CHAPTER TEN

Antenna Systems

¶ 10-1 Antenna Properties

Wave propagation and antenna design — For most effective transmission, the propagation characteristics of the frequency under consideration must be given due consideration in selecting the type of antenna to use. These have been discussed in Chapter Nine. On some frequencies the angle of radiation and polarization may be of relatively little importance; on others they may be all-important. On a given frequency, the particular type of antenna best suited for long-distance transmission may not be as good for shorter-range work as would a different type.

The important properties of an antenna or antenna system are its polarization, angle of radiation, impedance, and directivity.

Polarization — The polarization of a straight-wire antenna is its position with respect to the earth. That is, a vertical wire transmits vertically polarized waves and a horizontal antenna generates horizontally polarized waves (§ 9-1). The wave from an antenna in a slanting position contains both vertical and horizontal components.

Angle of radiation — The wave angle (§ 9-4) at which an antenna radiates best is determined by its polarization, height above ground, and the nature of the ground. Radiation is not all at one well-defined angle, but rather is dispersed over a more or less large angular region, depending upon the type of antenna. The angle is measured in a vertical plane with respect to a tangent to the earth at the transmitting point.

Impedance — The impedance (§ 2-8) of the antenna at any point is the ratio of voltage to current at that point. It is important in connection with feeding power to the antenna, since it constitutes the load resistance represented by the antenna. At high frequencies the antenna impedance consists chiefly of radiation resistance (§ 2-12). It is understood to be measured at a current loop (§ 2-12), unless otherwise specified.

Directivity — All antennas radiate more power in certain directions than in others. This characteristic, called *directivity*, must be considered in three dimensions, since directivity exists in the vertical plane as well as in the horizontal plane. Thus, the directivity of the antenna will affect the wave angle as well as the actual compass directions in which maximum transmission takes place.

Current — The field strength produced by an antenna is proportional to the current flowing in it. Since standing waves generally are present on an antenna, the parts of the wire carrying the higher current therefore have the greatest radiating effect.

Power gain — The ratio of power required to produce a given field strength, with a "comparison" antenna, to the power required to produce the same field strength with a specified type of antenna is called the *power gain* of the latter antenna. The term is used in connection with antennas intentionally designed to have directivity, and the field is measured in the optimum direction of the antenna under test. The comparison antenna almost always is a half-wave antenna having the same polarization as the antenna under consideration. Power gain usually is expressed in decibels (§ 3-3).

¶ 10-2 The Half-Wave Antenna

Physical and electrical length — The fundamental form of antenna is a single wire whose length is approximately equal to half the transmitting wavelength. It is the unit from which many more complex forms of antennas are constructed. It is sometimes known as a *Hertz* or *doublet* antenna.

The length of a half wave in space is:

$$Length\ (feet) = \frac{492}{Freq.\ (Mc.)} \qquad (1)$$

The actual length of a half-wave antenna will not be exactly equal to the half wave in space, but is usually about 5 per cent less because of capacitance at the ends of the wire (*end effect*). The reduction factor increases slightly as the frequency is increased. Under average conditions the following formula will give the length of a half-wave antenna to sufficient accuracy for frequencies up to 30 Mc.:

$$Length\ of\ half\text{-}wave\ antenna\ (feet) = \frac{492 \times 0.95}{Freq.\ (Mc.)} = \frac{468}{Freq.\ (Mc.)} \qquad (2)$$

At 56 Mc. and higher frequencies the somewhat larger end effects cause a slightly greater reduction in length, so that, for these higher frequencies,

$$Length\ of\ half\text{-}wave\ antenna\ (feet) = \frac{492 \times 0.94}{Freq.\ (Mc.)} = \frac{462}{Freq.\ (Mc.)}, \qquad (3)$$

$$or\ length\ (inches) = \frac{5540}{Freq.\ (Mc.)} \qquad (4)$$

Current and voltage distribution — When power is fed to such an antenna the current and voltage vary along its length (§ 2-12). The

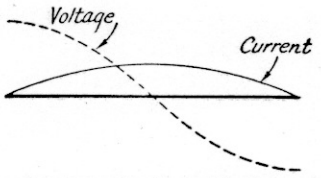


Fig. 1001 — Current and voltage distribution on a half-wave antenna. Current is maximum in center, nearly zero at ends. Voltage distribution is just the opposite.

distribution, which is practically a sine curve, is shown in Fig. 1001. The current is maximum at the center and nearly zero at the ends, while the opposite is true of the r.f. voltage. The current does not actually reach zero at the current *nodes* (§ 2-12), because of the end effect; similarly, the voltage is not zero at its node because of the resistance of the antenna, which consists of both the r.f. resistance of the wire (*ohmic resistance*) and the radiation resistance (§ 2-12). Usually the ohmic resistance of a half-wave antenna is small enough, in comparison with the radiation resistance, to be neglected for all practical purposes.

Impedance — The radiation resistance of a half-wave antenna in free space — that is, sufficiently removed from surrounding objects so that they do not affect the antenna's characteristics — is 73 ohms, approximately. The value under practical conditions will vary with the height of the antenna, but is commonly taken to be in the neighborhood of 70 ohms. It is pure resistance, and is measured at the center of the antenna. The impedance is minimum at the center, where it is equal to the radiation resistance, and increases toward the ends (§ 10-1). The actual value at the ends will depend on a number of factors, such as the height, the physical construction, and the position with respect to ground.

Conductor size — The impedance of the antenna also depends upon the diameter of the conductor in relation to its length. The figures above are for wires of practicable sizes. If the diameter of the conductor is made large, of the order of 1 per cent or more of the length, the impedance at the center will be raised and the impedance at the ends decreased. This increase in center impedance (of the order of 50 per cent for a diameter/length ratio of 0.025) is accompanied by a decrease in the Q (§ 2-10, 2-12) of the antenna, so that the resonance curve is less sharp. Hence, the antenna is capable of working over a wider frequency range. This effect is greater as the diameter/length ratio is increased, and is a property of some importance at the very-high frequencies where the wavelength is small.

Radiation characteristics — The radiation from a half-wave antenna is not uniform in all directions but varies with the angle with respect to the axis of the wire. It is most intense in directions at right-angles to the wire and zero along the direction of the wire itself, with intermediate values at intermediate angles. This is shown by the sketch of Fig. 1002, which represents the radiation pattern in free space. The relative intensity of radiation is proportional to the length of a line drawn from the center of the figure to the perimeter. If the antenna is vertical, as shown in the figure, then the field strength (§ 9-1) will be uniform in all horizontal directions; if the antenna is horizontal, the relative field strength will depend upon the direction of the receiving point with respect to the direction of the antenna wire.

¶ 10-3 Ground Effects

Reflection — When the antenna is near the ground the free-space pattern of Fig. 1002 is modified by reflection of radiated waves from the ground, so that the actual pattern is the resultant of the free-space pattern and ground reflections. This resultant is dependent upon the height of the antenna, its position or orientation with respect to the surface of the ground, and the electrical characteristics of the ground. The reflected waves may be in such phase relationship to the directly radiated waves that the two completely reinforce each other, or the phase relationship may be such that complete cancellation takes place. All intermediate values also are possible. Thus, the effect of a perfectly reflecting ground is such that the original free-space field strength may be multiplied by a factor which has a maximum value of 2, for complete reinforcement, and having all intermediate values to zero, for complete cancellation. Since waves are always reflected upward from the ground (assuming that the surface is fairly level), these reflections only affect the radiation pattern in the vertical plane — that is, in directions upward from the earth's surface — and not in the horizontal plane, or the usual geographical directions.

Fig. 1003 shows how the multiplying factor varies with the vertical angle for several representative heights for horizontal antennas. As the height is increased the angle at which complete reinforcement takes place is lowered, until for a height equal to one wavelength it occurs at a vertical angle of 15 degrees. At still greater heights, not shown on the chart, the first maximum will occur at still smaller angles.

When the half-wave antenna is vertical the maximum and minimum points in the curves of Fig. 1003 exchange positions, so that the nulls become maxima, and vice versa. In this

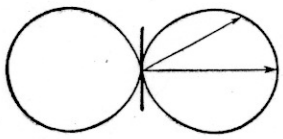


Fig. 1002 — The free-space radiation pattern of a half-wave antenna. The antenna is shown in the vertical position. This is a cross-section of the solid pattern described by the figure when rotated on its vertical axis. The "doughnut" form of the solid pattern can be more easily visualized by imagining the drawing glued to a piece of cardboard, with a short length of wire fastened on it to represent the antenna. Twirling the wire will give a visual representation of the solid radiation pattern.

case, the height is taken as the distance from ground to the center of the antenna.

Radiation angle — The vertical angle, or angle of radiation, is of primary importance, especially at the higher frequencies (§ 9-4, 9-5).

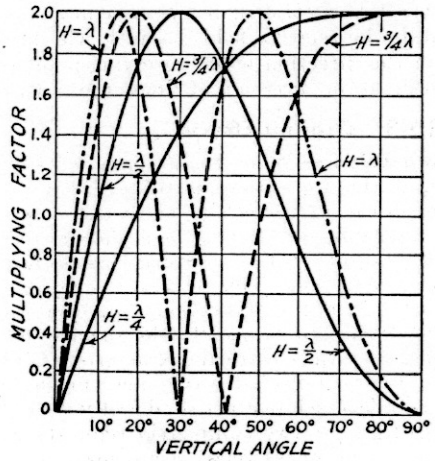


Fig. 1003 — Effect of ground on radiation of horizontal antennas at vertical angles for four antenna heights. This chart is based on perfectly conducting ground.

It is advantageous, therefore, to erect the antenna at a height which will take advantage of ground reflection in such a way as to reinforce the space radiation at the most desirable angle. Since low radiation angles usually are desirable, this generally means that the antenna should be high — at least ½ wavelength at 14 Mc., and preferably ¾ or 1 wavelength; at least 1 wavelength, and preferably higher, at 28 Mc. and the very-high frequencies. The physical height decreases as the frequency is increased, so that good heights are not impracticable; a half wavelength at 14 Mc. is only 35 feet, approximately, while the same height represents a full wavelength at 28 Mc. At 7 Mc. and lower frequencies the higher radiation angles are effective, so that again a reasonable antenna height is not difficult of attainment. Heights between 35 and 70 feet are suitable for all bands, the higher figures generally being preferable where circumstances permit their use.

Imperfect ground — Fig. 1003 is based on ground having perfect conductivity, which is not met with in practice. The principal effect of actual ground is to make the curves inaccurate at the lowest angles; appreciable high-frequency radiation at angles smaller than a few degrees is practically impossible to obtain at heights of less than several wavelengths. Above 15 degrees, however, the curves are accurate enough for all practical purposes, and may be taken as indicative of the sort of result to be expected at angles between 5 and 15 degrees.

The effective ground plane — that is, the plane from which ground reflections can be considered to take place — seldom is the actual surface of the ground but is a few feet below it, depending upon the character of the soil.

Impedance — Waves which are reflected directly upward from the ground induce a current in the antenna in passing, and, depending on the antenna height, the phase relationship of this induced current to the original current may be such as either to increase or decrease the total current in the antenna. For the same power input to the antenna, an increase in current is equivalent to a decrease in impedance, and vice versa. Hence, the impedance of the antenna varies with height. The theoretical curve of variation of radiation resistance for an antenna above perfectly reflecting ground is shown in Fig. 1004. The impedance approaches the free-space value as the height becomes large, but at low heights may differ considerably from it.

Choice of polarization — Polarization of the transmitting antenna is generally unimportant on frequencies between 3.5 and 30 Mc. However, the question of whether the antenna should be installed in a horizontal or vertical position deserves consideration for other reasons. A vertical half-wave antenna will radiate equally well in all *horizontal* directions, so that it is substantially non-directional, in the usual sense of the word. If installed horizontally, however, the antenna will tend to show directional effects, and will radiate best in the direction at right angles, or broadside, to the wire. The radiation in such a case will be least in the direction toward which the wire points. This can be readily seen by imagining that Fig. 1002 is lying on the ground, and that the pattern is looked at from above.

The vertical angle of radiation also will be affected by the position of the antenna. If it were not for ground losses at high frequencies, the vertical half-wave antenna would be preferred because it would concentrate the radiation horizontally. In practice, however, this theoretical advantage over the horizontal antenna is of little or no consequence.

At 1.75 Mc., vertical polarization will give more low-angle radiation, and hence is better for long-distance transmission; at this fre-

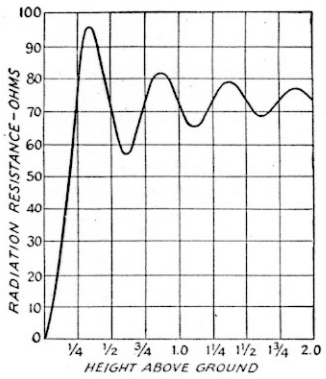


Fig. 1004 — Theoretical curve of variation of radiation resistance for a half-wave horizontal antenna, as a function of height above perfectly reflecting ground.

quency the ground wave also is useful, and must be vertically polarized. On very-high frequencies, direct-ray and lower troposphere transmission require the same type of polarization at both receiver and transmitter, since the waves suffer no appreciable change in polarization in transmission (§ 9-5, 9-6). Either vertical or horizontal polarization may be used, the latter being slightly better for longer distances.

Effective radiation patterns — In determining the radiation pattern it is necessary to consider radiation in both the horizontal and vertical planes. When the half-wave antenna is vertical, the vertical angle of radiation chosen does not affect the *shape* of the horizontal pattern, but only its relative amplitude. When the antenna is horizontal, however, both the shape and amplitude are dependent upon the angle of radiation chosen.

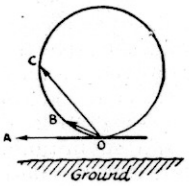


Fig. 1005 — Illustrating the importance of vertical angle of radiation in determining antenna directional effects. Ground reflection is neglected in this drawing of the free-space field pattern of a horizontal antenna.

Fig. 1005 illustrates this point. The "free-space" pattern of the horizontal antenna shown is a section cut vertically through the solid pattern. In the direction *OA*, horizontally along the wire axis, the radiation is zero. At some vertical angle, however, represented by the line *OB*, the radiation is appreciable, despite the fact that this line runs *in the same geographical direction* as *OA*. At some higher angle, *OC*, the radiation, *still in the same geographical direction*, is still more intense. The effective radiation pattern therefore depends upon which angle of radiation is most useful, and for long-distance transmission is dependent upon the conditions existing in the ionosphere. These conditions may vary not only from day to day and hour to hour, but even from minute to minute. Obviously, then, the effective directivity of the antenna will change along with transmission conditions.

At very-high frequencies, where only extremely low angles are useful for any but sporadic-*E* transmission (§ 9-7), the effective radiation pattern of the antenna approaches the free-space pattern. A horizontal antenna therefore shows more marked directive effects than it does at lower frequencies, on which high radiation angles are effective.

Theoretical horizontal-directivity patterns for half-wave horizontal antennas at vertical angles of 9, 15, and 30 degrees (representing average useful angles at 28, 14 and 7 Mc. respectively) are given in Fig. 1006. At intermediate angles the values in the affected regions also will be intermediate. Relative field strengths are plotted on a decibel scale (§ 3-3), so that they represent as nearly as possible the actual aural effect at the receiving station.

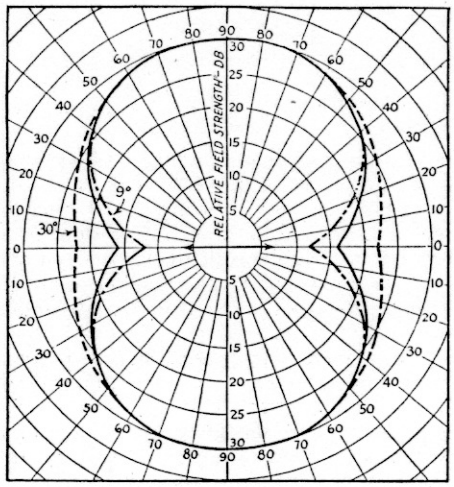


Fig. 1006 — Horizontal pattern of a horizontal half-wave antenna at three vertical radiation angles. The solid line is relative radiation at 15 degrees. Dotted lines show deviation from the 15-degree pattern for angles of 9 and 30 degrees. The patterns are useful for shape only, since the amplitude will depend upon the height of the antenna above ground and the vertical angle considered. The patterns for all three angles have been proportioned to the same scale, but this does not mean that the maximum amplitudes necessarily will be the same. The arrow indicates the direction of the horizontal antenna wire.

10-4 Applying Power to the Antenna

Direct excitation — When power is transferred directly from the source to the radiating antenna, the antenna is said to be directly excited. While almost any coupling method (§ 2-11) may be used, those most commonly employed are shown in Fig. 1007. Power usually is fed to the antenna at either a current or voltage loop (§ 10-2). If power is fed at a current loop, the coupling method is called *current feed;* if at a voltage loop, the method is called *voltage feed.*

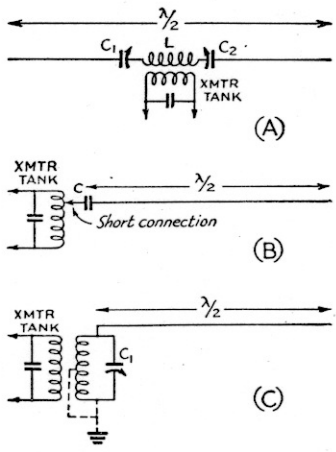


Fig. 1007 — Methods of directly exciting the half-wave antenna. A, current feed, series tuning; B, voltage feed, capacity coupling; C, voltage feed, with an inductively coupled antenna tank. In A, the coupling circuit is not included in the effective electrical length of the antenna.

Current feed — This method is shown in Fig. 1007-A. The antenna is cut at the center and a small coil coupled to the output tank circuit of the transmitter, with adjustable coupling so that the transmitter loading can be controlled. Since the addition of the coil "loads" the antenna, or increases its effective length because of the additional inductance, the series condensers, C_1 and C_2, are used to provide electrical means for reducing the length to its original unloaded value; in other words, their capacitive reactance serves to cancel the effect of the inductive reactance of the coil (§ 2-10).

