# Long-Wire Directive Antennas

## Design Methods for "V"'s and Rhombics

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THE more common type of directive array in amateur operation involves a multiplicity of reflectors, directors, phasing elements, radiators, etc., so arranged as to obtain the utmost power gain in a given direction. For obvious reasons these arrays are almost entirely confined to frequencies of 7 Mc. and higher. Moreover, such systems are rarely designed to permit multi-band operation and yet maintain the original directivity pattern with reasonable power gain.

### THE LONG SINGLE WIRE

The simplest solution to this problem is a long horizontal single-wire antenna that may be harmonically operated. For this case, however,

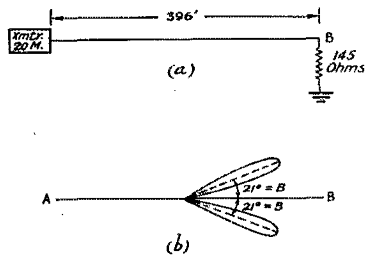


*FIG. 1—(A) SIMPLE FORM OF DIRECTIVE ANTENNA, USING A LONG WIRE TERMINATED IN ITS CHARACTERISTIC IMPEDANCE; (B) FREE-SPACE DIRECTIONAL CHARACTERISTIC (MAIN LOBE ONLY) OF THE ANTENNA AT (A)*

there still remain the shortcomings of a slight shift in directivity with frequency change, together with a power gain that is not all that might be obtained by other methods. For example, let us assume a wire 6 wavelengths long for 20 meters (396 ft.). To further simplify the explanation let us terminate the far end of this antenna in its characteristic impedance such as a 145-ohm non-inductive resistor (Fig. 1-A). This gives us a non-resonant type radiator and effectively reduces the rear radiation, resulting in a pattern similar to Fig. 1-B. (This diagram represents the theoretical free-space characteristic of the major lobes only.) The resulting directivity and power gain for harmonic operation of this antenna is then in accordance with the table in second column.

### THE INVERTED "V"

In 1930 Bell Laboratory experimenters [1] found that by a suitable arrangement of tilting one of

| | *Angle β (Directivity)* | *Power Gain (over ½ wave Hertz)* |
|---|---|---|
| 80 meters | 46.5° | 1.25 |
| 40 meters | 30.5° | 1.70 |
| 20 meters | 21.0° | 3.10 |
| 10 meters | 15.0° | 7.20 |

these long wires an additional increase in directivity and power gain was obtained (Fig. 2-A). By proper control of the length ($L$) and tilt angle ($\phi$) an optimum relationship between these quantities was found to exist (Fig. 2-B) that gave maximum directivity and power gain. This arrangement is vertically polarized and possesses the advantage that only one mast, or supporting structure, is required.

### THE HORIZONTAL "V"

In the same year RCA investigators [2] found that a greater power gain was obtainable along the bisector line of the acute angle made by two tilted wires than along the line perpendicular to the bisector as in the method just described, and that good results were obtained when this system was installed in a horizontal plane (horizontal polarization). This arrangement forms the basis for the well-known horizontal "V" (or "Vee" as it is sometimes called). This radiator (Fig. 3-A) when several wavelengths long may be harmonically operated without any appreciable directivity shift and with much greater power gains than can be obtained with the single wire. Moreover, the resulting power gain is greater than can be

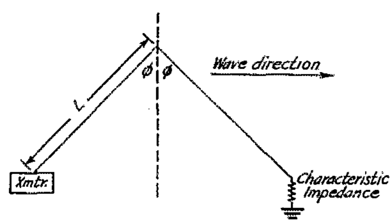


*FIG. 2-A—TILTED-WIRE ANTENNA OR "INVERTED V"*

produced by the usual reflector-director methods involving 2 or 3 elements.

The open-ended "V" as shown is bi-directional—that is, its major directive pattern is to the front and rear along the bisecting axis. Tilting the whole horizontal plane of the "V" will tend to

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increase the low-angle radiation off the low end and decrease it off the high end.

Fig. 3-B shows the dimensions that should be followed for an optimum design to obtain maximum power gain for different-sized "V" antennas. The longer-type systems give good performance on 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 "V" can be made unidirectional through eliminating the rear pattern by either of the following two methods:

(1) The use of another "V" ¼ wave to the rear to act as a reflector.

