controlled vertical radiation rhombics, part 1:
designing for high performance

For BIG performance — in a BIG backyard — try rhombics

Rhombics aren't for everyone. Not many Amateurs have sufficient space on their small city or suburban lots to accommodate the generous dimensions of this useful, efficient antenna. Mine measures 277 feet on each leg, and requires an area that measures 525 by 250 feet. Yet for those who have adequate land, rhombics can offer unusually high performance: the three wavelengths on my leg rhombic, for example, puts an *outstanding* signal into Europe on 30 meters, and when the 18 and 24 MHz bands are open, this antenna is all set to go.

In the mid-1930's, when the rhombic antenna was relatively new, ARRL experimenters[1] found it to be useful for long-distance radio communications. League personnel strung hundreds of feet of wire, in an enormous diamond configuration, through the Connecticut woods with astonishing results: signals from as far away as Australia were clearly heard.

As a young man, I duplicated the League's efforts behind my home in New Jersey. After climbing many trees, stringing springy lengths of No. 12 copperweld wire among and through their innumerable branches, I succeeded in constructing a rhombic antenna terminated in a 100-watt carborundum resistor and fed with a 600-ohm open-wire line. It was not until retirement that I was able to build other rhombics; this article, a result of these later experiments, describes the design of a rhombic that operates on the 160 through 10 meter bands and offers controlled vertical radiation in the 40 through 10 meter bands. This feature allows mechanical tuning to the best operating configuration for any band. (Fixed rhombics are best for one frequency and perform well over a 2 to 1 frequency range only.)

Because this rhombic is terminated in its characteristic impedance, it is nonresonant; its input impedance is essentially flat over its entire operating range. In steady use since the 1983 Radiosport contest — when I heard on 15 meters, such reports as "You're the only U.S. station coming through at this time," and "Your signal is overriding all other U.S. stations by 10 to 15 dB" — it has performed admirably and presented no maintenance or durability problems.

how does a rhombic work?

To begin, let's consider the rhombic's horizontal radiation plane, realizing that a rhombic is simply four long-wire antennas arranged in the shape of a rhombus or "diamond." By terminating the rhombic in its characteristic impedance (with a noninductive resistance), a unidirectional lobing pattern is obtained in the direction of the terminated end; (see **fig. 1**). The

By **Henry G. Elwell, Jr., N4UH,** Route 2, Box 20G, Cleveland, North Carolina 27013

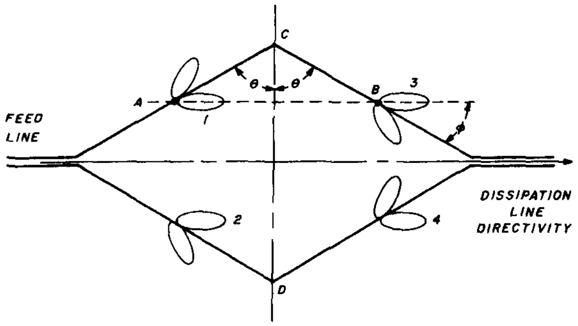

fig. 1. Unidirectional lobing pattern of a rhombic antenna is generated by terminating it in its characteristic impedance through a dissipation line. Lobes 1, 2, 3, and 4 combine their energy when θ, the tilt angle, is equal to 90 degrees minus ϕ.

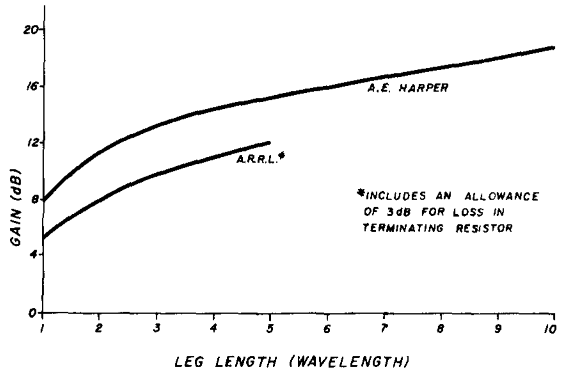

fig. 2. Free space gain of a rhombic antenna over a halfwave dipole for zero wave angle.

tilt angle, θ, shown in the figure, must be adjusted to equal 90 degrees minus the angle ϕ, between the main forward power lobe and the individual leg, which is determined by the antenna length. This ensures that maximum directivity is on a line bisecting the rhombic as indicated.

To obtain the correct phasing of the lobes for maximum radiation in the desired direction, the straight-line distance, AB, between the center of the legs, must be one-half wavelength less than the distance ACB. This follows from the fact that lobe 1 is 180 degrees out of phase with lobe 3. By making the distance between these lobes one-half wavelength (180 degrees) less, lobe 1 will arrive at point B in the correct phase to add to the field of lobe 3, and thus increase the intensity of radiation in the desired direction. A similar action takes place between lobes 2 and 4 on the other side of the rhombic. All other lobes combine to produce a cancellation of radiated energy in the line of the minor axis, CD. Correct termination of the antenna with approximately 800 ohms nonreactive resistance produces an almost infinite front-to-back ratio.

The issue of rhombic gain is a controversial one. **Figure 2** shows gain curves from two sources: *The ARRL Antenna Book,*[2] and *Rhombic Antenna Design,* by A. E. Harper.[3] Both curves are free-space directivity gains of a nonresonant rhombic over that of a dipole and are for *zero vertical angle of radiation.* E. Bruce, the major developer of the rhombic, shows some actual experimental data in his August, 1931, article in the *Proceedings of the Institute of Radio Engineers.*[4] His data shows that in comparison with a halfwave vertical antenna, his three wavelengths on a leg rhombic had a gain of 21 dB 10 percent of the time, to 7 dB 100 percent of the time, and 16 dB 50 percent of the time. Put another way, the rhombic was always 7 dB better than the halfwave vertical, and 10 percent of the time it was 21 dB better. That 21 dB relates to a power ratio of about 130; that is, a 1 kW output transmitter would have an effective radiated power of 130 kW with respect to a dipole — but only 10 percent of the time.

In a detailed article in the January, 1935, *Proceedings of the IRE,*[5] Bruce described experimental data showing that three and one-quarter wavelengths on a leg rhombic had 14 dB gain over a halfwave horizontal dipole at the same height. A Yagi producing 14 dB gain would require 12 elements — a rather large antenna; of course it would be capable of rotation over 360 degrees.

design

For optimum performance, a rhombic antenna should be designed for one frequency or a very small band of frequencies, the pattern for which is best suited to the propagation conditions of the radio circuit. Usually about all that a designer attempts to compute about this system is the characteristics of the main lobe. The enormous labor of computation quickly discourages analysis of a rhombic's complete radiation characteristics. Charts have been provided to assist in suitable designs as shown in the *ARRL Antenna Book*, or Laport's *Radio Antenna Engineering*, figure 3.81.[6] By careful design (and acceptance of less than optimum performance) a rhombic antenna may be made to operate over an almost 3 to 1 frequency range. This means that a fixed rhombic could operate from 3 to 9 MHz, or from 7 to 21 MHz, or over any similar frequency range. It will be shown later that a Controlled Vertical Radiation (CVR) rhombic can operate well from its lowest design frequency to as high as practical before beamwidth becomes too narrow for normal use.

To properly analyze a rhombic over a range of frequencies and desired vertical angle of radiation, it is necessary to have a method for observing quickly the effects of varying any single parameter in relation to all the others. These parameters are the antenna height above ground, the length of the legs, and the included angle between the legs, called the tilt angle (see **fig. 3**).

The length and tilt angle (**fig. 3A**) are actual dimensions of the antenna proper and affect the free-space pattern. The height of the antenna, however, affects the directional characteristics only through what is called "ground reflection." In **fig. 3B**, part of the radiated power goes directly from the antenna at the *vertical angle of radiation, delta*. The rest of the radiated power is directed toward the ground at the same angle. If the ground is assumed a perfect reflector, the wave that is directed toward the ground will be reflected, undiminished in strength in the same direction as the original directly radiated wave. If the ground reflected wave arrives at a distant point (your QTH, for example) in phase with the direct (sky) wave, *it will reinforce the received signal (voltage)*. If, however, it arrives exactly 180 degrees out of phase, it will completely cancel it.