Voltage feed — In Fig. 1007, at B and C the power is introduced into the antenna at a point of high voltage. In B, the end of the antenna is coupled to the output tank circuit through a small condenser, C; in C, a separate tank circuit, connected directly to the antenna, is used. This tank is tuned to the transmitter frequency, and should be grounded at one end or at the center of the coil, as shown.

Adjustment of coupling — Methods of tuning and adjustment of direct-feed systems correspond to those used with transmission lines, which are discussed in § 10-6.

Disadvantages of direct excitation — Direct excitation seldom is used except on the lowest amateur frequencies, because it involves bringing the antenna proper into the operating room and hence into close relationship with the house and electric wiring. This usually means that some of the power is wasted in heating poor conductors in the field of the antenna. Also, it often means that the shape of the antenna must be distorted, so that the expected directional effects are not realized, and likewise that the height will be limited. For these reasons, in high-frequency work practically all amateurs use transmission lines or feeder systems, which permit placing the antenna in a desirable location.

¶ 10-5 Transmission Lines

Requirements — A transmission line is used to transfer power, with a minimum of loss, from its source to the device in which the power is to be usefully expended. At radio frequencies, where every wire carrying r.f. current tends to radiate energy in the form of electromagnetic waves, special design is necessary to minimize radiation and thus cause as much of the power as possible to be delivered to the receiving end of the line.

Radiation can be minimized by using a line in which the current is low, and by using two conductors carrying currents of equal magnitudes but opposite phase so that the fields about the conductors cancel each other. For good cancellation of radiation, the two conductors should be kept parallel and quite close to each other.

Types — The most common form of transmission line consists of two parallel wires, maintained at a fixed spacing of two to six inches by insulating spacers or spreaders placed at suitable intervals (*open-wire line*). A second type consists of rubber-insulated wires twisted together to form a flexible line, without spacers (*twisted-pair line*). A third uses a wire inside of and coaxial with a tubing outer conductor, separated from the outer conductor by insulating spacers or "beads" at regular intervals (*coaxial* or *concentric line*). A variation of this type uses solid rubber insulation between the inner and outer conductors, the latter usually being made of metal braid rather than of solid tubing, so that the line will be flexible. Still another type of line uses only a single wire, without a second conductor (*single-wire feeder*); in this type, radiation is minimized by keeping the line current low.

Spacing of two-wire lines — The spacing between the wires of an open-wire line should be small in comparison to the operating wavelength, to prevent appreciable radiation. It is impracticable to make the spacing too small, however, because when the wires swing with respect to each other in a wind the line constants (§ 21-2) will vary, and thus cause a variation in tuning or loading on the transmitter. It is also desirable to use as few insulating spacers as possible, to keep the weight of the line to a minimum. In practice, a spacing of about six inches is used for 14 Mc. and lower frequencies, with four- and two-inch spacings being common on the very-high frequencies.

Balance to ground — For maximum cancellation of the fields about the two wires, it is necessary that the currents be equal in amplitude and opposite in phase. Should the capacity or inductance per unit length in one wire differ from that in the other, this condition cannot be fulfilled. Insofar as the line itself is concerned, the two wires will have identical characteristics only when the two have exactly the same physical relationships to ground and to other objects in the vicinity. Thus, the line should be symmetrically constructed and the two wires should be at the same height. Line unbalance can be minimized by keeping the line as far above the ground and as far from other objects as possible.

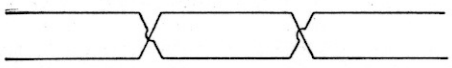


Fig. 1008 — Transposing a two-wire open transmission line preserves balance to ground and to near-by objects.

To overcome unbalance the line sometimes is transposed, which means that the positions of the wires are interchanged at regular intervals (Fig. 1008). This procedure is more helpful on long than on short lines, and usually need not be resorted to for lines less than a wavelength or so long.

Characteristic impedance — The square root of the ratio of inductance to capacity per unit length of the line is called the *characteristic* or *surge impedance*. It is the impedance

which a long line would present to an electrical impulse induced in the line, and is important in determining the operation of the line in conjunction with the apparatus to which it is connected.

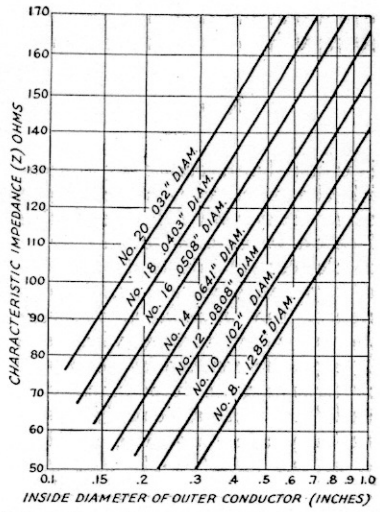


Fig. 1009 — Chart showing the characteristic impedances of typical spaced-conductor transmission lines.

The characteristic impedance of air-insulated transmission lines may be calculated from the following formulas:

Parallel-conductor line:

$$Z = 276 \log \frac{b}{a} \qquad (5)$$

where Z is the surge impedance, 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, etc.). Surge impedance as a function of spacing for lines using conductors of different sizes is plotted in chart form in Fig. 1009.

Coaxial or concentric line:

$$Z = 138 \log \frac{b}{a} \qquad (6)$$

where Z again is the surge impedance. In this case, b is the *inside diameter* (not radius) of the outer conductor and a is the *outside diameter* of the inner conductor. The formula is true for having air as the dielectric, and approximately so for a line having ceramic insulators so spaced that the major proportion of the insulation is air.

The surge impedance for typical concentric lines using various sizes of conductors is given in Fig. 1010.

When a solid insulating material is used between the conductors, because of the increase in line capacity the impedance decreases by the factor $1/\sqrt{K}$, where K is the dielectric constant of the insulating material.

The impedance of a single-wire transmission line varies with the size of the conductor, its height above ground, and its orientation with respect to ground. An average figure is about 500 ohms.

Electrical length — The electrical length of a line is not exactly the same as its physical length, for reasons corresponding to those causing end effect in antennas (§ 10-2). Spacers used to separate the conductors have dielectric constants larger than that of air, so that the waves do not travel quite as fast along a line as they would in air. The lengths of electrical quarter waves of various types of lines can be calculated from the formula:

$$Length\ (feet) = \frac{246 \times V}{Freq.\ (Mc.)} \qquad (7)$$

where V depends upon the type of line. For lines of ordinary construction, V is as follows:

Parallel-wire line	$V = 0.975$
Parallel-tubing line	$V = 0.95$
Concentric line (air-insulated)	$V = 0.85$
Concentric line (rubber-insulated)	$V = 0.56$–0.65
Twisted pair	$V = 0.56$–0.65

Input and output ends — The input end of a line is that connected to the source of power; the output end is that connected to the power-absorbing device. When a line connects a transmitter to an antenna, the input end is at the transmitter and the output end at the antenna; with the same line and antenna connected to a receiver, however, the energy flows from the antenna to the receiver, hence the input end of the line is at the antenna and the output end at the receiver.

Standing-wave ratio — The lengths of transmission lines used at radio frequencies are of the same order as the operating wavelengths, and therefore standing waves of current and voltage may appear on the line

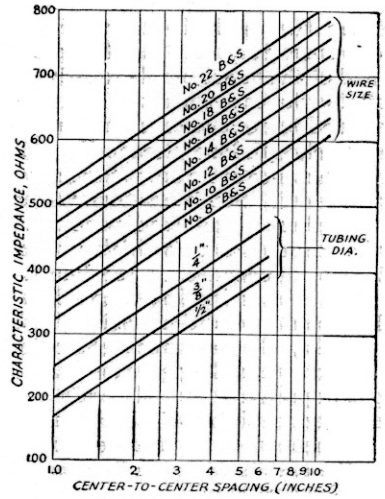


Fig. 1010 — The characteristic impedances of typical concentric lines. Tubing sizes are outside diameters.

(§ 2-12). The ratio of current (or voltage) at a loop to the value at a node (*standing-wave ratio*) depends upon the ratio of the resistance of the load connected to the output end of the line (its *termination*) to the characteristic impedance of the line itself. That is,

$$\textit{Standing-wave ratio} = \frac{Z_s}{Z_t} \text{ or } \frac{Z_t}{Z_s} \qquad (8)$$

where Z_s is the characteristic impedance of the line and Z_t is the terminating resistance. Z_t is generally called an impedance, although it must be non-reactive and therefore must correspond to a pure resistance for the line to operate as described. This means that, when the load or termination is an antenna, it must be resonant at the operating frequency.

The formula is given in two ways because it is customary to put the larger number in the numerator, so that the ratio will not be fractional. As an example, a 600-ohm line terminated in a resistance of 70 ohms will have a standing wave ratio of 600/70, or 8.57. The ratio on a 70-ohm line terminated in a resistance of 600 ohms would be the same. This means that, if the current as measured at a node is 0.1 ampere, the current at a loop will be 0.857 ampere.

A line terminated in a resistance equal to its characteristic impedance is equivalent to an infinitely long line; consequently there is no reflection, and no standing waves appear. The standing wave ratio therefore is 1. The input end of such a line appears as a pure resistance of a value equal to the characteristic impedance of the line.

Reactance, resistance, impedance — The input end of a line may show reactance as well as resistance, and the values of these quantities will depend upon the nature of the load at the output end, the electrical length of the line, and the line characteristic impedance. The reactance and resistance are important in determining the method of coupling to the source of power. Assuming that the load at the output end of the line is purely resistive, which is essentially the case since the load circuit is usually tuned to resonance, a line less than a quarter wavelength long electrically will show inductive reactance at its input terminals when the output termination is *less* than the characteristic impedance, and capacitive reactance when the termination is *higher* than the characteristic impedance. If the line is more than a quarter wave but less than a half wave long, the reverse conditions exist. With still longer lengths, the reactance characteristics reverse in each succeeding quarter wavelength. The input impedance is purely resistive if the line is an exact multiple of a quarter wave in length. The reactance at intermediate lengths is higher the greater the standing-wave ratio, being zero for a ratio of 1.

Impedance transformation — Regardless of the standing-wave ratio, the input impedance of a line a half-wave long electrically will be equal to the impedance connected at its output end; the same thing is true of a line any integral multiple of a half-wave in length. Such a line can be considered to be a one-to-one transformer. However, if the line is a quarter-wave (or an odd multiple of a quarter-wave) long, the input impedance will be equal to

$$Z_i = \frac{Z_s^2}{Z_t}$$

where Z_s is the characteristic impedance of the line and Z_t the impedance connected to the output end. A quarter-wave line can, therefore, be used as an *impedance transformer*, and by suitable selection of constants a wide range of input impedance values can be obtained. Furthermore, the impedance measured between the two conductors anywhere along the line will vary between the two end values, so that any intermediate impedance value can be selected. This is a particularly useful property, since a quarter-wave line can be short-circuited at one end (§ 2-12) and used as a *linear transformer* with an adjustable impedance ratio.

Losses — Air-insulated lines operate at quite high efficiency. Parallel-conductor lines average 0.12 to 0.15 db. (§ 3-3) loss per wavelength of line. These figures hold only if the standing-wave ratio is 1. The losses increase with the standing-wave ratio, rather slowly up to a ratio of 15 to 1, but rapidly thereafter. For standing-wave ratios of 10 or 15 to 1, the increase is inconsequential provided the line is well balanced.

Concentric lines with air insulation are excellent when dry, but losses increase if there is moisture in the line. Provision should be therefore made for making such lines air-tight, and they should be thoroughly dry when assembled. This type of line has the least radiation loss. The small lines (⅜-inch outer conductor) should not be used at high voltages; hence, it is desirable to keep the standing-wave ratio down.

Good quality rubber-insulated lines, both twisted pair and coaxial, average about 1 db. loss per wavelength of line. At the higher frequencies, therefore, such lines should be used only in short lengths if losses are important. These lines have the advantages of compactness, ease of installation, and flexibility. Ordinary lamp cord has a loss of approximately 1.4 db. per wavelength when it is dry, but its losses become excessive when wet. The parallel moulded-rubber type is best from the standpoint of withstanding wet weather. The characteristic impedance of lamp cord is between 120 and 140 ohms.

The loss in db. is directly proportional to the length of the line. Thus, a line which has a loss of 1 db. per wavelength will have an actual loss of 3 db. if the line is three wavelengths long. In the case of line losses, the length is not ex-

pressed in terms of electrical length but in physical length; that is, a wavelength of line, in feet, is equal to 984/frequency (Mc.) for computing loss. This permits a direct comparison of lines having the same physical length. The electrical lengths, of course, may differ considerably.

Resonant and non-resonant lines — Lines are classified as *resonant* or *non-resonant*, depending upon the standing-wave ratio. If the ratio is near 1, the line is said to be non-resonant. Reactive effects will be small, and consequently no special tuning provisions need be made for canceling them (§ 2-10) even when the line length is not an exact multiple of a quarter wavelength. If the standing-wave ratio is fairly large, the input reactance must be canceled or "tuned out" unless the line is a multiple of a quarter wavelength, and the line is said to be resonant.

¶ 10-6 Coupling to Transmission Lines

Requirements — The coupling system between a transmitter and the input end of a transmission line must provide means for adjusting the load on the transmitter to the proper value (impedance matching), and for tuning out any reactive component that may be present (2-9, 2-10, 2-11). The resistance and reactance considered are those present *at the input end of the line*, and hence have nothing to do with the antenna itself except insofar as the antenna load may affect the operation of the line (§ 10-5).

Untuned coil — One of the simplest systems, shown in Fig. 1011-A, uses a coil of a few turns tightly coupled to the plate tank coil. Since no provision is made for tuning, this system is suitable only for non-resonant lines which show practically no reactance at the input end. Loading on the transmitter may be varied by varying the coupling between the tank inductance and the *pick-up coil*, as it is frequently called, or by changing the number of turns on the pick-up coil. A slight amount of reactance is coupled into the tank circuit by the pick-up coil, since the flux leakage (§ 2-11) is high, so that some slight retuning of the plate tank condenser may be necessary when the load is connected.

Taps on tank circuit — A method suitable for use with open-wire lines is shown in Fig. 1011-B, where the line is tapped on a balanced tank circuit with taps equidistant from the center or ground point. This symmetry is necessary to maintain line balance to ground (§ 10-5). Loading is increased by moving the taps outward from the center. Any reactance present may be tuned out by readjustment of the plate tank condenser, but this method is not suitable for large values of reactance and therefore direct tapping is best confined to use with non-resonant lines.

Adjustment of untuned systems — Adjustment of either of the above systems is quite simple. Starting with loose coupling, apply power to the transmitter, and adjust the plate tank condenser for minimum plate current. If the current is less than the desired load value, increase the coupling and again resonate the plate condenser. Continue until the desired plate current is obtained, always keeping the plate tank condenser at the setting which gives minimum current.

Pi-section coupling — A coupling system which is electrically equivalent to tapping on the tank circuit, but using a capacity voltage divider in the plate tank circuit for the purpose, is shown in Fig. 1011-C. Since one side of the condenser across which the line is connected is grounded, some unbalance will be introduced into the transmission line. This method is used chiefly with low-power portable sets, because it is readily adjustable to meet a fairly wide range of impedance values. A single-ended amplifier, using either a screen-grid tube or a grid-neutralized triode (§ 4-7), is required, since the plate tank circuit is not balanced. Coupling is adjusted by varying C_1, re-resonating the circuit each time by means of C_2 until the desired amplifier plate current is obtained. In general, the coupling will increase as C_1 is made smaller with respect to C_2. Relatively large-capacity condensers are required to give a suitable impedance-matching range while maintaining resonance.

Pi-section filter — The coupling circuit shown in Fig. 1011-D is a low-pass filter capable of coupling between a fairly wide range of impedances. The method of adjustment is as follows: First, with the filter disconnected from the transmitter tank, 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 minimum. If this minimum is not the desired full-load plate current, 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 of the taps on the transmitter tank. Do not touch the tank condenser 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.*

With some lengths of resonant lines, particularly those which are not exact multiples of a quarter wavelength, it may be difficult to get proper loading with the pi-section coupler. Usually antennas of these lengths also will be difficult to feed with other systems of coupling, as well. In such cases, the proper output loading often can be obtained by varying the L/C ratio of the filter over a considerably wider range than is necessary for normal loads.

Series tuning — When the input impedance of the line is low, the coupling method shown in Fig. 1011-E may be used. This system, known as *series tuning*, places the coupling coil, tuning condensers and load all in series, and is particularly suitable for use with resonant lines when a current loop appears at the input end. As shown, two tuning condensers are used, to keep the line balanced to ground. However, one will suffice, the other end of the line being connected directly to the end of L_1.

The tuning procedure with series tuning is as follows: With C_1 and C_2 at minimum capacity, couple the antenna coil, L_1, loosely to the transmitter output tank coil, and observe the plate current. Then increase C_1 and C_2 simultaneously until a setting is reached which gives maximum plate current, indicating that the antenna system is in resonance with the transmitting frequency. Readjust the plate tank condenser to minimum plate current. This is necessary because tuning the antenna circuit will have some effect on the tuning of the plate tank. The new minimum plate current will be higher than with the antenna system detuned, but should still be well below the rated value for the tube or tubes. Increase the coupling between L_1 and L_2 by a small amount, readjust C_1 and C_2 for maximum plate current, and again set the plate tank condenser to minimum. Continue this process until the minimum plate current is equal to the rated plate current for the amplifier. Always use the degree of coupling between L_1 and L_2 which will just bring the amplifier plate current to rated value when C_1 and C_2 pass through resonance. The r.f. ammeters should indicate maximum feeder current at the resonance setting; these meters are not strictly necessary, but are useful in indicating the relative power output.