(2) The termination of the far end of each leg in its characteristic impedance (Fig. 3-C).

The first method is quite cumbersome for amateur practice and restricts correct operation to a single frequency band.

The second method is preferable because the system becomes non-resonant (no standing waves) and is therefore more readily adaptable to multi-band use. However, a serious drawback to this method is the fact that varying ground resistance causes a variation in the terminating resistance. This condition causes reflected losses that may become severe and thereby change the entire action of the system—particularly with harmonic operation.

Should unidirectional properties be the paramount desire it is recommended that an alternate

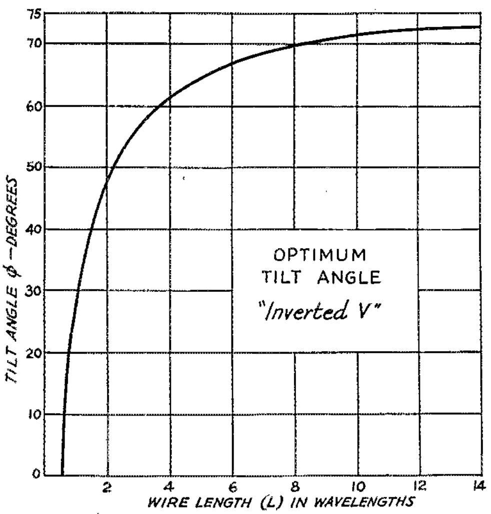


*FIG. 2-B—OPTIMUM TILT ANGLE VERSUS WIRE LENGTH (ONE LEG) FOR THE INVERTED "V" ANTENNA*

system be used. This brings us to the arrangement of two "V"s placed end-to-end, the system being terminated in its characteristic impedance; in other words, the terminated rhombic.

THE RHOMBIC ANTENNA

The "Rolls-Royce" of unidirectional antenna systems, either for transmitting or receiving, is the *terminated* rhombic, or diamond as it is some-

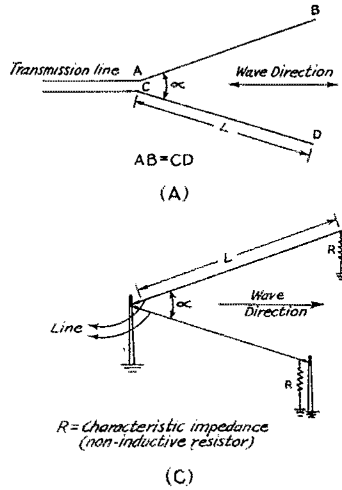


*FIG. 3—(A) THE "V" ANTENNA; (C) "V" ANTENNA TERMINATED TO ABSORB BACK RADIATION AND THUS PRODUCE A UNIDIRECTIONAL PATTERN*

times called. The *unterminated* rhombic, which is bidirectional and resonant, will be described later. For the present discussion all reference to the rhombic is in its terminated form. This discussion will also pertain to a rhombic installed in a horizontal plane above ground so as to provide horizontal polarization. (*Note:* This system also may be constructed in the vertical plane to obtain vertical polarization, which might be of some practical advantage in ultra-high frequency applications.)

It has only been in the past few years that the amateur has made any really practical use of the rhombic [3] and in nearly every case the increase in radiating performance has more than justified the installation. The system was perfected by the Bell Laboratories in the latter part of 1930 chiefly as an improved receiving antenna, and has been in more or less continual use by commercial interests for high-frequency transoceanic service since that time. The rhombic is a direct descendant of the previously-described *inverted* "V" and represents a radical improvement over that system in operation and performance.

The advantages of the rhombic are so numerous that we can conservatively summarize the matter by saying that it is among the best of all known directive systems—that is, by proper design, greater power gain and directivity may be realized for the rhombic than any other ordinary single or multi-wire radiator. The installation is not complicated—certainly a great deal simpler than the "curtain" arrays. By no means the least of its features (probably a major advantage with the amateur) is an inherently broad frequency characteristic.

