Chapter 13

Long Wire and Traveling Wave Antennas

The power gain and directive characteristics of the harmonic wires (which are "long" in terms of wavelength) described in Chapter 2 make them useful for long-distance transmission and reception on the higher frequencies. In addition, long wires can be combined to form antennas of various shapes that will increase the gain and directivity over a single wire. The term "long wire," as used in this chapter, means any such configuration, not just a straight-wire antenna.

Long Wires Versus Multielement Arrays

In general, the gain obtained with long-wire antennas is not as great, when the space available for the antenna is limited, as can be obtained from the multielement arrays in Chapter 8. However, the long-wire antenna has advantages of its own that tends to compensate for this deficiency. The construction of long-wire antennas is simple both electrically and mechanically, and there are no especially critical dimensions or adjustments.The long-wire antenna will work well and give satisfactory gain and directivity over a 2-to-1 frequency range; in addition, it will accept power and radiate well on any frequency for which its overall length is not less than about a half wavelength. Since a wire is not "long," even at 28 MHz, unless its length is equal to at least a half wavelength on 3.5 MHz, any long-wire can be used on all amateur bands that are useful for long-distance communication.

Between two directive antennas having the same theoretical gain, one a multielement array and the other a long-wire antenna, many amateurs have found that the long-wire antenna seems more effective in reception. One possible explanation is that there is a diversity effect with a long-wire antenna because it is spread out over a large distance, rather than being concentrated in a small space. This may raise the average level of received energy for ionospheric-propagated signals. Another factor is that long-wire antennas have directive patterns that are sharp in both the horizontal and vertical planes, and tend to concentrate the radiation at the low vertical angles that are most useful at the higher frequencies. This is an advantage that some types of multi-element arrays do not have.

General Characteristics of Long-Wire Antennas

Whether the long-wire antenna is a single wire running in one direction, or is formed into a V, rhombic or some other configuration, there are certain general principles that apply and some performance features that are common to all types. The first of these is that the power gain of a long-wire antenna as compared with a half-wave dipole is not considerable until the antenna is really long (its length measured in wavelengths rather than in a specific number of feet). The reason for this is that the fields radiated by elementary lengths of wire along the antenna do not combine, at a distance, in as simple a fashion as the fields from half-wave dipoles used as described in Chapter 8. There is no point in space, for example, where the distant fields from all points along the wire are exactly in phase (as they are, in the optimum direction, in the case of two or more collinear or broadside dipoles when fed with in-phase currents). Consequently, the field strength at a distance is always less than would be obtained if the same length of wire were cut up into properly phased and separately driven dipoles. As the wire is made longer, the fields combine to form an increasingly intense main lobe, but this lobe does not develop appreciably until the wire is several wavelengths long. This is indicated by the curve showing gain in **Fig 1**. The longer the antenna, the sharper the lobe becomes, and since it is really a hollow cone of radiation about the wire in free space, it becomes sharper in all planes. Also, the greater the length, the smaller the angle with the wire at which the maximum radiation occurs.

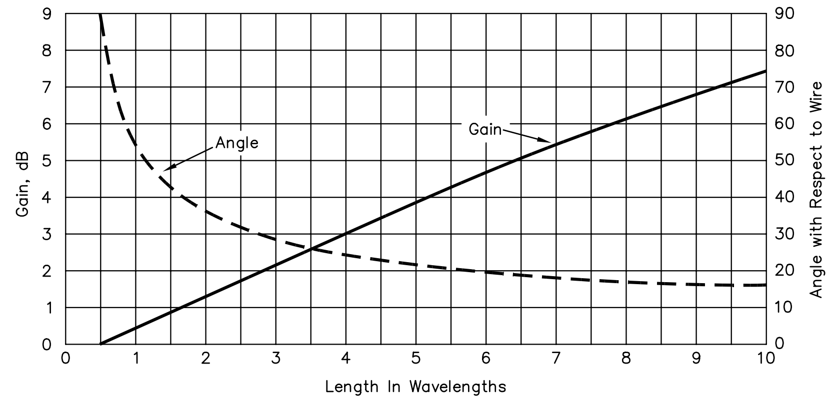

Fig 1—Theoretical gain of a long-wire antenna over a dipole in free space as a function of wire length. The angle, with respect to the wire, at which the radiation intensity is maximum also is shown.

Directivity

Because many points along a long wire are carrying currents in different phase (usually with different current amplitude as well), the field pattern at a distance becomes more complex as the wire is made longer. This complexity is manifested in a series of minor lobes, the number of which increases with the wire length. The intensity of radiation from the minor lobes is frequently as great as, and sometimes greater than, the radiation from a half-wave dipole. The energy radiated in the minor lobes is not available to improve the gain in the major lobe, which is another reason why a long-wire antenna must be long to give appreciable gain in the desired direction.

Driven and parasitic arrays of the simple types described in Chapter 8 do not have minor lobes of any great consequence. For that reason they frequently seem to have much better directivity than long-wire antennas, because their responses in undesired directions are well down from their response in the desired direction. This is the case even if a multielement array and a long-wire antenna have the same actual gain in the favored direction. For amateur work, particularly with directive antennas that cannot be rotated, the minor lobes of a long-wire antenna have some advantages. In most directions the antenna will be as good as a half-wave dipole, and in addition will give high gain in the most favored direction. Thus, a long-wire antenna (depending on the design) frequently is a good all-around radiator in addition to being a good directive antenna.

In the discussion of directive patterns of long-wire antennas in this chapter, keep in mind that the radiation patterns of resonant long wires are based on the assumption that each half-wave section of wire carries a current of the same amplitude. This is not exactly true, since energy is radiated as it travels along the wire. For this reason it is to be anticipated that, although the theoretical pattern is bidirectional and identical in both directions, actually the radiation (and reception) will be best in one direction. This effect becomes more marked as the antenna is made longer.

Wave Angles

The wave angle at which maximum radiation takes place from a long-wire antenna depends largely on the same factors that determine the wave angles of simple dipoles and multielement antennas. That is, the directive pattern in the presence of ground is found by adding the free-space vertical-plane pattern of the antenna to the ground-reflection factors for the particular antenna height used. These factors are discussed in Chapter 3.

As mentioned earlier, the free-space radiation pattern of a long-wire antenna has a major lobe that forms a hollow cone around the wire. The angle at which maximum radiation takes place becomes smaller, with respect to the wire, as the wire length is increased. This is shown by the broken curve in Fig 1. For this reason a long-wire antenna is primarily a low-angle radiator when installed horizontally above the ground. Its performance in this respect is improved by selecting a height that also tends to concentrate the radiation at low wave angles (at least $1/2$ λ for the lowest frequency). This is also discussed in Chapter 3.

Antenna systems formed from ordinary horizontal dipoles (that are not stacked) in most cases have a rather broad vertical pattern; the wave angle at which the radiation is maximum therefore depends chiefly on the antenna height. With a long-wire antenna, however, the wave angle at which the major lobe is maximum can never be higher than the angle at which the first null occurs (see **Fig 2**). This is true even if the antenna height is very low. (The efficiency may be less at very low heights, partly because the pattern is affected in such a way as to put a greater proportion of the total power into the minor lobes.) The result is that when considering radiation at wave angles below 15 or 20°, a long-wire antenna is less sensitive to height than are multielement arrays or simple dipoles. To assure good results, however, the antenna should have a height equivalent to at least a half wavelength at 14 MHz—that is, a minimum height of about 35 feet. Greater heights will give a worthwhile improvement at wave angles below 10°.

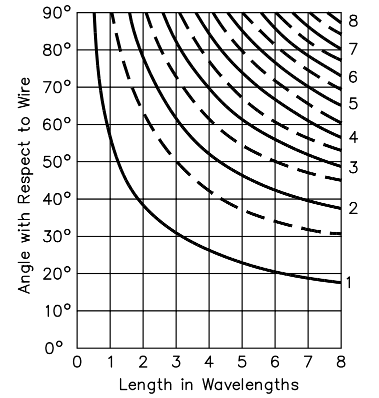

Fig 2—Angles at which radiation from long wires is maximum (solid curves) and zero (broken curves). The major lobe, no. 1, has the power gains given by Fig 1. Secondary lobes have smaller amplitude, but the maxima may exceed the radiation intensity from a half-wave dipole.

With an antenna of fixed physical length and height, both length and height (in terms of wavelength) increase as the frequency is increased. The overall effect is that both the antenna and the ground reflections tend to keep the system operating effectively throughout the frequency range. At low frequencies the wave angle is raised, but high wave angles are useful at 3.5 and 7 MHz. At high frequencies the inverse is true. Good all-around performance usually results on all bands when the antenna is designed for optimum performance in the 14-MHz band.

Calculating Length

In this chapter, lengths are always discussed in terms of wavelengths. There is nothing very critical about wire lengths in an antenna system that will work over a frequency range including several amateur bands. The antenna characteristics change very slowly with length, except when the wires are short (around one wavelength, for instance). There is no need to try to establish exact resonance at a particular frequency for proper antenna operation.

The formula for harmonic wires is satisfactory for determining the lengths of any of the antenna systems to be described. For convenience, the formula is repeated here in slightly different form:

$$\text{Length (feet)} = \frac{984(N - 0.025)}{f(MHz)}$$

where N is the antenna length in wavelengths. In cases where precise resonance is desired for some reason (for obtaining a resistive load for a transmission line at a particular frequency, for example) it is best established by trimming the wire length until the standing-wave ratio on the line is minimum.

LONG SINGLE WIRES

In Fig 1 the solid curve shows that the gain in decibels of a long wire increases almost linearly with the length of the antenna. The gain does not become appreciable until the antenna is about four wavelengths long, where it is equivalent to doubling the transmitter power (3 dB). The actual gain over a half-wave dipole when the antenna is at a practical height above ground will depend on the way in which the radiation resistance of the long-wire antenna and the comparison dipole are affected by the height. The exact way in which the radiation resistance of a long wire varies with height depends on its length. In general, the percentage change in resistance is not as great as in a half-wave antenna. This is particularly true at heights greater than one-half wavelength.

The nulls bounding the lobes in the directive pattern of a long wire are fairly sharp and are frequently somewhat obscured, in practice, by irregularities in the pattern. The locations of nulls and maxima for antennas up to eight wave-lengths long are shown in Fig 2.

Orientation

The broken curve of Fig 1 shows the angle with the wire at which the radiation intensity is maximum. There are two main lobes to the directive patterns of long-wire antennas; each makes the same angle with respect to the wire. The solid pattern, considered in free space, is the hollow cone formed by rotating the wire on its axis.

When the antenna is mounted horizontally above the ground, the situation depicted in **Fig 3** exists. Only one of the two lobes is considered in this drawing, and its lower half is cut off by the ground. The maximum intensity of radiation in the remaining half occurs through the broken-line semicircle; that is, the angle B (between the wire direction and the line marked wave direction) is the angle given by Fig 1 for the particular antenna length used.

In the practical case, there will be some wave angle (A) that is optimum for the frequency and the distance between the transmitter and receiver. Then, for that wave angle, the wire direction and the optimum geographical direction of transmission are related by the angle C. If the wave angle is very low, B and C will be practically equal. But as the wave angle becomes higher the angle C becomes smaller. In other words, the best direction of transmission and the direction of the wire more nearly coincide. They coincide exactly when C is zero; that is, when the wave angle is the same as the angle given by Fig 1.

