TM 11-314

WAR DEPARTMENT TECHNICAL MANUAL

ANTENNAS AND ANTENNA SYSTEMS

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WAR DEPARTMENT • 30 NOVEMBER 1943

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(For explanation of symbols see FM 21–6.)

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SECTION I

WAVE PROPAGATION

1. PURPOSE OF MANUAL. The purpose of this manual is to provide all signal and communication personnel with a clear, workable reference on the types of antennas used in radio communication.

2. SCOPE.

a. This manual deals with various families of antennas commonly employed in radio communication, together with the fundamental theory underlying their operation. Examples used are often based on data obtained by observations made in the amateur bands of 1.75, 3.5, 7, 14, 28, 56, 112, and 224 megacycles, because of the wealth of data available at those frequencies. However, an antenna for any frequency between those indicated will follow the design of antenna for the band nearest in frequency to it.

b. Basic knowledge of radio fundamentals as outlined in TM 11–455 and other War Department publications is assumed.

3. RADIO WAVES.

a. General. The answers to many of the questions as to why this or that type of antenna is better than another are to be found in the nature of radio waves and the ways in which they travel. The behavior of waves of different frequencies gives the clue to the important points in antenna design, besides being an interesting subject in its own right. With a few fundamental facts in mind, much that on the surface is highly mysterious becomes susceptible to reasonable explanation; thus an elementary knowledge of wave propagation not only leads to a clearer idea of what to expect, but also may be the means of avoiding false conclusions.

b. Behavior of radio waves. Unlike transmitting or receiving apparatus, radio waves cannot be seen or touched. We know them only indirectly, by their effects. We know that they travel with the speed of light (300,000 kilometers, or 186,000 miles, per second in vacuum), that they are electromagnetic, and that they can be refracted and reflected.

4. ELECTRIC AND MAGNETIC FIELDS. The energy in a radio wave is divided equally between an electric field and a magnetic field. The electric lines of force and the corresponding magnetic lines are always at right angles to each other. Imagine, for instance, a latticework of horizontal and vertical strips; if the vertical strips are called the electric lines of force, the horizontal strips will represent the magnetic lines. The whole lattice, that is, the plane containing the set of crossed lines, would represent the *wave front*, and the direction of the wave travel is always perpendicular to the wave front.

5. INTENSITY OF WAVE. The intensity of the wave is usually expressed in microvolts per meter, which is a measure of the dielectric stress produced by the electric field, or the voltage induced in a conductor 1 meter long held at right angles to the magnetic field.

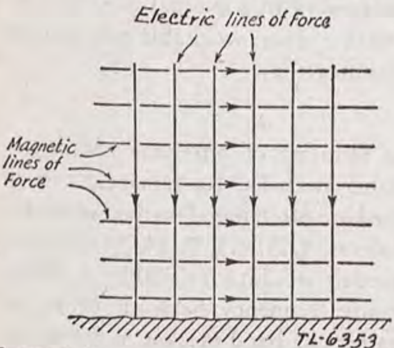

FIGURE 1. Representation of the magnetic and electric fields of a vertically polarized radio wave traveling along the ground. The arrows indicate the instantaneous directions of the fields for a wave traveling perpendicularly out of the page toward the reader.

6. POLARIZATION.

a. Direction of polarization.—The direction of the electric field, that is, that of the electric lines of force, is called the direction of the polarization of the wave. For instance, a wave with its electric field vertical is said to be vertically polarized, and one with its electric field horizontal is said to be horizontally polarized. A vertical antenna generates a vertically polarized wave, and a horizontal antenna generates a horizontally polarized wave.

b. Changes in polarization. Horizontally polarized waves are weakened more rapidly in traveling over the ground than are vertically polarized waves. Therefore, waves of low frequency traveling along the ground usually tend toward vertical polarization regardless of the orientation of the antenna. At high frequencies the polarization usually varies, sometimes quite rapidly, and often is circular or elliptical because the wave splits up into several components which follow different paths.

c. Antenna orientation. The energy taken from the wave by the receiving antenna will be greatest when the antenna orientation is the same as the direction of polarization of the arriving wave. Therefore, the orientation of the antenna is of considerable importance. However, at frequencies where sky-wave transmission is involved, the polarization of the received wave seldom bears any definite relation to the orientation of the transmitting antenna, because of the shift in polarization just mentioned in **b** above.

7. GROUND WAVES.

a. General. The waves radiated from an antenna may travel either along the surface of the ground, or in the atmosphere above the earth's surface. The ground wave is useful only for short distances at high frequencies, but the useful range increases as the frequency is lowered, until at the very low frequencies the ground wave may extend for hundreds of miles. This variation is due to the change in ground losses as the frequency is varied. Most field radio communication is carried on by means of the ground wave.

b. Polarization. A horizontally polarized wave traveling in contact with conducting ground falls off very rapidly as it progresses from the antenna, because the electric field is in effect short-circuited by the ground. On the other hand, the electric field of a vertically polarized wave, being perpendicular to the earth's surface, does not fall off nearly so rapidly. The ground acts like a conductor at frequencies up to about 5 megacycles, but more like a dielectric at higher frequencies.

8. SKY WAVES. The waves which travel above the earth's surface, or sky waves, are propagated in straight lines so long as the medium through which they are traveling is uniform. A wave leaving the earth's surface would never return, therefore, without some change in the medium capable of causing the wave to change its direction and be sent back to earth. Such a change in direction may be caused either by reflection or refraction. In reflection, the wave strikes a conducting medium which causes the energy to be reradiated in the same way that light waves striking a mirror are reflected. The more common process, refraction, is likewise similar to the refraction of light. That is, when the wave enters a medium which permits it to travel at higher velocity, the part which arrives first increases its speed, thus causing the wave front to bend back towards the earth.

The net result is quite the same as though the wave had been reflected instead of refracted, so that it is common to speak of a "reflected" wave even though the actual process is refraction. Obviously, there must be something in the upper atmosphere capable of reflecting or refracting radio waves; without it there could be no long distance high-frequency communication. This "something" is the ionosphere.

9. IONOSPHERE.

a. Ionization in upper atmosphere. Ultraviolet radiation from the sun striking the rarefied upper atmosphere causes ionization of the air particles, so that free electrons are present in the ionized region. The cloud of electrons is the refracting medium which causes radio waves to be bent back to the earth. The higher the degree of ionization, the greater the refracting power of the ionosphere. The air pressure, or density, also is a factor, since the greater the air pressure, the more of the wave energy is lost by absorption. Thus the higher the ionized layer, the more favorable the conditions for refraction.

b. Factors determining degree of refraction. The degree of refraction depends not only upon the density of the free electrons, that is, the ionization, but also upon the wavelength, or frequency, of the wave.

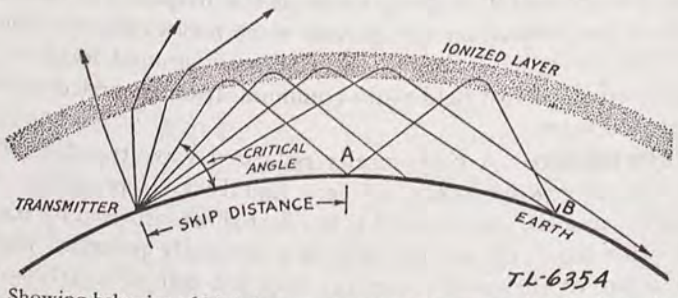

FIGURE 2. Showing behavior of high-frequency waves on encountering the ionosphere. (One wave is drawn showing the action of the wave front as it passes through the ionosphere.) Waves leaving the transmitter at angles above the critical are not bent enough to be returned to earth. A high-angle wave which returns at *A* may be reflected upward from the ground and rerefracted to appear at point *B* (two-hop transmission). Such a wave will often not be so strong at the receiving point as one which makes the journey from the transmitter to *B* in one hop.

The lower the frequency, the more easily the wave is bent. In general, the higher the frequency, the smaller is the bending, so that whether or not the wave returns to earth depends upon the angle at which it enters the ionosphere. Obviously, a wave which makes a very small angle with the ionosphere will not have to be bent so much as one which enters more nearly at right angles. Below a certain frequency, which depends on time of day, season, geographical location, etc., the waves may always be returned at whatever angle they enter the ionosphere.

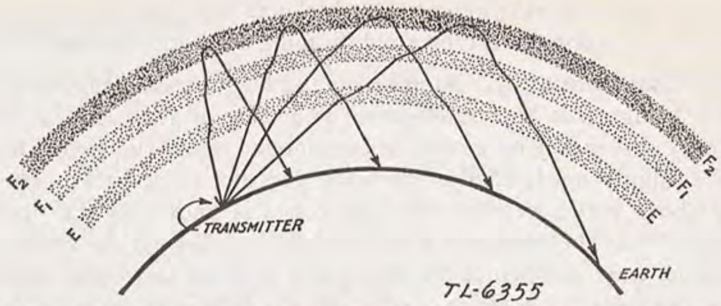

FIGURE 3. F_2 layer transmission at high frequencies (15 to 30 megacycles). The waves are partially bent in going through the two low erlayers, but not sufficiently to return to earth.

10. TRANSMISSION THROUGH IONOSPHERE.

a. The structure of the ionosphere is not simple, but for the purpose of illustrating in a general way the behavior of the sky wave, it will suffice to take as an example a single ionized layer such as that shown in figure 2. A sky wave of moderate frequency entering the layer will be bent back to earth, provided the angle which it makes with the ionosphere is small enough. As the angle at which the wave enters is increased, the wave returns to earth nearer the transmitting point, until a critical angle is reached at which the wave just manages to be bent back to earth. Waves entering at still higher angles will not be bent enough and therefore are useless for communication. Energy radiated at angles above the critical angle obviously is wasted because it passes through the ionosphere and is lost in outer space.

b. The critical angle varies with the frequency, becoming smaller as the frequency is raised until finally a frequency is reached at which the bending is too small even to return waves which enter the layer at the smallest possible angle. The frequency at which this occurs is not fixed, but depends upon the state of the ionosphere, a matter which will be discussed a little later.

11. LAYER HEIGHT AND CRITICAL FREQUENCIES.

a. Measuring height of ionosphere. By using a frequency low enough so that waves entering the ionosphere at the maximum angle, 90° (that is waves going vertically from the transmitting antenna to the ionosphere), are returned to earth, it is possible to measure the height of the ionosphere. This is done by measuring the time taken by the wave to go up and back, whence the distance readily can be calculated, since the speed of the waves is known, that is, the speed of light. The distance so found is called the "virtual height"; the *actual height* reached by the wave is somewhat less because a small amount of time is consumed in the turning around process. The ionosphere, however, is not like a flat mirror, but rather is a region having appreciable thickness with the ionization considered to be greatest at the center and thinning out both above and below.

b. Critical frequency. Suppose that as height measurements of this type are being made the transmitting frequency is gradually increased. Eventually a frequency range will be encountered where the virtual height increases rapidly until, finally, the wave does not come back. The frequency above which vertical reflection ceases is known as the "critical frequency." As the frequency is further increased beyond the critical frequency, the wave must enter the ionosphere at lower and lower angles in order to be refracted back to earth. At the lowest practicable angles, about 4° or 5° with the horizontal from the transmitting point, long-distance transmission is possible at frequencies up to as much as five times the critical frequency. The critical frequency is a measure of the ability of the ionosphere to return high-frequency waves to earth.

12. MULTIPLE LAYERS.

a. General. Measurement of critical frequencies has shown that there are several ionized layers in the ionosphere rather than only one. Thus there may be found a critical frequency at say 3,500 kilocycles for a layer of a certain height, but as the frequency is raised above 3,500 kilocycles new reflections from a higher layer will be found. This layer also shows a critical frequency and still higher frequencies may be reflected from a third layer at a greater height. The critical frequency of this layer marks the highest frequency at which overhead reflections can be obtained.

b. E layer. The various ionized regions or layers have been assigned identifying letters. The lowest is called the *E* layer. Its height is practically constant at about 70 miles. The density of the *E* layer varies considerably with the time of day, being greatest around noon and least at night. Thus the critical frequencies for the *E* layer are highest in the daytime and lowest at night. In the daytime, however, there is considerable absorption of energy from the wave in or below this layer, particularly on the lower frequencies, because of the relatively high air pressure in the lower part of the ionosphere.

c. F layer. The next higher layer is the *F* layer. The ionization decreases after sunset and usually reaches a minimum just before sunrise. Just after sunrise the *F* layer splits into two parts, the lower one being called the F_1 and the higher the F_2. These continue as separate layers throughout the day and merge into one, the *F*, just before sunset. The average heights for these layers are about 185 miles for the *F*, 140 to 160 miles for the F_1, and 150 to 250 miles for the F_2. The F_2 layer is the one principally responsible for returning the higher frequencies to earth at the greater distances in the daytime. At night the *F* layer is responsible for returning high-frequency waves to earth.

13. SKIP DISTANCE.

a. General. At frequencies above the critical frequency, the sky wave will not be returned to earth near the transmitter; even those waves which just manage to get refracted (that is, those just below the critical angle, will touch the surface at some considerable distance from the transmitter. The skip distance is the distance from the transmitter, in a given direction, to the point where a sky wave is first received. Sky waves "skip over" the intervening region, and hence no sky-wave signals can be heard.

b. Skip distance and frequency. The skip distance depends upon the frequency and the state of the ionosphere. In general, a larger distance will be skipped as the frequency is raised beyond the critical frequency. For a given frequency, the skip distance will depend upon the time of day, the season, and the phase of the sunspot cycle, as well as geographical location of the transmission path. There is, of course, no skip distance below the critical frequency of the F or F_2 layer since all sky waves of frequencies lower than this are reflected by the layer. However, if the frequency is too low or the power too little, their intensity will be too low to receive.

c. Region beyond skip zone. Beyond the skip zone the sky waves are returned to earth but get weaker and weaker with increasing distance, until finally beyond a certain distance called the "distance range," signals become unreadable.

14. MULTIPLE REFLECTION.

a. The waves which strike the earth's surface, after having been refracted by the ionosphere, will be reflected upwards again, especially those which do not arrive almost horizontally.

b. On reflection from the ground the waves again travel to the ionosphere, and if conditions are suitable, will be refracted once more and returned to earth a second time. This process, known as multiple reflection, may continue until the energy of the wave is completely absorbed. Most long-distance transmission is of this "multi-hop" type, since the height of even the F_2 layer is such that the greatest possible distance that can be covered in one hop, with a wave entering the ionosphere at the smallest angle, is usually only 2,500 miles. Because of energy loss on reflection from the ionosphere and ground, sky-wave radio transmission will in general be better the smaller the number of hops. Therefore, for long-distance transmissions, the wave should enter the ionosphere at a low angle so that a higher frequency can be used. Energy absorption in the ionosphere is less at the higher frequencies and so long-distance transmission is more readily possible on the higher frequencies.

c. It should be borne in mind that in multi-hop transmission the ionosphere conditions may vary greatly over the transmission path. In east-west transmission, for instance, the wave may start out in full daylight and complete its journey in darkness, or in north-south transmission may leave the transmitter in winter to arrive at a receiver in midsummer. These differences in time and seasons play an important part in determining the distance over which satisfactory transmission is possible.

15. FADING.

a. Causes. Since ionosphere conditions are not constant, it is to be expected that the refraction will not be perfectly uniform. Thus there is a gradual change in the transmission efficiency with the time of day. In addition, waves entering the ionosphere at different angles will be refracted differently, and a group of such waves may arrive at the receiving antenna at times in such phase as to aid each other, and at other times with phases which partially or wholly oppose. Also, the polarization of the incoming wave may shift while the receiving antenna polarization remains fixed. These effects cause the received signal strength to vary over a wide range, and this variation may be quite rapid, especially at the higher frequencies. In addition the transmission may be different for waves of slightly different frequencies, so that in the case of voice-modulated transmission involving side bands differing slightly from the carrier frequency, the carrier and various side-band components may not be transmitted in the same relative amplitudes and phases they had at the transmitter. This effect, known as "selective fading," causes distortion of the signal. There are also other causes of fading.

b. Overcoming effects of fading. Fading may be entirely different at two receiving points only a short distance apart. By using antennas separated a wavelength or two, to feed separate receivers the audio output of which can be combined, it is possible to take advantage of this effect to overcome the effects of fading. Separate antennas quite close together, but with different polarization, also will often work quite successfully. Such receiving arrangements are known as "diversity" systems.

16. VARIATIONS IN IONOSPHERE.

a. Periodic variations in radio transmission. Since the ionization of the layers depends upon ultraviolet radiation from the sun, the status of the ionosphere can be expected to follow changes in the sun's radiation as received in the upper atmosphere. Besides the daily variations already mentioned, there are three other types of regular variation. One such period occupies about 27 days, which is the period of the sun's rotation. There are also seasonal variations corresponding to the earth's revolution around the sun. Finally, there is a cyclic variation of about 11 years' period. This corresponds to the "sunspot cycle." Although it is not believed that sunspots directly affect radio transmission, there is a relation between sunspot activity and the quantity of ultraviolet radiation from the sun.

b. Effect of sunspot cycle. The effect of the sunspot cycle is to shift up or down the critical frequencies for all layers. At a sunspot minimum the critical frequencies are lowest, hence lower frequencies must be used for sky-wave communication. At this time, waves of 25 megacycles and above are only occasionally returned to earth by the regular layers. At a sunspot maximum, frequencies as high as 40 megacycles are often good for long-distance work in the daytime. For example, a typical service, assigned frequencies of about 18 and 8 megacycles for day and night use, respectively, has found for a limited period of days in midsummer at sunspot maximum that 18 megacycles can be used for 24-hour coverage. In contrast with this on the same service in midwinter at sunspot minimum, 24-hour coverage has been attained on 8 megacycles. The last sunspot maximum is considered to have occurred in 1937 and the next minimum is anticipated about 1944.

c. Seasonal variations. The yearly, or seasonal, variations are superimposed on the 11-year cycle. Higher frequencies can be used during the winter day than during the summer day, and during the summer night than during the winter night.

d. The 27-day cycle. Abnormal or disturbed radio conditions have shown a tendency to recur at about 27-day intervals. This corresponds to the rotation period of the sun. These disturbed radio conditions are particularly evident over communication paths which pass into or near the polar regions.

e. Diurnal variations. Diurnal variations, or variations with time of day, of distance ranges and useful frequencies, correspond to the diurnal variations in ionization of the ionosphere layers as explained in paragraph 12**b** and **c**.

17. VERY-HIGH-FREQUENCY PROPAGATION. The limiting frequency for regular long-distance transmission by means of the F_2 layer is usually not greater than 40 megacycles (see par. 16**b**). Frequencies above about 40 megacycles are unsuitable for regular communication over great distances, and their range is comparatively short. On these frequencies only ground wave communication is normally possible. The "surface wave" component of the ground wave, which owes its propagation chiefly to the electrical characteristics of the ground, becomes less and less important as the frequency is raised, and the "direct" and "ground reflected" wave components of the ground wave assume the predominant role at high frequencies. It should be noted that whereas the distance range of the ground wave at low frequencies can be increased effectively by increasing the radiated power, distance range at high frequencies can be increased effectively only by increasing the height of the transmitting and receiving antennas. Refraction and diffraction effects similar to those observed for visible light assume great importance at these higher frequencies. The lower frequencies in this range (30 to 60 megacycles) are frequently reflected at irregular and unpredictable times from dense clouds of electrons. These clouds constitute what is called "sporadic E layer" (see par. 20).

18. LINE-OF-SIGHT PROPAGATION.

a. Very-high-frequency transmission is somewhat comparable to the surface-wave transmission useful at low frequencies. However, at very high frequencies the surface wave is absorbed so rapidly as to be practically negligible at a short distance from the transmitter. If the transmitting location is visible from the receiver, the very-high-frequency signals can usually be transmitted reliably both day and night, with very little fading or other irregularities from atmospheric causes.

b. For very-high-frequency transmission, an extension of the transmitting range involves increasing the height of the transmitter or receiver, or both. It is possible, therefore, to obtain greater ranges with hilltop locations than between two low-lying points. The "shadow" effect of intervening hills or buildings is quite marked, when these interfere with the line of sight.

c. The distance to the horizon over level terrain (including normal refraction) is approximately

$$D=\sqrt{2h}$$

where h is the height in feet of the transmitting point and D the distance in miles. In case both the transmitting and receiving points are elevated, the line-of-sight distance will be the sum of the distances found by the formula for each location. This calculation assumes level ground between the two locations.

19. LOWER-ATMOSPHERE REFRACTION AND REFLECTION.

a. General. Radio waves are refracted and diffracted sufficiently to be returned to earth over a considerably longer distance than the line-of-sight or optical path. The actual bending is small, but takes place quite close to the ground (below 10,000 feet) in contrast with the height at which ionosphere refraction takes place. Refraction of this type is chiefly associated with changes in the dielectric constant of the atmosphere caused by the variation with height of the water vapor content of the air, together with associated variations in atmospheric temperature and density. Extraordinarily large reflections are caused by a "temperature inversion," that is, a layer of warm air over a lower lying cool layer. Under favorable atmospheric conditions, communication can be carried on at very high frequencies over distances of the order of a few hundred miles. However, such favorable atmospheric conditions are infrequent and unreliable, and regular communication by such means is not to be expected.

b. Fading. Very-high-frequency waves propagated in the lower atmosphere may show fading phenomena similar to those encountered at the lower frequencies.

20. SPORADIC "E" LAYER REFLECTION.

a. General. The sporadic "*E*" layer is not continuous, as in the case of the regular *E* layer, but probably consists of scattered patches or clouds of relatively dense ionization at a height approximately that of the *E* layer. The cause of this ionization is now known, but it has been found to be present nearly all the time. Occasionally, the ionization density rises to values which permit refraction of waves as high as 50 to 150 megacycles back to earth, and when this occurs, communication on this frequency over distances from about 500 to 1,400 miles is possible, provided a "cloud" or some portion of a cloud is situated about midway between the transmitter and receiver.

b. Frequency characteristic of sporadic E transmission. Sporadic *E* transmission differs from transmission through the lower atmosphere, not only in the distances which can be covered, but also in the frequency characteristic. The lower-atmosphere type of refraction is known to be effective for frequencies in excess of 100 megacycles whereas, sporadic *E* transmission very rarely occurs at frequencies as high as 100 megacycles. The presence of sporadic *E* reflections is indicated by abnormally short skip, a typical case being summer reception of 12-megacycle signals from a transmitter only 100 miles or so away, with strengths and qualities usually associated with short-distance ground-wave communication.

c. Seasonal variations. Sporadic *E* transmission in the continental United States and similar latitudes is usually most effective in the summer months, May through August, and is infrequently observed during the winter. In contrast with regular ionosphere transmission, there appears to be no definite relation between the occurrence of good conditions and the time of day, long-distance work having been carried on at mid-day as well as after midnight.

d. Two-hop transmission. Two-hop transmission by sporadic *E* layer at very high frequencies is relatively infrequent, since two patches of ionization are seldom favorably situated for permitting two reflections.

21. ANTENNA AND IONOSPHERE. From the above discussion of wave propagation, it is apparent that one of the functions of the antenna is to send a wave to the ionosphere in such a way that it will have the best chance of being returned to earth. Assuming that the wave will be reflected by the ionosphere, this is chiefly a matter of the angle at which the wave enters the layer, although in some cases polarization may be of importance. Furthermore, the desirable conditions may change considerably with frequency. In general, for ground-wave communication, vertical antennas are to be preferred since the ground wave is vertically polarized (see par. 6). For sky-wave communication at short distances, horizontal antennas are to be preferred since they can be made to radiate effectively at high angles.

The desirable vertical angle of radiation for waves of different frequencies can be summarized as follows:

a. 1.75 megacycles. Low-angle radiation is indicated for the longer distances. High-angle radiation may cause fading toward the limit of the ground-wave signal, because the downcoming waves add in random phase to the ground wave. Therefore, vertical antennas are to be preferred.

b. 3.5 megacycles. As at 1.75 megacycles, waves at all angles of radiation usually will be reflected, that is, there is no skip and so high-angle radiation can be used. It is true again, however, that long-distance coverage involves low-angle waves. Ground-wave coverage is in general also good at this frequency.

c. 7 megacycles. Under most daytime conditions, angles of radiation up to about 45° will be returned to earth; during the sunspot maximum, still higher angles are useful.

d. 14 megacycles. For long-distance transmission, most of the energy should be concentrated at angles below about 20°. This frequency is not generally useful for short distance sky-wave communication; 30° is about the maximum useful angle.

e. 28 megacycles. Angles of 10° or less are most useful. Polarization is not imporatnt so far as the ionosphere is concerned.

f. 56 megacycles. The lowest possible angle of radiation is most useful for all types of transmission. Vertical polarization has been used chiefly for ground-wave transmission, although horizontal polarization also is successful. In general, in ground-wave transmission the *same* polarization should be used at both transmitter and receiver. There is no evidence to favor any particular type of polarization, for the occasional sky-wave transmission by means of the sporadic *E* layer.

g. Higher frequencies. As in the case of 56-megacycle lower-atmosphere transmission, either horizontal or vertical polarization may be used, so long as the same type is employed at both ends of the circuit.

SECTION II

ANTENNA FUNDAMENTALS

22. STRENGTH OF FIELD SURROUNDING WIRE.

a. General. The strength of the field radiated from a section of wire carrying radio-frequency current depends upon the length of the wire and the value of the current flowing in it. For a given frequency and power input to the wire, the current will be highest when the reactance of the wire at the frequency of the r. f. current is zero, just as the current in a circuit consisting of a coil and condenser is highest when the net reactance of the circuit is zero—in other words, when the circuit is resonant.

b. Shortest resonant wire. The shortest length of wire which will resonate to a given frequency is one which is just long enough to permit an electric charge to travel from one end to the other and then back again in the time of one r. f. cycle. If the speed at which the charge travels is equal to the velocity of light, or 300,000,000 meters per second, the distance which it will cover in one cycle will be equal to this velocity divided by the frequency in cycles per second, or

$$\lambda = \frac{300,000,000}{f}$$

in which λ is the wavelength in meters. Since the charge traverses the wire twice, the length of wire needed to permit the charge to travel a distance λ in one cycle is $\lambda/2$, or one-half wavelength. Therefore the shortest *resonant* wire will be a half wavelength long.

c. Explanation of length of shortest resonant wire. The reason for this length can be made clear by a simple example. Imagine a trough with barriers at each end. If an elastic ball is started along the trough from one end, it will strike the far barrier, bounce back, travel along to the near barrier, bounce again, and continue until the energy imparted to it originally is all dissipated. If, however, whenever it returns to the near barrier it is given a new push just as it starts away, its back-and-forth motion can be kept up indefinitely. The impulses, however, must be *timed* properly; in other words, the rate or frequency of the impulses must be adjusted to the length of travel and the rate of travel. Or, if the timing of the impulses and the speed of the ball are fixed, the length of the trough must be adjusted to "fit." In the case of the antenna, the speed is constant, leaving the alternatives of adjusting the frequency to a given length of wire, or the length of wire to a given frequency. The latter is usually the practical condition.

d. Length of half-wave antenna. By changing the units in the equation just given, and dividing by 2, the more useful formula is obtained. In this case

$$l = \frac{492}{f\ (megacycles)}$$

l is the length *in feet* of a *half* wavelength for a frequency *f* given in megacycles, when the wave travels with the velocity of light. This formula is the basis upon which several significant lengths in antenna work are developed. It represents the length of a half wavelength in space, or when no factors which modify the speed of propagation exist.

23. CURRENT AND VOLTAGE DISTRIBUTION.

a. Dissipation of energy. If the wire in the first illustration had been infinitely long, the charge, or electric potential (voltage), and the current—an electric current is simply a charge in motion—would both decrease slowly with distance from the source. The slow decrease would result from dissipation of energy in the form of radio waves and in heating the wire because of its resistance. When the wire is short, however, the charge is reflected when it reaches the far end, just as the ball bounced back from the barrier.

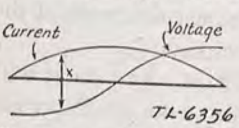

FIGURE 4. Current and voltage distribution on a half-wave wire. In this conventional representation the distance at any point (X, for instance) from the wire, represented by the heavy line, to the curve gives the relative intensity of current or voltage at that point.

b. Changes in current flow. With radio-frequency excitation of a half-wave antenna, there is, of course, not just a single charge but a continuous supply of energy, varying in voltage according to a sine-wave cycle. This might be considered as a series of charges, each of slightly different amplitude than the preceding one. When a charge reaches the end of the antenna and is reflected, the direction of current flow reverses, since the charge is now traveling in the opposite direction. However, the next charge is just reaching the end of the antenna, so there are two currents of practically the same amplitude flowing in opposite directions. The resultant current at the end of the antenna therefore is zero. As you move farther back from the end of the antenna the magnitudes of the outgoing and returning currents are no longer the same because the charges causing them have been supplied to the antenna at different parts of the r-f cycle. There is less cancelation, therefore, and a measurable current exists. The greatest difference, that is, the largest resultant current, will be found to exist a quarter wavelength away from the end of the antenna. As you move back still farther from this point the current will decrease until, a half wavelength away from the end of the antenna, it will reach zero again. Thus in a half-wave antenna the current is zero at the ends and maximum at the center.

c. Variance of voltage along wire. The voltage, or electrical potential, along the wire will behave differently; it is obviously greatest at the end since at this point there are two practically equal charges adding. As you move back along the wire, however, the outgoing and returning charges are not equal and their sum is smaller. At the quarter-wave point the returning charge is of equal magnitude but of opposite sign to the outgoing charge, since at this time the polarity of the voltage wave from the source has reversed (one-half cycle). The two voltages therefore cancel each other and the resultant voltage is zero. Beyond the quarter-wave point, away from the end of the wire, the voltage again increases, but this time with the opposite polarity.

d. Voltage and current inversely proportional. It will be observed, therefore, that the voltage is maximum at every point where the current is minimum, and vice versa. The polarity of the current or voltage reverses every half wavelength along the wire, but the reversals do not occur at the same points for both current and voltage; the respective reversals occur, in fact, at points a quarter wave apart. The distribution of current and voltage along the wire follows, for all practical purposes, a sine curve. The phenomenon of standing waves is easily observed by inserting an ammeter at various points along the wire to measure the current or by using a voltage-sensitive device such as a neon lamp to indicate the voltage maxima and minima.

e. Loop and node. A maximum point on a standing wave is called a loop (or antinode); a minimum point is called a node.

24. HARMONIC OPERATION. If there is reflection from the end of a wire, the number of standing waves on the wire will be equal to the length of the wire divided by a half wavelength. Thus, if the wire is two half waves long there will be two standing waves; if three half waves long, three standing waves, and so on. These longer wires, each multiples of a half wave in length, also will be resonant, therefore, to the same frequency as the single half-wave wire. When an antenna is two or more half waves in length at the operating frequency it is said to be harmonically resonant, or to operate at a harmonic, the number of the harmonic being the number of standing waves on the wire. For example, a wire two half waves long is said to be operating on its second harmonic; one which is three half waves long is on its third harmonic, and so on.

25. ELECTRICAL LENGTH.

a. Relation of electrical length to physical length. The electrical length of a linear circuit such as an antenna wire is not necessarily the same as its physical length in wavelengths or fractions of a wavelength. Rather, the electrical length is measured by the *time* taken for the completion of a specified phenomenon. For instance, imagine two linear circuits having such different characteristics that the speed at which a charge travels is not the same in both. Suppose you wish to make both circuits resonant to the same frequency, and for that purpose adjust the physical length of each until a charge started at one end travels to the far end, is reflected, and completes its return journey to the near end in exactly the time of one r. f. cycle. Then it will be found that the physical length of the circuit with the lower velocity of propagation is shorter than the *physical* length of the other. The *electric* lengths, however, are identical, each being a half wave.

b. Alternating circuits. In a-c circuits the instantaneous values of current or voltage are determined by the instant during the cycle at which the measurement is made (assuming, of course, that such a measurement could be made rapidly enough). If the current and voltage follow a sine curve, which is the usual case, the time, for any instantaneous value, can be specified in terms of an angle, the sine of which gives the instantaneous value when multiplied by the *peak* value of the current or voltage. A complete sine curve occupies the 360° of a circle, and represents one cycle of a-c current or voltage. Thus a half cycle is equal to 180°, a quarter cycle to 90°, and so on.

c. Linear circuits. It is often convenient to use this same form of representation for linear circuits. When the electrical length of such a circuit is such that a charge, *traveling in one direction*, takes the time of one cycle to traverse it, the length of the circuit is said to be 360°. This corresponds to one wavelength. On a wire a half wave in electrical length the charge completes a one-way journey in one-half cycle, and its length is said to be 180°. The angular method of measurement is quite useful for lengths which are not easily remembered fractions such as one-half and one-quarter wavelength, or multiples of such fractions.

26. VELOCITY OF PROPAGATION.

a. At radio frequencies. The speed or velocity at which electromagnetic waves travel through a medium depends upon the dielectric constant of the medium. At radio frequencies the dielectric constant of air is unity. For all practical purposes electromagnetic waves travel with the speed of light both through air and the vacuum of space, but are slowed down somewhat by other mediums of transmission such as wire, ionized layers, etc.

b. At dielectric constants greater than 1. If the dielectric constant is greater than 1, the velocity of propagation is lowered. Thus the introduction in appreciable quantity of insulating material which has a dielectric constant greater than 1 will cause a slowing down of the speed of the wave. This effect is frequently encountered in practice in connection with both antennas and transmission lines, and causes the electrical length of the line or antenna to be somewhat greater than the actual physical length.

27. LENGTH OF HALF-WAVE ANTENNA.

a. Method of calculating physical length. The electrostatic capacity at the ends of a half-wave antenna is higher than might be expected because of the presence of the insulators which support the antenna. For ordinary antenna systems this "end effect," for the reason described in paragraph 26, causes the physical length of the antenna to be about 5 percent less than the length of a half wave in space. The percentage varies slightly with different installations, but as a good average the length of a half-wave antenna may be taken to be

$$l\,(feet) = \frac{492 \times 0.95}{f\,(megacycles)}$$

or

$$l\,(feet) = \frac{468}{f\,(megacycles)}$$

This formula is sufficiently accurate, for all practical purposes, for finding the physical length of a half-wave antenna for a given frequency, but does not apply to antennas longer than a half wave in length.

b. Current and voltage in half-wave antenna. The current at the ends of the antenna does not quite reach zero because of the end effect, as there is some current flowing into the end capacity. Similarly, the voltage at the center does not pass through zero, but drops to some low, but finite, value at the point where the reversal in polarity takes place. This is because some energy is radiated from the antenna and because some energy is consumed by the resistance of the antenna; hence there must be some voltage present to force the current to flow.

28. ANTENNA RESISTANCE.

a. Power loss in antenna. The energy supplied to an antenna is dissipated in the form of radio waves and in heat losses in the wire and nearby dielectrics. The radiated energy is the useful part, but so far as the antenna is concerned it represents a loss just as much as the energy lost in heating the wire is a loss. In either case the dissipated power is equal to $I^2 R$; in the case of heat losses, the R is a real resistance, but in the case of radiation R is an assumed resistance, which, if it had actually been present, would have dissipated the same power that actually disappears by radiation. This fictitious resistance is called the radiation resistance. The total power loss in the antenna is therefore equal to $I^2 (R_o + R)$, where R_o is the radiation resistance and R the real resistance, or ohmic resistance.

b. Ohmic and radiation resistance. Since the current varies at different parts of the antenna, it is necessary to specify the point at which it is measured. The current, radiation resistance, and ohmic resistance are always measured at a current maximum, or loop, except when the antenna length is less than ½λ. For a half-wave antenna in free space, that is, entirely removed from any objects which might affect its operation, including the earth, the radiation resistance is equal to about 73 ohms. This value is modified by the presence of conductors or dielectric materials in the field of the antenna, and by the presence of the ground. The ohmic resistance depends upon the size of the conductor and the material of which it is made. The resistance of copper wire of size No. 14 or larger is quite small, at high frequencies, compared to the radiation resistance, so that most of the energy loss in a half-wave antenna is by radiation. Because of this, most of the energy supplied to a half-wave antenna is radiated in the form of electromagnetic waves. In other words, a half-wave antenna is generally a very efficient radiator.

29. ANTENNA IMPEDANCE.

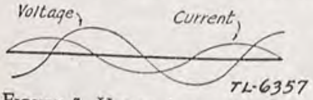

FIGURE 5. Harmonic operation of a long wire. The wire is long enough to contain several half waves. The current and voltage curves cross the heavy line representing the wire to indicate that there is a reversal in the direction of the current, and a reversal in the polarity of the voltage, at intervals of a half wavelength. The reversals of current and voltage do not coincide, but occur at points a quarter wavelength apart.

a. Effect of reactance on phase. The impedance of an electrical circuit is equal to the voltage divided by the current. If in an a-c circuit the voltage and current are in phase, that is, reach their positive maxima and negative maxima together, the impedance is resistive only. If reactance is present, however, the maxima of current and voltage do not coincide and the current and voltage are said to be out of phase. The difference in phase is measured by the fraction of a cycle separating corresponding points on the voltage and current waves, and, since this is a matter of time, can again be expressed in degrees.

b. Phase in half-wave antenna. In the half-wave antenna the current and voltage are approximately 90° out of phase, as already explained, except at the center where the standing wave of voltage is changing polarity. At this point the voltage and current are in phase, and the impedance is resistive only. At all other points along the antenna the impedance is largely reactive. As shown by figure 4, the voltage increases and the current decreases as you move away from the center of the antenna and, since impedance is equal to E/I, the impedance progressively increases, reaching equal maximum values at the ends.

c. Antenna in multiples of half-wave length. If the antenna is some multiple of a half wave in length, as in figure 5, the impedance reaches its lowest value (and is resistive) at each current loop, and its highest value at each voltage loop. The impedance thus goes through regular cycles just as do the standing waves of current and voltage.

d. Importance of impedance. The antenna impedance is important in connection with the methods of feeding power to the antenna, since the impedance at the point at which the power is introduced determines whether the power must be supplied at high voltage and low current, low voltage and high current, and so on.

30. RADIATION PATTERNS.

a. Infinitesimally small length of wire. The radiation from an infinitesimally small length of wire carrying a radio-frequency current is a maximum in the plane perpendicular to the wire and zero along its axis. It varies as the sine of the angle between the wire and a line from the wire through the point at which the radiation intensity is measured.

b. Wire of appreciable length. You can consider a wire of appreciable length to be made up of a chain of such elemental point radiators, and find that when this is the case the field strength is no longer distributed in the same way as for the elemental length. The waves radiated by the elemental lengths do not add in quite the same way in different directions with respect to the wire.

c. Complete radiation pattern. **(1)** The situation is much more complex when a wire consisting of a series of infinitesimally small radiators is considered, since it is necessary to take into account the effect of the radiation from each elementary length, which indicates not only an allowance for varying current values in different parts of the wire, but also phase differences. Formulas for relative intensity of radiation in any direction from wires of any length are available, however. The solutions of the formulas give the radiation pattern of the antenna considered. The complete radiation pattern is a solid figure in which the distance from the center to any point on the surface gives the relative intensity of radiation in that direction from the antenna, the antenna being the point at the center. The patterns differ greatly for antennas of different lengths.

(2) The solid pattern of radiation from any straight single wire in free space is always symmetrical with respect to the axis of the wire. Therefore, if the pattern is cut by any plane containing the wire axis the cross section of the pattern will always be the same. The outline of the section of the solid pattern on such a plane is the plane directive diagram. Such a diagram for a half-wave antenna is shown in figure 6. It is usually plotted on polar coordinate paper (paper with radial lines marking the 360° of angle in a circle, and with a linear scale of concentric circles for marking amplitudes). The plane directive diagram is very useful in antenna work, but it must be remembered that this type of diagram shows only two dimensions of a three-dimensional figure. The third dimension always must be specified in practical work.

(3) If a plane is passed through the doughnut-shaped solid pattern of a half-wave antenna at right angles to the axis of the wire, the cross section of the solid pattern will be a circle. In this plane, therefore, the radiation is of equal intensity in all directions.

(4) Although the actual antenna wire is represented in figure 6, it is important to keep in mind that in any directive diagram or radiation pattern the antenna is represented simply by a point at the center of the pattern. Every plane which is passed through the solid pattern to get a plane directive diagram must therefore pass through the center of the pattern.

d. Nulls and lobes. The points on the pattern where the radiation is zero are called "nulls," and the curved section from one null to the next on the plane diagram, or the corresponding section on the solid pattern, is called a "lobe."

31. RADIATION AND INDUCTION FIELDS.

a. Strength of inductive fields. In addition to the radiation fields already described, there are also magnetic and electric fields about an antenna which correspond to the ordinary magnetic field about a coil carrying current or between the plates of a charged condenser. In other words these induction fields result from the self-inductance and self-capacity of the antenna. The strength of the induction fields is inversely proportional to the square of the distance from the antenna, while the radiation fields die away directly with the distance. The two kinds of fields have equal intensity at a distance equal to the wavelength divided by 2π, or slightly less than one-sixth wavelength. At distances greater than about 1½ wavelengths, the induction field is negligible compared with the radiation field.

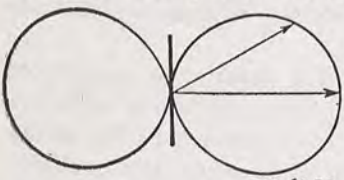

Figure 6. Plane directive diagram of a half-wave antenna. The solid line shows the direction of the wire, although the antenna itself is considered to be simply a point at the center of the diagram. The length of the arrow represents the relative field strength in that direction. The "doughnut" form of the soild directive pattern can be visualized by imagining the drawing glued to a piece of stiff cardboard with a short length of wire fastened at the center, in the position occupied by the solid line, to represent the antenna. Then twirling the wire rapidly will give a representation of the actual solid pattern.

b. Use of strength measurements. The induction field is of little importance because it decreases so rapidly with distance. However, in making field strength measurements in the vicinity of an antenna its existence must be kept in mind and the antenna not approached too closely if the strength of the radiation field only is to be measured.

32. RECIPROCITY.

a. General. The various properties of an antenna apply both to transmitting and receiving, subject to some qualifications when the path of the waves between the transmitting and receiving points involves propagation through the ionosphere. Thus the more efficient the antenna for transmitting, the more effective it will be for receiving. The directive properties will be the same for both transmission and reception, and, in the case of directive antenna systems, the gain will be the same on both transmitted and received signals. The current distribution and impedance will likewise be identical whether the energy is fed directly to a half-wave antenna from the transmitter or whether it is picked up from passing waves of the same frequency. This is in general true for an antenna of length equal to a multiple of a half wave, but not for antennas of other lengths.

b. Long-distance transmission. In long-distance transmission the observed behavior may sometimes be at variance with this rule because the waves may not take exactly the same paths through the ionosphere when going in opposite directions. Therefore an incoming wave may not strike the antenna at the same angle, in either the horizontal or vertical planes, which gives the best results for a transmitted wave the destination of which is the source of the received signal. Thus the two waves may be utilizing different parts of the directive pattern of the antenna, with some departure from complete reciprocity. This situation is usually quite unlikely to occur, especially at high frequencies. Any observed departure from reciprocity is more likely to arise from apparatus or noise level differences at the two locations.

at a given vertical angle from an antenna, gives the resultant relative radiation intensity at that same angle. The limiting conditions are those represented by the direct ray and reflected ray being exactly in phase and exactly out of phase when both, assuming there are no ground losses, have exactly equal amplitudes. Thus the resultant field strength may be either twice the field strength from the antenna alone, or zero.

b. Variation with antenna height. The way in which the reflection factor (based on perfectly conducting ground) varies with antenna height is

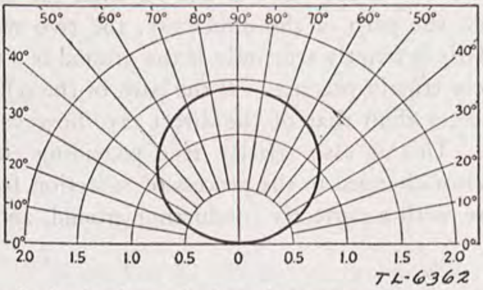

FIGURE 9. Ground reflection factor, horizontal antennas one-eighth wavelength high.

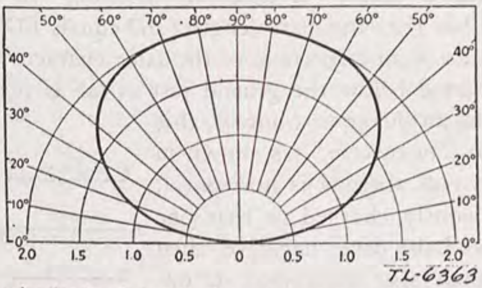

FIGURE 10. Ground reflection factor, horizontal antennas one-fourth wavelength high.

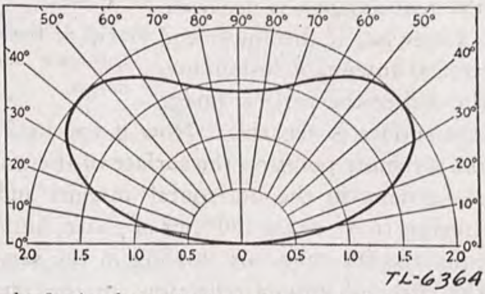

FIGURE 11. Ground reflection factor, horizontal antennas three-eighths wavelength high.

shown in the series of graphs in figures 9 to 26, inclusive. Figures 9 to 20, inclusive, apply to horizontal antennas of any length, and to vertical antennas an *even* number of half waves long. Figures 21 to 27, inclusive, apply to vertical antennas an *odd* number of half waves long. Comparing the two sets, it is seen that the positions of nulls (multiplying factor zero) and maxima (multiplying factor 2) are interchanged for the two sets of conditions. It must be remembered that these graphs are not plots of vertical patterns of antennas, but represent simply multiplying factors representing the result of reflection from the ground. With the distinction between vertical and horizontal antennas noted, the graphs apply equally

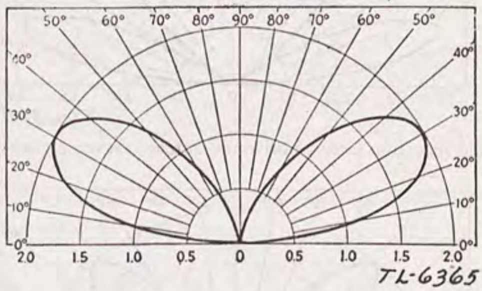

FIGURE 12. Ground reflection factor, horizontal antennas one-half wavelength high.

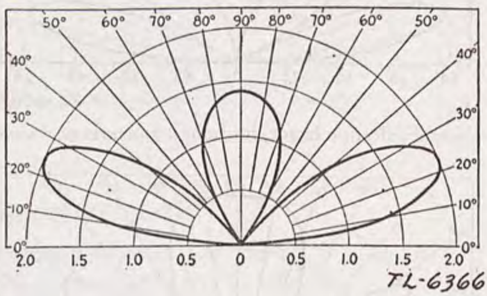

FIGURE 13. Ground reflection factor, horizontal antennas five-eighths wavelength high.

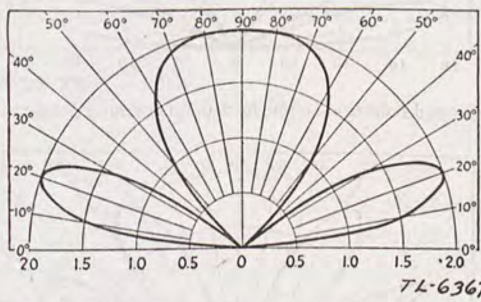

FIGURE 14. Ground reflection factor, horizontal antennas three-fourths wavelength high.

well to *all* antennas. Also, it should be understood that they apply at vertical angles only. The ground makes no distinction between geographical directions in reflecting waves.

c. Nulls and maxima. Figure 27 shows the angles at which nulls and maxima occur as a function of the height of the antenna. This chart gives

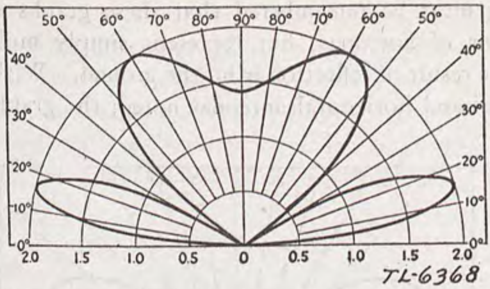

FIGURE 15. Ground reflection factor, horizontal antennas seven-eighths wavelength high.