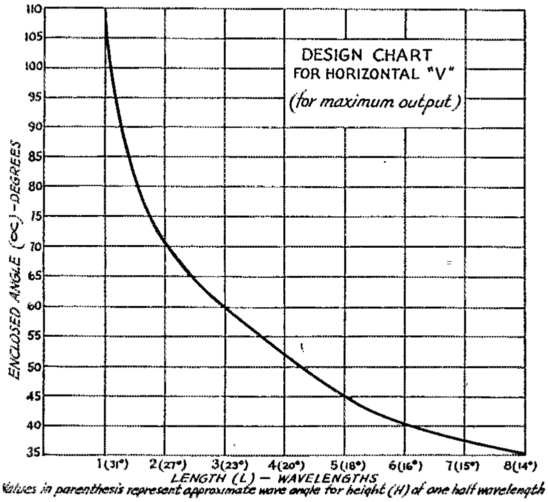


*FIG. 3-B—DESIGN CHART FOR HORIZONTAL "V" ANTENNAS*

*Enclosed angle between wires versus length of sides.*

Excellent efficiency is obtained over a 2 to 1 frequency range, and on some of the larger systems a 4 to 1 range may be obtained with fair performance. On this basis it is advisable from the standpoint of multi-band operation to design the rhombic for a fundamental of 20 meters, which will then permit operation on 10 and 40 meters and in some cases satisfactory performance over the entire group of amateur bands.

### RHOMBIC DESIGN

Most of the design data thus far given in various amateur publications have been rather vague and, in some cases, a trifle misleading.

As a remedy for this situation it is intended to offer design information in as "digestible" manner as possible. The general theory of the rhombic [4] will be omitted, but in so doing please do not get the idea that it is just another one of those lucky hit-or-miss systems that "just happened" to work. Some good sound engineering and mathematical principles are involved in the development of the rhombic for which the actual measured results bear out the calculated "theoretical" results to a startlingly close agreement.

First of all, in deciding on a "good location" for the rhombic it is advisable to select as flat a section of terrain as possible, because any tilt in the horizontal plane of the rhombic will lead to distorted effects upon the wave angle. If the ground is sloping it is good practice to construct the rhombic so that its whole horizontal plane is also sloping parallel to the ground. Of course, any inconsequential short sloping sections of the earth may be neglected for all practical purposes.

Next, the rhombic dimensions are worked out from a given set of conditions for which *there exists a single optimum design for maximum output.*

To obtain maximum output for an "ideal" condition the only given design factor is the wave angle (or angle of radiation) from which is determined optimum height, length, and angle of tilt (Fig. 4).

This so-called "ideal" design may be classified into either of two alternative arrangements:

(1) *The Maximum Output Method,* in which the greatest possible amplitude for the wave angle is obtained but *not* with its maximum radius at the line indicating the given wave direction of the directive pattern (Fig. 5-A).

(2) *The Alignment Method,* in which the major lobe of the directive pattern is symmetrical with the wave angle (Fig. 5-B).

The former permits the greatest possible output whereas the latter, at only a slight sacrifice in output, has the features of a better signal-to-noise ratio for reception purposes together with the requirement of less overall space for the installation.

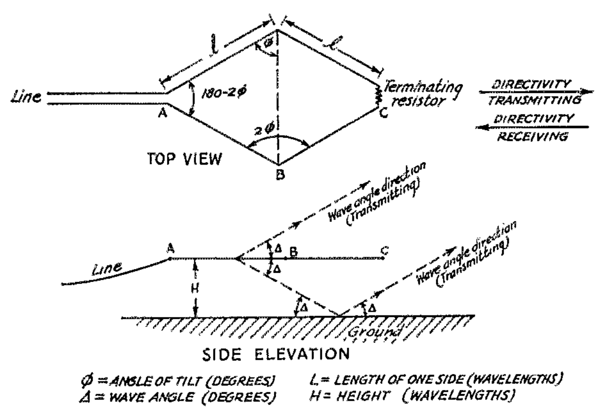


*FIG. 4—THE HORIZONTAL RHOMBIC OR DIAMOND ANTENNA, TERMINATED*

The design procedure for either condition is shown in Fig. 6, together with several examples of how this chart may be applied. Wave angles from 10° to 30° are shown in the design charts since it is considered that this is the most useful range for practical use. Something in the range of 12° to 25° is probably the best to strive for to obtain overall DX performance. Higher frequency-band operation of a rhombic produces a lower wave angle than the fundamental frequency-band, and vice-versa for lower frequency-band application. The chart shown in Fig. 6 is computed from the following formulas:

(1) $H = \frac{\lambda}{4 \sin \Delta}$

(2) $\sin \phi = \cos \Delta$

(3) $l = \frac{\lambda}{2 \sin^2 \Delta}$
(for maximum output method)

(4) $l = \frac{.371 \lambda}{\sin^2 \Delta}$
(for alignment method)

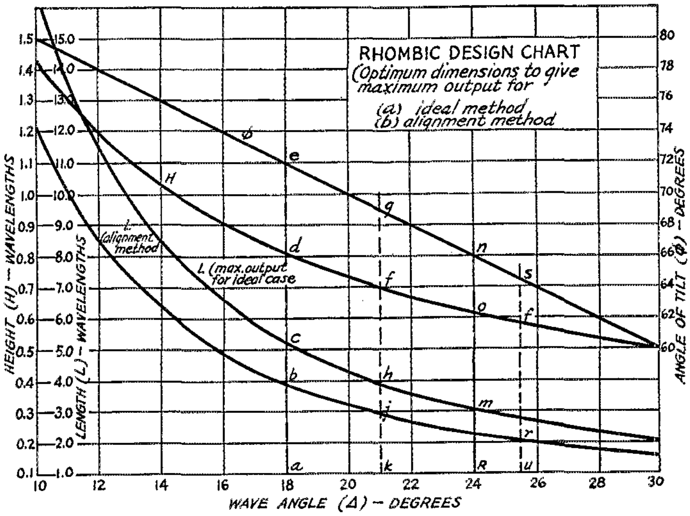


FIG. 6—RHOMBIC ANTENNA DESIGN CHART

*The use of the Chart is illustrated by the following examples:*

*(1) Given: Desired wave angle (Δ) = 18°.*
*To Find: H, L, Φ.*
*Method:*
*Draw vertical line thru point "a" (18° wave angle-abscissa).*
*Read intersection of this line on each curve on its corresponding scale.*
*e = angle of tilt (Φ).*
*d = height (H).*
*c = length (L) for ideal case.*
*b = length (L) for alignment case.*
*Result:*
*Φ = 72°.*
*H = .81 wavelengths.*
*L (ideal) = 5.25 wavelengths } either may be*
*L (alignment) = 3.87 wavelengths } used (see text).*

*(2) Given: Available and effective height (H) = .7 wavelengths.*
*To Find: H, L, Φ, Δ.*
*Method:*
*Draw vertical line thru point "f" (.7 wavelengths on curve H).*
*Read intersection of this line on each curve on its corresponding scale.*
*g = angle of tilt (Φ).*
*h = length (L) for ideal case.*
*j = length (L) for alignment case.*
*k = wave angle (Δ).*
*Result:*
*Φ = 69°.*
*L (ideal) = 3.9 wavelengths } either may*
*L (alignment) = 2.9 wavelengths } be used (see text).*
*Δ = 21°.*

*(3) Given: Length for 1 side (ideal case) L = 3.0 wavelengths.*
*To Find: H, Φ, Δ.*
*Method:*
*Draw vertical line thru point "m" (3.0 wavelengths on curve L— ideal case).*
*Read intersection of this line on each curve on its corresponding scale.*
*n = angle of tilt (Φ).*
*o = height (H).*
*p = wave angle (Δ).*
*Result:*
*Φ = 66°.*
*H = .618 wavelengths.*
*Δ = 24°.*

*(4) Given: Length for 1 side (alignment method) L = 2.0 wavelengths.*
*To Find: H, Φ, Δ.*
*Method:*
*Draw vertical line thru point "r" (2.0 wavelengths on curve L—alignment case).*
*Read intersection of this line on each curve on its corresponding scale.*
*s = angle of tilt (Φ).*
*t = height (H).*
*u = wave angle (Δ).*
*Result:*
*Φ = 64.5°.*
*H = .581 wavelengths.*
*Δ = 25.5°.*

where λ = wavelengths
Δ = wave angle (degrees)
φ = angle of tilt (degrees)
$l$ = length of one leg (wavelengths)
$H$ = effective height (wavelengths)

In the event that the situation arises wherein it is impossible to meet these design requirements for some reason or other (i.e., lack of longitudinal space, height, etc.) there are, fortunately, two *compromise* design methods that allow operation at only a slight gain reduction over the "ideal" cases just described.