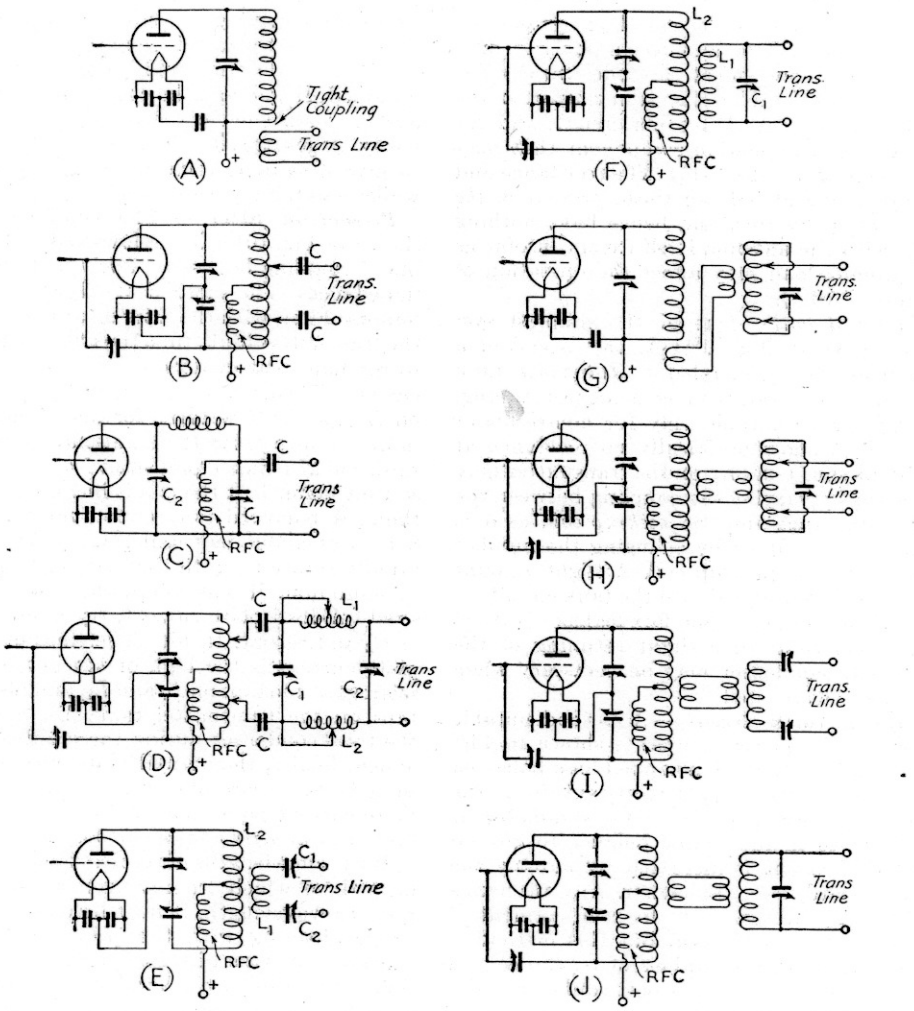


Fig. 1011— Methods of coupling the transmitter output to the transmission line. Application, circuit values and adjustment are discussed in the text. The coupling condensers, C, are fixed blocking condensers used to isolate the transmitter plate voltage from the antenna. Their capacity is not critical, 500 $\mu\mu$fd. to 0.002 μfd. being satisfactory values, but their voltage rating should at least equal the plate voltage on the final stage.

Parallel tuning — When the line has high input impedance, the use of parallel tuning, as shown in Fig. 1011-F, is required. Here the coupling coil, tuning condenser and line all are in parallel, the load represented by the line being directly across the tuned coupling circuit. If the line is non-reactive, the coupling circuit will be tuned independently to the transmitter frequency; line reactance can be compensated for by tuning of C_1 and, if necessary, adjustment of L_1 by means of taps. Parallel tuning is suited to resonant lines when a voltage loop appears at the input end.

The tuning procedure is quite similar to that with series tuning. Find the value of coupling between L_1 and L_2 which will bring the plate current to the desired value as C_1 is tuned through resonance. Again, a slight readjustment of the amplifier tank condenser may be necessary to compensate for the effect of coupled reactance.

Link coupling — Where tuning of the circuit connected to the line is necessary or desirable, it is possible to separate physically the line-tuning apparatus and the plate tank circuit by means of link coupling (§ 2-11). This is often convenient from a constructional standpoint, and has the advantage that, with proper construction, there will be somewhat less harmonic transfer to the antenna, since stray capacity coupling is lessened with the smaller link coils.

Figs. 1011-G and H show a method which can be considered to be a variation of Fig. 1011-B. The first (G) is suitable for use with a single-ended plate tank, the second (H) for a balanced tank. The auxiliary tank on which the transmission line is tapped may have adjustable inductance as well as capacity, to provide a wide range of reactance variation for compensating for line reactance. The center of the auxiliary tank inductance may be grounded, if desired. The link windings should be placed at the grounded parts of the coils, to reduce capacity coupling and consequent harmonic transfer. With this inductively coupled system, the loading on the auxiliary tank circuit increases as the taps are moved outward from the center, but, since this decreases the Q of the circuit, the coupling to the plate tank simultaneously decreases (§ 2-11). Hence, a compromise adjustment giving proper loading must be found in practice. Loading also may be varied by changing the coupling between one link winding and its associated tank coil; either tank may be used for this purpose. When the auxiliary tank is properly tuned to compensate for line reactance, the plate tank tuning will be practically the same as with no load; hence, the plate tank condenser need be readjusted only slightly to compensate for the small reactance introduced by the link.

Link coupling also may be used with series and parallel tuning, as shown in Figs. 1011-I and J. The coupling between one link and its associated coil may be made variable, to give the same effect as changing the coupling between the plate tank and antenna coils in the ordinary system. The tuning procedure is the same as described above for series and parallel tuning. In the case of single-ended tank circuits the input link is coupled to the grounded end of the tank coil, as in Fig. 1011-G.

Circuit values — The values of inductance and capacity to use in the antenna coupling system will depend upon the transmitting frequency, but are not particularly critical. With series tuning (Fig. 1011-E, I), the coil may consist of a few turns of the same construction as is used in the final tank; average values will run from one or two turns at very-high frequencies to perhaps 10 or 12 at 1.75 Mc. The number of turns preferably should be adjustable so that the inductance can be changed should it not be possible to reach resonance with the condensers used. The series condensers should have a maximum capacity of 250 or 350 $\mu\mu$fd. at the lower frequencies; the same values will serve even at 28 Mc., although 100 $\mu\mu$fd. will be ample for this and the 14-Mc. band. Still smaller condensers can be used at very-high frequencies. Since series tuning is used at a low-voltage point in the feeder system, the plate spacing of the condensers does not have to be large. Ordinary receiving-type condensers are large enough for plate voltages up to 1000, and the smaller transmitting condensers have high-enough voltage ratings for higher-power applications. In high-power radiotelephone transmitters it may be necessary to use condensers having a plate spacing of approximately 0.15 to 0.2 inch.

In parallel-tuned circuits (F, G, H, J) the antenna coil and condenser should be approximately the same as those used in the final tank circuit. The antenna tank circuit must be capable of being tuned independently to the transmitting frequency, and, if possible, provision should be made for tapping the coil, so that the L/C ratio can be varied to the optimum value (§ 2-11) as determined experimentally.

In Fig. 1011-D, C_1 and C_2 may be 100 to 250 $\mu\mu$fd. each, the higher-capacity values being used for lower-frequency operation (3.5 and 1.75 Mc.). Plate spacing should be, in general, at least half that of the final-amplifier tank condenser. For operation from 1.75 to 14 Mc., L_1 and L_2 each may consist of 15 turns, 2½ inches in diameter, spaced to occupy 3 inches length, and tapped every three turns. Approximate settings are 15 turns for 1.75 Mc., 9 turns for 3.5 Mc., 6 turns for 7 Mc., and 3 turns for 14 Mc. The coils may be wound with No. 14 or No. 12 wire. This method of coupling is very seldom used at very-high frequencies.

Harmonic reduction — It is important to prevent, insofar as possible, harmonics in the output of the transmitter from being transferred to the antenna system. Untuned (Fig. 1011-A) and directly coupled (Figs. 1011-B) systems do not discriminate against harmonics, and hence are more likely to cause harmonic

radiation than the inductively coupled tuned systems. Low-pass filter arrangements, such as those at C and D, Fig. 1011, do discriminate against harmonics, but the direct coupling frequently is a source of trouble in this respect.

In inductively coupled systems, care must be taken to prevent capacity coupling between coils. Link coils always should be coupled at a point of ground potential (§ 2-13) on the plate tank coil, as also should series- and parallel-tuned coils (E and F), when possible. Capacity coupling can be practically eliminated by the use of a Faraday shield (§ 4-9) between the plate tank and antenna coils.

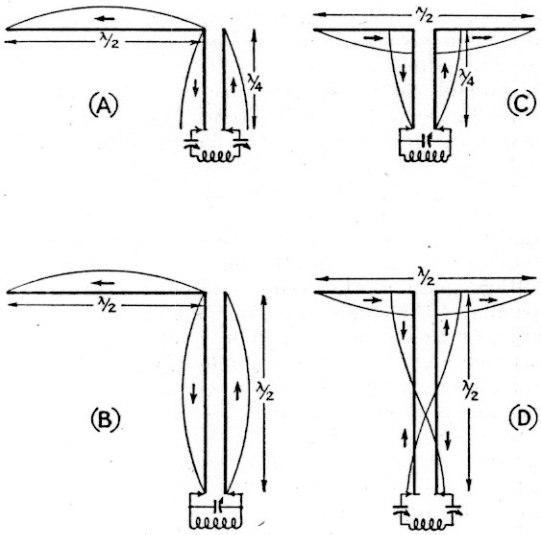


Fig. 1012 — Half-wave antennas fed from resonant lines. A and B are end-feed systems for use with quarter- and half-wave lines; C and D are center-feed systems. The current distribution is shown for all four cases, arrows indicating the instantaneous direction of current flow.

¶ 10-7 Resonant Lines

Two-wire lines — Because of its simplicity of adjustment and flexibility with respect to the frequency range over which an antenna system will operate, the resonant line is widely used with simple antenna systems. Constructionally, the spaced or "open" two-wire line is best suited to resonant operation; rubber-insulated lines, such as twisted pair, have excessive losses when operated with standing waves.

Connection to antenna — A resonant line is usually — in fact, practically always — connected to the antenna at either a current or voltage loop. This is advantageous, especially when the antenna is to be operated at harmonic frequencies, since it simplifies the problem of determining the coupling system to be used at the input end of the line.

Half-wave antenna with resonant line — It is often helpful to look upon the resonant line simply as an antenna folded back on itself. Such a line may be any whole-number multiple of a quarter wave in length; in other words, any total wire length which will accommodate a whole number of standing waves. (The "length" of a two-wire line is, however, always taken as the length of one of the wires.)

Quarter- and half-wave resonant lines feeding half-wave antennas are shown in Fig. 1012. The current distribution on both antenna and line is indicated. It will be noted that the quarter-wave line has maximum current at one end and minimum current at the other, determined by the point of connection to the antenna. The half-wave line, however, has the same current (and voltage) values at both ends.

If a quarter-wave line is connected to the end of an antenna, as shown in Fig. 1012-A, then at the transmitter end of the line the current is high and the voltage low (low impedance), so that series tuning (§ 10–6) can be used. Should the line be a half-wave long, as at 1012-B, current will be minimum and voltage maximum (high impedance) at the transmitter end of the line, just as it is at the end of the antenna. Parallel tuning therefore is required (§ 10-6). The line could be coupled to a balanced final tank through small condensers, as in Fig. 1011-B, but the inductively coupled circuit is preferable. An end-fed antenna with resonant feeders, as in 1011-A and B, is known as the "Zeppelin" or "Zepp" antenna.

The line also may be inserted at the center of the antenna at the maximum-current point. Quarter- and half-wave lines used in this way are shown at Fig. 1012-C and D. In C, the antenna end of the line is at a high-current low-voltage point (§ 10-2); hence, at the transmitter end the current is low and the voltage high. Parallel tuning therefore is used. The half-wave line at D has high current and low voltage at both ends, so that series tuning is used at the transmitter end.

The four arrangements shown in Fig. 1012 are thoroughly useful antenna systems, and are shown in more practical form in Fig. 1013. In each case the antenna is a half wavelength long, the exact length being calculated from Equations 2, 3 or 4 (§ 10-2) or taken from the charts of Fig. 1016. The line length should be an integral multiple of a quarter wavelength and may be calculated from equation 5 (§ 10-5), the result being multiplied by any whole number which gives a total length convenient for reaching from the antenna to the transmitter. If there is an *odd* number of quarter waves on the line in the case of the end-fed antenna, series tuning should be used at the transmitter end; if an *even* number of quarter waves, then parallel tuning should be used. With the center-fed antenna the reverse is true.

Practical line lengths — In general, it is best to use line lengths that are integral multiples of a quarter wavelength. Intermediate lengths will give intermediate impedance values and will show reactance (§ 10-5) as well. The tuning apparatus is capable of compensating for reactance, but it may be difficult to get

suitable transmitter loading because simple series and parallel tuning are suitable for only low and high impedances, respectively, and neither will perform well with impedances of the order of a few hundred ohms. Such values of impedance may reduce the Q of the coupling circuit to a point where adequate coupling cannot be obtained (§ 2-11). However, some departure from the ideal length is possible — even as much as 25 per cent of a quarter wave in many cases — without undue difficulty in tuning and coupling. In such cases the type of tuning to use, whether series or parallel, will depend on whether the feeder length is nearer an odd number of quarter waves or nearer an even number, as well as on the point at which the feeder is connected to the antenna.

Line current — The feeder current as read by the r.f. ammeters is useful for tuning purposes only; the absolute value is of little importance. When series tuning is used the current will be high, but very little current will be indicated in a parallel-tuned system. This is because of the current distribution on the feeders, as shown by Fig. 1012. 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 conclusions 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. Many amateurs, in fact, use flashlight or dial lamps for this purpose, instead of meters. They are inexpensive, 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.

Antenna length and line operation — Insofar as the operation of the antenna itself is concerned, departures of a few per cent from the exact length for resonance are of negligible consequence. Such inaccuracies may influence the behavior of the feeder system, however, and as a result may have an adverse effect on the operation of the system as a whole. This is true particularly of end-fed antennas, such as are shown in Fig. 1013-A and -B.

For example, Fig. 1014-A shows the current distribution on the half-wave antenna and quarter-wave feeder when the antenna length is correct. At the junction of the "live" feeder and the antenna the current is minimum, so that the currents in the two feeder wires are equal at all corresponding points along their length. When the antenna is too long, as in B, the current minimum occurs at a point on the antenna proper, so that at the top of the live feeder there is already appreciable current flowing, whereas at the top of the "dead" feeder the current must be zero. As a result the feeder currents are not balanced, and some power will be radiated from the line. In C, the antenna is too short, bringing the current

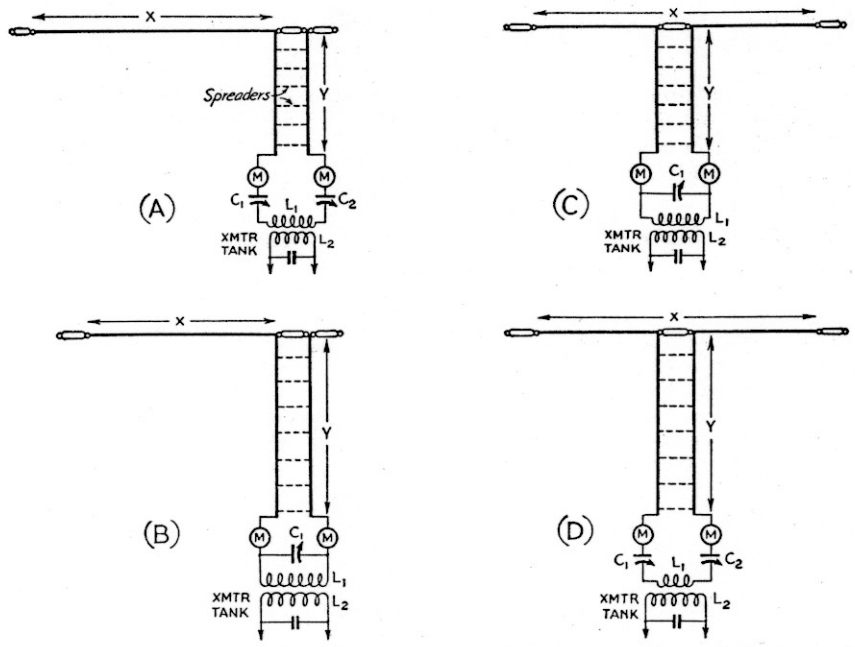


Fig. 1013 — Practical half-wave antenna systems using resonant-line feed. In the center-feed systems, the antenna length, X, does not include the length of the insulator at the center. Line length is measured from the antenna to the tuning apparatus; leads in the latter should be kept short enough so their effect can be neglected. The use of two r.f. ammeters, M, as shown is helpful for balancing feeder currents; however, one meter is sufficient to enable tuning for maximum output, and may be transferred from one feeder to the other, if desired. The systems at (A) and (C) are for feeders an odd number of quarter waves in length; (B) and (D) are for feeders a multiple of a half wavelength. The drawings correspond electrically to the half-wave antenna systems shown in Fig. 1012.

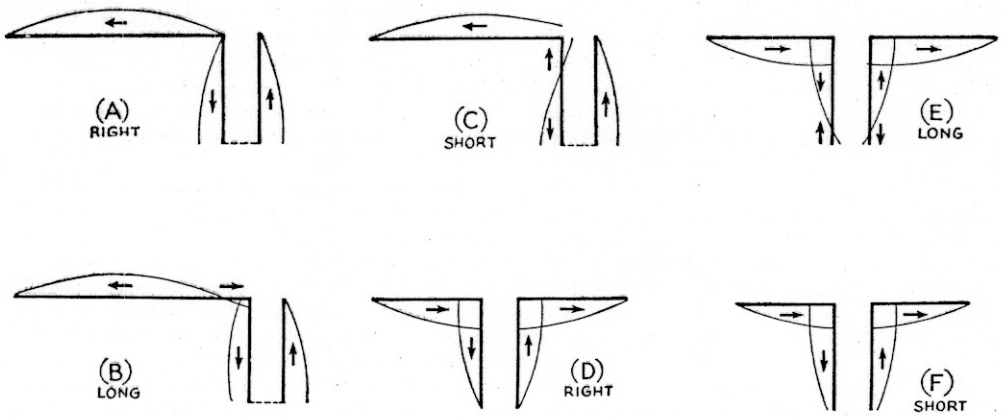


Fig. 1014 — Illustrating the effect on feeder balance of incorrect antenna length for various types of antenna systems. In end-feed systems, the current minimum shifts above or below the feeder junction, unbalancing the line. With center feed out, incorrect antenna length does not unbalance the transmission line, as it does with end feed.

minimum to a point on the live feeder, so that again the currents are unbalanced. The more serious the unbalance, the greater the radiation from the line.