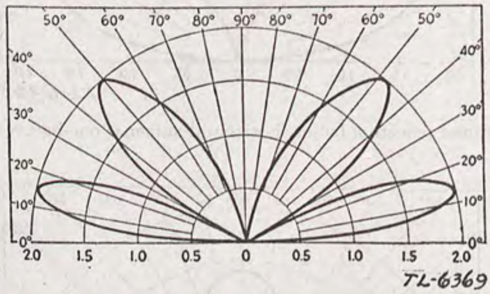

FIGURE 16. Ground reflection factor, horizontal antennas one wavelength high.

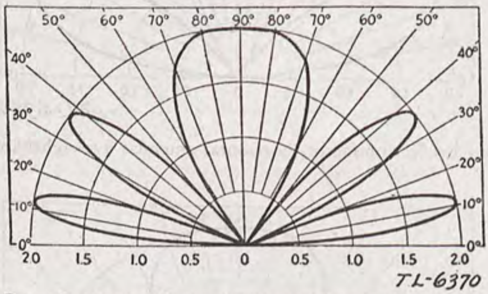

FIGURE 17. Ground reflection factor, horizontal antennas 1¼ wavelengths high.

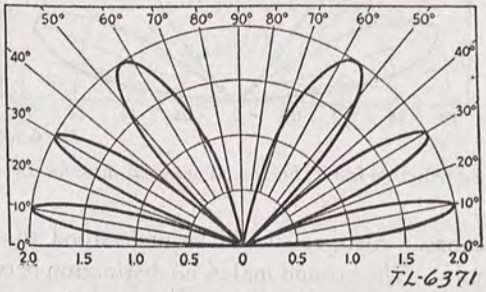

FIGURE 18. Ground reflection factor, horizontal antennas 1½ wavelengths high.

a rough idea of the ground reflection pattern for heights intermediate to those shown in detail in figures 9 to 26, inclusive, and also facilities picking the right height for any desired angle of radiation.

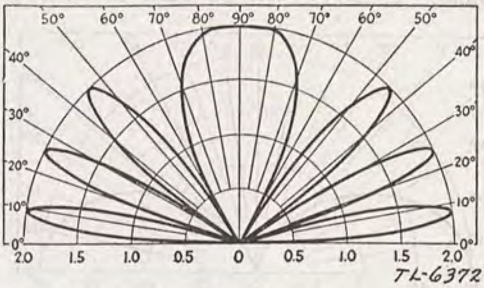

FIGURE 19. Ground reflection factor, horizontal antennas 1¾ wavelengths high.

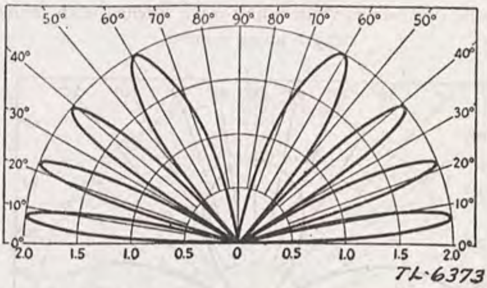

FIGURE 20. Ground reflection factor, horizontal antennas two wavelengths high.

36. GROUND CHARACTERISTICS.

a. Effect of ground losses. As already indicated, the charts are based on reflection from a perfectly conducting ground. In practice, the ground does not act like a perfect conductor at high frequencies. The effect of ground losses is to reduce the amplitude of the reflected wave so that the maximum reflection factor is something less than 2 and the null does not reach zero. Also, there may be a shift in phase with reflection which further changes the actual picture.

b. Ground losses at different angles. At all except the lowest angles these effects are small, and no serious error is introduced by assuming that the ground acts like a perfect reflector. The effect at angles below about 10° is to give increasingly more attenuation than is indicated by the charts, until at about 3° and lower there is no radiation, for all practical purposes. This applies to either horizontal or vertical antennas, so that the reflection factor at the horizontal with a half-wave vertical antenna which theoretically is 2, actually is zero. Thus the apparent advantage of the vertical antenna at very small angles is not realized at high frequencies.

c. Ground losses at different frequencies. At frequencies below 4 megacycles ground losses are of less consequence, and the charts become more nearly true for all vertical angles.

d. Reflecting plane of ground. The effective reflecting plane of the ground, that is, the surface from which the reflection is considered to take place at the heights given in the charts, seldom coincides with the actual surface of the ground. Usually it will be found that this plane appears to

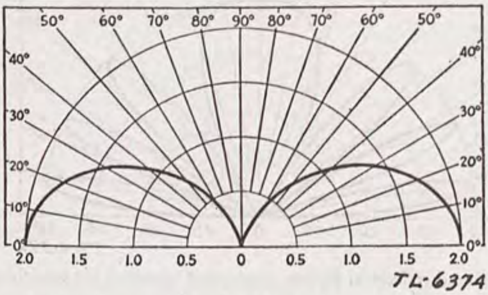

FIGURE 21. Ground reflection factor, vertical half-wave antenna with center one-fourth wavelength above ground.

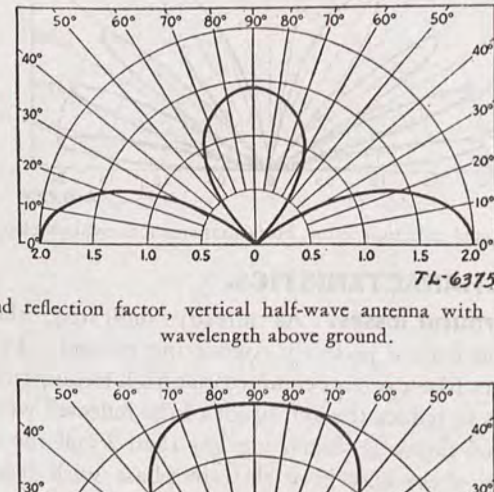

FIGURE 22. Ground reflection factor, vertical half-wave antenna with center three-eighths wavelength above ground.

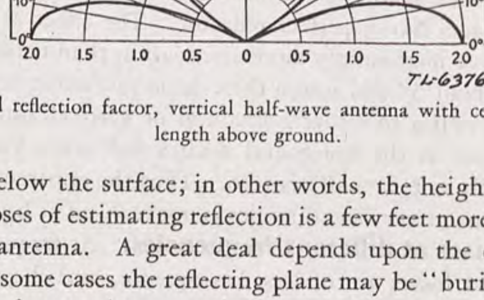

FIGURE 23. Ground reflection factor, vertical half-wave antenna with center one-half wavelength above ground.

be a few feet below the surface; in other words, the height of the antenna taken for purposes of estimating reflection is a few feet more than the actual height of the antenna. A great deal depends upon the character of the ground, and in some cases the reflecting plane may be "buried" a surprising distance. Thus in some instances the charts will not give an accurate indication of the effect of reflection. On the average, however, they will give a quite satisfactory representation of reflection effects, with the qualifications with respect to high frequencies and low angles mentioned above.

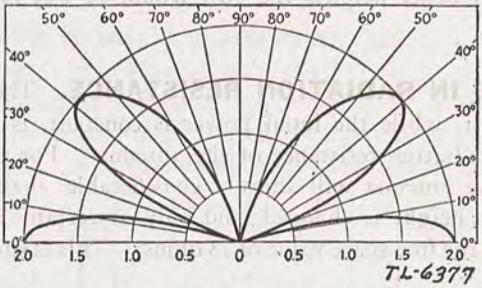

FIGURE 24. Ground reflection factor, vertical half-wave antenna with center three-fourths wavelength above ground.

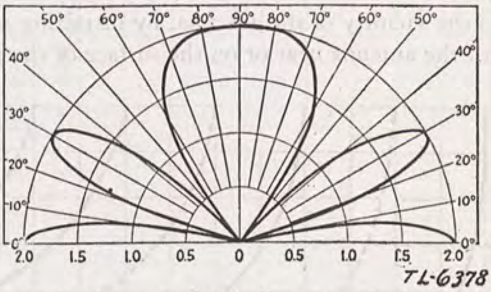

FIGURE 25. Ground reflection factor, vertical half-wave antenna with center one wavelength above ground

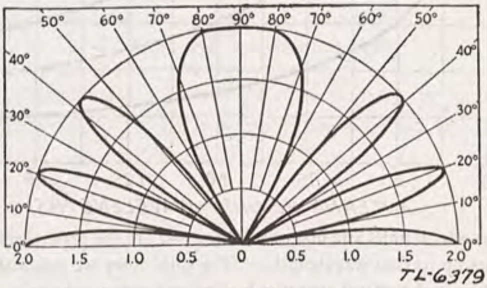

FIGURE 26. Ground reflection factor, vertical half-wave antenna with center 1½ wavelengths above ground.

37. INDUCED CURRENT IN ANTENNA. Waves radiated from the antenna directly downward reflect vertically from the ground and, in passing the antenna on their upward journey, induce a current in it. The magnitude and phase of this induced current depends upon the height of the antenna above the reflecting surface. The total current in a transmitting antenna thus consists of two components, one caused by the power from the transmitter, the other caused by absorption of energy from the reflected wave. The second component is of course smaller than the first, but at some heights the two will be more or less in phase, thus giving a higher total current than would result from the same input power to an antenna in free space; at other heights the two would be out of phase and the opposite is true.

38. CHANGES IN RADIATION RESISTANCE. The change in current with height, while the input power is constant, is equivalent to a change in the radiation resistance of the antenna. For example, a horizontal half-wave antenna will show a considerable change in radiation resistance as its height is changed, and only at certain heights will the resistance equal the free-space value of 73 ohms. This is shown in figure 27.

39. GROUND SCREENS.

a. Effect of screens. The effect of a perfectly-conducting ground can be simulated, in the vicinity of the antenna, by installing a metal screen or mesh underneath the antenna near or on the surface of the ground. Such a

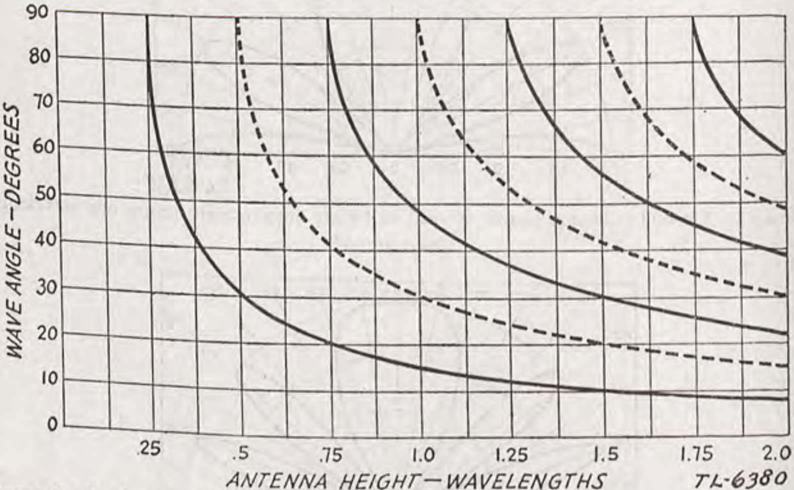

FIGURE 27. Angles at which nulls and maxima (factor = 2) in the ground reflection factor appear for antenna heights up to two wavelengths. The solid lines are maxima, dashed lines nulls, for horizontal antennas or vertical antennas having a length equal to an even multiple of one-half wavelength. For vertical antennas an odd number of half waves long, the dashed lines are maxima and the solid lines nulls. For example, if it is desired to have the ground reflection give maximum reinforcement of the direct ray at a 20° wave angle (angle of radiation) the antenna height should be 0.75 wavelength. The same height will give a null at 42° and a second maximum at 90°.

screen often will improve the performance of the antenna by reducing losses in the ground near the antenna where, because of the high intensity of the radiation, such losses are most serious. The screen is most effective at the higher frequencies. It should preferably extend at least a half wavelength in every direction from the antenna, although good results have been reported with screens having about 25 percent smaller dimensions. Caution must be used in employing such screens, because a poorly designed screen, or one having poor ground connections, may be much worse than no screen at all.

b. Relationship to height of antenna. Besides reducing losses, a good ground screen rather effectively establishes the height of the antenna so far as the radiation resistance is concerned. For this purpose, the height will be the actual height of the antenna above the screen. Since reflection from a screen of reasonable dimensions takes place only at high

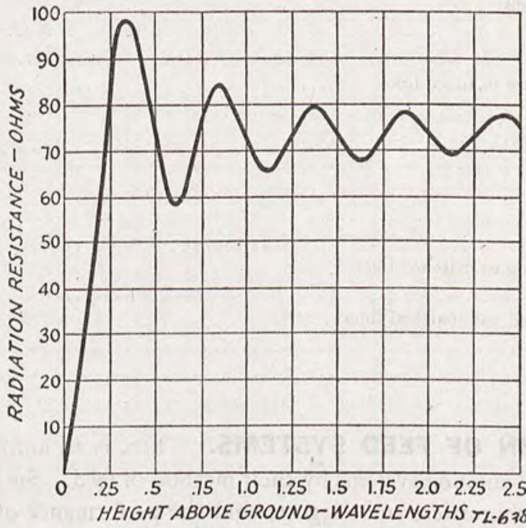

FIGURE 28. Variation in radiation resistance of a horizontal half-wave antenna with height above perfectly conducting ground.

angles, however, the presence of the screen will not appreciably modify the effect of the actual ground at the lower angles, because the low-angle waves are reflected at considerable distance from the antenna.

SECTION IV

FEEDER SYSTEMS

40. FUNCTION OF FEED SYSTEMS. There is an unfortunate tendency to describe antenna systems by their method of feed. Such description gives rise to ambiguities, and suggests that the performance of the antenna is dependent on the type of feed system used. Such is not the case. The *sole function of any feed system is to transport power from the transmitter to the antenna with a minimum of loss.* There would be no need for feed systems if it were not for the fact that surrounding objects will modify and reduce the effectiveness of any antenna, and it is therefore desirable to have the antenna placed in the clear, away from houses, wires, metal pipes and poles, and thick trees. In multi-element arrays (to be described later), the transmission line is also used to phase properly the elements.

41. TYPES OF FEED SYSTEMS.

a. Tuned and matched. Feed or transmission lines are of two general types, *tuned* and *matched.* As explained previously, if a line is infinitely long, a current started down it will eventually dissipate, and hence there will be no reflection and consequent standing waves. This holds for both a one- or two-wire line. Any line has a *characteristic impedance* which depends on the size and spacing of the conductors. If the line is cut to some finite length and a resistance equal to the characteristic impedance is used to replace the length of line that was running out an infinite length, there will still be no reflections because, for the portion of the line being considered, nothing has been changed. A transmission line terminated in its characteristic impedance, and thus having no standing waves on it, is called a "matched" or "flat" line. It is of importance to remember that the line must be terminated in a *resistance;* a reactive component in the terminating load will cause standing waves even though the load impedance (in ohms) is equal to the characteristic impedance. For this reason, any reactive component in the load must be tuned out or canceled before a perfect match can be obtained.

b. Effect of impedance. If a line of finite length is not terminated in its characteristic impedance, there will be current and voltage reflections from the end which will combine with the current flowing toward the

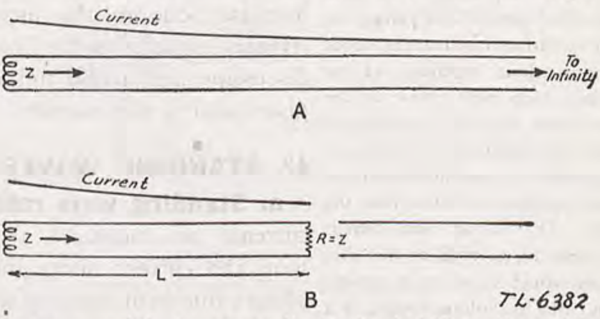

FIGURE 29. As shown at (A), the current distribution is fairly uniform along an infinitely long line, attenuating slightly because of losses in the line. The line can be any finite length, *L*, as at (B), and still have nearly uniform current distribution along it, if it is terminated by a resistance equal to the characteristic impedance of the line.

end to form *standing* waves. If the impedance at the end of the line is higher than the characteristic impedance, there will be a voltage maximum or *loop* at the end of the line, and also approximately every half wavelength in toward the sending end of the line. If the impedance at the end of the line is lower than the characteristic impedance of the line, a current loop will appear at the end of the line, and approximately every half wavelength in toward the sending end of the line. The greater the difference between the impedance of the line and the terminating impedance, the greater the *mismatch* is said to be, and the greater will be the amplitude of the standing waves of current and voltage.

c. Standing waves. The standing waves cannot exist unless the line is excited with radio-frequency energy. In order to excite more easily a transmission line it is usually necessary to tune the line at the transmitter end with a coil and condenser combination, the coil also being used to couple the line to the transmitter. Lines with standing waves on them are called "resonant" or "tuned" lines. With standing waves on the line, the current and voltage distribution will be as shown in figure 30. It will be noted that for a resistive load, a voltage maximum and a current minimum always appear at the same point, and vice versa.

d. Qualification of half wavelength. It was mentioned above that the current (and voltage) loops appear approximately one-half wavelength apart. When we mention a half wavelength without qualification we mean a half wavelength in air, and, since the velocity of the wave is less along the wire than in air, a wavelength along a wire is slightly less than a wavelength in air. As the impedance of the lines is decreased (by using closer spacing or larger conductors, or both), the velocity is decreased due to the increased distributed capacity of the line. Further discussion and actual figures will be given later in this section.

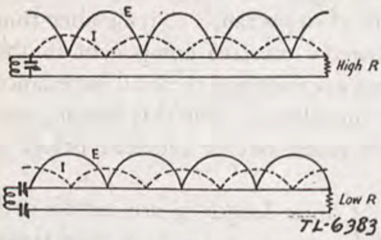

FIGURE 30. A line terminated by other than its characteristic impedance will have standing waves of current and voltage on it. If the termination impedance is higher than the characteristic impedance of the line, a voltage loop will appear at the termination and at every half wavelength back toward the sending end. A current loop will appear at the termination if the terminating impedance is lower than the characteristic. The voltage and current loops have been represented in this diagram as they would show up by testing with a neon bulb (for voltage loops) or a bridging ammeter (for current loops) along the line. It should be remembered that any two successive loops along the same wire are out of phase, as are corresponding loops on different wires.

42. STANDING WAVES.

a. Standing wave ratio. If the currents are measured at a current loop and current minimum, or *node*, along a line with standing waves on it, it will be found that the ratio of the loop-current to node-current will be the same as the ratio of the line and terminating impedances. This is called the "standing-wave ratio." Thus, for example, if a 600-ohm line is terminated by either a 72- or a 5,000-ohm resistance, the mismatch and the standing-wave ratio will be 8.3 to 1 in either case. The standing-wave ratio is a direct indication of the degree of mismatch along a line, and is useful in the adjustment of matched lines.

b. Normal use. Any line used to feed an antenna will have no standing waves along it, if it is connected to the antenna at a point where the impedance is resistive and matches that of the line. This is normally impractical, except in some special cases to be described later, and the line usually operates with some standing waves on it. This is no particular disadvantage, if the line is not more than several wavelengths long, and the standing-wave ratio is not higher than about 10 to 1.

43. TUNED LINES.

a. General. Resonant lines enjoy widespread use, because of their flexibility and reliability. Except in a few special cases, the use of a tuned line is the only way that multi-band operation of the same antenna and feed line can be obtained. It is obvious that, since a line can be considered as simply part of the antenna folded back on itself to prevent radiation, power can be put into the system on any frequency to which it can be tuned.

b. Point of connection. Tuned lines are usually connected to the antenna system at one end or at the center, although in an antenna several half wavelengths long they may be connected at any voltage or current loop.

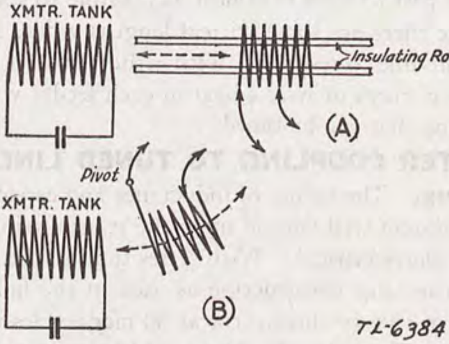

FIGURE 31. Two simple ways of varying the coupling between the final tank and the antenna coil.

If the line is connected to the end of the antenna (or any other voltage loop), the line is thus terminated in a high impedance and a voltage loop will appear at the end of the line and every half wavelength back along the line.

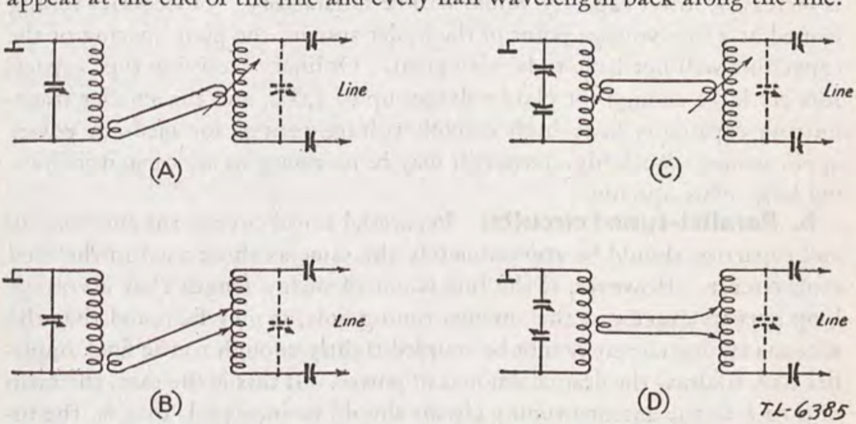

FIGURE 32. Four methods of link coupling the antenna tuning unit to the final amplifier tank. (A) and (B) are for unbalanced tanks, and the link is placed near a low-voltage point on the amplifier tank coil. The balanced tanks, at (C) and (D), have the link loop at the center, where the r. f. voltage is low. Coupling is varied by changing the position of the loop with respect to the antenna coil or by moving the taps.

If the line is connected to the center of a half-wave antenna (or any current loop in an antenna several half wavelengths long), the line is terminated in a low impedance and a current loop will appear at the end of the line and every half wavelength back along the line. It is thus easy to determine whether a voltage or current loop will appear at the transmitter end of the line. If a voltage loop is to appear at the transmitter end of the line, a parallel-tuned circuit should be used to bring the system into resonance, and a series-tuned circuit should be used if a current loop is to appear at the transmitter end of the line. The line, of course, does not have to be any exact length, since the tuned circuit will compensate for a good deal of deviation, but it is best to have it as near as possible to some multiple of a quarter wave, since there are some critical lengths where it will be found difficult to bring the line to resonance with either series or parallel tuning. In such a case, a few turns of wire added in each feeder will usually bring the length up to one that can be tuned.

44. TRANSMITTER COUPLING TO TUNED LINES.

a. Series tuning. The values of inductance and capacity to use in the antenna coupling system will depend upon the transmitting frequency, but they are not particularly critical. With series tuning, the coil may consist of a few turns of the same construction as used in the final tank; average values will run from two to three turns at 30 megacycles to perhaps 10 or 12 at 4 megacycles. The coil preferably should be such that the inductance can be varied in case it is not possible to reach resonance with the condensers used. This can be done by shorting-out a few turns of the coil at one end with a jumper connection. The series capacitors should have a maximum capacity of 250 or 350 $\mu\mu$f at the lower frequencies, and as the frequency is increased, lower capacity values will be satisfactory. Since series tuning is used at a low-voltage point in the feeder system, the plate spacing of the capacitors will not have to be very great. Ordinary receiving type capacitors are large enough for plate voltages up to 1,000, and the smaller transmitting capacitors have high enough voltage ratings for medium power applications. With high power, it may be necessary to use capacitors having large plate spacing.

b. Parallel-tuned circuits. In parallel-tuned circuits the antenna coil and capacitor should be approximately the same as those used in the final tank circuit. However, if the line is not of such a length that a voltage loop appears exactly at the antenna tuning unit, it may be found that the antenna tuning circuit cannot be coupled tightly enough to the final amplifier tank to draw the desired amount of power. If this is the case, the ratio of C to L in the antenna tuning circuit should be increased, that is, the inductance should be decreased by shorting or removing turns.

c. Coupling tuning circuit to transmitter tank coil. The simplest and most straightforward method of coupling the antenna tuning circuit to the transmitter final tank coil is to place it alongside the tank coil, with some provision for swinging it or moving it away, to vary the coupling. This has the disadvantage of introducing some capacity unbalance to the transmitter and antenna tuning circuit, as well as requiring that the antenna feed line be run from the lead-in point, where it enters the building, over to the transmitter.

45. LINK COUPLING.

a. General. An alternative system that enjoys widespread use is link coupling. This allows the antenna tuning unit to be mounted on the wall where the feed line enters the room. A low-impedance line of twisted flexible wire, or enameled wire, spaced by small ceramic spacers, or coaxial cable, can be used for the link. The close-spaced open line is better at 30 megacycles and higher frequencies than is the twisted pair, although the twisted pair is normally quite satisfactory at the lower frequencies.

b. Fixed and variable links. Typical link-coupling circuits are shown in figure 32. Variable link coils can be used at either the final amplifier tank coil or the antenna coil. The fixed links consist of two or three turns of wire wrapped around the plate coil at a low r. f. voltage point and insulated from the coil. Both the double link and the tapped coil system work with the same efficiency. It is somewhat easier to adjust the coupling with the variable link assembly. The link should be wound or tapped on the antenna coil symmetrically at the center of the antenna coil, where the r. f. voltage is least. By thus reducing the capacity coupling, there is less chance of capacity transfer of the harmonic energy and radiation at these undesirable frequencies. The values of antenna tuning capacitors and coil are the same as with the straight inductively coupled system.

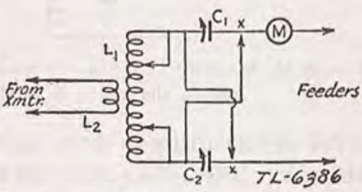

FIGURE 33. Circuit diagram of the antenna tuning unit.

c. Tuning the antenna. To tune the antenna, first loosen the antenna coupling (by swinging out the link or removing the taps from the antenna coil), and tune the final amplifier for minimum plate current. Swing in the link about halfway (or tap on to one turn either side of center), and tune the antenna unit for a maximum rise in plate current. The final amplifier tuning capacitor should be tuned for minimum plate current again, but the setting should not have changed appreciably from the original no-load setting. The coupling can be increased, by moving in the link (or tapping across more turns), until the final amplifier is drawing rated plate current. When the coupling and tuning adjustments are correct there will be practically no detuning effect on the transmitter tank; that is, the resonance setting (minimum plate current) should be the same both with and without the link in place but, of course, the current values will be different. If such is not the case, it indicates an abnormal amount of capacity coupling caused by unbalance in the system or overcoupling caused by too many turns at one or both ends of the link line. If the final cannot be loaded heavily enough, it indicates that too high an *L-C* ratio is present in the antenna tuning unit, where parallel tuning is being used, and the inductance should be reduced. No trouble should be experienced with series tuning.

In general, it is best to use the minimum number of link turns that will give sufficient coupling.

d. Alternate methods for odd lengths of feeders. There will be some odd lengths of feed lines that cannot be coupled with either a series or parallel circuit, even though the *L-C* ratio is reduced as mentioned above. In such cases, the feeder length should be changed by adding or subtracting about one-eighth wavelength of line or by adding loading coils in the line. Another alternative is to tap the feed line down toward the center of the coil of a parallel-tuned antenna circuit, as shown in figure 34. This will

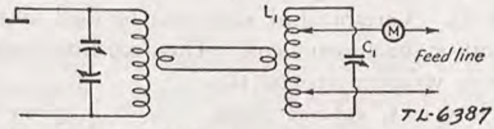

FIGURE 34. In cases where sufficient loading cannot be obtained with either series or parallel tuning, the feeders should be tapped-in on a parallel-tuned circuit.

work satisfactorily in many cases, but if the line must be tapped too near the center before the system can be loaded properly, it will be found that the center of the coil gets quite warm, indicating considerable loss in the coil. Any heating in the antenna coupling system indicates inefficiency and loss of antenna power, and the coupling system should be checked and changed if possible.

46. PI-NETWORK COUPLING.

a. Method and description of adjustment. A pi-section coupling network is shown in figure 35. This is a low-pass filter, and is capable of coupling between a fairly wide range of impedances such as is encountered in going from series to parallel tuning. Suitable constants are given under the diagram. The method of adjustment is as follows: First, with the network disconnected, tune the transmitter tank to resonance, as evidenced by minimum plate current. Then, with trial settings of the clips on L_1 and L_2 (few turns for high frequencies, more for lower), tap the input clips on the final tank coil at points equidistant from the center so that about half the coil is included between them. A balanced tank circuit must be used. Set C_2 at about half scale, apply power, and rapidly rotate C_1 until the plate current drops to a minimum. If this minimum is not the desired full-load plate current value, try a new setting of C_2 and repeat. If, for all settings of C_2 the plate current is too high or too low, try new settings of the taps on L_1 and L_2, and also on the transmitter tank. Do not touch the tank capacitor during these adjustments. When, finally, the desired plate current is obtained, set C_1 carefully to the exact minimum plate-current point. *This adjustment is important in minimizing harmonic output.*

b. Use of pi-network. The pi-network method of coupling is very useful in portable work, because it makes it possible to put power into almost any length of wire. For portable application, it is usually used in the unbalanced version (by shorting L_2) and, since single-ended unbalanced amplifiers are generally used, the tank capacitor and C_1 become the same capacitor. The pi-network coupling is convenient in this application, but it should not be used for fixed-station work because of its lack of harmonic-rejection properties except under critical adjustment conditions.

47. FEEDER CURRENT.

a. General. The feeder current as read by the r. f. ammeters is useful for tuning purposes only; the absolute value is of little importance when working with tuned lines. When series tuning is used, the current will be high, while but very little current will be indicated in a parallel-tuned system. With a given antenna and tuning system, of course, the greatest power will be delivered to the antenna when the readings are highest. However, should the feeder length be changed, no useful conclusion can be drawn from comparison between the new and old readings. For this reason, any indicator which registers the relative intensity of r. f. current can be used for tuning purposes. Flashlight or dial lamps may be used for this purpose instead of meters. They are cheap, and when shunted by short lengths of wire so that considerable current can be passed without burn-out, will serve very well even with high-power transmitters.

b. Current balance. Meters are useful in tuned lines for indicating current balance in the line. There will be a minimum of radiation from the line when the currents are balanced, provided the current readings are taken at the same relative points on each wire of the line. If an unbalance of more than 10 percent is indicated, it is well to spend some time in adjusting the line. Unbalance in the line can be caused by unequal feeder lengths, unequal feeder capacity to ground or, in any unsymmetrical antenna system (like the Zepp and unlike a center-fed), incorrect length of antenna. Radiation from the tuned feed line is not particularly serious, except where the feed line runs close to absorbing objects, or where one is trying to obtain good directivity and wishes to reduce spurious radiation and reception.

48. LINE SPACING.

a. Desired spacing. For effective cancelation of radiation, the spacing between the two wires must be small in comparison to the wavelength; a separation of 0.01 wavelength or less is desirable. For 20 megacycles and lower, the wires need not be closer than 6 inches, the length of the popular feeder spreaders manufactured for this purpose. Four inches is an optimum spacing for 20 megacycles and higher.

b. Faults of close spacing. From the practical standpoint, too close spacing is undesirable, especially with long sections of line. The wires inevitably swing with respect to each other when there is wind; if the spacing is close, this means that insulating spreaders must be installed at frequent

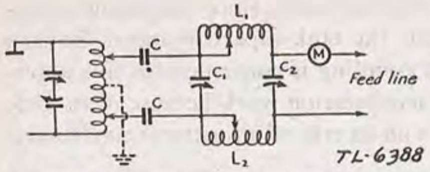

FIGURE 35. A pi-section network for coupling to a tuned line. C_1 and C_2 may be 100 to 1,000 μf each, depending upon the frequency of operation. Plate spacing should, in general, be about half that of the final tank capacitor. For operation from 1.8 to 14 megacycles, L_1 and L_2 should each be 15 turns of No. 12 or 14 wire wound on a 2½-inch diameter to occupy 3 inches winding length, and tapped every 3 turns. Approximate settings are 15 turns for 1.8 megacycles, 9 turns for 3.5 megacycles, 6 turns for 7 megacycles, and 3 turns for 14 megacycles. *C* is a blocking capacitor of 0.001 μf or so.

intervals to prevent the wires from touching, and this in turn increases the weight of the line. Swinging also causes a varying detuning effect, since the change in spacing represents a change in capacity which reacts on the transmitter, and is evidenced by periodic variations in loading. For work on communication frequencies, the 6-inch spacing represents a compromise which works out well in practice.

c. When it is necessary that two or more open transmission lines run near each other, they should be separated by a distance not less than 10 times the line spacing, if mutual coupling is to be avoided.

49. MATCHED LINES.

a. General. As explained earlier in this section, standing waves do not exist on a transmission line terminated in the characteristic, or surge, impedance. Such lines may resemble the resonant lines in physical construction, but their operation and adjustment are different. In contrast to the resonant lines, nonresonant or matched (or flat) lines may be of any desired length. They are excellent for feeding an antenna at some distance from the transmitter, but have the disadvantage that their use normally restricts the antenna to one narrow band of frequencies.

b. Surge impedance. The surge impedance of a line consisting of two parallel conductors depends upon the inductance and capacity of the line per unit of length. In turn, these quantities depend upon the size of the conductors, their spacing, and the dielectric constant of the medium between the conductors. When the dielectric is air, the surge impedance of two parallel conductors is given by

$$Z=276\ log\frac{b}{a}$$

where Z is the surge impedance in ohms, b the spacing, center to center, and a the radius of the conductor. The quantities b and a must be measured in the same units (inches, centimeters, etc.). Surge impedance as a function of spacing and wire size is plotted in chart form in figure 36.

c. Coaxial lines. A common form of transmission line consists of a wire located axially in a metal tube, the two being insulated from each other. This type of line is useful for special applications where the radiation must be reduced to negligible proportions, and where low impedance is required. The surge impedance of such a concentric or coaxial line is given by

$$Z = 138 \log \frac{b}{a}$$

where Z is the impedance in ohms, b is the inside diameter of the outer conductor, and a is the outside diameter of the inner conductor. The formula is correct for air dielectric and approximately so for a line having ceramic insulators so spaced that the major portion of the insulation is air. Figure

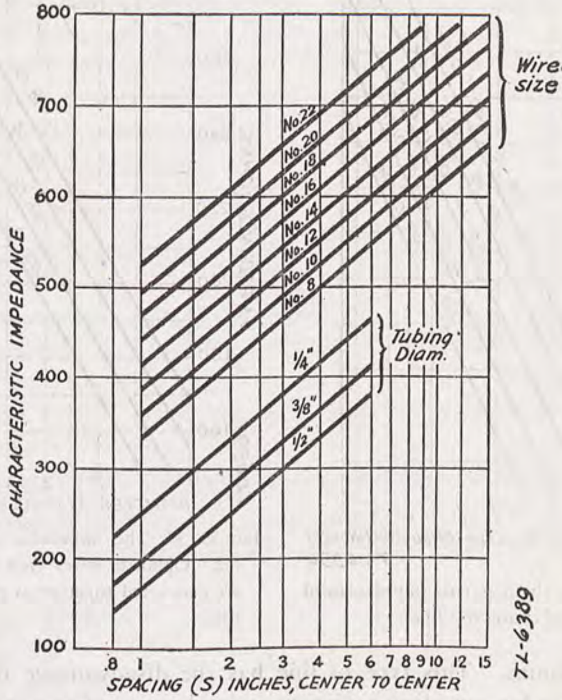

FIGURE 36. The characteristic impedances of typical spaced-conductor transmission lines.

37 gives impedance values for typical conductors. Well designed concentric lines are hermetically sealed at both ends and filled with dehydrated air or an inert gas such as nitrogen, to prevent the condensation of moisture inside the line.

d. Multiple-wire lines. Because it is impractical to go below certain impedance values with a two-wire line, and where it is not desirable to use metal tubing (as in a low-frequency Q-match system, described later), it is possible to obtain a low-impedance line with four or more wires. The four wires can be equally spaced on the periphery of a circle, opposite wires being paralleled. In actual practice, disks of bakelite or other insulation are used for spacers, the four holes for the wires being drilled in the form at the proper points, and the wires are then threaded through and tied.

Figure 38 gives impedance values for normal spacing and the usual sizes of wire.

e. Single-wire line. Still another type of line is simply a single wire. The surge impedance of such a line made of No. 14 wire will be approximately 500 ohms.

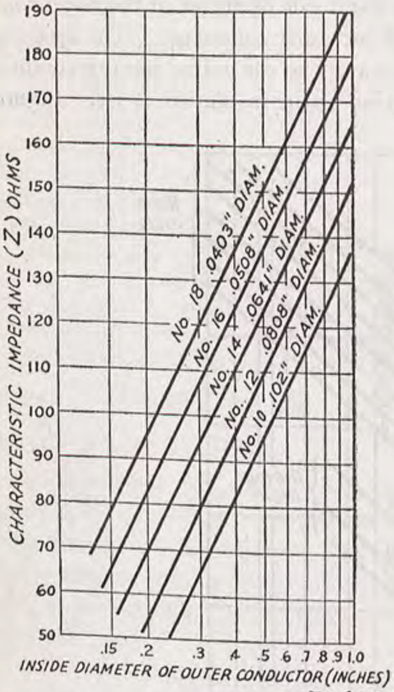

Figure 37. The characteristic impedances of typical concentric lines.

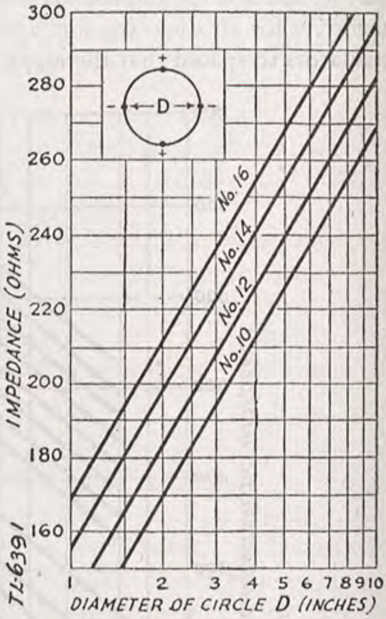

Figure 38. The impedance of a four-wire ine. Opposite wires (not adjacent ones) are connected together at each end of the line.

This type of line has the disadvantage that no provision is made for canceling radiation as in the case of the two-wire line. However, if the line is not too long, the radiation will be relatively small, because the current in the line is small compared to the antenna current. If the line is tied into the antenna at a point where the impedance is 500 ohms, no standing waves will appear.

50. LOW-IMPEDANCE LINE.

a. Rubber-covered and twisted wire. It can be seen from the formula for the characteristic impedance of a two-wire line that the closer the spacing and the larger the wires, the lower will be the impedance. It happens that the impedance of a two-wire line composed of twisted rubber-covered wire of the type used in house wiring will be approximately that of the center of a half-wave antenna itself, thus simplifying the method of connecting the line to the antenna. Such discrepancy as may exist between line and antenna impedance can be compensated for by a slight fanning of the line where it connects to the two halves of the antenna, as will be explained in section V. The twisted-pair line is a convenient type to use, since it is easy to install and the r. f. voltage on it is low, because of the low impedance. This makes insulation an easy matter. The losses are somewhat higher than those in spaced lines with air insulation, however, and will increase with frequency. For transmitting purposes, special twisted line having lower losses than ordinary rubber-covered wire should be used if available.

b. Checking for standing waves. Since it is difficult to examine a low-impedance line for standing waves, the easiest way to check the performance is with an auxiliary length of line. The current can be read in each leg of the line and recorded. Then an auxiliary quarter wavelength of line is added to the line and coupled to the transmitter as before, making sure to load the transmitter to the same input. The current in the line, read at the transmitter end, should be very nearly the same as before. For a final check, an auxiliary eighth-wavelength piece of line can be added. If the readings are quite close in the three cases, there are no standing waves on the line, and it is properly terminated. If the readings are not close, the termination *at the antenna end* must be adjusted. A very rough check for the proper operation of a low-impedance line is to let the transmitter run for 5 or 10 minutes, feeding the line. If, after this time, there are no spots along the line warmer than other spots, it is safe to assume that no serious standing waves are present.

51. TRANSMITTER COUPLING TO MATCHED LINES.

a. Methods of coupling. Similar coupling methods are used with all types of two-wire matched lines, whether of high or low impedance.

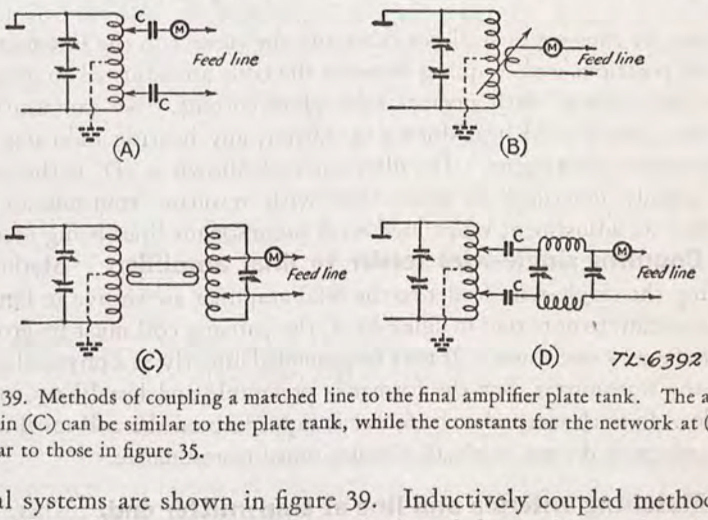

FIGURE 39. Methods of coupling a matched line to the final amplifier plate tank. The antenna tank in (C) can be similar to the plate tank, while the constants for the network at (D) are similar to those in figure 35.

Several systems are shown in figure 39. Inductively coupled methods are preferable to direct coupling when a single-ended or unbalanced tank feeds a balanced transmission line; this avoids line unbalance which might occur with direct coupling. In the direct-coupled circuits, the fixed capacitors are useful only when the output amplifier plate supply is series-fed to the plate. These capacitors, when used, should have a rating somewhat above the maximum plate voltage used and should have a comparatively high capacity, depending upon the frequency used. The current rating should be higher than any current encountered in normal operation, which can be calculated by

$$I=\sqrt{\frac{W}{Z}}$$

where I is the current in amperes, W is the power output in watts, and Z is the impedance of the line.

b. Placement of taps or coupling coil. The taps or coupling coil (fig. 39 (A) and (B)) should be placed symmetrically, about the center or r. f. ground point on the coil. The taps or coupling should be adjusted to make the final amplifier draw normal plate current; if the line is operating properly the taps will not affect the setting of the plate tank capacitor. In the case of the method shown at figure 39(C), the coupling tank is first adjusted to resonance with the plate tank circuit, using very loose coupling.

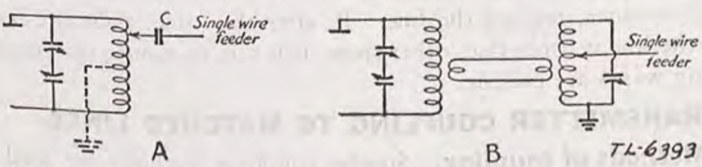

FIGURE 40. Methods of coupling the single-wire feeder to the final tank circuit. It is important to ground the set (A) or the antenna tuning circuit (B).

The taps are then set at trial positions and the current in the line measured. The tap positions and coupling between the coils are adjusted to give maximum line current with normal tube plate current. No portion of the coupling tank should heat during operation; any heating indicates losses and incorrect adjustment. The filter network shown at (D) is the same as that already described in connection with resonant transmission lines (fig. 35), its adjustment when used with nonresonant lines being identical.

c. Coupling single-wire feeder to final amplifier. Methods of coupling the single-wire feeder to the final amplifier are shown in figure 40. It is important to note that in figure 40(B) the antenna coil must be grounded for satisfactory operation. It may be grounded directly to a physical ground or to the transmitter, but the former is preferable and less likely to cause trouble. In both methods, the feeder is tapped up on the coil until normal plate current is drawn, with all circuits tuned to resonance.

d. Matching antenna and line at transmitter end. There is no adjustment at the transmitter end of a line that will reduce the standing waves on an improperly terminated line and, for this reason, the line should be matched at the antenna as carefully as possible in every case.

52. MATCHING THE LINE.

a. General. In the matched lines just described, impedance matching depends upon connecting the line to an appropriate point on the antenna. Twisted-pair lines and concentric lines can be made to match the impedance of an antenna at a current loop (55 to 100 ohms), and can thus be connected directly to the radiator, but in most cases it is necessary to use some type of impedance-matching transformer between the line and the antenna. The transformer ordinarily used does not resemble the ordinary coupled r-f transformer, but is simply a section of transmission line.

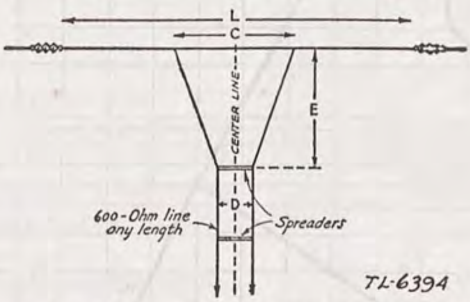

FIGURE 41. Delta match for a half-wave antenna. It is important that the matching section, *E*, come straight away from the antenna without any bends. Formulas for calculating the lengths *C* and *E* are given in section V.

b. Delta match. Because of the extremely close spacing required, it is impracticable to construct an open-wire line that will have a surge impedance low enough to work directly into a half-wave antenna. Such wire lines usually have impedances between 400 and 700 ohms (see fig. 36),

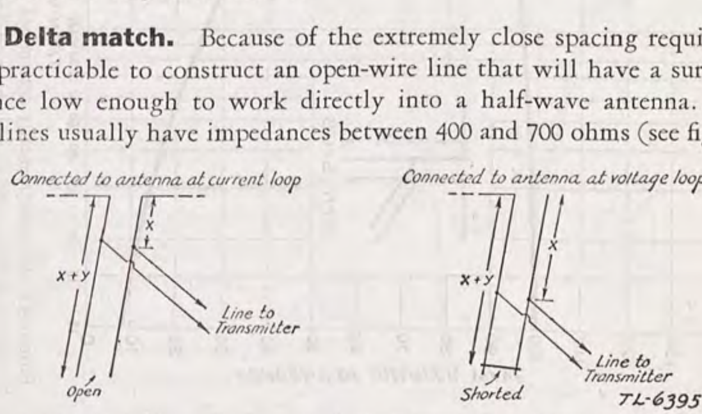

FIGURE 42. Quarter-wave matching sections. The distances X and $X+Y$ can be found from the graph in figure 43.

600 ohms being a widely used value that can be obtained with No. 12 wire spaced 6 inches. An open-wire line can be matched to a half-wave antenna by "fanning out" the end of the line and tapping onto the antenna at critical points. Figure 41 shows how this is done. The section *E* is fanned to have a gradually increasing impedance so that its impedance at the antenna end

will be equal to the impedance at the antenna section *C*, while the impedance at the lower end matches that of the transmission line. Formulas for calculating the lengths *C* and *E* for matching a 600-ohm line at any frequency are given in section V. Performance of the line and match can be checked by examining the line for standing waves, their presence indi-

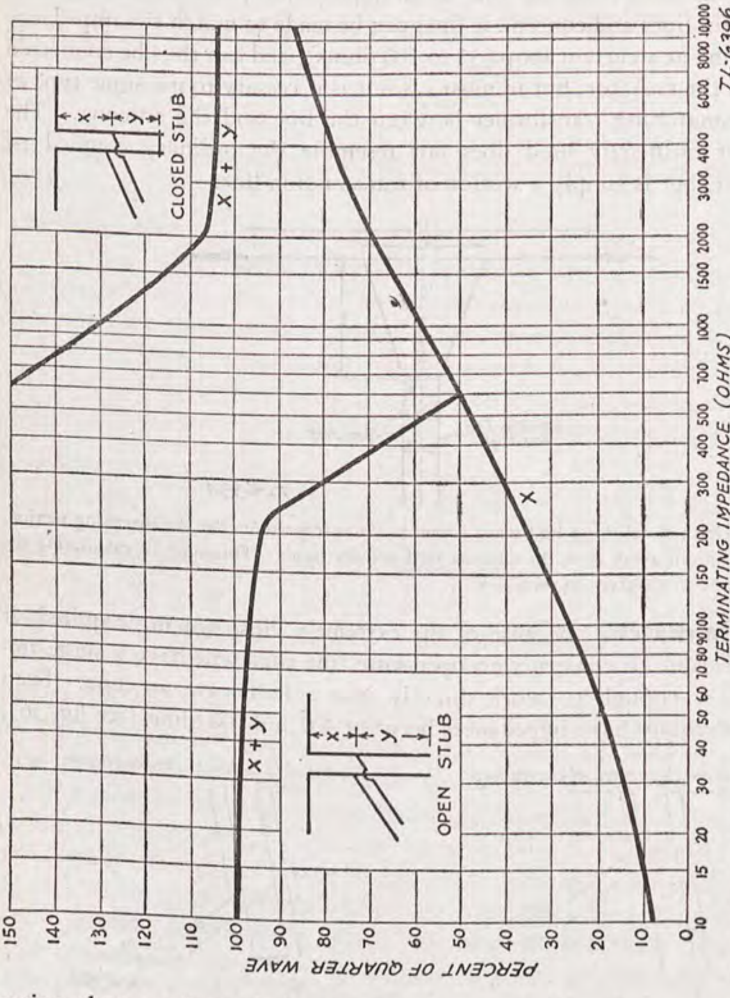

FIGURE 43. An experimentally determined chart showing the point of attaching the feed line to a quarter-wave matching section and the modification of length of the section for various impedances. The chart holds only for a 600-ohm line. "*x*" is the distance from impedance to feeder, "*x*+*y*" is the total length of the matching section.

cating that a mismatch is present. A neon bulb will serve as a rough indication of standing waves along the line, or an r. f. galvanometer can be used as described later.

c. Quarter-wave matching sections.—(1) General. A widely popular form of matching transformer is the quarter-wave matching section. Two methods of using them are shown in figure 42. If the quarter-wave section is connected to a voltage loop of the antenna, it is necessary to short the matching section, while the section is left open if it is connected to a current loop of the antenna.