In the practical case, neither the maximum of 6 dB reinforcement nor the complete cancellation ever occurs, since the ground is never a perfect reflector. Also, the reflected wave rarely reaches the unreflected wave exactly in phase or exactly out of phase unless the antenna is being used at a frequency exactly that of the design frequency. The effects of the ground reflection will be treated separately from those due to antenna length and tilt angle.

A computer can be used to observe the effect of changing certain parameters. However, it is much easier to see such changes by means of a graphical method Donald Foster described in the October, 1937 issue of the *Proceedings of the IRE*. "If the direction of zero and maxima of K^2 (the radiation function) are plotted on a spherical blackboard with the rhombus at the center, they consist of a coaxial system of small circles, of alternating maxima and zero . . . around one arm of the antenna as an axis, and an identical system of circles around the other arm of the antenna. The angle between the axis of the circles is the angle 2A (see **fig. 3A**) of the rhombus. This pattern on the sphere is ideally suited to representation on the plane by means of the sterographic projection."[7]

While his method probably sounds complicated, it actually summarizes a very simple and easily grasped idea of what happens as the parameters are changed. Antenna enthusiasts will recognize the "zero and maxima of K^2" as the first null and main lobe of the antenna field intensity graph of "Angle with Respect to Wire Axis vs Length of Wire in Wavelength" shown in figure 15 in the second chapter of the *ARRL Antenna Book*.

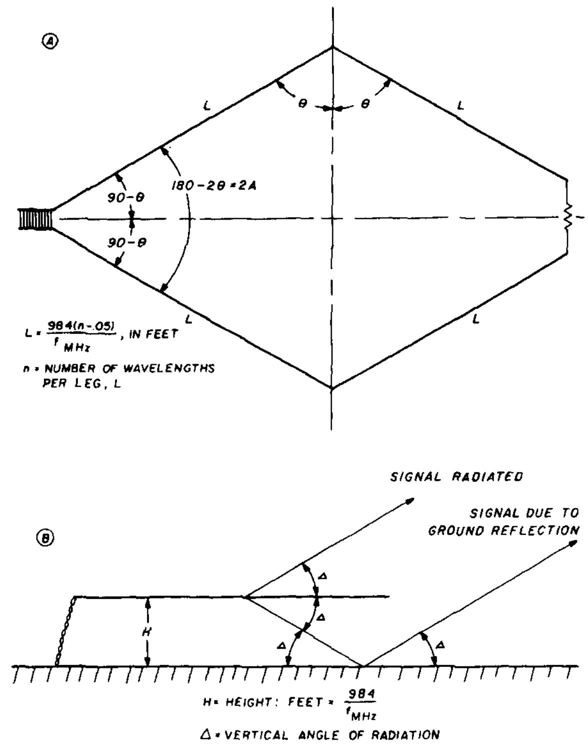

fig. 3. Definition of rhombic antenna parameters. In (A) Length, L, and tilt angle, θ, are actual dimensions of the antenna and affect free-space pattern. In (B), part of the radiated power goes directly from the antenna at angle Δ.

Without going into the mathematics of their construction, the following discussion will help you to make your own stereographic representation.

construction of stereographic overlays

The free-space pattern charts are made by the use of **fig. 4**, which shows the angles of the maxima and nulls in long wires. This is the same as figure 15 of chapter 2 of the *ARRL Antenna Book*, but shows up to the 8th maxima and null instead of just the first.

Step 1. Draw a 6-inch diameter circle and place perpendicular vertical and horizontal lines through its center; refer to **fig. 5**.

Step 2. Lay out 0 to ±90 degree tick marks around the periphery of the circle counterclockwise and clockwise from the right horizontal line intersection of the circle.

Step 3. From the −90 degree position on the perimeter of the circle, draw straight lines to 0, ..., 80, 90 degrees and label the points where they intersect the horizontal line as 0, 10, ..., 70, 80 degrees. For ease of viewing **fig. 5**, only the 20, 50, and 70 degree lines are shown.

The labeled points represent the vertical angle of

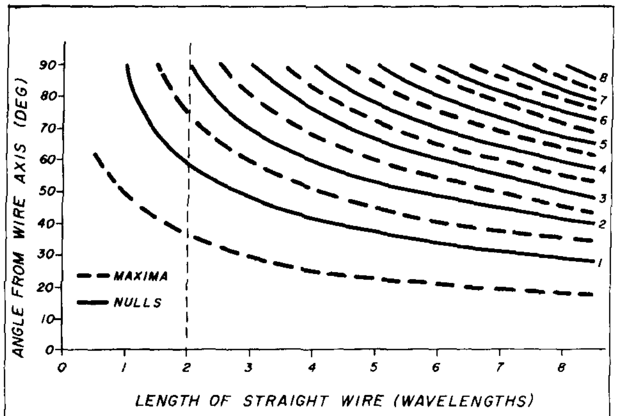

fig. 4. Angles of maxima and nulls in long wires carrying standing waves.

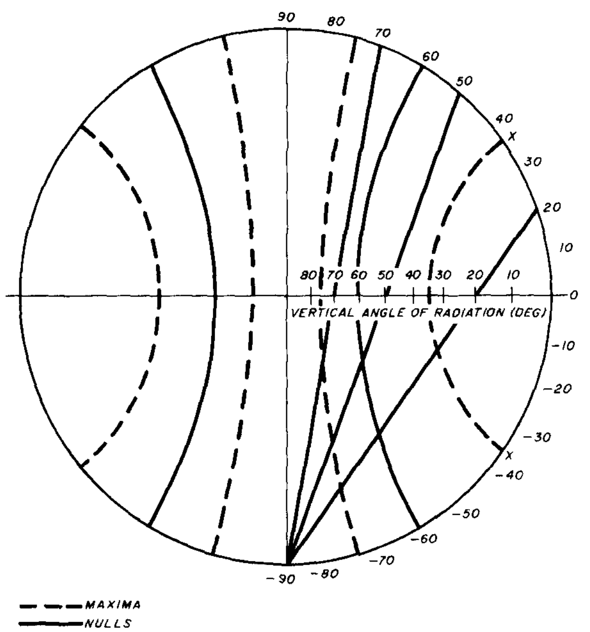

fig. 5. Stereographic map of the radiation pattern for a two-wavelength straight wire in free space.

radiation of the rhombic. It will be necessary for future work to have this as an overlay for a scale for determining the vertical angle of fire of other rhombic designs.

Step 4. Determine the number of wavelengths to be analyzed (2 wavelengths, for example).

Step 5. Using **fig. 4**, draw a vertical line up from the 2 wavelength point to the curve. Read off the indicated value.

Step 6. Tabulate the angle of maxima and nulls from Step 5; maxima at 36 and 75 degrees, nulls at 60 and 90 degrees.

Step 7. Place a mark on the circle perimeter at ±36 degrees. Draw a dotted circle through those two points and the 36 degree point on the horizontal line. The center of that radius must lie on the horizontal line extended to the right of the circle. That dotted line represents the first maximum of a radiating wire two wavelengths long. Repeat for ±75 degrees, which represents the second maximum. Repeat the same two angles from the left side of the chart, which represent the reverse direction of fire.

Step 8. Place marks at ±60 and 90 degrees and draw solid-line curves, which represent the first and second nulls respectively. Repeat for the reverse direction.

You now have a one-leg pattern of a two-wavelength long rhombic. You will need two of them for analysis, as will be explained.

A ground reflection overlay is also needed and is made as follows.

Step 1. Draw a 6-inch diameter circle with a perpendicular horizontal and vertical line through its center; see **fig. 6.**

Step 2. Determine the number of wavelengths above ground the antenna is to be placed (one wavelength, for example).

Step 3. Using **fig. 7,**[8] tabulate the null and maximum vertical angles of radiation for the chosen height. For one wavelength (360 degrees) we have 15 degrees, 48 degrees maximum and a 30 degree null.

Step 4. Place the scale for determining the vertical angle of fire of the rhombic under the 6-inch circle and place a mark on the horizontal line at the 15 degree, 48 degree, and 30 degree vertical angle of fire points.

Step 5. Draw dotted-line circles through the 15 and 48 degree marks using the center of the 6-inch circle so as to produce concentric circles. Draw a solid-line circle through the 30-degree line in the same manner. The dotted circles represent the first and second maxima, and the solid line represents the first null.

The three stereographic maps are all that are required to design a two wavelength on a leg rhombic mounted one wavelength above the ground. All other maps are made the same way for different leg lengths and heights.