The first compromise method is based on an original given premise of length and height from which is determined the proper angle of tilt and corresponding wave angle

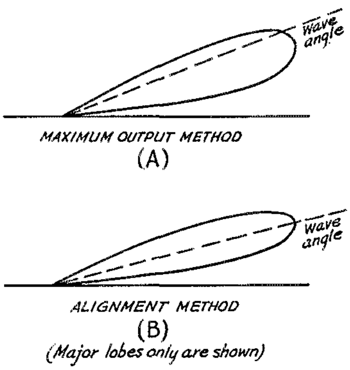


FIG. 5—TYPICAL VERTICAL CHARACTERISTICS FOR THE RHOMBIC

*Antenna Obtained by the Maximum Output Method (A), and the Alignment Method (B).*

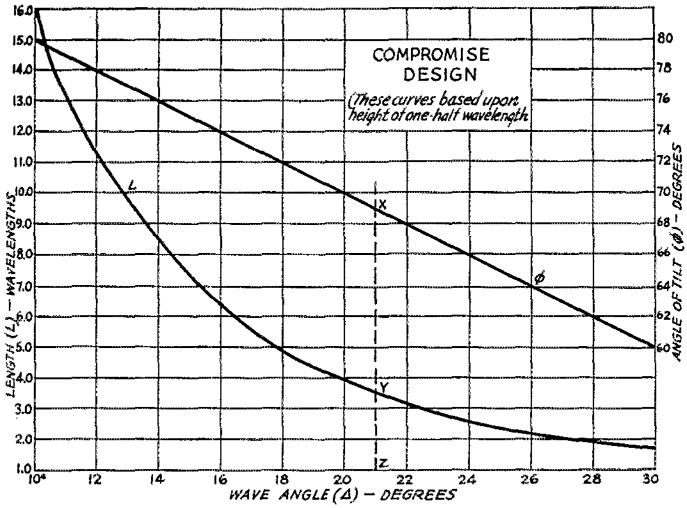


FIG. 7—COMPROMISE METHOD DESIGN CHART FOR RHOMBIC ANTENNAS WITH FIXED HEIGHT (ONE-HALF WAVELENGTH)

*The following example illustrates the use of the Chart:*

*Given:* Height = ½ wavelength. Available length of one leg = 3.5 wavelengths.
*To Find:* Angle of Tilt (Φ). Wave Angle (Δ).
*Method:* Place straight edge on curve "L" at 3.5 wavelengths (point y) and draw line XYZ. Read angle Φ from intersection at point X (right hand ordinate) and angle Δ at point Z (intersection of abscissa).
*Result:* H = ½ wavelength, L = 3.5 wavelengths — given. Tilt angle Φ = 69 degrees, Wave angle Δ = 21 degrees — from curves.

for maximum output. Fig. 7 illustrates the procedure to be followed for this set of conditions. This chart is based upon an effective height of ½ wavelength, which represents a practical value for most amateurs to deal with. For any different height other than the one shown the curve may be plotted from the expression:

$$\frac{H}{\tan\left(\frac{2\pi H \sin\Delta}{\lambda}\right)} = \frac{\lambda}{2\pi \sin\Delta} - \frac{l \sin\Delta}{\tan\left(\frac{\pi l \sin^2\Delta}{\lambda}\right)}$$

(Note: the solution of this equation for $l$ in terms of wavelength (λ) may be obtained by the trial and error method.)