(2) Calculating length. The length of the quarter-wave open-wire matching section can be calculated from

$$L\ (\textit{feet}) = \frac{246}{\textit{Frequency (megacycles)}}$$

This will give an approximate length, and the section should always be tuned after it has been put in place. The exact length of the matching section and the position of the line taps must be determined experimentally, since it will depend upon the impedance of the line as well as the antenna impedance at the point of connection. The impedance of the line is not important—the quarter-wave section can be used to match practically any line impedance. The lower the impedance of the line, the nearer to the current loop on the matching section will be the proper point of connection.

(3) Use of thermomilliammeter. Although flashlight and other small lamps can be used to adjust a quarter-wave section (or "matching stub"), a thermomilliammeter is the ideal instrument for proper tuning. It can be rigged as shown in figure 44, so that it can be used to show the average current in the feed wires.

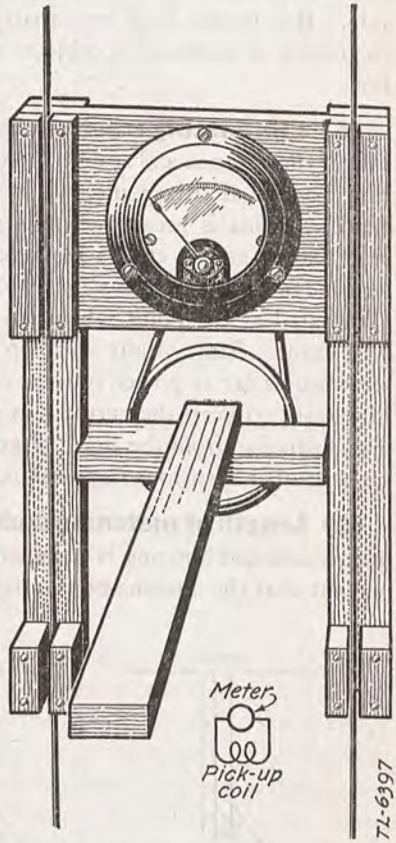

FIGURE 44. Instrument for measuring average line current between wires of a transmission line.

(4) Adjusting matching section. The first step in adjusting the matching section is to bring it and the antenna into resonance. This can best be done by exciting the antenna from a temporary antenna at least a half wavelength away (the transmitter being on the proper frequency, of course) and adjusting the length of the stub until maximum current is obtained in the shorting bar. The shorting-bar current can be read by shunting the thermomilliammeter across it or, if the current is very low, by using the meter as the shorting bar. After the maximum current has been obtained, the temporary antenna can be removed and the feed line tapped onto the stub about one-eighth wavelength from a current loop. The line is coupled to the antenna and the meter (or flashlight bulb) is used to examine the line for standing waves (difference in current along the line). The line is tapped at various points on the matching stub until a place is found that gives the minimum standing-wave ratio. The stub length can then be increased slightly (by 1 or 2 inches at 14 megacycles, for example), and the line again examined for standing waves. After slight readjustments of stub length and line-tap position, the line will be perfectly "flat" and there will be no standing waves along its length. If a meter is used to check the current, both wires of the line should be checked to make sure the current is the same in each side. If it is not, look for capacity unbalance of the line (one side closer to ground or surrounding objects than the other) or a sharp bend in the line.

(5) Eliminating reactive component. It should be kept in mind that if the antenna and stub are tuned to resonance independently by excitation from an auxiliary antenna, it will never be possible to match the line exactly. This is because there is always a reactive component along the stub except at the ends. However, by making the closed stub slightly longer (or an open stub slightly shorter), the reactive component can be eliminated at the point where the line is tapped on, and a perfect match will ensue. Some slight standing waves along the line are of little consequence as far as power transfer to the antenna is concerned. It is more important to keep the currents in the line balanced at all times, to minimize radiation from the line. Figure 43 is a chart of stub lengths and tapping points for various impedances.

(6) Length of matching stub. When the connection between matching section and antenna is unbalanced, as in any end-fed system, it is important that the antenna be the right length for the operating frequency if

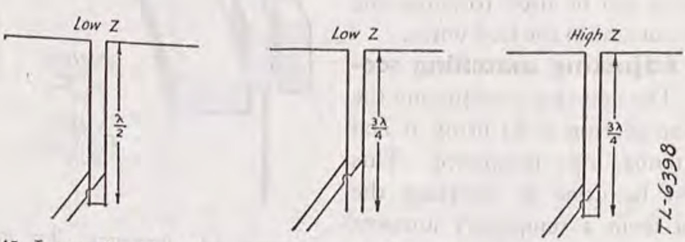

FIGURE 45. Longer lengths than quarter-wave can be used for matching stubs. A half-wave section used to match a low impedance must be closed, while a three-quarter-wave section is open if matching a low impedance, and closed if matching a high impedance.

a good match is to be obtained. The balanced center-fed system is much less critical in this respect, any deviation in the correct length of the antenna being made up in the matching stub. A matching stub does not necessarily need to be a quarter wave long. It can be made any multiple of a quarter wavelength, and it is often more convenient to adjust a half-wave or three-quarter-wave stub. Application of these lengths is shown in figure 45.

d. "Q" antenna.—(1) General. The impedance of a two-wire line of ordinary construction (400 to 600 ohms) can be matched, without tapping, to the impedance of the center of a half-wave antenna by the use of a quarter-wave line of special characteristics. The matching section must have low surge impedance, and therefore is commonly constructed of large diameter conductors of aluminum or copper tubing, with fairly close spacing. This type of antenna is known as the "Q" antenna. It is shown in figure 46. The important dimensions are the length of the two halves

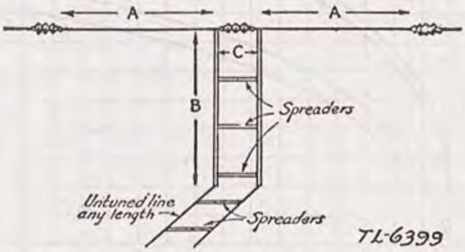

FIGURE 46. The "Q" match used with a half-wave antenna. Formulas for calculating the lengths and spacing are given in the text.

of the antenna, *A*, the length of the matching section, *B*, and the spacing between the two conductors of the matching section, *C*, and the impedance of the untuned transmission line connected to the lower end of the matching section.

(2) Conductor spacing. The required surge impedance for the matching section is

$$Z_s = \sqrt{Z_1 Z_2}$$

where Z_s is the impedance of the matching section, and Z_1 and Z_2 are the impedances being matched (line and antenna impedances). A quarter-wave section matching a 600-ohm line to the center of a half-wave antenna (72 ohms), for example, should have a surge impedance of 208 ohms. The spacings between conductors of various sizes of tubing and wire for different surge impedances are given in graphical form in figure 36. With half-inch tubing, for example, the spacing should be 1.5 inches for an impedance of 208 ohms.

(3) Length. The length, *B*, of the matching section should be equal to a quarter wavelength, and is given by

$$L\ (feet) = \frac{234}{Frequency\ (megacycles)}.$$

(4) Other application. The Q-match system can also be applied to antennas longer than a half wavelength. Figure 47 gives the impedances necessary to match various long-wire antennas to representative lines.

(5) Height. The height above ground will also affect the resistance at the current loops of any antenna (see sec. V) and should be considered when designing the matching section.

e. Corrective stubs.—(1) Use. A method of matching, or correcting, that resembles the quarter-wave matching section previously described is the so-called "corrective stub." It consists of an open or closed stub

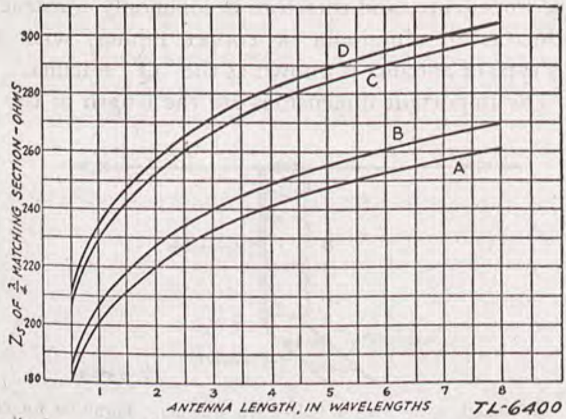

FIGURE 47. Required surge impedance of "Q" matching sections for radiators of various lengths. Curve *A* is for a line impedance of 440 ohms, curve *B* for 470 ohms, curve *C* for 580 ohms, and curve *D* for 600 ohms. Dimensions for the matching section can be obtained from figure 36.

that can be connected to the line at a convenient point, and it will eliminate the standing waves on the line from that point back to the transmitter end. It will have no effect on the line between the point of attachment and the antenna. However, in a case where a perfect match has not been obtained at the antenna and the line is long, it is possible to save some loss in the line due to standing waves by eliminating the standing waves between the point of attachment of the corrective stub and the transmitter.

(2) Standing-wave ratio. The corrective stub system is shown in figure 48. In order to use it one must first determine the standing-wave

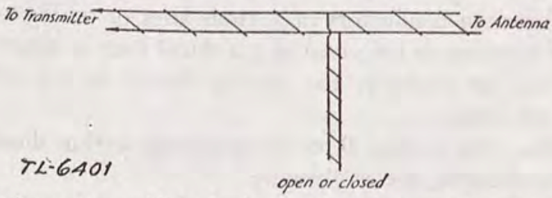

FIGURE 48. The "corrective stub" is simply a section of transmission line hung on the line at the proper place. It is first necessary to determine the standing-wave ratio of the line; the position and length of the stub can then be found from figure 49.

ratio on the line (ratio of current node to current loop values), and the points where the loop and node occur. The chart in figure 49 gives the length and position of the corrective stub for various standing-wave ratios.

An open stub is used near a current loop, and a closed stub near a current node.

(3) Function. The stub performs much the same function as the quarter-wave matching section, but can be inserted at any convenient point along the line, two positions being possible for every half wavelength of line. It should be placed as close to the antenna as is convenient, in order to make as much of the line as possible act as a matched line.

53. COMPARISON OF TUNED AND MATCHED LINES.

a. General. Practically all of the various types of lines just described may be used with elaborate as well as simple antennas. Tuned lines are, in general, easier to adjust than the matched types, and have the advantage that they are adaptable to more than one frequency more readily than are the matched line types of feed. However, the losses are somewhat higher in a tuned line than in a matched line. A comparison of the losses in a 600-ohm tuned line for various terminating impedances is shown in figure 50. It is apparent that if the line termination is about 40 ohms or less, as in the case of some of the close-spaced directive systems, the standing-wave ratio rises so high that serious losses ensue. In fact, the losses in the line can quite easily exceed the gain of the antenna system, resulting in a net loss instead of a gain.

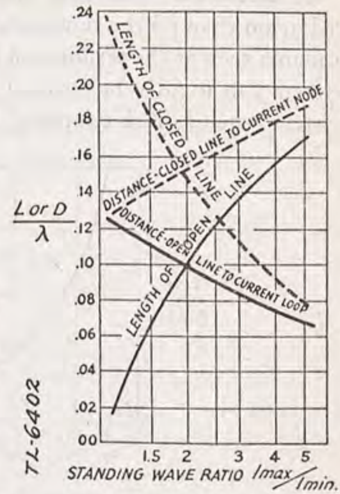

FIGURE 49. Distance and length of the line or loop of the corrective stub are given in fractions of a wavelength, but this value can easily be converted, since one wavelength equals $\frac{984}{\textit{Frequency (megacycles)}}$. All distances are measured from the current loop or node *toward* the transmitter.

b. Checking the line. Regardless of the type of line, the currents in the two wires should be kept as nearly equal as possible. An unbalance of current in the line can result in incomplete cancelation of radiation with resultant radiation losses from the line. The current in each wire of a two-wire line should be checked at some convenient point and, if the unbalance is greater than 10 percent, a check of the line should be made. Line unbalance can be caused by unequal lengths of wire in the line, capacity unbalance to ground or, in the case of an unsymmetrical antenna system, incorrect length of antenna. For the latter reason, symmetrical antenna systems are always better from the standpoint of minimum feeder radiation. Capacity unbalance can be introduced at any place along the line where one side of the line has more capacity to ground (or a grounded object) than the other, or it can be introduced right at the coupling to the plate tank. Grounding the center of the coupling coil will sometimes help here, or a Faraday shield can be used.

54. HARMONIC RADIATION.

a. General. Matched line systems usually result in lower harmonic radiation than do the tuned line systems, except in the case of a broad-band antenna such as the terminated rhombic. Harmonic transfer to the antenna system can usually be reduced by the use of a purely inductively-coupled system (such as link coupling). The pi-section filter, unless tuned exactly

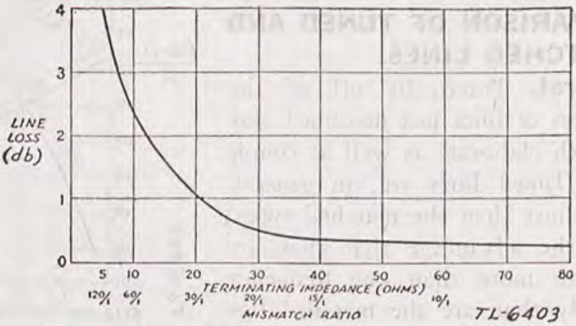

FIGURE 50. An experimentally determined chart of the losses in 1½ wavelengths of tuned line for various terminating impedances. The loss in 1½ wavelengths of untuned line is about 0.2 decibel.

as described, is notoriously bad for its harmonic-passing tendencies and should be avoided except for portable work, where its advantage of feeding practically any length of wire overshadows the disadvantage of harmonic radiation.

b. Use of link coil for harmonic suppression. Since harmonics are usually transferred to the antenna by capacity coupling, it is desirable to reduce or eliminate the capacity coupling in every case. Link coupling is excellent in this respect, provided the link is kept at ground potential. This can be done by placing the link at the low-voltage points on the coils (at the part of the coil where it is bypassed to ground, or the center of a balanced circuit) or, in stubborn cases, by grounding the link. The link coil should be made up of turns wound close together, and they should never extend over an appreciable length of the tank coil.

c. Use of Faraday shield. In the case of untuned transmission lines, the center of the coupling coil can be grounded (this also affords good drainage for static charges), or a Faraday shield can be used. The Faraday shield, in its simplest form, consists of a comb of metal between the two coils to prevent capacity coupling. No closed loops of wire should be present in a Faraday shield, since induced currents would cause heating and losses. If the shield is used between two coils the ends of which are coupled, the shield should be flat, and if it is used between two concentric coils, it must be concentric between the two coils. In either case, it can be made by winding wire spaced its own diameter on a flat or round form depending on the use) on which has first been placed a sheet of celluloid or heavy paper. The wire can be anything from No. 22 to No. 14. Bare wire is the easiest to use. The winding is painted with several coats of collodion or coil dope and, when dry, the entire winding is cut in a straight line parallel to the axis of the coil. Adjacent ends of each loop of the coil are soldered to a straight wire. The resultant sheet of parallel wires, insulated from each other but fastened at one end, is grounded and used as a shield between the tank coil and the output coil. It prevents capacity coupling, but has no effect on the magnetic coupling.

d. Single-wire feeder. A single-wire feeder capacity-coupled to the tank circuit will have practically no discrimination to harmonics and, for this reason, the inductively-coupled system is preferable.

55. LINE VELOCITY. The velocity of radio-frequency current along a line varies with the type of line, and this will modify the calculations for quarter-wave matching sections of various kinds, such as in the Q-match system. The length of a quarter-wave length of line can be calculated from

$$L\ (feet) = \frac{246\ V}{Frequency\ \ (megacycles)}$$

where V will depend upon the type of line used. The factors are as follows for the common types:

Parallel open wire line	$V=0.975$
Parallel tubing	$V=0.95$
Concentric tubes	$V=0.85$
Twisted pair	$V=0.56$–0.65

To obtain a half-wave or full-wave section, multiply L by 2 or 4, respectively.

56. LINE LOSSES. As mentioned previously, the loss in a matched 600-ohm open line is about 0.12 to 0.15 decibel per wavelength of line and, if tuned, will vary, depending upon the standing-wave ratio. The best rubber-covered low-impedance lines have a loss of about 1 decibel per wavelength of line—ordinary rubber-covered lamp cord has a surge impedance of about 140 ohms and about 1.4 decibel loss per wavelength when dry. It is practically worthless when wet, but can be used for many indoor applications. Two lengths may be paralleled to give a 70-ohm line, but the loss figure remains the same. The parallel molded-rubber type of lamp cord has a surge impedance of about 120 ohms, and it will stand the weather much better.

SECTION V

HALF-WAVE ANTENNAS

57. CHARACTERISTICS.

a. General. The simple half-wave antenna is probably more widely used than any other type since it is easy to install and adjust. It will, furthermore, give excellent results both in transmission and in reception, and, when suitable feeding methods are used, is readily adaptable to use on more than one band. The important characteristics of the half-wave antenna—radiation resistance, impedance variation along its length, current and voltage distribution, etc.—have already been discussed in section II. The free-space radiation pattern also was discussed in that section.

b. Characteristics retained regardless of method of feeding. At the outset it is essential to keep thoroughly in mind that a single wire antenna having a total length of one-half wavelength at the operating frequency is always a half-wave antenna, no matter what special name may be given it. It has been the practice to label an antenna by the method of feeding it, and such terms as "Zepp," "single-wire-fed Hertz," "doublet," "center-fed doublet," "Y doublet," "J," and various others are applied to what is essentially the identical antenna. The characteristics of a half-wave antenna are the same no matter what feed method is used. Of course, the results may vary somewhat with different feed methods depending upon the efficiency of the feeder, length of the line, and the accuracy with which it is matched to the antenna. These variations are

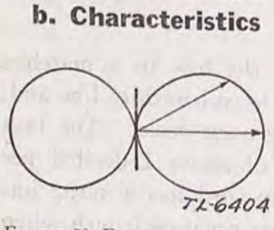

FIGURE 51. Free-space radiation pattern of a half-wave antenna parallel to the ground. The pattern is in the plane of the wire, viewed from above.

not chargeable to the antenna itself, however, since a given half-wave antenna in a given location will radiate a given amount of power fed to it in just the same way regardless of the means by which the power gets into the antenna.

58. POLARIZATION.

a. Effect of mounting. Half-wave antennas usually are suspended either horizontally or vertically, depending upon the type of polarization desired. The way in which the antenna is mounted does affect its directivity, however, and may also affect its efficiency when losses in nearby objects are considered.

b. Vertical and horizontal suspension. Referring to figure 51, imagine that the antenna is being looked down upon from a height, with the page representing the surface of the ground. The antenna is therefore horizontal. The directive diagram shows the relative intensity of radiation *along the surface of the ground* in various compass directions; maximum radiation is broadside to the antenna and minimum radiation is off the ends. If, however, the antenna is suspended vertically, the horizontal directive pattern will be simply a circle; in other words, the radiation is equally intense in all directions. A vertical antenna is nondirectional in the horizontal plane, while a horizontal antenna shows marked directional effects in the same plane.

c. Loss of energy. The losses in local objects tend to be somewhat lower with a horizontal antenna than with a vertical antenna. For a given height of pole or other supporting structure, a horizontal antenna usually will be farther away from the ground, trees, etc., since all of the wire is at the maximum height of the poles. When the antenna is vertical, however, its lower end is considerably nearer the ground, and if the pole height is the same, only the top of the antenna will be at the same height as the horizontal antenna. The greater proximity of the ground and other energy-absorbing objects usually means that more of the energy in the radiated waves is absorbed before it gets well started on its way.

59. EFFECTIVE DIRECTIVE DIAGRAMS.

a. Vertical and horizontal angles. The purely horizontal directive diagram of an antenna does not always give a true indication of the directive performance of the antenna, since at high frequencies the waves which are useful for communication always depart or arrive at some angle above the horizontal. Thus when the half-wave antenna is horizontal, there may be considerable useful radiation off the ends at *some angle above the horizontal*, although the plane diagram of figure 51, which shows horizontal radiation from a horizontal antenna, indicates that in the direction of the wire axis there is none. This can be made clear by examination of figure 52, which shows a horizontal half-wave antenna with a section of its free-space radiation pattern, taken on a plane cutting vertically through the wire. The effect of the ground is neglected. The lines *OA*, *OB*, and *OC* all point in the same geographical direction, but make different angles in the vertical plane with the antenna, corresponding to different angles of radiation. So far as compass directions are concerned, all three waves are leaving the end of the antenna. The purely horizontal wave *OA* has zero amplitude, but at a somewhat higher angle corresponding to the line *OB*, the field strength is appreciable. At a still higher angle corresponding to the line *OC* the field strength is still greater. The higher the angle considered, the greater the field strength in the same compass direction, for the figure shown. It should be obvious, therefore, that in plotting a directive diagram it is necessary to specify the angle of radiation for which the diagram applies. The shape of the diagram will be altered considerably at different radiation angles when the antenna is horizontal.

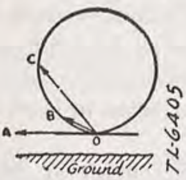

FIGURE 52. The effective directive pattern of the antenna depends upon the angle of radiation considered. As shown by the arrows, the field strength in a given compass direction will be quite different at different vertical angles.

b. Effect of frequency in directivity. Since the useful angles of radiation vary with frequency, as described in section I, the directivity of the antenna also will depend upon the frequency. In order to plot diagrams which represent the performance of the antenna under average conditions, it is necessary to choose radiation angles which are representative of transmission and reception on the frequency considered. Even on one frequency the most useful angle will depend upon the distance to be covered; for short distances, just beyond the limit of the first skip zone, the highest angles which will permit reflection from the ionosphere are most useful, while for extremely long distances low angles are most desirable since low angles give the smallest number of skips and hence the lowest attenuation. Thus the directivity of the antenna will also vary with the transmission distance and with ionosphere variations, which in turn depend upon the various factors described in section I.

c. Average directivity. It might seem from the discussion that it would be impossible to predict the directivity of the half-wave antenna without all sorts of qualifications, and in one sense that is true. However, it is possible to get a very good idea of the average directivity of the antenna for work over long distances (long, for the frequency considered) by choosing the angle which on the average represents about the center of the band of angles found to be useful for the purpose. Angles of 9°, 15°, and 30° have been selected, representing the midband angles for 28, 14, and 7 megacycles, respectively. The corresponding patterns are shown in figure 53. The diagrams should not be taken too literally, however, in view of the preceding discussion, but rather should be considered simply as an indication of the type of directivity to be expected for average work.

60. VERTICAL HALF-WAVE.

a. Vertical directivity. The directive pattern of a vertical half-wave antenna is a circle regardless of the angle of radiation considered. That is, for any given angle in the vertical plane the field strength is the same in any compass direction. The field strength will be different for each vertical angle, or angle of radiation, but the shape of a diagram will not change when the angle is changed. This being the case, the horizontal directivity can be neglected since there is none. The vertical directivity, or field strength at various angles of radiation, is the characteristic of interest. In a practical antenna system this will depend upon the height of the antenna above ground, as described in section III.

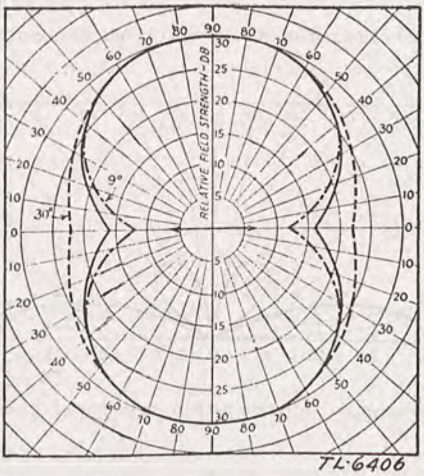

FIGURE 53. Directive patterns of a horizontal half-wave antenna at three radiation angles, 9°, 15° (solid line), and 30°. The direction of the antenna itself is shown by the arrow. These patterns are plotted to a 30-decibel scale, which is about proportional to signal strength as determined by ear. If 30 decibel represents an S9 signal, 0 on the scale will be about S1. All three patterns are plotted to the same maximum, but the actual amplitudes at the various angles will depend upon the antenna height, as described in section III. The patterns shown here show only the *shape* of the directive diagram as the angle is varied.

b. Effect of ground on pattern. The relative intensity of radiation at various vertical angles will depend upon the free-space radiation pattern of the antenna alone and the modifications of that pattern brought about by reflection of the waves from the ground. The theoretical pattern is found by multiplying the field strength of the free-space pattern at each vertical angle by the ground reflection factor for that same angle. The ground reflection factors vary with the height of the antenna, as shown in section III. The effect of the ground on the pattern of a half-wave vertical antenna is shown in the charts of figures 54 to 57, inclusive. These are theoretical patterns, based on the assumption of a perfectly-conducting ground. Except for the fact that the maximum radiation is not purely horizontal because of ground losses, they are fairly representative of actual practice. The practical result of ground losses is to curve the lower end of the pattern inward, somewhat as shown by the dotted lines. These charts illustrate the importance of height in relation to frequency. The height is in terms of

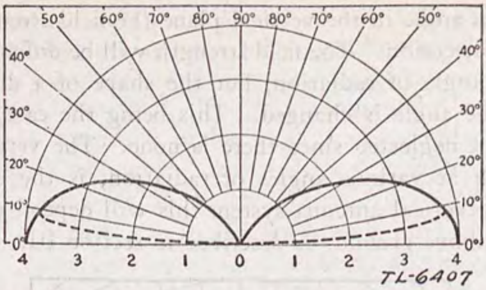

FIGURE 54. Vertical-plane radiation pattern, at height of one-quarter wavelength.

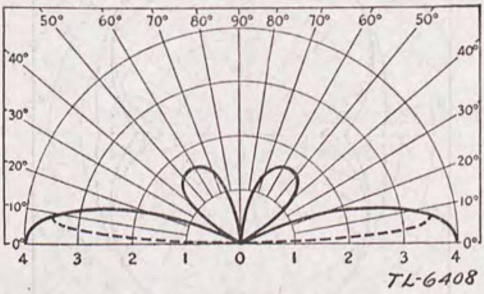

FIGURE 55. Vertical-plane radiation pattern, at height of one-half wavelength.

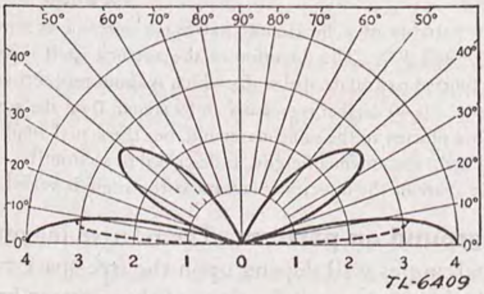

FIGURE 56. Vertical-plane radiation pattern, at height of three-quarter wavelength.

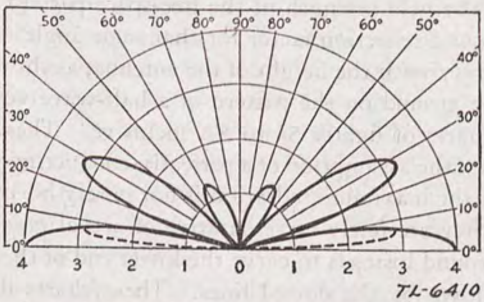

FIGURE 57. Vertical-plane radiation pattern, at height of one wavelength.

fractions of a wavelength. The higher the antenna, the sharper the directive characteristic in the vertical plane. If conditions permit, a height should be chosen which concentrates the radiation of the vertical angle most suitable for communication on the frequency used.

c. Height of antenna above ground. At frequencies above 12 megacycles it is best to have the antenna as high as possible so that it will be well clear of energy-absorbing objects in the vicinity. The height used, however, should be such that a null will not appear in the region of the most useful angles of radiation. Usually, the actual height above the ground will not be exactly the same as the equivalent height for which the type of reflection indicated takes place. The equivalent reflecting surface is generally a few feet below the actual surface. It may pay to move the antenna up and down over a range of a few feet, continuing the test over a period of some days, to determine the best actual height. When a ground screen is used, the screen acts as the conducting surface, and if its radius is of the order of a half wavelength or more, the antenna height can be considered to be its actual height above the screen.

61. HORIZONTAL HALF-WAVE.

a. Shape of directive diagram. The shape of the directive diagram of a horizontal antenna depends upon the radiation angle, as already described. The way in which it varies is shown in figure 53, for the three reference angles, 9°, 15°, and 30°. At still higher angles the pattern approaches a circle, which means that a half-wave antenna working at high angles shows practically no directive effects. This is actually the case on 3.5 megacycles, at least for moderate distances, and often applies on higher frequencies. At long distances, where the lower angles are more useful, the "pulling in" effect at the ends of the antenna may be more pronounced.

b. Orientation of antenna. The antenna should always be run in a direction which will give the greatest field strength in the most desired direction of communication. This means that the half-wave antenna should be broadside to the desired direction. For instance, if communication on an east-west line is most desired, the antenna should run from north to south. Proper orientation of the antenna is most important at the higher frequencies, where low-angle radiation is most useful, because it is at low angles that the antenna shows the most pronounced directivity.

c. Effect of height on directivity.—(1) Shape. The height of the horizontal antenna does not affect the *shape* of the directive diagram at a given radiation angle, but simply changes the intensity of radiation. The effect of the ground is similar to the case of the vertical antenna, although as explained in section III the angles at which the nulls and maxima occur are reversed.

(2) Angle. The effect of height on the angle of radiation is shown in figures 58 to 69, inclusive, for several heights. Since the free-space pattern

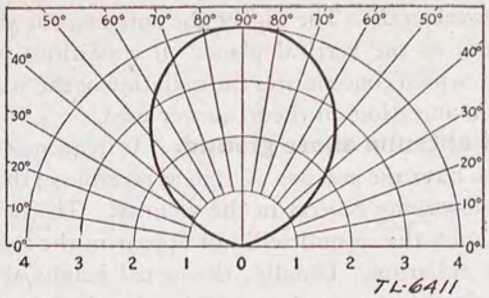

Figure 58. In direction of wire; height one-fourth wavelength.

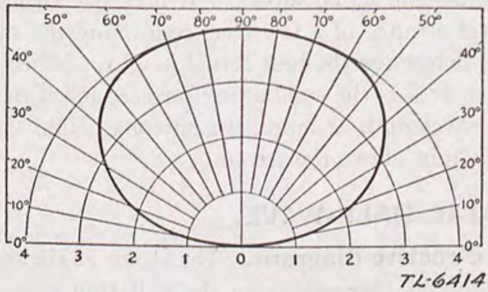

Figure 59. At right angles to wire; height one-fourth wavelength.

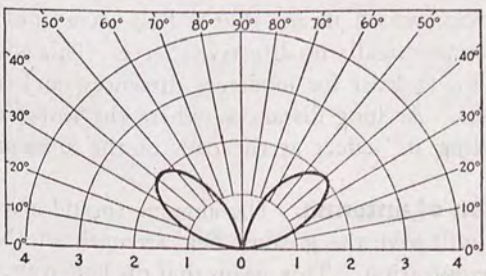

Figure 60. In direction of wire; height one-half wavelength.

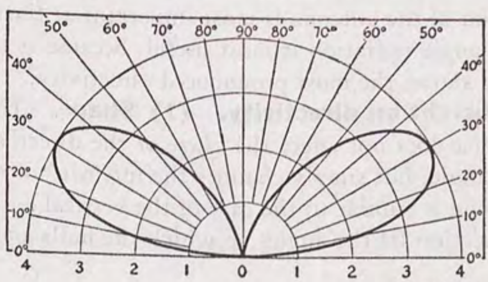

Figure 61. At right angles to wire; height one-half wavelength.

of a horizontal antenna is not a circle, it would take an infinite number of diagrams of this type to give a complete picture of the vertical characteristic at all horizontal directions. In these charts, the shape of the vertical

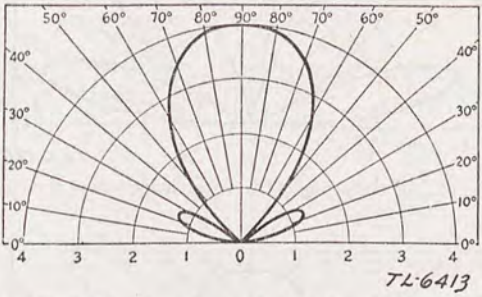

FIGURE 62. In direction of wire; height three-fourth wavelength.

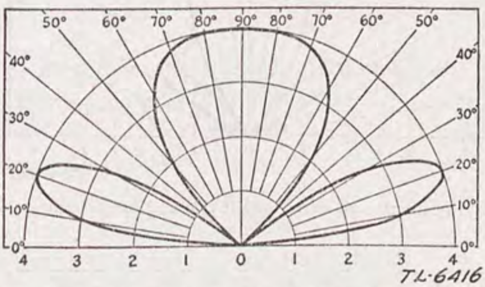

FIGURE 63. At right angles to wire; height three-fourth wavelength.

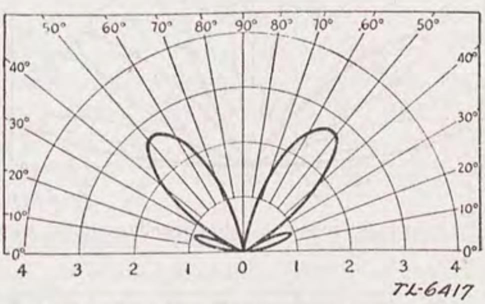

FIGURE 64. In direction of wire; height one wavelength.

characteristic is shown for the direction in which the antenna runs (minimum radiation) and broadside to the antenna (maximum radiation). At intermediate directions the vertical characteristic will assume a shape which depends upon how close the direction considered is to one or the other of the two limiting directions shown.

(3) Height to be used. A height of at least a half wavelength is necessary for appreciable radiation at angles of the order of 15°, and greater heights are desirable. At the higher frequencies, where low-angle radia-

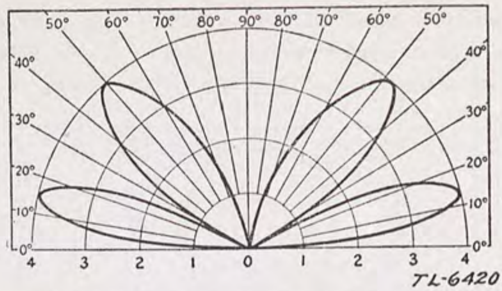

Figure 65. At right angles to wire; height one wavelength.

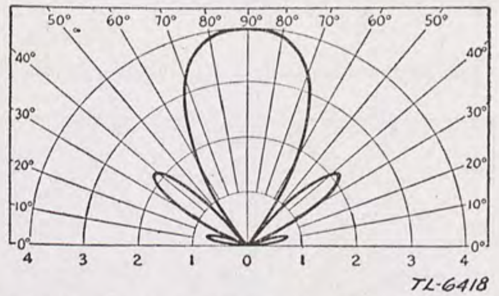

Figure 66. In direction of wire; height one and one-fourth wavelengths.

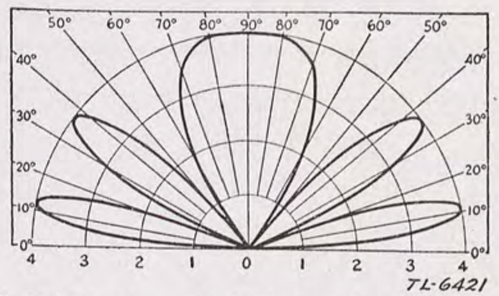

Figure 67. At right angles to wire; height one and one-fourth wavelengths.

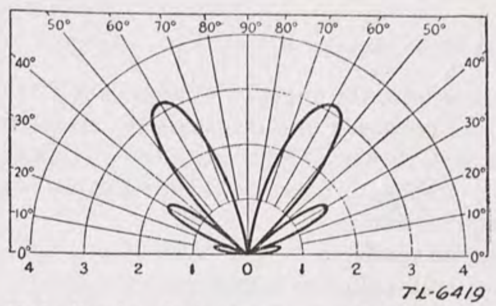

Figure 68. In direction of wire; height one and one-half wavelengths.

tion is necessary, the heights needed are easier to attain, since the height is in terms of fractions of a wavelength. A height should be chosen which centers the radiation in the most useful group of angles for the frequency used, and heights which put nulls in these angles should be avoided. As in the case of the vertical antenna, the effective ground plane, for purposes

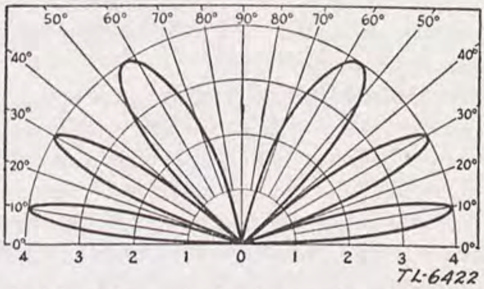

FIGURE 69. At right angles to wire; height one and one-half wavelengths.

of reflection, usually is a few feet below the actual surface of the ground, while a ground screen of suitable size tends to act as the actual reflecting plane. These patterns are theoretical, and assume a perfectly conducting ground. Losses in the ground tend to reduce the maximum intensity of the lobes and to prevent the appearance of complete nulls. The positions of nulls and maxima may also be shifted slightly, but on the whole the charts are quite representative of actual performance.

62. RADIATION RESISTANCE.

a. General. The theoretical value of about 73 ohms for the radiation resistance of a half-wave antenna in free space is modified by the presence of the ground. For a horizontal half wave above perfectly conducting ground the actual value oscillates about the value of 73 ohms as shown in figure 28. The actual value of radiation resistance may be considerably above or below 73 ohms, particularly when the height is slightly less or slightly more than a half wavelength.

b. Effect of variation. This variation in radiation resistance has little practical effect on the efficiency of a half-wave antenna because the loss or ohmic resistance is still quite low in comparison to the radiation resistance even at heights which give values of the order of 50 ohms. It is of interest chiefly because it may affect the termination of nonresonant feeder systems, particularly those types intended to match into the center of the antenna without adjustment in the field.

63. LENGTH OF HALF-WAVE ANTENNA.

a. Formula. It was pointed out in section II that because of end effects the physical lengths of a half-wave antenna averages 5 percent less than the length of a half wave in space. The factor varies somewhat with frequency, being 0.96 for frequencies below 3,000 kilocycles and 0.94 for frequencies above 30 megacycles. The factor of 0.95 applies throughout the frequency range of particular interest in this section, however, so that for frequencies from 1.5 to 30 megacycles this formula—

$$\textit{Length of half wave (feet)} = \frac{468}{f\ (\textit{megacycles})}$$

is sufficiently accurate. Antennas for frequencies lying outside this range are treated in separate sections.

b. Effect of small variation in length. In practice, the actual length of the antenna may be found to depart slightly from the figure given by the formula, principally because of height above ground and the proximity of such objects as poles, trees, and buildings, to the antenna. This variation may be neglected in most cases, except possibly so far as it may affect feeder performance, a subject which will be discussed later. Aside from this, a small percent variation in length will have no appreciable effect on the characteristics of the antenna itself.

c. Method for making mechanically suitable connection. A point of some concern to many constructors, particularly beginners, is that of determining the actual length of the antenna, since in practical construction it is necessary to run the wire through the supporting insulator and twist it back on itself to make a mechanically suitable connection. The best plan is to clean off all the insulation on the last 8 or 10 inches of wire and run it through the eye of the insulator, leaving a few inches of the bright wire over which the end can be twisted. The joint should be carefully soldered so that a closed loop is formed, both mechanically and electrically. The measurement can then be made to the insulator eye when the wire is stretched tight.

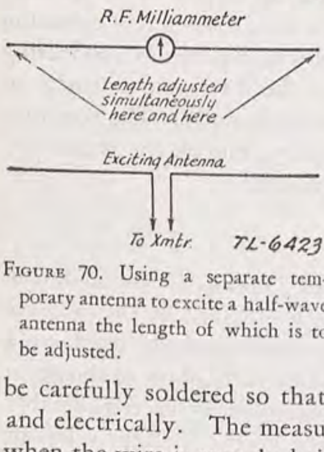

Figure 70. Using a separate temporary antenna to excite a half-wave antenna the length of which is to be adjusted.

64. DETERMINING LENGTH.

a. General. There are several methods by which the electrical length of the antenna may be adjusted quite accurately to a half wave at the desired frequency. All of them involve disconnecting the feeders from the antenna. Needless to say, the adjustment should be made with the antenna in its final position.

b. Galvanometer method.—(1) General. One such arrangement is shown in figure 70. An r. f. galvanometer is connected in the center of the antenna, either by inserting it in the wire or by connecting it across several inches of the wire. The full-scale range of the meter will depend upon the amount of power available and the coupling to the auxiliary antenna. The latter may be a temporary affair strung somewhere in the vicinity, preferably a half wavelength or more away from the antenna to be adjusted. It is connected to the transmitter by any convenient type of transmission line.

(2) Range of galvanometer. The conventional current-squared galvanometer, which has a full-scale range of 115 milliamperes, will be satisfactory for powers up to 100 watts when connected directly in the center of the antenna. For larger powers it can be connected across a few inches of the antenna, the connections being made at equal distances from the center of the wire.

(3) Method of use. Starting out with the antenna known to be slightly long for the frequency, the power input to the transmitter is adjusted to give a suitable reading on the antenna meter. Then equal lengths of wire (a few inches) are clipped off *each* end of the antenna, so that the meter remains in the center, and the meter reading noted. The power input to the transmitter should be kept constant. This process should be repeated, with the meter readings recorded each time, until the current has passed through a maximum and begins to decrease. The length which gives the highest meter reading is the correct one for that frequency. A curve of antenna current against length may be plotted so that the exact maximum can be determined in case it falls between two arbitrarily selected lengths in the experimental procedure.

(4) Use of binoculars. Since the antenna length must be adjusted with the antenna in position, the determination of the correct length may be a somewhat tedious task because it will usually be necessary to lower the wire to change the length. Also, with this method it will often be necessary to use binoculars to read the ammeter, which is not altogether easy if there is a breeze.

c. Vacuum-tube oscillator method. An alternative method is to use a vacuum-tube oscillator loosely coupled to the antenna as shown in

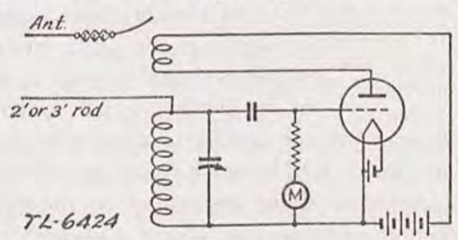

FIGURE 71. The grid-dip method of checking the frequency of a half-wave antenna. The oscillator circuit may be of any type so long as it can be tuned to the frequency at which the antenna is resonant. With 45 to 90 volts on the plate, a 10,000-ohm grid leak will be satisfactory when a 0-5 d-c milliammeter is used in series. The feedback should be adjusted to bring the pointer to about half scale.

figure 71. A low-range (0-1 to 0-5) d-c milliammeter is connected in series with the oscillator grid leak and a small pick-up antenna connected to the oscillator grid. When the pick-up antenna is brought near the antenna to be checked, the oscillator is tuned to the point which gives

maximum dip in grid current indicating that the antenna is taking energy, at its resonant frequency, from the oscillator. With the coupling loosened so that the pointer just flickers downward noticeably at resonance, the frequency of the oscillator should be checked by any convenient frequency-measuring means. If the frequency is too low, the antenna should be shortened a bit and checked once more; similarly, if the frequency is too high the antenna should be lengthened. Since it will not usually be possible to bring the oscillator itself close to the antenna, a small double type pick-up antenna may be connected to a twisted-pair line and the latter run to the oscillator, which may then be operated from the ground. The pick-up antenna may be temporarily fastened to one of the insulators supporting the antenna so that it will be near a high-voltage point. To avoid the possibility of resonance in the desired frequency range in the line, the grid current should first be checked with the pick-up antenna considerably removed from the regular antenna, to make sure that there is no dip within a reasonable range of the operating frequency.

d. Additional half-wave section method. Still a third method makes use of the fact that the addition of a half-wave section to a line does not disturb the line's operation when the additional section is exactly an electrical half wave. In this method the antenna is end-fed by a tuned line which can be disconnected from the antenna at will, as shown in figure 72. Either series or parallel tuning can be used at the transmitter end of the line, depending upon the line length. With the line disconnected from the antenna, the tuning is adjusted to give maximum feeder current, using the loosest coupling which will give a satisfactory reading. (Without the antenna connected, the meter readings will be quite high, so very loose couplings should be used at the start.) Then the feeder is clipped to the antenna, and, *without changing the coupling*, the tuning is again adjusted for maximum feeder current. The current will be much lower, but this does not matter; it is the tuning adjustment giving resonance, or the maximum current, whatever that maximum value may be, which is wanted. If the capacitor or capacitors are found to be set at lower capacity than before, the antenna is too long; if at higher capacity, the antenna is too short. When the antenna is exactly the right length, the capacitor settings will be the same either with or without the antenna connected.

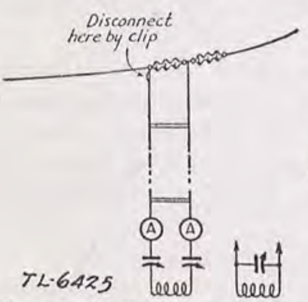

FIGURE 72. Using a transmission line to determine the resonant frequency of the antenna. The method is described in the text.

e. Accuracy required. Adjustment of the antenna length by one of the methods described is not necessary unless it is desired to get the most accurate feeder match at one frequency. This accuracy is not needed in the case of lines of ordinary length since, as described in section IV, a mismatch ratio of 2 or 3 to 1 does not appreciably increase the losses in a line which is not more than a wavelength or so long. It is useful when the line is unusually long, so that feeder losses become appreciable when a mismatch occurs, but in most cases this is not a consideration. Furthermore, the length is correct for one frequency only, and for another frequency in the same band the antenna will no longer be exactly an electrical half wave.

65. METHODS OF FEED.

a. General. In the following sections, the application of the various types of transmission lines to the half-wave antenna will be discussed. The information given here should be used in conjunction with the design and adjustment data given in section IV for the type of line under consideration. The discussions in section IV are perfectly general; only those conditions peculiar to the half-wave antenna are given attention in this section. The feed methods apply equally well to antennas installed either vertically or horizontally, or, for that matter, to those which slant. Although as a matter of convenience most of the diagrams show horizontal antennas, it should be kept in mind that the position of the antenna with respect to ground does not affect the feed method.

b. End or voltage feed.—(1) General. The simplest, although not the best, method of feeding power to the half-wave antenna is to connect one end through a low-capacity capacitor to the final tank coil of the transmitter, as shown in figure 73 (A). This is often called "end feed" or "voltage feed." The disadvantage of this system is that it necessitates bringing the end of the antenna into the station, which usually means that the height must be limited and that the dielectric losses in nearby objects will be comparatively high. It involves no feeder or tuning apparatus, however, and is useful on the lower frequencies where there may not be room enough for a regular antenna-feeder system.