During World War II Richard Bluhm, W2KXD, adapted Foster's graphical method to make it practical for use by the average person. In an unpublished paper[9] written in 1944, he provided a means of rapidly designing horizontal rhombic antennas using Foster's stereographic overlays. Even though the data obtained by his method is not precise, results obtained during wartime erection of rhombics by the military bear out mathematical calculations with excellent accuracy.

The design of my rhombic is based on W2KXD's method. In discussions with him, we both felt that his stereographic charts (almost 50 in number) should be available to Amateurs interested in designing and constructing rhombics.*

Figure 5 is the stereographic representation of the free-space radiation function of one leg of a rhombic antenna. The length of this leg is two wavelengths. Let's review it for emphasis. Looking from right to left on **fig. 5**, there is first a dotted line, then a solid line, then a dotted line and so forth. The dotted curves represent the maxima circles described by Foster. The solid curves represent the zero circles. A drawing identical to **fig. 5** is then superimposed on the drawing shown in **fig. 5**. Each represents the radiation function of a two-wavelength leg of a rhombic antenna.

Suppose it is desired to have a tilt angle of 70 degrees. From **fig. 3A** we can calculate 2A = 40 degrees. By rotating the superimposed drawings so that a 40 degree angle is realized between the axes of the two legs, we obtain the actual free-space radiation pattern of a rhombic antenna with two wavelength legs, and a tilt angle of 70 degrees; see **fig. 8**.

By studying **fig. 8**, it can be seen that the first dotted lines of the two drawings intersect at point X; that is the main lobe. Next, consider the first dotted line of the lower leg and note that it intersects the second dotted line of the upper leg at point Y. The second dotted line of the lower leg intersects the first dotted line of the upper leg at point Z. Other points of intersection are at points A, B, C, D, E, F, and G as shown in **fig. 8**. These intersection points of the dotted circles represent points of maximum radiation, or lobes, of the antenna.

A line drawn from the center of the figure through point X is extended to the edge of the great circle. This line is now called "the axis of the antenna," and is the line in which the strongest lobe of the rhombic lies. The strongest, or main lobe of a rhombic will always fall exactly midway between the two legs of the antenna if it is designed correctly.

The next step is to number the dotted curves at the periphery of the circle for ease of handling. The dotted lines of the upper leg are numbered 1, 2, 3, and 4, starting with the lower end of the first dotted line and going clockwise. The dotted lines of the lower leg are also numbered 1, 2, 3, and 4, but starting at the upper end of the first dotted line, and going counterclockwise.

When a Number 1 curve intersects another Number 1 curve, the resulting point is that of maximum radiation of the antenna. Other intersection points, called minor lobes, do not reach the level of the (1,1) intersection point. For instance, (refer to **table 1**), a Number 1 dotted curve intersecting a Number 2 dotted curve, points Y and Z on **fig. 8**, gives a lobe which is 10.6 dB lower in level than a (1,1) intersection. A (2,2) intersection point A on **fig. 8** is 21.1 dB lower

*A complete set of approximately 50 8½ by 11 inch overlays may be obtained from the author. These overlays are in photocopied form and will have to be made into transparencies for actual use. — **Editor.**

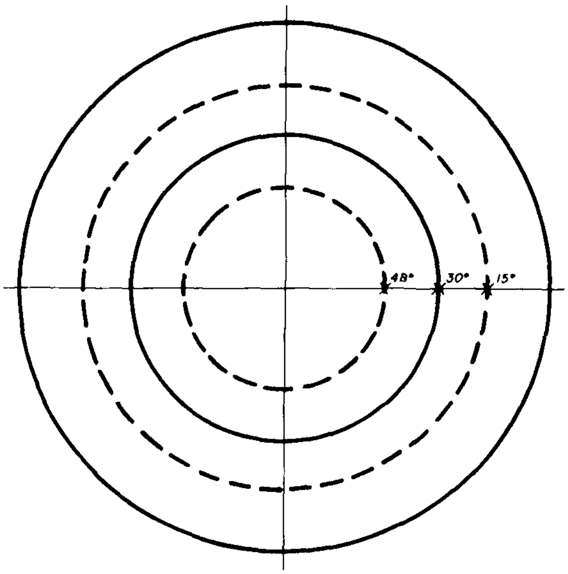

fig. 6. Ground interference pattern; antenna height one wavelength.

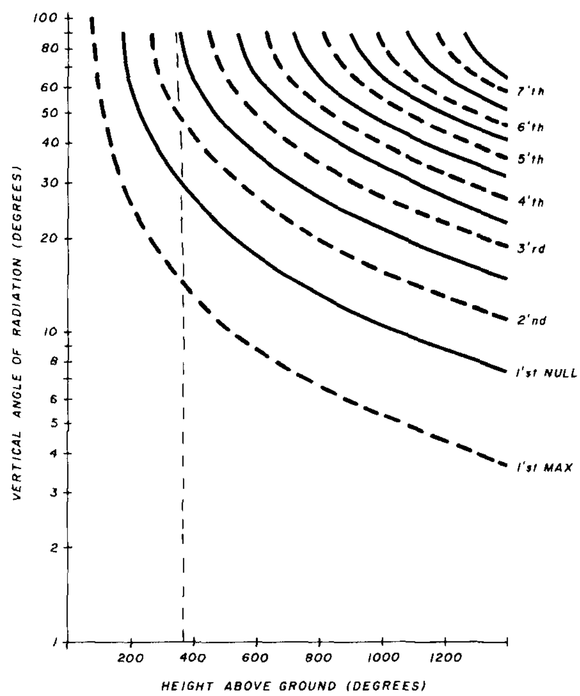

fig. 7. Vertical radiation angle vs. maximum and null angles for various antenna heights in electrical degrees.

table 1. Decibel differences between main lobe and subsequent minor lobes on rhombic antennas.

	rhombic radiation lobes										
	1	2	3	4	5	6	7	8	9	10	11
1	0										
2	10.6	21.1									
3	15.1	25.6	30.10								
4	18.0	28.6	33.10	36.0							
5	20.2	30.8	35.25	38.2	40.40						
6	21.9	32.5	37.00	40.0	42.10	43.9					
7	23.4	34.0	38.50	41.1	43.60	45.3	46.8				
8	24.6	35.2	39.70	42.6	44.80	46.6	48.0	49.3			
9	25.7	36.3	40.80	43.7	45.90	47.7	49.1	50.4	51.4		
10	26.7	37.3	41.75	44.7	46.90	48.6	50.1	51.3	52.4	53.40	
11	27.6	39.2	42.60	45.6	47.75	49.5	51.0	52.2	53.3	54.25	55.1

power difference (dB)

in level than the (1,1) intersection. The (4,4) intersection, point G is 36 dB lower, and so forth.

As the number of wavelengths on a leg increases, the number of dotted curves increases. For a composite overlay of two ten-wavelength legs, there will be twenty dotted curves per leg. **Table 1** gives levels only up to the eleventh curve since the minor lobes beyond this point are so weak in comparison to the main lobe as to be negligible. If at any time a solid curve intersects two dotted curves at or near their intersection, the lobe made by these curves intersecting will be cancelled or considerably reduced. That holds true in all cases. For instance, the (1,2) intersections, or the Y and Z points in **fig. 8**, are very close to the outside circle, which represents the horizon. Since these two lobes are depressed to just above the horizon, they may be considered as absorbed by surrounding hills or buildings, so that they will be of little use.

To find the vertical angle of fire of each of the lobes, **fig. 9** is superimposed on the drawings. **Figure 9** is the scale used for determining the vertical angle of fire for the various lobes of the rhombic antenna. When **fig. 9** is placed coincident with **fig. 8** (all figures are transparent), the main lobe, point X, will be at a 30 degree vertical angle of fire. Points Y and Z have about 5 degree vertical angle of fire, which is too low to be usable except at the higher frequencies. Point A has about a 73 degree angle, points B and C about 90 degrees, and so forth.