The maximum radiation from the antenna can be aligned with a particular geographical direction at a given wave angle by means of the following formula.

$$\cos C = \frac{\cos B}{\cos A}$$

In most amateur work the chief requirement is that the wave angle should be as low as possible, particularly at 14 MHz and above. In this case it is usually satisfactory to make angle C the same as that given by Fig 1.

It should be borne in mind that only the maximum point of the lobe is represented in Fig 3. Radiation at higher and lower wave angles in any given direction will be proportional to the way in which the actual pattern shows the field strength to vary as compared with the maximum point of the lobe.

Tilted Wires

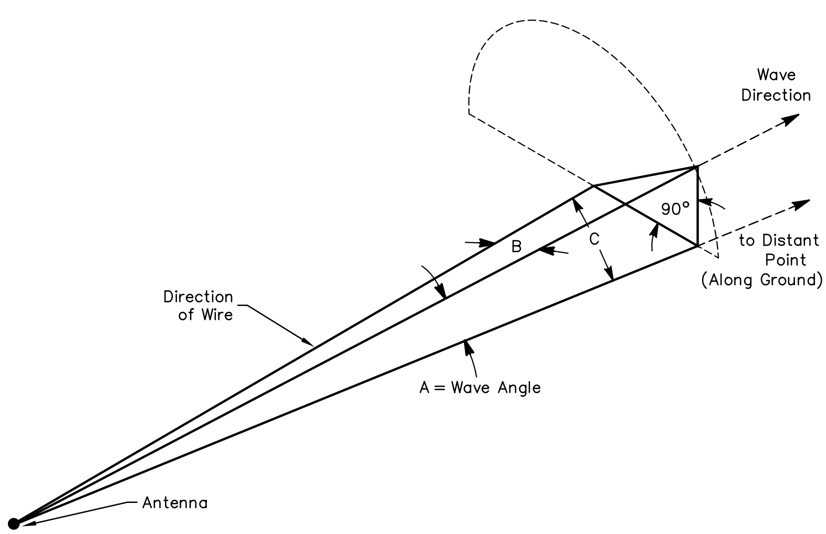

Fig 3—This drawing shows how the hollow cone of radiated energy from a long wire (broken-line arc) results in different wave angles (A) for various angles between the direction of the wire and the direction to the distant point (B).

Fig 3 shows that when the wave angle is equal to the angle which the maximum intensity of the lobe makes with the wire, the best transmitting or receiving direction is that of the wire itself. If the wave angle is less than the lobe angle, the best direction can be made to coincide with the direction of the wire by tilting the wire enough to make the lobe and wave angle coincide. This is shown in **Fig 4**, for the case of a one-wavelength antenna tilted so that the maximum radiation from one lobe is horizontal to the left, and from the other is horizontal to the right (zero wave angle). The solid pattern can be visualized by imagining the plane diagram rotating about the antenna as an axis.

Since the antenna is neither vertical nor horizontal in this case, the radiation is part horizontally polarized and part vertically polarized. In computing the effect of the ground, the horizontal and vertical components must be handled separately. In general, the directive pattern at any given wave angle becomes unsymmetrical when the antenna is tilted. For small amounts of tilt (less than the amount that directs the lobe angle horizontally), and for low wave angles, the effect is to shift the optimum direction closer to the line of the antenna. This is true in the direction in which the antenna slopes downward. In the opposite direction the low-angle radiation is reduced.

Feeding Long Wires

It is pointed out in Chapter 26 that a harmonic antenna can be fed only at the end or at a current loop. Since a current loop changes to a node when the antenna is operated at any even multiple of the frequency for which it is designed, a long-wire antenna will operate as a true long wire on all bands only when it is fed at the end.

A common method of feeding is to use a resonant open-wire line, as described in Chapter 26. This system will work on all bands down to the one, if any, at which the antenna is only a half wave long. Any convenient line length can be used if the transmitter is matched to the line input impedance by the methods described in Chapter 25.

Two arrangements for using nonresonant lines are given in **Fig 5**. The one at A is useful for one band only since the matching section must be a quarter wave long, approximately, unless a different matching section is used for each band. In B, the Q-section impedance should be adjusted to match the antenna to the line as described in Chapter 26, using the value of radiation resistance given in Chapter 2. This method is best suited to working with a 600-Ω transmission line. Although it will work as designed on only one band, the antenna can be used on other bands by treating the line and matching transformer as a resonant line. In this case, as mentioned earlier, the antenna will not radiate as a true long wire on even multiples of the frequency for which the matching system is designed.

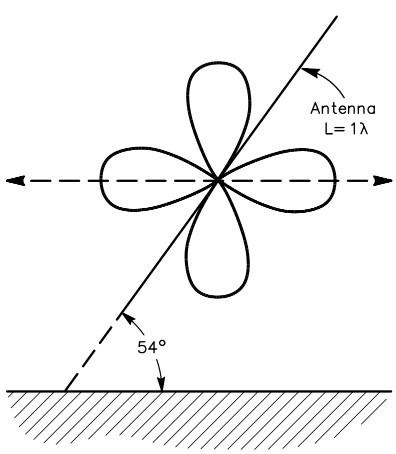

Fig 4—Alignment of lobes for horizontal transmission by tilting a long wire in the vertical plane.

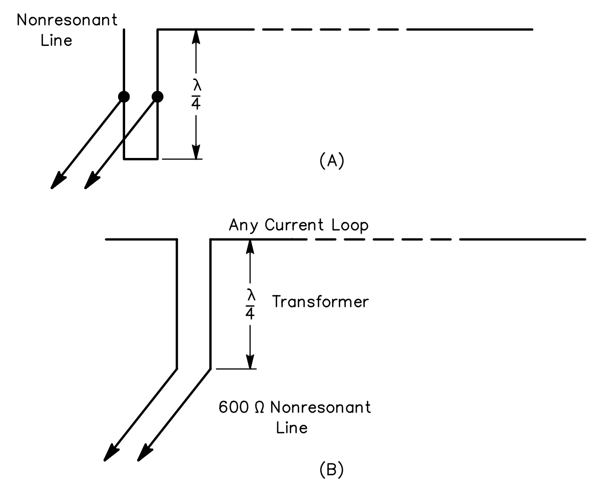

Fig 5—Methods of feeding long single-wire antennas.

The end-fed arrangement, although the most convenient when tuned feeders are used, suffers the disadvantage that there is likely to be a considerable antenna current on the line, as described in Chapter 26. In addition, the antenna reactance changes rapidly with frequency for the reasons outlined in Chapter 2. Consequently, when the wire is several wavelengths long, a relatively small change in frequency—a fraction of the width of a band—may require major changes in the adjustment of the transmitter-to-line coupling apparatus. Also, the line becomes unbalanced at all frequencies between those at which the antenna is exactly resonant. This leads to a considerable amount of radiation from the line. The unbalance can be overcome by using two long wires in one of the arrangements described in succeeding sections.

COMBINATIONS OF RESONANT LONG WIRES

The directivity and gain of long wires may be increased by using two wires placed in relation to each other such that the fields from both combine to produce the greatest possible field strength at a distant point. The principle is similar to that used in designing the multielement arrays described in Chapter 8. However, the maximum radiation from a long wire occurs at an angle of less than 90° with respect to the wire, so different physical relationships must be used.

Parallel Wires

One possible method of using two (or more) long wires is to place them in parallel, with a spacing of $^1/_2$ wavelength or so, and feed the two in phase. In the direction of the wires the fields will add in phase. However, since the wave angle is greatest in the direction of the wire, as shown by Fig 3, this method will result in rather high-angle radiation unless the wires are several wavelengths long. The wave angle can be lowered, for a given antenna length, by tilting the wires as described earlier. With a parallel arrangement of this sort the gain should be about 3 dB over a single wire of the same length, at spacings in the vicinity of $^1/_2$ wavelength.

THE V ANTENNA

Instead of using two long wires parallel to each other, they may be placed in the form of a horizontal V, with the angle between the wires equal to twice the angle given by Fig 1 for the particular length of wire used. The currents in the two wires should be *out of phase*. Under these conditions the plane directive patterns of the individual wires combine as shown in **Fig 6**. Along a line in the plane of the antenna and bisecting the V, the fields from the individual wires reinforce each other at a distant point. The other pair of lobes in the plane pattern is more or less eliminated, so the pattern becomes essentially bidirectional.

The directional pattern of an antenna of this type is sharper in both the horizontal and vertical planes than the patterns of the individual wires composing it. Maximum radiation in both planes is along the line bisecting the V. There are minor lobes in both the horizontal and vertical patterns, but if the legs are long in terms of wavelength the amplitude of the minor lobes is small. When the antenna is mounted horizontally above the ground, the wave angle at which the radiation from the major lobe is maximum is determined by the height, but cannot exceed the angle values shown in Fig 1 for the leg length used. Only the minor lobes give high-angle radiation.

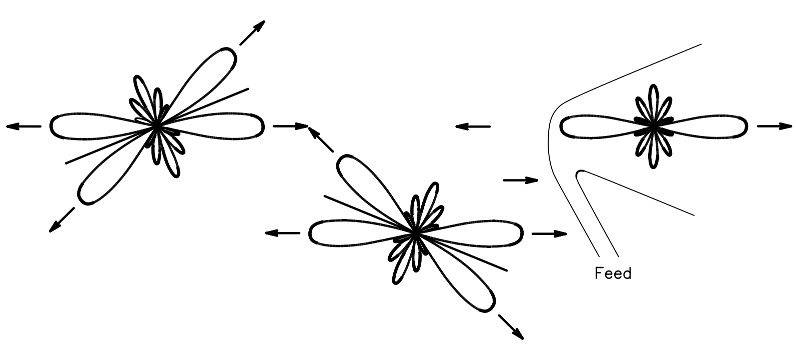

Fig 6—Two long wires and their respective patterns are shown at the left. If these two wires are combined to form a V with an angle that is twice that of the major lobes of the wires and with the wires excited out of phase, the radiation along the bisector of the V adds and the radiation in the other directions tends to cancel.

The gain and directivity of a V depend on the length of the legs. An approximate idea of the gain for the V antenna may be obtained by adding 3 dB to the gain value from Fig

1 for the corresponding leg length. The actual gain will be affected by the mutual impedance between the sides of the V, and will be somewhat higher than indicated by the values determined as above, especially at longer leg lengths. With 8-wavelength legs, the gain is approximately 4 dB greater than that indicated for a single wire in Fig 1.

Lobe Alignment

It is possible to align the lobes from the individual wires with a particular wave angle by the method described in connection with Fig 3. At very low wave angles the required change in the apex angle is extremely small; for example, if the desired wave angle is 5° the apex angles of twice the value given in Fig 1 will not need to be reduced more than a degree or so, even at the longest leg lengths which might be used.

When the legs are long, alignment does not necessarily mean that the greatest signal strength will be obtained at the wave angle for which the apex angle is chosen. Keep in mind that the polarization of the radiated field is the same as that of a plane containing the wire. As illustrated by the diagram of Fig 3, at any wave angle other than zero, the plane containing the wire and passing through the desired wave angle is not horizontal. In the limiting case where the wave angle and the angle of maximum radiation from the wire are the same, the plane is vertical, and the radiation at that wave angle is vertically polarized. At in-between angles the polarization consists of both horizontal and vertical components.