(2) Use of coupling capacitor. The coupling capacitor, *C*, is used simply for insulation in case the final tank is series-fed, to prevent plate voltage from appearing between the antenna and ground. Its capacity may be quite low; in fact, a capacitor of the disk neutralizing type may be used. The capacitor need not be variable, however, and may be constructed from two pieces of copper or aluminum sheet 1 or 2 inches square. A variable capacitor will permit some adjustment of loading, but the same adjustment can be attained by tapping the antenna at the proper point on the tank coil. Whichever method is most convenient may be used. With the tap, the blocking or coupling capacitor can be a mica unit of about 100-$\mu\mu$f capacity and a voltage rating higher than the maximum d-c plate voltage (twice the d-c plate voltage on a plate-modulated class C stage).

(3) Adjustment of coupling. The method of adjustment is as follows: With the antenna disconnected from the tank, tune the tank to resonance (minimum plate current). Then tap the antenna on the coil at a point near zero r. f. potential. In the case of a single-ended tank circuit this will be near the end of the coil opposite that connected to the plate; with a balanced tank, near the center tap. Retune the tank to resonance, again indicated by minimum plate current. The new minimum will be higher than without the antenna connected, however. The setting of the plate tank capacitor will change little, if at all, if the antenna is exactly a half wave at the operating frequency. An appreciable change in the capacitor setting will indicate that the antenna length is incorrect; short, if more capacity must be used, and long if less capacity is necessary. Move the tap towards the plate end of the coil a turn at a time, retuning the tank each time, until the amplifier is drawing full-load plate current. This will be the rated plate current for the tube or tubes if the amplifier is properly excited. A rough idea of the output can be obtained by touching a neon lamp to the end of the antenna; if the brightness of the glow passes through a maximum before the tap is moved up to the position which gives rated plate current, the point of maximum output has been passed, and the tap should be returned to the point which gives the brightest glow. If this happens, the amplifier probably is not being driven properly (insufficient excitation).

(4) Variable coupling capacitor. If a variable coupling capacitor is available, the capacitor may be connected directly to the end of the tank. The adjustment procedure is similar, but instead of moving the tap up on the coil the capacitor capacity is increased from minimum in steps, with the final tank being retuned each time, until the maximum output or rated plate current is reached. The plate spacing of the coupling capacitor must be at least that of the plate tank capacitor, although only a small capacity is used.

(5) Effect of capacity coupling. Capacity coupling of the antenna is likely to lead to trouble with harmonic radiation since the antenna also will be resonant to any harmonics which may be developed in the amplifier. Also, if the antenna is not just the right length, a standing wave may develop on the transmitter. As a result the transmitter may assume an r. f. potential above ground, so that parts of the circuit which should be "dead" for r. f. turn out to be "hot."

(6) Inductive coupling. Troubles of preceding types can be largely avoided by using inductive coupling between the transmitter and antenna, as shown in figure 73 (B). In this case the antenna is tapped on a separate tank, tuned to the same frequency as the transmitter, and coupled inductively to the transmitter tank coil. The coupling circuit should be grounded either at one end or at the center—it does not matter particularly which is used—through a short connection to a good ground separate from the transmitter ground. To adjust, couple L_1 and the tank coil loosely, and tune C_1 to resonance. There will be but a slight rise in plate current as C_1 passes through resonance, provided the coupling is very loose. Increase the coupling in small steps, retuning C_1 and the plate capacitor to resonance each time, until the rated plate current is secured. The right coupling is that which will make the plate current drop off as C_1 is tuned to either side of resonance, and just rise to the full-load value (with the plate capacitor tuned for minimum plate current) with C_1 at resonance. The coupling circuit should have about the same L/C ratio as the final tank circuit, although the values are not critical. The voltage rating of C_1 should be the same as that of the plate tank capacitor.

c. Center or current feed.—(1) General. Another method of putting power into the antenna without a feeder system is sometimes used. It is called center feed, and is shown in figure 74. The half-wave antenna is in two sections, with the center brought into the station. This scheme has the same disadvantages as to losses and lack of height as the end-feed method, although the losses may be somewhat lower because the part of the antenna entering the station is at low r. f. voltage.

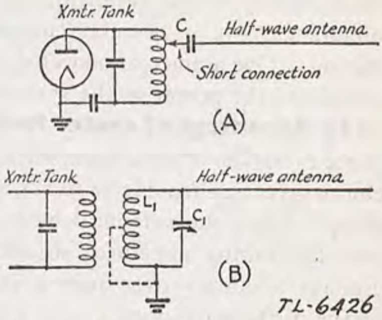

FIGURE 73. Voltage feed to an antenna. With this method no feeders are used, but the end of the antenna must be brought into the station.

(2) Antenna coupling. The antenna is coupled to the final tank by means of a small coil, L_1, the reactance of which is tuned out by means of the two capacitors, C_1 and C_2. The size of the coil is not critical; it need have only sufficient turns to give adequate coupling for power transfer between the final tank and antenna. Usually a few turns, varying from one or two at the higher-frequency bands to 10 or so at the medium-frequency bands, of the same diameter as the tank coil, will be sufficient. The antenna capacitors, C_1 and C_2, have to carry only a relatively small r. f. voltage, hence the plate spacing may be smaller than the spacing of the plate tank capacitor. The maximum capacity needed depends upon the frequency and the size of L_1, as given under the diagram.

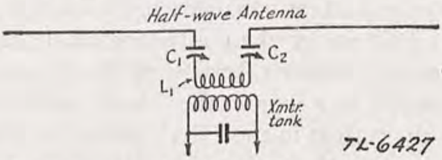

FIGURE 74. Current-fed antenna without feeders. The number of turns for L_1 is not critical; average values will be from 2 or 3 turns at 28 megacycles to 10 or 12 turns at 3.5 megacycles, using the same type of winding as the plate tank coil. C_1 and C_2 should be identical; maximum capacity needed will vary from 250 to 350 $\mu\mu f$ at 3.5 megacycles to 100 $\mu\mu f$ at 28 megacles. The larger size can be used for all frequencies between these limits.

(3) Tuning adjustment. The tuning adjustment is done in the same manner as described in paragraph 65**b(3)**. Starting with L_1 decoupled from the tank circuit, tune the tank to resonance. Then increase the coupling in small steps, tuning C_1 and C_2 simultaneously for maximum plate current and the tank capacitor for minimum, until the minimum plate current is the rated current for the amplifier. Use the smallest value of coupling which will give this condition. Ammeters may be inserted to read the antenna current, maximum current indicating maximum power in the antenna. One ammeter connected in either of the antenna leads will suffice to indicate the power in the system as a whole.

(4) Advantage of center feed. The center-feed arrangement tends to reduce radiation of even harmonics, and because of the inductive coupling, seldom gives any trouble with r. f. at supposedly "dead" spots in the transmitter. Also, the antenna length need not be figured with extreme care, since the tuning apparatus inserted at its center permits varying the resonant frequency over quite a range on either side of the resonant frequency of the wire alone.

d. End feed with resonant transmission line (Zepp).—(1) General. (a) The use of a transmission line between the transmitter and antenna permits locating the latter in the most advantageous position available. One of the most popular types of feed for a half-wave antenna is a resonant line with one wire connected to one end of the antenna. This arrangement, commonly known as a "Zepp" antenna, is shown in figure 75. The transmission line preferably should be some multiple of a quarter wave in length, or nearly so.

(b) Since only one side of the transmission line is connected to the antenna, there is always a slight unbalance in the line, even when the two currents are exactly 180° out of phase all along the line. The two wires do not act independently, however, because of the coupling between them, and therefore the current at a loop in the "dead" or open feeder does not differ greatly from the current in the "live" feeder, or the side of the line connected to the antenna. Hence there is but little radiation from the line, provided the antenna length is correct.

(2) Incorrect length. The effect on feeder balance of incorrect length is shown in figure 76, which shows an antenna with quarter-wave feeders. Instantaneous current directions also are shown. When the antenna length is correct, as at (A), the feeder currents are opposite in phase all along their length, and of approximately the same amplitude in each feeder. If the antenna is too long, however, as at (B), the current goes through a reversal on the antenna so that the standing wave on the live feeder is moved along as compared to that on the dead feeder. Thus the feeder currents are not exactly out of phase and there will be some radiation from the line. The effect of too short an antenna is shown in (C), where the standing wave on the live feeder has been moved in the opposite direction. There must always be a current node at the end of the dead feeder, so that the current distribution on this feeder is not greatly affected by the antenna length. The greater the departure of the antenna length from a true electrical half wave the greater the feeder unbalance, and hence the higher the radiation from the line. In most cases a small amount of line radiation does no particular harm, so it will usually suffice to cut the antenna for the most used frequency and line radiation can be neglected for work over a range of a few percent either side of the optimum frequency. This is particularly true for short lines. As the line becomes longer—a few wavelengths or more—the energy radiated becomes a greater percentage of the

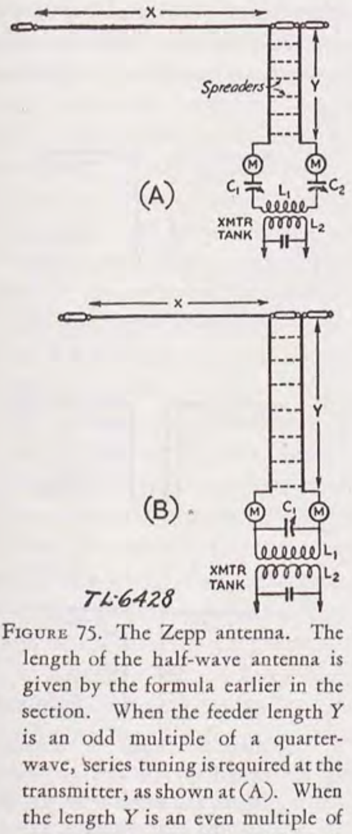

Figure 75. The Zepp antenna. The length of the half-wave antenna is given by the formula earlier in the section. When the feeder length *Y* is an odd multiple of a quarter-wave, series tuning is required at the transmitter, as shown at (A). When the length *Y* is an even multiple of quarter-wave, parallel tuning is needed (B). Method of coupling is described in section IV.

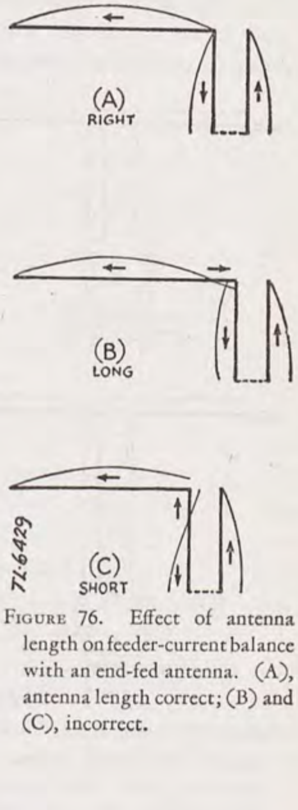

Figure 76. Effect of antenna length on feeder-current balance with an end-fed antenna. (A), antenna length correct; (B) and (C), incorrect.

total fed to the system, and the frequency range over which operation can be carried out with negligible line losses becomes smaller.

(3) Feeder length. For ease of coupling power into the system it is advisable to make the feeder length a multiple of a quarter wavelength. Some departure from this length can be tolerated, because the discrepancies can be made up to some extent in the tuning apparatus where the line is coupled to the transmitter. However, lengths which fall nearly midway between quarter-wave lengths often give trouble, making it hard to find a tuning adjustment which will "take power" from the transmitter.

(4) Coupling to transmitter. The most popular coupling system for the Zepp antenna consists of a coil and one or two capacitors arranged either for series or parallel tuning, depending upon the feeder length; series tuning for feeders an odd multiple of a quarter wave in length, parallel tuning for even multiples. Series tuning and parallel tuning correspond respectively to voltage feed and current feed as previously described. The same considerations apply to the coil and capacitor constants and ratings, and the tuning procedure is that already described. The similarity of a quarter-wave feeder with series tuning to the current-

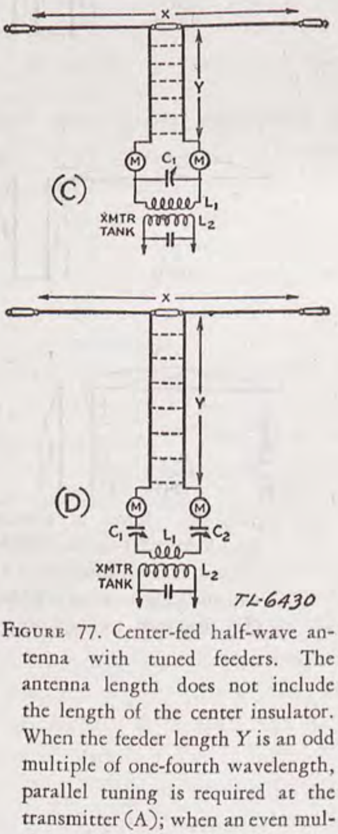

FIGURE 77. Center-fed half-wave antenna with tuned feeders. The antenna length does not include the length of the center insulator. When the feeder length *Y* is an odd multiple of one-fourth wavelength, parallel tuning is required at the transmitter (A); when an even multiple, series tuning is used (B). See section IV for coupling and tuning data.

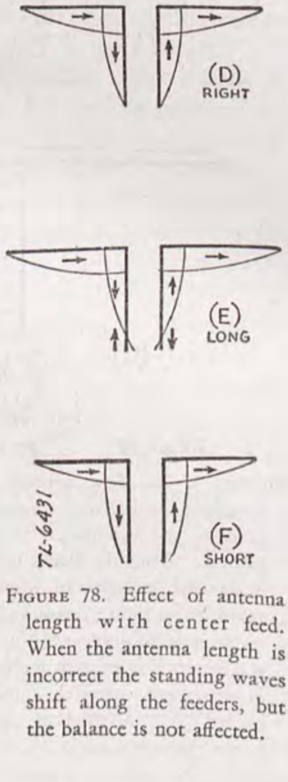

FIGURE 78. Effect of antenna length with center feed. When the antenna length is incorrect the standing waves shift along the feeders, but the balance is not affected.

fed half-wave antenna is readily appreciated, if the two halves of the antenna of figure 75 are imagined to be bent to form a parallel-wire transmission line. Likewise, parallel tuning with half-wave feeders is readily comparable to voltage feed to a half-wave antenna (fig. 73) except that a second half-wave wire is connected to the other side of the coupling tank to eliminate radiation. A ground connection on the coupling coil is not necessary with the feeder system, but can be used if desired. It should be made to the center of the coupling coil, however, and not to one end Besides series and parallel tuning, other coupling arrangements suitable for use with resonant lines, as shown in section IV, may be used with the Zepp antenna.

e. Current or center feed with resonant feeders.—(1) General. Instead of feeding at the end, the resonant transmission line may be inserted in the center of the half-wave antenna as shown in figure 77. With this arrangement the feeder is connected to a low-impedance point in the antenna, so that the impedance looking into the feeder at the transmitting end is just the opposite, for the same feeder length, to the case with the Zepp antenna. Thus a quarter-wave feeder shows high impedance at the transmitter and parallel tuning is required, while a half-wave feeder shows low impedance and series tuning is necessary. The general rule is: Use series tuning with feeders an even multiple of a quarter wave in length, and parallel tuning with odd multiples.

(2) Advantages over end feed. With center feed, incorrect antenna length does not unbalance the feeders, so long as both sides of the antenna are the same length. In other words, if the system is symmetrical, a situation such as that shown in figure 76 cannot occur. Rather, the standing waves on the feeders shift as indicated in figure 78. The nodes and loops move symmetrically along *both* feeders, so that a considerable departure from the resonant frequency will not cause feeder radiation. Such an antenna can be worked over a very wide frequency range with practically no loss of efficiency. In addition, the inherent unbalance of the Zepp system is not present with the transmission line connected to the center of the antenna, since the two wires of the line are equally loaded. On the whole, therefore, this arrangement is preferable to the Zepp from the standpoint of feeder operation. As in the case of the Zepp antenna, the preferred feeder lengths are those which are close to multiples of a quarter wavelength. Again, any type of coupling suitable for use with resonant lines (sec. IV) can be employed.

66. USE OF NONRESONANT LINES.

a. General. As explained in section IV, a transmission line which is terminated in a resistance equal to its characteristic impedance will not have standing waves, and no special length is needed for proper operation. This feature is often advantageous, because it is sometimes inconvenient to make the length of a line one of the quarter-wave multiples desirable for satisfactory power transfer. An important feature in the use of nonresonant or "flat" lines is the method by which the impedance at the antenna is matched to the line impedance. This distinguishes the various types of matched feeder systems used with half-wave antennas.

b. Transmission lines having impedance equal to antenna radiation resistance.—(1) Twisted pair. The simplest method of assuring a match between the antenna and the line is to make the line impedance equal to the antenna resistance. In the case of the half-wave antenna this resistance averages about 73 ohms at the center, so that a line of 73 ohms impedance is required.

(a) Construction. It is not practicable to construct an open-wire line having this value of impedance, but one can be made by using rubber-insulated wire, which not only permits the two conductors to be quite closely spaced but also further raises the capacity per unit length by providing a higher dielectric constant in the medium between the wires. A line of this type is simply connected into the center of the half-wave antenna, as shown in figure 79. It may be made any convenient length. At the transmitter end it can be coupled to the final tank by means of one or two turns of wire, without any special tuning apparatus. However, a tuned coupling circuit can be used, if desired, as shown in section IV.

(b) Accuracy of match. The accuracy of the match will naturally depend upon the exact value of line impedance—twisted pairs of different types have differing impedances, as listed in section IV—and, in addition, will depend upon the height and location of the antenna. The effect of height on the resistance has been already discussed in section III. It is possible to make the antenna impedance match the line impedance, if the latter is in the vicinity of 70 ohms, simply by adjusting the height of the antenna until standing waves are minimized. The antenna impedance will be affected somewhat by nearby trees and buildings, but it is impossible to forecast the magnitude of this effect. The best plan is to keep the antenna as much in the clear as possible.

(c) Importance of antenna length. For a good match, it is essential that the antenna be the right length; the correct length for the operating frequency can be determined by one of the methods already described. If the line impedance is somewhat lower than the antenna impedance, a better match can be brought about by fanning the last few inches of the line (see fig. 79) to form a V. The amount of fanning necessary will depend upon the relative antenna and line impedances, and usually will be between 6 and 18 inches. The match may be checked by inserting ammeters in each antenna leg at the junction of feeder and antenna, adjusting the V until the current is maximum.

(d) Measurement of standing waves. It is not readily possible to measure directly the standing waves on a twisted-pair line. One method of checking is to measure the current into the line at the transmitter end, then temporarily insert a section about a quarter wave long (electrical length) between the regular line and the coupling coil, and read the current into the new section of line. If the current is within 10 percent or so of its previous value, the line is quite well matched. A badly mismatched line will show "hot spots" along its length if operated for a period of time with a few hundred watts input, since the losses are higher at the voltage loops when standing waves of appreciable magnitude are present.

(e) Permissible standing wave ratio. As shown in section IV, the increased line loss for standing wave ratios of 2 or 3 as compared to a really "flat" line is not serious. If the line is properly matched to the antenna

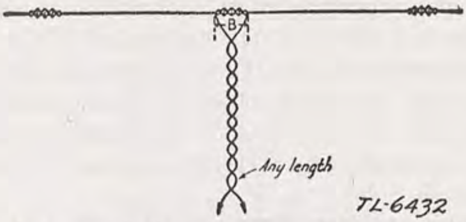

FIGURE 79. Twisted-pair feed to a half-wave antenna. The antenna length does not include that of the center insulator. The distance *B* depends upon the relative impedance of the antenna and the line, as described in the text. As much as 18 inches may be beneficial.

at one frequency, therefore, it will work quite efficiently over a fair range of frequencies on either side of the correct one. If the antenna is to be used over a whole band of frequencies, the system should be carefully matched for a frequency near the center of the band. Compared to air-insulated lines, losses in a twisted-pair feeder are high. Such lines, therefore, should be used only in short lengths (in terms of wavelength). The loss in a twisted-pair line increases markedly as moisture is absorbed in the insulation. It pays, therefore, to use high quality lines and to take precautions against rain. Where the line connects to the antenna the V should be well covered with rubber tape, and care should be taken to keep the waterproof covering on the line intact. Ordinary lamp cord is not recommended because of lack of weatherproofing.

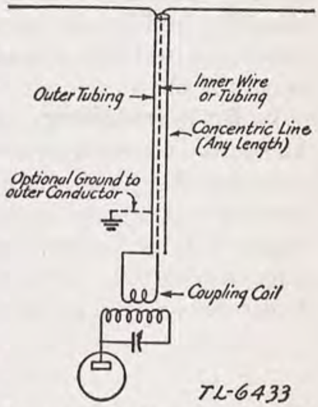

FIGURE 80. Half-wave antenna fed by 70-ohm concentric line, either air- or rubber-insulated. See section IV for coupling details. The antenna length does not include the length of the center insulator.

(f) Harmonic suppression. With twisted-pair feed, radiation of even harmonics of the transmitter frequency is quite low, because the line is badly mismatched at even multiples of the fundamental frequency. Odd harmonics can readily be radiated, however. A coupling system which discriminates against harmonics is to be preferred.

(2) Concentric or coaxial line feed.—(a) General. A 70-ohm concentric cable, either rubber- or air-insulated, can be used to replace the twisted-pair feeder described in section IV. The arrangement is shown in figure 80. If a rubber-insulated cable is used, all of the remarks in the preceding section on adjustment, use, and losses, apply with equal force.

(b) Losses in line. With air-insulated lines, that is, lines in which the inner and outer conductors are held at fixed spacing by means of high grade ceramic spacers, which form a relatively small part of the total dielectric, the losses are negligible, even in unusually long lines. The type consisting of a copper tube inclosing a concentric wire is especially good from the standpoint of being weather proof, and there is practically no loss by radiation from such a line. Data for conductor sizes and spacing to make a 70-ohm line are given in section IV. Also available are flexible concentric lines of the requisite impedance consisting of a braided-wire outer sheath inclosing a stranded inner conductor, the two being separated by cup-shaped ceramic or polystyrene spacers. These are also low loss, but less impervious to moisture than the solid type.

(c) Matching and coupling adjustments. Matching and coupling adjustments are the same as for twisted-pair feeders. An antenna with this type of feed is equally capable of working over a reasonable frequency range without excessive loss because of standing waves.

67. IMPEDANCE MATCHING SYSTEMS.

a. General. When an open-wire line of conventional construction is to be operated nonresonant with a half-wave antenna, some form of special matching arrangement must be used at the antenna end, since the line impedance is of the order of 500 to 600 ohms while the antenna resistance is only 70 ohms.

b. Delta matching. The delta matching transformer as applied to a half-wave antenna is shown in figure 81. The principle of operation has been described in section IV. As is the case in all matched systems, the antenna length must be correct for the operating frequency if an exact match is to be secured. The length can be adjusted independently, as already described. For a 600-ohm line, the coupling length, E, and the feeder clearance, C, are given by the following formulas:

$$E\ (feet) = \frac{123}{f\ (megacycles)}$$

$$C\ (feet) = \frac{148}{f\ (megacycles)}$$

where f is the frequency in megacycles. The dimensions given are based on an antenna resistance of 73 ohms and therefore will be subject to some modification if the actual resistance differs from that figure because of the antenna height or other factors. The correct adjustment, in case the line is not satisfactorily flat, can be obtained by cut-and-try variations of the dimensions C and E until standing waves on the line are minimized. When adjusted for the center of a narrow band of frequencies, this type of antenna system is capable of working at good efficiency over the whole band. Any of the coupling systems described in section IV suitable for working with a 600-ohm line may be used to transfer power from the transmitter to the line. One should be adopted which will help discriminate against harmonics, however, since this system will radiate even and odd harmonics of the fundamental frequency fairly well as compared to other antenna-feeder arrangements.

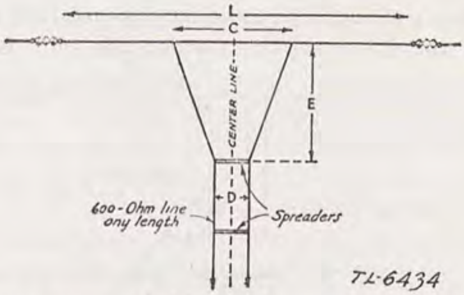

FIGURE 81. Half-wave antenna with delta matching transformer. The antenna length *L* is calculated by the formula previously given in this section. Dimensions *C*, *D*, and *E* are calculated as described in the text.

c. Matching stubs.—(1) General. A nonresonant line of the order of 600 ohms can be readily matched to a half-wave antenna through the use of linear matching transformers of the type described in section IV. Such a matching section or stub can be connected either to the center or to the end of a half-wave antenna, where the antenna impedance is resistive, as shown in figure 82. If a quarter-wave stub is terminated at the center of the antenna where the resistance is low, the impedance looking into the other end of the stub is high; therefore an open-ended stub is required. On the other hand, if the stub is terminated at the end of the antenna, where the resistance is high, the impedance looking into the other end of the stub is low, hence a closed stub is called for. The closed stub is more convenient to adjust, so if the stub feeds into the center of the antenna it may be more convenient to make it a half wave long, which will permit using a shorting link on the far end.

(2) Adjustment. Matching stubs resemble the quarter-wave or half-wave resonant feeders used with the Zepp and center-fed antennas both in electrical and mechanical properties. Ordinarily the stub has a surge impedance of 600 ohms, although other values may be used. Like these antenna systems, the center-fed arrangement is more symmetrical and can be more accurately adjusted, since both wires are connected to the antenna.

(3) Importance of antenna length. In the end-feed arrangement it is essential for accurate matching that the antenna length be an electrical half wave for the operating frequency. Departure from this length leads to the same sort of performance illustrated in figure 76. Although a reasonable frequency range can be covered without serious loss from mismatch and radiation from the stub, better performance in both respects will be secured when the stub connects to the center of the antenna. In this case, the antenna will work well over an entire narrow band of frequencies if its length is adjusted for the center of the band.

(4) End-fed system. With the end-fed system, the antenna length should first be adjusted independently to the operating frequency, with the stub disconnected. After this is done, the stub may be connected to the antenna (but not to the line) and, using the same method, the shorting link adjusted so that the whole system, antenna and stub, is resonant at the

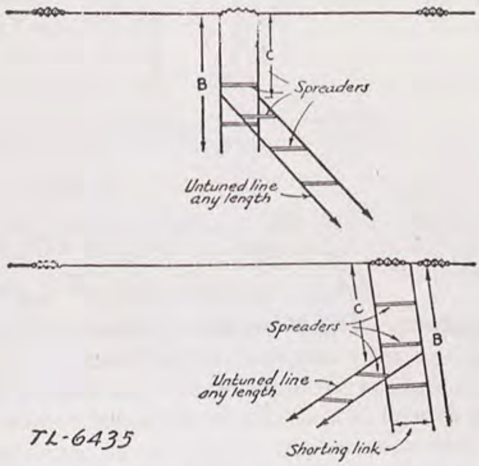

FIGURE 82. Use of quarter-wave stubs to match an open-wire line to a half-wave antenna. In the upper drawing, the antenna length does not include the length of the center insulator. Data on adjustment will be found in section IV, together with additional information on the use of matching stubs. The end-fed system shown in the lower drawing is often called a J antenna when the antenna and stub are vertical.

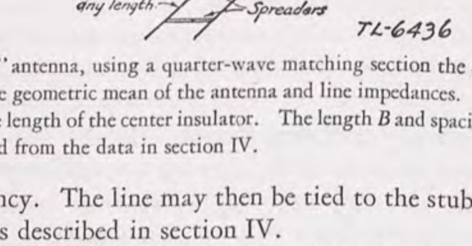

FIGURE 83. The "Q" antenna, using a quarter-wave matching section the characteristic impedance of which is the geometric mean of the antenna and line impedances. The antenna length does not include the length of the center insulator. The length *B* and spacing *C* of the matching section can be found from the data in section IV.

operating frequency. The line may then be tied to the stub and the matching carried out as described in section IV.

(5) Center-feed system. With center feed, the antenna length is not critical, since discrepancies can be made up by adjustment of the stub. The antenna and stub may be resonated as a unit, independently of the line, again using the methods described earlier in this section. With a quarter-wave stub this will involve clipping the free ends until resonance is secured.

It is best to start out with the stub intentionally long. Once the system is resonant the feeders may be attached and their position on the stub adjusted for minimum standing waves as described in section IV. A further "touching up" of the stub length, as described in section IV, may be necessary for an exact match.

(6) Harmonic suppression. These antenna systems will radiate harmonics to some extent, although the mismatch on harmonic frequencies is bad enough so that comparatively little harmonic energy reaches the antenna. However, it is advisable to use a coupling system which will help discriminate against harmonics. Section IV should be consulted for suitable coupling arrangements for working into an open-wire line.

d. Q-bar matching.—(1) General. By using a quarter-wave line of suitable characteristic impedance, an open-wire line can be matched to the center of a half-wave antenna without the necessity for tapping on the matching transformer. The linear transformer impedance must be the geometric mean of the antenna and line impedances, as described in section IV. Data for the construction of such a transformer are also given in that section.

(2) Using linear matching transformer. The 73-ohm antenna resistance can be matched to a 600-ohm line by using a linear matching transformer having an impedance of 210 ohms, approximately, connected as shown in figure 83. The "Q" section must be constructed with large diameter conductors to achieve this impedance. Conventionally, it is made of tubing of about ½-inch diameter, usually aluminum, supported by insulating spacers which maintain the correct center-to-center spacing between the conductors. With ½-inch tubing, this spacing will be 1.5 inches to match 73 ohms to 600. Spacings for other sizes of conductors can be found by consulting section IV.

(3) Length of antenna. For an exact impedance match, the antenna length must be correct for the operating frequency. The correct length can be determined by one of the methods given earlier in this section. The length of the "Q" section also must be correct; it can be determined by the same methods if made slightly long to begin with, by disconnecting it from the antenna and using a movable shorting link on one end. The match will be affected by the height of the antenna, just as in the case of twisted-pair or concentric-cable-fed lines. If appreciable standing waves are present on the line when the antenna is installed, they can be minimized by varying the spacing of the "Q" bars, providing the antenna and "Q" section lengths are correct. In any event, the losses from standing waves will not be serious when operation is carried on in various parts of a band, providing the system is first correctly adjusted for the center of the band.

(4) Harmonic suppression. The "Q" matching system with a half-wave antenna discriminates against even harmonics of the transmitter frequency, just as in the case of other center-fed systems. Nevertheless, it is advisable, in the interests of low harmonic radiation, to use a tuned coupling circuit to provide further attenuation of the harmonics. Section IV may be consulted for suitable circuits and operating data.

e. Single-wire feed.—(1) General. The single-wire matched line can also be used to feed a half-wave antenna. Of all the various feeder systems available it is probably the least desirable, for three reasons. First, the line radiation tends to be higher because there is no second wire with out-of-phase current to cancel the radiation from the first. Hence there is always *some* radiation, which can be minimized only by as accurate matching as possible so that the line current will reach the lowest possible value. Second, a single-wire-fed antenna radiates rather well on harmonics

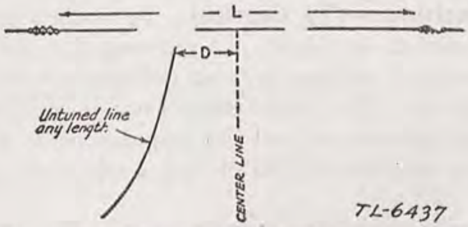

FIGURE 84. The single-wire-fed half-wave antenna. Length *L* is calculated as previously described.

(it is often used for that purpose) and particular precautions must be taken to prevent harmonics of the operating frequency from getting into the system. Third, the efficiency of the feeder is dependent upon the characteristics of the ground over which it is installed, since the return circuit is through the ground. Ground having good conductivity is essential to the performance of the feeder, and relatively poor results may be expected if the ground is very rocky, or dry and sandy, for any considerable depth.

(2) Length of antenna. For a good impedance match it is essential, as with other nonresonant lines, that the antenna length be correct for the operating frequency. The length may be adjusted independently as previously described in this section. The other critical dimension, shown in figure 84, is the distance *D* from the center of the antenna to the point where the feeder is attached. The distance *D* will depend upon the size of the feeder wire, since this determines the characteristic impedance of the feeder. *D* is equal to the length of the antenna multiplied by a factor which varies with the wire size. For No. 12 wire the factor is 0.133; for No. 14 wire, 0.139; and for No. 16 wire, 0.144.

(3) Feeder tap. Placing the feeder tap incorrectly does not change the resonant frequency of the antenna, but affects only the standing-wave ratio on the feeder. However, if the antenna is the wrong length, standing waves on the feeder cannot be eliminated no matter what the position of the tap. The feeder should leave the antenna at right angles for a distance of at least a quarter wave, and sharp bends in the feeder should be avoided if possible.

(4) Frequency range. The single-wire-feed system can be operated over a fair frequency range without serious losses. At frequencies other than that for which the antenna is resonant the standing wave of current on the antenna shows a discontinuity where the feeder joins the antenna, and of course standing waves show on the feeder. The antenna length can be checked by inserting an ammeter in the antenna on each side of the feeder, as close to the junction as possible; if the antenna length is correct, the ammeter readings will be equal. Standing waves on the feeder can be checked by the procedure outlined in section IV.

SECTION VI

DRIVEN ARRAYS

68. GENERAL. As has already been pointed out, no radiating system radiates equally well in all directions. Some antennas show directional effects in the vertical plane, but none in the horizontal (simple vertical antennas), and most show directional effects in both the vertical and horizontal planes (horizontal antennas). These directional effects are not very marked in simple antennas, however, and it is only when more complicated systems are used that the term "directional" is normally applied.

69. FUNDAMENTALS.

a. Gain. The merit of a directional antenna is usually measured in terms of its *gain*, which can be defined as the ratio of the power that must be supplied to a standard comparison antenna to lay down a given signal at a distant point to the power that must be supplied to the directional system to give the same signal strength.

b. Example. An antenna with a gain of five requires only one-fifth the power that the comparison antenna would to give the same signal or, in other words, using the directive antenna with the same power is equivalent to increasing your power five times. The comparison antenna is usually taken as a half-wave antenna in the same plane and at the same height above ground as the directional system. In the case of a *stacked* system (to be described later), the height of the comparison antenna is taken as the center of the directional system.

c. Use. The gain realized in transmitting is also obtained in receiving and, if a directional system is available, it should be used for both transmitting and receiving, by means of an antenna change-over relay or switch. The old adage that "you can't work 'em if you can't hear 'em" is all too true.

70. DIRECTIVITY.

a. Characteristic. The *directivity* of an antenna relates to the sharpness or narrowness of the radiation pattern; the sharper the pattern, the greater the directivity. Directivity and gain normally go hand in hand, but some systems are capable of added directivity with little or no gain. In this case, the directivity is useful in reducing interference in receiving, but no increase in signal strength is obtained.

b. Types. Antennas with sharp patterns in the horizontal plane are said to have good *horizontal directivity.* Antennas with sharp patterns in the vertical plane are said to have good *vertical directivity.*

71. PHASED SYSTEMS.

a. Types. All phased systems are derived from three essential types: collinear, broadside, and end-fire.

(1) Collinear array. Elements in same line, currents in phase. Horizontal arrays exhibit horizontal directional effects with no change in vertical angle from that of a half wave. Vertical elements exhibit vertical directional effects, but the horizontal pattern is the same as that of a half

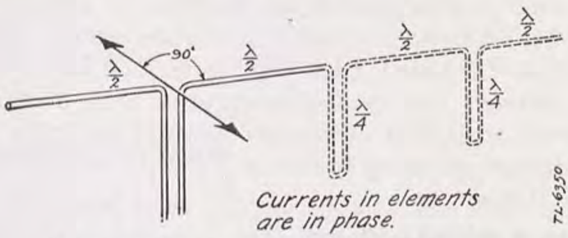

FIGURE 85. Collinear arrays. Currents in elements are in phase

wave. Gain depends upon number of elements and spacing center to center. Spacing center to center usually is one-half wave, that is, the elements are end to end, except for the phasing stub (an odd $\frac{\lambda}{4}$ length long) between them. Elements can be 0.64 wavelength long instead of $\frac{\lambda}{2}$. Gain is increased over the array using $\frac{\lambda}{2}$ elements. When elements are more than $\frac{\lambda}{2}$ long, the phasing stubs are shorter than those used with $\frac{\lambda}{2}$ elements. Radiation is always bidirectional.

(2) Broadside array. $\frac{\lambda}{2}$ elements mounted adjacent, currents in phase, directional effects in a plane perpendicular to plane of elements. Vertical elements are usually used in order to obtain horizontal directivity. Gain depends upon number of elements and spacing. Radiation is always bidirectional.

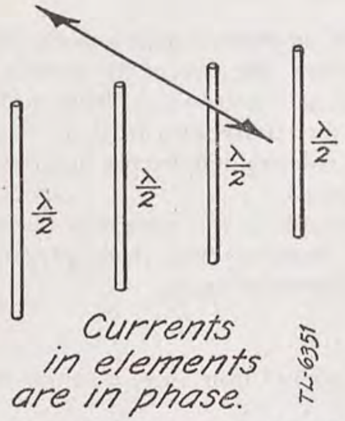

FIGURE 86. Broadside arrays. Currents in elements are in phase.

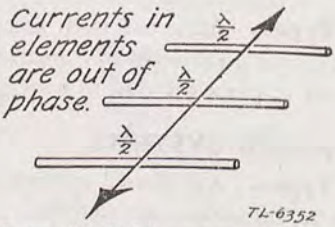

FIGURE 87. End-fire arrays. Currents in elements are out of phase.

(3) End-fire arrays. $\frac{\lambda}{2}$ elements adjacent, currents out of phase, directional in same plane as elements, perpendicular to axis of elements. Radiation is either bidirectional or unidirectional depending upon element spacing and phase difference. Gain depends on number of elements, spacing, and phasing. This type of array gives both horizontal and vertical directivity, regardless of whether mounted vertically or horizontally. Horizontal mounting results in a sharper horizontal pattern than does vertical mounting.

b. Elements of phased systems. The elements used in phased arrays are usually a half wavelength long because they are then easiest to feed and phase, but some systems use elements that are five-eights wavelength long, and some employ shortened elements. However, unless otherwise specified, one should visualize half-wave elements in all of these discussions.

c. Combinations. Combinations of the various systems will combine their effects and result in a much sharper radiation pattern in both planes. There are no bargains in directional antennas. The end-fire system, which gives a sharpened pattern in both the horizontal and vertical planes, is often difficult to construct and feed. The other systems, although easier to feed, require more space.

d. Feeding. Difficulty in feeding is brought about by the fact that as antenna elements are moved closer together, the radiation resistance is decreased (in some close-spaced systems it goes as low as 10 or 15 ohms). This lowered radiation resistance, the load that the feed line must tie into, results in a high standing-wave ratio on a tuned line, with consequent losses. If a matched system is used, it is found that the antenna system tunes quite sharply (is said to have "high Q"), and will take power only over a narrow frequency band. In general, collinear and broadside arrays have a higher impedance (lower Q) than do the end-fire systems.

TABLE I.—Theoretical gain of collinear half-wave antennas

Spacing between center of adjacent half-waves	Number of half-waves in array versus gain in decibels				
	2	3	4	5	6
½ wave	1.8	3.3	4.5	5.3	6.2
¾ wave	3.2	4.8	6.0	7.0	7.8

e. Plane of polarization. The plane of polarization of any directional system is the same as the plane of polarization of one of the elements. Vertical and horizontal elements in the same array do not result in very practical systems, since the radiation divides up into the two planes of polarization in proportion to the number of elements radiating in each plane. The resultant is a vector addition of the two components. In general, horizontal elements appear to be better than vertical ones, because they result in quieter reception. There is not much choice on transmitting, except that it is usually easier to put horizontal elements "in the clear."

72. COLLINEAR ARRAYS.

a. Fundamental type. The system shown in figure 88 is the fundamental type of collinear array. The gain for various numbers of elements is given in table I, and the free-space patterns are given in figures 89 and 91. The gain and sharpness of the patterns depend upon the number of elements and their spacing, center-to-center. Although three-fourths wavelength spacing gives greater gain, it is difficult to construct a suitable phase-reversing system when the ends of the antenna elements are widely separated. For this reason, the half-wave spacing is generally used. The length of the elements is not critical and if, in a system of three or four collinear half-wave elements, the elements are not exactly a half wave long, no harm will be done as long as all of the radiating elements are the same length, so that the current in the phasing sections will be balanced, and result in a minimum of radiation from these sections. For this reason it is preferable to feed the system at the center, thus making it symmetrical and less prone to feeder unbalance and radiation.

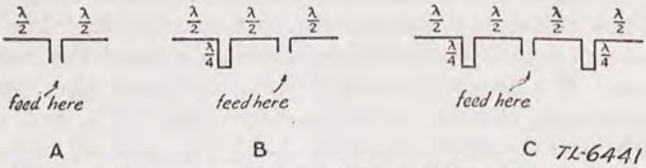

FIGURE 88. The simplest form of collinear array is shown at (A). The systems at (B) and (C) have greater gain, but require the use of the quarter-wave phasing sections. All feed points shown are high-impedance. Collinear arrays can also be fed from one end, but the current distribution is not as good as with a balanced or nearly balanced system.

b. Adjusting phasing sections. The phasing sections of a collinear array of more than two elements can be adjusted by first balancing the two center elements. This is done by trimming them until the feeder currents are equal. Then a phasing section and additional element (that has been cut to the same length as the already adjusted elements) is hung onto one of the elements already in place, and the phasing section (which was deliberately

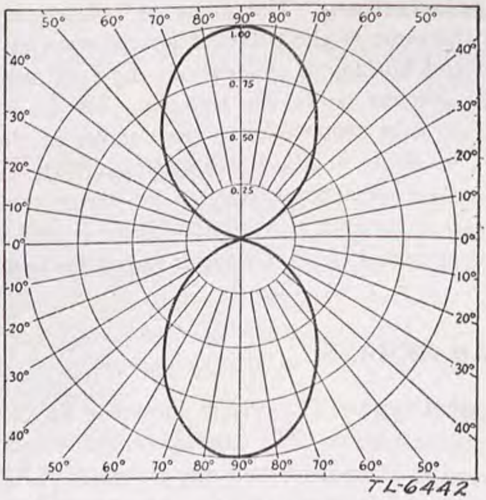

FIGURE 89. Free-space diagram for a two-element collinear array with half-wave elements. The scale is simply relative field strength.

made slightly too long) is shortened until maximum current appears at the shorting bar, with constant input to the transmitter. The process is then repeated on the other side of the system. Adjusting the current to maximum at the shorting bar does not insure that the element length is exactly a half wavelength (or whatever is counted on), but it does minimize radiation from the phasing section. The calculated length of the element will be close enough.

c. Use of tuned feeders. A collinear array with tuned feeders will work on more than one band but, unless it is only a two-element affair, the radiation will only be broadside on the band for which the array is cut. The two-element collinear array will give broadside radiation on the band for which it is designed and on the next lower frequency band, although the gain and directivity will be less.

73. EXTENDED DOUBLE ZEPP.

a. Use. If a two-element broadside array is contemplated, and some additional room is available, it is advisable to use the "extended double Zepp." This is similar to the two collinear half waves in phase except that 0.64-wavelength elements are used instead of 0.5-wavelength ones. With tuned feeders, it is an excellent two-band affair and has greater gain on two bands than if only half-wave elements were used.

b. Length of elements. The length of the elements is not critical, since the gain increases as the elements are lengthened from 0.5 wavelength up to 0.64 wavelength, but they should not exceed the 0.64 figure, because

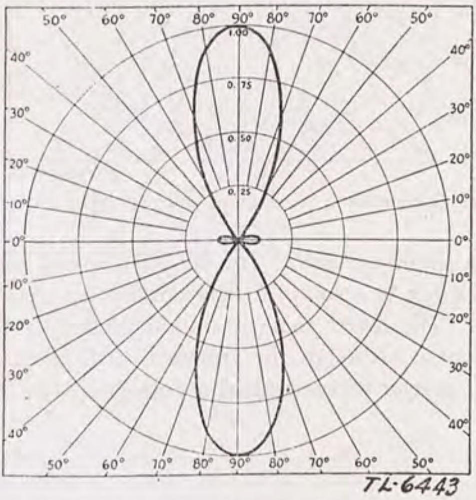

Figure 90. Free-space diagram for a three-element collinear array with half-wave elements.

the gain falls off after that. The extended double Zepp principle can also be applied to more than two elements, and figure 92 shows the dimensions for several 14-megacycle variations. Figure 93 shows the free-space pattern of a two-element extended double Zepp.

74. BROADSIDE ARRAYS.

a. Gain and directivity. The gain and directivity of broadside arrays also depend upon the number of elements and the spacing, the gain for different spacings being shown in table II. Half-wave spacing is generally used, since it simplifies the feeding problem when the array has more than two elements.

b. Plane of elements. Broadside arrays can be used with either vertical or horizontal elements. In the former case, the horizontal pattern is quite sharp while the vertical pattern is the same as that of one element alone. If the elements are horizontal, the pattern is sharpened in the vertical plane, giving low-angle radiation, but the horizontal-plane pattern is

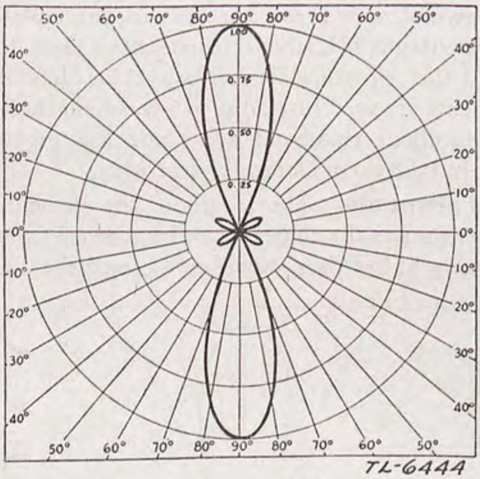

FIGURE 91. Free-space diagram for a four-element collinear array with half-wave elements.

the same as for a single element. The height required limits the number of elements which can be suspended horizontally, so that more than two are seldom used. The lower element should preferably be a half wavelength above ground, although the system is still effective if the lower element is only a quarter wavelength above ground.

TABLE II

THEORETICAL GAIN OF BROADSIDE HALF-WAVE ELEMENTS AT DIFFERENT SPACINGS

Separation in fractions of wavelength	Gain in decibels
5/8	4.8
3/4	4.6
1/2	4.0
3/8	2.4
1/4	1.0
1/8	.3

THEORETICAL GAIN VERSUS NUMBER OF BROADSIDE ELEMENTS WITH HALF-WAVE SPACING

Number of elements	Gain in decibels
2	4
3	5.5
4	7
5	8
6	9

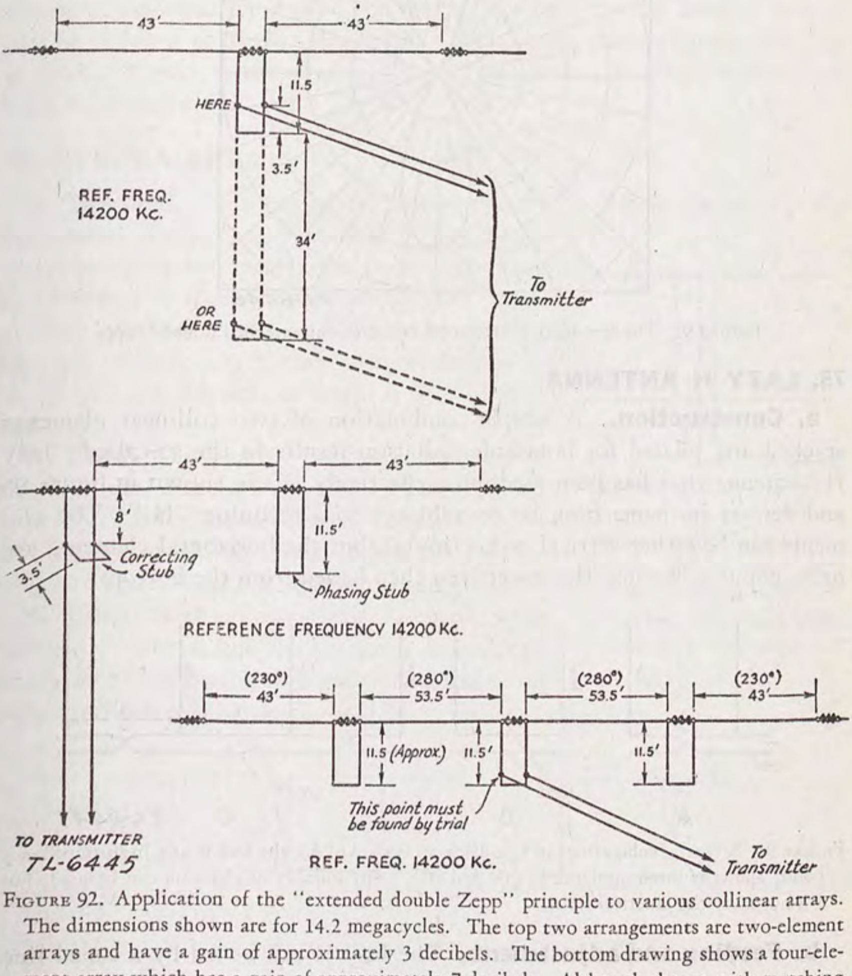

FIGURE 92. Application of the "extended double Zepp" principle to various collinear arrays. The dimensions shown are for 14.2 megacycles. The top two arrangements are two-element arrays and have a gain of approximately 3 decibels. The bottom drawing shows a four-element array which has a gain of approximately 7 decibels. Although shown with matching sections, tuned feeders can be used.