The great thing about this stereographic method of analysis is that angle 2A between the two legs can be easily changed. As the angle is made greater, the two legs move apart, the main intersection travels out toward the horizon, and the vertical angle of radiation becomes less. Angle 2A can be increased until the intersection of the number one dotted curve reaches the horizon with a vertical radiation angle of 0 degrees. Further separation between the two legs causes the main lobe to split into two lobes. Although not obvious, the two split lobes are excessively sharp horizontally; yet despite this sharpness, the gain must necessarily be very low. Some of the minor lobes will have magnitudes as great or perhaps greater than the main lobe. The energy of the system is leaking out through other lobes in other directions rather than being concentrated in the main lobe. It might be difficult to discover this situation by arithmetical computations, but it is quicky observed by using stereographic charts. For a fixed rhombic beam, the upper frequency use is limited at the point at which the beam splits.

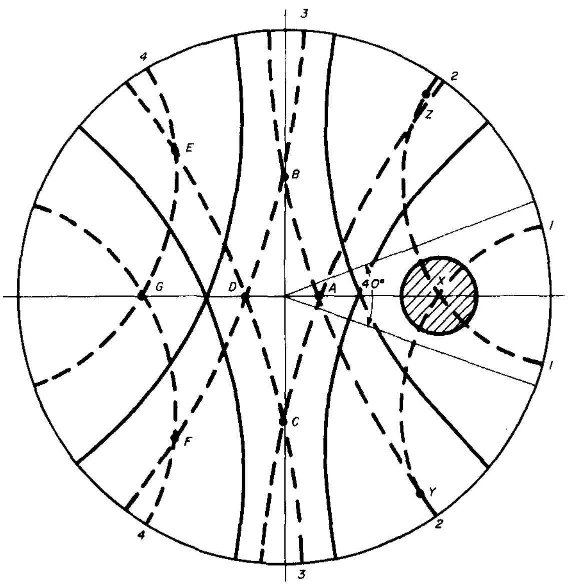

fig. 8. Free space pattern, two-wavelength. Note: the horizontal and vertical lines are for reference to the antenna plane only and are not seen in the overlays.

ground reflection effects

We must now consider the ground reflection or ground interference effects on the free-space pattern of the two wavelength rhombic discussed above. To keep it simple, an antenna height of one-half wavelength will be used; it has only one reflection agent. **Figure 10** shows the ground pattern, which is the dotted circle, for one-half wavelength high antenna superimposed on **fig. 8**. Dotted lines represent an in-phase reflection reaching the antenna, whereas solid lines represent cancellation. The one-half wavelength height has no out-of-phase reflection radiation.

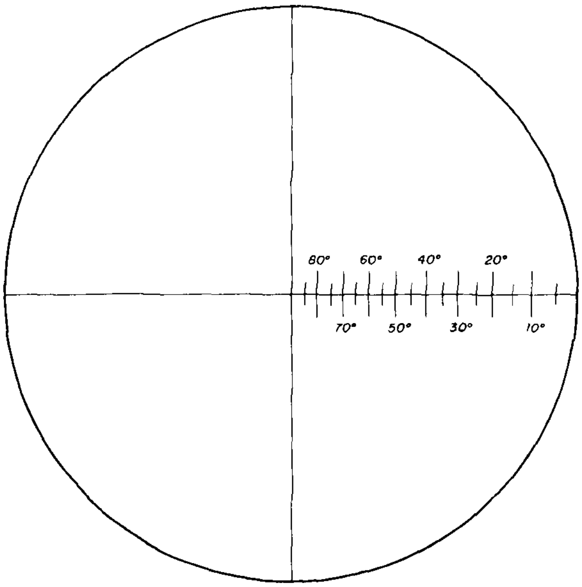

fig. 9. Scale to determine vertical angles of fire on rhombic antennas.

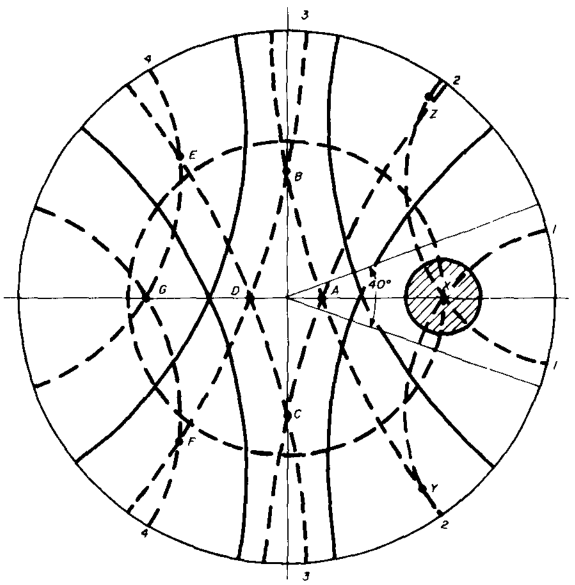

fig. 10. Superimposition of two-wavelength rhombic free-space pattern and one-half wavelength height ground interference pattern.

Note that the dotted circle intersects the free space antenna pattern exactly at point X, which is the main lobe point. (This happened only because the problem was done before writing this article, of course). That means the in-phase reflection has arrived to reinforce the main lobe. As noted previously, an additional 6-dB reinforcement of the main lobe has occurred. Points Y and Z of **fig. 10** are quite distant from the dotted circle and therefore are not reinforced. That means the main lobe has now increased to 16.6 dB instead of only 10.6 dB stronger than the next two strongest lobes (Y and Z) merely by choosing the correct antenna height.

Point A, the next strongest lobe, has not been reinforced by ground reflection and consequently has also been reduced with reference to the main lobe. Points B, C, E, F, and G are relatively close, however, to the reflection circle. While they will not be reinforced by 6 dB, since they are not exactly on the reflection circle, they have been reinforced by perhaps 4 dB so they have only decreased by a matter of, say, 2 dB with respect to the main lobe.

The wavelength height of the antenna may be raised by using higher towers for a given frequency or by increasing to a higher frequency with fixed antenna height. As the wavelength height of the antenna is raised, the number of reflection circles increases, and a number of solid lines representing ground interference appears on the stereographic overlays. For example, at a height of one wavelength, two reflection circles separated by an interference solid-line circle appear. At two wavelengths, there are four reflecting dotted circles and three interference circles. Different ground interference pattern overlays are therefore required.

design of 20-meter rhombic

Now we have an idea of what the use of the overlays can do for us in designing rhombics. Let's apply that information to the design of a rhombic for use on the 20-meter band. We want it to be four wavelengths on a leg and have it one wavelength high. The problem is to determine the best tilt angle for these conditions. Note that this is not the proper way to start a rhombic antenna design. The proper way is to first determine the radio circuit path desired, and therefore the desired vertical angle of radiation between the transmitting and receiving stations; review reference 8. Then design the rhombic to include that radiation angle. However, the stated problem will best review the use of the stereographic overlays, permitting you to do what you really want to do.

Superimpose two "leg pattern — four wavelengths" and one "ground interference pattern — one wavelength." Rotate the two leg pattern overlays so that their (1,1) curves intersect at the outermost dotted circle of the ground interference chart. Measuring the angle between the two legs, we find it to be 42-1/2 degrees, which is the angle 2A of **fig. 3A**. The tilt angle, θ, will be calculated to be 68-3/4 degrees. If the scale for determining the vertical angle of fire, **fig. 9**, is placed on the other charts, it shows the vertical angle of radiation for our rhombic to be 14 degrees. **Figure 11** shows the resulting composite of the overlays, first maxima only.