Strictly speaking, a line having an unbalanced connection, such as the one-way termination at the end of an antenna, cannot be truly balanced even though the antenna length is correct. This is because of the difference in loading on the two sides. The effect of this difference is fairly small when the currents are balanced, however.

If the antenna is fed at the center the undesirable effects of incorrect antenna length balance out, so that the line operates properly under all conditions. This is shown in Fig. 1014 at D, E and F. So long as the two halves of the antenna are of equal length the distribution of current on the feeders will be symmetrical, so that no unbalance exists even for antenna lengths considerably removed from the correct value.

¶ 10-8 Non-Resonant Lines

Requirements — The advantages of non-resonant transmission lines — minimum losses, and elimination of the necessity for tuning — make this type of operation attractive. The chief disadvantage of the non-resonant line, aside from the necessity for more care in initial adjustment, is that when "matched" to the ordinary antenna the match is perfect only for one frequency, or at most for a small band of frequencies on either side of the frequency for which the matching is done. Except for a few special systems, this means that the antenna is unsuitable for work on more than one amateur band.

Adjustment of a non-resonant line is simply a process of adjusting the terminating resistance to match the characteristic impedance of the line. To accomplish this the antenna itself must be resonant at the selected frequency, and the line must then be connected to it in such a way that the antenna impedance as looked at by the line is the right value. The matching may be done by connecting the line at the proper spot along the antenna, by inserting an impedance-transforming device between the antenna and line, or by using a line having an impedance equal to the center impedance of the antenna.

In the following discussion of ways in which different types of lines may be matched to the antenna, a half-wave antenna is used as an example. Other types of antennas may be treated by the same methods, making due allowance for the order of impedance that appears at the end of the line when more elaborate systems are used.

Single-wire feed — In the single-wire-feed system, the return circuit is through the ground. There will be no standing waves on the feeder when its characteristic impedance is matched by the impedance of the antenna at the connection point. The principal dimensions (Fig. 1015) are the length of the antenna, *L*, and the distance, *D*, from the exact center of the antenna to the point at which the feeder is attached. Approximate dimensions can be obtained from Fig. 1016 for an antenna system having a fundamental frequency in any of the most-used amateur bands.

In constructing an antenna system of this type, the feeder must run straight away from the antenna (at a right angle) for a distance of at least one-third the length of the antenna. Otherwise the field of the antenna will affect the feeder and cause faulty operation. There

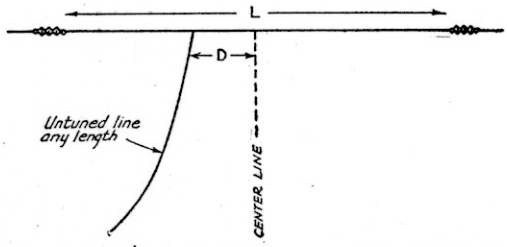


Fig. 1015 — Single-wire-feed system. The length, *L*, (one-half wavelength) and the feeder location, *D*, for various bands are determined from the charts of Fig. 1016.

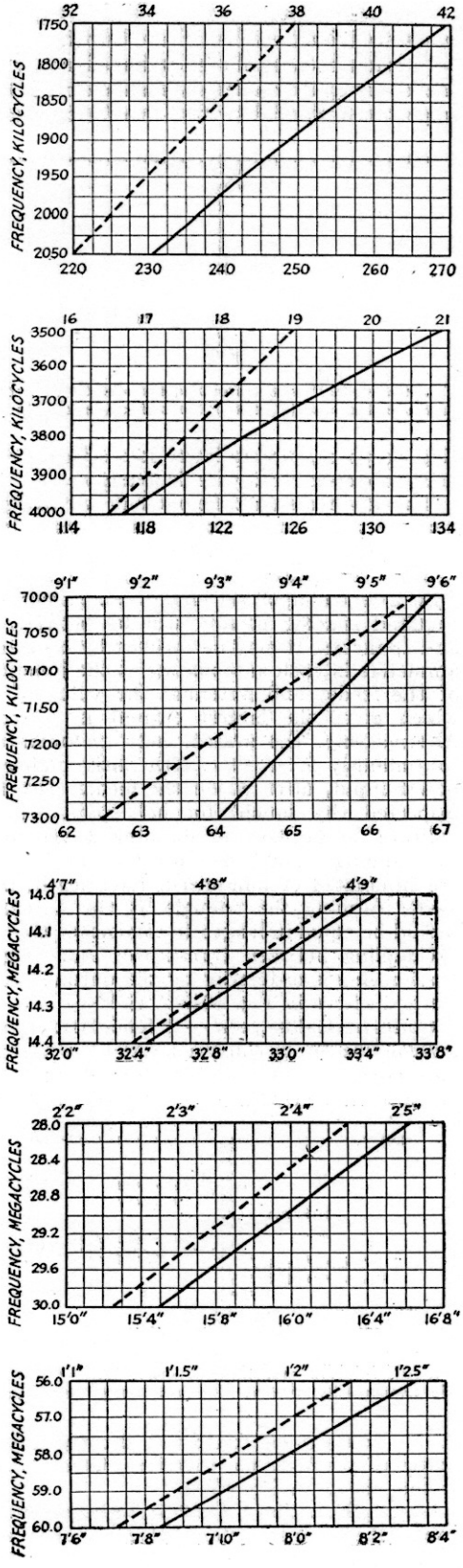


Fig. 1016 — Charts for determining the length of half-wave antennas for use on various amateur frequencies. Solid lines indicate antenna length in feet (lower scale); dotted lines indicate the point of connection for a single-wire feeder (upper scale) measured from center of antenna.

should be no sharp bends in the feeder wire at any point.

With the coupling system shown in Fig. 1017-A, the process of adjustment is as follows: Starting at the ground end of the tank coil, the tap is moved towards the plate end until the amplifier draws the rated plate current. The plate tank condenser should be readjusted each time the tap is changed, to bring the plate current back to minimum. The amplifier is loaded properly when this "minimum" value is the rated current. The condenser, *C*, in the feeder is for the purpose of insulating the antenna system from the high-voltage plate supply when series plate feed is used. It should have a voltage rating somewhat higher than that of the plate supply. Almost any capacity greater than 500 $\mu\mu$fd. will be satisfactory. The condenser is unnecessary, of course, if parallel plate feed is used.

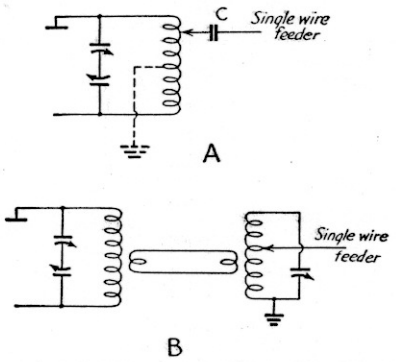


Fig. 1017 — Methods of coupling the feeder to the transmitter in a single-wire-feed system. Circuits are shown for both single-ended and balanced tank circuits.

Inductive coupling to the output circuit is shown in Fig. 1017-B. The antenna tank circuit should tune to resonance at the operating frequency, and the loading is adjusted by varying the coupling between the two tanks, both being kept tuned to resonance.

Regardless of the type of coupling, a good ground connection is essential with this system. Single-wire feed works best over moist ground, and poorly over rock and sand.

Twisted-pair feed — A two-wire line composed of twisted rubber-covered wires can be constructed to have a surge impedance approximately equal to the 70-ohm impedance at the center of the antenna itself, thus permitting connecting the line to the antenna as shown in Fig. 1018. Any discrepancy which 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 shown at *B* in Fig. 1018.

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 the quality of insulation a matter of less importance. Special twisted line for transmitting purposes, having lower losses than ordinary rubber-covered wire, is available.

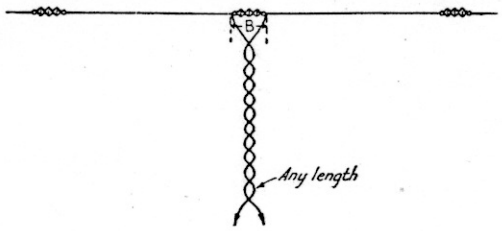


Fig. 1018 — Half-wave antenna center-fed by a twisted-pair line. Fanning (*B*) compensates for line impedance.

The antenna should be one-half wavelength long for the frequency of operation, as determined by charts of Fig. 1016 or the formulas (§ 10-2). The amount of "fanning" (dimension *B*) will depend upon the kind of cable used; the required spacing usually will be between 6 and 18 inches. It may be checked by inserting ammeters in each antenna leg at the junction of the feeder and antenna; the value of *B* which gives the largest current is correct. Alternatively, the system may be operated continuously for a time with fairly high r.f. power input, after which the feeder may be inspected (by touch) for hot spots. These indicate the presence of standing waves, and the fanning should be adjusted until they are eliminated or minimized. Each leg of the feeder forming the triangle at the antenna should be equal in length to dimension *B*.

Coupling between transmitter and transmission line is ordinarily by the untuned coil method shown in Fig. 1011-A (§ 10-6).

Concentric-line feed — A concentric transmission line can be constructed to have a surge impedance exactly equal to the 70-ohm impedance at the center of a half-wave antenna.

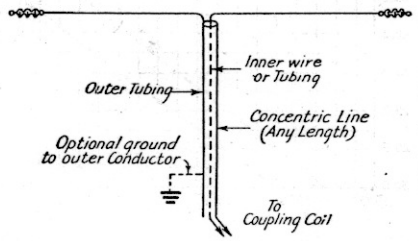


Fig. 1019 — Half-wave antenna center-fed by a concentric transmission line of 70 ohms surge impedance.

Such a line can be connected directly to the center of the antenna, therefore, forming the system shown in Fig. 1019.

Solving Equation 6 (§ 10-5) for an air-insulated concentric line shows that, to obtain a 70-ohm surge impedance, the inside diameter of the outer conductor should be approximately 3.2 times the outside diameter of the inner conductor. This condition can be fulfilled by using standard 5/16-inch (outside diameter) copper tubing for the outer conductor and No. 14 wire for the inner. Ceramic insulating spacers are available commercially for this combination. Rubber-insulated concentric line having the requisite impedance for connection to the center of the antenna also is available.

The operation of such an antenna system is similar to that of the twisted-pair system just described, and the same transmitter coupling arrangements may be used (§ 10-6).

The outer conductor of the line may be grounded, if desired. The feeder system is slightly unbalanced, because the inner and outer conductors do not have the same capacity to ground. There should be no radiation from a line having a correct surge impedance, however.

Delta matching transformer — Because of the extremely close spacing required, it is impracticable to construct an open-wire transmission line which will have a surge impedance low enough to work directly into the center of a half-wave antenna. Such wire lines usually have impedances between 400 and 700 ohms, 600 ohms being a widely used value. It is necessary, therefore, to use other means for matching the line to the antenna.

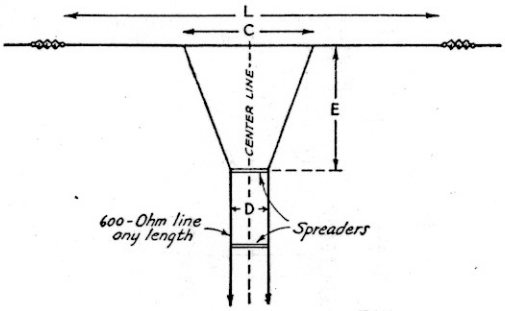


Fig. 1020 — Delta-matched antenna system. The dimensions *C*, *D*, and *E* are found by formulas given in the text. It is important that the matching section, *E*, come straight away from the antenna without any bends.

One method of matching is illustrated by the system shown in Fig. 1020. The matching section, *E*, is "fanned" to have a gradually increasing impedance so that its impedance at the antenna end will be equal to the impedance of the antenna section, *C*, while the impedance at the lower end matches that of a practicable transmission line.

The antenna length, *L*, the feeder clearance, *E*, the spacing between centers of the feeder wires, *D*, and the coupling length, *C*, are the important dimensions of this system. The system must be designed for exact impedance values as well as frequency values, and the dimensions therefore are fairly critical.

The length of the antenna is figured from the formula (§ 10-2) or taken from Fig. 1016.

The length of section C is computed by the formula:

$$C\ (feet) = \frac{148}{Freq.\ (Mc.)}$$

The feeder clearance, E, is found from the equation:

$$E\ (feet) = \frac{123}{Freq.\ (Mc.)}$$

The above equations are for feeders having a characteristic impedance of 600 ohms and will not apply to feeders of any other impedance. The proper feeder spacing for a 600-ohm transmission line is computed to a sufficiently close approximation by the following formula:

$$D = 75 \times d$$

where D is the distance between the centers of the feeder wires and d is the diameter of the wire. If the wire diameter is in inches the spacing also will be in inches, and if the wire diameter is in millimeters the spacing also will be in millimeters.

Methods of coupling to the transmitter are discussed in § 10-6, those shown in Figs. 1011-C, D, G and H being suitable.

"Q"-section transformer — The impedance of a two-wire line of ordinary construction (400 to 600 ohms) can be matched to the impedance of the center of a half-wave antenna by utilizing the impedance-transforming properties of a quarter-wave line (§ 10-5). The matching section must have low surge impedance and therefore is commonly constructed of large-diameter conductors such as aluminum or copper tubing, with fairly close spacing. This system is known as the "Q" antenna. It is shown in Fig. 1021. The important dimensions are the length of the antenna, the length of the matching section, B, 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.

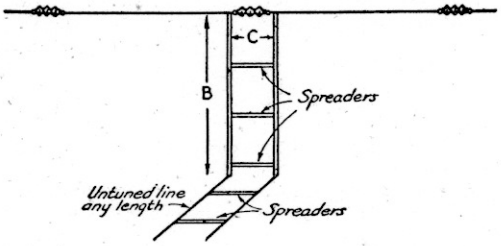


Fig. 1021 — The "Q" antenna, using a quarter-wave impedance-matching section with close-spaced conductors.

The required surge impedance for the matching section is

$$Z_s = \sqrt{Z_1 Z_2} \qquad (9)$$

where Z_1 is the input impedance and Z_2 the output impedance. Thus a quarter-wave section matching a 600-ohm line to the center of a half-wave antenna (72 ohms) 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 Fig. 1009. With ½-inch tubing, the spacing should be 1.5 inches for an impedance of 208 ohms.

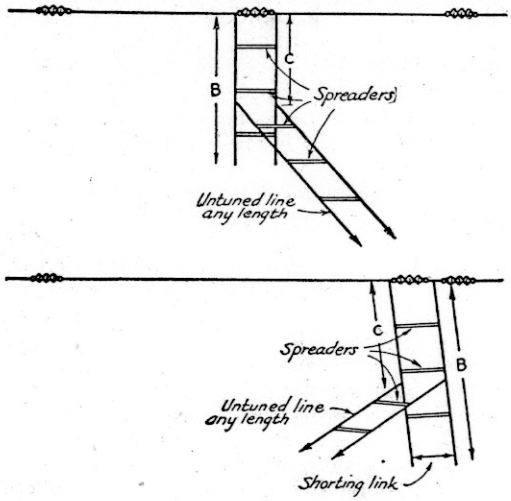


Fig. 1022 — Half-wave antenna systems with quarter-wave open-wire linear impedance-matching transformers.

The length of the matching section, B, should be equal to a quarter wavelength, and is given by

$$Length\ of\ quarter\text{-}wave\ line\ (feet) = \frac{234}{Freq.\ (Mc.)}$$

The length of the antenna can be calculated from the formula (§ 10-2), or taken from the charts of Fig. 1015.

This system has the advantage of the simplicity of adjustment of the twisted-pair feeder system and at the same time the superior insulation of an open-wire system. Figs. 1011-B, D, G and H (§ 10-6) represent suitable methods of coupling to the transmitter.

Linear transformers — Fig. 1022 shows two methods of coupling a non-resonant line to a half-wave antenna through a quarter-wave linear transformer (§ 10-5) or matching section. In the case of the center-fed antenna, the free end of the matching section, B, is open (high impedance), since the other end is connected to a low-impedance point on the antenna. With the end-fed antenna, the free end of the matching section is closed through a shorting bar or link; this end of the section has low impedance, since the other end is connected to a high-impedance point on the antenna (§ 10-7).

In the center-fed system, the antenna and matching section should be cut to lengths found from the equations in § 10-2 and § 10-5. Any necessary on-the-ground adjustment can be made by adding to or clipping off the open ends of the matching section. The matching

section in the end-fed system can be adjusted by making the line a little longer than necessary and adjusting the system to resonance by moving the shorting link up and down. Resonance can be obtained by exciting the antenna at the proper frequency from a temporary antenna near by and measuring the current in the shorting bar by a low-range r.f. ammeter or galvanometer. The position of the bar should be adjusted for maximum current reading. This should be done before the transmission line is attached to the matching section.

The position of the line taps must be determined experimentally, since it will depend upon the impedance of the line as well as on the antenna impedance at the point of connection. The procedure is to take a trial point, apply power to the transmitter, and check the transmission line for standing waves. This can be done by measuring the current in the wires, using a device of the type pictured in Fig. 1023. The hooks (which should be sharp enough to cut through the insulation, if any, on the wires) are placed on one of the wires, the spacing between them being adjusted to give a suitable reading on the meter. At any one position along the line the currents in the two wires should be identical. Readings taken at intervals of a quarter wavelength will indicate whether or not standing waves are present.