Broadside arrays can be fed by either tuned lines or matching sections and matched lines. Figure 94 shows typical examples.

c. Stacked arrays. Whenever elements are mounted above each other, as in the case of a collinear system with vertical elements or a broadside array with horizontal elements, the elements are said to be "stacked." Stacked arrays have the advantages that they result in the low-angle radiation so necessary for distance work and that they minimize ground losses.

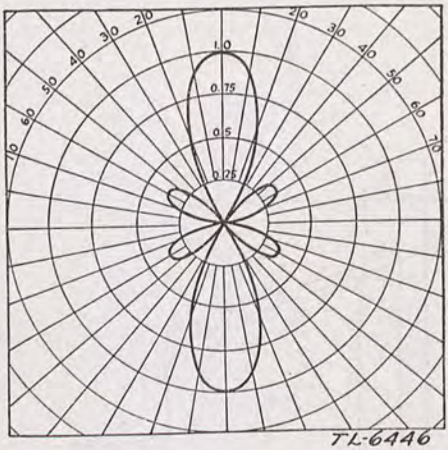

FIGURE 93. The free-space pattern of a two-element extended double Zepp.

75. LAZY H ANTENNA.

a. Construction. A simple combination of two collinear elements stacked and phased for broadside radiation results in the so-called "lazy H" antenna that has been used quite effectively. It is shown in figure 95 and derives its name from its resemblance to a reclining "H." The elements can be either vertical or horizontal, but the horizontal elements are more popular, because the system can then be fed from the bottom.

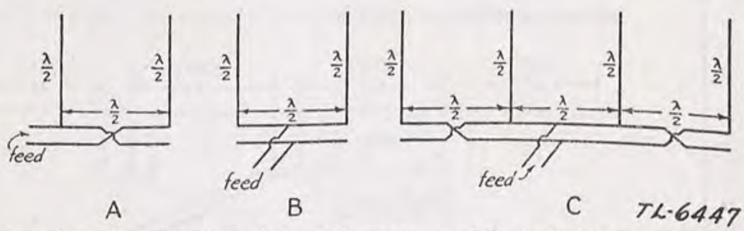

FIGURE 94. Several combinations of broadside arrays. At (A), the feed is at a high-impedance point, and it is low-impedance in (B) and (C). Any number of elements can be used, but 6 is normally the practical limit.

b. Feeding and adjustment. The lazy H can be fed by a tuned line or with a matched line and matching section. If the elements have been cut with a fair degree of accuracy, and the system is erected at least a half wavelength from surrounding objects that might affect its tuning, the system can be tuned simply by the tuned line or the quarter-wave matching section. If exact adjustment is desired, the top elements can be connected and the system tuned (either by tuned feeders or adjusting the shorting bar of the matching section). Then the lower elements can be clipped on experimentally, and their length varied slightly until they show no effect on the *tuning* of the system. The bottom elements will affect the resistance of the system and if a matching section is being used, the line will have to be tapped lower on the section, but the tuning should remain the same.

c. Spacing. If it is not possible to have the lower section at least a quarter wavelength above ground, you can cheat a bit on the spacing between the top and bottom sections by pulling the phasing section aside by means of an auxiliary rope. The spacing between top and bottom section can be reduced to almost three-eights wavelength without too much loss in gain. However, the phasing section must always be a half wavelength long electrically.

76. STERBA ARRAY.

a. General. Another modification of stacked collinear elements is the horizontal Sterba array shown in figure 96. This system is very nearly the same as the lazy H except that it is a closed circuit and consequently can be defrosted or desleeted by running enough 60-cycle alternating current, from a 5- or 10-volt transformer, to warm it up and melt the ice.

b. Feed. Two methods of feed are shown in the diagram, although the simpler point of feed is point *F*, since the impedance at this point is fairly close to 600 ohms, and a line can be connected directly without serious standing waves.

c. Use. Sterba arrays can be used with vertical elements, but the necessary height can be obtained only with elaborate structures or on the ultrahigh frequencies.

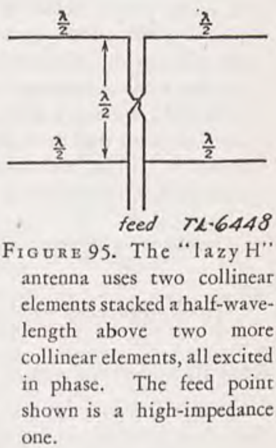

FIGURE 95. The "lazy H" antenna uses two collinear elements stacked a half-wavelength above two more collinear elements, all excited in phase. The feed point shown is a high-impedance one.

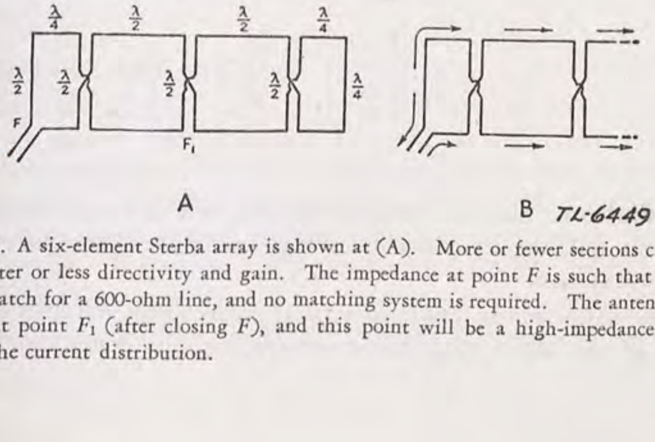

FIGURE 96. A six-element Sterba array is shown at (A). More or fewer sections can be used for greater or less directivity and gain. The impedance at point *F* is such that it provides a fair match for a 600-ohm line, and no matching system is required. The antenna can also be fed at point F_1 (after closing *F*), and this point will be a high-impedance one. (B) shows the current distribution.

77. BRUCE ARRAY.

a. General. Still another version of the broadside antenna is the Bruce array, shown in figure 97.

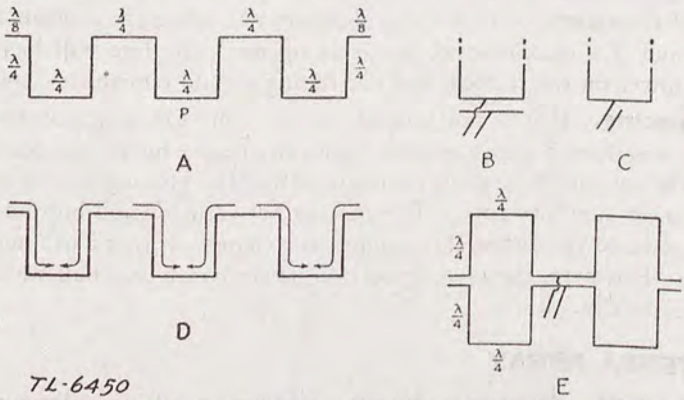

FIGURE 97. The Bruce array is shown at (A). Any number of elements can be used, although the system should include at least three half-wavelengths of wire, if any appreciable gain is to be obtained. The system can be fed at one end of the wire (a high-impedance point) or, preferably, at the center (point *P*) by either of the methods shown at (B) and (C). This will be a medium-impedance point. The current distribution is shown at (D). It is apparent that the currents in the vertical elements are all in phase, while the currents on the horizontal elements tend to cancel. Two Bruce arrays can be stacked, as at (E), to improve the vertical directivity, and make the feed truly symmetrical. The length of the elements can be found from the formulas:

$$\text{Quarter-wave elements: } \textit{Length (feet)} = \frac{246}{\textit{Frequency (megacycles)}}$$

$$\text{Eighth-wave elements: } \textit{Length (feet)} = \frac{110}{\textit{Frequency (megacycles)}}$$

TABLE III.—*Theoretical gain of two end-fire (180° phase difference) half-wave elements with various spacings*

Spacing in fractions of wavelength	Gain in decibels
1/8	4.3
1/20	4.1
1/4	3.8
3/8	3.0
1/2	2.2
5/8	1.7

b. Radiation. Since the radiation from a wire is proportional to the current in it, only the center portion of each half-wave is used for radiation in the Bruce system.

c. Use. Although it results in vertical polarization and does not have the gain of the arrays with half-wave spacing, the Bruce can be quite effective when height is limited. If two Bruce arrays are placed one above the other, as in figure 97, vertical directivity will be improved.

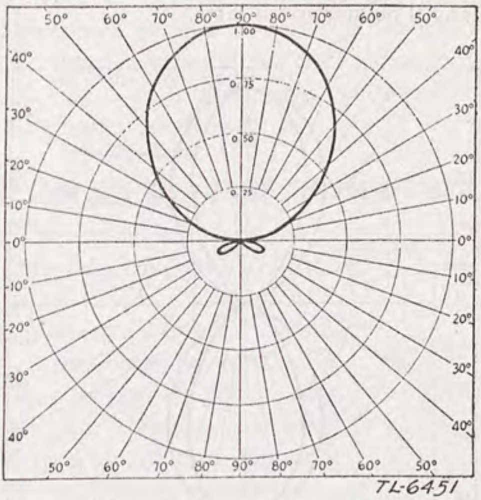

FIGURE 98. Free-space pattern of two half-wave elements spaced a quarter wavelength and fed 90° out-of-phase. The radiation is in the direction of the element with the lagging current.

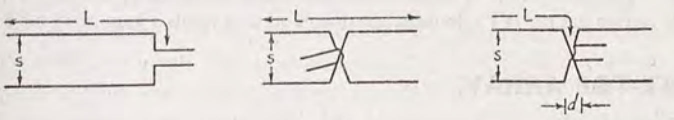

FIGURE 99. The flat-top beam. The single-section affairs (A) and (B) can be either end-fed, (A), or center-fed, (B). If center-fed with tuned feeders, it becomes a two-section array on the second-harmonic frequency, and can thus be used on two frequencies. The length *L* is not critical, and can be anything from seven-sixteenths to six-tenths of a wavelength. But in any flat-top beam, all lengths *L* should be exactly equal. The spacing should be between one-sixth and one-eighth of a wavelength, although the system will still show gain when the spacing is as high as a half wavelength. The distance *d* in the two-section array (C) should be about 2 feet. The feed at (A) and (C) is high-impedance; that at (B) is low-impedance.

78. END-FIRE ARRAYS.

a. General. End-fire arrays give the greatest gain and directivity for a given space, and are widely used.

b. Disadvantages. They have the disadvantages that their radiation resistance is low, which makes them more difficult to feed, and they tune more sharply, which throws off the tuning in wet weather.

c. Feeding. If two parallel half waves are fed 180° out-of-phase, their gain will increase as the spacing is decreased, as can be seen from table III. The radiation resistance is lowered at the same time. Fed out-of-phase, they acquire a unidirectional characteristic at certain spacings and phasings, as can be seen in figure 98. Feeding other than 180° out-of-phase is somewhat difficult and end-fire arrays are not normally used in this fashion, although methods will be mentioned later.

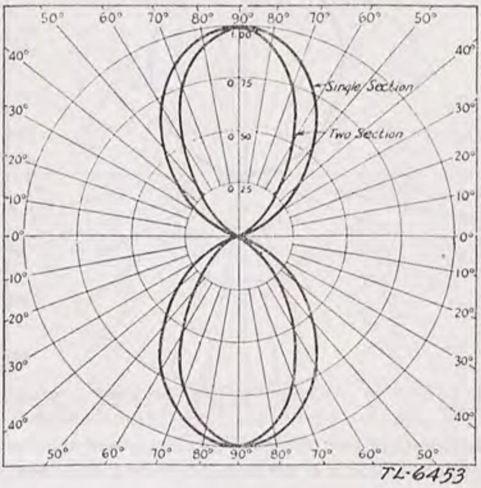

FIGURE 100. Free-space pattern of single-section and two-section flat-top beams. The gain of the single-section flat top is 4.3 decibels, the double-section yields a gain of about 6 decibels.

79. FLAT-TOP ARRAY.

a. General. The maximum gain for an end-fire array is obtained with eighth- to sixth-wave spacing, and the ordinary utilization of the principle is often called the "W8JK array," after the amateur who first used it. It is also known as the "flat-top array." Several versions are shown in figure 99.

b. Feeding. It can be fed by either a matched or tuned line, at either the end or the center, although the center is preferable. A two-element affair is called a "single-section flat top," one with four elements is called a "two-section flat top," and so on. If a single-section flat top is fed with a tuned line at the center, it becomes a two-section affair at the second harmonic (with quarter-wave spacing), and thus can be used for two-band operation. This makes a practical rotatable array for frequencies above 12 megacycles.

c. Adjustment. The array is adjusted by tuning the line or the quarter-wave matching section (if an untuned line is used). The length of the elements is not critical, and they can be anything from seven-sixteenths to six-tenths of a wavelength. However, it is important that they all be exactly the same length. The longer elements will give a sharper beam in the horizontal plane.

d. Advantages. End-fire arrays of this type have the advantage that, when used in the horizontal plane, they result in a lower effective angle of radiation than can be obtained by any other type of phased array of equivalent height. Close-spaced end-fire arrays with vertical elements do not give a particularly sharp horizontal pattern (although the null is quite marked), but will result in a lower angle of radiation than would be obtained with a single vertical element.

80. COMBINATION OF END-FIRE WITH OTHER SYSTEMS.

a. General. The end-fire principle can be combined with the broadside and collinear systems to give many different combinations, but most of them introduce structural difficulties, and they are not normally used. The four-section flat top is of course a combination of end-fire and collinear elements, and offers the most practical type of structure, because it can be strung from two wooden spreaders.

b. Spacing and phase difference. If possible, it is particularly advantageous to combine the end-fire and other systems with quarter-wave spacing and 90° phase difference, to obtain unidirectional characteristics. Figure 101 shows how two lazy H antennas can be spaced a quarter wavelength and fed to give a choice of two unidirectional characteristics. Other adaptations will suggest themselves. The phase difference can best be adjusted by listening or transmitting tests, adjusting the difference in line lengths until minimum back-reception or radiation is obtained. Each antenna should have its matching section and line adjusted separately—the phasing adjustment is made only with the length of one of the feed lines. As can be seen, transposing one set of feeders at the transmitter end will reverse the phase difference and the direction of maximum radiation.

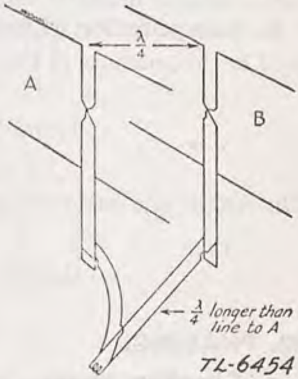

FIGURE 101. Two antenna systems, arranged for end-fire radiation, can be controlled from the station by running two separate feed lines to the transmitter and making one feed line a quarter wavelength longer than the other. If the lines are connected as shown in the diagram, the radiation will be unidirectional in the direction *A* through *B*. Reversing one feed line at the transmitter will make the system unidirectional in the opposite direction. Although shown here applied to two "lazy H" antennas, the principle can be used with any systems fed by flat lines and spaced an odd multiple of a quarter wavelength.

81. ELEMENTS IN PHASED ARRAYS.

a. Importance of dimensions. Since it is important in phased arrays to have all of the dimensions exact (except in the collinear and flat top types), care should be taken that these dimensions are calculated properly. Although nearby objects can load the elements and modify their electrical length, an antenna "in the clear" can be calculated with a good deal of accuracy. The end effect that modifies the length of radiators is, for the most part, caused by the dielectric of the insulator, and elements that are supported at a current loop will not show this effect to such a degree. However, most antenna elements are supported at a voltage loop, and consequently suffer the end effect. Half-wave phasing sections have to be made somewhat shorter than a half wavelength in air because of the dielectric of the spacers. Self-supporting elements work out to be about the same length as wire ones because, being self-supporting, they have a greater diameter and more capacity.

b. Computation of length. The length of the half-wave elements used in the antennas in this chapter should be computed from

$$\text{Length (feet)} = \frac{468}{\text{Frequency (megacycles)}}$$

The length of a half-wave phasing section should be computed from

$$\text{Length (feet)} = \frac{480}{\text{Frequency (megacycles)}}$$

82. PHASING.

a. Checking phase. It is desirable to be able to trace out the relative phase of the currents in a multi-element antenna, in order to understand how a system operates or to check on the possibilities of a newly devised system. Many diagrams of multi-element antennas show arrows indicating the relative direction of currents throughout the system, but this is sometimes confusing to one who is not familiar with it.

b. Plus and minus method. A somewhat simpler method of checking the phasing in an antenna system that can be applied to any type of antenna is shown in figure 102. It consists of starting at a known high-voltage point on a wire, arbitrarily marking that point "plus" and then following along that wire and alternately marking each half-wave point "minus" and "plus." For example, in the "lazy H" shown in figure 102, the point *E* on wire No. 1 is selected for the starting point, and the marks are made along that wire. Where the lower right-hand element attaches at *L*, both wires (the element and the feed line) are traced out. Then, knowing that the two-wire line connected at *L* must have currents out-of-phase on it, a mark of opposite polarity (minus) is made on the other leg of a line where it joins the antenna at *L*. The rest of the antenna is then traced. An examination of the marks now shows that this is a workable system: the currents are in the same direction in all wires, as indicated by the relative positions of the plus and minus signs, and the phasing section is properly connected, since the currents are in opposition along it. Figure 102 (B) shows the result if the phasing section is not reversed. Obviously, the system will not work as a broadside array, because the upper and lower collinear sections are not in phase. As a further example, a Sterba array is shown in figure 102 (C). Here a point such as *F* is used as a starting point, since it is known that if the phasing sections are to operate as phasing sections with no radiation, the current in the two wires must be out-of-

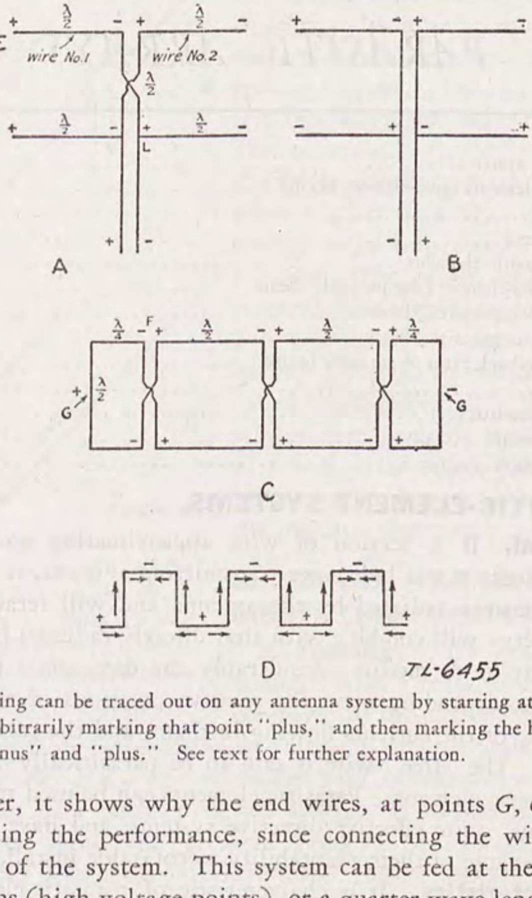

FIGURE 102. Phasing can be traced out on any antenna system by starting at a voltage loop on the wire, arbitrarily marking that point "plus," and then marking the half-wave points alternately "minus" and "plus." See text for further explanation.

phase. Further, it shows why the end wires, at points *G*, can be closed without affecting the performance, since connecting the wires does not affect the rest of the system. This system can be fed at the ends of the phasing sections (high-voltage points), or a quarter-wave length from one of these points (high-current points). Figure 102 (D) shows still another example, in this case a Bruce array. However, in this case it is a little clearer to draw in the arrows to represent the current.

SECTION VII

PARASITIC ARRAYS

83. PARASITIC-ELEMENT SYSTEMS.

a. General. If a section of wire approximating a half wave in length is brought near a half-wave transmitting antenna, it will intercept some of the energy radiated by the antenna and will reradiate it. The reradiated energy will combine with that directly radiated by the antenna in such a way as to modify considerably the directional pattern of the antenna alone, depending upon the relative positions of the two wires, the magnitude of the currents flowing in them, and the relative phases of the currents. The "free" wire is said to be parasitically excited, and is called a parasitic element. Parasitic elements can be used to form, with a driven antenna, quite effective directive systems, and have enjoyed wide popularity, because of their adaptability to rotatable installations.

b. Characteristics. It is characteristic of parasitic-element systems to show maximum radiation in one direction, as contrasted with the many wholly driven systems which are bidirectional. This is a useful feature, especially for a rotatable system, because it helps to reduce interference in receiving from directions other than that over which communication is being carried on, and also reduces the interference which the transmitter might otherwise cause in those same directions. The parasitic element, which is always parallel to the driven element (the driven element usually is called the "antenna," although the term really should be used to include the whole system), is called a "reflector" when it causes reinforcement of the radiation along the direction looking from the parasitic element to the antenna, and a "director" when maximum radiation is along a line looking from the antenna to the driven element. This is shown in figure 103.

c. Current. The phase of the current in the parasitic element with respect to that in the antenna depends upon the spacing between the two elements and the tuning of the parasitic element. The tuning is usually adjusted by changing the length of the parasitic element, although regular tuning means may be employed instead. A reflector is usually tuned to a frequency somewhat lower than the operating frequency; that is, the reflector is slightly longer than the antenna. The converse is true of a director; it should be tuned to a frequency somewhat higher than the operating frequency, or its length should be slightly less than that of the antenna. It is possible, however, to tune either a reflector or director to the operating frequency directly, in which case it is called "self-resonant." Whether the self-resonant parasitic element operates as a director or reflector is determined by the spacing between the antenna and the parasitic element.

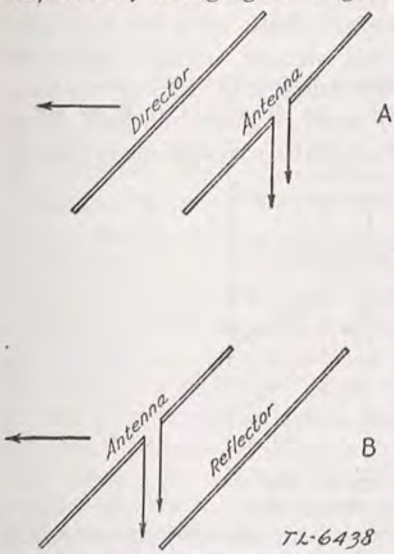

FIGURE 103. Antenna systems using a single parasitic element. In (A) the parasitic element acts as a director, in (B), as a reflector, the terms referring to the direction, with respect to the antenna, in which maximum radiation takes place.

84. SINGLE PARASITIC ELEMENTS (two-element beam).

a. Spacing. The gain in field strength with a reflector or director as compared to the antenna alone will depend upon the spacing between the two elements and the tuning (or length) of the parasitic element. The maximum gain obtainable with a single parasitic element, as a function of the spacing, is shown in figure 104. The two curves show the greatest gain to be expected when the element is tuned for optimum performance either as a director or a reflector. The shift from director to reflector, with the corresponding shift in direction as shown in figure 103, is accomplished simply by tuning the parasitic element—usually, in practice, by changing its length. In other words, the parasitic element may be either a director or reflector at any spacing.

b. Maximum gain. With the parasitic element tuned to act as a director, maximum gain is secured when the spacing is approximately 0.1 wavelength. The peak is rather sharp, and the gain drops off rapidly at greater or smaller spacings. When the parasitic element is tuned to work as a reflector, the spacing which gives maximum gain is about 0.15 wavelength, with a fairly broad peak. The director will give slightly more gain than the reflector, but the difference is less than ½ decibel and there is consequently little choice between the two types of operation on the basis of these theoretical curves. In practice, other considerations may influence the selection.

c. Tuning. In only two cases are the gains shown in figure 104 secured when the parasitic element is self-resonant. These occur at 0.1- and 0.25-wavelength spacing, with the parasitic element acting as director and reflector, respectively. For reflector operation, it is necessary to tune the parasitic element to a lower frequency to secure maximum gain at all spacings less than 0.25 wavelength, while at greater spacings the reverse is

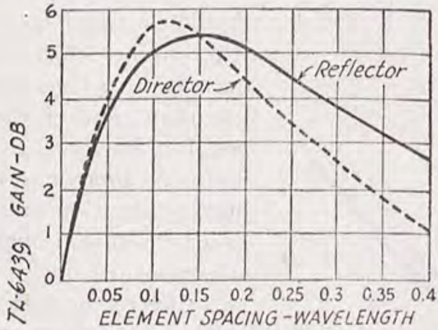

FIGURE 104. The maximum possible gain obtainable with a parasitic element over a half-wave antenna alone. The parasitic element tuning is supposed to be adjusted for greatest gain at each spacing. The effect of resistance loss in the elements is not included.

true. The closer the spacing the greater the detuning required. On the other hand, the director must be detuned toward a higher frequency (that is, its length must be made less than the self-resonant length) at spacings greater than 0.1 wavelength in order to secure maximum gain. The amount of detuning necessary becomes greater as the spacing is increased. At less than 0.1 wavelength spacing the director must be tuned to a lower frenquency to secure the maximum gains indicated by the curve.

85. ATTENUATION.

a. General. Besides gain, another important consideration in the selection of the type of operation (director or reflector) for the parasitic element and its tuning is the amount by which the signal is reduced in the direction opposite to that in which maximum gain is secured. To get the best unidirectional effect it is obviously desirable to secure, along with high gain, maximum attenuation to the rear. In other words, the front-to-back ratio should be as high as possible.

b. Gain and attenuation. The conditions which give maximum gain forward do not give maximum signal reduction, or attenuation, to the rear. It is necessary to sacrifice some gain to get the highest front-to-back ratio. The reduction in backward response is brought about by adjustment of the tuning or length of the parasitic element. With a reflector, the length must be made slightly greater than that which gives maximum gain, at spacings up to 0.25 wavelength. The director must be shortened somewhat to achieve the same end, with spacings of 0.1 wavelength and more. The tuning condition, or length, which gives maximum attenuation to the rear is considerably more critical than that for maximum gain, so that a good front-to-back ratio can be secured without sacrificing more than a small part of the gain.

c. Choice between maximum gain and maximum attenuation. For the sake of good reception, general practice is to adjust for maximum front-to-back ratio rather than for maximum gain. Larger front-to-back ratios can be secured with the parasitic element operated as a director rather than as a reflector. With the optimum director spacing of 0.1 wavelength, the front-to-back ratio with the director tuning adjusted for maximum gain is only 5.5 decibles (the back radiation is equal to that from the antenna alone). By proper director tuning, however, the ratio can be increased to 17 decibles; the gain in the desired direction is in this case 4.5 decibles, or 1 decible less than the maximum obtainable.

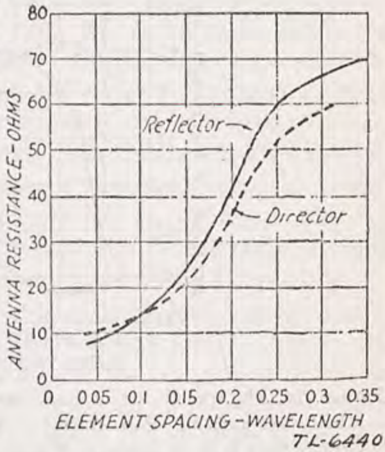

FIGURE 105. Radiation resistance as a function of spacing, when the parasitic element is adjusted for the gains given in figure 104.

86. RADIATION RESISTANCE.

a. General. The radiation resistance as measured at the center of the antenna, or driven element, varies as shown in figure 106 for the spacings and tuning conditions which give the gains indicated by the curves of figure 104. These values, especially in the vicinity of 0.1-wavelength spacing, are quite low compared to the 73-ohm radiation resistance of the half-wave antenna alone. The reflector and director curves coincide at 0.1 wavelength, both showing a value of 14 ohms. At greater spacings the radiation resistance increases, with the reflector showing somewhat higher values than the director.

b. Importance. The low radiation resistance at the spacings giving highest gain is important in three ways. First, the radiation efficiency goes down because with a fixed loss resistance more of the power supplied to the antenna is lost in heat and less is radiated, as the radiation resistance approaches the loss resistance in magnitude. Second, the selectivity of the antenna system becomes higher as the radiation resistance decreases. This means that optimum performance can be secured over only a narrow band of frequencies as compared with the frequency-performance characteristic of a higher-resistance antenna. Third, the number of suitable feeder systems becomes limited, and adjustment becomes more critical.

c. Reduction of loss resistance. The loss resistance can be decreased by using low-resistance conductors for the antenna elements. This means, principally, large diameter conductors, usually tubing of aluminum, copper, or copper-plated steel. Such conductors have mechanical

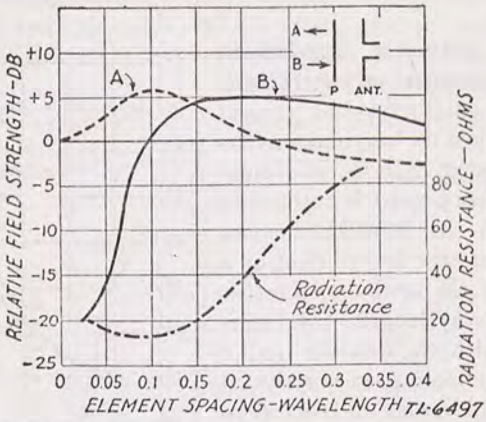

FIGURE 106. The special case of a self-resonant parasitic element used in conjunction with a half-wave antenna. Zero decibel is the field strength from a half-wave antenna alone. Greatest gain is in the direction *A* at spacings less than 0.14 wavelength; in direction *B* at greater spacings. Between 0.1 and 0.225 wavelength there is no attenuation in either direction.

advantages as well, in that it is relatively easy to provide adjustable sliding sections for changing length, while the fact that they can be largely selfsupporting makes them well adapted for rotary antenna construction.

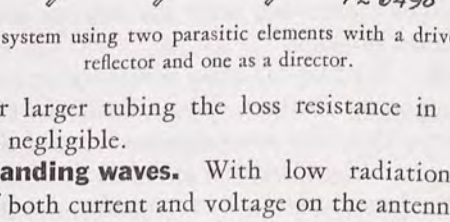

FIGURE 107. Antenna system using two parasitic elements with a driven antenna, one as a reflector and one as a director.

With half-inch or larger tubing the loss resistance in any two-element antenna should be negligible.

d. Effect of standing waves. With low radiation resistance the standing waves of both current and voltage on the antenna reach considerably higher maximum values than is the case with the antenna alone. For this reason, losses in insulators at the ends of the elements become more serious. The use of tubing rather than wire helps to reduce the end voltage and, furthermore, the tubing does not require support at the ends, thus eliminating the insulators and one source of power loss.

87. SELF-RESONANT PARASITIC ELEMENTS.

a. General. The special case of the self-resonant parasitic element is of interest, since it gives a good idea of the performance as a whole of two-element systems, even though the results can be modified by detuning the parasitic element. Figure 106 shows gain and radiation resistance as a function of the element spacing for this case. Relative field strength in the direction *A* of the small drawing is indicated by curve A; similarly for curve *B*. The front-to-back ratio at any spacing is the difference in the values at that spacing for curves *A* and *B*. Whether the parasitic element is functioning principally as a director or reflector is determined by whether curve *A* or curve *B* is on top; it can be seen that the principal function shifts at about 0.14 wavelength spacing. That is, at closer spacings the parasitic element is principally a director, while at greater spacings it is chiefly a reflector. At 0.14 wavelength the radiation is the same in both directions; in other words, the antenna is bidirectional with a gain of about 4 decibels.

b. Effect of detuning. The front-to-back ratios that can be secured with the parasitic element self-resonant are not very great, except in the case of extremely close spacings. Spacings of the order of 0.025 wavelength are hardly practicable with outdoor construction, however, since it would be difficult, if not impossible, to make the elements sufficiently stable, mechanically. Better practice is to use spacings of at least 0.1 wavelength, and detune the parasitic element for greatest attenuation in the backward direction.

c. Change in radiation resistance. The radiation resistance increases rapidly for spacings greater than 0.15 wavelength, while the gain, with the parasitic element acting as a reflector, decreases quite slowly. If front-to-back ratio is not an important consideration, a spacing as great as 0.25 wavelength can be used without much reduction in gain, while the radiation resistance approaches that of a half-wave antenna alone. Spacings of this order are particularly suited to antennas using wire elements, such as multi-element arrays consisting of combinations of collinear and broadside elements.

88. ADJUSTMENT OF TWO-ELEMENT (ONE PARASITIC) BEAM.

a. Assembly. Assemble the array. If possible, make adjustments after the array has been installed at its permanent operating height above ground. If this location is inaccessible, the adjusting may be accomplished on the ground before raising to the final height. Attach a transmission line of approximately 28 ohms impedance to the antenna, or if a higher impedance line is used, connect it to the antenna through a suitable matching transformer.

b. Auxiliary equipment. Either provide a field strength meter (see sec. XIV), or erect a simple half-wave antenna with a radio frequency thermo-galvanometer connected in the center of same at some convenient location in front of the array. Good insulation on this antenna is not important. However, the antenna must be tightly strung and very rigid. Distance between the array and the field strength antenna is not too important; however, it is well to erect the field strength antenna at a distance of approximately one wavelength away if possible.

c. Procedure. At this stage, a comparatively low power level may be fed to the radiator in the array—50 watts or less will usually suffice. With the director turned away from the field strength antenna, and with the radiator interposed between the director and field strength antenna, slowly begin adjusting the length of the director. The adjustments should be made an inch or less at a time, making sure at all times that a tight connection is maintained. This adjustment should be continued until the *lowest possible* current is indicated by the galvanometer in the field strength antenna. When the director length which provides the lowest reading, as indicated above, has been ascertained, the array will then be accurately adjusted for maximum radiation off the director side and minimum radiation off the radiator side. After the *lowest* current reading is obtained, the director should be *slightly lengthened* to a point which provides a meter reading approximately 10 percent higher than absolute minimum. With the array adjusted in this manner, it will have an impedance of 28 ohms.

d. Checking adjustments. After completing the adjustments as above, rotate the array 180° so that the director faces the field strength antenna, or move the field strength meter to the opposite side of the array. It should then be found that in this position the current in the field strength antenna will be at least 10 times as great as in the former position, with the director away from the field strength antenna. This indicates that the power ratio of radiation off the director side to radiator side is at least 10 to 1, or that there is an increase in radiation off the front compared to the back, of at least 10 decibels.

89. THREE-ELEMENT (TWO PARASITIC) BEAM.

a. General. It is possible to use two parasitic elements in conjunction with a driven antenna to give a further increase in directivity and gain. In such a case, it is best practice to use one parasitic element as a reflector and the other as a director, all three being in the same plane, as shown in figure 107. Experimental work indicates that the optimum spacings are the same as those for single elements; that is, director spacing of 0.1 wavelength and reflector spacing of 0.15 wavelength give maximum gain. Also, the previous remarks about tuning for gain and maximum front-to-back ratio continue to hold good. In some cases, the reflector is spaced 0.1 wavelength rather than 0.15 from the antenna, in order to secure mechanical symmetry; this reduces the possible gain somewhat, as is evident from figure 104, but the difference is small. Loss resistance becomes more important when two parasitic elements are used, because the radiation resistance as measured at the center of the driven antenna drops to a low value with close spacings. With the director spaced 0.1 wavelength, and the reflector 0.1 to 0.15 wavelength, radiation resistances of the order of 8 to 10 ohms are encountered. Good-sized tubing of good conductivity must be used for the elements if the gain possibilities of the system are to be realized. Further, the system becomes even more selective to frequency than the two-element antenna, so that peak performance can only be secured over a still smaller range of frequencies.

b. Adjustment.—(1) Assembly. Assemble and install the three-element array, following the same procedure as outlined for the two-element array. Also erect the field strength antenna in exactly the same manner, keeping in mind that the field strength antenna *must* be in the same

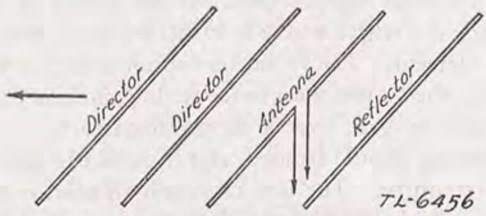

FIGURE 108. A four-element antenna system, using two directors and one reflector in conjunction with a driven antenna.

plane as the array. Attach a transmission line of approximately 8 ohms impedance to the antenna, or if a higher impedance line is used, connect it to the antenna through a suitable matching transformer.

(2) Preliminary adjustment of director. Feed a low power level (50 watts or less) to the radiator as previously outlined, with the *reflector* facing the field strength antenna and disconnected at the center. Then, begin adjusting the *director* length for lowest current in the field strength antenna, and leave the director adjustment at this point.

(3) Adjustment of reflector. Next, allowing the *director* to remain connected, reconnect the *reflector* and adjust the length of the *reflector*, until a still *lower* current begins to appear at the field strength antenna. Continue adjusting the *reflector* until the lowest possible current is indicated in the field strength antenna.

(4) Final adjustment of director. The array should now be rotated 180° (or the field strength antenna moved to the other side of the array) so that the *director* faces the field strength antenna. It is now well to readjust very slightly the length of the *director* to a point which provides absolute maximum current as indicated by the field strength antenna. When this position is located, the three-element array will be correctly adjusted and should provide a front-to-back ratio of approximately 15 to 25 decibels, a gain of 6 to 7 decibels over a half-way dipole in the same plane, and should reflect an impedance of approximately 8 ohms to the transmission line.

90. FOUR-ELEMENT (THREE PARASITIC) BEAM.

a. General. Additional parasitic elements may be added to any reasonable extent desired, and in an early form of this type of antenna (Yagi) several directors were used ahead of the driven element, with one reflector behind. With close spacing, two directors in addition to a single reflector represents about the practical limit so far as usefulness is concerned, since the continually decreasing radiation resistance is being met by a rising loss resistance, because of the greater number of elements. For the purpose of the rotatable antenna four elements represent a practical limit in mechanical construction as well as in performance. The four-element arrangement is shown in figure 108. Again the spacing and tuning considerations for single parasitic elements apply. Directors are spaced at intervals of 0.1 wavelength, while the reflector may be either 0.1 or 0.15 wavelength away from the driven element. The radiation resistance is 5 to 6 ohms, so that resistance losses in the system must be reduced as much as possible, if appreciable improvement in gain over a three-element array is to be secured. Large diameter tubing should be used, and it should be mounted rigidly to insure electrical stability. The low radiation resistance gives a four-element system quite high selectivity, so that optimum performance can be secured over but a relatively small band of frequencies on either side of that for which the system is alined.

b. Adjustment.—(1) Assembly. Assemble and install the four-element array in the same manner as outlined for the two- and three-element arrays. Set up the field strength antenna at the same distance away from and in the same manner as previously indicated. Be sure that the field strength antenna is in the same plane as the array. Attach a transmission line of approximately 5 ohms impedance to the antenna, or if a higher impedance line is used, connect it to the antenna through a suitable matching transformer.

(2) Preliminary adjustment of first director. With a power level of about 50 watts being fed to the radiator and with the *reflector* facing the field strength antenna but disconnected at the center, adjust the *director* which is closest to the radiator until a minimum current appears in the field strength antenna.

(3) Adjustment of second director. Adjust the second *director* which is farthest from the field strength antenna, until a slightly *lower* current is indicated in the field strength antenna. The first director should be connected and left at its previous setting while adjusting the second director.

(4) Adjustment of reflector. Reconnect the center of the *reflector* and adjust for a still *lower* current reading at the center of the field strength antenna.

(5) Final adjustment of director. The array may now be rotated through 180° (or the field strength antenna moved to the other side of the antenna) so that the field strength antenna is in front of the array, faced by the director. It may now be well to check the adjustment of all elements, and may perhaps be necessary to readjust somewhat the length of the directors. These should be adjusted with the array in this position for maximum or *highest* current in the field strength antenna. When adjustment of the four-element array is completed, the forward gain should be 7 to 9 decibels over a reference horizontal dipole erected in the same plane and at the same height above ground. The front-to-back ration should be 20 to 30 decibles.

91. GAIN AND FRONT-TO-BACK RATIO OF PARASITIC BEAMS.

a. General. The gain of arrays using parasitic elements is not readily calculated, nor is it easy to measure under conditions which hold in actual operation. It is impracticable to measure field strengths at the vertical angles useful for communication, while horizontal measurements do not necessarily give a true picture of the antenna's performance, particularly with respect to front-to-back ratios. There is no question, however, about the effectiveness of the systems.

b. Average gains and front-to-back ratios. On the basis of ground measurements and actual experience, average gains and front-to-back ratios realizable under normal conditions in practice are about as follows:

Number of elements	Gain over half wave (decibels)	Front-to-back ratio (decibels)
2	4 to 5	10 to 15
3	6 to 7	15 to 25
4	7 to 9	20 to 30

A great deal depends upon the care with which the system is adjusted. Maximum front-to-back ratios, in particular, are obtained only at the frequency for which the system is tuned.

92. METHODS OF FEED.

a. General. In antenna systems using close-spaced parasitic elements, the low radiation resistance makes feeding the antenna a special problem. When the radiation resistance is below 30 ohms, an ordinary resonant line of the open-wire type should not be used if its length is more than a half wavelength, since the losses resulting from the drastic mismatch will reduce the over-all gain of the system. Therefore, some means should be used to provide at least an approximate match between the antenna and the line. The methods shown in figure 109 are most appropriate. Although in each case a 600-ohm line is indicated, other types may be substituted in (A), (B), and (C) by suitable changes in the tap positions in (A) and (B), or by choice of proper impedance in the quarter-wave matching section in (C). For lines of appreciable length, however, the open-wire type is recommended, because its losses are the lowest of any of those commonly used.

b. Matching stub arrangement. The matching stub arrangements in (A) and (B) are of the type already described in section IV, and are similarly adjusted. Because of the low terminating impedance, it is desirable to use a fairly low impedance stub, since the adjustment will be less critical. No special impedance value is necessary; simply construct the stub of tubing and use close spacing. Provision should be made for keeping the stub conductors rigidly spaced with respect to each other. The matching section of the familiar "Q" antenna makes a good stub for this purpose. The half-wave stub at (B) is somewhat more convenient to adjust than the open-ended arrangement at (A), provided its length can be accommodated. See section IV for the adjustment procedure.

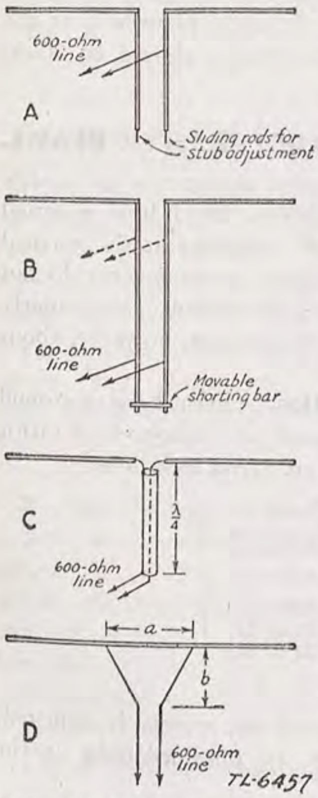

FIGURE 109. Recommended methods of feeding the driven antenna element in close-spaced parasitic arrays. The parasitic elements are not shown. (A) and (B), open and closed stub matching transformers; (C), quarter-wave matching section ("Q"); (D), delta matching transformer.

c. Quarter-wave matching section. In (C), a concentric line is used to bring about a match between the antenna and transmission line. The impedance of any practicable open two-conductor quarter-wave section is too high to be suitable for the purpose, hence the necessity for the concentric line. The matching section impedance is given by the equation

$$Z_o = \sqrt{Z_1 Z_2}$$

where Z_0 is the required surge impedance of the matching section, Z_1 the antenna impedance, and Z_2 the impedance of the transmission line. Assuming a 600-ohm transmission line, the required matching-section impedance varies from 95 ohms for a 15-ohm antenna to 55 ohms for a 5-ohm antenna. The ordinary 70-ohm line strikes a happy medium between these two values; it will give an exact match at about 8.5 ohms and the mismatch is less than 2:1 even at the extremes of 5 and 15 ohms. With this order of mismatch the line losses will not measurably increase over the perfectly matched condition, even though the line is quite long. For all practical purposes, therefore, a 600-ohm line can be matched to any type of parasitic array—two, three, or four elements—simply by connecting it to the center of the antenna through a quarter-wave section of

70-ohm line. In the interests of minimum loss and to get a known impedance value, the air-insulated type of line is to be preferred. The length of the antenna and the length of the line should be independently adjusted to resonance, if possible, although the formulas given in sections IV and V may be used without consequential error. The antenna may be resonated by one of the methods described in section V, and the line by the method given in section X. Rubber-insulated twisted-pair or concentric lines also may be used for the purpose. The standing wave ratio on the matching section is quite high, so the losses will be higher than normal for this type of line, but since only a short length is required, the actual loss is not high enough to be serious. The line length in this case will be considerably less than a quarter wavelength in space; the approximate length can be found by reference to section IV, but the line had best be adjusted to a quarter wavelength at the operating frequency before installation, using the oscillator method described in section X. The flexibility of the rubber-insulated line may give it preference in some installations. Whatever the type of line used, it need not run in a straight line, but can be coiled up or bent in any convenient fashion.

d. Delta matching transformer. The delta matching section shown in figure 109(D) is quite suitable for open-fire lines. It has the advantage that cutting the antenna element in two to insert the line is not necessary. The sides of the delta should be kept as rigid as possible to avoid detuning in a wind. The dimensions *a* and *b* should be determined experimentally, since they will depend considerably upon the number of elements in the antenna, the spacing between them, their tuning conditions, and the size of the conductors used. Dimension *b* should be about 15 percent greater than *a*, both being varied simultaneously, while a check is maintained on the standing-wave ratio on the line (see sec. IV) until standing waves are minimized. It is not necessary to strive for a perfectly "flat" line, since the losses will not increase perceptibly with standing wave ratios of 3 or 4 to 1 on a 600-ohm line.

93. FREQUENCY CHARACTERISTICS.

a. General. The selectivity of the various antenna systems becomes, as already mentioned, increasingly higher as the number of elements is increased. The system, therefore, should be adjusted for optimum performance on the frequency which is going to be used most. Changing the operating frequency is equivalent to shifting the tuning of its parasitic elements, and it is readily possible for an element to act as a director at one end of a band of frequencies and a reflector at the other, when it has been cut to operate as one of the two at the center of the band.

b. Off-frequency operation. Since the element length is not highly critical for good gain, but is highly so for attenuation to the rear, the chief effect of operating the antenna "off frequency" is to reduce the front-to-back ratio without greatly affecting the forward gain. In some cases, the gain may actually increase, at a frequency slightly different from that for which the system was adjusted, when the initial adjustment was made to secure maximum front-to-back ratio. For transmitting, therefore, the ordinary antenna will work quite satisfactorily over a small frequency band. It will also give good gain over the same band for receiving, but only near the right frequency will it give the attenuation to the rear for which it was designed. There will usually be no trouble in getting the antenna to accept power when the frequency is shifted. A change in frequency usually brings with it a change in radiation resistance, but this is readily conpensated for by adjustment of the coupling at the transmitter. The relatively small mismatch at the antenna will not materially increase the losses in an open-wire line.