All the essential design factors of the rhombic have been found. They are: leg length = four wavelengths; height = one wavelength, tilt angle = 68-3/4 degrees, angle of fire = 14 degrees. The relative strength of the minor lobes and the front-to-back ratio can be found by referring to **table 1**. The front-to-back ratio in this case is about 51 dB. This is found by determining the intersection of the last two dotted curves which lie on the line extending in back of the main lobe. These will always be the dotted curves nearest the left-hand edge of the solid circle of the leg patterns (not shown in **fig. 11**). In this case they are the Number 8 curves counting from right to left on the leg patterns. Referring to **table 1**, the lobes produced by the intersection of the Number 8 curves or (8,8) point is 49.3 dB weaker than the main or (1,1) lobe. The main lobe has a ground reinforcement of 6 dB. Because the ground reflection pattern does not pass

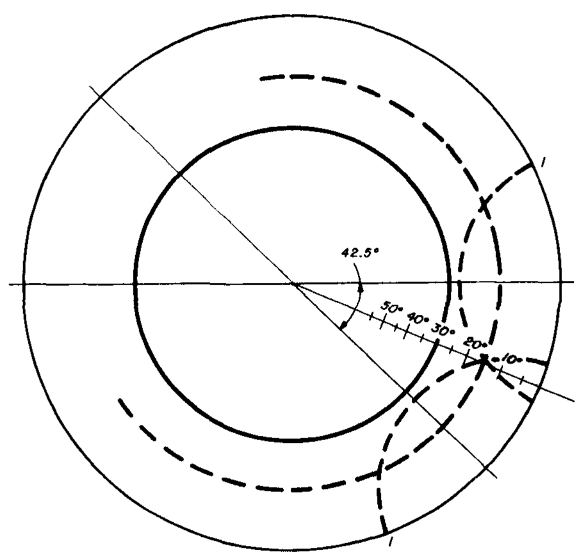

fig. 11. Overlay of two two-wavelength leg patterns, a ground interference pattern one wavelength high, and scale for determining vertical angle of radiation. Intersection with the first maximum ground interference line of first maximum (1,1) produces a 2A = 42-1/2 degree angle, and a vertical angle of radiation of 14 degrees.

directly through the (8,8) lobe, but only near it, a ground reflection of about 4 dB will accrue. The difference between these two reinforcements is thus 2 dB, which further increases the front-to-back radio to 51.3 dB. In round numbers, this is about 51 dB. The vertical angle of radiation of the (8,8) lobe is about 22 degrees.

Note that there is a (7,7) rear lobe falling exactly on the second ground reflection circle. However, the vertical angle of radiation is about 48 degrees, which will probably be lost into space at 14 MHz.

determination of vertical and horizontal radiation patterns

Figure 12 duplicates **fig. 8**, but with many lines eliminated to make the figure less "busy." Radial lines have been drawn from the center of the figure through each lobe point and extended a distance beyond the horizon circle. Starting at the axis of the antenna, the angle between the lobes is measured and recorded. These radial lines at the recorded angles are then reproduced on polar coordinate paper; see **fig. 13**. The radial lines at their correct angular displacement from the axis of the antenna are marked with their corresponding dotted line intersections. That is, the axis of the antenna will be marked with (1,1) and (2,2) because the Number 1 dotted curves and the Number 2 dotted curves have their intersections on that line. The other lines are similarly marked.

Next the ground interference pattern for an antenna height of one-half wavelength as shown in **fig. 10** is examined and the strength of all lobes as previously discussed (**table 1**), are tabulated. They are:

(1,1) =	0 dB	(3,3) =	−30.1 dB
(2,1) =	−16.6 dB	(4,3) =	−35.1 dB
(2,2) =	−21.1 dB	(4,4) =	−38.0 dB
(3,2) =	−27.6 dB		

The scale on the polar coordinate paper is then laid out from 0 dB through 50 dB in 10-dB increments; see **fig. 13**, and the lobes are plotted with reference to these circles.

This is only a relative pattern because it does not take into account the effect on the pattern of the different vertical angles of fire. For instance, the (2,1) lobes are greatly attenuated because of their low angle of fire, resulting in absorption by surrounding hills or buildings if in the vicinity of the antenna. However, the pattern does show the relative strengths of the peaks of the lobes in the horizontal plane and should prove very useful.

The determination of the strengths of the lobes at any point on, with the exception of the peak, is not readily determined through the use of the stereographic projection. The horizontal angle covered by the major lobe may be roughly found by drawing a

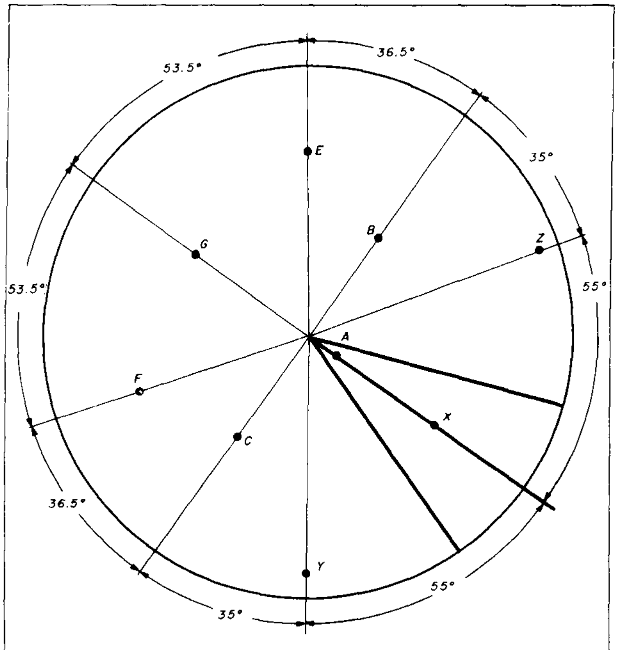

fig. 12. Same as fig. 8, but with intersection points only shown with angular displacement of intersections from main lobe direction.

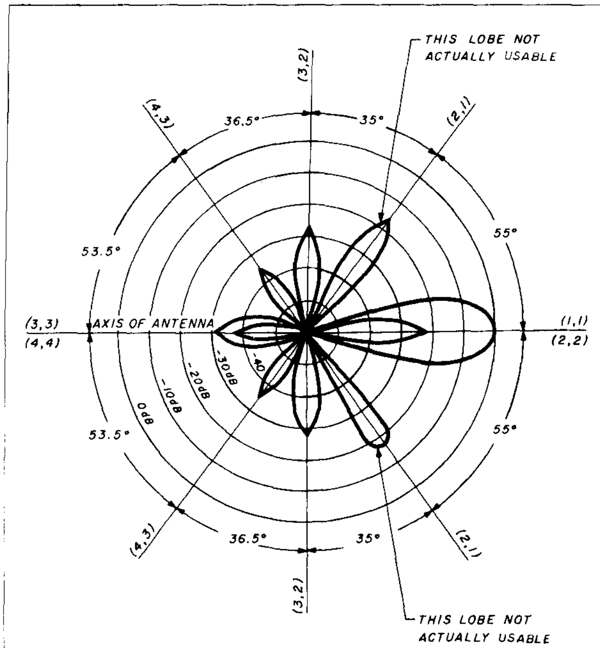

fig. 13. Horizontal plane pattern for two-wavelength rhombic antenna. ϕ = 70; antenna height = one-half wavelength.

circle with the center at the (1,1) intersection, (or at the center of the spherical triangle formed by the intersection of Number 1 curve and the ground interference circle, depending on whether all three curves intersect in one point or not) and a radius equal to one-half the distance between the intersection (or spherical triangle) and the nearest solid null curve. Lines tangent to this small circle drawn from the center of the large circle will form an angle which is a rough estimate of the usable horizontal beam width. On **fig. 8**, the small shaded circle is the circle mentioned above. The beamwidths of the minor lobes are not readily obtainable, but this should not prove objectionable since the major lobe is the only one which is used in most of the cases.

The vertical plane diagram is constructed in a similar manner as the horizontal pattern, except that **fig. 9** is used to determine the vertical angles. These are:

(1,1) = 29 degrees	(3,3) = 75 degrees
(2,1) = 7 degrees	(4,3) = 27 degrees
(2,2) = 75 degrees	(4,4) = 30 degrees
(3,2) = 35 degrees	

This gives some interesting results. Above about 7 MHz the (2,2) and (3,3) lobes may be considered useless since they will penetrate the ionosphere at such high angles. As previously stated, the (2,1) lobes are radiated at such a low angle as to be useless on all but extremely local signals or at extremely high frequencies.

Returning to the vertical plane pattern, radial lines are again laid out, only this time the vertical angles of fire are used in place of the horizontal radiation angles. All those lobes falling to the left of the center of the circle are plotted to the left and all those falling to the right are plotted to the right. Those falling to the left will be (3,3), (4,3), (3,2) and (4,4). Those falling to the right will be (1,1), (2,1) (3,2) and (2,2). Since the (3,2) lobes fall exactly on the center line of the circle, see **fig. 8**, (axis of the antenna being horizontal) one will be plotted to the left, and one to the right. This is not a strictly accurate geometrical layout of the pattern but will suffice since the determination of the relative strengths of the lobes in the vertical plane is all that is desired. The levels determined for the horizontal plane pattern may be used, without change, for the vertical plane pattern. The complete vertical plane pattern is shown in **fig. 14**.

