current by equations (13) and (18) for several frequencies on either side of the resonance frequency, shows that the static coupling gives a sharper resonance effect.

ω	I_3 By Equation (13)	I_2 By Equation (18)
$0.90 \times 3 \times 10^5$	$0.31 \times 10^{-4} E$	$0.45 \times 10^{-4} E$
$0.94 \times 3 \times 10^5$	$0.96 \times 10^{-4} E$	$1.40 \times 10^{-4} E$
$0.98 \times 3 \times 10^5$	$10.00 \times 10^{-4} E$	$12.00 \times 10^{-4} E$
$1.00 \times 3 \times 10^5$	$22.20 \times 10^{-4} E$	$20.00 \times 10^{-4} E$
$1.02 \times 3 \times 10^5$	$8.00 \times 10^{-4} E$	$14.60 \times 10^{-4} E$
$1.06 \times 3 \times 10^5$	$1.10 \times 10^{-4} E$	$1.86 \times 10^{-4} E$
$1.10 \times 3 \times 10^5$	$0.44 \times 10^{-4} E$	$0.68 \times 10^{-4} E$

SUMMARY: The expressions for the secondary frequencies secondary current, and secondary resonance current of electrostatically coupled circuits are derived theoretically. The system is shown to be practically monofrequent even for fairly close coupling between primary and secondary circuits.

The results obtained are compared with the corresponding expressions for inductive coupling. In a practical numerical example, it is found that the secondary resonance currents in the two cases are of the same order of magnitude but that the electrostatic coupling yields superior sharpness of resonance.

THE WAVE LENGTH RELATION FOR A GENERALIZED BESSEL'S ANTENNA*

By

A. Press

(Assistant Professor of Electrical Engineering, University of California, Berkeley, California)

In the December issue for 1918 of the Proceedings of The Institute of Radio Engineers the writer indicated how the problem of a vertical antenna should be treated, taking into account the variable distribution of both inductance and capitance per unit of length of the aerial. The subjoined paper goes into the matter more fully and a plot is given for undamped waves both of the voltage and current distributions for such an antenna. An antenna length (height) l is assumed, together with an impressed frequency f, such that for a wave length λ the following relation is assumed to hold:

$$\frac{\pi l}{\lambda} = 1.$$

It is then found that a voltage nodal point exists near the bottom of the antenna which corresponds to a current antinode. Thus, when adjustments are made along the coupling coil to obtain maximum current in the antenna wire,*this corresponds to a maximum potential with respect to neutral of the free end of the aerial In the analysis below no account is taken of resistance. Where radiation takes place, the voltage and current distributions will occur as before, but the voltage will be practically in time phase with the current. A true fixed antinode is, of course, a physical impossibility just as much so as in the vibration of a violin string.

Assuming that the antenna is $l = 100$ feet (30.5 m.) in height, then the entire horizontal scale $\left(\frac{x}{l}\right)$, Figure 2 corresponds to unity, for this height. If, then, at the top of the antenna a maximum potential of 100,000 volts with respect to neutral is assumed, this would mean from the curve that at 27.5 feet (8.4 m.) the voltage would be one-tenth of the maximum voltage. The nodal point, however, occurs at 20 feet (6 m.), so that for this adjustment maximum potential magnification will occur at the free end of the aerial. Correspondingly for this point the aerial current will be a maximum.

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* Received by the Editor, June 4, 1919.

A vertical antenna is assumed with negligible resistivity and leakage conductance, and then the differential equations to be solved are

$$L\frac{di}{dt} = -\frac{dv}{dx}$$

$$C\frac{dv}{dt} = -\frac{di}{dx}$$

where v and i are the voltage and current functions with respect to x and t. It has been shown by the writer (previous citation) that as a function of x up to 200 feet (61 m.) it is possible to write

$$L = a x^n$$

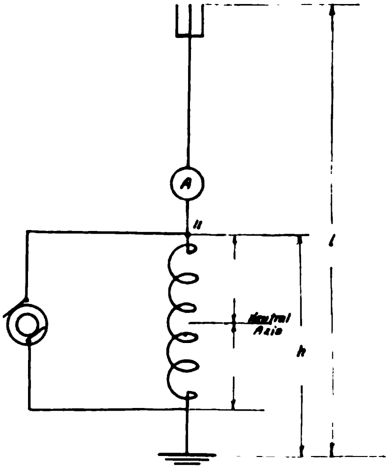

FIGURE 1

where $\quad a = 7 \times 10^{-9}; \; n = 0.13$

provided L is measured in henrys per centimeter. Moreover, it has also been shown that with the same degree of approximation

$$C = \beta x^{-n}$$

where if C is measured in farads per centimeter

$$\beta = 1.58 \times 10^{-12}$$

and n is as before.