94. HEIGHT ABOVE GROUND.

a. General. Reflection from the ground takes place in the same way with parasitic element arrays as with any other type of antenna. The reflection factors shown in section III apply with equal force, therefore. It is obviously desirable to choose a height which will aid in producing maximum radiation at the angles most useful for the type of communication to be carried on. Since this subject has already been covered in earlier sections, it need not be discussed further here.

b. Effect on determining radiation resistances. Height above ground also plays an important part in determining the radiation resistance of the array, especially when the elements are horizontal. The radiation resistance figures so far discussed in this section are the free-space values, and they will be modified in much the same way as the radiation resistance of a horizontal half-wave antenna is modified in the presence of the ground. Since it is advantageous to keep the radiation resistance from dropping to too low values, heights which cause a reduction in resistance should be avoided. Thus, a height of the order of 0.6 wavelength (fig. 28) is likely to give poorer performance than 0.5 wavelength, contrary to the customary impression that every bit of height gained is reflected in better performance. Since the effective ground plane usually is below the surface, the height cannot be determined very accurately without some type of measurement. One rather simple method is to "explore" with a horizontal half-wave antenna the height of which can be readily adjusted. With an r. f. meter in its center, and keeping constant input to the transmitter, the height should be changed in small steps while readings are taken of the antenna current. A height which gives maximum antenna current of course represents a height at which the radiation resistance is low, and vice versa.

95. MULTI-ELEMENT ARRAYS.

a. Parasitic reflectors and directors. Parasitic reflectors or directors may be used with any of the broadside or collinear arrays described in section VI. The close spacing which gives greatest gains is not very suitable for this type of antenna, however, because it is practically impossible to get enough mechanical rigidity in wire elements to prevent bad detuning in a breeze.

b. Use of one set of parasitic elements. It is more practical to use only one set of parasitic elements, one behind each driven element in the array, tuned to work as a reflector. Quarter-wave spacing between driven and parasitic elements is satisfactory mechanically, and does not involve much loss of gain. With proper tuning, that is, with the reflector slightly longer than the condition which gives self-resonance, a theoretical gain of about 4 decibels and a front-to-back ratio of about 10 decibels can be secured. The correct length can be determined by measurement as described previously, using one pair of elements for the purpose. Then all the parasitic elements can be made the same length.

SECTION VIII

LONG SINGLE WIRES

96. DIRECTIONAL AND RESISTANCE CHARACTERISTICS.

a. Concentration of radiation. As pointed out in the previous section, the maximum radiation from a half-wave antenna is broadside to the wire, with some modification introduced by the height above ground.

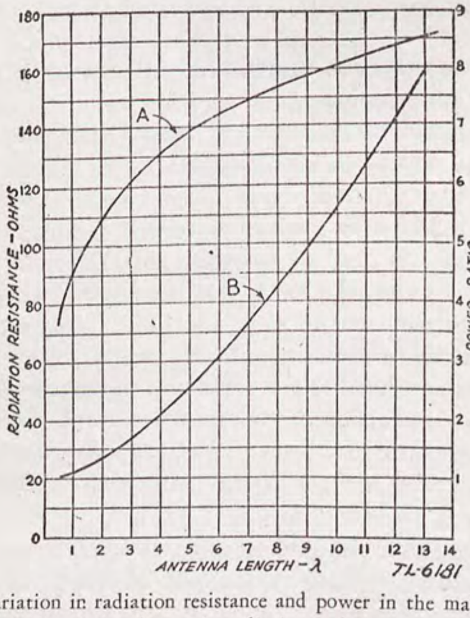

FIGURE 110. The variation in radiation resistance and power in the major lobe of long-wire antennas. Curve *A* shows the change in radiation resistance with antenna length, while curve *B* shows the power in the lobes of maximum radiation for long-wire antennas as a ratio to the maximum of a half-wave antenna.

However, when the wire is a wavelength or more long, the radiation tends to concentrate more and more off the ends, although some minor lobes appear and fill in the radiation in other directions. Further, the long wire antenna radiates more power in its most favorable direction than does a half-wave antenna in its favorite direction. This power gain is obtained at the expense of radiation in other directions. By properly orienting a long-wire antenna, it is possible to put out a stronger signal in the desired direction than would be possible with a half-wave antenna.

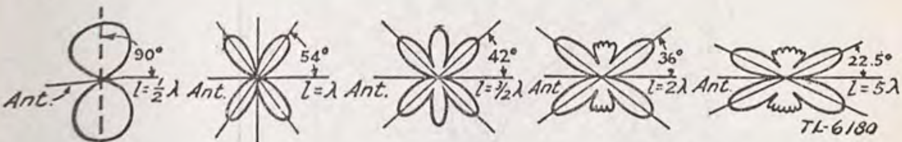

FIGURE 111. Free-space diagrams of typical long-wire antennas.

b. Antenna length and radiation resistance. As in the case of the half-wave antenna, the long-wire antenna will normally be worked at resonance, so that maximum power can be introduced into it. The radiation resistance as measured at a current loop becomes larger as the antenna length is increased. Figure 110 shows how the radiation resistance and power gain of the major lobe increases as the length of the antenna is increased. The radiation resistance given is the free-space resistance and will be modified by the height above ground, similar to the case of the half-wave antenna.

c. Free-space patterns. Free-space patterns of a few long-wire antennas are given in figure 111. These are not the patterns obtained in

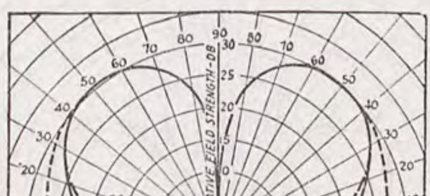

FIGURE 112. The horizontal pattern for a one-wavelength antenna at vertical angles of 9°, 15°, and 30°.

actual practice, because of the ground modification, and also because they show only what would be obtained along the horizontal plane, where no radiation is ever obtained in actual practice. However, they serve to show how the pattern is modified as the length of the radiator changes.

d. Practical patterns. More practical patterns are shown in figures 112 to 117, inclusive. These patterns show the radiation of various long-wire antennas for various vertical angles of radiation. The height above ground

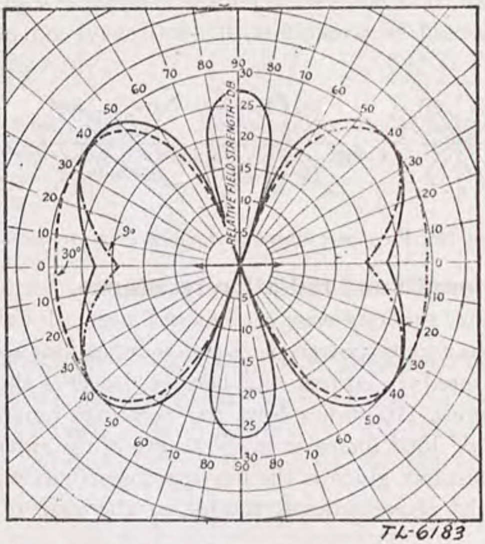

FIGURE 113. The horizontal pattern for a 1½-wavelength antenna at vertical angles of 9°, 15°, and 30°.

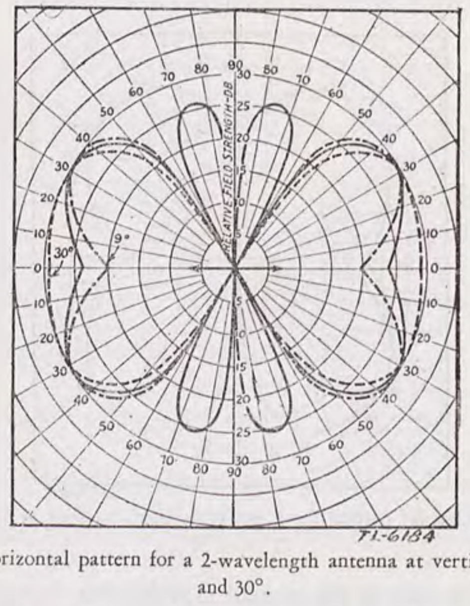

FIGURE 114. The horizontal pattern for a 2-wavelength antenna at vertical angles at 9°, 15°, and 30°.

does not modify these patterns, but it does have an effect on the gain of the antenna over a half wave. Reference to figures 112 to 117, inclusive, gives the factors that should be applied to the antenna pattern for various heights and, if possible, the antenna should be hung at a height that gives the maximum radiation at the desired vertical angle. In any event, a study

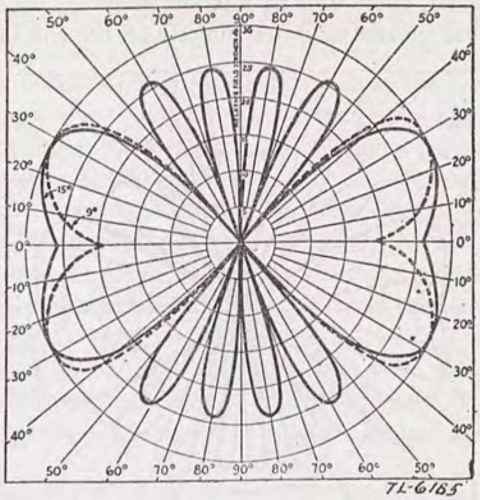

FIGURE 115. The horizontal pattern for a three-wavelength antenna at vertical angles of 9° and 15°.

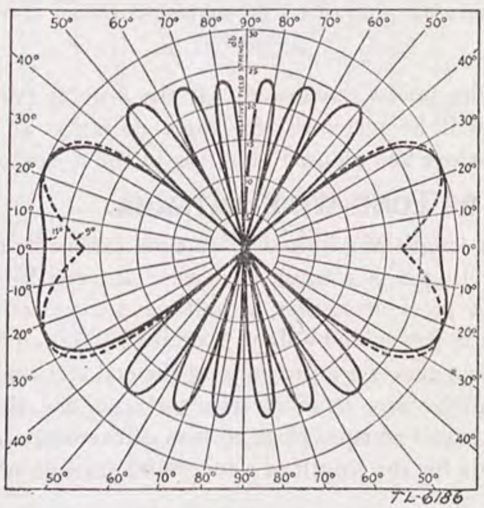

FIGURE 116. The horizontal pattern for a four-wavelength antenna at vertical angles of 9° and 15°.

of figures 112 to 117, inclusive, will allow one to predict with a fair degree of accuracy the performance of a proposed long-wire antenna.

e. Angles of major and minor lobes and of nulls. For wires longer than five wavelengths, the chart shown in figure 118 shows the angles of the major and minor lobes and also the nulls of the free-space pattern.

f. Effect of ground slope. The above patterns are for the wire at equal height above the ground throughout its length. If the wire is sloping on level ground, there will be a modification of the pattern, usually tending to result in greater radiation directly off the end of the wire in the

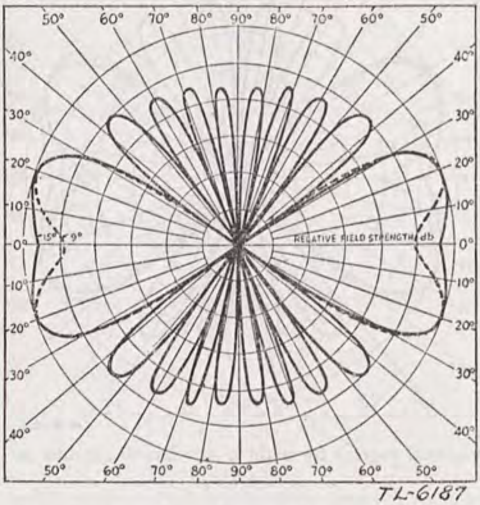

FIGURE 117. The horizontal pattern for a five-wavelength antenna at vertical angles of 9° and 15°.

direction the wire points downward. If the wire is parallel to sloping ground, there will be increased low-angle radiation in the downward direction of the slope and reduced radiation in the opposite direction.

97. LENGTH OF LONG-WIRE ANTENNA.

a. The proper length of a long-wire antenna cannot be found by simply multiplying the length of a single half-wave antenna by an integer. As mentioned in the previous section, a half-wave antenna is shorter than a half wavelength in free space by about 5 percent because of the end effect of the wire, but these effects operate only on the end sections of the antenna; in other parts of the wire these effects are absent, and the wire length is approximately that of an equivalent portion of the wave in space.

b. The formula for the length of a long-wire antenna is

$$\textit{Length (feet)} = \frac{492\,(N-0.05)}{\textit{Frequency}\quad\textit{(megacycles)}}$$

where N is the number of *half* waves on the antenna. From this it is apparent that an antenna cut for any particular frequency will be slightly off resonance at exactly twice that frequency (on the second harmonic), or four times that frequency (on the fourth harmonic). This effect is not important except where tuned feeders are used at one end of the antenna, in which case there will be some unbalance of current in the feeders at the harmonic frequencies. A symmetrical system would, of course, be free from this slight disadvantage.

98. FEEDING LONG-WIRE ANTENNA. All that has been said about the feeding and adjustment of a half-wave antenna applies equally as well to the long-wire antenna, except for one stipulation: since the currents in adjacent sections of a long-wire antenna must be out-of-phase, the feeder system must not upset this relationship. This requirement is met by feeding the long-wire antenna at one end or at a current loop. A two-wire feeder cannot be inserted at a current node (except at the end of the wire), since this invariably brings the currents in two adjacent half-wave sections in phase; if the phase in one section could be reversed, then the currents in the feeders would be in phase, and the feeder radiation would not be canceled out. This does not mean that the antenna would not work if the current in two adjacent half waves were in phase; it simply means that the antenna would not be functioning as a long-wire antenna, and the patterns given would not hold without modification.

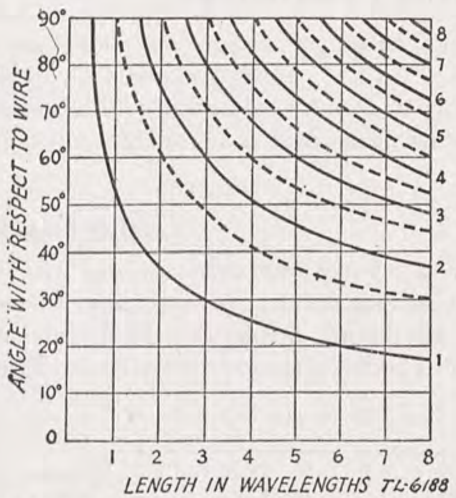

FIGURE 118. A chart of the angles the major and minor lobes (solid lines) make with the wire, for different length antennas. The dotted lines represent the nulls. No. 1 is the major lobe and has the gain given in figure 110.

99. END-FED LONG-WIRE ANTENNA. The coupling, adjustment, and tuning of an end-fed long-wire antenna is exactly the same as for a half-wave antenna and need not be mentioned in great detail, since it has already been covered in section IV. However, it should be pointed out that, while it is possible to put power into almost any length of long wire, several experimenters have found that careful pruning of the length of the long end-fed antenna leads to greater ease of coupling, and possibly better transfer efficiency. The exact length can be determined experimentally by the same means as outlined for the half wave; the antenna should introduce no reactance to the tank circuit to which it is connected (have no effect on the tuning when connected).

100. TUNED FEEDERS FOR LONG WIRE. Tuned feeders are probably the most practical for the long wire, since they permit operation over a wide range of frequencies with all of the antenna "in the clear."

101. MATCHING SECTIONS.

a. Quarter-wave and Q-match systems can be used with the long-wire antenna. However, the use of a quarter-wave matching section will limit the operation to one narrow band of frequencies, and the Q system must be used as tuned feeders for frequencies other than the one for which it is adjusted.

b. In designing quarter-wave matching sections and Q-match sections, it should be remembered that the radiation resistance for a long-wire antenna is higher than for a half-wave (see fig. 110), and this must be taken into account in calculating the values of the matching section. However, because of the increased radiation resistance, the long-wire antenna tunes more broadly than one of lower resistance.

SECTION IX

V ANTENNAS

102. GENERAL. As pointed out in section VIII, the lobe of maximum radiation from a single long wire makes a more acute angle with the wire, and the power in the lobe becomes greater, as the length of the wire (in wavelengths) is increased. There are several ways in which long harmonic wires can be combined to add the effects of the single wires and give greater gain.

103. ECHELON ANTENNA.

a. Design. If two long wires are made parallel to each other and excited out-of-phase, the radiation will cancel in the direction perpendicular to the plane of the wires. The radiation is then maximum in the plane of the wire and at angles equal to those of the lobes for a single wire of equal

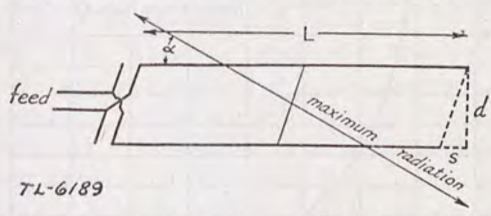

FIGURE 119. The echelon antenna uses two long parallel wires excited out-of-phase. In its simplest form it is a bidirectional affair, although it can be made unidirectional by the addition of two more elements. See text for dimensions *s* and *d*. The angle is the angle of the major lobe for the length *L*, and can be obtained from figure 118.

length. If the two wires are staggered, two of the four lobes will disappear, providing the stagger and spacing of the wires are correct for their lengths. This form of antenna is shown in figure 119 and is called the echelon antenna. It is normally used with the wires in the horizontal plane, but it can be used with the wires in a vertical plane. However, when the wires are used in the vertical plane they must be slanted to make the lobe come down to a reasonable angle with the horizontal and this necessitates supports that are too high for all practical purposes. The horizontal echelon antenna should be at least a wavelength above ground for best results.

b. Amount of stagger. The amount of stagger can be calculated from

$$s\ (feet) = \frac{492 \sin \alpha}{f\ (megacycles) \sin 2\alpha}$$

and the distance between wires is given by

$$d\ (feet) = \frac{492 \cos \alpha}{f\ (megacycles) \sin 2\alpha}$$

where α=angle of maximum radiation from a single wire (obtained from figure 118). As an example, an echelon antenna with three-wavelength legs would be spaced a half wavelength and staggered 0.29 wavelength.

c. Unidirectional echelon antenna. The echelon antenna can be made unidirectional by introducing another pair of wires at quarter-wave space and 90° phase relation with the first pair, but this is a refinement used only in commercial installations.

d. Feeding of echelon antenna. The two wires of the echelon should be fed as shown in figure 119 so that the radiation from the feeders will be minimized and not tend to cancel the directivity.

e. Objection to echelon antenna. The principal objection to the echelon antenna is the fact that the gain becomes significant only when wires of at least three wavelengths are used and when the height can be

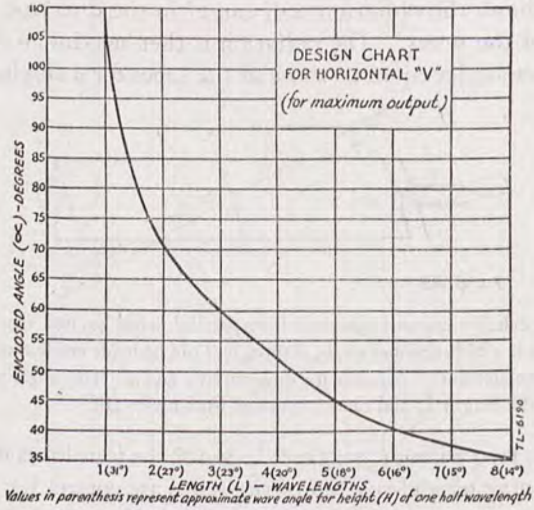

FIGURE 120. Design chart for horizontal V antennas. The inclosed angle between sides is shown plotted against the length of the legs in wavelengths. The actual length of the legs in feet can be found from the formula in section VIII.

made at least a wavelength. These figures are not hard to attain at the highest frequencies, however.

104. NATURE OF V ANTENNA. Two wires combined to form a V at such an angle that the main lobes reinforce along the line bisecting the V make a very effective directional antenna. If the two sides of the V are excited 180° out-of-phase, by connecting the two-wire feed line to the apex of the V, the lobes add up along the line of the bisector and tend to cancel in other directions, as shown in figure 120. The V antenna is essentially a bidirectional system, and the gain depends upon the length (in wavelengths) of the wires. The V is a simple antenna to build and operate, providing the necessary room is available, and with tuned feeders it can be operated satisfactorily over a wide frequency range, although it is, of course, optimum for only one. Nevertheless, it will show considerable gain over a wide frequency range, the gain increasing as the frequency increases. The longer the V, the less will be the departure from optimum angle as the frequency is varied.

105. DESIGN OF V ANTENNA.

a. The chart in figure 121 gives the dimensions that should be followed for an optimum design to obtain maximum power gain from a V beam. The wave angle referred to is a vertical angle of maximum radiation for a height of one-half wavelength, and this angle becomes less for any given length as the height above ground is increased. Tilting the whole horizontal plane of the V will tend to increase the low-angle radiation off the low end and decrease it off the high end. If the ground slopes, the antenna should be made parallel to the ground and preferably with the open end of the V down the slope.

b. The gain of the V beam can be increased by stacking two beams one above the other, a half wavelength apart, and feeding them so that the legs on one side are in phase with each other and out of phase with the legs on the other side. This will result in a greatly lowered angle of radiation. The bottom V should be at least a quarter wavelength above the ground, preferably a half wavelength.

c. Two V beams can be broadsided to form a W and give greater gain. It is used by many commercial short-wave stations.

d. The V beam can be made unidirectional by using a reflector at least a quarter wavelength in back of the antenna. A better plan is to use another V placed an odd quarter wavelength in back of the first and to excite the two with a phase difference of 90°. The system will be unidirectional in the direction of the antenna with the lagging current for quarter-wave separation. This limits the use of the antenna to operation on a narrow frequency range, however.

106. UNIDIRECTIONAL V's. The V can be made unidirectional and aperiodic by terminating the open ends of the V to ground through resistors. These resistors must dissipate almost half the power fed to the antenna and the ground connection must be an excellent one. Because of the practical difficulties involved, terminated V's are not often used, although they present excellent possibilities.

107. FEEDING THE V.

a. The V beam is most conveniently fed by tuned feeders, since they permit multi-band operation. If an untuned line is used, the quarter-wave

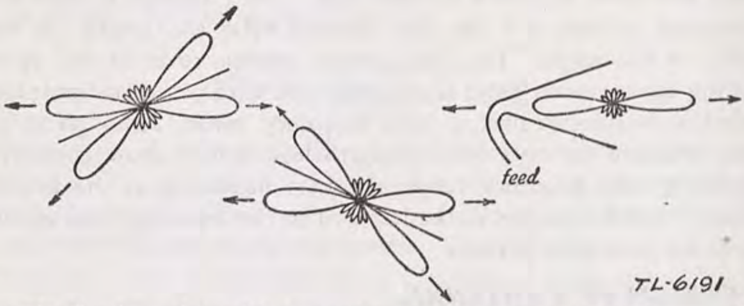

FIGURE 121. Two long wires and their respective patterns are shown in the diagram. If these two wires are combined to form a V, the angle of which is twice that of the major lobes of the wires, and the wires are excited out-of-phase, the radiation along the bisector of the V adds and the radiation in the other direction tends to cancel.

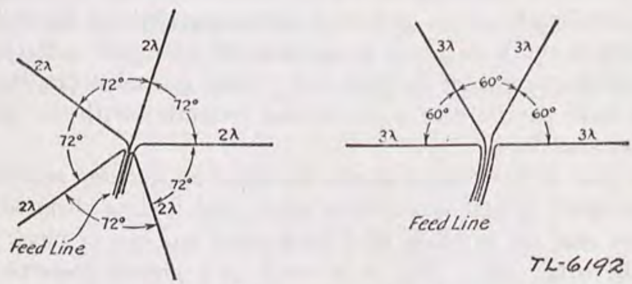

FIGURE 122. Two suggestions for V-beam combinations. The two-wavelength affair at the left gives good general coverage because it gives a choice of five directions. The system at the right gives more gain but a choice of only three directions. (Since the systems are bi-directional, "direction" means along a bidirectional line.) Other combinations could be: seven four-wavelength elements arranged radially at 51½°; five five-wavelength elements arranged half-radially at 45°; nine six-wavelength elements arranged radially at 40°.

matching section is as convenient as any, since it allows the entire system to be tuned before attaching the feeders, by simply adjusting the shorting bar on the matching section. The length of the wires in a V beam is not at all critical, but it is important that both wires be of the same electrical length. Balanced feeder currents (in a tuned line) give sufficient indication of balanced lengths in the antenna proper.

b. The terminated V is fed by a 600-ohm line, and a good match will be obtained with almost any combination. The terminating resistors should be adjusted for minimum standing waves on the feeders and the performance should be checked on several frequencies throughout a band.

108. V-BEAM COMBINATIONS.

a. The V beam lends itself admirably to a general coverage system by arranging several V beams radially and selecting the one in the desired direction by switching to the proper feeder combination. Figure 122 shows the general principle and gives the length and angle combinations that can be used.

b. The proper pair of wires can be selected by running all of the feeder wires into the station (the feeder spaces will be hoops instead of bars), or the antennas can be switched at the pole by means of a remote relay.

c. In any V-beam combination, it is important that the flat-top lengths be so adjusted that going from one combination to the next will not affect the tuning at the transmitter end. This can be readily done by progressively pruning the antennas at the far ends until they all match up. Care must be taken, of course, that the wire in each feeder is exactly the same length if they are all brought into the station.

109. OBTUSE ANGLE V's. It might be considered that an obtuse angle could be used, since, if it were fed at one end and properly proportioned, the lobes should reinforce along the perpendicular to the bisector. However, for the same amount of wire, the obtuse angle V is definitely inferior to the acute angle V. Two obtuse angle V's, side by side to form a diamond, are discussed in section X.

SECTION X
RHOMBIC ANTENNAS

110. GENERAL.

a. The family of antennas of which the rhombic, or diamond, antenna represents the highest development—and, in fact, the most practicable form—differs somewhat in principle from the antenna types already described. Previously discussed antennas operate with standing waves of current and voltage along the wires; this section deals principally with antenna systems in which the current is practically uniform in all parts of the antenna.

b. In its elementary form, such an antenna would consist of a single wire grounded at the far end through a resistor having a value equal to the characteristic impedance of the antenna, as shown in figure 123. This termination, just as in the case of an ordinary transmission line, eliminates standing waves. The current, therefore, decreases uniformly along the wire as the terminated end is approached, the decrease being caused by loss of energy by radiation and by resistance loss in the wire. The energy remaining when the end of the antenna is reached is dissipated in the terminating resistor. For such an antenna to be a good radiator, its length must be fairly long, in terms of wavelength, because the current is relatively small. Hence, greater wire length is necessary to radiate the same energy as that radiated from a shorter antenna with the higher current which results with standing waves. Also, the wire must not be too close to the ground so that the return path through the ground will cause cancellation of the radiation. If the wire is sufficiently long it will be practically nonresonant over a wide range of operating frequencies.

111. DIRECTIONAL CHARACTERISTIC. The directional characteristic of a nonresonant long-wire antenna differs from that of a resonant long wire of the same length in an important respect. The terminated wire is practically unidirectional, giving greatest response to incoming signals which arrive from the general direction in which the wire points, looking along the antenna toward the terminated end. The directional characteristic varies with the length of the wire, in a fashion somewhat similar to the shift in directional characteristic of resonant long-wire antennas, as shown in figure 124, but in every case the radiation or response is considerably smaller in the backward direction than in the forward.

112. RADIATION PATTERNS. The free-space pattern of a nonresonant long-wire antenna would have the usual solid form discussed earlier in this manual, the drawings of figure 124 representing cross sections in planes containing the wire. The angle which the main lobe makes with the wire depends upon the antenna length, but because of the different type of current distribution these angles are not the same for resonant and nonresonant antennas of the same length. The difference is most marked for short wires (the main lobe makes an angle of about 45° with the nonresonant antenna and 54° with the resonant antenna, when both are one wavelength long) but for lengths of two wavelengths and more the differences are so small as to be negligible. The energy which, in the case of a resonant wire, would be radiated in the backward direction, as absorbed by the terminating resistor in the case of the nonresonant antenna.

113. USE OF NONRESONANT ANTENNA PRINCIPLE. The elementary nonresonant antenna is not an especially good radiator in the single-wire form just described, but the general principle is utilized in the construction of highly effective unidirectional antenna systems.

114. TILTED-WIRE ANTENNAS.

a. Principles. The type of antenna shown in figure 125 is the forerunner of the diamond or rhombic type, and is of interest for that reason, although now seldom used. The principle of operation resembles the combining of major lobes of radiation already described in section IX, although in a somewhat different fashion. For example, suppose that each of the sides, or legs, of the V is two wavelengths long, so that the major lobe of *each* wire makes an angle of 36° with the wire. Then the tilt angle ϕ (half the total angle included between the wires) may be adjusted so that the major lobes of radiation from the two wires will add in the desired direction. The tilt angle then becomes the complement of the angle which the main lobe makes with each wire. This is shown in figure 125, for horizontal transmission to the right in the figure. In directions other than to the right in the plane containing the antenna, the radiation from the individual wires will tend to cancel more or less completely.

b. Adjusting tilt angle. When the lobes of the two wires are aligned in this way, the currents induced in the antenna by a wave coming from the desired direction do not add exactly in phase at the receiver end. For this condition to be met a somewhat smaller tilt angle is required. This tilt angle ϕ is made such that the projection of one leg on a line joining the two ends of the antenna (in the figure, the ground forms such a line) is exactly one-half wavelength less than the length of the leg. The difference between the tilt angle for coincidence of the major lobes and that for optimum phasing is greatest with the shorter leg lengths; for example, with a leg one wavelength long, ϕ is about 45° for alignment of the lobes, but 30° for optimum phasing. With lengths greater than two wavelengths, the difference is of the order of but a few degrees. In general, the optimum angle for best all around performance lies between the two.

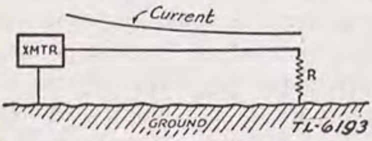

FIGURE 123. The terminated long-wire antenna which is the basis of nonresonant antenna design. The current falls off slowly from the transmitter and to the terminating resistor, but there are no standing waves.

c. Attaining unidirectional characteristic. The terminating resistor at the far end absorbs the back radiation, just as in the case of the elementary form of terminated antenna, so that the antenna is essentially unidirectional.

d. Difficulties of tilted-wire antennas. The form of titled-wire antenna, shown in figure 125, is simple in construction, since only one pole is required. However, for all but quite high frequencies, the pole height needed to provide the proper title angle for a leg length great enough to provide appreciable gain is difficult to obtain. Also, it is difficult to secure a satisfactory termination because of variation in ground resistance with weather conditions. This might be overcome by the use of a large ground screen under the antenna and extending a half wavelength or so beyond the wire in all directions, but the installation of such a screen probably would be impracticable in most locations. A form of transmission-line termination also may be used, with the far end of the antenna connected to the center of a half wave running parallel to the ground and perpendicular to the line of the antenna. The impedance at the center of such a wire will be low, and currents induced by the incoming waves from the desired direction will balance out. However, such a termination is good only for the frequency for which the wire is cut, so that a wide frequency range is not possible. These difficulties are overcome by the use of the diamond-shaped, or rhombic, antenna.

115. DESCRIPTION OF RHOMBIC ANTENNA. The rhombic antenna, shown schematically in figure 126, consists of two tilted-wire antennas of the type shown in figure 125, placed side by side. The terminating resistor is connected between the far ends of the two sides, and is made approximately equal to the characteristic impedance of the antenna as a unit. The rhombic may be constructed either horizontally or vertically, but practically always is made horizontal, except at ultrahigh frequencies, since the pole height required is considerably less Also, horizontal polarization is equally, if not more, satisfactory, at the frequencies for which this antenna is suited.

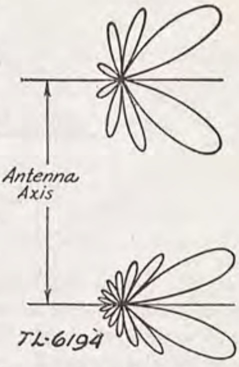

Figure 124. Typical radiation patterns (cross section of solid figure) for terminated long wires. (A) length two wavelengths; (B) four wavelengths; both for an idealized case in which there is no decrease of current along the wire. In practice, the pattern is somewhat distorted by wire attenuation.

116. ADVANTAGES OF RHOMBIC ANTENNA. The rhombic antenna is probably the ideal arrangement for obtaining maximum gain in a given direction, where the ground space necessary for its construction is available. It will give excellent results over a frequency range of more than 2 to 1, and will also radiate well, although with reduced gain and directivity, at frequencies considerably lower than that for which it is designed. Along with the excellent frequency characteristic, it also gives higher gains than any other types of antennas except a very few which require much more elaborate construction. In addition, it is not critical as to adjustment or operation.

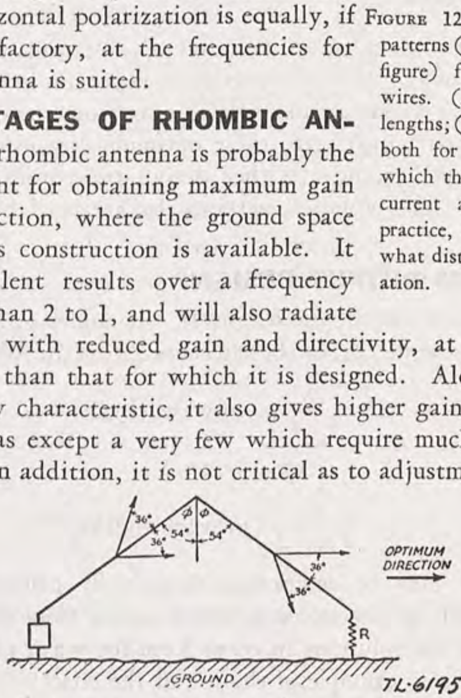

Figure 125. The tilted-wire antenna showing the directions of the main lobes for each wire for legs two wavelengths long, when the tilt angle ϕ is adjusted for alignment of the lobes.

117. HORIZONTAL WAVE ANGLE. In the horizontal form the general principles for determining the tilt angle, ϕ, are the same as already described. However, the choice of the tilt angle is modified somewhat by the fact that the maximum radiation is not in the plane of the antenna, but is at some angle with respect to the ground. This is true of all horizontal antennas, and has already been discussed in section III on ground effects. In the design of a rhombic antenna, therefore, the angle of maximum radiation (often called the wave angle) above the ground must first be considered. It is desired, naturally, to make the antenna radiate and receive best at the angles which normally are most effective for communication on the frequency to be used. Since rhombic antennas are chiefly used for high-frequency work, angles of the order of 0° to 20° above the horizon are of most interest.

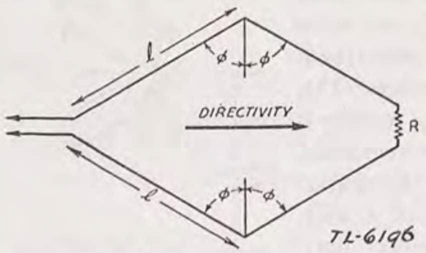

FIGURE 126. The rhombic or diamond antenna. The important elements are the leg length, l, the tilt angle ϕ, the height (not shown), and the terminating resistor R.

118. DETERMINING DIMENSIONS. Once the desired wave angle is selected, there are three quantities to be determined: the tilt angle, ϕ, the antenna height, H, and the length of each leg, l. For a given wave angle there is one set of these dimensions which will give maximum radiation in the desired direction, or maximum response to signals coming from the desired direction. The design method which gives these optimum dimensions is called the "maximum output" method. Other design procedures, known as the "alignment" and "compromise" methods also are available to meet special conditions.

119. MAXIMUM OUTPUT DESIGN.

a. For maximum output, the height H, tilt angle, ϕ, and leg length, l, for a selected wave angle, Δ, can be determined from the following formulas:

$$H=\frac{\lambda}{4\,sin\,\Delta}\ \text{(in wavelengths)}$$

$$sin\,\phi = cos\,\Delta$$

$$l=\frac{\lambda}{2\,sin^2\,\Delta}\ \text{(in wavelengths)}$$

These quantities may be determined directly by calculation, with the assistance of a table of trigonometric functions, or from the chart of figure 127, which gives the solutions in curve form for wave angles from 10° to 30°. Following is an example of the use of the chart:

Given: Desired wave angle $(\Delta)=18°$.
To find: H, l, ϕ.
Method:

Draw vertical line through point *a* (18° wave angle abscissa).
Read intersection of this line on each curve on its corresponding scale.
e=angle of tilt (ϕ).
d=height (H).
c=length (l).

Result:

$\phi=72°$.

$H=0.81$ wavelengths.

$l=5.25$ wavelengths.

b. The chart also may be used to determine the other three quantities provided any one of the four is given; usually, the height, H, and length, l

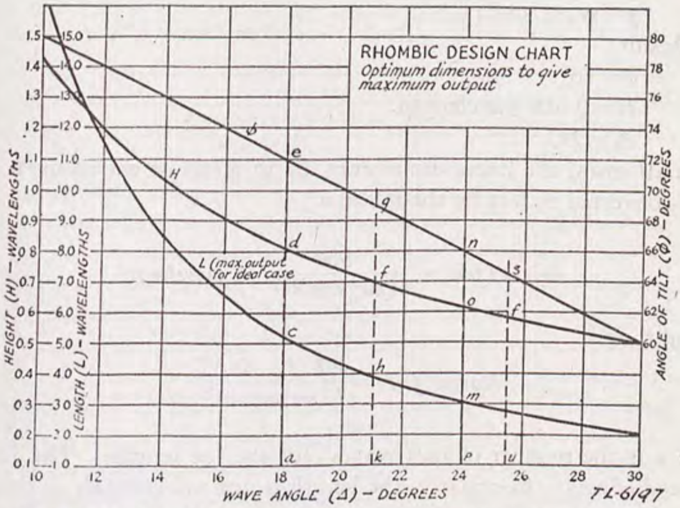

FIGURE 127. Rhombic antenna design chart for maximum-output design.

will be subject to limitations. In this case the curves will give the corresponding wave angle $\triangle$. It may readily occur, however, that the value of $\triangle$ so obtained will not be a desirable value for communication on the frequency under consideration; reduced height or length will raise the angle of radiation. The following examples illustrate the use of the chart in this way:

Given: Available and effective height $(H)=0.7$ wavelength.

To find: l, ϕ, $\triangle$.

Method:

Draw vertical line through point f (0.7 wavelength on curve H). Read intersection of this line on each curve on its corresponding scale.

g=angle of tilt (ϕ).

h=length (l).

k=wave angle ($\triangle$).

Result:

$\phi=69°$.

$l=3.9$ wavelengths.

$\triangle=21°$.

Given: Length for 1 side $l=3.0$ wavelengths.

To find: H, ϕ, $\triangle$.

Method:

Draw vertical line through point m (3.0 wavelengths on curve l).

Read intersection of this line on each curve on its corresponding scale.

n=angle of tilt (ϕ).

o=height (H).

p=wave angle (Δ).

Result:

$\phi=66°$.

H=0.618 wavelength.

$\Delta=24°$.

c. In all cases, the linear dimensions are in terms of wavelength. This may be converted to feet by the relation

$$height\ (feet)=\frac{984}{f\ (megacycles)}=1\ wavelength$$

for height, and

$$length\ (feet)=\frac{492\ (N-0.05)}{f\ (megacycles)}$$

(where n is the number of half waves) for the leg length. The latter includes end effects. In practice, the length is not too critical, so end effects may be ignored and the leg length calculated on the basis of the length of a wave in space with negligible error.

120. COMPROMISE DESIGNS.

a. In cases where the height or length, or both, of the antenna are limited, compromise design methods which will give greatest antenna output under the existing conditions are available. Antennas designed according to these compromise methods give smaller output than is obtained by the maximum output method, depending upon how far the antenna dimensions depart from the ideal case. A decrease in height can be compensated for by an increase in length without much loss in output, but if the length has to be reduced considerably below the ideal case a more serious loss in output is suffered.

b. When the length and height are both subject to variation, with the length the determining factor, the chart of figure 128 may be used. This chart gives the tilt angle and height in terms of the leg length and wave angle, but may also be used to determine the other two quantities when the leg length and height are known. The following examples give typical uses of the chart:

Given:

Length (l)=2 wavelengths.

Desired wave angle (Δ)=20°.

To find: H, ϕ.

Method:

Draw vertical line through point *a* ($l=2$ wavelengths) and point *b* on abscissa ($\Delta=20°$).

Read angle of tilt (ϕ) for point *a* and height (H) from intersection of line *ab* at point *c* on curve *H*.

Result:

$\phi=60.5°$.

$H=0.73$ wavelength.

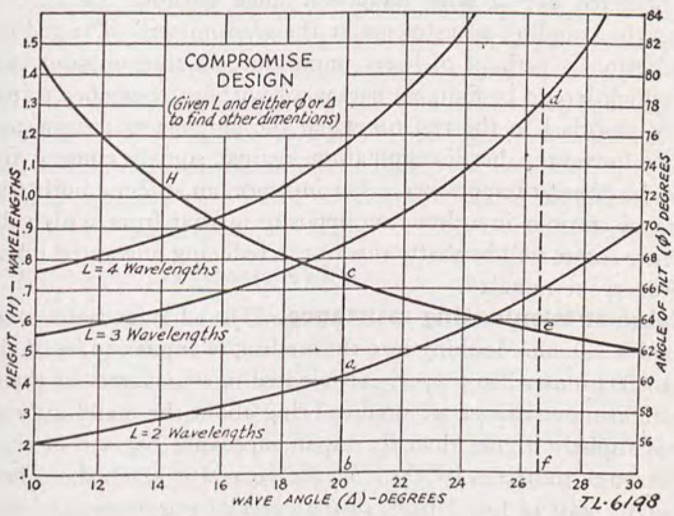

FIGURE 128. Compromise design chart for various leg lengths.

Given:

Length (l)=3 wavelengths.

Height (H)=0.56 wavelength.

To find: ϕ, Δ.

Method:

Draw vertical line from point *e* on curve *H* at 0.56 wavelength.

Read intersection of this line on curve $l=3$ wavelengths (point *d*) for ϕ and intersection at point *f* on the abscissa for Δ.

Result:

$\phi=78°$.

$\Delta=26.6°$.

c. Leg lengths of two, three, and four wavelengths are indicated. For other lengths, a fair idea of the other three quantities can be secured by interpolating, or new curves for any desired leg length can be plotted from the following equation, substituting the desired value of l in terms of wavelength:

$$\sin \phi = \frac{l-0.371}{l \cos \Delta}$$

Solution of this equation for the various values of $\triangle$ given on the chart will give the corresponding tilt angles.

121. TERMINATING RESISTANCE.

a. Importance. The terminating resistance plays an important part in the operation of the rhombic antenna; upon it depends the unidirectivity of the antenna, and the lack of resonance effects. A properly terminated antenna will show practically constant impedance at its input and so that it can be operated over a wide frequency range without the necessity for changing the coupling adjustments at the transmitter. The reduction of back radiation is perhaps of lesser importance in transmission, since the energy which would be radiated backward without resistance termination is simply absorbed in the resistor when the antenna is terminated. For reception, however, the discrimination against signals coming from the rear may be of great importance. For instance, an antenna built for working distance stations in a direction opposite to that from which domestic interference comes will be vastly superior in reducing unwanted interference when properly terminated.

b. Value of terminating resistance. The characteristic impedance of a rhombic antenna, looking into the sending or input end, is of the order of 700 to 800 ohms when properly terminated in a resistance at the far end. The terminating resistance required to bring about the matching condition usually is slightly higher than the input impedance because of the loss of energy through radiation by the time the far end is reached. The correct value usually will be found to be of the order of 800 ohms, and should be determined experimentally if the "flattest" possible antenna is desired. For average work, however, a noninductive resistance of 800 ohms can be used with the assurance that the operation will not be far from optimum.

c. Requirements. The terminating resistor must meet certain requirements if best results are to be secured. It should be practically a pure resistance at the operating frequencies; that is, its inductance and capacitance should be negligible. It must also be capable of dissipating about half the r-f power supplies to the antenna by the transmitter. This power is wasted only in the sense that it is not being used for back radiation; even without any terminating resistor it would not contribute to the forward radiation.

d. Use of resistors.—(1) Supplying a purely resistive load of great enough power-dissipating capability was until recently a considerable problem, but there are now available suitable noninductive resistors from several manufacturers for power up to and including 1,000 watts. These may be used either singly, when capable of dissipating the necessary power, or in combination so that several units of equivalent total power rating may be added to give the proper resistance. To lower capacity effects it is desirable to use several units, say three, in series even when one alone will safely dissipate the power. The two outer units should be identical and each should have one-fourth to one-third the total resistance, with the center unit making up the difference. The units should be installed in a weatherproof housing at the end of the antenna to protect them and to permit mounting without mechanical strain. The connecting leads should be short so that little extraneous inductance is introduced.

(2) Alternatively, the terminating resistance may be placed at the end of an 800-ohm line connected to the end of the antenna. This will permit placing the resistors and their housing at a point convenient for adjustment, rather than at the top of the pole. The line length is not critical, since it operates without standing waves, and hence is nonresonant.

e. Alternate termination. One type of termination sometimes employed is an 800-ohm transmission line, closed at the far end, constructed of resistance wire. The line must be long enough to provide a satisfactory value of resistance load, which usually makes the length quite cumbersome. The simple terminating resistor is preferable for installations where low power is used exclusively.

122. CHECKING TERMINATION.

a. General. The correctness of the termination may be checked by a simple means, provided it is possible to get at the input end of the antenna conveniently. A small balanced (push-pull) oscillator (fig. 129) used in conjunction with a receiver, may be used for the purpose. The oscillator should be capable of tuning over the frequency range for which the antenna is to be used, and its coil should be arranged to permit tapping on the antenna terminals symmetrically about the center tap. Suitable tap points may be predetermined by using an 800-ohm carbon resistor as a load, the taps being adjusted so that the oscillator is not too heavily loaded.

b. Checking procedure. The checking procedure is as follows: With the antenna disconnected, set the oscillator to some frequency within the desired range, and tune to zero beat on the receiver. Then connect the antenna and, without touching the oscillator tuning condenser, retune the receiver to zero beat. If the frequency changes appreciably the input impedance of the antenna has a reactive component, showing that the terminating resistor is not of the correct value. If the change is small, a second check should be made at a different oscillator frequency to make sure that the first test did not happen to be made on a frequency at which the antenna, even though improperly terminated, was resonant. Should both checks show an appreciable frequency change the terminating resistance should be changed about 10 percent, and the procedure repeated. A few back-and-forth trials will determine the value of terminating resistance which gives the least frequency change, and hence makes the antenna input impedance as nearly resistive as possible. An oscillator having a fairly high L/C ratio in its tuned circuit will be most sensitive.

c. Alternate procedure. If it is not convenient to work directly at the antenna terminals the method may be modified to connect the antenna to the oscillator through a half-wave transmission line, which will reproduce at the oscillator the conditions existing at the antenna. An ordinary 600-ohm line is convenient; the impedance is not particularly important since the line is resonant. The line should be cut for some convenient frequency and then its exact resonant frequency determined by connecting it to the oscillator but not to the antenna, although it should be in the position in which it will be used. The oscillator frequency should then be adjusted to a value which does not change when the line is disconnected from the oscillator. Once this frequency is found, the oscillator is left alone, and the line connected between oscillator and antenna, after which the procedure becomes the same as that already described. Checks on other frequencies may be made by using other lines of different lengths.

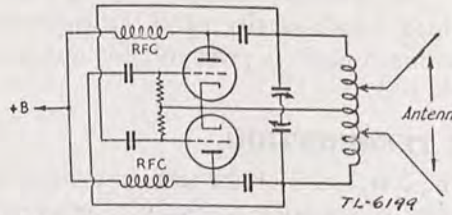

FIGURE 129. A push-pull oscillator may be used for checking the effectiveness of the resistor termination on the antenna. A Hartley circuit is shown, but any balanced circuit capable of working over about 3:1 frequency range will be satisfactory. It should be battery operated.

d. Overcoming effect of nonuniform impedance. Because the separation of the antenna wires is continually changing, the impedance is not uniform along the length of the antenna of a single wire rhombic. This effect can be overcome by using two or more wires, one above the other, for each side of the antenna, starting with no separation at the ends and gradually increasing the separation to a maximum at the apex of the side angle. The use of a multiple wire curtain lowers the impedance of the antenna. A three-wire curtain rhombic has an impedance in the neighborhood of 600 ohms, thus simplifying the feeding of such an antenna.