It will not usually be possible to obtain complete elimination of standing waves when the matching stub is exactly resonant. The line taps should be adjusted for the smallest obtainable standing-wave ratio. Then a further "touching up" of the matching-stub tuning will eliminate the remaining standing wave, provided the adjustments are carefully made. The stub must be readjusted, because when resonant it exhibits some reactance as well as resistance at all points except at the ends, and the slight lengthening or shortening of the stub is necessary to tune out this reactance. The required readjustment will be quite small, however.

When the connection between the matching section and the antenna is unbalanced, as in the end-fed system, it is important that the antenna be the right length for the operating frequency if a good match is to be obtained

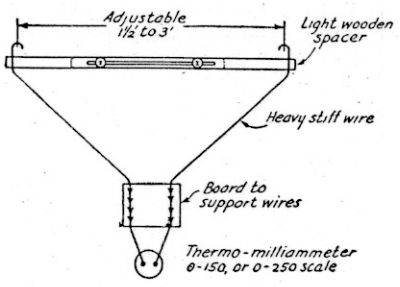


Fig. 1023 — Line-current measuring device for checking standing waves in adjusting untuned transmission lines.

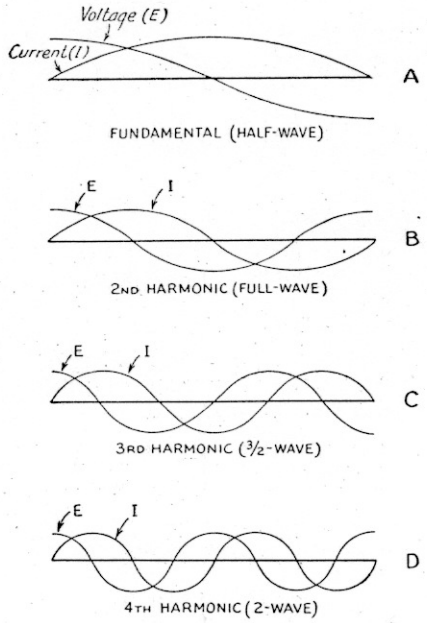


Fig. 1024 — Standing-wave current and voltage distribution along an antenna when it is operated at various harmonics of its fundamental resonant frequency.

(§ 10-7). The balanced center-fed system is less critical in this respect. The shorting-bar method of tuning the center-fed system to resonance may be used if the matching section is extended to a half wavelength, bringing a current loop at the free end.

An impedance mismatch of several per cent is of little consequence so far as power transfer to the antenna is concerned. It is relatively easy to get the standing-wave ratio down to 2 or 3 to 1, a perfectly satisfactory condition in practice. Of considerably greater importance is the necessity for getting the currents in the two wires balanced, both as to amplitude and phase. If the currents are not the same at corresponding points on adjacent wires and the loops and nodes do not also occur at corresponding points, there will be considerable radiation loss. Perfect balance can be brought about only by perfect symmetry in the line, particularly with respect to ground. This symmetry should extend to the coupling apparatus at the transmitter. An electrostatic shield between the line and the transmitter coupling coils often will be of value in preventing capacity unbalance, and at the same time will reduce harmonic radiation.

10-9 Long-Wire Antennas

Definition — An antenna will be resonant so long as an integral number of standing waves of current and voltage can exist along its length; in other words, so long as its length is some integral multiple of a half wavelength. When the antenna is more than a half-wave long it usually is called a long-wire antenna, or a harmonic antenna.

Current and voltage distribution — Fig. 1024 shows the current and voltage distribution along a wire operating at its fundamental frequency (where its length is equal to a half wavelength) and at its second, third and fourth harmonics. For example, if the fundamental frequency of the antenna is 7 Mc., the current and voltage distribution will be as shown at A. The same antenna excited at 14 Mc. would have current and voltage distribution as shown at B. At 21 Mc., the third harmonic of 7 Mc., the current and voltage distribution would be as in C; and at 28 Mc., the fourth harmonic, as in D. The number of the harmonic is the number of half waves contained in the antenna at the particular operating frequency.

The polarity of current or voltage in each standing wave is opposite to that in the adjacent standing waves. This is shown in the figure by drawing the current and voltage curves successively above and below the antenna (taken as a zero reference line), to indicate that the polarity reverses when the current or voltage goes through zero. Currents flowing in the same direction are *in phase;* in opposite directions, *out of phase.*

It is evident that one antenna may be used for harmonically related frequencies, such as the various amateur bands. The long-wire or harmonic antenna is the basis of multi-band operation with one antenna.

Physical lengths — The length of a long-wire antenna is not an exact multiple of that of a half-wave antenna because the end effects (§ 10-2) 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. The formula for the length of a long-wire antenna, therefore, is

$$Length\ (feet) = \frac{492\ (N-0.05)}{Freq.\ (Mc.)} \qquad (10)$$

where N is the number of *half* waves on the antenna. From this, it is apparent that an antenna cut as a half wave for a given frequency will be slightly off resonance at exactly twice that frequency (on the second harmonic) because of the different behavior of end effects when there is more than one standing wave on the antenna. For instance, if the antenna is cut to exact fundamental resonance on the second harmonic (full wave) it should be 2.6 per cent longer, and on the fourth harmonic (two wave), 4 per cent longer. The effect is not very important except for a possible unbalance in the feeder system (§ 10-7), which may result in some radiation from the feeder in end-fed systems.

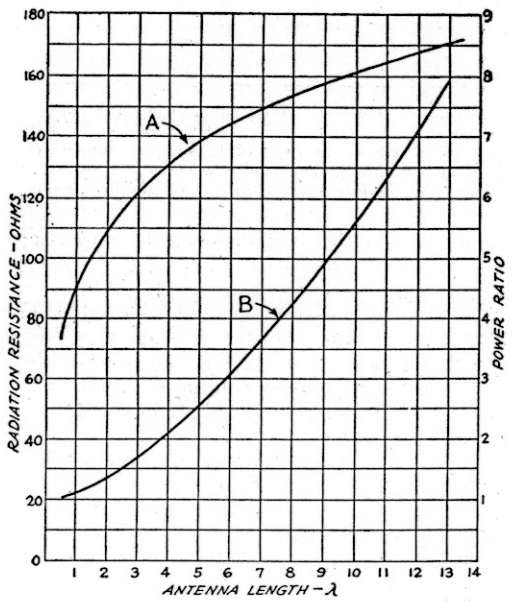


Fig. 1025 — Curve A shows variation in radiation resistance with antenna length. Curve B shows power in lobes of maximum radiation for long-wire antennas as a ratio to the maximum radiation for a half-wave antenna.

Impedance and power gain — The radiation resistance as measured at a current loop becomes larger as the antenna length is increased. Also, a long-wire antenna radiates more power in its most favorable direction than does a half-wave antenna in its most favorable direction. This power gain is secured at the expense of radiation in other directions. Fig. 1025 shows how the radiation resistance and the power in the lobe of maximum radiation vary with the antenna length.

Directional characteristics — As the wire is made longer in terms of the number of half wavelengths, the directional effects change. Instead of the "doughnut" pattern of the half-wave antenna, the directional characteristic splits up into "lobes" which make various angles with the wire. In general, as the length of the wire is increased the direction in which maximum radiation occurs tends to approach the line of the antenna itself.

Directional characteristics for antennas one wavelength, three half-wavelengths, and two wavelengths long are given in Figs. 1026, 1027 and 1028, for three vertical angles of radiation. Note that, as the wire length increases, the radiation along the line of the antenna becomes more pronounced. Still longer antennas can be considered to be practically "end-on" radiators, even at the lower radiation angles.

Methods of feeding — In a long-wire antenna, the currents in adjacent half-wave sections must be out of phase, as shown in Fig. 1029 and Fig. 1024. The feeder system must not upset this phase relationship. This requirement is met by feeding the antenna at either end or at any current *loop.* A two-wire feeder cannot be inserted at a current *node,* however, because 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 necessarily would have to be in phase and the feeder radiation would not be canceled out.

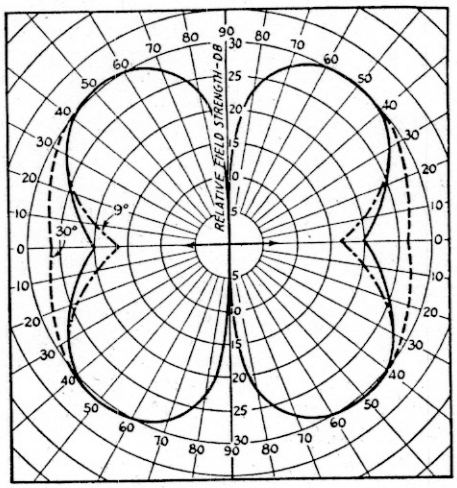


Fig. 1026 — Horizontal patterns of radiation from a full-wave antenna. The solid line shows the pattern for a vertical angle of 15 degrees; dotted lines show deviation from the 15-degree pattern at 9 and 30 degrees. All three patterns are drawn to the same relative scale; actual amplitudes will depend upon the height of the antenna.

Either resonant or non-resonant feeders may be used. With the latter, the systems employing a matching section (§ 10-8) are best. The non-resonant line may be tapped on the matching section, as in Fig. 1022, or a "Q" type section, Fig. 1021, may be employed. In such case, Fig. 1030 gives the required surge impedance for the matching section. It can also be calculated from Equation 9 (§ 10-8) and the radiation resistance data in Fig. 1025.

Methods of coupling the line to the transmitter are the same as described in § 10-6 for the particular type of line used.

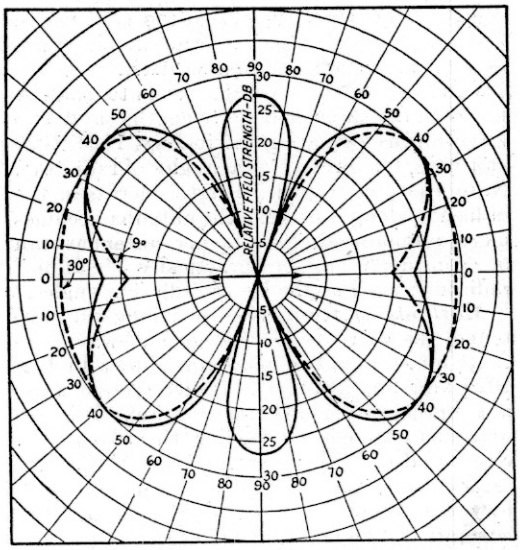


Fig. 1027 — Horizontal patterns of radiation from an antenna three half-waves long. The solid line shows the pattern for a vertical angle of 15 degrees; dotted lines show deviation from the 15-degree pattern at 9 and 30 degrees. Minor lobes coincide for all three angles.

¶ 10-10 Multi-Band Antennas

Principles — As suggested in the preceding section, the same antenna may be used for several bands by operating it on harmonics. When this is done it is necessary to use resonant feeders, since the impedance matching for non-resonant feeder operation can be accomplished only at one frequency unless means are provided for changing the length of a matching section and shifting the point at which the feeder is attached to it. A matching section which is a quarter wavelength long at one frequency will be a half wavelength long at twice that frequency, and so on; and changing the length of the wires, even by switching, is so inconvenient as to be impracticable.

Also, the current loops shift to a new position on the antenna when it is operated on harmonics, further complicating the feed situation. It is for this reason that half-wave antennas center-fed by rubber-insulated lines are practically useless for harmonic operation; on all even harmonics there is a voltage maximum at the feed point, and the impedance mismatch is so bad that there is a large standing-wave ratio and consequently high losses in the rubber dielectric.

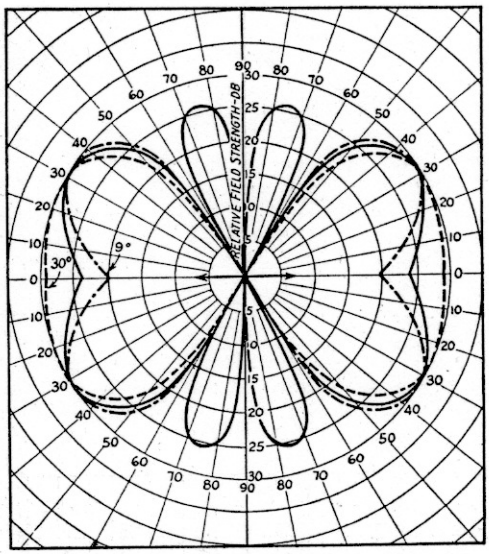


Fig. 1028 — Horizontal patterns of radiation from an antenna two wavelengths long. The solid line shows the pattern for a vertical angle of 15 degrees; dotted lines show deviation from the 15-degree pattern at 9 and 30 degrees. The minor lobes coincide for all three angles.

When the same antenna is used for work in several bands, it must be realized that the directional characteristic will depend on the band in use.

Simple systems — Any of the antenna arrangements shown in § 10-7 may be used for multi-band operation by making the antenna a half wave long at the lowest frequency to be used. The feeders should be a quarter wave, or some multiple of a quarter wave, long at the

TABLE I

MULTI-BAND RESONANT-LINE-FED ANTENNAS

Antenna Length (ft.)	*Feeder Length (ft.)*	*Band*	*Type of Tuning*
With end feed: 243	120	1.75-Mc. 'phone	series
		4-Mc. 'phone	parallel
		14 Mc.	parallel
		28 Mc.	parallel
136	67	3.5-Mc. c.w.	series
		7 Mc.	parallel
		14 Mc.	parallel
		28 Mc.	parallel
134	67	3.5-Mc. c.w.	series
		7 Mc.	parallel
67	33	7 Mc.	series
		14 Mc.	parallel
		28 Mc.	parallel
With center feed: 272	135	1.75 Mc.	parallel
		3.5 Mc.	parallel
		7 Mc.	parallel
		14 Mc.	parallel
		28 Mc.	parallel
137	67	3.5 Mc.	parallel
		7 Mc.	parallel
		14 Mc.	parallel
		28 Mc.	parallel
67.5	34	7 Mc.	parallel
		14 Mc.	parallel
		28 Mc.	parallel

The antenna lengths given represent compromises for harmonic operation because of different end effects on different bands. The 136-foot end-fed antenna is slightly long for 3.5 Mc., but will work well in the region which quadruples into the 14-Mc. band (3500–3600 kc.). Bands not listed are not recommended for the particular antenna. The center-fed systems are less critical as to length; the 272-foot antenna, for instance, may be used for both c.w. and 'phone on either 1.75 or 4 Mc. without loss of efficiency.

On harmonics, the end-fed and center-fed antennas will not have the same directional characteristics, as explained in the text.

same frequency. Typical examples, together with the type of tuning to be used, are given in Table I. The figures given represent a compromise designed to give satisfactory operation on all the bands considered, taking into account the change in required length as the order of the harmonic goes up.

A center-fed half-wave antenna will not operate as a long wire on harmonics, because of the phase reversal at the feeders previously mentioned (§ 10-9). On the second harmonic the two antenna sections are each a half wave long, and, since the currents are in phase, the directional characteristic is different from that of a full-wave antenna even though the over-all

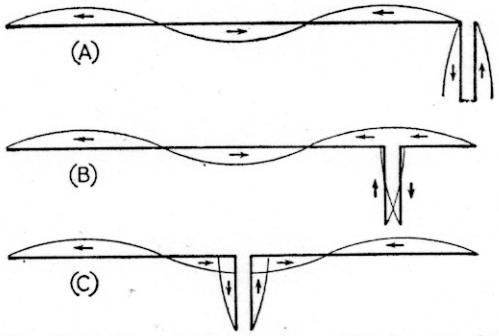
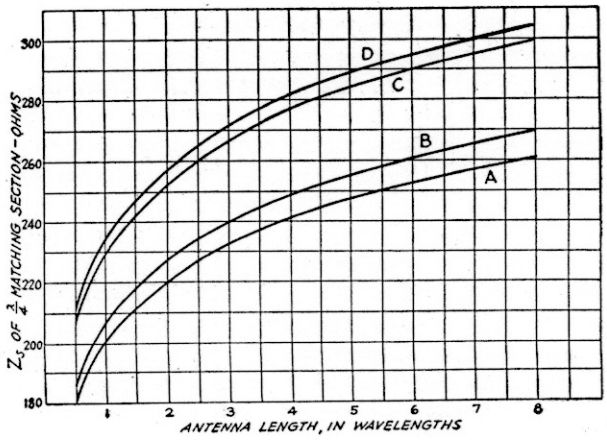


Fig. 1029 — Current distribution and feed points for long-wire antennas. A 3/2-wave antenna is used as an illustration. With two-wire feed, the line may be connected at the end of the antenna or at any current *loop* (but not at a current node) for harmonic operation.

length is the same. On the fourth harmonic each section is a full wave long, and, again because of the direction of current flow, the system will not operate as a two-wavelength antenna. It should not be assumed that these systems are not effective radiators; it simply means that the directional characteristic will not be that of a long wire having the same over-all length. Rather, it will resemble the characteristic of one side of the antenna, although not necessarily having the same exact form.