When two wires are combined into a V, the polarization planes have opposite slopes. In the plane bisecting the V, this makes the horizontally polarized components of the two fields add together numerically, but the vertically polarized components are out of phase and cancel completely. As the wave angle is increased, the horizontally polarized components become smaller, so the intensity of horizontally polarized radiation decreases. On the other hand, the vertically polarized components become more intense but always cancel each other. The overall result is that although alignment for a given wave angle will increase the useful radiation at that angle, the wave angle at which maximum radiation occurs (in the direction of the line bisecting the V) is always below the wave angle for which the wires are aligned. As shown by **Fig 7**, the difference between the apex angles required for optimum alignment of the lobes at wave angles of 0° and 15° is rather small, even when the legs are many wavelengths long.

For long-distance transmission and reception, the lowest possible wave angle usually is the best. Consequently, it is good practice to choose an apex angle between the limits represented by the two curves in Fig 7. The actual wave angle at which the radiation is maximum will depend on the shape of the vertical pattern and the height of the antenna above ground.

When the leg length is small, there is some advantage in reducing the apex angle of the V because

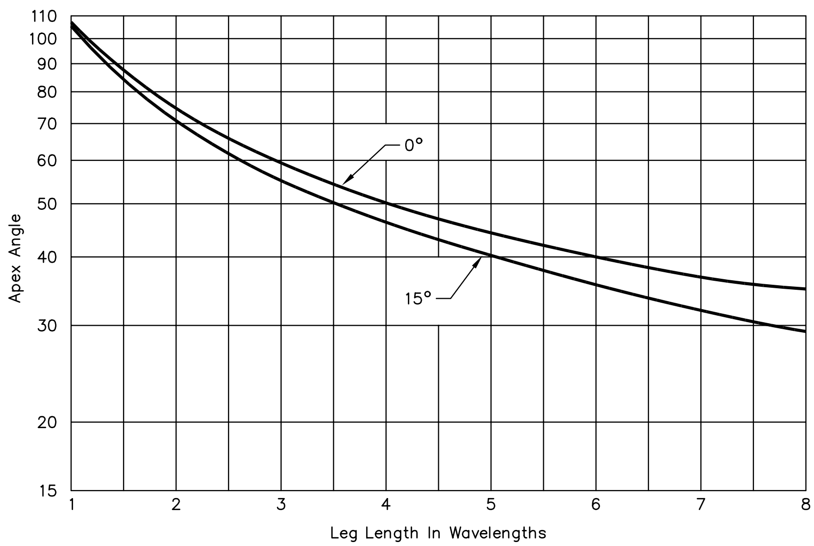

Fig 7—Apex angle of V antenna for alignment of main lobe at different wave angles, as a function of leg length in wavelengths.

this changes the mutual impedance in such a way as to increase the gain of the antenna. For example, the optimum apex angle in the case of 1-λ legs is 90°.

Multiband Design

When a V antenna is used over a range of frequencies—such as 14 to 28 MHz—its characteristics over the frequency range will not change greatly if the legs are sufficiently long at the lowest frequency. The apex angle, at zero wave angle, for a 5-wavelength V (each leg approximately 350 feet long at 14 MHz) is 44°. At 21 MHz, where the legs are 7.5 wavelengths long, the optimum angle is 36°, and at 28 MHz where the leg length is 10 wavelengths it is 32°. Such an antenna will operate well on all three frequencies if the apex angle is about 35°. From Fig 7, a 35° apex angle with a 5-wavelength V will align the lobes at a wave angle of something over 15°, but this is not too high when it is kept in mind that the maximum radiation actually will be at a lower angle. At 28 MHz the apex angle is a little large, but the chief effect will be a small reduction in gain and a slight broadening of the horizontal pattern, together with a tendency to reduce the wave angle at which the radiation is maximum. The same antenna can be used at 3.5 and 7 MHz, and on these bands the fact that the wave angle is raised is of less consequence, as high wave angles are useful. The gain will be small, however, because the legs are not very long at these frequencies.

Other V Combinations

A gain increase of about 3 dB can be had by stacking two Vs one above the other, a half wavelength apart, and feeding them with in-phase currents. This will result in a lowered angle of radiation. The bottom V should be at least a quarter wavelength above the ground, and preferably a half wavelength.

Two V antennas can be broadsided to form a W, giving an additional 3-dB gain. However, two transmission lines are required and this, plus the fact that five poles are needed to support the system, renders it impractical for the average amateur.

The V antenna can be made unidirectional by using a second Vplaced an odd multiple of a quarter wavelength in back of the first and exciting the two with a phase difference of 90°. The system will be unidirectional in the direction of the antenna with the lagging current. However, the V reflector is not normally employed by amateurs at low frequencies because it restricts the use to one band and requires a fairly elaborate supporting structure. Stacked Vs with driven reflectors could, however, be built for the 200 to 500-MHz region without much difficulty. The overall gain for such an antenna (two stacked Vs, each with a V reflector) is about 9 dB greater than the gains given in Fig 1.

Feeding the V

The V antenna is most conveniently fed with tuned feeders, since they permit multiband operation. Although the length of the wires in a V beam is not at all critical, it is important that both wires be of the same electrical length. If the use of a nonresonant line is desired, probably the most appropriate matching system is that using a stub or quarter-wave matching section. The adjustment of such a system is described in Chapter 26.

THE RESONANT RHOMBIC ANTENNA

The diamond-shaped or rhombic antenna shown in **Fig 8** can be looked upon as two acute-angle Vs placed end-to-end. This arrangement is called a resonant rhombic, and has two ad-vantages over the simple V that have caused it to be favored by amateurs. For the same total wire length it gives somewhat greater gain than the V. A rhombic 4 wavelengths on a leg, for example, has better than 1 dB gain over a V antenna with 8 wavelengths on a leg. And the directional pattern of the rhombic is less frequency sensitive than the V when the antenna is used over a wide frequency range. This is because a

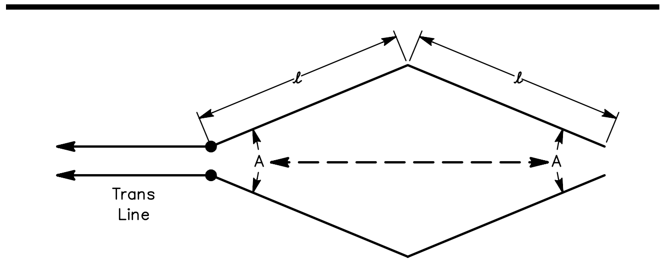

Fig 8—The resonant rhombic or diamond-shaped antenna. All legs are the same length, and opposite angles of the diamond are equal. Length ℓ is an integral number of half wavelengths.

change in frequency causes the major lobe from one leg to shift in one direction while the lobe from the opposite leg shifts the other way. This tends to make the optimum direction stay the same over a considerable frequency range. The leg lengths of the rhombic must be an integral number of half wavelengths in order to avoid reactance at its feed point. It is for this reason that the antenna bears the name *resonant* rhombic. The disadvantage of the rhombic as compared with the V is that one additional support is required.

The same factors that govern the design of the V antenna apply in the case of the resonant rhombic. The angle A in Fig 8 is the same as that for a V having a leg length equal to ℓ, Fig 8. If it is desired to align the lobes from individual wires with the wave angle, the curves of Fig 7 may be used, again using the length of one leg in taking the data from the curves. The diamond-shaped antenna also can be operated as a terminated antenna, as described later in this chapter, and much of the discussion in that section applies to the resonant rhombic as well.

The direction of maximum radiation with a resonant rhombic is given by the broken-line arrows in Fig 8; that is, the antenna is bidirectional. There are minor lobes in other directions, their number and intensity depending on the leg length. When used at frequencies below the VHF region, the rhombic antenna is always mounted with the plane containing the wires horizontal. The polarization in this plane, and also in the perpendicular plane that bisects the rhombic, is horizontal. At 144 MHz and above, the dimensions are such that the antenna can be mounted with the plane containing the wires vertical if vertical polarization is desired.

When the rhombic antenna is to be used on several HF amateur bands, it is advisable to choose the apex angle, A, on the basis of the leg length in wavelengths at 14 MHz. This point is covered in more detail in connection with both the V and the terminated rhombic. Although the gain on higher frequency bands will not be quite as favorable as if the antenna had been designed for the higher frequencies, the system will radiate well at the low angles that are necessary at such frequencies. At frequencies below the design frequency, the greater apex angle of the rhombic (as compared with a V of the same total length) is more favorable to good radiation than in the case of the V.

The resonant rhombic antenna can be fed in the same way as the V. Resonant feeders are necessary if the antenna is to be used in several amateur bands.

TERMINATED LONG-WIRE ANTENNAS

All the antenna systems considered so far in this chapter have been based on operation with standing waves of current and voltage along the wire. Although most antenna designs are based on using resonant wires, resonance is by no means a necessary condition for the wire to radiate and intercept electromagnetic waves efficiently. The result of using nonresonant wires is reactance at the feed point, unless the antenna is terminated.

In **Fig 9**, let us suppose that the wire is parallel with the ground (horizontal) and is terminated by a load Z equal to its characteristic impedance, Z_0. The load Z can represent a receiver matched to the line. The resistor R is also equal to the Z_0 of the wire. A wave coming from direction X will strike the wire first at its far end and sweep across the wire at some angle until it reaches the end at which Z is connected. In so doing, it will induce voltages in the antenna, and currents will flow as a result. The current flowing toward Z is the useful output of the antenna, while the current flowing toward R will be absorbed in R. The same thing is true of a wave coming from the direction X′. In such an antenna there are no standing waves, because all received power is absorbed at either end.

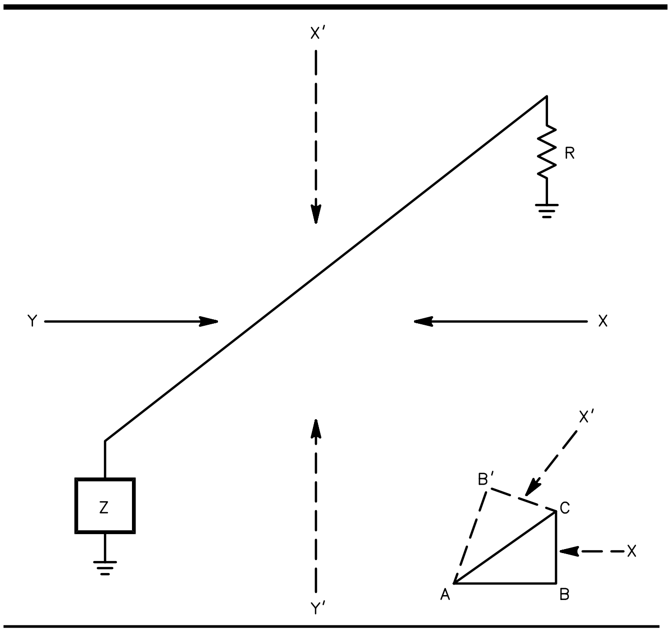

Fig 9—Terminated long-wire antenna.

The greatest possible power will be delivered to the load Z when the individual currents induced as the wave sweeps across the wire all combine properly on reaching the load. The currents will reach Z in optimum phase when the time required for a current to flow from the far end of the antenna to Z is exactly one-half cycle longer than the time taken by the wave to sweep over the antenna. A half cycle is equivalent to a half wavelength greater than the distance traversed by the wave from the instant it strikes the far end of the antenna to the instant that it reaches the near end. This is shown by the small drawing, where AC represents the antenna, BC is a line perpendicular to the wave direction, and AB is the distance traveled by the wave in sweeping past AC. AB must be one-half wavelength shorter than AC. Similarly, AB′ must be the same length as AB for a wave arriving from X′.