123. ADJUSTING FOR MAXIMUM FRONT-TO-BACK RATIO.

a. It is theoretically possible to obtain an infinite front-to-back ratio with a terminated rhombic antenna, and in practice very large values can actually be secured. However, when the antenna is terminated in its characteristic impedance the infinite front-to-back ratio can be secured only at frequencies for which the leg length is an odd multiple of a quarter wavelength. At other frequencies the front-to-back ratio decreases, and is smallest at frequencies for which the leg length is a multiple of a half wavelength. The greatest reduction in front-to-back ratio occurs for short antennas; the greater the number of half waves on a leg the higher the front-to-back ratio at frequencies for which the leg length is a multiple of a half wave.

b. When the leg length is not an odd multiple of a quarter wave at the frequency under consideration, the front-to-back ratio can be made infinite by slightly decreasing the value of terminating resistance. This permits a small reflection from the far end of the antenna which cancels out, at the input end, the residual response. With large antennas the front-to-back ratio may be made very large over the whole frequency range by experimental adjustment of the terminating resistance. When this is done the antenna will show slight resonance effects, but these are small enough to be neglected since the resistance is changed only a few percent from the optimum value for eliminating standing waves.

c. Modification of the terminating resistance also permits "steering" the back null over a small horizontal range, so that signals coming from a particular spot not exactly to the rear of the antenna may be minimized. This refinement is seldom necessary, although it is well to keep it in mind should an occasion for its use arise.

124. METHODS OF FEED.

a. If the broad frequency characteristic of the rhombic antenna is to be fully utilized, the feeder system used with it must be similarly broad. This practically dictates the use of a transmission line of the same characteristic impedance as that shown at the antenna input terminals, or approximately 750 to 800 ohms (600 ohms for three-wire curtain rhombic). Data for the construction of such lines will be found in section IV. It will be found, however, that the spacing required for an 800-ohm line is rather awkward, and also that rather small wire must be used. Both these considerations are disadvantageous mechanically, and the radiation from the line also tends to be comparatively high at high frequencies, because of the wide spacing.

b. While the usual matching stub can be used to provide an impedance transformation to more satisfactory line impedances, this limits the operation of the antenna to a comparatively narrow range of frequencies centering about that for which the stub is adjusted. On the whole, the best plan is to connect a 600-ohm line directly to the antenna, and accept the small mismatch which results. The operation of the antenna will not be adversely affected, and since the standing-wave ratio is quite low (1.33 to 1) the additional loss over the perfectly matched condition will be unappreciable, even for rather long lines. The chief disadvantage is that at some frequencies a slight readjustment of the coupling to the transmitter may be necessary to maintain constant input.

c. Any of the coupling systems suitable for working into a 600-ohm line, as described in section IV, will be suitable.

125. GENERAL CONSIDERATIONS.

a. Level ground. To realize the performance indicated by the design data previously given, particularly with respect to the wave angle to be obtained, it is desirable that the rhombic be installed over practically level ground. The various designs are all based on lining up the free-space radiation of the antenna with the reflected waves from flat ground. If the ground slopes uniformly, it may be expected that the computed wave angle will be obtained if the antenna is constructed parallel to the slope. However, the angle in this case is that made with the ground over which the antenna is erected, provided the slope extends considerably beyond the limits of the antenna, and this should be taken into account in determining the actual angle which the wave will make with the horizon.

b. Type of soil. The design data likewise are based on perfectly reflecting ground, which of course is not found in practice. However, it has been established that the results are not greatly changed by the normal type of ground, at least for wave angles of the order of those under consideration. The kind of soil, therefore, is not of great consequence.

c. Performance under unfavorable conditions. Experience with rhombic antennas has shown that excellent results can be obtained even though the existing conditions are far from ideal. "Haywire" antennas which perforce ran over uneven ground, through trees, and even were not at a uniform height above ground have given surprisingly good results. Nevertheless, it will pay to do the best possible job of meeting the design data indicated by the charts. The point is that the antenna will give good results even in unlikely locations, provided reasonable care is used in construction and it is made as large as the circumstances will permit.

d. Importance of length. Generally speaking, the gain of the rhombic antenna will depend principally on its length. Height as well as length plays and important part in the determination of the optimum wave angle, but height has a much smaller effect on the gain than length. Antennas designed by the maximum output method will give average gains of the order of 14 to 16 decibels over a half-wave antenna, depending upon the wave angle which happens to be most effective at the time. The compromise design gives smaller gains, averaging in the neighborhood of 10 to 12 decibels, if the leg length is not too greatly reduced. If the leg lengths indicated by the maximum output design method are not permissible, then base the design on the greatest leg length which can be accommodated in the available space. The length of each leg should be at least two wavelengths at the lowest operating frequency.

126. UNTERMINATED RHOMBICS.

a. Disadvantages. The rhombic antenna may be used without the resistor termination, although two of the desirable features of the antenna are sacrificed by unterminated operation. The antenna becomes bidirectional instead of unidirectional, and it is no longer possible to use the feeder as a matched line. This means that, in reception, the signal-to-noise and signal-to-interference ratios are poorer, and the feeder system must be retuned for each change in operating frequency. Since standing waves appear on both antenna and feeder, series or parallel tuning must be used at the transmitter according to the number of quarter waves which happen to exist on the system at the particular operating frequency.

b. Shift in lobe of maximum radiation. When the rhombic antenna is unterminated, the difference in the current distribution (no standing waves, terminated, as against standing waves, unterminated) changes somewhat the angle which the lobe of maximum radiation makes with each leg of the antenna. This effect already has been mentioned earlier in this section. The shift in the lobe is negligible, however, if each leg is two or more wavelengths long and, as a result, the same design methods previously discussed may be used.

c. Gain in forward direction. The gain in the forward direction is nearly the same whether or not the antenna is terminated in a resistor. A small decrease may be expected because, in the terminated rhombic, the power dissipated in the resistor is not quite half the total power supplied to the antenna, while with the unterminated antenna the radiated power divides about equally in both directions. That is, with the terminated antenna, slightly more than half the power is radiated in the forward direction, while without the termination the division between front and back is about 50–50.

d. Comparison with V-type antennas. The unterminated rhombic antenna can be looked upon as two V-type antennas placed end-to-end, or as two obtuse angle V's placed side by side. Comparison between the unterminated rhombic and the V antenna is difficult because of lack of data. Experience indicates, however, that for the same *over-all* length the rhombic gives greater gain than the single V.

127. SECONDARY LOBES.

a. General. Since the radiation patterns of the individual legs of which long-wire antennas, including the rhombic, are composed are multilobed, it is to be expected that the antenna will radiate, or respond to incoming signals, in directions other than that of the main lobe. With some lengths, heights, and tilt angles, certain secondary lobes may exhibit considerable strength, although their effects are confined to only a few degrees in the horizontal plane. Likewise, there may be a large number of null points, or near nulls, in the directive diagram.

b. Importance. It is important, particularly in reception, to recognize the existence of secondary lobes, because despite the marked gain in the direction for which the antenna is laid out, casual listening often gives the impression that signals can be heard almost equally well in all directions. The nulls usually are quite sharp, so that their presence often is difficult to detect. Of course, if the rhombic is properly terminated the reduction in back response will be very apparent.

c. Comparison with half-wave antenna. It is a fact that some of the secondary lobes often give considerable gain over a half-wave antenna, while others are at least comparable in effect to radiation in the same direction from a half wave. In one sense this is an advantage, because in practice one finds that, along with high gain in the desired direction, the secondary lobes permit communication practically around the horizon with results at least as good as would be obtained with a half-wave antenna. It is not especially a sign that the antenna is not working properly if this is the case.

128. SMALL RHOMBICS.

a. Limitations. The outstanding results which have been secured with rhombic antennas of ample size often tempt the builder whose space is restricted to try his luck with a small antenna, and hope for the best. It should be realized, however, that long-wire antennas do not really begin to perform unless they are actually "long"—in the case of the rhombic, at the very least two, and preferably three wavelengths on a leg. The gain decreases rapidly when the wire length is decreased, and the ability of the antenna to work well over a wide frequency range also is impaired. Where space is restricted, considerably more gain can be obtained by the use of phased half-wave elements, as described in sections VI and VII.

b. Advantage. The small rhombic has at least one advantage, however, over the phased arrays. It will accept power on any frequency for which the sides will be resonant, and will radiate it in some fashion at least. It will not exhibit the expected directive effects, however, except on the band for which it is designed. If one simply wants a small amount of gain and directivity on one frequency, plus the ability to use the same antenna on other frequencies without being too greatly concerned about maximum effectiveness, a small rhombic might be worth a try.

129. RHOMBICS FOR OPERATION OVER WIDE FREQUENCY RANGE. Good operation may be obtained over a fairly wide frequency range, if care is taken in the construction of the rhombic. For optimum results, the frequency range should not be greater than 2½ to 1. If one frequency is of more importance than the others, the antenna should be constructed for this frequency; it must be borne in mind that if satisfactory operation is to be obtained, the antenna must be at least two wavelengths on each leg at the lowest operating frequency. If all frequencies of operation are of equal importance, the antenna should be constructed for the middle of the range, with each leg of sufficient length to be two wavelengths at the lowest operating frequency.

SECTION XI

ANTENNAS FOR MEDIUM AND LOW FREQUENCIES—THE MARCONI

130. SKY-WAVE AND GROUND-WAVE TRANSMISSION.

a. Sky-wave transmission. With respect to sky-wave transmission, the requirements which the antenna system must meet on medium and low frequencies do not differ materially from those which hold on the high-frequency bands. Of course, waves entering the ionosphere even vertically are reflected back to earth so that there is no such phenomenon as skip distance on these frequencies. However, it is still true that to cover the greatest possible distance the waves must enter the ionosphere at low angles. Although a given distance may be covered by multiple hops when the radiation angle is high, there will usually be less absorption, and hence the signal strength will be greater at the same point when the wave reaches it by only one hop.

b. Ground-wave transmission. At medium and low frequency the ground wave assumes considerable importance in transmission. The useful range of the ground wave will depend upon the transmitter power, the frequency, the background noise at the receiver, and the type of soil over which the wave must travel. If the antenna system radiates most of the transmitter power at relatively low angles, particularly along the ground, the ground wave will give reliable communication over distances from 50 to several hundred miles, the latter distances applying where conditions are particularly favorable, as when the path is mostly over sea water.

131. POLARIZATION.

a. Vertically polarized antenna. It was mentioned in section I that a ground wave is predominantly vertically polarized. Thus, an antenna which is to produce a good ground wave likewise must be a vertical one. This dictates the use of an antenna system the radiating part of which is mostly vertical.

b. Horizontally polarized antenna. A horizontal antenna will produce very little ground wave. At night on the higher medium frequencies a horizontal antenna will give better results for long-distance work since nighttime ionosphere conditions permit the reflected wave to return to earth without excessive attenuation.

132. VERTICAL ANTENNA DESIGN CONSIDERATIONS.

a. Night coverage. For good night coverage at distances toward the limit of the ground wave it is desirable to use an antenna which will give

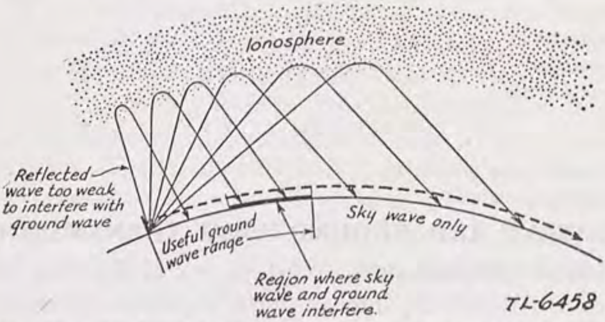

FIGURE 130. How sky waves interfere with the ground wave to cause a bad fading area. This is typical of night conditions, when sky waves are refracted without much attenuation in the ionosphere.

comparatively little radiation at angles above about 45°. This is because the high-angle radiation returns to earth within the useful range of the ground wave, and in the outer part of this range may have intensity comparable to that of the ground wave itself. The sky waves arrive at the ground in random phase with respect to the ground wave, giving rise to severe fading in this area (see fig. 130). The antenna should therefore confine its radiation to angles sufficiently low so that the nearest point to the transmitter at which sky waves return to earth is just beyond the limits of the ground wave.

b. Location of antenna. A vertical antenna will be most effective when it can be erected in a fairly clear spot so that the ground wave is not absorbed in nearby buildings. Frame buildings are not likely to cause much trouble, but it is best to keep clear of steel structures by at least a wavelength or two.

133. GROUNDED ANTENNAS.

a. Vertical quarter-wave antenna. It was explained in section II that the smallest self-resonant antenna is an electrical halfwave in length.

A mechanical analogy such an antenna is a flat strip of spring metal firmly supported at its center, with both ends free to vibrate (see fig. 131). Experience has proved that if half the spring is cut off, leaving the remaining half supported at one end, the free end of the remaining half will still vibrate at the original rate when set into oscillation. A similar condition exists if a half-wave antenna is cut in two, making its length a quarter wave, and then one end grounded. The grounded quarter-wave antenna will resonate at the same frequenecy as an ungrounded half-wave antenna. Consider that the missing half of the antenna is supplied by the "image" of the antenna in the ground. The directional characteristic of a grounded quarter-wave antenna will be the same as that of a half-

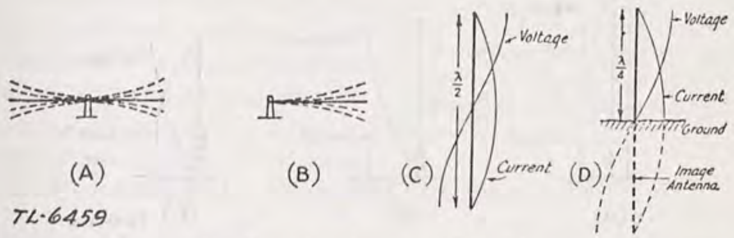

FIGURE 131. Mechanical analogy of steel spring to half- and quarter-wave antennas.

wave antenna in free space, because of reflection from the ground. Thus a vertical grounded quarter-wave antenna will have a circular radiation pattern in the horizontal plane. In the vertical plane, however, the radiation will decrease from maximum along the ground to zero at the perpendicular.

b. "Loading" antenna. The grounded antenna may be much smaller than a quarter wave and still be made resonant by "loading" it with inductance at the base, as in figure 132. This is the type of antenna normally used by field radio. By adjusting the inductance of the loading coil, even very short wires can be tuned to resonance. However, the efficiency of the wire as a radiator is decreased considerably by decreasing its length. This is because the current at the top of a simple vertical wire such as is indicated in the figures is necessarily zero, so that as the length is reduced, less and less of the wire is carrying the high current which produces the greatest radiation.

134. CURRENT AND VOLTAGE DISTRIBUTION.

a. General. The current along a grounded quarter-wave vertical wire varies practically sinusoidally, as is the case with a half-wave wire, and is highest at the ground connection. The r-f voltage, however, is highest at the open end and minimum at the ground. The current and voltage distribution are shown in figure 132 (A). When the antenna is shorter than a quarter wave but is loaded to resonance, the current and voltage distribution are part sine waves along the antenna wire. If the loading coil is substantially free from distributed capacity, the voltage across it will increase uniformly from minimum at the ground, as shown at (B) and (C), while the current will be the same throughout.

b. Power supplied to antenna. The radiation resistance of a grounded quarter-wave vertical antenna is approximately 36 ohms. With shorter antennas the radiation resistance decreases. The radiation resistance is particularly important in the case of a grounded antenna not only in connection with methods of feeding but also because the ratio of the

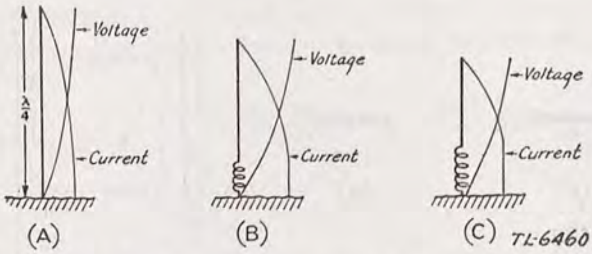

FIGURE 132. Current and voltage distribution on a grounded quarter-wave antenna (A) and on successively shorter antennas loaded to resonate at the same frequency.

radiation resistance to the resistance of the ground contact system determines the portion of power supplied to the antenna which is actually radiated. The total power dissipated in the antenna is equal to

$$I^2(R_o+R_g)$$

where I is the current at the base of the antenna, R_o the radiation resistance, and R_g the resistance of the ground connection. Since only I^2R_o produces useful radiation, while I^2R_g is pure loss, it is important to keep the ground resistance as low as possible. If, for instance, the two resistances are equal, only half the power supplied to the antenna will be radiated; the other half simply represents a loss in the ground connection.

c. Increasing radiation resistance. If the grounding resistance is fixed, the ratio of radiated power to power lost in the ground connection can be increased by increasing the radiation resistance of the antenna. The radiation resistance as measured at the base of the antenna can be increased by making the antenna longer than a quarter wave, when the current distribution becomes as shown in figure 133. The highest value is secured when the length becomes a half wave, since this length brings a current node at the ground connection.

d. Shifting of maximum current point. Note that as the length increases beyond a quarter wave, the maximum current point on the antenna is no longer at the base, but has moved up on the wire. When the antenna height is a half wave, the current is maximum halfway up, or one-quarter wavelength above the ground. The upward shift in the current loop is beneficial in two respects: a greater length of wire is carrying high current, thus giving greater effective radiation, and the high-angle radiation is decreased.

e. Keeping current loop high. Since the heights required for realization of these desirable characteristics are difficult to obtain, the object of design of vertical grounded antennas which are necessarily of heights less than one-fourth wavelength is to make the current loop come near the top of the antenna, and to keep the current as large as possible throughout the length of the vertical wire. A number of methods can be employed for this purpose.

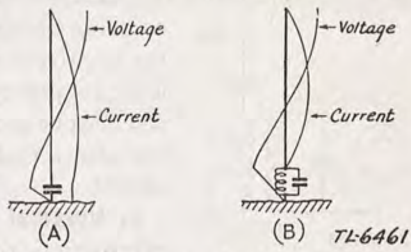

FIGURE 133. Current and voltage distribution on grounded antennas longer than one-fourth wavelength. (A), between one-fourth and three-eighths wave, approximately; (B), half-wave.

135. BENT ANTENNAS.

a. General. Perhaps the simplest method of meeting the fundamental requirement of keeping the current loop high is to use a bent antenna

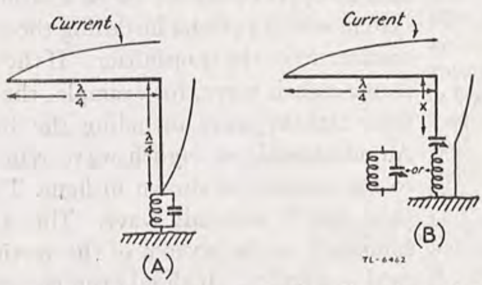

FIGURE 134. Bent antennas using a quarter-wave horizontal section to bring a current loop at the top of the vertical wire. A quarter-wave vertical section is shown at (A); at (B) the height *X* is made as great as the circumstances permit. Series tuning may be used for lengths of *X* up to about one-eighth wavelength; parallel tuning for greater lengths of *X*.

such as is shown in figure 134(A) with part of the antenna vertical and part horizontal. This type of antenna is used with the SCR–177B. The horizontal part should be one-quarter wave in length so that the current loop will appear at the top of the vertical portion. The current distribution will be as shown in the drawing, assuming that the vertical portion is one-quarter wave high.

b. Antenna height. The lower end of the antenna is grounded through a loading circuit which tunes the system to resonance and also provides a means for coupling power from the transmitter into the antenna.

The constants of the loading circuit will depend upon the total length of the antenna system, and therefore depend upon the antenna height. For heights between 40 and 70 feet a circuit of the type shown in figure 135 will be suitable, provided the leads between the bottom of the antenna and the coupling circuit, and between the loading circuit and the effective ground, are negligible in length. These leads are part of the effective length of the antenna, and must be added to the antenna length in determining the actual constants required in the loading circuit.

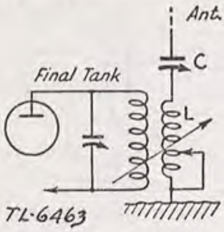

FIGURE 135. The practical loading and coupling circuit for antennas of the type shown in figure 134(B) when the height X is one-eighth wavelength or less (up to 65 feet approximately). The series tuning condenser C should be 250 to 500 $\mu\mu f$; receiving-type condensers will suffice for moderate powers. Coil L may consist of 20 turns of No. 12 wire space-wound (6 turns per inch) to a diameter of 3 inches, arranged so that it can be tapped conveniently at least every few turns. These values are satisfactory for a frequency range of 4,000–1,500 kilocycles. Tuning procedure is that for series tuning as described in section IV. An r. f. ammeter may be connected in series with the antenna where it joins C. A 2.5-ampere instrument will suffice for powers up to a few hundred watts.

c. Vertical part of antenna. For maximum effectiveness, the vertical part of the antenna should actually be vertical, and not simply run off at some convenient angle from the operating position to the top of the pole. The wire may come down the pole on stand-off insulators, or may be pulled down vertically from the horizontal strain insulator after the fashion shown in figure 135. Wire guys on the pole should be broken up at intervals of 25 feet or so with egg type insulators to prevent pick-up of r. f. energy from the antenna.

d. Feeder system.—(1) Antennas of this type offer an opportunity for use of a rather simple feeder system which permits installing the antenna at some distance from the transmitter. If the antenna height is one-eighth wave, for example, the total length is three-eighths wave including the horizontal part. An additional one-eighth-wave wire may be added to the antenna as shown in figure 137 to make the total length one-half wave. This extra section is connected to the bottom of the vertical wire and is used as a feeder. It should run parallel to and fairly close to the ground for as much of its length as possible (a height of 6 or 7 feet is permissible so that it will not be a hazard to walkers) and terminate at the transmitter in a parallel-tuned circuit the other end of which is grounded. (The length of the ground lead should be included in the feeder length.) At this point the impedance looking into the feeder and antenna has its highest value so that losses in the ground connection are relatively low. There will be very little current in the ground lead under these conditions, but an ammeter inserted at the base of the vertical portion will read about 70 percent of the current at the top.

(2) Such a feeder does comparatively little radiating because it is parallel to and close to the ground and because it represents the section of the antenna which carries the least current. In cases where the antenna height is not an eighth wavelength, the feeder length, including the ground lead, should be one-half wavelength less the actual length of the antenna from the base to the far end of the horizontal portion. The length of a half wave is given closely enough by the formula

$$\textit{Length of } \tfrac{1}{2} \textit{ wave (feet)} = \frac{468{,}000}{f\,(\textit{kilocycles})}.$$

(3) The feeder may be made longer or shorter than the exact length necessary to make the whole system a half wave long, if more convenient, provided the whole system is brought to resonance by means of the coupling system. However, excessive length in a feeder of this type is not desirable. Also, it is preferable to have the length to the ground connection a half wave so that the current in the ground lead will be minimum, which means lowest loss in the ground connection.

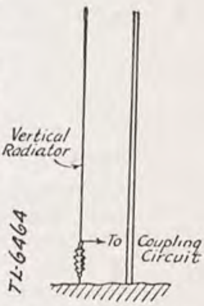

FIGURE 136. An arrangement for keeping the main radiating portion of the antenna vertical.

136. FOLDED-TOP ANTENNAS.

a. Horizontally polarized radiation. The horizontal part of an antenna of the type shown in figures 134 and 137 naturally radiates part of the total power supply by the transmitter. This horizontally polarized radiation does not contribute to the surface wave, and is practically all at high angles.

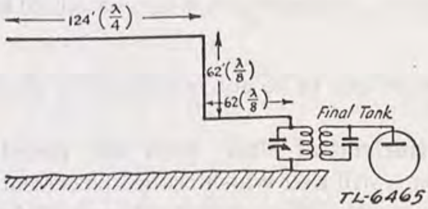

FIGURE 137. Bent antenna one-eighth wave high, with a "feeder" section making the total length one-half wavelength. The length figures are for 1,900 kilocycles. The parallel-tuned coupling circuit should be capable of being tuned independently to the operating frequency, and the inductance of the coil preferably should be variable by means of taps so that the optimum L/C ratio can be secured.

b. Minimizing radiation from horizontal portion of antenna. Radiation from the horizontal portion can be minimized by folding the wire so that the field about one section cancels, at least partially, the field from the adjacent section. The folds can be made in a variety of ways, several of which are shown in figure 138. The desirable condition is to have adjacent wires carrying currents of the same order of magnitude so that the cancelation will be as great as possible. Reduction of radiation from the top section means an increase in the power available for the vertical portion.

c. Method of folding. An incidental advantage of folding the top section is that less ground space is needed for the installation of the system. Also, with some arrangements it is possible to drop the vertical portion from the center of the horizontal part, if a more convenient installation results from so doing. The folded wires should be 1 or 2 feet apart, and may be fastened to small wooden spreaders as shown in figure 139. The

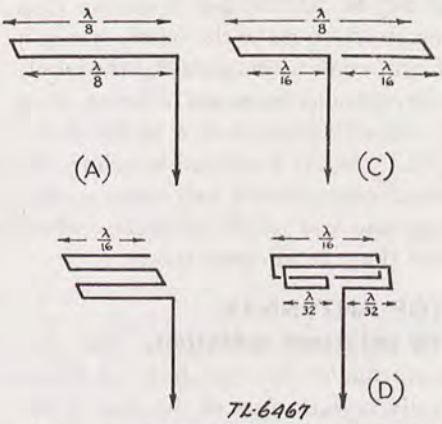

FIGURE 138. Several ways in which the top quarter-wave section may be folded to reduce radiation Spacing between folded wires is not critical; from 1 to 4 feet is satisfactory provided some means is provided to keep close-spaced wires from swinging in relation to each other. The lengths of the connecting pieces at the folds should be counted in the total length of the quarter-wave top section. One-eighth wave is approximately 60 feet; one-sixteenth wave 30 feet, and so on.

folds may be worked out to be accommodated in almost any reasonable ground space.

d. Length of horizontal wire. With the folded-top antenna the desirable condition is still that which brings the current loop to the top of the vertical portion. Therefore, the total length of the folded horizontal wire should be equal to one-fourth wavelength at the operating frequency.

e. Frequency range. Both this and the plain bent antenna may be designed for a particular frequency, and will work equally well over a wide frequency range if the loading-coupling circuit is retuned when the frequency is changed.

f. Feeding methods. The feeding methods already described for the bent antenna may be used equally well with the folded-top arrangement.

g. Branching of currents in top section. A somewhat different top-folded arrangement, used by the British Marconi Company, is shown in figure 140. The top section is made practically completely nonradiating by branching the currents through parallel wire sections. Thus the current flowing into the top, at the junction with the vertical section, branches in opposite directions as shown. At the ends, the current again divides between the two outer wires. A current node occurs at the midpoints of the outside wires, and the relative phases are such that a continuous wire section may be used. The whole flat top is a quarter wave long, which requires more ground space than is needed for the folded-top systems already described. The branching arrangement makes the currents in the

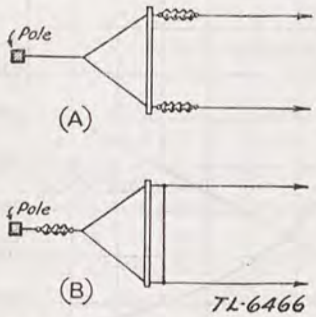

FIGURE 139. How spreaders may be used, (A) for open ends and (B) for closed ends. The spreaders may be made of light wood.

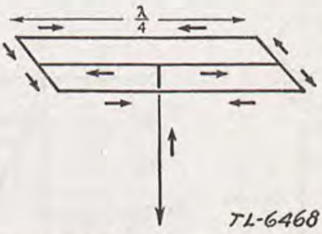

FIGURE 140. Folded-top antennas with branched wires to provide practically complete cancelation of radiation from the top section. The top shown here is equivalent to a simple quarter-wave horizontal section. The vertical portion may be any length up to a quarter wave, the greater heights being more effective as in the case of the bent and top-folded antennas of figures 134, 137, and 138.

two halves of each horizontal wire flow in opposite directions, thus minimizing radiation perpendicular to the top wires, and there is additional field cancelation because of the folding.

h. Current and ground loss.—(1) As previously stated, for minimum ground connection loss it is desirable to make the antenna system a half wave long so that there will be a current node at the grounding point. With vertical sections less than a quarter wave high, the average current over the vertical portion is not as large, under these conditions, as when the length is adjusted to bring a current loop at its top. Thus one design gives somewhat lower current but lower ground loss, the other higher current but higher ground loss. Usually a compromise between the two will give the most effective radiation. For average grounds, however, it will be found that the field strengths will differ in but a small degree for either type of operation, provided the vertical section of the antenna is between about 50 and 70 feet in height.

(2) For the minimum ground loss condition the *total* length of the wire is simply made equal to one-half wavelength. The length of the folded part then becomes the figure found by the formula previously given less the length of the vertical portion. As before, maximum effectiveness of the folds will be obtained when adjacent wires are carrying nearly equal currents.

137. TOP-LOADED ANTENNAS.

a. General. Instead of bending or folding up the antenna length required for resonance, it is possible to use a simple vertical wire with concentrated capacity and/or inductance at its top to simulate the effect of the missing length. This system is more critical as to frequency, that is, it is not quite as tolerant with respect to working over a band of frequencies, but is structurally advantageous since only one pole is required.

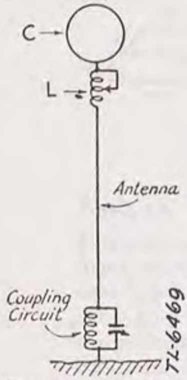

FIGURE 141. Top-loaded antenna. A parallel-tuned circuit, independently resonant at the operating frequency, is required for coupling to the transmitter when the top loading is adjusted to bring a current minimum at the lower end of the antenna.

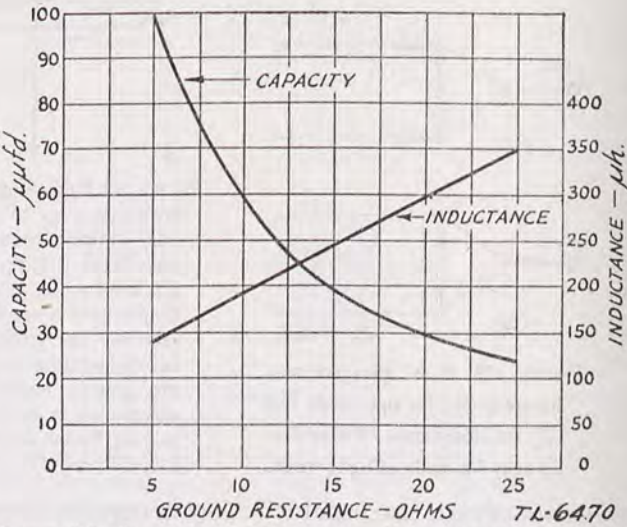

FIGURE 142. Capacity and inductance required at the top of a vertical antenna as a function of ground resistance, for a frequency of 1,875 kilocycles.

b. Capacity and inductance. The top-loading apparatus may consist simply of a capacity or, better, a capacity and inductance suitably proportioned. The capacity used is not the usual type of capacitor, which would be ineffective since the connection is one-sided, but consists of a metallic structure which exhibits the necessary capacity to space. Practically any sufficiently large metallic structure can be used for the purpose, but simple geometric forms such as the sphere, cylinder, and disk are preferred because of the relative ease with which their capacity can be calculated. The inductance may be the usual type of r. f. coil, with suitable protection from the weather.

c. Ratio of inductance to capacity. The ratio of inductance to capacity depends, for a given frequency, principally upon the ground resistance. Figure 142 is a set of curves giving the values for 1,875 kilocycles, which is representative of the 1,715- to 2,000-kilocycle band. These curves are based on obtaining 75 percent of the maximum possible increase in field strength over an antenna of the same height without top loading. An inductance coil of reasonably low-loss construction is assumed. The general rule is to use as large a capacity as the circumstances will permit, since an increase in capacity will cause an improvement in the field strength. It is particularly important to do this when, as is usually the case, the ground resistance is not known and cannot be measured.

d. Capacity of three geometric forms. The capacity of three geometric forms is shown by the curves of figure 143 as a function of their size. For the cylinder, the length is specified equal to the diameter. The sphere, disk, and cylinder can be constructed from sheet metal, if such construction is feasible, but the capacity will be practically the same in each case if a skeleton type of construction, using screening or wire networks, is used. The disk is probably the easiest to make, and has less wind resistance than either of the other two shapes. A disk of the openwork type is shown in figure 145.

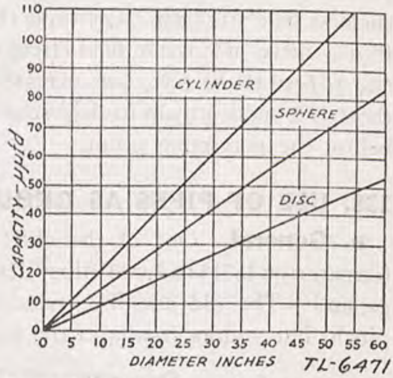

Figure 143. Capacitance of sphere, disk, and cylinder as a function of their diameters. The cylinder length is assumed equal to its diameter.

e. Feeding bottom of antenna. The bottom of the antenna is fed through a parallel-tuned circuit with one side grounded, as in figure 141. The adjustment procedure is as follows: Starting with all of *L* shorted out,

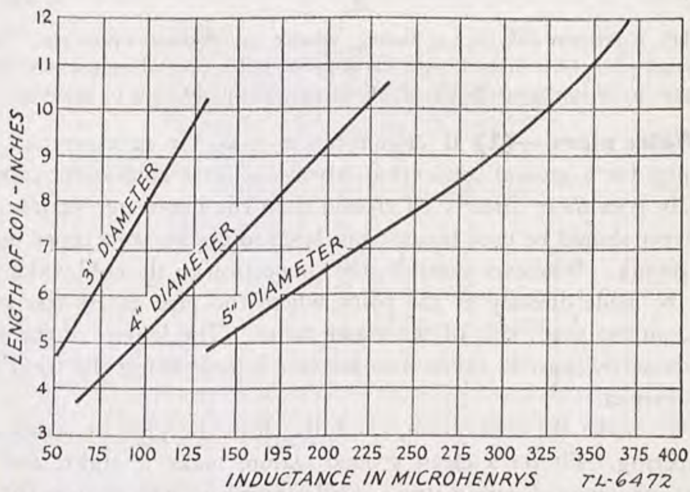

Figure 144. Inductance of coils of various diameters wound with No. 14 wire, eight turns per inch.

adjust the tuning to give a satisfactory transmitter input, using the method for parallel-tuned circuits described earlier in this manual. Measure the field strength by means of a simple field-strength meter (vacuum tube voltmeter and antenna), or by using a receiver, equipped with an S-meter, some distance away. Comparative readings only are needed. Next, move the tap on L to include a few turns, readjust the coupling and parallel-circuit tuning to maintain the same transmitter input, and note the new field strength. Continue this process until all of L is in the circuit. Plot a curve of relative field strength against turns in L; the curve should rise at first as the turns are increased until a critical point is reached where there is a sudden drop in field strength. Finally, set L a turn or two just below the maximum point.

138. USE OF PIPES AS GROUNDS.

a. General. One of the chief problems of obtaining optimum performance on 1,715 to 2,000 kilocycles is that of getting a good low-resistance ground. The old standby connection to a water pipe may serve in a pinch, but seldom results in the best possible antenna performance.

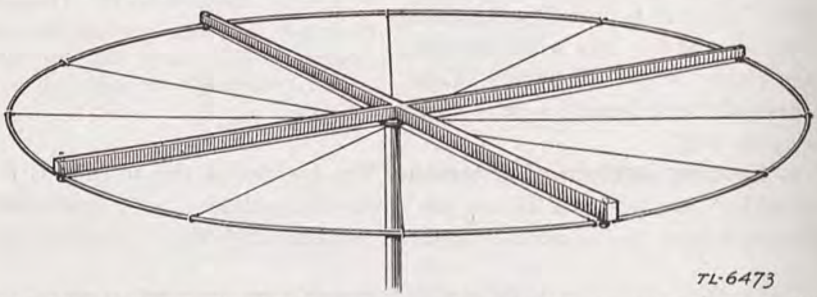

FIGURE 145. A skeleton disk for top loading, suitable for 160-meter operation. This disk, constructed with a 4-foot diameter outer rim of quarter-inch copper tubing and wire "spokes," has a capacity of approximately 40 $\mu\mu$f. Connec tion should be made to its center.

b. Water pipes.—(1) If circumstances make it necessary to use a water pipe for a ground connection, always select a cold-water pipe since it usually goes more directly to ground than the hot-water variety. Gas pipes never should be used because insulated joints are sometimes included in the piping. Wherever possible, the connection to the cold water piping should be made directly at the point where the pipe enters the ground; that is, on the street side of the water meter. The length of the ground lead necessarily must be taken into account in computing the total length of the antenna.

(2) To make the connection, carefully clean the pipe by scraping and sandpapering. Fit on a clean ground clamp, make it tight, and make sure that the ground wire makes a good electrical connection to the strap. Solder it if necessary. The assembly may be rubber-taped to prevent oxidation if there is considerable dampness.

(3) If it is impossible to reach the pipe at the point where it enters the ground, a connection of the type described above may be made to any convenient cold-water pipe as a secondary resort. In such cases, estimation of the effective length of the ground lead is difficult, since piping systems sometimes are rather extensive and hence have considerable capacity to ground. The effective length usually will be appreciably less than the actual length of the shortest path which might be traced back to ground along the piping, and in the case of a ground to a heating system may be quite small because of the large masses of metal at the radiators. In such cases the amount of loading for bringing the system to resonance must be determined experimentally.

c. Pipes driven into soil. A simple outdoor ground may be made by driving a length of 1-inch pipe (6 feet or more) into the soil. If possible, pick a spot where there is considerable natural moisture; the resistance will be less under such conditions. Four pipes arranged at the corners of a 10-foot square, all connected together at the top, will be considerably better than one.

d. Use of chemicals with pipes or rods. A quite good low-resistance ground connection can be made as shown in figure 146, if the space is available and some digging is permissible. The chemicals increase the conductivity of the ground in the vicinity of the grounding pipes or rods and thus reduce the losses from current flow.

139. RADIAL GROUNDS.

a. The ideal form of ground is a series of conductors buried 1 or 2 feet beneath the surface, radiating like the spokes of a wheel from under the

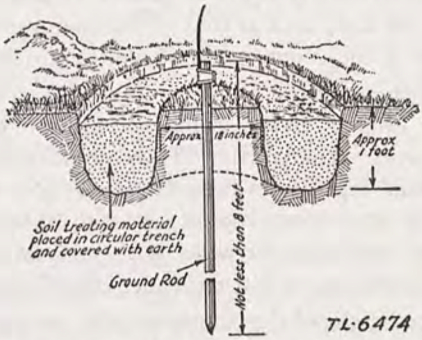

FIGURE 146. Ground system treated to increase conductivity. The circular trench is filled with rock salt, magnesium sulfate, or copper sulfate, put in dry and then flooded with water. After treatment, the trench is covered with earth. Fifty pounds of treating material so disposed will have a life of 2 or 3 years.

vertical part of the antenna, as shown in figure 147. Such a ground system not only reduces I^2R losses at the ground connection but, provided it is made extensive enough, also reduces losses in the ground in the immediate vicinity of the antenna.

b. Better results can be expected as the length of the radial wires is increased. There is no necessity for a length greater than one-half wavelength, however, and even one-tenth wavelength will give satisfactory performance. This calls for a length of about 50 feet per radial, or a total diameter of about 100 feet for the ground system. As many radials as possible should be used.

140. COUNTERPOISE.

a. General. The counterpoise is a form of capacity ground which is quite effective. Its use is particularly beneficial when an extensive buried system is not practicable, or when an ordinary pipe ground cannot be made to have sufficiently low resistance, as in rocky or sandy soils. It is used extensively by field radio units. Mobile radio sets use the body of the conveyance as a counterpoise.

b. Size and capacity. To work properly, a counterpoise must be large enough to have considerable capacity to ground, which means that it should cover as much ground area as the location will permit. No specific dimensions are necessary, nor is the number of wires particularly critical. A good form is an approximately circular arrangement using radial wires with cross connectors joining them at intervals, as in figure 148(A). There is no particular necessity for extending the radius of a circular counterpoise beyond a half wavelength, nor is it desirable that the lengths of the individual wires bear any particular relation to the wavelength. Rather, the intention is to have the counterpoise act as a pure capacity instead of exhibiting resonance effects. The capacity of the counterpoise will be approximately equal to that of a condenser consisting of two plates each of the same area as that of the counterpoise, with spacing equal to the height of the counterpoise above the ground.

c. Shape. The shape of the counterpoise may be made anything convenient; square or oblong arrangements are usually relatively easy to construct and will work satisfactorily. There should not be too few wires, but on the other hand separations between wires up to 10 or 15 feet will do no harm on fairly large counterpoises, and 5 to 10 feet on smaller ones. It is a good plan to join adjacent wires with jumpers at intervals about equal to the wire separation so that resonance effects will be minimized.

d. Height. The height of the counterpoise is not particularly critical. It is best to construct it high enough to be out of the way, which ordinarily means from 6 to 10 feet above the ground. Remember that the height of the antenna is reduced by the amount of counterpoise height.

e. Insulation from ground. Satisfactory results have been secured with counterpoises simply lying on the ground, or with large screens of chicken wire similarly laid under the antenna. However, the best performance will be secured, as a general rule, when the counterpoise is insulated from ground. When in contact with the ground surface, the losses are likely to be higher because the counterpoise tends to act either as a poorly conducting direct ground or as a leaky dielectric condenser.

141. ANTENNAS FOR SMALL SPACE OR HEIGHT.

a. Keeping antenna clear of surrounding buildings. The antennas discussed thus far have been designed to take advantage of the transmission characteristics of the medium-and low-frequency range. A vertical antenna must be quite clear of surrounding buildings, particularly those of steel construction, if good results are to be secured. If the height required for this purpose is not obtainable, then a horizontal wire must suffice. No useful purpose is served in erecting a vertical antenna between buildings which are going to absorb most of the radiated energy, or which perhaps reradiate some of the energy to make the horizontal directional pattern of the antenna poor in the most desired directions of communication.

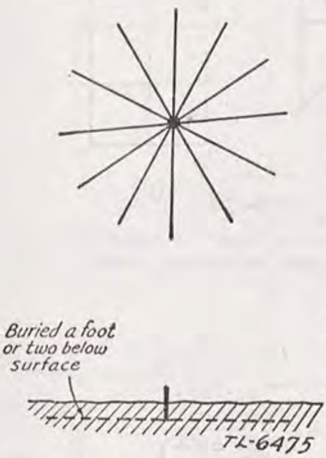

FIGURE 147. The best ground is a radial system of buried copper strip or heavy bare copper wire.

b. Antenna must be resonant. The fundamental requirement for an antenna which cannot be designed for these frequencies is that it must be resonant at the operating frequency. That is, it must accept as much power as possible from the transmitter, even though the radiation of the power must be left more or less to chance. It is desirable to get the high-current portion of the antenna well away from buildings, if this is possible. The antenna may be bent, if necessary, to fit the available space, but the bends should be made with a view to their effect on the performance of the antenna as a radiator.

c. Length of antenna. To make tuning easy, it is desirable that the antenna length be a multiple of a quarter wavelength, with reasonable limits. The ground lead should be short, although as already explained the length of this lead may depend upon the grounding system.

d. Bending antenna. If no space sufficient to allow the antenna to be installed in a straight line is available, it may be bent to fit. The far end may be bent down, as shown in figure 149 (C), or even back on the antenna as in figure 149 (D). In the latter case at least one-eighth wavelength of the near end (the high-current part) should be unparalleled by the bent wire, since there is partial cancelation of the radiation from the folded-back part. Bends in horizontal directions may be made at several points along the wire, in cases where this is necessary, provided the angle between the bent portions is as large as possible. Try not to have less than a right-angle bend, especially in the high-current portion of the antenna. The flat top may also consist of multiple wires connected together at the top of the vertical portion. This lowers the resonant frequency of the antenna. This type of antenna is known as a crowfoot antenna. Its counterpoise should take the same shape as the flat top.

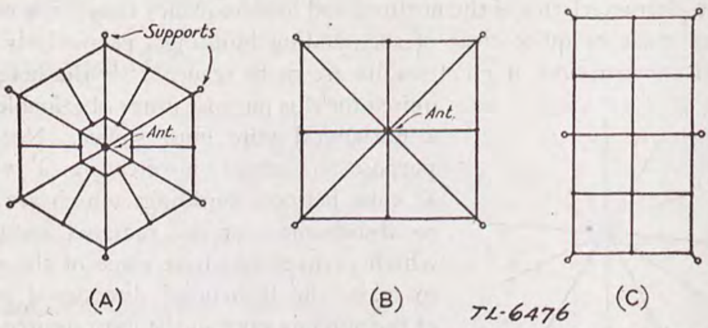

FIGURE 148. Some suggested forms of counterpoise. Perfect symmetry is not essential, but it is desirable to extend the counterpoise as nearly as possible for the same distance in each direction from the antenna.

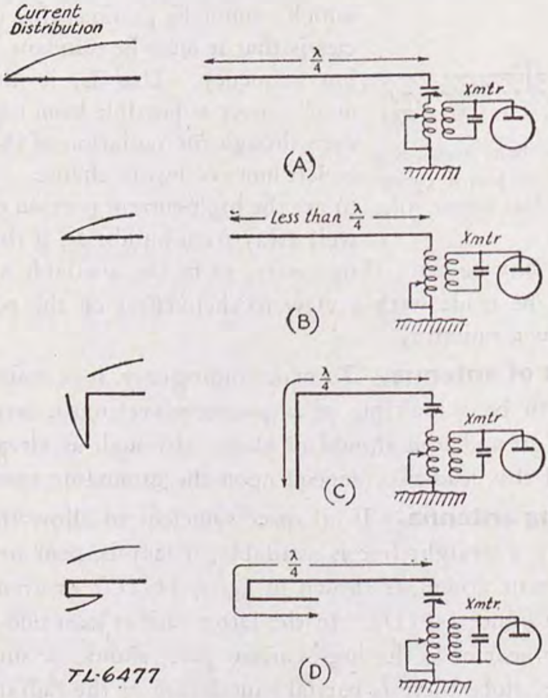

FIGURE 149. Typical arrangements of a quarter-wave horizontal antenna, for installation where height or space is limited. Current distribution is shown for each case.

e. Location of maximum current point. A disadvantage of the quarter-wave "random" antenna is the fact that the high-current end, which does the most radiating, is the end brought into the station. If there is at least one quite long straight stretch available for erecting the antenna, it is a better plan to make the antenna length such that the maximum current point comes at the middle of the straight section. This means that the wire should be a quarter wave long from the middle of the span

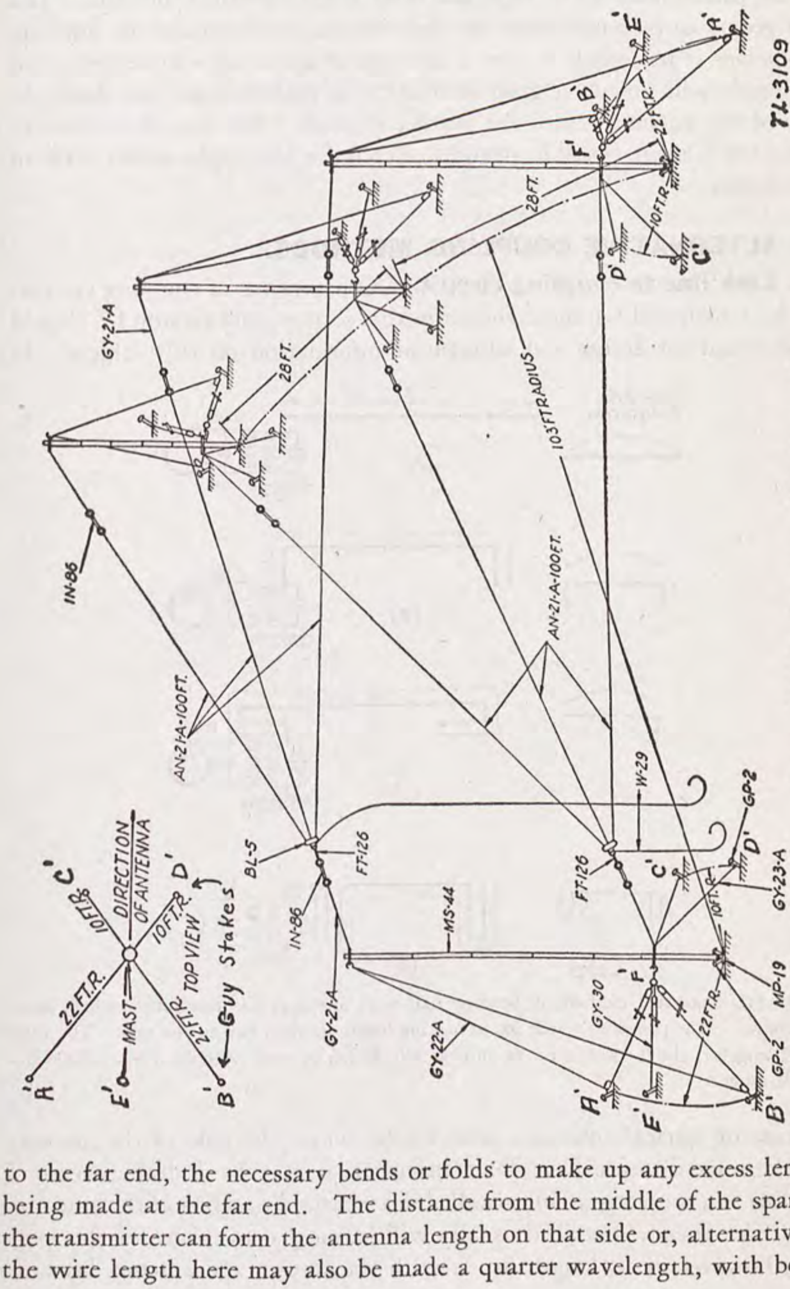

Figure 150. Crowfoot antenna (low frequency).

to the far end, the necessary bends or folds to make up any excess length being made at the far end. The distance from the middle of the span to the transmitter can form the antenna length on that side or, alternatively, the wire length here may also be made a quarter wavelength, with bends or folds, to make a half-wave antenna and thus bring a voltage loop at the coupling point.

f. Summary. Antennas of this type will work quite well, especially for moderate distances at night, even though they are not capable of the type of performance to be expected from a good vertical antenna. The chief points to be remembered are that it is easiest to make the antenna take power if its length is near a multiple of a quarter wavelength, and that bends will not do a great deal of harm provided they are made in parts of the antenna where the current is small. The aim should be to obtain the longest possible straight stretch for the high-current part of the antenna.