Through the use of different height curves, leg length curves, and tilt angles, unwanted lobes may be eliminated or effectively reduced and desired lobes may be reinforced. The use of leg lengths longer than eight or ten wavelengths is inadvisable because of the subsequent reduction in width and height of the radiated lobes. A reduction of this sort is conducive to fading and makes the aiming of the antenna extremely critical.

A compass rose may be superimposed on the drawing as an aid in determining the angle between the legs of the antenna and the angles between the main lobe and the minor lobes. The use of an angle between the table 2. Beamwidth as a function of leg length. Beamwidth is the point where power is 3 dB down from the maximum power point.

leg wavelength	beamwidth (degrees)	number DXCC countries within beamwidth (from North Carolina) forward direction	reverse direction
1	30	84	4
2	25	77	4
4	17	63	4
6	10	43	4
8	8	40	4
10	6	35	3

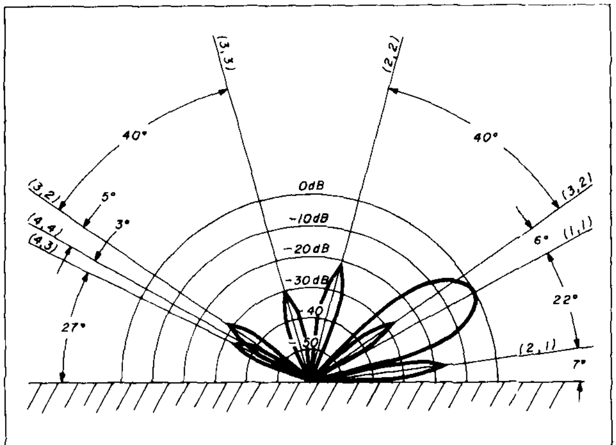

fig. 14. Vertical plane pattern for two-wavelength rhombic antenna. ϕ = 70; antenna height = one-half wavelength.

legs, such that the two Number 1 curves do not intersect, should be avoided, because this will effectively eliminate the major lobes, which is the most effective source of power from the rhombic antenna.

multiband operation

One of the most useful features of a rhombic antenna, as previously mentioned, is its ability to operate efficiently over a wide frequency range. The two-wavelength rhombic illustrated in **fig. 8** will be used as an example. Suppose it is desired to operate this antenna on 4 MHz. Its legs will then be two wavelengths long and its height will be one-half wavelength. On 4 MHz, using the formulas of **fig. 3**, two wavelength legs will be 485 feet long, and the height of the antenna will be 123 feet. Now, if the operating frequency is made 8 MHz, the length of the legs will be four wavelengths long at this frequency, and the antenna height will be one wavelength. Suitable overlays for the leg length and antenna height for this frequency are now set up, retaining the 70 degree tilt angle previously used. The major lobe will now be found to have an angle of fire equal to 15 degrees which is approximately the optimum angle of fire for 8 MHz. The horizontal azimuthal angle covered by the major lobe has now been reduced to 17 degrees instead of the original 25 degrees. The antenna will work practically as well, therefore, on 8 MHz, as it does on 4 MHz. The only change worth noting is the reduction of the beamwidth, since the 15 degree angle of fire is about optimum for 8 MHz, as is the 30 degree angle for 4 MHz.

Suppose the frequency were now increased to 12 MHz. The legs will now be six wavelengths long and the height will be one and one-half wavelengths. The pattern is again set using the appropriate overlays. It will be noted that the two (1,1) curves, depressed to the horizon, form a spherical triangle with the first ground interference circle. While this materially reduces the strength of the major lobe, it is still usable. The angle of fire is taken from the center of the spherical triangle and is found to be about 7 degrees. While this is rather low for 12 MHz, it will work fairly well in locations where the antenna is well out in the clear and away from any trees or buildings. This rhombic antenna, therefore, may be said to be extremely effective over a 2 to 1 frequency range (4 - 8 MHz) and fairly effective over a 3 to 1 frequency range (4 - 12 MHz). It would work over any 3 to 1 frequency range, 6 to 18 MHz, 8 to 24 MHz, or any similar range. Of course appropriate leg lengths and heights would have to be used for two wavelength legs and one-half wavelength for the lowest frequency.

beamwidth

The beamwidth of a rhombic is generally a function of the leg length. **Table 2** indicates beamwidth versus leg length. Beamwidth is defined as the angle where a 3 dB loss has occurred from the maximum power point. From Salisbury, North Carolina, with the rhombic pointed at approximately 47 degrees from north, which is the bearing for London, England, many countries can be worked as shown in **table 2**.

By switching the feedpoint to the rhombic including the terminating resistor, to the opposite end of the

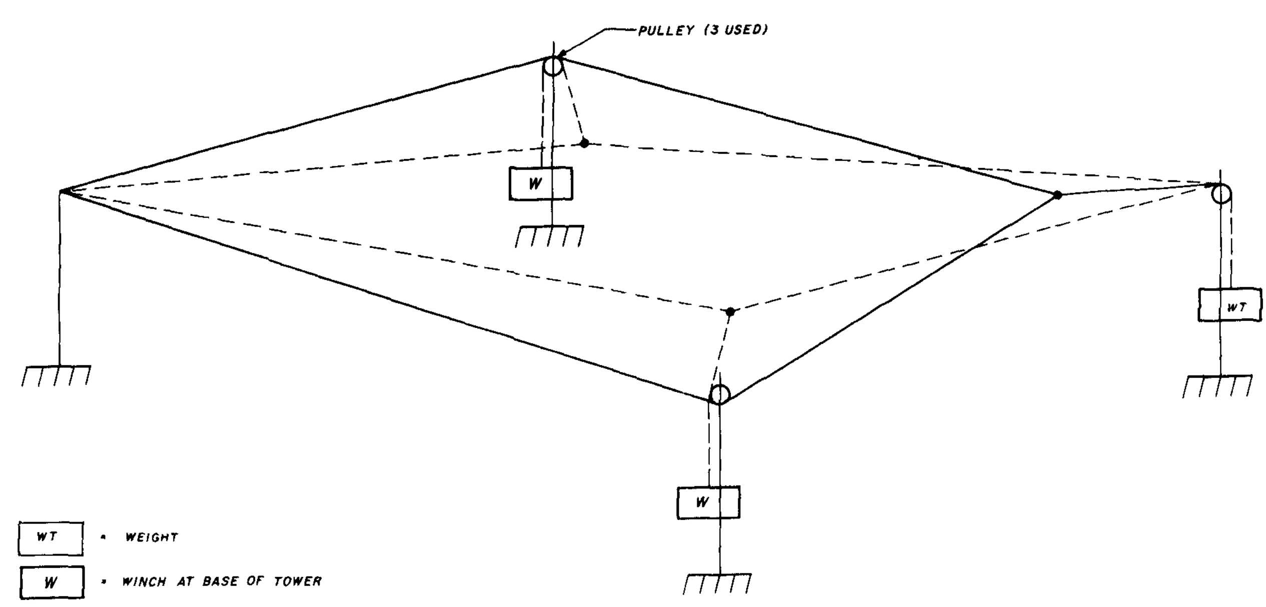

fig. 15. A controlled vertical radiation (CVR) rhombic antenna showing extremes between lowest frequency use (solid lines) and highest frequency use (dotted lines.).

rhombic, its direction of fire will be reversed 180 degrees. **Table 2** also shows the number of DXCC countries workable within the stated beamwidths in the reverse direction — not very many. It is, however, a "pipeline" through Mexico, Pitcairn Island, Clipperton, and MacQuarie. With a rhombic on Japan, South America should be blanketed in the reverse direction. Unless you are interested in a particular point-to-point radio path, rhombics longer than 10 wavelenths are too narrow for general use.

controlled vertical radiation rhombic

Now that you know how to design a rhombic antenna, let's move on to a more specific aspect of design, the controlled vertical radiation (CVR) rhombic. Bruce and Beck, in the April, 1935 *Proceedings of the IRE*[10] described experiments made with a steerable rhombic during reception of transoceanic shortwave signals. The first and last I'd read about it in Amateur Radio was an article in April, 1937, issue of *QST*.[11] In this account, W6AUX and W7CNX reported on their operation of a CVR rhombic in the 20-meter band. While not claiming anything new, I am expanding the CVR principle to provide a rhombic that can operate at a design efficiency anyplace in the Amateur bands with a limitation only on the minimum acceptable beamwidth.