A wave arriving at the antenna from the opposite direction Y (or Y′), will similarly result in the largest possible current at the far end. However, since the far end is terminated in R, which is equal to Z, all the power delivered to R by the wave arriving from Y will be absorbed in R. The current traveling to Z will produce a signal in Z in proportion to its amplitude. If the antenna length is such that all the individual currents arrive at Z in such phase as to add up to zero, there will be no current through Z. At other lengths the resultant current may reach appreciable values. The lengths that give zero amplitude are those which are odd multiples of $^1/_4$ wavelength, beginning at $^3/_4$ wavelength. The response from the Y direction is greatest when the antenna is any even multiple of $^1/_2$ wavelength long; the higher the multiple, the smaller the response.

Directional Characteristics

The explanation above considers the phase but not the relative amplitudes of the individual currents reaching the load. When the appropriate correction is made, the angle with the wire at which radiation or response is maximum is given by the curve of **Fig 10**. The response drops off gradually on either side of the maximum point, resulting in lobes in the directive pattern much like those for harmonic antennas, except that the system is essentially unidirectional. Typical patterns are shown in **Fig 11**. When the antenna length is 3/2 λ or greater, there are also angles at which secondary maxima (minor lobes) occur; these secondary maxima have peaks approximately at angles for which the length AB, Fig 9, is less than AC by any odd multiple of one-half wavelength. When AB is shorter than AC by an even multiple of a half wavelength, the induced currents cancel each other completely at Z, and in such cases there is a null for waves arriving in the direction perpendicular to BC.

The antenna of Fig 9 responds to horizontally polarized signals when mounted horizontally. If the wire lies in a plane that is vertical with respect to the earth, it responds

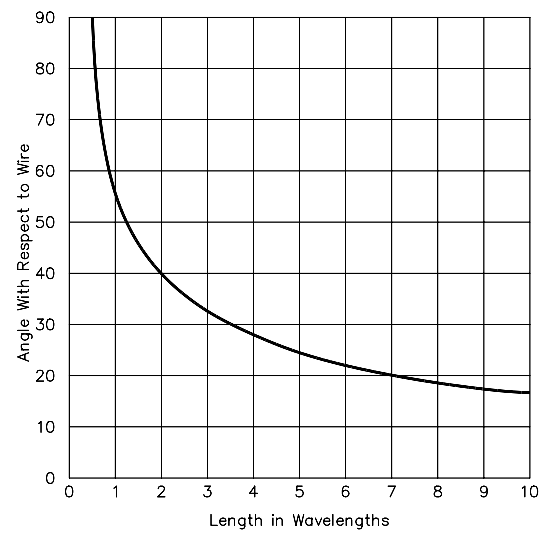

Fig 10—Angle with respect to wire axis at which the radiation from a terminated long-wire antenna is maximum.

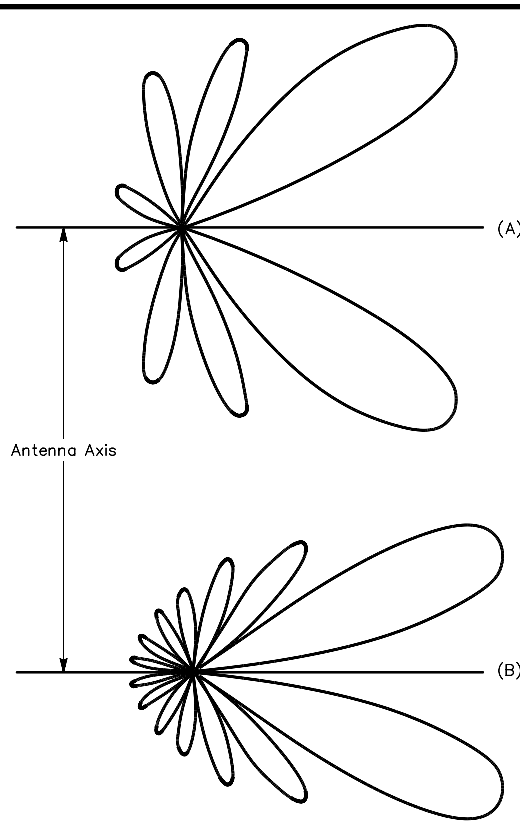

Fig 11—Typical radiation patterns (cross section of solid figure) for terminated long wires. At A, the length is two wavelengths, at B, four wavelengths, both for an idealized case in which there is no decrease of current along the wire. In practice, the pattern is somewhat distorted by wire attenuation.

to vertically polarized signals. By reciprocity, the directive characteristics for transmitting are the same as for receiving. For average conductor diameters and heights above ground, 20 or 30 feet, the Z_0 of the antenna is of the order of 500 to 600 Ω.

It is apparent that an antenna operating in this way has much the same characteristics as a transmission line. When it is properly terminated at both ends there are traveling waves—but no standing waves—on the wire. Consequently the current is essentially the same all along the wire over any given period of time. Actually, it decreases slightly in the direction in which the current is flowing because of energy loss by radiation as well as by ohmic loss in the wire and the ground. The antenna can be looked upon as a transmission line terminated in its characteristic impedance, but having such wide spacing between conductors (the second conductor in this case is the image of the antenna in the ground) that radiation losses are by no means inconsequential.

A wire terminated in its characteristic imped- ance will work on any frequency, but its dir- ectional characteristics change with frequency as shown by Fig 10. To give any appreciable gain over a dipole, the wire must be at least a few wavelengths along. The angle at which maximum response occurs can be in any plane that contains the wire axis, so in free space the major lobe will be a hollow cone. In the presence of ground, the discussion given in connection with Fig 3 applies, with the modification that the angles of best radiation or response are those given in Fig 10, rather than by Figs 1 or 2. As comparison of the curves will show, the difference in the optimum angle between resonant and terminated wires is quite small.

The Sloping V

The sloping V antenna, illustrated in **Fig 12**, is a terminated system. Even though it is simple to construct and offers multiband operation, it has not seen much use by amateurs. Only a single support is required, and the antenna should provide several decibels of gain over a frequency ratio of 3 to 1 or greater.

For satisfactory performance, the leg length, ℓ, should be a minimum of one wavelength at the lowest operating frequency. The height of the support may be ½ to ¾ of the leg length.The feed-point impedance of the sloping V is on the order of 600 Ω. Therefore, open-wire line may be used for the feeder or, alternatively, a coaxial transmission line and a step-up transformer balun at the apex of the V may be used.

The terminating resistors should each be noninductive with a value of 300 Ω and a dissipation rating equal to one-half the transmitter output power. The grounded end of the resistors should be connected to a good RF ground, such as a radial system extending beneath the wires of the V. A single ground stake at each termination point will likely be insufficient; a pair of wires, one running from each termination point to the base of the support will probably prove superior.

By using the data presented earlier in this chapter, it should be possible to calculate the apex angle and support height for optimum lobe alignment from the two wires at a given frequency. Ground reflections will complicate the calculations, however, as both vertical and horizontal polarization components are present. Dimensions that have proved useful for point-to-point communications work on frequencies from 14 to 30 MHz are a support height of 60 feet, a leg length of 100 feet, and an apex angle of 36°.

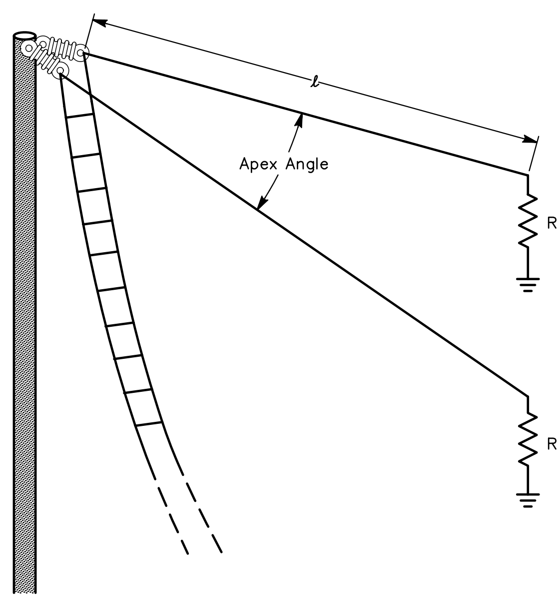

Fig 12—The sloping V antenna.

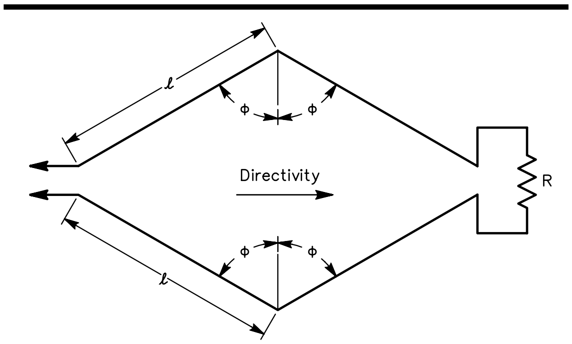

Fig 13—The terminated rhombic antenna.

THE TERMINATED RHOMBIC ANTENNA

The highest development of the long-wire antenna is the terminated rhombic, shown schematically in **Fig 13**. It consists of four conductors joined to form a diamond, or rhombus. All sides of the antenna have the same length and the opposite corner angles are equal. The antenna can be considered as being made up of two V antennas placed end to end and terminated by a noninductive resistor to produce a unidirectional pattern. The terminating resistor is connected between the far ends of the two sides, and is made approximately equal to the characteristic impedance of the antenna as a unit. The rhombic may be constructed either horizontally or vertically, but is practically always constructed horizontally at frequencies below 54 MHz, since the pole height required is considerably less. Also, horizontal polarization is equally, if not more, satisfactory at these frequencies.

The basic principle of combining lobes of maximum radiation from the four individual wires constituting the rhombus or diamond is the same in either the terminated type shown in Fig 13, or the resonant type described earlier in this chapter. The included angles should differ slightly because of the differences between resonant and terminated wires, as just described, but the differences are almost negligible.

Tilt Angle

In dealing with the terminated rhombic, it is a matter of custom to talk about the “tilt angle” (ϕ in Fig 13), rather than the angle of maximum radiation with respect to an individual wire. The tilt angle is simply 90° minus the angle of maximum radiation. In the case of a rhombic antenna designed for zero wave angle, the tilt angle is 90° minus the values given in Fig 10.

Fig 14 shows the tilt angle as a function of the antenna leg length. The curve marked “0°” is used for a wave angle of 0°; that is, maximum radiation in the plane of the antenna. The other curves show the proper tilt angles to use when aligning the major lobe with a desired wave angle. For a wave angle of 5° the difference in tilt angle is less than 1° for the range of lengths shown. Just as in the case of the resonant V and resonant rhombic, alignment of the wave angle and lobes always results in still greater radiation at a lower wave angle, and for the same reason, but also results in the greatest possible radiation at the desired wave angle.

The broken curve marked “optimum length” shows the leg length at which maximum gain is obtained at any given wave angle. Increasing the leg length beyond the optimum will result in lessened gain, and for that reason the curves do not extend beyond the optimum length. Note that the optimum length becomes greater as the desired wave angle decreases. Leg lengths over 6 λ are not recommended because the directive pattern becomes so sharp that the antenna performance is highly variable with small changes in the angle, both horizontal and vertical, at which an incoming wave reaches the antenna. Since these angles vary to some extent in ionospheric propagation, it does not pay to attempt to use too great a degree of directivity.