The second compromise design method is based upon a premise of a given length (somewhat reduced over the ideal case) and wave angle to determine the remaining optimum dimensions for best operation. Fig. 8 represents the design chart and method to be followed for this condition. Curves for values of length of 2, 3 and 4 wavelengths are shown, and additional curves for any length may be similarly plotted from the relationship:

(Continued on page 72)

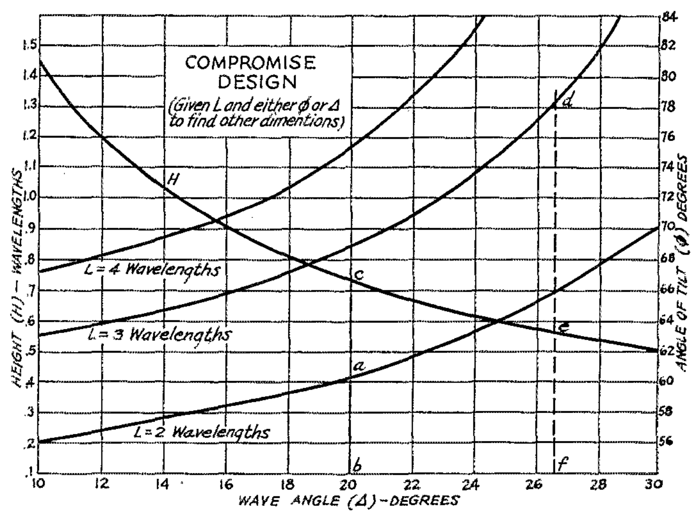


FIG. 8—COMPROMISE METHOD DESIGN CHART FOR VARIOUS LEG LENGTHS AND WAVE ANGLES

*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 thru 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 = .73 wavelengths.

*(2) Given:* Length (L) = 3 wavelengths. Angle of tilt (Φ) = 78°.
*To Find:* H, Δ.
*Method:* Draw vertical line from point "d" on curve L = 3 wavelengths at Φ = 78°. Read intersection of this line on Curve H (point "e") and intersection at point "f" on the abscissa for Δ.
*Result:* H = .56 wavelengths. Δ = 26.6°.

which calls for a single master switch or a "press-to-talk" button.

It will be noted from the photographs that wherever leads are taken through a metal partition a rubber grommet is used. Such practice, while not necessarily essential, in the end invariably pays for itself in the elimination of insulation breakdown at a time when repairs are difficult and inconvenient. Such a grommet is also used in the chassis hole through which passes the flexible drive to the crystal holder.

The standard G.R. jack-top output terminal posts are used, rather than conventional binding posts, so that should this exciter at any time be used with more than one final amplifier for operation on different bands, much awkward work behind the relay rack in shifting leads is reduced to the simple operation of changing plugs.

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## Long-Wire Antennas

*(Continued from page 46)*

$$\sin \phi = \frac{l - .371\,\lambda}{l \cos \Delta}$$

Regardless of which design method is followed the pertinent fact remains that *there is an optimum set of dimensions for the rhombic to obtain maximum results under a specific given condition.*

Briefly summarizing, with all other dimensions being correct any 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.

### TERMINATING THE RHOMBIC

The rhombic, when terminated in its characteristic impedance, becomes unidirectional and non-resonant and should be operated as such to realize the best overall results, either for transmission or reception.

Experiments have shown that a value of 800 ohms is correct for the terminating resistor for *any* properly constructed rhombic and that the system behaves as a pure resistive load under this condition. Higher or lower values of resistance cause the rhombic to act as a reactive load, thereby considerably reducing the efficiency of the broad frequency characteristic.

This terminating resistor must be capable of safely dissipating ½ the power output (to eliminate the rear pattern) and be absolutely non-inductive. Such a resistor may be made up from a carbon or graphite rod or from a long 800-ohm transmission line. If the carbon rod or a similar form of lumped resistance is used the device should be suitably protected from weather effects, i.e., covered with good asphaltic compound and sealed in a small light-weight box or fibre tube.

The 800-ohm value of terminating resistance may be substantially lowered by running an equal and parallel-connected wire under each leg of the rhombic. For instance, a distance of about 12 inches separation between two such parallel connected wires for each leg will permit the use of a 600-ohm terminating resistor. This is of particular advantage where 600-ohm connecting lines and coupling equipment are available or more practical to use.

A terminated rhombic also requires an impedance match at the input end to prevent reflection losses or standing waves. The transmission line in this case is untuned and may be any length. To accomplish this, the 800-ohm terminated rhombic should be fed with an 800-ohm transmission line and a 600-ohm rhombic by a 600-ohm transmission line.

An 800-ohm line may be constructed from No. 16 A.W.G. wire spaced 20 inches or from No. 18 A.W.G. wire spaced 16 inches. The 600-ohm line, which is the common form for most Zepp feeders, is constructed from No. 12 A.W.G. wire spaced 6 inches.