Antennas with a few other types of feed systems may be operated on harmonics for the higher-frequency bands, although their performance is somewhat impaired. The single-wire-fed antenna (§ 10-8) may be used in this way; the feeder and antenna will not be matched exactly on harmonics, with the result that standing waves will appear on the feeder, but the system as a whole will radiate. A better match will be obtained if the point of connection of the feeder to the antenna is made exactly one-third the antenna length from one

Fig. 1030 — Required surge impedance of quarter-wave matching sections for radiators of various lengths. Curve A is for a transmission-line impedance of 440 ohms, Curve B is for 470 ohms, Curve C for 580 ohms and Curve D for 600 ohms. Dimensions for matching sections of the required impedance are obtained from Fig. 1009.



end. While this disagrees slightly with the figures given for a half-wave antenna, it has been found to work better on the harmonic frequencies. The "Q" antenna (§ 10-8) also can be operated on harmonics, but the line cannot

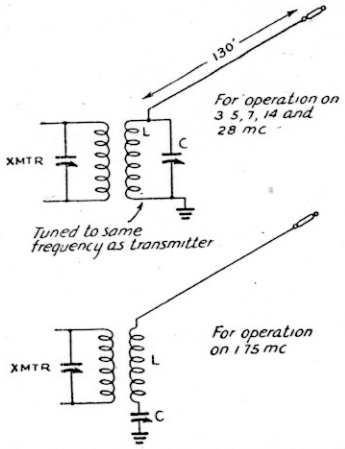


Fig. 1031 — A simple antenna system for five amateur bands. The antenna is voltage fed on 3.5, 7, 14 and 28 Mc., working on the fundamental, second, fourth and eighth harmonics, respectively. For 1.75 Mc. the system is a quarter-wave grounded antenna, in which case series tuning must be used. The antenna wire should be kept well in the clear and should be as high as possible. If the length of the antenna is increased to approximately 260 feet, voltage feed can be used on all five bands.

operate as a non-resonant line except at the fundamental frequency of the antenna. For harmonic operation the line must be tuned, and therefore the feeder length is important. The tuning system will depend upon the number of quarter waves on the line, including the "Q" bars. The concentric-line-fed antenna (§ 10-8) may be used on harmonics, if the concentric line is air-insulated. Its operation on harmonics is similar to that of the "Q." This antenna is not recommended for multi-band operation with a rubber-insulated line, however.

The delta-match system (§ 10-8) can be used on harmonics, although some standing waves will appear on the line. *Any* system can be used on harmonic frequencies by tying the feeders together at the transmitter end and feeding the system as a single wire by means of a tuned circuit coupled to the transmitter.

A simple antenna system, without feeders, for operation on five bands is shown in Fig. 1031. On all bands from 3.5 Mc. upward it operates as an end-fed antenna — half wave on 3.5 Mc., long wire on the other bands. On 1.75 Mc. it is only a quarter wave in length, and must be worked against ground (§ 10-14). On this band, since it is fed at a high-current point, series tuning (§ 10-6) must be used.

Antennas for restricted space — If the space available for the antenna is not large enough to accommodate the length necessary for a half wave at the lowest frequency to be used, quite satisfactory operation can be secured by using a shorter antenna and making up the missing length in the feeder system. The antenna itself may be as short as a quarter wavelength and still radiate fairly well, although of course it will not be as effective as one a half wave long. Nevertheless, such a system is useful where operation on the desired band otherwise would be impossible.

Resonant feeders are a practical necessity with such an antenna system, and a center-fed antenna will give best all-around performance. With end feed the feeder currents become badly unbalanced, and, since lengths midway between those requiring series or parallel tuning ordinarily must be used to bring the entire system to resonance, coupling to the transmitter often becomes difficult.

With center feed practically any convenient length of antenna can be used, if the feeder length is adjusted to accommodate at least one half wave around the whole system. Typical cases are shown in Fig. 1032, one for an antenna having a length of one quarter wave (A) and the other for an antenna somewhat longer (C) but still not a half wave long. Current distribution is shown for both fundamental and second harmonic. From the points marked *X*, resonant feeders any convenient number of quarter waves in length may be extended to the operating room. The sum of the distances on each wire from *X* to the antenna end must equal a half wave. It is sufficiently accurate to use Equation 2 (§ 10-2) in calculating this length. Note that *X*-*X* is a high-current point on these shortened antennas, corresponding to the center of a half-wave antenna. It is also apparent that the antenna

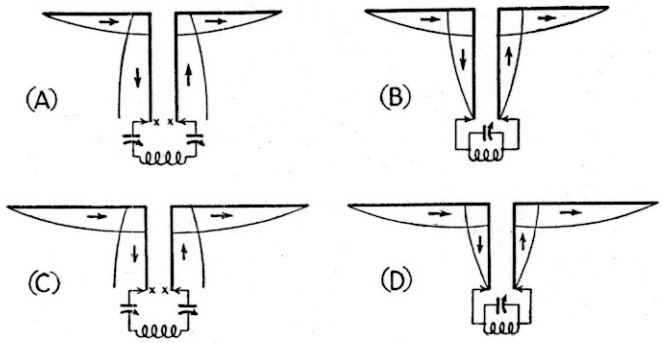


Fig. 1032 — Current distribution on short antennas. Those at the left are too short for fundamental operation, one (A) having an over-all length of one quarter wave; the other (C) being longer but not a half wave long. These systems may be used wherever space to erect a full half-wave antenna is not available. The current distribution for second-harmonic operation is shown at the right of each figure (B and D). In A and C, the total length around the system is a half wavelength at the fundamental frequency. In B and D, the over-all length is a full wave. Arrows show the instantaneous direction of current flow.

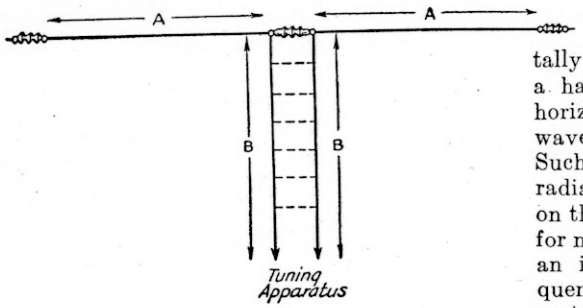


Fig. 1033 — Practical arrangement of a shortened antenna. The total length, A + B + B + A, should be a half wavelength for the lowest-frequency band, usually 3.5. Mc. See Table II for lengths and tuning data.

at A is a half-wave antenna on the next higher-frequency band (B).

A practical antenna of this type can be made as shown in Fig. 1033. Table II gives a few recommended lengths. Remembering the preceding discussion, however, the antenna can be made any convenient length, provided the feeder is considered to "begin" at *X*-*X* and the line length is adjusted accordingly.

Bent antennas — Since the field strength at a distance is proportional to the current in the antenna, the high-current part of a half-wave antenna (the center quarter wave, approximately) does most of the radiating (§ 10-1). Advantage can be taken of this fact when the space available does not permit erecting an antenna a half-wave long. In this case the ends may be bent, either horizontally or vertically, so that the total length equals a half wave, even though the straightaway horizontal length may be as short as a quarter wave. The operation is illustrated in Fig. 1034. Such an antenna will be a somewhat better radiator than the arrangement of Fig. 1032-A on the lowest frequency, but is not as desirable for multi-band operation because the ends play an increasingly important part as the frequency is raised. The performance of the system in such a case is difficult to predict, especially if the ends are vertical (the most convenient arrangement), because of the combination of horizontal and vertical polarization as well as dissimilar directional characteristics.

TABLE II

ANTENNA AND FEEDER LENGTHS FOR SHORT MULTI-BAND ANTENNAS, CENTER-FED

Antenna length (ft.)	*Feeder length (ft.)*	*Band*	*Type of tuning*
137	68	1.75 Mc. 3.5 Mc. 7 Mc. 14 Mc. 28 Mc.	series parallel parallel parallel parallel
100	38	3.5 Mc. 7 Mc. 14 Mc. 28 Mc.	parallel series series series or parallel
67.5	34	3.5 Mc. 7 Mc. 14 Mc. 28 Mc.	series parallel parallel parallel
50	43	7 Mc. 14 Mc. 28 Mc.	parallel parallel parallel
33	51	7 Mc. 14 Mc. 28 Mc.	parallel parallel parallel
33	31	7 Mc. 14 Mc. 28 Mc.	parallel series parallel

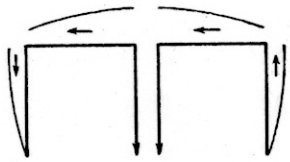


Fig. 1034 — Folded arrangement for shortened antennas. The total length is a half wave, not including the feeders. The horizontal part is made as long as convenient and the ends dropped down to make up the required length. The ends may be bent back on themselves like feeders to cancel radiation partially. The horizontal section should be at least a quarter-wave long.

¶ 10-11 Long-Wire Directive Arrays

The "V" antenna — It has been emphasized that, as the antenna length is increased, the lobe of maximum radiation makes a more acute angle with the wire (§ 10-9). Two such wires may be combined in the form of a horizontal "V" so that the main lobes from each wire will reinforce along a line bisecting the angle between the wires. This increases both gain and directivity, since the lobes in directions other than along the bisector cancel to a greater or lesser extent. The horizontal "V" antenna therefore transmits best in either direction (is bi-directional) along a line bisecting the "V" made by the two wires. The power gain depends upon the length of the wires. Provided the necessary space is available, the "V" is a simple antenna to build and operate. It can also be used on harmonics, so that it is suitable for multi-band work. The "V" antenna is shown in Fig. 1035.

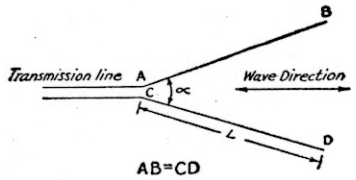


Fig. 1035 — The "V" antenna, made by combining two long wires in such a way that each reinforces the radiation from the other. The important quantities are the length of each leg and the angle between the legs.

Fig. 1036 shows the dimensions that should be followed for an optimum design to obtain maximum power gain for different-sized "V" antennas. The longer systems give good performance in multi-band operation. Angle α is approximately equal to twice the angle of maximum radiation for a single wire equal in length to one side of the "V."

The wave angle referred to in Fig. 1036 is the vertical angle of maximum radiation (§ 10-1). 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.

The gain increases with the length of the wires, but is not exactly twice the gain for a single long wire as given in Fig. 1025. In the longer lengths the gain will be somewhat increased, because of mutual coupling between the wires. A "V" eight wavelengths on a leg, for instance, will have a gain of about 12 db. over a half-wave antenna, whereas twice the gain of a single 8-wavelength wire would be only approximately 9 db.

The two wires of the "V" must be fed out of phase, for correct operation. A resonant line may simply be attached to the ends, as shown in Fig. 1035. Alternatively, a quarter-wave matching section may be employed and the antenna fed through a non-resonant line (§ 10-8). If the antenna wires are made multiples of a half wave in length (use Equation 10, § 10-9, for computing the length), the matching section will be closed at the free end.

The rhombic antenna — The horizontal rhombic or "diamond" antenna is shown in Fig. 1037. Like the "V," it requires a good deal of space for erection, but it is capable of giving excellent gain and directivity. It also can be used for multi-band operation. In the terminated form shown in Fig. 1037, it operates like a non-resonant transmission line, without standing waves, and is uni-directional. It may also be used without the terminating resistor, in which case there are standing waves on the wires and the antenna is bi-directional.

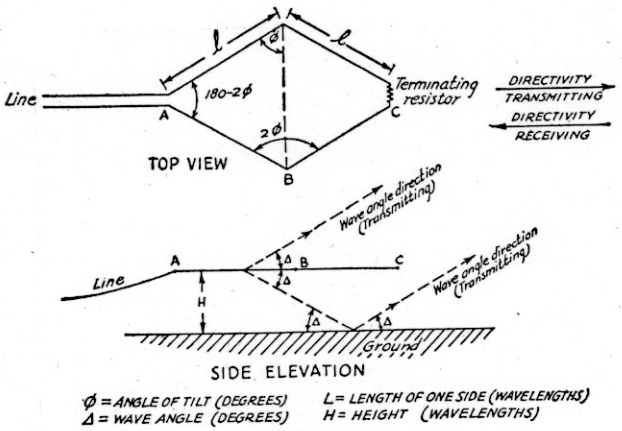


Fig. 1037 — The horizontal rhombic or diamond antenna, terminated. Important design dimensions are indicated; details in text.

The important quantities influencing the design of the rhombic antenna are shown in Fig. 1037. While several design methods may be used, the one most applicable to the conditions existing in amateur work is the so-called "compromise" method. The chart of Fig. 1038 gives design information based on a given length and wave angle to determine the remaining optimum dimensions for best operation. Curves for values of length of 2, 3 and 4 wavelengths are shown, and intermediate values may be interpolated.

With all other dimensions correct, an increase in length causes an increase in power gain and a slight reduction in wave angle. An increase in height also causes a reduction in wave angle and an increase in power gain, but not to the same extent as a proportionate increase in length.

For multi-band work, it is satisfactory to design the rhombic antenna on the basis of 14-Mc. operation, which will permit work on the 7- and 28-Mc. bands as well.

A value of 800 ohms is correct for the terminating resistor for any properly constructed rhombic, and the system behaves as a pure resistive load under this condition. The terminating resistor must be capable of safely dissipating one-half the power output (to eliminate the rear pattern), and should be non-inductive. Such a resistor may be made up from a carbon or graphite rod or from a long 800-ohm transmission line using resistance wire. If the carbon rod or a similar form of lumped resistance is used, the device should be suitably protected from weather effects, i.e., it should be covered with a good asphaltic compound and sealed in a

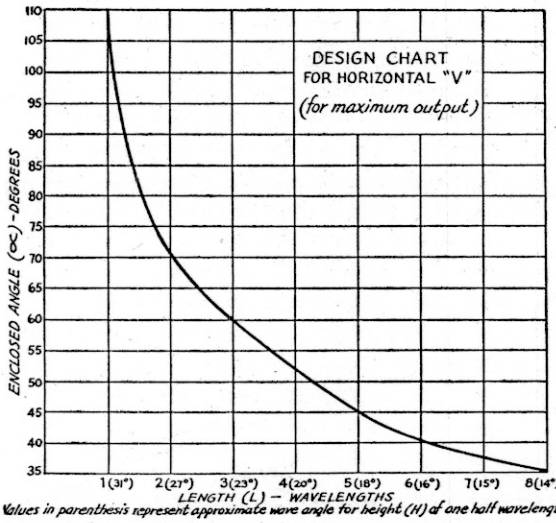


Fig. 1036 — Design chart for horizontal "V" antennas, giving the enclosed angle between sides vs. the length of the wires.

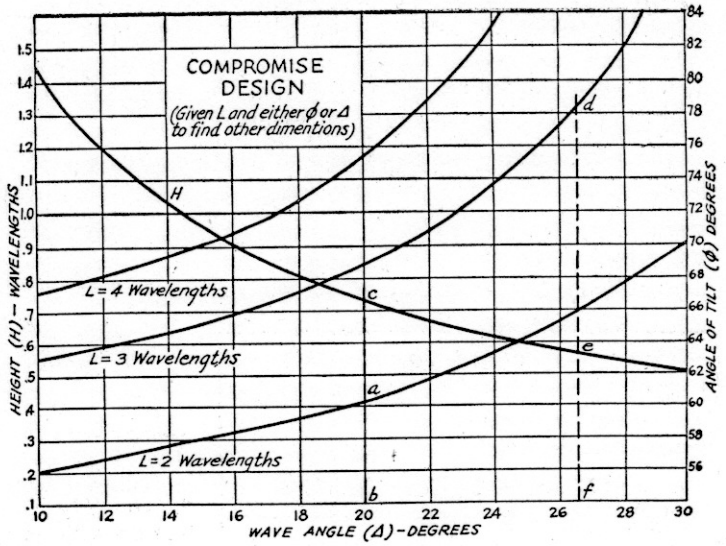


Fig. 1038 — Compromise-method design chart for rhombic antennas of various leg lengths and wave angles. The following examples illustrate the use of the chart:

(1) 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 (Δ = 20°.) Read angle of tilt (Φ) for point *a* and height (H) from intersection of line *ab* at point *c* on curve H.
Result:
Φ = 60.5°.
H = 0.73 wavelength.

(2) Given:
Length (L) = 3 wavelengths.
Angle of tilt (Φ) = 78°.
To Find: H, Δ.
Method:
Draw a vertical line from point *d* on curve L = 3 wavelengths at Φ = 78°. Read intersection of this line on curve H (point *e*) for height, and intersection at point *f* on the abscissa for Δ.
Result:
H = 0.56 wavelength.
Δ = 26.6°.

small, light-weight box or fibre tube. Suitable resistors are available commercially.

For feeding the antenna, the antenna impedance will be matched by an 800-ohm line, which may be constructed from No. 16 wire spaced 20 inches or from No. 18 wire spaced 16 inches. The 800-ohm line is somewhat ungainly to install, however, and may be replaced by an ordinary 600-ohm line with only a negligible mismatch. Alternatively, a matching section may be installed between the antenna terminals and a low-impedance line. However, when such an arrangement is used, it will be necessary to change the matching-section constants for each different band of operation.

The same design details apply to the unterminated rhombic as to the terminated type. Resonant feeders are preferable for the unterminated rhombic. A non-resonant line may be used by incorporating a matching section at the antenna, but is not readily adaptable to multi-band work.

Rhombic antennas will give a power gain of 10 db. or more, when constructed according to the charts given. In general, the larger the antenna, the greater the power gain.

¶ 10-12 Directive Arrays with Driven Elements

Principles — By combining individual half-wave antennas into an *array* with suitable spacing between the antennas (called *elements*) and feeding power to them simultaneously, it is possible to make the radiated fields from the individual elements add in a favored direction, thus increasing the field strength in that direction as compared to that produced by one antenna element alone. In other directions the fields will more or less oppose each other, giving a reduction in field strength. Thus a power gain in the desired direction is secured at the expense of a power reduction in other directions.

Besides the spacing between elements, the instantaneous direction of current flow (*phase*) in individual elements determines the directivity and power gain. There are several methods of arranging the elements. If they are strung end to end, so that all lie on the same straight line, the elements are said to be *collinear*. If they are parallel and all lying in the same plane, the elements are said to be *broadside* when the phase of the current is the same in all, and *end-fire* when the currents are not in phase. Elements which receive power from the transmitter through the transmission line are called *driven elements*.

The power gain of a directive system increases with the number of elements. The proportionality between gain and number of elements is not simple, however. The gain depends upon the effect which the spacing and phasing has upon the radiation resistance of the elements, as well as upon their number.

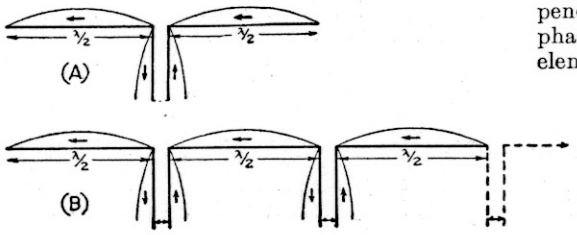


Fig. 1039 — Collinear half-wave antennas in phase. The system at A is generally known as "two half waves in phase." B is an extension of the system; in theory the number of elements may be carried on indefinitely, but practical considerations usually limit the elements to four.