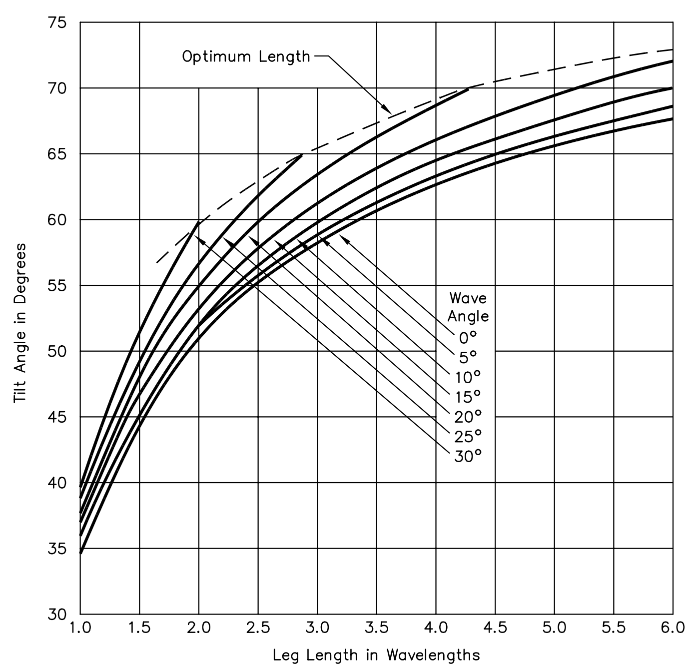

Fig 14—Rhombic-antenna design chart. For any given leg length, the curves show the proper tilt angle to give maximum radiation at the selected wave angle. The broken curve marked “optimum length” shows the leg length that gives the maximum possible output at the selected wave angle. The optimum length as given by the curves should be multiplied by 0.74 to obtain the leg length for which the wave angle and main lobe are aligned (see text, “Alignment of Lobes”).

Multiband Design

When a rhombic antenna is to be used over a considerable frequency range, it is worth paying some attention to the effect of the tilt angle on the gain and directive pattern at various frequencies. For example, suppose the antenna is to be used at frequencies up to and including the 28-MHz band, and that the leg length is to be 6 λ on that band. For zero wave angle, the optimum tilt angle is 68°, and the calculated free-space directive pattern in the vertical plane bisecting the antenna is shown in **Fig 15**, at B. At 14 MHz, this same antenna has a leg length of three wavelengths, which calls for a tilt angle of 58.5° for maximum radiation at zero wave angle. The calculated patterns for tilt angles of 58.5 and 68° are shown at A in Fig 15. These show that if the optimum tilt for 28-MHz operation is used, the gain will be reduced and the wave angle raised at 14 MHz. In an attempt at a compromise, we might select a wave angle of 15°, rather than zero, for 14 MHz. As shown by Fig 14, the tilt angle here is larger and thus more nearly coincides with the tilt angle for zero wave angle on 28 MHz. From the chart, the tilt angle for three wavelengths on a leg and a 15° wave angle is 61.5°. The patterns with this tilt angle are shown in Fig 15 for both the 14 and 28-MHz cases. The effect at 28 MHz is to decrease the gain at zero wave angle by more than 6 dB and to split the radiation in the vertical plane into two lobes, one of which is at a wave angle too high to be useful at this frequency.

Inasmuch as the gain increases with the leg length in wavelengths, it is probably better to favor the lower frequency in choosing the tilt angle. In the present example, the best compromise probably would be to split the difference between the optimum tilt angle for the 15° wave angle at 14 MHz and that for zero wave angle at 28 MHz; that is, use a tilt angle of about 64°. Design dimensions for such an antenna are given in **Fig 16**.

The patterns of Fig 15 are in the vertical plane through the center of the antenna only. In vertical planes making an angle with the antenna axis, the patterns may differ considerably. The effect of a tilt angle that is smaller than the optimum is to broaden the horizontal pattern, so at 28 MHz the antenna in the example would be less directive in the horizontal plane than would be the case if it were designed for optimum performance at that frequency. It should also be noted that the patterns given in Fig 15 are free-space patterns and must be multiplied by the ground-reflection factors for the actual antenna height used, if the actual vertical patterns are to be determined. (Also see later discussion on lobe alignment.)

Power Gain

The theoretical power gain of a terminated rhombic antenna over a dipole (both in free space) is given by the curve of **Fig 17**. This curve is for zero wave angle and includes an allowance of 3 dB for power

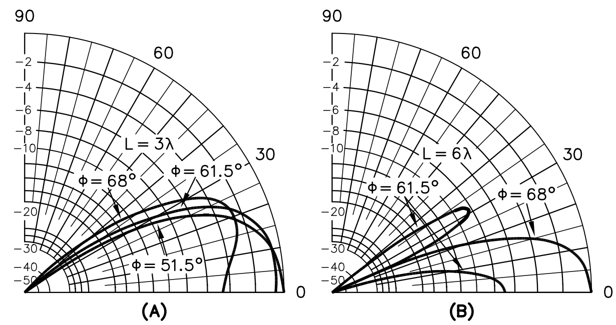

Fig 15—These drawings show the effect of tilt angle on the free-space vertical pattern of a terminated rhombic antenna having a leg length of three wavelengths at one frequency and six wavelengths at twice the frequency. These patterns apply only in the direction of the antenna axis. Minor lobes above 30° are not shown.

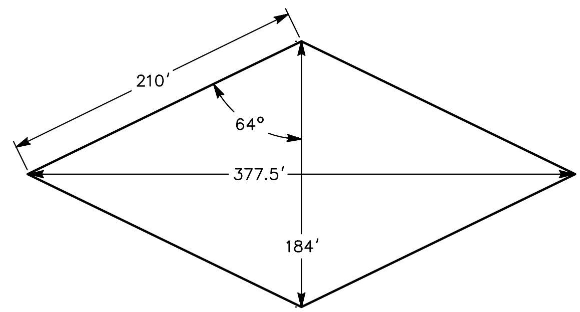

Fig 16—Rhombic antenna dimensions for a compromise design between 14 and 28-MHz requirements, as discussed in the text. The leg length is 6 λ at 28 MHz, 3 λ at 14 MHz.

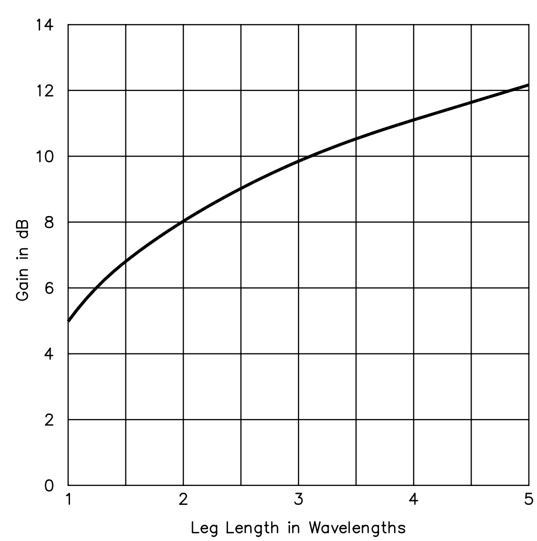

Fig 17—Theoretical gain of a terminated rhombic antenna over a half-wave dipole in free space. This curve includes an allowance of 3 dB for loss in the terminating resistor.

dissipated in the terminating resistor. The actual gain of an antenna mounted horizontally above the ground, as compared with a dipole at the same height, can be expected to vary a bit either way from the figures given by the curve. The power lost in the terminating resistor is probably less than 3 dB in the average installation, since more than half of the input power is radiated before the end of the antenna is reached. However, there is also more power loss in the wire and in the ground under the antenna than in the case of a simple dipole, so the 3 dB figure is probably a representative estimate of overall loss.

Termination

Although there is no marked difference in the gain obtainable with resonant and terminated rhombics of comparable design, the terminated antenna has the advantage that over a wide frequency range it presents an essentially resistive and constant load to the transmitter. In addition, terminated operation makes the antenna essentially unidirectional, while the unterminated or resonant rhombic is always bidirectional (although not symmetrically so). In a sense, the power dissipated in the terminating resistor can be considered power that would have been radiated in the other direction had the resistor not been there. Therefore, the fact that some of the power (about one-third) is used up in heating the resistor does not mean an actual loss in the desired direction.

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

The terminating resistor must be practically a pure resistance at the operating frequencies; that is, its inductance and capacitance should be negligible. Ordinary wire-wound resistors are not suitable because they have far too much inductance and distributed capacitance. Small carbon resistors have satisfactory electrical characteristics but will not dissipate more than a few watts and so cannot be used, except when the transmitter power does not exceed 10 or 20 W or when the antenna is to be used for reception only. The special resistors designed either for use as "dummy" antennas or for terminating rhombic antennas should be used in other cases. To allow a factor of safety, the total rated power dissipation of the resistor or resistors should be equal to half the power output of the transmitter.

To reduce the effects of stray capacitance it is desirable to use several units, say three, in series even when one alone will safely dissipate the power. The two end units should be identical and each should have $^1/_4$ to $^1/_3$ the total resistance, with the center unit making up the difference. The units should be installed in a weatherproof housing at the end of the antenna to protect them and to permit mounting without mechanical strain. The connecting leads should be short so that little extraneous inductance is introduced.

Alternatively, the terminating resistance may be placed at the end of an 800-Ω line connected to the end of the antenna. This will permit placing the resistors and their housing at a point convenient for adjustment rather than at the top of the pole. Resistance wire may be used for this line, so that a portion of the power will be dissipated before it reaches the resistive termination, thus permitting the use of lower-wattage lumped resistors. The line length is not critical, since it operates without standing waves.

Multiwire Rhombics

The input impedance of a rhombic antenna constructed as in Fig 13 is not quite constant as the frequency is varied. This is because the varying separation between the wires causes the characteristic impedance of the antenna to vary along its length. The variation in Z_0 can be minimized by a conductor arrangement that increases the capacitance per unit length in proportion to the separation between the wires.

The method of accomplishing this is shown in **Fig 18**. Three conductors are used, joined together at the ends but with increasing separation as the junction between legs is approached. For HF work the spacing between the wires at the center is 3 to 4 feet, which is similar to that used in commercial installations using legs several wavelengths long. Since all three wires should have the same length, the top and bottom wires should be slightly farther from the support than the middle wire. Using three wires in this way reduces the Z_0 of the antenna to approximately 600 Ω, thus providing a better match for practical open-wire line, in addition to smoothing out the impedance variation over the frequency range.

A similar effect (although not quite as favorable) is obtained by using two wires instead of three. The three-wire system has been found to increase the gain of the antenna by about 1 dB over that of a single-conductor version.

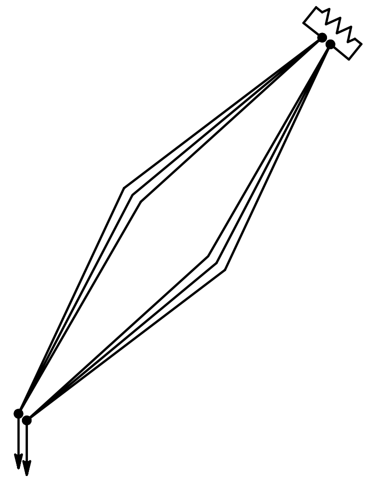

Fig 18—Three-wire rhombic antenna. Use of multiple wires improves the impedance characteristic of a terminated rhombic and increases the gain somewhat.