Separating out the variables the following equations were deduced (previous citation):

$$\frac{d^2 i}{d x^2} + \frac{n}{x}\frac{d i}{d x} = q^2 i$$

$$\frac{d^2 v}{d x^2} - \frac{n}{x}\frac{d v}{d x} = q^2 v$$

with

$$q^2 = -\frac{1}{V^2}\frac{d^2}{d t^2}$$

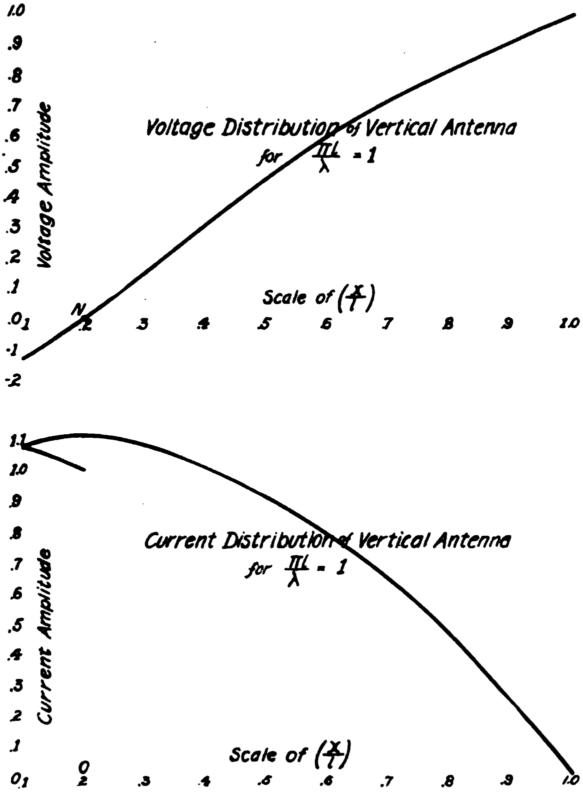

FIGURE 2.

and V is the velocity of light in centimeters. To meet the conditions of the problem the complete solution

$$i = A \cdot \frac{I_m(q x)}{x^m} + B \cdot \frac{I_{-m}(q x)}{x^m}$$

is to be investigated subject to the condition that

$$m=\tfrac{1}{2}\,(n-1)=\tfrac{1}{2}\,(0.13-1)=-0.435.$$

This will mean that all the x's of the term I_{-m} will have plus indices.

To satisfy the boundary conditions we note that at

$$x=l=\text{antenna height},$$

the current must be zero. Again, at $x=h$, where the exciting circuit is coupled to the antenna, the voltage to neutral is assumed to be

$$v_h=V/_{x=h}=E_h \sin pt.$$

Introducing the first condition we have

$$0=A\cdot I_m\,(ql)+B\cdot I_{-m}\,(ql)$$

$$B=-A\cdot\frac{I_m\,(ql)}{I_{-m}\,(ql)}.$$

For the voltage relation again, we must have

$$C\frac{dv}{dt}=-\frac{di}{dx}$$

However, for Bessel's Functions, we also have

$$\frac{d}{dx}\cdot\frac{I_m}{x^m}=q\cdot\frac{I_{m+1}}{x^m}$$

$$\frac{d}{dx}\cdot\frac{I_{-m}}{x^m}=q\cdot\frac{I_{-m-1}}{x^m}$$

(see Heaviside "Electromagnetic Theory," volume 2, page 245) and thus

$$C\frac{dv}{dt}=-A\,q\cdot\frac{I_{m+1}}{x^m}-B\,q\cdot\frac{I_{-m-1}}{x^m}$$

or again

$$v=\{I_m\,(q\,l)\cdot I_{-m-1}\,(q\,x)-I_{-m}\,(q\,l)\cdot I_{m+1}\,(q\,x)\}\,.\;x^{m+1}\cdot\frac{A\,q}{t_1\,\beta\,I_{-m}\,(q\,l)}.$$

This voltage equation must conform to the condition for $x=h$. However, it will be best to consider the maximum potential at $x=l$, and then

$$v_l=\{I_m\cdot I_{-m-1}-I_{-m}\cdot I_{m+1}\}_{ql}\cdot l^{m+1}\cdot\frac{A\,q}{t_1\,\beta\,I_{-m}\,(q\,l)}=E\sin pt$$

from which A/t_1 can be evaluated. Thus we have on substitution

$$v=\left\{\frac{I_m(ql)\cdot I_{-m-1}(qx)-I_{-m}(ql)\cdot I_{m+1}(qx)}{I_m(ql)\cdot I_{-m-1}(ql)-I_m(ql)\cdot I_{m+1}(ql)}\right\}\cdot\left(\frac{x}{l}\right)^{m+1}\quad E\sin pt$$