142. ALTERNATIVE COUPLING METHODS.

a. Link line to coupling circuit. Other types of coupling systems may be substituted for those shown in this section, and section IV should be consulted for design and adjustment information on this subject. In

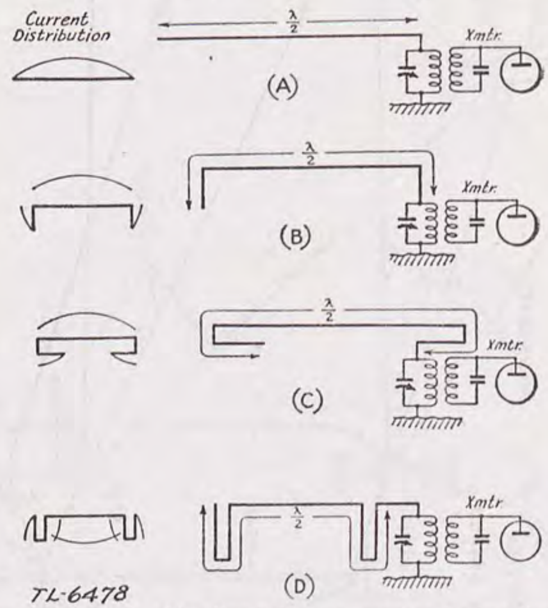

FIGURE 151. Suggested methods of bending half-wave antennas for installation where space is limited. The points to watch for in making bends are discussed in the text. The total wire length is about 250 feet for an antenna which can be used over the 1,500–2,000-kilocycle range.

the case of vertical antennas, particularly, where the base of the antenna may be some distance from the transmitter, it may be desirable to use a link line to a coupling circuit installed in a weatherproof box at the antenna. The feeder already described usually will be more convenient for this purpose, however, if its length fits in with the station and antenna lay-out.

b. Filter type of coupler. The pi-section filter type of coupler is especially convenient with antennas shorter than a quarter wavelength, but should be tuned carefully as described in section IV to prevent harmonic radiation. A quarter-wave grounded antenna inherently discriminates against even harmonics but this is not true of several of the systems described in this section since some of them approach or equal a half wavelength in total wire length.

c. Connecting antenna with transmitter. When the antenna proper is located at some distance from the transmitter the two may be connected by means of a transmission line, either tuned or untuned, of one of the types described in section IV. The principles of design and operation are exactly as set forth in that section. Probably in the majority of cases, however, the distance does not justify the use of such a line.

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SECTION XII
VERY-HIGH-FREQUENCY ANTENNAS

143. RANGE OF VERY-HIGH-FREQUENCY TRANSMISSION.

Very-high-frequency transmission and reception differs from lower frequency work in that it is normally carried out by means of semioptical transmission paths, and not by means of a sky wave. However, this does

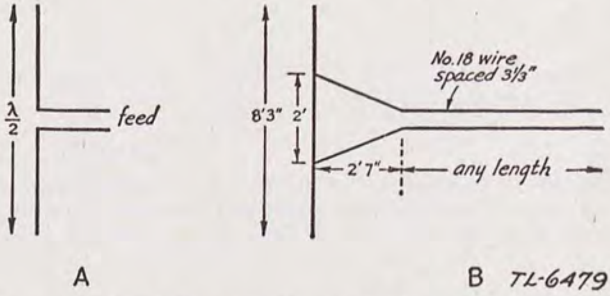

FIGURE 152. Two methods of feeding a simple vertical radiator. That shown at (A) is with a tuned line, while (B) shows a 56-megacycle antenna with delta match. The dimensions are approximate, and may be subject to some slight modification if it is found that coupling the feeders to the tank coil changes the tuning considerably. The 2-foot dimension may have to be changed slightly, to affect a better match, by tapping the line at slightly different points than shown in the sketch.

not mean that communication cannot be carried on over greater than sight ranges, and it is not uncommon for a well-equipped 56-megacycle station to have a consistent range of 40 to 50 miles, and sometimes up to 100 miles. Contacts over distances greater than 50 miles are most frequent at night during the summer, in the latitudes of the continental United States.

144. VERTICAL AND HORIZONTAL ANTENNAS. On the very high frequencies, signals sent from a vertical antenna are vertically polarized and can only be received well on a vertical antenna, and signals from a horizontal antenna are horizontally polarized and are only received well on a horizontal antenna.

145. USE OF DIRECTIVE SYSTEM. It has been found that directive antenna systems will extend the operating range on 56 megacycles to such a degree that suitable communication can be carried on with a directive system where no signal could be put through with a simple antenna. Because of the small physical dimensions of antennas on the very high frequencies, there is practically no reason why the very-high-frequency antenna should not be a directive affair, except possibly in the case of mobile or portable work. Further, since the only radiation effective at these frequencies is at quite a low angle with respect to the ground, every effort should be made to concentrate the radiation as near to the horizontal as possible.

146. LOW-Q SYSTEM.

a. It is desirable to keep the "Q" of the very-high-frequency antenna as low as possible, because the bands are proportionately wide and a high-Q system could not be made to take power, except over a small portion of the band. "Q" simply relates to the sharpness of resonance of the antenna—a high-Q antenna is one of low radiation resistance, and consequently has a sharp resonance characteristic. Close-space arrays with either driven or parasitic elements are to be avoided because of their high "Q," and arrays with quarter-wave (or greater) spacing should be used if the array is to be effective over a wide frequency range.

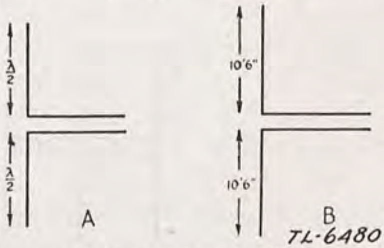

FIGURE 153. Two types of collinear array. Either can be fed by a matching section and untuned line or with a tuned line. (B) is an "extended double Zepp" for 56 megacycles.

b. The "Q" of a very-high-frequency antenna can be lowered by using heavy wire or even metal tubing for the elements. Tubing of ½-inch or even 1-inch diameter is not too unwieldy for the elements of an array at these frequencies, and it has the further advantage that the elements will be self-supporting, this avoiding any possible loss due to poor insulation at the voltage loops.

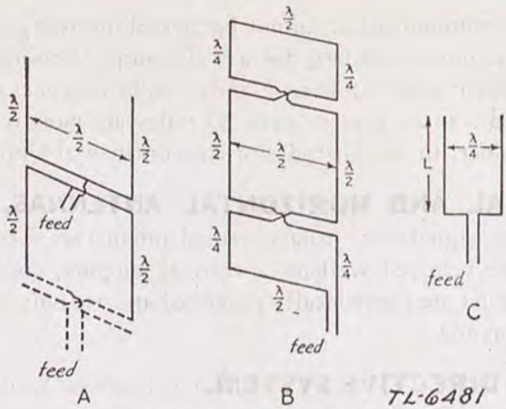

FIGURE 154. The system shown at (A) is a vertical "lazy H" and can be fed at either of the points shown. (B) is a vertical Sterba. Both of these systems are bidirectional in the broadside direction. The antenna shown at (C) is a simple end-fire system—*L* can be anything from a half-wave to 0.64 wavelength, with greater gain being obtained with the longer elements.

147. POSITION AND HEIGHT OF ANTENNA. It is particularly important that the very-high-frequency antenna be placed in the clear, and as high as possible. The field strength at a distance is dependent on the height of the antenna, and adding height is like getting more watts output from the transmitter.

148. TUNED AND MATCHED LINES. Tuned lines can be used to feed the very-high-frequency antennas, but matched ones are recommended,

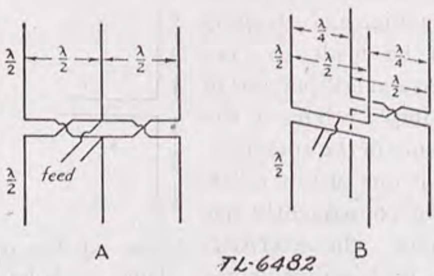

FIGURE 155. The very-high-frequency antenna at (A) is an extension of the "lazy H" that will give greater horizontal directivity. The system at (B) is a "lazy H" with parasitic reflectors spaced a quarter wavelength from the antenna, to give unidirectional radiation. The length of the parasitic elements should be adjusted for minimum back radiation (see sec. IX).

used with suitable matching systems. If an open-wire line is used, either tuned or matched, it should be carefully balanced as to length, and the spacing should not exceed 4 inches. Coaxial line is excellent for feeding very-high-frequency antennas. Feed lines should be carefully balanced and made with small spacing to reduce the radiation from the line, since radiation can become quite serious at these frequencies.

149. HALF-WAVE ANTENNAS. Even though directive systems are undoubtedly the most effective, good results can be obtained with simple half-wave antennas. Although it is more convenient to end-feed a vertical antenna, center feed is preferable so that the feed line can be more readily balanced, and remain balanced over the whole band. Tuned feeders can be run to the center of the radiator, or a delta match can be used with an untuned transmission line. Figure 152 shows suggested methods of feeding a half-wave radiator for the very high frequencies.

150. SIMPLE COLLINEAR ANTENNAS. By placing a second vertical element above the first, a collinear antenna results which will give increased low-angle radiation and consequently greater signal strength. Figure 153 shows two collinear arrays, one with half-wave elements and one with the "extended double Zepp" (sec. VIII) elements. The latter, which gives somewhat more gain, has had considerable popularity on very high frequencies. The elements can be made of copper tubing and supported on the side of a pole by stand-off insulators, or the antenna can be of wire suspended from a suitable support. Either tuned feeders or a matching section can be used, as explained in section VIII.

151. LENGTH OF ELEMENTS.

a. The formula given for the length of a half-wave antenna on the lower frequencies must be modified somewhat for the higher frequencies, and because of the greater end effect at these frequencies. The length of a half-wave element can be found from

$$\textit{Length (inches)} = \frac{5540}{\textit{Frequency (megacycles)}}$$

b. The length of a half-wave section of open-wire line is still

$$\textit{Length (inches)} = \frac{5760}{\textit{Frequency (megacycles)}}$$

c. A quarter-wave radiator or open line will be half the length of the half-wave value.

d. A reflector element should be spaced a quarter wavelength back of the radiator, and its length made the same as a half wavelength of open line for the same frequency.

152. PHASED ARRAYS.

a. General. Several types of phased arrays particularly suited to very-high-frequency work are shown in figures 154 and 155. Tubing elements can be used with a simple wooden framework to support them at their centers, or wire elements can be used, strung in a boxlike wooden framework or simply hung from a rope. The various arrays can be adjusted, if it is found to be necessary, by the methods outlined in section VIII.

b. End-fire antenna. The end-fire antenna of figure 154 (C) is particularly simple to construct by supporting the two vertical elements of copper tubing from the top of a single vertical pole, and running the feed line down the pole. If the pole can be made to rotate 90°, full advantage can be taken of the directivity of this simple system. While this type of antenna will not show as sharp a lobe as the broadside type of array, it will show a very definite null which is useful in reducing interference in congested areas. Its pattern is similar to a figure eight, with the nulls broadside to the plane of the elements.

c. Vertical and horizontal polarization. When the antennas are constructed as shown in the drawings, the polarization will be vertical. For horizontal polarization the elements should be mounted horizontally. In all cases, except figure 154 (C), this simply means that the drawings should be rotated 90°; the antenna of figure 154 (C) should be mounted so that the plane containing the two elements is parallel to the ground.

153. PARASITIC ARRAYS.

a. Directive arrays with parasitic elements are frequently used at very high frequencies. As stated before, the spacing between elements should not be too close, otherwise the antenna will be useful only over a small frequency range. Half- to one-inch tubing should be used for the elements, for mechanical reasons as well as to lower the losses and "Q."

b. A popular antenna of this type is the three element beam, with quarter wave spacing between elements. In other respects, it is similar to the three-element beam described in section VII, and the elements may be cut to size using the same formulas. The feed system shown in figure 109 (B) is recommended. Final adjustment of element lengths by means of field-strength measurements may be carried out as described in section VII.

154. COAXIAL VERTICAL RADIATOR. If only a single vertical radiator can be used, and it is necessary to run the line for 30 feet or more, serious thought should be given to the use of coaxial-line feed. It is doubtless the best method of feeding a simple antenna, as testified to by the many police and other very-high-frequency installations where no horizontal directivity is desirable but where a maximum of efficiency is required. Although it is possible to run the coaxial line directly to the center of the antenna with no modifications, it is much better to use the method shown in figure 156. This amounts to feeding the antenna at the center with coaxial line but short-circuits the possibility that the whole coaxial line may act as a vertical radiator, resulting in high-angle radiation and loss of signal strength. The wire extends a quarter wavelength above the juncture of the line and the outer sheath. Because there is no field in the inside of the sheath, the coaxial line can run up through it with no harmful effects. The coaxial line should have an impedance of around 70 ohms (see sec. IV), although this is not critical and any value up to 120 ohms can be used without serious mismatch.

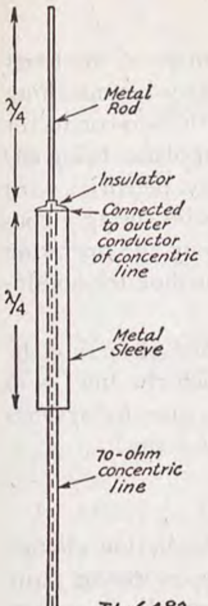

FIGURE 156. The coaxial vertical radiator is one of the most efficient methods for feeding a vertical half-wave antenna. The wire above the sheath is a quarter wavelength long, and the sheath is also a quarter wavelength long. The sheath and wire combine to form a half-wave radiator, and the concentric line feeding the system works to best advantage because of the way it is introduced. If desired, a horizontal ground screen or radial-wire counterpoise can be installed just below the bottom of the sheath (but not connected to it) to increase low-angle radiation. The entire system should be mounted as high as possible.

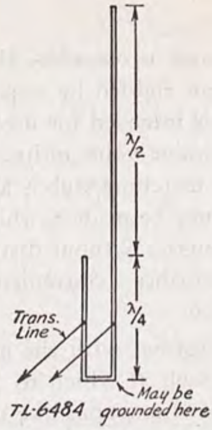

FIGURE 157. The J antenna. It is usually constructed of metal tubing; frequently with the three-quarter-wave vertical section as an extension of a grounded metal mast. The stub may be adjusted by a sliding shorting bar.

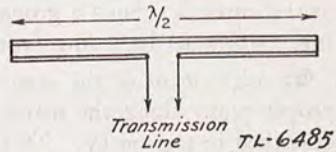

FIGURE 158. Folded dipole for increasing the value of impedance at the feed point.

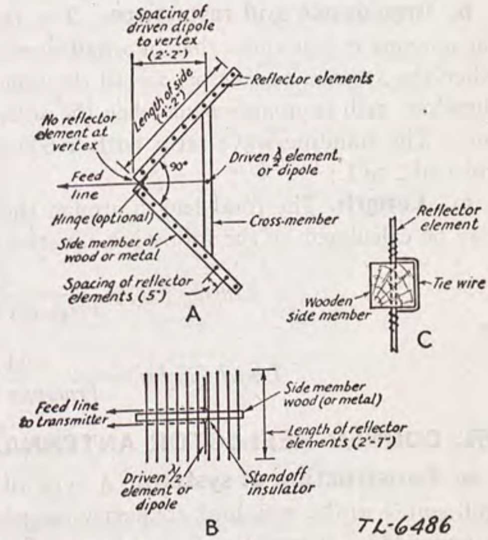

FIGURE 159. A corner reflector antenna system with grid type reflector. The reflector elements are stiff wire or tubing. The dimensions are for 224 megacycles. The gain of the system is close to 10 decibels.

155. J ANTENNA.

a. The J antenna, so called because it resembles the shape of the letter "J," is a half-wave vertical element end-fed by a quarter-wave matching stub, as shown in figure 157. It is intended for use with two-conductor open-wire transmission lines, a suitable value of line impedance being 600 ohms. Since the lower end of the matching stub is at zero potential with respect to earth, a direct ground may be made to this point, using a connecting wire of any convenient length, without disturbing the operation of the antenna. Such a ground furnishes a convenient method for obtaining continuous lightning protection.

b. Adjustment of the system, together with the method of finding the proper point along the matching stub at which to attach the line, is as described in section IV. This type of antenna, like the center-fed systems described earlier, is used when a nondirectional pattern is desired.

156. FOLDED DIPOLE.

a. General. An arrangement which combines the radiation characteristics of a half-wave antenna with the impedance-transforming properties of a quarter-wave line is shown in figure 158. Essentially it consists of a center-fed half-wave antenna with another half-wave element connected directly between its ends. The spacing between the two sections should be quite close—not more than a few percent of the wavelength. As used at very high frequencies, the spacing is of the order of 1 or 2 inches with elements constructed of metal tubing.

b. Impedance and resonance. The impedance at the terminals of the antenna is four times that of a half-wave antenna, or nearly 300 ohms, when the antenna conductors are all the same diameter. A 300-ohm line, therefore, will be nonresonant when the antenna is connected to its output end. The standing-wave ratio with a 600-ohm line will be only of the order of 2 to 1.

c. Length. The total length around the loop formed by the antenna may be calculated by the following equation:

$$Length\ (feet) = \frac{955}{Frequency\ (megacycles)}$$

or

$$Length\ (inches) = \frac{11{,}450}{Frequency\ (megacycles)}$$

157. CORNER REFLECTOR ANTENNA.

a. Construction of system. A type of antenna system particularly well suited to the very-high-frequency ranges is the corner reflector shown in figure 159. It consists of two plane surfaces set at an angle of 90°, with the antenna set on a line bisecting this angle.
The distance of the antenna from the vertex should be 0.5 wavelength, but some compromise designs can be built with closer spacings (see table

TABLE IV

Frequency band	Length of side	Length of reflector elements	Number of reflector elements	Spacing of reflector elements	Spacing of driven dipole to vertex
224–230 mc (1¼-meter)	4′ 2″	2′ 7″	20	5″	2′ 2″
112–116 mc (2½-meter)	8′ 4″	5′ 2″	20	10″	4′ 4″
112–116 mc * (2½-meter)	6′ 8′,	5′ 2″	16	10″	3′ 6″
56–60 mc (5-meter)	16′ 8″	10′ 4″	20	1′ 8″	8′ 8″
56–60 mc * (5-meter)	13′ 4″	10′ 4″	16	1′ 8″	6′ 11″

* Dimensions of square-corner reflector for 224, 112, and 56 megacycles. Alternative designs are listed for 112 and 56 megacycles. These designs, marked (*), have fewer reflector elements and shorter sides, but the effectiveness is only slightly reduced. There is no reflector element at the vertex in any of the designs.

IV). The plane surfaces do not need to be solid, and can most easily be made of wire or metal rod elements spaced about 0.1 wavelength apart. The elements do not have to be connected together electrically.

b. Effect on resistance. The resistance of the antenna is raised when a corner reflector is used.

c. Location of transmission line. The transmission line should be run out at the rear of the reflector to keep the system as symmetrical as possible and thus avoid any unbalance. Two simple antennas which can be used with the corner reflector are shown in figure 160.

d. Use with horizontal and vertical antenna. The corner reflector can be used with the antenna either horizontal or vertical, and the plane of polarization will be the plane of the antenna. The relative positions of the antenna and reflector must remain the same, however, which means that a support for both horizontal and vertical polarization would require a means for rotating the reflector about its horizontal axis.

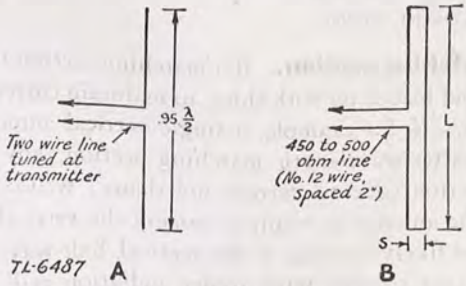

FIGURE 160. Dipoles suitable for use with the corner reflector antenna system. The length L is 25 inches for 224 megacycles, $s=1$ inch for the same band.

e. Characteristics of corner reflector antenna. The corner reflector antenna will give a gain of nearly 10 decibels over a simple half-wave antenna. It has excellent front-to-back and front-to-side ratios, these being of the order of 35 and 25 decibels, respectively, in a typical case. It is also quite free from secondary lobes of appreciable amplitude.

158. FEEDING VERY-HIGH-FREQUENCY ANTENNA.

a. Types of lines. As mentioned before, close spacing and balance are important factors in very-high-frequency operation so that the radiation from the line will be minimized. For this reason, the coaxial line is doubtless the best type of feed for the very-high-frequency antenna, but the open-wire line is quite effective if care is taken in its construction. Low-impedance twisted-pair lines, and solid rubber insulated concentric lines are not to be recommended, although they will not be bad for short distances of less than a wavelength. The desirable type of coaxial line is one using ceramic beads or some other good material for insulation.

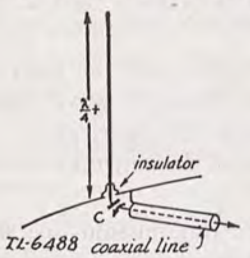

FIGURE 161. Matching the concentric line to a vertical quarter-wave radiator is expedited by using a condenser *C* in series with the inner conductor. The radiator is made slightly longer than a quarter wavelength and the condenser tunes out the reactance. *C* can be a 50-$\mu\mu$fd midget variable.

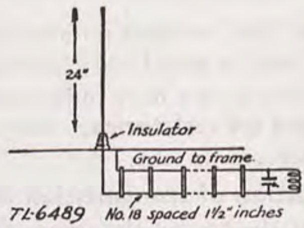

FIGURE 162. Quarter-wave antenna system for 112-megacycle mobile work.

b. Use of matching section. If a matching section is used, it should be symmetrical and loaded on both sides, to maintain current balance in the matching section. If, for example, a single vertical antenna is fed at the bottom by a quarter-wavelength matching section, any radiation from the matching section (due to current unbalance) will combine with the radiation from the antenna to result in raising the vertical angle of radiation. This is less likely to occur if the vertical half-wave antenna is fed at the center. Less trouble with feeder radiation will be experienced with any symmetrical system, which simply means a system with equal amounts of wire each side of the end of the feeder.

159. ANTENNAS FOR MOBILE WORK.

a. A common type of antenna used with very-high-frequency mobile installations is a quarter-wave grounded vertical fed by a concentric line. The antenna should be so placed on the vehicle that it is as high and as much in the clear as possible.

b. It is difficult to examine the concentric line for standing waves, and other means of adjusting the length of the antenna must be used. Further, the impedance of a quarter-wavelength antenna is around 40 ohms, a value which can be matched by most solid-dielectric concentric lines. Concentric lines having characteristic impedances of 70 to 100 ohms may be used to feed a quarter-wavelength antenna as follows: A series condenser is used between the inner conductor of the concentric line and the bottom of the quarter-wave radiator, as shown in figure 161. The antenna is made longer in small steps, and the condenser adjusted until the concentric line introduces a minimum of reactance at the transmitter (shows the least detuning effect on the tank circuit). The method is simply to vary the length of the radiator until it shows an impedance near that of the line, and then to cancel the reactance by the series condenser. Some mismatch can, of course, be tolerated, but the system just described will give a closer match.

c. When the transmitter is installed close to the antenna, a tuned feeder, either a quarter or half wavelength long, can be used to good advantage. With a quarter-wave rod antenna, one feed wire should connect to the bottom of the rod and the other to the vehicle frame near the antenna insulator, as shown in figure 162. The feeder should be approximately a half wave long in such case. With a half-wave antenna, regular Zepp feed can be used, one wire being connected to the bottom of the antenna and the other being left free. With the latter type of feed the line should be approximately a quarter wave long.

SECTION XIII

ORIENTATION OF ANTENNAS

160. FINDING DIRECTION.

a. Unsuitability of Mercator projection. It is probably no news to most people nowadays that true direction from one place to another is not what it appears to be on the old Mercator school map. On such a map, if one starts "east"from central Kansas, he winds up in the neighborhood of Lisbon, Portugal. Actually, as a minute's experiment with a strip of paper on a small globe will show, a signal starting due east from Kansas never hits Europe at all but goes into the southern part of Portuguese West Africa. If, therefore, it is desired to determine the direction of some distant point from one's own location, the ordinary Mercator projection is utterly useless.

b. Methods of finding true bearing. True bearing, however, may be found in several ways: The first, by mathematics, will not be treated here since it involves a working knowledge of spherical trigonometry or instruction in the use of specialized navigation tables; the second is the method of working direct from a globe; and the third involves the use of a special type of world map which *does* show true direction from a specific location to other parts of the world.

161. WORKING FROM A GLOBE.

a. Entirely satisfactory bearings for beam purposes can be taken from an ordinary globe with nothing more complicated than a small school protractor of the type available in any school supply or stationery store. For best results, however, the globe should be at least 8 inches in diameter.

b. From a piece of thin paper, cut out a small circle—something like a 3-inch circle for use with an 8-inch globe. Put a pin through the center and draw a straight line from the center to any point on the circumference. Then put the paper circle on the globe, sticking the center pin into your location. Using the edge of a sheet of plain paper as a straightedge, line up the straight line on your paper circle so that it points north; this is done by laying the straightedge against the center pin and running it up to the

North Pole at the top of the globe, then turning the paper circle until the straight line on it coincides with the straightedge. When you have done this, stick another pin through the paper circle into the globe to hold it in position with this line pointing north.

FIGURE 163. A direction indicator made from a semicircle of thin metal can be fitted easily to a small globe. Pins at the ends permit fastening one end to the home location, the other to the antipodes. The paper scale is marked in miles to show approximate distances (12,000 miles to the semicircle).

c. Now all you have to do is to use your paper straightedge from the center pin to such points as you wish, drawing short lines on your paper circle and labeling them as required. These lines may be extended later to the periphery of the circle. With your protractor it is now a simple matter to determine the bearing, in degrees from north, of any of the points.

d. If your problem is to lay out a long wire to best advantage, make a diagram from the data in section VIII, showing the angular direction of the lobes, and superimpose this on your direction chart, adjusting it until the theoretical power lobes seem to take in the points in which you are interested. The direction of the wire can then be determined with the protractor.

162. AZIMUTHAL MAPS. Unlike the Mercator projection, the azimuthal map shows true bearings for all parts of the world from any single point. By tracing the directional pattern of the antenna system on a sheet of tissue paper, then placing the paper over the azimuthal map with the origin of the pattern at one's location, the "coverage" of the antenna will be readily evident. This is a particularly useful method when a multi-lobed antenna, such as any of the long single-wire systems, is to be laid out so that the main lobes cover as many desirable directions as possible. Often a set of such patterns will be of considerable assistance in determining what length antenna to put up, as well as the direction in which it should run.

163. DETERMINING TRUE NORTH.

a. General. Determining the direction of distant points is of little use in erecting a directive array unless it can be put up in the desired direction. This, in turn, demands a knowledge of the direction of *true* north (as against magnetic north), since all our directions from globe or map are worked in terms of true north. There are several ways in which north may be determined.

b. By direction of city streets. Frequently, the streets of a city or town are laid out, quite accurately, in north-south and east-west directions.

c. By compass.—(1) Type of compass needed. Get as large a compass as you can. It is difficult, though not impossible, to get satisfactory results with the pocket type. In any event, the compass *must* have degree graduations (not more than 2° per division) for satisfactory results. A lensatic type compass will give very good accuracy.

(2) Correction for declination. It must be remembered that the compass points to *magnetic* north, not true north. The amount by which magnetic north differs from true north in a particular location is known as "declination." This declination must be known before starting work. When correcting your "compass north," do so *opposite* to the direction of the *declination*. For instance, if the variation for your locality is 12° west (meaning that the compass points 12° west of north) then true north is found by counting 12° *east* of north as shown on the compass.

(3) Technique of using compass. When taking the bearing, make sure that the compass is located well away from ironwork fencing, pipes, etc. Place the instrument on a wooden tripod or support of some sort, at a convenient height as near eye level as possible. Make yourself a sighting stick from a flat stick about 2 feet long with a nail driven upright in each end (for use as sights) and then, after the needle of the compass has settled down, carefully lay this stick across the face of the compass—with the necessary allowance for declination—to line it up on true north. *Be sure you apply the declination correctly.* This same sighting stick and compass rig can also be used in laying out directions for supporting poles for antennas in other directions, provided, of course, that the compass dial is graduated in degrees.

d. By Pole Star. The Pole Star also may be used in determining the direction of true north. An advantage is that the Pole Star bears true north, so that no corrections are necessary. Disadvantages are that some people have difficulty identifying the Pole Star, which is none too bright at best, and that because of its comparatively high angle above the horizon it is not always easy to sight on it accurately. In any event, it is a handy check on the direction secured by other means.

e. By sun.—(1) With some slight preparation, the sun can easily be used for determination of true north. One of the most satisfactory methods is described below. The method is based on the fact that exactly at noon, local time, the sun bears due south, so that at that time the shadow of a vertical stick or rod will bear true north. (In the Southern Hemisphere, substitute "south" for "north" in all cases, and shift the months in the table by 6 months. For example, January corrections for July, March for September, etc.)

(2) Two corrections to your standard time must be made to determine the exact moment of true local noon. The first is a longitude correction. Standard Time is time at some particular meridian of longitude: EST is based on the 75th meridian, CST on the 90th meridian, MST on the 105th meridian, and PST on the 120th meridian. From an atlas, determine the difference between your own longitude and the longitude of your time meridian. Getting this to the nearest 15 minutes of longitude is close enough. Example: Fort Monmouth, New Jersey, which runs on 75th meridian time (EST) is at 74°42′ longitude, or a difference of 58′. Now, for each 15′ of longitude, figure 1 minute of time; thus 58′ is equivalent to approximately 4 minutes of time (there are 60 "angle" minutes to a degree, so that each degree of longitude equals 4 minutes of time). SUBTRACT this correction from noon if you are *east* of your time meridian; ADD it if you are *west*.

TABLE V

[Apply to clock time as indicated by the sign, to get time of true noon]

January	1	+	4 minutes.	July	10	+	5 minutes.
	10	+	8 minutes.		20	+	6 minutes.
	20	+	11 minutes.		30	+	6 minutes.
	30	+	13 minutes.				
February	10	+	14 minutes.	August	10	+	5 minutes.
	20	+	14 minutes.		20	+	3 minutes.
	28	+	13 minutes.		30		0 minutes.
March	10	+	10 minutes.	September	10	−	3 minutes.
	20	+	7 minutes.		20	−	6 minutes.
	30	+	4 minutes.		30	−	10 minutes.
April	10	+	1 minute.	October	10	−	13 minutes.
	20	−	1 minute.		20	−	15 minutes.
	30	−	3 minutes.		30	−	16 minutes.
May	10	−	4 minutes.	November	10	−	16 minutes.
	20	−	3 minutes.		20	−	14 minutes.
	30	−	2 minutes.		30	−	11 minutes.
June	10	−	1 minute.	December	10	−	7 minutes.
	20	+	1 minute.		20	−	2 minutes.
	30	+	3 minutes.		30	+	2 minutes.

(3) To the resulting time, apply a further correction for the date, from table V. The resulting time is the time, by Standard Time, when it will be true noon at your location. Put up your vertical stick (use a plumb bob to make sure it is actually vertical). Check your watch with Standard Time, and at the time indicated from your calculations, mark the position of the shadow. That is true north.

SECTION XIV

PHANTOM ANTENNAS AND FIELD STRENGTH METERS

164. NATURE OF PHANTOM ANTENNAS. A phantom antenna is simply a resistance capable of dissipating power from the transmitter. It is a useful adjunct to transmitter tuning, in that it can be made to indicate the order of r. f. power output being secured, and also avoids radiating a signal during the tuning-up period. By selection of proper constants it is possible to make the phantom antenna simulate the actual feeder system to which the transmitter is to be connected, so that tuning can be predetermined.

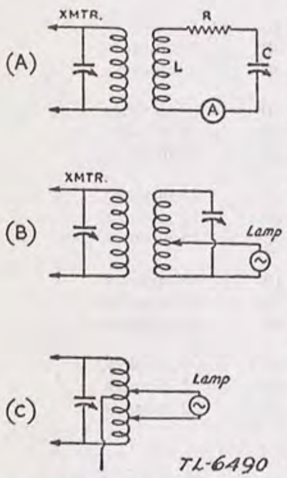

FIGURE 164. Three types of circuits for using phantom antennas. Alternatively, the phantom antenna may be substituted for the feeders, using the regular coupling apparatus, or even installed in place of the antenna at the end of the transmission line.

165. CONNECTIONS FOR PHANTOM ANTENNAS. Some typical connections for phantom antennas are shown in figure 164. In (A), the resistor *R* should be noninductive and should have a low value, normally of the order of 25 ohms or less. Antenna A-62 (Phantom) is a phantom antenna of this type, designed to be connected across the terminals of a transmission line. A small lamp, inductively coupled to the tuned circuit, is used in place of a series meter to indicate resonance. In (B) and (C) either a resistor or an electric lamp can be used, these connections being suitable for resistances up to a few thousand ohms. The coupling can be varied by means of the taps on the coils, or (in (A) and (B)) by changing the coupling between the coils themselves.

166. USE OF LAMP. An ordinary 115-volt lamp is about the handiest form of phantom antenna, and can be used for the measurement of power at frequencies up to 56 megacycles. It is best to choose a size of lamp which is rated at about the expected power output of the transmitter. With the transmitter tuned and the coupling to the phantom adjusted to give maximum lamp brilliance, the amount of illumination can be judged by eye as compared to that from a similar lamp in a 115-volt socket, to determine whether the transmitter output is higher or lower than the lamp rating. For more accurate measurement some sort of photometer is necessary. A photographic exposure meter of the photoelectric type is well suited to this purpose. It should be set up at some convenient distance which gives a satisfactory reading; then the lamp phantom is disconnected from the transmitter and connected to the 115-volt line through a resistor or variable control which can be adjusted so that the meter gives the same reading as before. The power input to the lamp, which will be the same as the r. f. power output of the transmitter, can be measured by a wattmeter or by taking readings of voltage and current at the lamp. The small universal test instruments are quite suitable for the purpose. Care should be taken in making these measurements to prevent extraneous light from acting on the exposure meter and introducing error. The apparatus may be mounted in a box to keep out light, if necessary.

167. USE OF NONINDUCTIVE RESISTORS. When noninductive resistors are used instead of lamps the power may be determined by measuring the r. f. current through the resistor with an r. f. ammeter of suitable range. $P=I^2R$. The instrument range necessary can be found by substituting the resistance and the probable power into the formula. Resistors capable of handling moderate amounts of power have recently been made available, and have low enough distributed capacity and inductance to be substantially purely resistive at frequencies up to and including 14 megacycles. Skin effect raises the effective resistance of the lower values using fairly large wire, so that low-resistance units may actually have more resistance than the label shows at the higher frequencies. Skin effect may be neglected with types using filamentary wire, and with carbon types.

168. USE OF CARBON RESISTORS. Carbon resistors of the 1-watt size are practically noninductive and noncapacitive in values up to several thousand ohms, for frequencies up to 60 megacycles. In the higher ranges, however, the shunting capacity of leads and end caps causes the apparent resistance to decrease. Values below 5,000 ohms or so are excellent for r. f. work, their only disadvantage being the limited power-handling capability. For measurement work, where only a small amount of power need be dissipated, they are very useful since the r. f. and d-c resistances are practically identical.

169. FIELD-STRENGTH METER.

a. General. An r. f. field-strength meter is a simple instrument for checking the adjustment and performance of an antenna. It may be used to check the proper adjustment of the antenna itself, the antenna radiation pattern, and the adjustment of a matching system. In addition, it may be used to check a transmission line for standing waves, and even to check the neutralization of an r. f. amplifier stage. The circuit of a simple field-strength meter is shown in figure 165. For field strength measurements, a half-wave

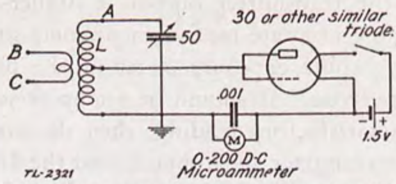

FIGURE 165. Simple field-strength meter. Inductance *L* should be made plug-in, so that the proper inductance for the operating frequency can be inserted.

doublet should be connected to terminals *B* and C. The antenna may be located some distance from the field-strength meter (it should be at least one wavelength from the antenna, and more if convenient) and connected to the meter by means of a low-impedance transmission line.

b. Checking standing waves. For checking standing waves along a transmission line, a piece of rod or stiff wire 1 to 2 feet long should be connected at *A*. Then as the rod is run along one wire of the transmission line (care being taken to keep the rod in the same plane at all times and not to change its position along the wire), watch the meter for a change in reading. Any large change in current reading indicates the presence of standing waves.

SECTION XV

SELECTION OF FREQUENCY FOR A GIVEN RANGE

170. SOURCES OF INFORMATION. The information listed in the following table must not be considered infallible. The figures represent average values only, and variations may be expected. For current information, consult *High-Frequency Radio Transmission Conditions*, prepared by the U. S. Department of Commerce, Interservice Radio Propagation Laboratory, Washington, D. C., and distributed by the Office of the Chief Signal Officer, Military Intelligence Branch, Washington, D. C.

TABLE VI

DAY—SUMMER

Distance (miles)	Frequency (megacycles)	Distance (miles)	Frequency (megacycles)
5,000 and over	22	500	10–14
4,000	20	400	10–12
3,000	18	300	8–10
2,000	16–18	200	6–8
1,500	14–18	150	6
1,000	12–16	100	4–5
750	12–14	50	2–4

NIGHT—SUMMER

5,000 and over	8–14	500	2–6
4,000	6–14	400	2–5
3,000	6–14	300	2–4
2,000	5–12	200	2–4
1,500	4–10	150	2–4
1,000	4–8	100	2–4
750	2–8	50	2–4

Table VI—Continued

DAY—WINTER

Distance (miles)	Frequency (megacycles)	Distance (miles)	Frequency (megacycles)
5,000 and over	18	500	6–10
4,000	16–18	400	6–8
3,000	14–18	300	5–6
2,000	12–18	200	4–6
1,500	10–16	150	4
1,000	10–12	100	2–4
750	8–10	50	2–5

NIGHT—WINTER

Distance (miles)	Frequency (megacycles)	Distance (miles)	Frequency (megacycles)
5,000 and over	5–8	500	2–5
4,000	4–8	400	2–4
3,000	4–8	300	2–4
2,000	4–6	200	2–4
1,500	4–6	150	2–4
1,000	3–6	100	2–4
750	2–5	50	2–5

SECTION XVI

RADIO DIRECTION-FINDING ANTENNAS

171. REQUIREMENTS FOR DIRECTION-FINDING ANTENNA. Theoretically, any antenna which exhibits directional characteristics can be used in direction finding. For practical purposes, the antenna should be small and rotatable, and must work well over a wide frequency range.

172. TYPES OF DIRECTION-FINDING ANTENNAS. The most commonly used types of antennas for radio direction finding are the *loop* and the *Adcock.*

173. LOOP ANTENNA.

a. The loop antenna consists of a number of turns of wire wound in the form of a loop, as shown in figure 166. If the loop is turned so that its plane is perpendicular to the arriving radio wave, a current will be induced in both sides of the loop. However, these currents will be out-of-phase, so that the resulting output will be zero. This position is known as the "null position." If the loop is turned so that its axis points toward the arriving wave, the currents will no longer cancel, and voltage will be present across the terminals. If a receiver equipped with some indicating device such as a signal strength ("R") meter is connected to the loop, the direction of the station may be determined. Because the position of minimum output is much easier to determine than that of maximum output, the antenna usually is adjusted to indicate the null, which will be 90° off the line of direction to the station emitting the signal.

b. In the method described above, it is impossible to determine from which direction the waves are arriving. All that is indicated is the line of direction. In order to add "sense" to the antenna (that is, to make it capable of indicating which way along the line of direction the station actually lies) a vertical antenna is added to the unit, with provisions for coupling it to the output of one side of the loop. If it is known to which side the vertical is coupled, it is a simple matter to determine the direction of the radiating station; the signal will be greatest when the side of the loop to which the vertical is coupled points toward the transmitter. In this case, also, it is more practical to use the position indicating the null than that indicating maximum signal strength. This null will be 90° away from the nulls obtained without the sense antenna. After determining the direction of the source of the wave with the sense antenna, it is common practice to disconnect it and obtain the final null reading with the loop alone.

c. For more accurate readings, two loop antennas often are combined, with their planes at right angles. These are fed into a receiver having two radio frequency sections and two intermediate frequency sections. The signal strength in each is shown by a dual meter arranged to indicate when the output from both loops is the same. Sense is determined by coupling the output of a vertical antenna to the output of one of the loops.

174. ADCOCK ANTENNA.

a. The Adcock antenna consists of a vertical end-fire array, arranged as shown in figure 167. The horizontal portion is shielded in order to mini-

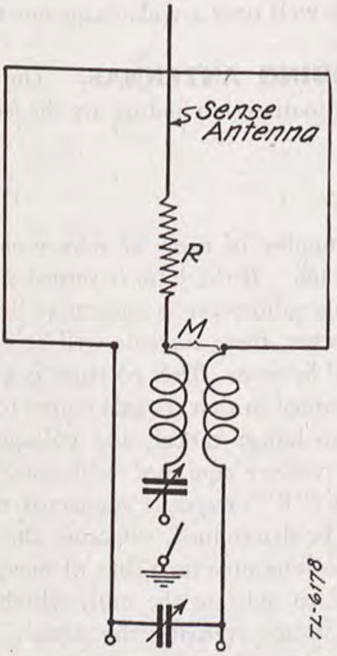

Figure 166. Loop antenna with sensing antenna.

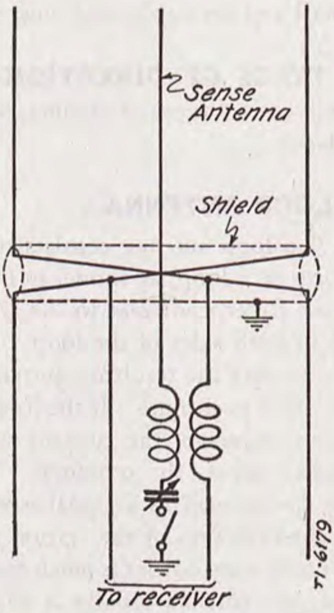

Figure 167. Adcock antenna with sensing antenna.

mize the pick-up of horizontally polarized waves. As in the loop antenna, greatest output will be obtained when the array is pointed toward the transmitting station, and minimum output when the array is at an angle of 90° with the direction of the arriving wave. Also as in the loop antenna, it is impossible to determine the sense of the arriving wave without an auxiliary vertical antenna. This is mounted between the two elements of the array, and is used in the same manner as with the loop array.

b. Adcock antennas often are combined and used in the same manner as the combined loop antennas.

c. Because radio waves frequently are bent in their passage, and because it is difficult to separate the vertically and horizontally polarized waves, accurate readings are not always possible in the frequency range of about 1.5 to 20 megacycles, inclusive.

INDEX

TECHNICAL MANUAL

ANTENNAS AND ANTENNA SYSTEMS

CHANGES No. 1 }

WAR DEPARTMENT,
WASHINGTON 25, D. C., 22 May 1944.

TM 11-314, 30 November 1943, is changed as follows:

FIGURE 3.—F_2 layer transmission at high frequencies (15 to 30 megacycles). The waves are partially bent in going through the two lower layers, but not sufficiently to return to earth.

20. SPORADIC "E" LAYER REFLECTION.

a. General. The sporadic *"E"* * * * the *E* layer. The cause of this ionization is not known, but it has been found to be present nearly all the time. Occasionally, the ionization * * * transmitter and receiver.

* * * * * * *

67. IMPEDANCE MATCHING SYSTEMS.

* * * * * * *

b. Delta matching. The delta matching * * * as already described. For a 600-ohm line, the coupling length, ***C,*** and the feeder clearance, ***E,*** are given by the following formulas:

$$C\ (feet)=\frac{123}{f\ (megacycles)}$$

$$E\ (feet)=\frac{148}{f\ (megacycles)}$$

where f is the frequency in megacycles. The dimensions given * * * antenna-feeder arrangements.

* * * * * * *

86. RADIATION RESISTANCE.

a. General. The radiation resistance as measured at the center of the antenna, or driven element, varies as shown in figure **105** for the spacings and tuning conditions which give the gains indicated by the curves of figure 104. These values, especially * * * than the director.

* * * * * * *

603555°—44——13

92. METHODS OF FEED.

*   *   *   *   *   *   *

d. Delta matching transformer. The delta matching section shown in figure 109 (D) is quite suitable for open-wire lines. It has the * * * 600-ohm line.

104. NATURE OF V ANTENNA. Two wires combined * * * effective directional antenna. If the two sides of the V are excited 180° out-of-phase, by connecting the two-wire feed line to the apex of the V, the lobes add up along the line of the bisector and tend to cancel in other directions, as shown in figure **121.** The V antenna * * * frequency is varied.

105. DESIGN OF V ANTENNA.

a. The chart in figure **120** gives the dimensions that should be followed for an optimum design to obtain maximum power gain from a V beam. The wave angle * * * down the slope.

*   *   *   *   *   *   *

125. GENERAL CONSIDERATIONS.

*   *   *   *   *   *   *

d. Importance of length. Generally speaking, the * * * on its length. Height as well as length plays an important part in the determination of the optimum wave angle, but height has a much smaller effect on the gain than length. Antennas designed by * * * lowest operating frequency.

127. SECONDARY LOBES.

*   *   *   *   *   *   *

c. Comparison with half-wave antenna. It is a * * * a half wave. In one sense this is an advantage, because in practice one finds that, along with high gain in the desired direction, the secondary lobes permit communication practically around the horizon for emergency purposes. It is not * * * is the case.

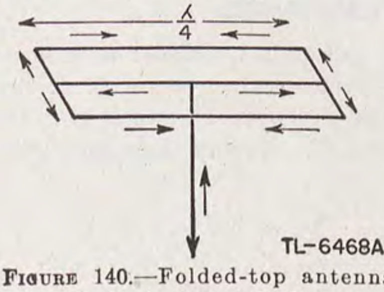

Figure 140.—Folded-top antennas * * * 137, and 138.

163. DETERMINING TRUE NORTH.

*   *   *   *   *   *   *

e. By sun.

*   *   *   *   *   *   *

(2) Two corrections to * * * is close enough. Example: Fort Monmouth, New Jersey, which runs on 75th meridian time (EST) is at **74°02′** longitude, or a difference of 58′. Now, for each * * * you are *west.*

*   *   *   *   *   *   *

INDEX (Superseded)

[A. G. 300.7 (12 May 44).]

BY ORDER OF THE SECRETARY OF WAR:

G. C. MARSHALL,
Chief of Staff.

OFFICIAL:
J. A. ULIO,
Major General,
The Adjutant General.

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For explanation of symbols, see FM 21-6.

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