Front-to-Back Ratio

It is theoretically possible to obtain an infinite front-to-back ratio with a terminated rhombic antenna, and in practice very large values can be had. However, when the antenna is terminated in its characteristic impedance the infinite front-to-back ratio can be obtained only at frequencies for which the leg length is an odd multiple of a quarter wavelength, as described in the section on terminated long wires. The front-to-back ratio is smallest at frequencies for which the leg length is a multiple of a half wavelength.

When the leg length is not an odd multiple of a quarter wave at the frequency under consideration, the front-to-back ratio can be made very high by decreasing the value of terminating resistance slightly. This permits a small reflection from the far end of the antenna, which cancels out the residual response at the input end. With large antennas, the front-to-back ratio may be made very large over the whole frequency range by experimental adjustment of the terminating resistance. Modification of the terminating resistance can result in a splitting of the back null into two nulls, one on either side of a small lobe in the back direction. Changes in the value of terminating resistance thus permit “steering” the back null over a small horizontal range so that signals coming from a particular spot not exactly to the rear of the antenna may be minimized.

Ground Effects

Reflections from the ground play exactly the same part in determining the vertical directive pattern of a horizontal rhombic antenna that they play with other horizontal antennas. Consequently, if a low wave angle is desired, it is necessary to make the height great enough to bring the wave angle into the desired range of values given by the charts in Chapter 23.

Alignment of Lobes, Wave Angle and Ground Reflections

When maximum antenna response is desired at a particular wave angle (or maximum radiation is desired at that angle), the major lobe of the antenna can be aligned not only with the wave angle as previously described, but also with a maximum in the ground-reflection factor. When this is done it is no longer possible to consider the antenna height independently of other aspects of rhombic design. The wave angle, leg length, and height become mutually dependent.

This method of design is of particular value when the antenna is built to be used over fixed transmission distances for which the optimum wave angle is known. It has had wide application in commercial work with terminated rhombic antennas, but seems less desirable for amateur use where, for the long-distance work for which rhombic antennas are built, the lowest wave angle that can be obtained is the most desirable. Alignment of all three factors is limited in application because it leads to impractical heights and leg lengths for small wave angles. Consequently, when a fairly broad range of low wave angles is the objective, it is more satisfactory to design for a low wave angle and simply make the antenna as high as possible.

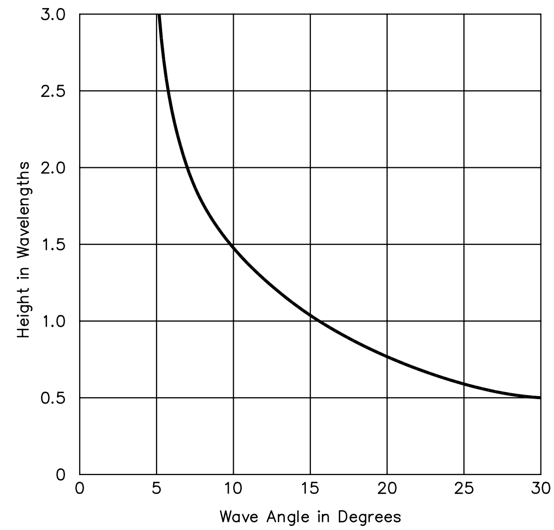

Fig 19—Antenna height to be used for maximum radiation at a desired wave angle. This curve applies to any type of horizontal antenna.

Fig 19 shows the lowest height at which ground reflections make the radiation maximum at a desired wave angle. It can be used in conjunction with Fig 14 for complete alignment of the antenna. For example, if the desired wave angle is 20°, Fig 19 shows that the height must be 0.75 λ. From Fig 14, the optimum leg length is 4.2 λ and the tilt angle is just under 70°. A rhombic antenna designed this way will have the maximum possible output that can be obtained at a wave angle of 20°; no other set of dimensions will be as good. However, it will have still greater output at some angle lower than 20°, for the reasons given earlier. When it is desired to make the maximum output of the antenna occur at the 20° wave angle, it may be accomplished by using the same height and tilt angle, but with the leg length reduced by 26%. Thus for such alignment, the leg length should be $4.2 \times 0.74 = 3.1$ λ. The output at the 20° wave angle will be smaller than with 4.2 λ legs, however, despite the fact that the smaller antenna has itsmaximum radiation at 20°. The reduction in gain is about 1.5 dB.

Methods of Feed

If the broad frequency characteristic of the rhombic antenna is to be utilized fully, the feeder system must be similarly broad. Open-wire transmission line of the same characteristic impedance as that shown at the antenna input terminals (approximately 700 to 800 Ω) may be used. Data for the construction of such lines is given in Chapter 24. While the usual matching stub can be used to provide an impedance transformation to more satisfactory line impedances, this limits the operation of the antenna to a comparatively narrow range of frequencies centering about that for which the stub is adjusted. Probably a more satisfactory arrangement would be to use a coaxial transmission line and a broadband transformer balun at the antenna feed point.

Wave Antennas

Perhaps the best known type of wave antenna is the Beverage. Many 160-meter enthusiasts have used Beverage antennas to enhance the signal-to-noise ratio while attempting to extract weak signals from the often high levels of atmospheric noise and interference on the low bands. Alternative antenna systems have been developed and used over the years, such as loops and long spans of unterminated wire on or slightly above the ground, but the Beverage antenna seems to be the best for 160-meter weak-signal reception. The information in this section was prepared by Rus Healy, NJ2L.

THE BEVERAGE ANTENNA

A Beverage is simply a wire antenna, at least one wavelength long, supported along its length at a fairly low height and terminated at the far end in its characteristic impedance. This antenna is shown in **Fig 20A**.

Improved HF reception with Beverage antennas may result from propagation conditions at a given time. However, because the incoming sky waves above medium frequency arrive at moderate and high angles, and because their polarization changes at random during reflection from the ionosphere, these waves do not excite a Beverage in the same way as MF signals. The wave antenna is responsive mostly to very low angle incoming waves that maintain a constant (vertical) polarization. These conditions are nearly always satisfied on 160 meters, and most of the time on 80 meters. As the frequency is increased, however, the polarization and arrival angles are less and less constant and favorable, making Beverages less effective at these frequencies. Many amateurs have, however, reported consistently excellent performance from Beverage antennas at frequencies as high as 10 MHz.

Beverage Theory

The Beverage antenna acts like a long transmission line with one lossy conductor (the earth), and one good conductor (the wire). Beverages have excellent directivity if erected properly, but they are quite inefficient. Therefore, they are not suitable for use as transmitting antennas.

Because the Beverage is a traveling-wave antenna, it has no standing waves resulting from radio signals. After a wave strikes the end of the Beverage from the desired direction, the wave induces voltages along the antenna and continues in space as well. Fig 20B shows part of a wave on the antenna resulting from a desired signal. This diagram also shows the tilt of the wave. The signal induces equal voltages in both directions. The resulting currents are equal and travel in both directions; the component traveling toward the termination end moves *against* the wave and thus builds down to a very low level at the termination end. Any residual signal resulting from this direction of current flow will be absorbed in the termination (if the termination is equal to the antenna impedance). The component of the signal flowing in the other direction, as we will see, becomes a key part of the received signal.

As the wave travels along the wire, the wave in space travels at approximately the same velocity. (There is some phase delay in the wire, as we shall see.) At any given point in time, the wave traveling along in space induces a voltage in the wire in addition to the wave already traveling on the wire (voltages already induced by the wave). Because these two waves are nearly in phase, the voltages add and build toward a maximum at the receiver end of the antenna.

This process can be likened to a series of signal generators lined up on the wire, with phase dif-

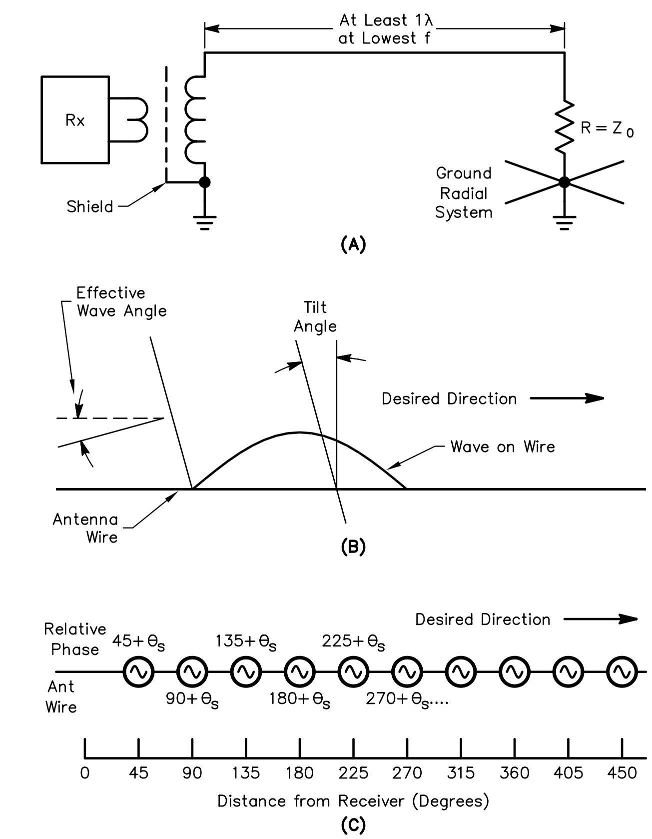

Fig 20—At A, a simple one-wire Beverage antenna with a variable termination impedance and a matching transformer for the receiver impedance. At B, a portion of a wave from the desired direction is shown traveling down the antenna wire. Its tilt angle and effective wave angle are also shown. At C, a situation analogous to the action of a Beverage on an incoming wave is shown. See text for discussion.

ferences corresponding to their respective spacings on the wire (Fig 20C). At the receiver end, a maximum voltage is produced by these voltages adding in phase. For example, the wave component induced at the receiver end of the antenna will be in phase (at the receiver end) with a component of the same wave induced, say, 270° (or any other distance) down the antenna, after it travels to the receiver end.

In practice, there is some phase shift of the wave on the wire with respect to the wave in space. This phase shift results from the velocity factor of the antenna. (As with any transmission line, the signal velocity on the Beverage is somewhat less than in free space.) Velocity of propagation on a Beverage is typically between 85 and 98% of that in free space. As antenna height is increased to a certain optimum height (which is about 10 feet for 160 meters), the velocity factor increases. Beyond this height, only minimal improvement is afforded, as shown in **Fig 21**. These curves are the result of experimental work done in 1922 by RCA, and reported in a *QST* article (November 1922) entitled "The Wave Antenna for 200-Meter Reception," by H.H. Beverage. The curve for 160 meters was extrapolated from the other curves.

Phase shift (per wavelength) is shown as a function of velocity factor in **Fig 22**, and is given by

$$\theta = 360 \left(\frac{100}{k} - 1 \right)$$

where k = velocity factor of the antenna in percent.