A CVR rhombic is simply a rhombic whose shape may be changed by physical means; see **fig. 15**. By having pulleys on the side towers and one end tower,

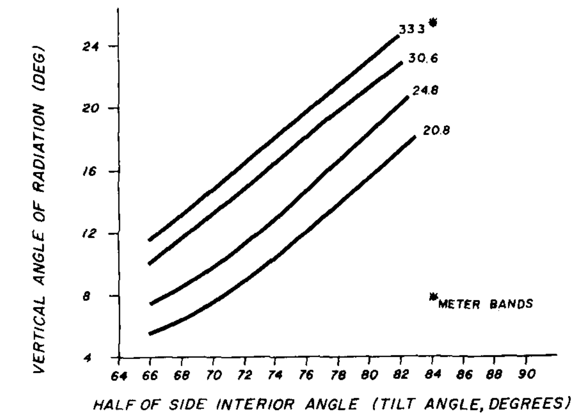

fig. 16. Change of vertical angle of radiation with change of tilt angle for various operating frequencies. (By E. Bruce in 1935.)

the tilt angle of the rhombic may be changed and set to any desired number of degrees.

Let's see what Bruce and Beck say about that. They were studying rapid fading in radio circuits, and the possible cause being the interaction of different components of a radio signal having different transmission times. Their past observations had indicated that fading was affected by the directivity of the receiving antenna. *Tests in 1934 had shown that a* greater degree of angular spread between multiple path waves exist in the incident vertical plane than in the horizontal plane. So they devised a rhombic of the type of **fig. 15** and ran extensive tests. Their article concludes, "It is believed that the results, discussed in this paper, demonstrate that sharp angular discrimination is a basically sound method of combating selective fading."

Of greater interest to Amateurs is not the minimizing of fading, but the fact Bruce's and Beck's tests showed that the vertical angle of radiation from a rhombic can be varied 12 to 14 degrees for a given frequency. While it's possible to do that with a Yagi antenna by raising and lowering its tower, how many hams would want to do that? The compromise — a good one — is to have a high Yagi for long-haul or band-opening contacts, and a low one for staying within the skip zone into Europe when the band is wide open. However, we're talking about a rhombic with superior gain over a Yagi when the rhombic is operating at its peak.

Figure 16 is a copy of the Bruce/Beck curve showing steerability, at several wavelengths, of the horizontal rhombic antenna used for fading reduction studies. We can call it the vertical radiation angle versus the rhombic tilt angle. Think about setting your rhombic on 20 meters for a 7 degree vertical angle of radiation as sunrise approaches to get real long haul or early band openings, and then as the day continues, changing the radiation angle to 12 degrees or more to put a commanding signal into Europe when the band is fully opened. When motorized, it would be possible to tune the antenna for maximum received signal strength from the desired location.

In the 1937 *QST* article, using the same idea, Moore and Johnson concluded the following:

1. *That there is an optimum angle in the vertical plane for transmission as well as reception.*

2. *That the optimum angle for transmission and reception are close together although not necessarily coincident.*

3. *That there is, under normal conditions, only a very limited region in the vertical plane in which useful radiation takes place, and that energy directed into any other region in the vertical plane is largely wasted.*

4. *That the optimum angle of transmission changes from time to time with changes of seasons and conditions, but that there is no material change within a short interval of time.*

5. *That controlled directivity in the vertical plane is relatively more important than directivity in the horizontal plane.*[11]

Now that rotatable arrays are the accepted thing, the fifth claim is debatable. However, in the 1930's one would have assumed Bruce and Beck meant that the proper vertical angle of radiation to a given point is more important than the gain of the antenna; gain and directivity, at that time, seemed to have been synonymous. A very high gain antenna whose vertical angle of radiation over-shot the desired reception point would be a poor performer in comparison to a dipole whose vertical angle of radiation was such as to give maximum reception at the receiving point.

From earlier discussions, we have learned that the vertical angle of radiation does change as we vary the tilt angle of the rhombic. That change is very easy to see with the stereographic overlays. Unfortunately for the earlier investigators, Foster did not publish his works until October, 1937.[7]

We must not be left with the impression that we are getting something for nothing when we change the vertical angle of radiation by tuning the tilt angle. If you recall the analysis section above, you will remember that the tilt angle during design is adjusted to fall on a dotted circle of the ground interference pattern to give a 6 dB boost from the ground reflected signal. By tuning the tilt angle during operating periods, that ground reinforcement deteriorates. However, this is where point five of the Moore/Johnson[11] conclusions becomes important; controlled directivity in the vertical plane is more important than gain in the horizontal plane. Since we can tune the tilt angle for maximum received signal, the law of reciprocity of transmitted/received signals says we are at the best operating conditions for the radio path in use.

The most interesting thing about being able to change the configuration of the rhombic is the ability to tune the antenna to the operating Amateur band desired. It was earlier stated that a fixed rhombic can be made to work reasonably well over a range of frequencies of 3 to 1. As the frequency gets higher, the vertical angle of radiation gets lower until at some frequency the main lobe splits and the rhombic no longer has high operating performance.

The CVR rhombic can be adjusted for peak performance at any Amateur band. For example, if for a given arrangement, the antenna frequency is increased to the lobe splitting point, it is necessary only to lengthen the overall configuration to raise the vertical angle of radiation and bring the split lobes together again at the higher frequencies.

RF feed to a rhombic

This discussion of feeding RF to the rhombic is based on the understanding that the antenna will be terminated in its characteristic impedance. By so terminating it, we can take advantage of the excellent front-to-back ratio that distinguishes this antenna from other types, as discussed earlier. The method of termination will be discussed later.

The antenna input impedance changes with frequency even when terminated. Various authorities show that an impedance change occurs from as much as 850 ohms to 600 ohms over a frequency range of 4 to 23 MHz. However, because of the relatively small percentage change, the worst SWR based on a center impedance of 750 ohms would be 1.25:1. So the problem boils down to getting from the transmitter output of 50 ohms to the antenna's 750 ohms (see **fig. 17**).

It can be seen that the main transmission feeder line is a 600 ohm, two-wire open line, with provisions to feed either end of the rhombic antenna. A switching arrangement at the center of the antenna permits exchanging the RF feedline and dissipation line to allow remote switching of direction of fire while maintaining a high front-to-back ratio in the chosen direction.

You can get to 600 ohms from 50 ohms immediately by using a 12:1 ratio balun. Barker and Williamson makes a 5 kW 12:1 balun; you can also wind your own. Six hundred ohms for the main transmission line was advisable in my case because of the availability of a 118 watt, 600-ohm type CX. The Globar Division of The Carborundum Company makes a non-inductive resistor that can be used in conjunction with the dissipation line as the termination resistance.

Impedance changes from 750 ohms to 600 ohms are required to get to the 600-ohm line from the two ends of the rhombic. A transmission line whose characteristic impedance is gradually tapered from one value to another may be used as a coupling transformer providing the change in impedance along the line is sufficiently gradual.

When a tapered-line transformer with a minimum length is desired, the characteristic impedance must be tapered exponentially between the two limiting values. One can avoid complicated design computations by using an exponentially tapered line section at least one-half wavelength long at the lowest frequency to be transmitted and connecting it directly between the antenna and the transmission line. Such a line was used between the 750-ohm antenna input and the 600-ohm main transmission line. Since I wanted to use the rhombic on 80 meters, a half-wave exponential line of 137 feet in length was constructed for each end of the rhombic.