Collinear arrays — Simple forms of collinear arrays, with the current distribution, are shown in Fig. 1039. The two-element array at A is popularly known as "two half waves in phase." It will be recognized as simply a center-fed antenna operated at its second harmonic. The way in which the number of elements may be extended for increased directivity and gain is shown in Fig. 1039-B. Note that quarter-wave transmission lines are used between each element; these give the reversal in phase necessary to make the currents in individual antenna elements all flow in the same direction at the same instant. Another way of looking at it is to consider that the whole system is a long wire, with alternate half-wave sections folded so that they do not radiate. Any phase-reversing section may be used as a quarter-wave matching section for attaching a non-resonant feeder (§ 10-8), or a resonant transmission line may be substituted for any of the quarter-wave sections. Also, the antenna may be end-fed by any of the systems previously described (§ 10-7, 10-8), or any element may be center-fed. It is best to feed at the center of the array, so that the energy will be distributed as uniformly as possible among the elements.

TABLE III

THEORETICAL GAIN OF COLLINEAR HALF-WAVE ANTENNAS

Spacing between centers of adjacent half waves	*Number of half waves in array vs. gain in db.*				
	2	3	3	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

The gain and directivity depend upon the number of elements and their spacing, center-to-center. This is shown by Table III. Although ¾-wave 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 most generally used in actual practice.

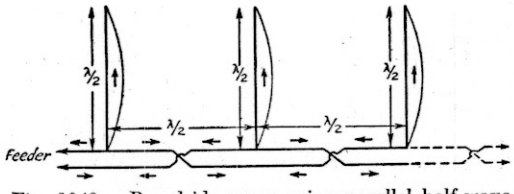


Fig. 1040 — Broadside array using parallel half-wave elements. Arrows indicate the direction of current flow. Transposition of the feeders is necessary to bring the antenna currents in phase. Any reasonable number of elements may be used. The array is bi-directional, with maximum radiation "broadside" or perpendicular to the plane of the antennas (perpendicularly through this page).

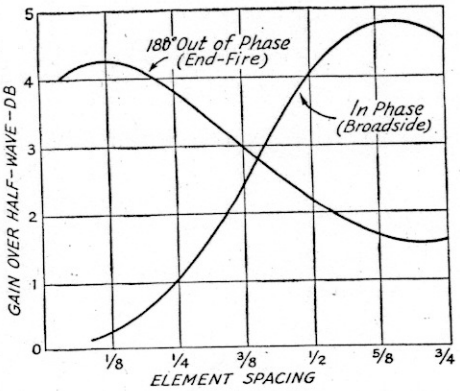


Fig. 1041 — Gain vs. spacing for two parallel half-wave elements combined as either broadside or end-fire arrays.

Collinear arrays may be mounted either horizontally or vertically. Horizontal mounting gives increased horizontal directivity, while the vertical directivity remains the same as for a single element at the same height. Vertical mounting gives the same horizontal pattern as a single element, but concentrates the radiation at low angles. It is seldom practicable to use more than two elements vertically at frequencies below 14 Mc. because of the excessive height required.

TABLE IV

THEORETICAL GAIN VS. NUMBER OF BROADSIDE ELEMENTS (HALF-WAVE SPACING)

No. of elements	*Gain*
2	4 db.
3	5.5 db.
4	7 db.
5	8 db.
6	9 db.

Broadside arrays — Parallel antenna elements with currents in phase may be combined as shown in Fig. 1040 to form a *broadside* array, so named because the direction of maximum radiation is broadside to the plane containing the antennas. Again the gain and directivity depend upon the number of elements and the spacing, the gain for different spacings being shown in Fig. 1041. Half-wave spacing generally is used, since it simplifies the problem of feeding the system when the array has more than two elements. Table IV gives theoretical gain as a function of the number of elements with half-wave spacing.

Broadside arrays may be suspended either with the elements all vertical or with them horizontal and one above the other (*stacked*). In the former case the horizontal pattern becomes quite sharp, while the vertical pattern is the same as that of one element alone. If the array is suspended horizontally, the horizontal pattern is equivalent to that of one element

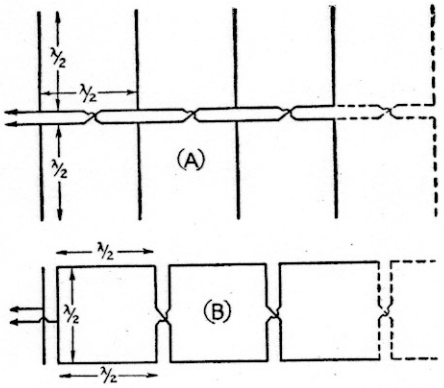


Fig. 1042 — Combination broadside and collinear arrays. A, with vertical elements; B, with horizontal elements. Both arrays give low-angle radiation. Two or more sections may be used. The gain in db. will be equal, approximately, to the sum of the gain for one set of broadside elements (Table IV) plus the gain of one set of collinear elements (Table III). For example, in A each broadside set has four elements (gain 7 db.) and each collinear set two elements (gain 1.8 db.), giving a total gain of 8.8 db. In B, each broadside set has two elements (gain 4 db.) and each collinear set three elements (gain 3.3 db.), making the total gain 7.3 db. The result is not strictly accurate, because of mutual coupling between the elements, but is good enough for practical purposes.

while the vertical pattern is sharpened, giving low-angle radiation.

Broadside arrays may be fed either by resonant transmission lines (§ 10-7) or through quarter-wave matching sections and non-resonant lines (§ 10-8). In Fig. 1040, note the "crossing over" of the feeders, which is necessary to bring the elements in proper phase relationship.

Combined broadside and collinear arrays — Broadside and collinear arrays may be combined to give both horizontal and vertical directivity, as well as additional gain. The general plan of constructing such antennas is shown in Fig. 1042. The lower angle of radiation resulting from stacking elements in the vertical plane is desirable at the higher frequencies. In general, doubling the number of elements in an array by stacking will raise the gain from 2 to 4 db., depending upon whether vertical or horizontal elements are used — that is, whether the stacked elements are of the broadside or collinear type.

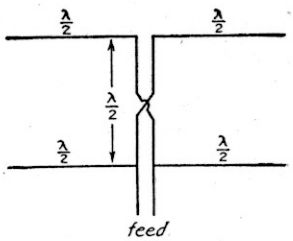


Fig. 1043 — A four-element combination broadside-collinear array, popularly known as the "lazy H" antenna. A closed quarter-wave stub may be used at the feed point to match into a 600-ohm transmission line, or resonant feeders may be attached at the point indicated. The gain over a half-wave antenna is 5 to 6 db.

The arrays in Fig. 1042 are shown fed from one end, but this is not especially desirable in the case of large arrays. Better distribution of energy between elements, and hence better all-around performance, will result when the feeders are attached as nearly as possible to the center of the array. Thus, in the 8-element array at A, the feeders could be introduced at the middle of the transmission line between the second and third set of elements, in which case the connecting line would not be transposed. Alternatively, the antenna could be constructed with the transpositions as shown and the feeder connected between the adjacent ends of either the second or third pair of collinear elements.

A four-element array of the general type shown in Fig. 1042-B, known as the "lazy H" antenna, has been quite frequently used. This arrangement is shown, with the feed point indicated, in Fig. 1043.

End-fire arrays — Fig. 1044 shows a pair of parallel half-wave elements with currents out of phase. This is known as an *end-fire* array, because it radiates best along the line of the antennas, as shown.

The end-fire array may be used either vertically or horizontally (elements at the same height), and is well adapted to amateur work because it gives maximum gain with relatively close element spacing. Fig. 1041 shows how the gain varies with spacing. End-fire elements may be combined with additional collinear and

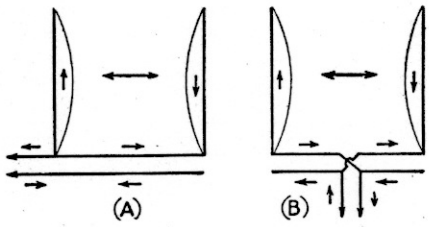


Fig. 1044 — End-fire arrays using parallel half-wave elements. The elements are shown with half-wave spacing to illustrate feeder connections. In practice, closer spacings are desirable, as shown by Fig. 1041. Direction of maximum radiation is shown by the large arrows.

broadside elements to give a further increase in gain and directivity.

Either resonant or non-resonant lines may be used with this type of array. Non-resonant lines preferably are matched to the antenna through a quarter-wave matching section (§ 10-8).

Checking phasing — Figs. 1042 and 1044 illustrate a point in connection with feeding a phased antenna system which sometimes is confusing. In Fig. 1044, when the transmission line is connected as at A there is no cross-over in the line connecting the two antennas, but when the transmission line is connected to the center of the connecting line the cross-over becomes necessary (B). This is because in B the two halves of the connecting line are simply *branches* of the same line. In other

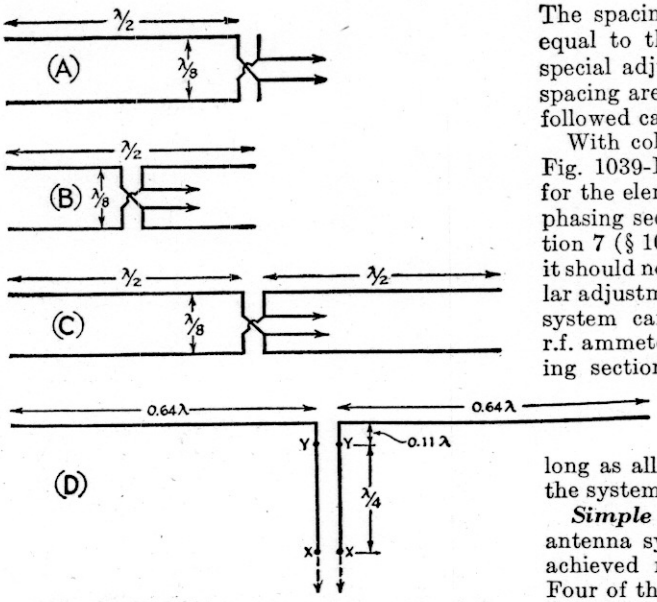


Fig. 1045 — Simple directive antenna systems. A is a two-element end-fire array; B is the same array with center feed, which permits use of the array on the second harmonic, where it becomes a four-element array with quarter-wave spacing. C is a four-element end-fire array with ⅛-wave spacing. D is a simple two-element broadside array using extended in-phase antennas ("extended double-Zepp"). The gain of A and B is slightly over 4 db. On the second harmonic, B will give about 5 db. gain. With C, the gain is approximately 6 db., and with D, approximately 3 db. In A, B and C, the phasing line contributes about 1/16th wavelength to the transmission line; when B is used on the second harmonic, this contribution is ⅛ wavelength. Alternatively, the antenna ends may be bent to meet the transmission line, in which case each feeder is simply connected to one antenna. In D, points *Y-Y* indicate a quarter-wave point (high current) and *X-X* a half-wave point (high voltage). The line may be extended in multiples of quarter waves, if resonant feeders are to be used. A, B, and C may be suspended on wooden spreaders. The plane containing the wires should be parallel to the ground.

words, even though the connecting line in B is a half wave in length, it is not actually a half-wave line but *two quarter-wave lines in parallel.* The same thing is true of the untransposed line of Fig. 1042. Note that, under these conditions, the antenna elements are in phase when the line is not transposed, and out of phase when the transposition is made. The opposite is the case when the half-wave line simply joins two antenna elements and does not have the feed line connected to its center, as in Fig. 1040.

Adjustment of arrays — With arrays of the types just described, using half-wave spacing between elements, it will usually suffice to make the length of each element that given by the equation for a half-wave antenna in § 10-2, while the half-wave phasing lines between the parallel elements can be calculated from the formula:

$$\text{Length of half-wave line (feet)} = \frac{492 \times 0.975}{\text{Freq. (Mc.)}} = \frac{480}{\text{Freq. (Mc.)}}$$

The spacing between elements can be made equal to the length of the phasing line. No special adjustments line or element length or spacing are needed, provided the formulas are followed carefully.

With collinear arrays of the type shown in Fig. 1039-B, the same formula may be used for the element length while the quarter-wave phasing section can be calculated from Equation 7 (§ 10-5). If the array is fed at its center it should not be necessary to make any particular adjustments, although, if desired, the whole system can be resonated by connecting an r.f. ammeter in the shorting link on each phasing section and moving the link back and forth to find the maximum current position. This refinement is hardly necessary in practice, however, so long as all elements are the same length and the system is symmetrical.

Simple arrays — Several simple directive antenna systems using driven elements have achieved rather wide use among amateurs. Four of these systems are shown in Fig. 1045. Tuned feeders are assumed in all cases; however, a matching section (§ 10-8) readily can be substituted if a non-resonant transmission line is preferred. Dimensions given are in terms of wavelength; actual lengths can be calculated from the equations in § 10-2 for the antenna and from Equation 7 (§ 10-5) for the resonant transmission line or matching section In cases where the transmission-line proper connects to the mid-point of a phasing line, only *half* the length of the latter should be added to the line to find the quarter-wave point.

At A and B are two-element end-fire arrangements using close spacing. They are electrically equivalent; the only difference is in the method of connecting the feeders. B may also be used as a four-element array on the second harmonic, although the spacing is not quite optimum (Fig. 1041) for such operation.

A close-spaced four-element array is shown at C. It will give about 2 db. more gain than the two-element array.

The antenna at D, commonly known as the "extended double Zepp," is designed to take advantage of the greater gain possible with collinear antennas having greater than half-wave center-to-center spacing, but without introducing feed complications. The elements are made longer than a half wave in order to bring this about. The gain is 3 db. over a single half-wave antenna, and the broadside directivity is quite sharp.

The antennas of A and B may be mounted either horizontally or vertically; horizontal suspension (with the elements in a plane parallel to the ground) is recommended, since this tends to give low-angle radiation without an unduly sharp horizontal pattern. Thus these systems are useful for coverage over a wide horizontal angle. The system at C, when mounted horizontally, will have a sharper horizontal pattern than the two-element arrays.

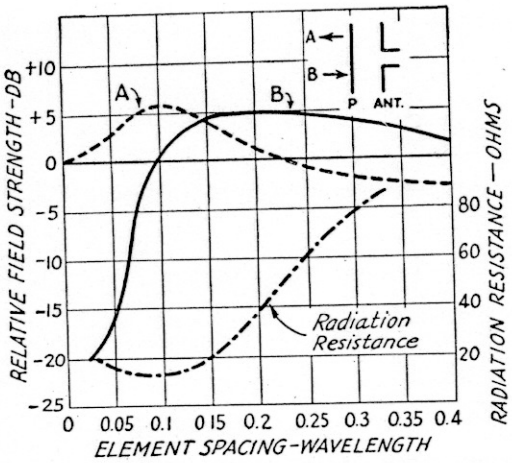


Fig. 1046 — Gain vs. element spacing for an antenna and one parasitic element. The reference point, 0 db. is the field strength from a half-wave antenna alone. The greatest gain is in direction A at spacings of less than 0.14 wavelength, and in direction B at greater spacings. The front-to-back ratio is the difference in db. between curves A and B. Variation in radiation resistance of the driven element also is shown. These curves are for a self-resonant parasitic element. At most spacings the gain as a reflector can be increased by slight lengthening of the parasitic element; the gain as a director can be increased by shortening. This also improves the front-to-back ratio.

¶ 10-13 Directive Arrays with Parasitic Elements

Parasitic excitation — The antenna arrays described in § 10-12 are bi-directional; that is, they will radiate in directions both to the "front" and to the "back" of the antenna system. If radiation is wanted in only one direction (for instance, north only, instead of north-south), it is necessary to use different element arrangements. In most of these arrangements the additional elements receive power by induction or radiation from the driven element, generally called the "antenna," and re-radiate it in the proper phase relationship to achieve the desired effect. These elements are called *parasitic* elements, as contrasted to the driven elements which receive power directly from the transmitter through the transmission line.

The parasitic element is called a *director* when it reinforces radiation on a line pointing to it from the antenna, and a *reflector* when the reverse is the case. Whether the parasitic element is a director or reflector depends upon the parasitic element tuning (which usually is adjusted by changing its length), and, particularly when the element is self-resonant, upon the spacing between it and the antenna.

Gain vs. spacing — The gain of an antenna-reflector or an antenna-director combination varies chiefly with the spacing between the elements. The way in which gain varies with spacing is shown in Fig. 1046, for the special case of self-resonant parasitic elements. This chart also shows how the attenuation to the "rear" varies with spacing. The same spacing does not necessarily give both maximum forward gain and maximum backward attenuation. Backward attenuation is desirable when the antenna is used for receiving, since it greatly reduces interference coming from the opposite direction to the desired signal.

Element lengths — The antenna length is given by the formulas in § 10-2. The director and reflector lengths must be determined experimentally for maximum performance. The preferable method is to aim the antenna at a receiver a mile or more distant and have an observer check the signal strength (on the "S" meter) while the reflector or director is adjusted a few inches at a time, until the length which gives maximum signal is found. The attenuation may be similarly checked, the length being adjusted for minimum signal. In general, for best front-to-back ratio the length of a director will be about 4 per cent less than that of the antenna. The reflector will be about 5 per cent longer than the antenna.

Simple systems; the rotary beam — Four practical combinations of antenna, reflector and director elements are shown in Fig. 1047. Spacings which give maximum gain or maximum front-to-back ratio (ratio of power radiated in the desired direction to power radiated in the opposite direction) may be taken from Fig. 1046. In the chart, the front-to-back ratio in db. will be the sum of gain and attenuation at the same spacing.