Similarly, for the current relation we also have

$$i=\left\{\frac{I_{-m}(ql)\cdot I_m(qx)-I_m(ql)\cdot I_{-m}(qx)}{\text{same denominator}}\right\}\frac{\beta}{(xl)^m}\cdot\frac{p}{ql}\quad E\cos pt$$

The denominator occurring in both the v and i functions can be very much simplified by means of the relation respecting conjugate functions given in Heaviside, "Electromagnetic Theory," volume 2, page 245. A text dealing with the "Symbolic Methods of Oliver Heaviside" is in course of preparation. Moreover, by introducing the P_{-m} functions deduced from the I_m functions by dividing out with the first term, the following simplified formulas result:

$$v=\left\{P_m(ql)\cdot P_{-m}(qx)-\left(\frac{\pi x}{\lambda}\right)^2\left(\frac{x}{l}\right)^m\cdot\frac{P_{-m}(ql)\cdot P_{m+1}(qx)}{m(m+1)}\right\}\cdot E\sin pt$$

$$i=\left\{P_m(ql)\cdot P_{-m}(qx)\left(\frac{l}{x}\right)^{2m}-P_{-m}(ql)\cdot P_m(qx)\right\}\frac{\beta p}{2m\,l^{2m}}\cdot E\cos pt$$

The last two formulas are especially calculable when the following general formula for P_m is used:

$$P_m(qx)=1+\frac{X}{1(m+1)}\left(1+\frac{X}{2(m+2)}\left(1+\frac{X}{3(m+3)}\left(1+\cdot\ \cdot\ \cdot\right.\right.\right.$$

where in our case

$$X^{\frac{1}{2}}=\frac{\pi x}{\lambda}j$$

The P_m functions, Figure 3, for $m=-0.435$ have been plotted. It should be noted that if for simplicity we take

$$\frac{\pi l}{\lambda}=1\quad\text{then}\quad\frac{x}{l}=\frac{\pi x}{\lambda}$$

and therefore only a single argument need be used for investigational purposes. The appended curves for v and i as functions of $\frac{x}{l}$ have been plotted by means of the above formulas.

It will be noticed from the graph that if we consider 80 per cent of the length of the antenna height as measuring $\frac{1}{4}$ of the wave length, then, since $\pi l = \lambda$,

$$4 \times 0.8l = 3.2l \quad \lambda.$$

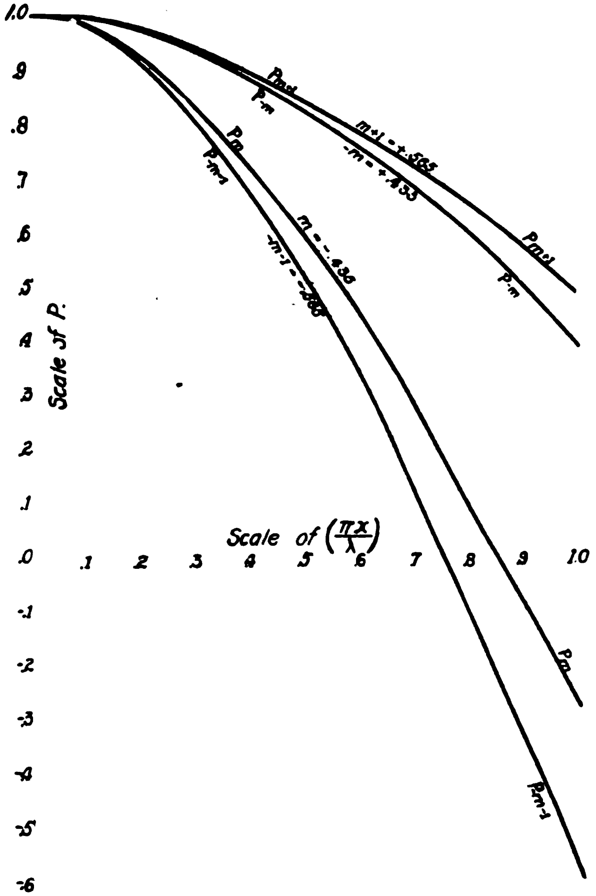

FIGURE 3

Thus, on this basis, the ordinary four times rule substantially holds, but reference should be had to measurements from the true nodal or resonant point along the antenna.

Berkeley, California,
May 29, 1919.

SUMMARY: The differential equations for an antenna of negligible resistance and leakage conductance are set up. Proceeding from previously deduced values of the inductance and capacity per centimeter along the antenna, the solution is obtained in terms of Bessel's Functions for the voltage and current distribution along the antenna. After simplification, the solution is interpreted, and curves enabling its ready employment are given.