The 800-ohm line is somewhat ungainly to install. It may be replaced by low-impedance lines of the concentric or twisted pair variety by the incorporation of a coupling network between the 800-ohm and low-impedance line connection. Such a coupling unit might be installed in a box at the base of the first pole or supporting structure. If such an arrangement is used it will be necessary to change the network constants for each different band of operation.

The coupling methods for the transmission line of a terminated rhombic to the final amplifier are straightforward. Either link, direct capacity, or impedance network types of coupling are the preferred methods to use.

THE UNTERMINATED (OPEN ENDED) RHOMBIC

The unterminated rhombic is a bi-directional and resonant system and closely resembles the open "V" in operation and performance. The same design details apply to the unterminated rhombic as for the terminated type. Ordinary 600-ohm *tuned* feeders are preferable to use for the unterminated rhombic and "V" and may be coupled to the transmitter by the usual parallel- or series-tuned resonant circuits. Matched-impedance lines may be used on these resonant systems by the use of the well-known matching sections or "stubs" but such procedure is not readily adaptable to multi-band work.

If bi-directional properties are desired an open "V" of the same *overall* length is preferable to the unterminated rhombic. For example, a "V" of 5 wavelengths on a side has a greater power gain than an unterminated rhombic with legs 2½ wavelengths long (5 wavelengths total for one complete side of the rhombic). On the other hand a "V" of only 2½ wavelengths on a side has less power gain than an undetermined diamond 2½ wavelengths on a leg.

The only instance where an unterminated rhombic should be used in place of the open "V" is where it would be impossible to install a "V" of the same overall length due to insufficient dimensions of available space.

To realize the full benefits from a rhombic or "V" some provision should be made to permit the use of the array as a receiving antenna by the incorporation of suitable relay or switching

(*Continued on page 106*)

## Long-Wire Antennas

*(Continued from page 74)*

methods in the line. The directivity effects and power gain are readily noticed when used for reception. The signal-to-noise ratio is also greatly improved along the major horizontal directive lobe. Many cases have been known where received signals on the usual doublet were so far below the noise level that it was practically impossible to determine that the signal was actually there—but by the use of the "V" or rhombic the same signal was brought up to a good QSA5 level.

For rhombics 2 wavelengths on a leg or greater, and for "V"s 4 wavelengths on a side or greater, power gains of 18 to 30 over a single half-wave Hertz are obtainable for the same transmitter power, which makes these systems a veritable "power plant" for low-power transmitters.

A few final hints should not be amiss at this point:

(1) In figuring harmonic lengths for the proper length of each side, etc., the following formula will give the result with reasonable accuracy:

$$\text{length in feet} = \frac{492\ (2K - .05)}{\text{freq. (in Mc.)}}$$

$K$ = number of wavelengths

(2) Before this length is correctly determined and cut it is advisable to play safe by using hard drawn or some other forms of "stretchless" wire to maintain the original dimensions.

(3) In figuring directions be sure to use a great circle map—the usual straight maps will throw you a long way off on your beam calculations.

Moral: "Be the ham who owns one!"

BIBLIOGRAPHY

[1] Bruce, "Developments in Short Wave Directive Antennas," *Proc. I.R.E.* August, 1931.

[2] Carter, Hansell and Lindenblad, "Development of Directive Transmitting Antennas by RCA Communications, Inc." *Proc. I.R.E.* October, 1931.

Carter, "Circuit Relations in Radiating Systems," *Proc. I.R.E.*, June, 1932.

[3] Hull and Rodimon, "Plain Talk about Rhombic Antennas," *QST*, November, 1936.

Moore and Johnson, "Directed Vertical Radiation with Diamond Antennas," *QST*, April, 1937.

[4] Bruce, Beck and Lowry, "Horizontal Rhombic Antennas," *Proc. I.R.E.* Jan., 1935.

A.R.R.L. *Amateur Handbook* (Antenna Chapter).

## How Would You Do It?

*(Continued from page 28)*

between them. The link coils on the tank coils may be the usual two or three turns wound between the turns of the tank coil windings at the coldest point and permanently connected to plugs on the form in the usual manner. The vari-