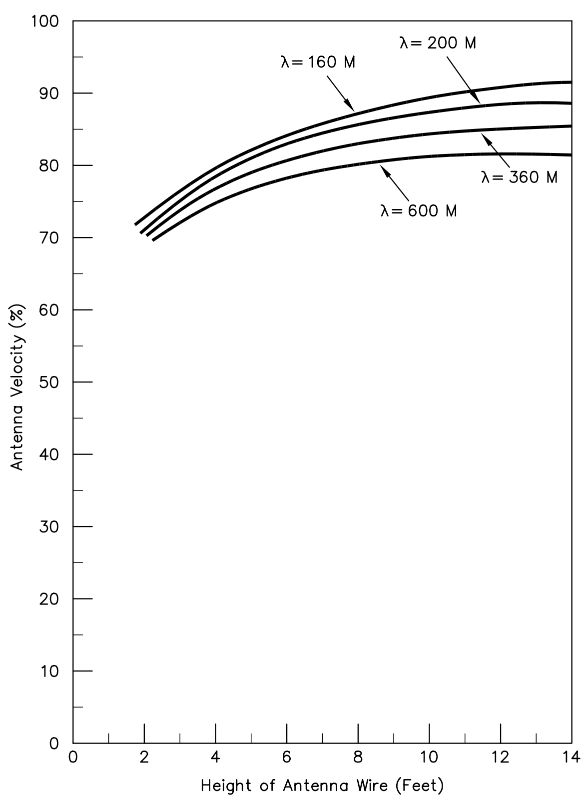

Fig 21—Signal velocity on a Beverage increases with height above ground, and reaches a practical maximum at about 10 feet. Improvement is minimal above this height. (The velocity of light is 100%.)

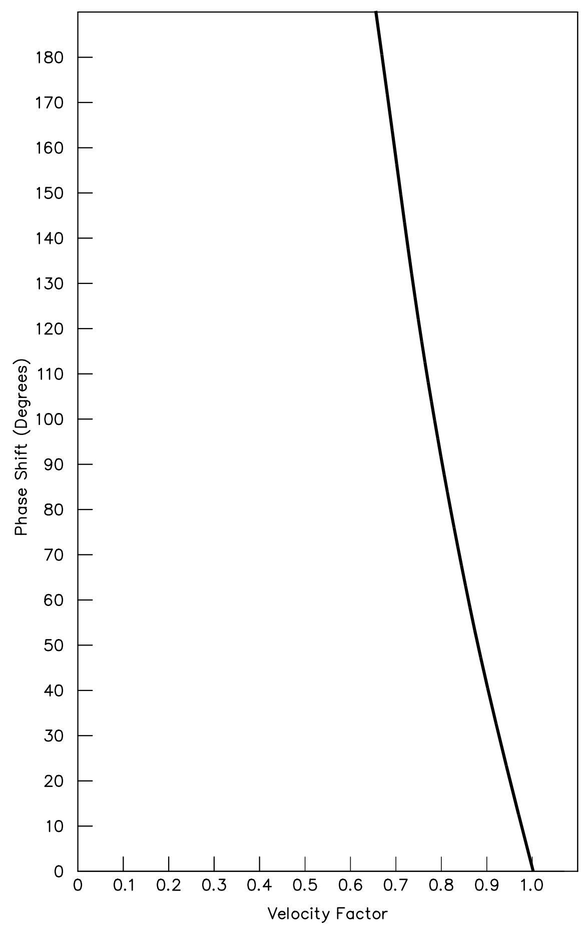

Fig 22—This curve shows phase shift (per wavelength) as a function of velocity factor on a Beverage antenna. Once the phase shift for the antenna goes beyond 90°, the gain drops off from its peak value, and any increase in antenna length will decrease gain.

The signals present on and around a Beverage antenna are shown graphically in A through D of **Fig 23**. These curves show relative voltage levels over a number of periods of the wave in space and their relative effects in terms of the total signal at the receiver end of the antenna.

Termination and Performance in Other Directions

The performance of a Beverage antenna in directions other than the favored one is quite different than previously discussed. Take, for instance, the case of a signal arriving perpendicular to the wire (90° either side of the favored direction). In this case, the wave induces voltages along the wire that are essentially *in phase*, so they arrive at the receiver end more or less out of phase, and thus cancel. (This can be likened to a series of signal generators lined up along the antenna as before, but having no progressive phase differences.)

As a result of this cancellation, Beverages exhibit deep nulls off the sides. Some minor sidelobes will exist, as with other horizontal antennas, and will increase in number with the length of the antenna.

In the case of a signal arriving from the rear of theantenna, the behavior of the antenna is very similar to its performance in the favored direction. The major difference is that the signal from the rear adds in phase at the *termination* end and is absorbed by the termination impedance.

For proper operation, the Beverage must be terminated at both ends in an impedance equal to the Z_0 of the antenna. This consists of matching the receiver impedance to the antenna at one end and terminating the other end in a resistor of the correct value.

If the termination impedance is not equal to the characteristic impedance of the antenna, some part of the signal from the rear will be reflected back toward the receiver end of the antenna. If the termination impedance is merely an open circuit (no terminating resistor), total reflection will result and the antenna will exhibit a bidirectional pattern (still with very deep nulls off the sides). An unterminated Beverage will not have the same response to signals in the rearward direction as it exhibits to signals in the forward direction because of attenuation and reradiation of part of the reflected wave as it travels back toward the receiver end. The difference in response is typically on the order of 3 dB for a 1-λ single-wire Beverage (see **Figs 24** and 25).

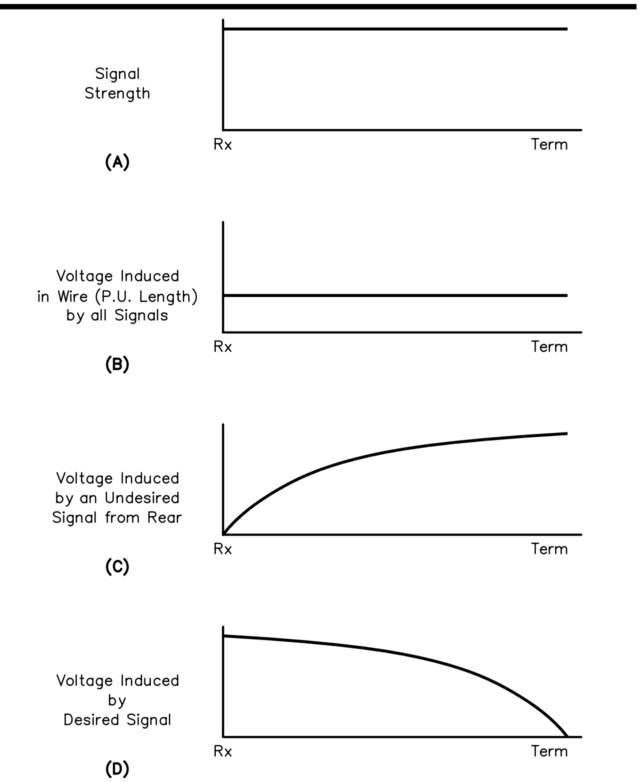

Fig 23—These curves show the voltages that appear in a Beverage antenna over a period of several cycles of the wave. Signal strength (at A) is constant over the length of the antenna during this period, as is voltage induced per unit length in the wire (at B). (The voltage induced in any section of the antenna is the same as the voltage induced in any other section of the same size, over the same period of time.) At C, the voltages induced by an undesired signal from the rearward direction add in phase and build to a maximum at the termination end, where they are dissipated in the termination (if $Z_{term} = Z_0$). The voltages resulting from a desired signal are shown at D. The wave on the wire travels closely with the wave in space, and the voltages resulting add in phase to a maximum at the receiver end of the antenna.

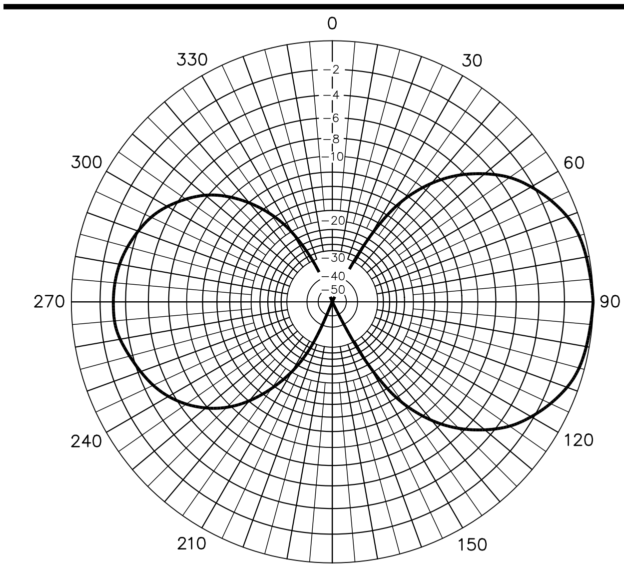

Fig 24—Directive pattern of a one-wavelength long unterminated Beverage antenna.

If the termination is between the extremes (open circuit and perfect termination in Z_0), the peak direction and intensity of signals off the rear of the Beverage will change. As a result, an adjustable reactive termination can be employed to "steer" the nulls to the rear of the antenna (see **Fig 26**). This can be of great help in eliminating an interfering signal from a rearward direction (typically 30-40° either side of the back direction).

To determine the appropriate value for a terminating resistor, it is necessary to know the characteristic impedance (surge impedance), Z_0, of the Beverage. It is interesting to note that Z_0 is not a function of the *length* of the Beverage, but only the wire size and height above ground. Characteristic impedance can be found empirically by choosing some resistive value within the typical range of 400-600 Ω and then adjusting it for optimum rejection of rearward signals. This method takes time, patience and (frequently) a second person to execute. It is far easier to start with a value that you know is close. The surge impedance of a single-wire Beverage is given by:

$$Z_0 = 138 \times \log\left(\frac{4h}{d}\right)$$

where

Z_0 = characteristic impedance of the Beverage
h = wire height above ground
d = wire diameter (in the same units as h)

Another important aspect of terminating the Beverage is the assurance of a good RF ground for the termination. This is most easily accomplished by laying radial wires on the ground at the termination end. This is important, as the effective impedance of the termination will approach the Z_0 of the wire only if the RF ground at the termination is nearly ideal. This presents something of a problem for the Beverage builder, because, as mentioned earlier, the maximum signal will be induced into the antenna when the ground under the antenna is poor. Some have quipped that the best location at which to erect a Beverage is in a desert with a salt marsh at the termination end.

As with many other antennas, improved directivity and gain can be achieved by lengthening the

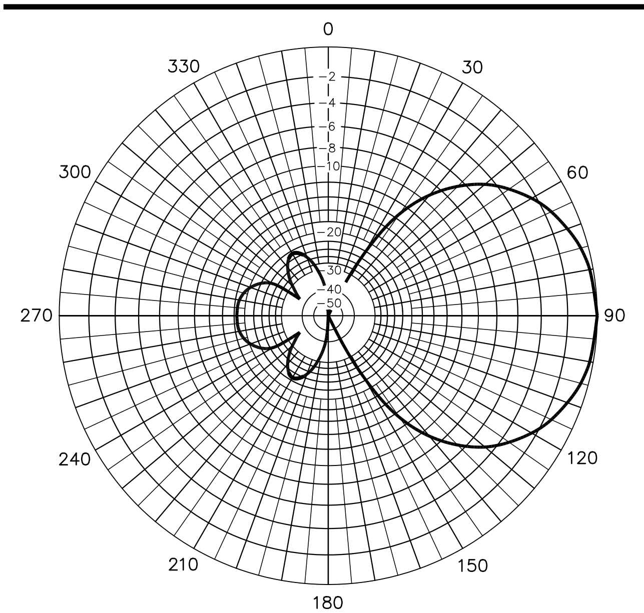

Fig 25—Directive pattern of a one-wavelength Beverage that is terminated in its characteristic impedance.