Systems of this type are popular for rotary-beam antennas, where the entire antenna system is rotated, to permit its gain and directiv-

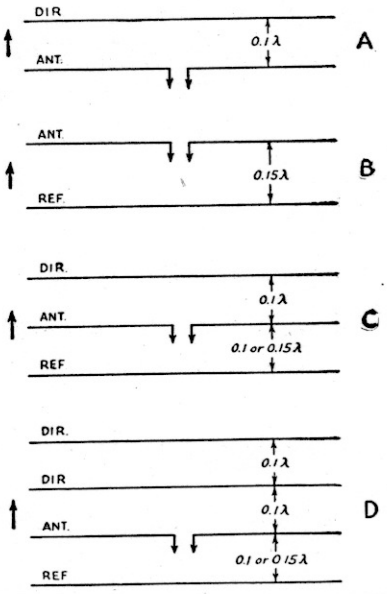


Fig. 1047 — Half-wave antennas with parasitic elements. A, with reflector; B, with director; C, with both director and reflector; D, two directors and one reflector. Gain is approximately as shown by Fig. 1046, in the first two cases, and depends upon the spacing and length of the parasitic element. In the three- and four-element arrays a reflector spacing of 0.15 wavelength will give slightly more gain than 0.1-wavelength spacing. Arrows show direction of maximum radiation. The array should be mounted horizontally (top views are shown).

ity to be utilized for any compass direction. They may be mounted either horizontally (with the plane containing the elements parallel to the earth) or vertically.

Arrays using more than one parasitic element, such as those shown at C and D in Fig. 1047, will give more gain and directivity than is indicated for a single reflector and director by the curves of Fig. 1046. The gain with a properly adjusted three-element array (antenna, director and reflector) will be 5 to 7 db. over a half-wave antenna. Somewhat higher gain still can be secured by adding a second director to the system, making a four-element array. The front-to-back ratio is correspondingly improved as the number of elements is increased.

The elements in close-spaced (less than one-quarter wavelength element spacing) arrays preferably should be made of tubing of one-half- to one-inch diameter, both to reduce the ohmic resistance (§ 10-2) of the conductors and to secure mechanical rigidity. If the elements are free to move with respect to each other, the array will tend to show detuning effects under windy conditions.

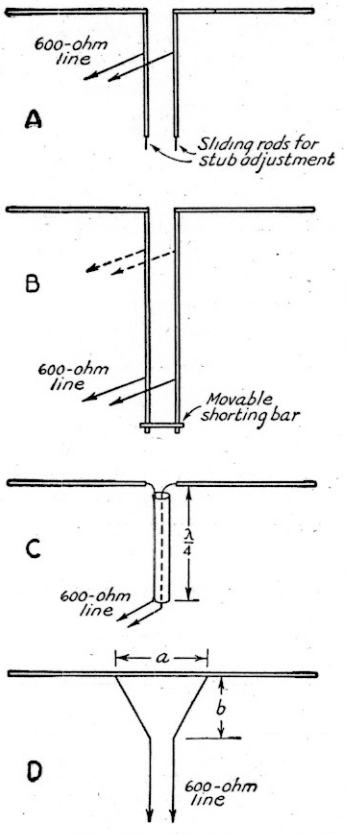


Fig. 1048 — Recommended methods of feeding the driven antenna element in close-spaced parasitic arrays. The parasitic elements are not shown. A, quarter-wave open stub; B, half-wave closed stub; C, concentric-line quarter-wave matching section; D, delta matching transformer. Adjustment details are discussed in the text.

Feeding close-spaced arrays — While any of the usual methods of feed may be applied to the driven element of a parasitic array, the fact that, with close spacing, the radiation resistance as measured at the center of the driven element drops to a very low value makes some systems more desirable than others. The preferred methods are shown in Fig. 1048. Resonant feeders are not recommended for lengths greater than a half wavelength.

The quarter- or half-wave matching stubs shown at A and B in Fig. 1048 preferably should be constructed of tubing with rather close spacing, in the manner of the "Q" section. This lowers the impedance of the matching section and makes the position of the line taps somewhat less difficult to determine accurately. The line adjustment should be made only with the parasitic elements in place, and after the correct element lengths have been determined, it should be checked to compensate for changes likely to occur because of element tuning. The procedure is the same as that described in § 10-8.

The concentric-line matching section at C will work with fair accuracy into a close-spaced parasitic array of 2, 3 or 4 elements without necessity for adjustment. The line is used as an impedance-inverting transformer, and, if its characteristic impedance is 70 ohms, it will give an exact match to a 600-ohm line when the resistance at the termination is about 8.5 ohms. Over a range of 5 to 15 ohms the mismatch, and therefore the standing-wave ratio, will be less than 2 to 1. The length of the quarter-wave section may be calculated from Equation 7 (§ 10-5).

The delta matching transformer shown at D is an excellent arrangement for parasitic arrays, and is probably easier to install, mechanically, than any of the others. The positions of the taps (dimension *a*) must be determined experimentally, along with the length, *b*, by checking the standing-wave ratio on the line as adjustments are made. Dimension *b* should be about 15 per cent longer than *a*.

Sharpness of resonance — Peak performance of a multi-element directive array depends upon proper phasing or tuning of the elements, which in all but the simplest systems can be exact for one frequency only. However, there is some latitude, and most arrays will work well over a relatively narrow region such as the 14 Mc. band. If frequencies in all parts of the band are to be used, the antenna system should be designed for the mid-frequency; on the other hand, if only one frequency in the band will be used for the greater portion of the time, the antenna might be designed for that frequency and some degree of misadjustment tolerated on the occasionally used spare frequencies.

When reflectors or directors are used the tolerance is usually less than in the case of driven elements, partly because the parasitic-element lengths are fixed and the operation may change appreciably as the frequency passes from one side of resonance to the other, and partly be-

cause the close spacing ordinarily used results in a sharp-tuning system. With parasitic elements, operation should be confined to a small region about the frequency for which the antenna is adjusted if peak performance is to be secured.

Combination arrays — It is possible to combine parasitic elements with driven elements to form arrays composed of collinear driven and parasitic elements and combination broadside-collinear-parasitic elements. Thus two or more collinear elements might be provided with a collinear reflector or director set, one parasitic element to each driven element. Or both directors and reflectors might be used. A broadside-collinear array could be treated in the same fashion.

When combination arrays are built up, a rough approximation of the gain to be expected may be obtained by adding the gains for each type of combination. Thus the gain of two broadside sets of four collinear arrays with a set of reflectors, one behind each element, at quarter-wave spacing for the parasitic elements, would be estimated as follows: From Table III, the gain of four collinear elements is 4.5 db. with half-wave spacing; from Fig. 1041 or Table IV, the gain of two broadside elements at half-wave spacing is 4.0 db.; from Fig. 1046, the gain of a parasitic reflector at quarter-wave spacing is 4.5 db. The total gain is then the sum, or 13 db. for the sixteen elements. Note that using two *sets* of elements in broadside is equivalent to using two elements, so far as gain is concerned; similarly with sets of reflectors, as against one antenna and one reflector. The actual gain of the combination array will depend, in practice, upon the way in which the power is distributed between the various elements and upon the effect which mutual coupling between elements has upon the radiation resistance of the array, and may be somewhat higher or lower than the estimate.

A great many directive antenna combinations can be worked out by combining elements according to these principles.

10-14 Miscellaneous Antenna Systems

Grounded antenna — The grounded antenna is used almost exclusively for 1.75-Mc. work, where the length required for a half-wave antenna would be excessive for most locations. An antenna worked "against ground" need be only a quarter-wave long, approximately, because the earth acts as an electrical "mirror" which supplies the missing quarter wave. The current is maximum at the ground connection with a quarter-wave antenna, just as it is at the center of a half-wave antenna.

On 1.75 Mc. the most useful radiation is from the vertical part of the antenna, since vertically polarized waves are characteristic of ground-wave transmission. It is therefore desirable to make the down-lead as nearly vertical as possible, and also as high as possible. This gives low-angle sky-wave transmission, which is most useful for long-distance work at night, in addition to a good ground wave for local work. The horizontal portion contributes to high-angle sky-wave transmission, which is useful for covering short distances on this band at night.

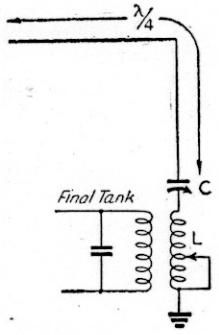


Fig. 1049 — Typical grounded antenna for 1.75 Mc., consisting of a vertical section and a horizontal section having a total length (including the ground lead, if the latter is more than a few feet long) of one-quarter wavelength. Coil L should have about 20 turns of No. 12 wire on a 3-inch diameter form, tapped every two or three turns for adjustment. C is a 250 to 500 $\mu\mu fd.$ variable. The inductive coupling between L and the final tank coil should be variable.

Fig. 1049 shows a grounded antenna with the top folded to make the length equal to a quarter wave. The antenna coupling apparatus consists of the coil, L, tuned by the series condenser, C, with L inductively coupled to the transmitter tank circuit (§ 10-4, 10-6).

For computation purposes, the *over-all* length of a grounded system is given by

$$\text{Length (feet)} = \frac{236}{f\ (Mc.)}$$

This is the *total* length from the far end of the antenna to the ground connection. The length is not critical, since departures of the order of 10 to 20 per cent can be compensated by the tuning apparatus.

The ground should preferably be one with conductors buried deep enough to reach natural moisture. In urban locations, good grounds can be made by connecting to the water mains where-they enter the house; the pipe should be scraped clean and a low-resistance connection made with a tightly fastened ground clamp. If no water supply pipes are available, several rods or pipes six to eight feet long may be driven into the ground at intervals of six or eight feet, all being connected together. The transmitter should be located so as to make the ground lead as short as possible.

In locations where it is impossible to secure a good ground connection, because of sandy soil or other considerations, it is preferable to use a counterpoise or capacity ground instead of an actual ground connection. The counterpoise consists of a system of wires, insulated from ground and running horizontally above the earth beneath the antenna. The counterpoise should have a sufficient number of wires of sufficient length to cover well the area immediately under the antenna. The wires may be formed into any convenient shape; i.e., they may be spread out fan-shape, in a radial pattern, or as three or more parallel wires sepa-

rated a few feet and running beneath the antenna. The counterpoise may be elevated six feet or so above the ground, so that it will not interfere with persons walking under it. A low-resistance connection should be made between the usual ground terminal of the transmitter and each of the wires in the counterpoise.

"J" antenna — This type of antenna, frequently used on the very-high frequencies when vertical polarization is desired, is simply a half-wave radiator fed through a quarter-wave matching section, (§ 10-8), the whole being mounted vertically as shown in Fig. 1050. Adjustment and tuning are as described in § 10-8. The bottom of the matching section, being at practically zero r.f. potential, can be grounded through a metallic conductor for lightning protection.

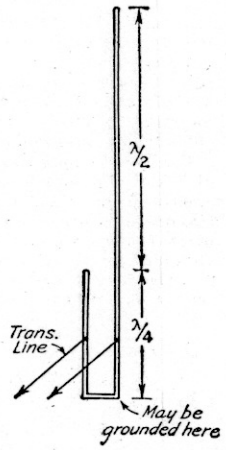


Fig. 1050 — **The "J" antenna. It is usually constructed of metal tubing, frequently with the ¼-wave vertical section mounted as an extension of a grounded metal mast. The stub may be adjusted by a sliding shorting bar.**

Coaxial antenna — With the "J" antenna there is likely to be some radiation from the matching section and the transmission line, which tends to combine with the radiation from the antenna in such a way as to raise the angle of radiation. As this is undesirable at very-high frequencies, where the lowest possible radiation angle is essential, the coaxial antenna shown in Fig. 1051 was developed to eliminate feeder radiation. The center conductor of a 70-ohm concentric transmission line is extended one quarter wave beyond the end of the line, to act as the upper half of a half-wave antenna. The lower half is provided by the quarter-wave sleeve, the upper end of which is connected to the outer conductor of the concentric line. The sleeve acts as a shield about the transmission line and very little current is induced on the outside of the line by the antenna field. The line is non-resonant, since its characteristic impedance is the same as the center impedance of the half-wave antenna (§ 10-2). The sleeve may be made of copper or brass tubing of suitable diameter to clear the transmission line. The coaxial antenna is somewhat difficult to construct, but is superior to simpler systems at low radiation angles.

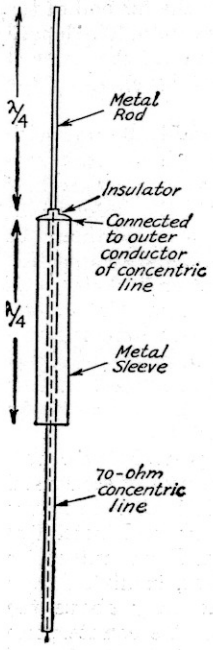


Fig. 1051 — **Coaxial antenna. The insulated inner conductor of the 70-ohm concentric line is connected to the quarter-wave metal rod which forms the upper half of the antenna.**

Folded dipole — An arrangement which combines the radiation characteristics of a half-wave antenna with the impedance-transforming properties of a quarter-wave line (§ 10-5) is shown in Fig. 1052. 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 per cent of the wavelength. As used at very-high frequencies, the spacing is of the order of an inch or two when the elements are constructed of metal tubing.

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 all are the same diameter. A 300-ohm line will therefore be non-resonant when the antenna is connected to its output end (§ 10-5), while the standing-wave ratio with a 600-ohm line will be only of the order of 2 to 1.

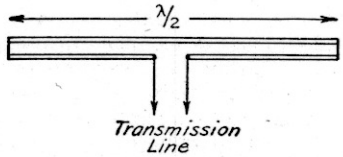


Fig. 1052 — **Folded dipole for increasing the value of impedance at the feed point to match a transmission line.**

The total required length around the loop formed by the antenna may be calculated by Equation 10 (§ 10-9) for a total length of one wavelength.

Corner reflector antenna — A type of antenna system particularly well-suited to the v.h.f. ranges above 56 Mc., is the "corner" reflector, shown in Fig. 1053. It consists of two plane surfaces set at an angle of 90°, with the antenna set on a line bisecting this angle. For maximum performance, the distance of the antenna from the vertex should be 0.5 wavelength, but compromise designs can be built with closer spacings (see Table V). The plane surfaces need not be solid sheets, and can most easily be made of spines spaced about 0.1 wavelength apart. The spines do not have to be connected together electrically.

The resistance of the antenna is raised when a corner reflector is used. 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 Fig. 1054.

The corner reflector can be used with the antenna either horizontal or vertical, and the

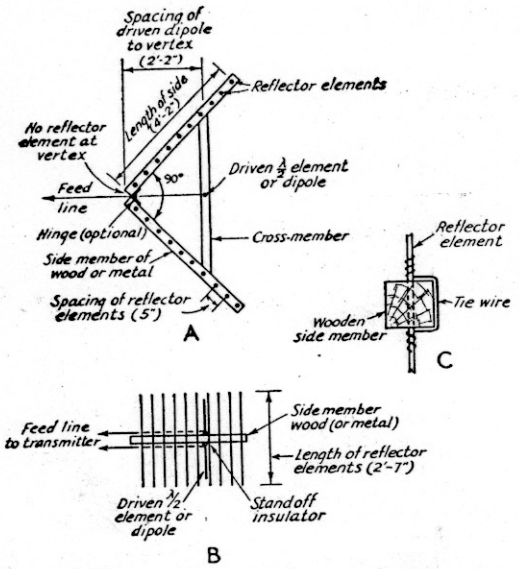


Fig. 1053 — A corner reflector antenna system with a spine- or grid-type reflector. The reflector elements are made of stiff wire or tubing. The dimensions shown are for 224 Mc., and should be doubled for 112 Mc. (See Table V.) The gain of the system is close to 10 db.

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.

Receiving antennas — Nearly all of the properties possessed by an antenna as a radiator also apply when it is used as a receiving antenna. Current and voltage distribution, impedance and resistance, and directional characteristics are the same in a receiving antenna as they would be if it were used as a transmitting antenna. This reciprocal behavior makes possible the design of a receiving antenna of optimum performance based on the same considerations as have been discussed for transmitting antennas.

The simplest form of receiving antenna is a wire of random length, which acts as a conductor in the field of the radiated wave and in which distributed voltages are induced by the wave. The longer the wire, the greater the energy it abstracts from the wave. Because of the high sensitivity of modern receivers, a large antenna is not necessary for picking up signals at good strength. An indoor wire only 15 to 20 feet long will give quite good results, although a longer wire outdoors is better.

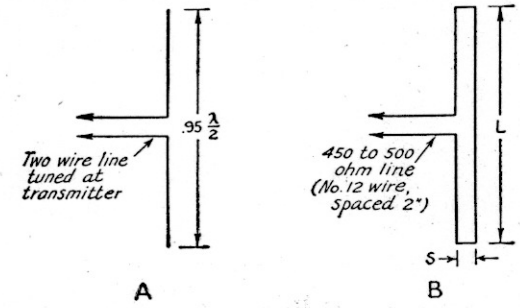


Fig. 1054 — Dipoles suitable for use with the corner reflector antenna system. The radiator length, *L*, is 25 inches for 224 Mc., and *s* = 1 inch for the same band.

The use of a tuned antenna greatly improves the operation of the receiver, because the signal strength is greater in proportion to the stray noises picked up by the antenna than is the case with wires of random length. Since the transmitting antenna usually is given the best location, it can also be used to great advantage for receiving. This is especially true when a directive antenna is used. A change-over switch or relay, connected in the antenna leads, can be used to transfer the connections from the receiver to the transmitter while the latter is on the air. The directional effects and power gain of directive transmitting antennas are the same for receiving as for transmitting.

TABLE V

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″	4′ 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 the 224-, 112-, and 56-Mc. bands. Alternative designs are listed for the 112- and 56-Mc. bands. 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.

In selecting a directional receiving antenna it is preferable to choose a type which gives very little response in all but the desired direction (small minor lobes). This is even more important than high gain in the desired direction, because the cumulative response to noise and unwanted-signal interference in the smaller lobes may offset the advantage of increased desired-signal gain.

The auxiliary elements in the antenna system — transmission line and receiver coupling — should be arranged to avoid direct pick-up of undesired-signal or noise energy, which would impair the directivity. This requires a balanced transmission line without standing waves, a carefully shielded and balanced receiver input circuit, and a good ground on the receiver.