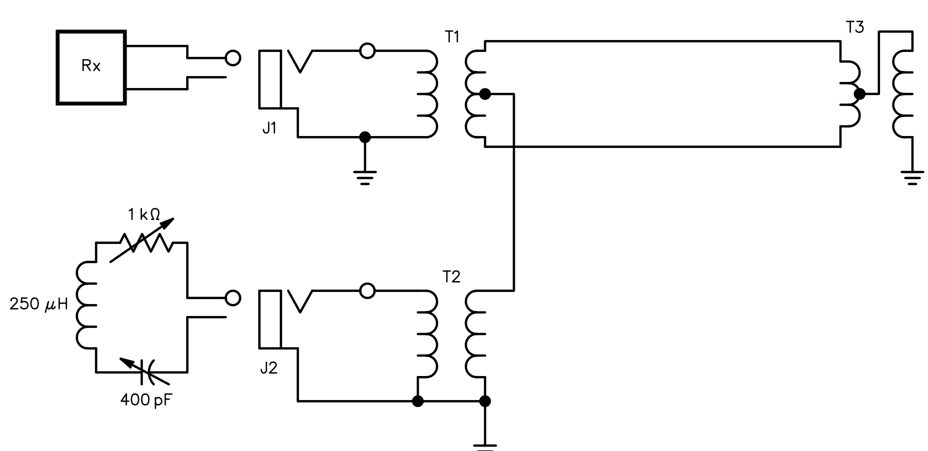

Fig 26—A two-wire Beverage antenna which has provisions for direction switching and null steering. Performance improves with height to a point, and is optimum for 1.8-MHz operation at about 10 to 12 feet. Parts identifications are for text reference.

antenna and by arranging several antennas into an array. One item that must be kept in mind is that (as mentioned earlier) by virtue of the velocity factor of the antenna, there is some phase shift of the wave on the antenna with respect to the wave in space. Because of this phase shift, although the directivity will continue to sharpen with increased length, there will be some optimum length at which the gain of the antenna will peak. Beyond this length, the current increments arriving at the receiver end of the antenna will no longer be in phase, and will not add to produce a maximum signal at the receiver end. This optimum length is a function of velocity factor and frequency (it is also dependent on the number of wires—see later text), and is given by:

$$L = \frac{\lambda}{4\left(\frac{100}{k} - 1\right)}$$

where

L = maximum effective length
λ = signal wavelength in free space (same units as L)
k = velocity factor of the antenna in percent

Because velocity factor increases with height (to a point, as mentioned earlier), optimum length is somewhat longer if the antenna height is increased. The maximum effective length also increases with the number of wires in the antenna system. For example, for a two-wire Beverage like the bidirectional version shown in Fig 26, the maximum effective length is about 20% longer than the single-wire version. A typical length for a single-wire1.8-MHz Beverage (made of #16 wire and erected 10 feet above ground) is about 1200 feet.

The Two-Wire Beverage

The antenna shown in Fig 26 has the major advantage of having signals from both directions available at the receiver simultaneously. Also, because there are two wires in the system (equal amounts of signal voltage are induced in both wires), greater signal voltages will be produced.

Refer to Fig 26. A signal from the left direction induces equal voltages in both wires, and equal in-phase currents flow as a result. The reflection transformer (at the right-hand end of the antenna) then inverts the phase of these signals and reflects them back down the antenna toward the receiver, using the antenna wires as a balanced open-wire transmission line. This signal is transformed at T1 and is available at J1.

Signals traveling from right to left also induce equal voltages in each wire, and they travel in phase toward the receiver end, through T1, and into T2. Signals from thisdirection are available at J2.

Another convenient feature of the two-wire Beverage is the ability to steer the nulls off either end of the antenna while receiving in the opposite direction. For instance, if the series RLC network shown at J2 is adjusted while the receiver is connected to J1, signals can be received from the left direction while interference coming from the right can be partially or completely nulled. The nulls can be steered over a 60° (or more) area off the right-hand end of the antenna. The same null-steering capability exists in the opposite direction with the receiver connected at J2 and the termination connected at J1.

The two-wire Beverage is typically erected at the same height as a single-wire version. The two wires are at the same height and are spaced uniformly (12 to 18 inches apart). The impedance of the antenna depends on the wire size, spacing and height, and is given by

$$Z_0 = 69 \times \log\left[\frac{4h}{d}\sqrt{1 + \frac{(2h)^2}{S}}\right]$$

where

Z_0 = Beverage impedance
S = wire spacing
h = height above ground
d = wire diameter (in same units as S and h)

For proper operation, transformers T1, T2 and T3 must be carefully wound. Small toroidal ferrite cores are best for this application, with those of high permeability (μ_i = 125 to 5000) being the easiest to wind (fewest turns) and having the best high-frequency response. Trifilar-wound coils are most convenient. These principles also apply to single-wire Beverages. See Chapters 25 and 26 and *The ARRL Handbook* for information on winding toroidal transformers.

It should be mentioned that, even though Beverage antennas have excellent directive patterns if terminated properly, gain never exceeds about –3 dBi in most practical installations. However, the directivity that the Beverage provides results in a much higher signal-to-noise ratio for signals in the desired direction than almost any other antenna that can be used practically at low frequencies. The result of this is that instead of listening to an S9 signal with 20-dB over S9 noise and interference on a vertical, a Beverage will typically allow you to copy the same signal at S5 with only S1 (or lower) noise and interference, everything else being equal. This is certainly a worthwhile improvement!

Practical Considerations

There are a few basic principles that must be kept in mind when erecting Beverage antennas if optimum performance is to be realized.

1) Plan the installation thoroughly, including choosing an antenna length consistent with the optimum length values discussed earlier.

2) Keep the antenna as straight and as nearly level as possible over its entire run. Avoid following the terrain under the antenna too closely—keep the antenna level with the *average* terrain, avoiding changes in height over gullies, ditches, etc.

3) Use the largest wire practical and avoid joining multiple pieces of wire together to form the span if the antenna is to be permanent. The use of larger wire will keep losses, undesired phase shift, and fragility to a minimum. Joints in wire are subject to corrosion over time.

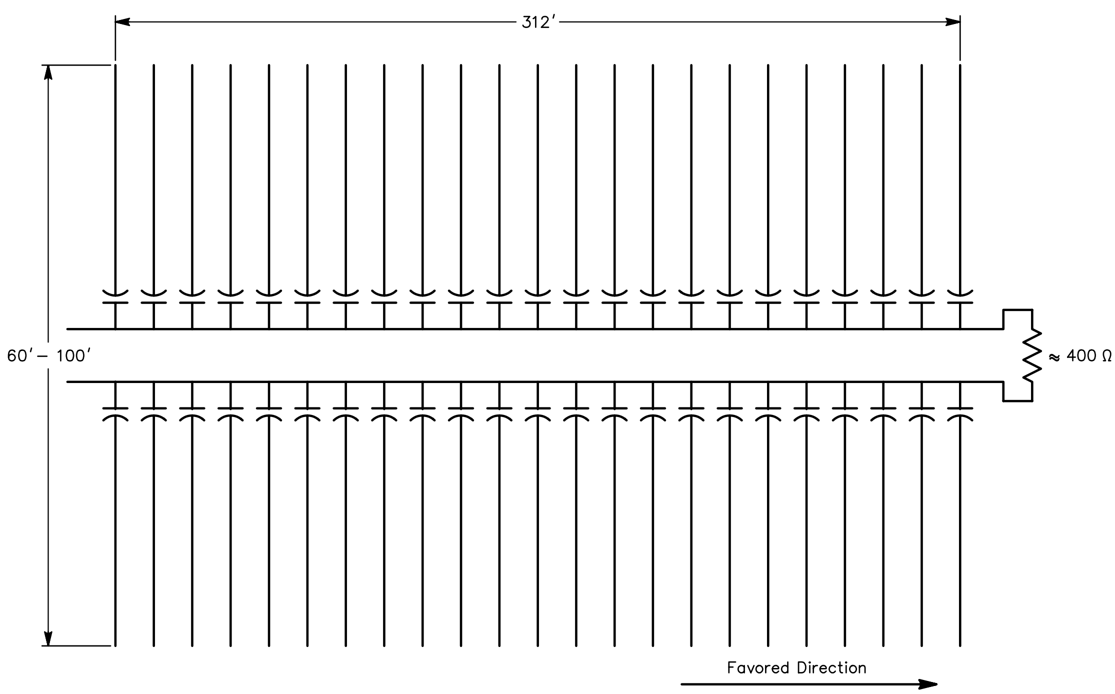

Fig 27—The fishbone antenna provides higher gain per acre than does a rhombic. It is essentially a wave antenna which evolved from the Beverage.

4) Minimize the lengths of vertical downleads at the ends of the antenna. Their effect is detrimental to the directive pattern of the antenna. It is best to slope the antenna wire from ground level to its final height (over a distance of 50 feet or so) at the feed-point end. Similar action should be taken at the termination end. Be sure to seal the transformers against weather.

5) Use a noninductive resistor for terminating a single-wire Beverage.

6) Use high-quality insulators for the Beverage wire where it comes into contact with the supports.

7) Keep the Beverage away from parallel conductors such as electric power and telephone lines for a distance of at least 200 feet. Perpendicular conductors may be crossed with relatively little interaction, but *do not cross any conductors that may pose a safety hazard.*

FISHBONE ANTENNAS

Another type of wave antenna is the fishbone, which, unlike the Beverage, is well suited to use at HF. A simple fishbone antenna is illustrated in **Fig 27**. Its impedance is approximately 400 Ω. The antenna is formed of closely spaced elements that are lightly coupled (capacitively) to a long, terminated transmission line. The capacitors are chosen to have a value that will keep the velocity of propagation of RF on the line more than 90% of that in air. The elements are usually spaced approximately 0.1 wavelength (or slightly more) so that an average of seven or more elements are used for each full wavelength of transmission-line length. This antenna obtains low-angle response primarily as a function of its height, and therefore, is generally installed 60 to 120 feet above ground. If the antenna is to be used for transmission (for which it is well suited because of its excellent gain and broadband nature), transmitting-type capacitors must be used, since they will be required to handle substantial current.

The English HAD fishbone antenna, shown in its two-bay form in **Fig 28**, is less complicated than the one of Fig 27. It may be used singly, of course, and may be fed with 600-Ω open-wire line. Installation and operational characteristics are similar to the standard fishbone antenna.

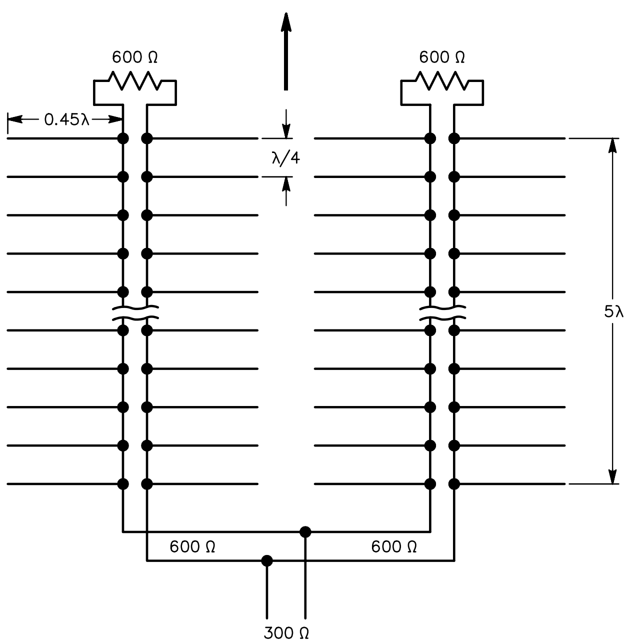

Fig 28—The English HAD fishbone antenna is a simplified version of the standard fishbone. It may be used as a single-bay antenna fed with 600-Ω open-wire line.

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