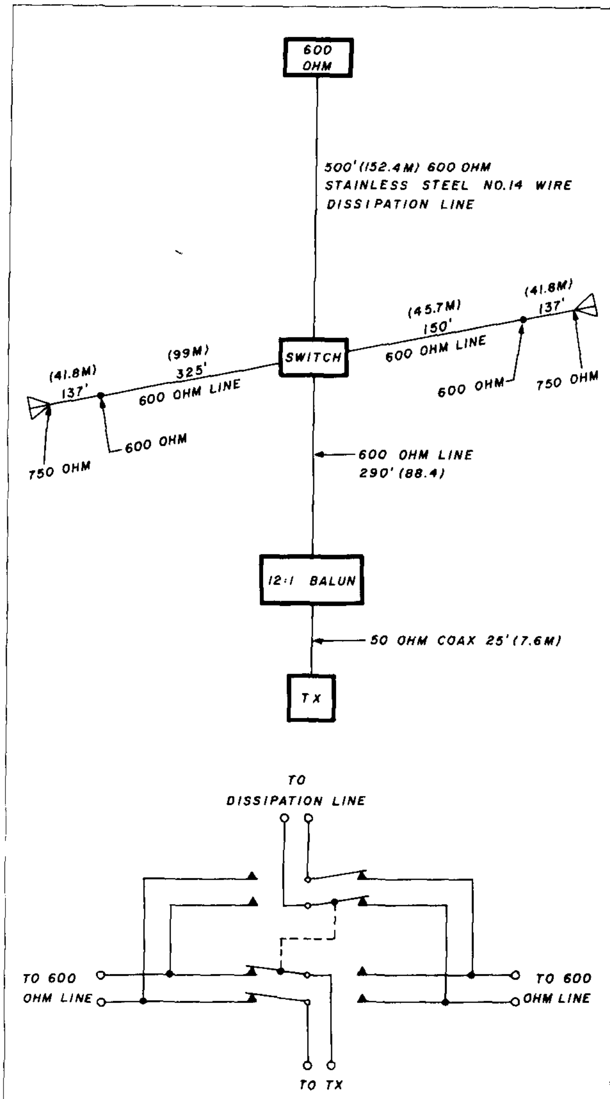

fig. 17. (A) Matching to the rhombic and changing its firing direction is accomplished by using a 12:1 balun, *transmission line switch and dissipation line.* (B) Transmission line changeover requires an effective 4 PDT switch.

rhombic termination

If you don't wish to reverse the direction of radiation of the rhombic, a non-inductive resistor may be installed directly at the far end of the rhombic. The power rating of the resistor should be at least one-third of the power going into the antenna; two-thirds of the input power is radiated before it reaches the far end. For example, if the power to the antenna is 500 watts, key down, the terminating resistor should be able to dissipate about 170 watts.

An alternative is to use a balanced lossy line of high dissipation rating. I used a 600-ohm dissipation line (No. 14 Stainless Steel wire) 500 feet long. The 600-ohm, 118-watt non-inductive resistor terminates the line. As seen in **fig. 17**, remote controlled switching circuits permit swapping of the transmitting and dissipation line to permit reversing the direction of fire of the rhombic.

motorized configuration changer

Figure 15, previously referred to, is a very simplified picture of how to change the configuration of the rhombic. However, because the motorizing of the configuration change by remote means was the most difficult part of the project to develop successfully, some guidelines may be useful.

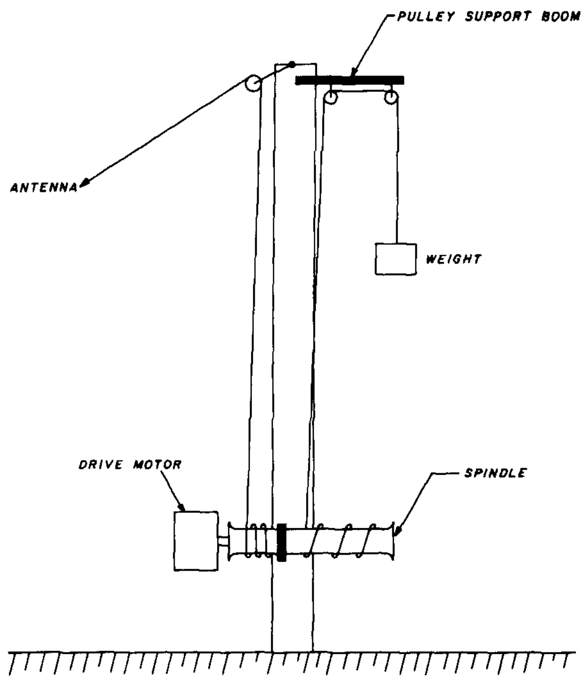

fig. 18. Counterbalancing system to reduce motor drive load.

The first attempt to motorize the configuration was done by a motor at the far end of the array with the weights on the side tower to maintain proper tension in the antenna as the configuration was changed. Don't do it that way! As the rhombic becomes "longer," its legs approach a straight line. The force required to pull the rhombic becomes increasingly greater and a very large motor is required. A better way is to pull the legs in from the side as depicted in **fig. 15.** An analogy is the difficulty in tightening a violin string as opposed to the ease of plucking it from the middle.

Two identical motors — of only modest power — are required. To further reduce the motor power requirements, a counter-balancing arrangement should be used; see **fig. 18.** Using such a system permits a lower motor output because it must only overcome the difference in antenna force versus the counterweight force as the system moves off its equilibrium point, a point of zero motor output requirement.

The drive motors have to be capable of reversing and require a gear reduction to not only increase output torque, but to give slow spindle speed; a spindle rotation speed of 20-30 RPM is good. A 230-volt reversible motor with integral gearing to give 50 foot-pound torque at a speed of 75 RPM was originally tried. That proved inadequate even with the counterbalancing system. A further gear reduction of 4:1 using a chain drive proved acceptable. That was with a 65 pound counter-balance weight, and a 200 pound far-end weight. A surplus synchro connected to the gear motor drive at the closest-to-the-house side-tower permits remote indication of the configuration at the operating position during dark hours. It was necessary to use a gear step-down arrangement so that the synchro makes only one revolution of the entire configuration change.

acknowledgements

A project of this size cannot be accomplished without help. First I'd like to thank Marshall Etter, W2ER, whose long-distance correspondence gave me a fuller understanding of the practical aspects of rhombic antenna construction gleaned from his many years at RCA Riverhead Receiving Station; his knowledge boosted my confidence as well. Fred McGinnis, WD4KJZ, assisted in handling the lines and furnished muscle as we erected four towers — two 70-footers, one 80-footer, and 70 feet of a 100-footer. (Fred is 70+ years old and I was 63 at the time, so we made a great team.) John Fleming, WD4FFX, put up the last 30 feet of the 100 footer, which I declined to climb. Bill McCune, W2IRC, built the spindles and other mechanical parts and provided assistance and advice in the guying of the towers. Richard Bluhm, W2KXD, gave counsel on the Foster charts and design work. Alan Sielke, a non-ham, gave advice on structural loads on the towers from his civil engineering background and loaned me the transit. Norman Gertz, K1AA, furnished the 600-ohm terminating resistor as well as old military publications pertaining to rhombics. Gene Black, W2LL, furnished the old-style 600-ohm DPDT antenna relays needed for direction reversal. Millie Elwell, KA4ECM, helped in the initial survey of the rhombic towers and contributed encouragement and patience.

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ham radio

controlled vertical radiation rhombics

part 2: antenna erection and performance

Four towers, careful siting and plenty of wire yield topnotch results

Very few projects can be completed without compromise, and erecting a rhombic antenna is no exception. In this project, the compromise lay between *tower height and low-frequency operation.* An antenna height of about 65 feet was the maximum desired; this meant that 7 MHz would be the lowest design frequency. The desire to have no more than eight wavelengths on the 28-MHz band established the leg length. As pointed out in part 1 of this article, an eight-wavelength array produced an 8-degree beamwidth, and anything less was not desired. Thus two wavelengths on 7 MHz equals 277 feet. The antenna performs well on the 7, 10, 14, 18, 21, 24, and 28 MHz bands and to a lesser extent on the 1.8- and 4-MHz bands.

Based on the height and leg length, the tilt angle for the various bands was determined, with special emphasis on the lowest and highest bands – 7 and 28 MHz, respectively. These bands would determine the greatest width between the side towers and the greatest length between the end towers. **Figure 1** shows the horizontal layout of the designed rhombic, emphasizing the 7 and 28 MHz configurations. Note that a 2 A angle (see **part 1, fig. 3**) of 50 and 20 degrees are required for the 7 and 28 MHz configurations, respectively. This requires the let-out of the rhombic from the side towers of about 72 feet to go from 7 to 28 MHz (see **table 1**). The resulting takeup at the end tower is about 45 feet.

The determination of these parameters is a matter of trigonometry and is not detailed here.

geographical bearing and antenna layout

The determination of the location of the four towers is the crucial point of the design; once the towers are set in concrete, they can't be moved. Two points to consider in this regard are the desired bearing of the rhombic from true north and the allowance for a gap between pulleys and down lead. The downlead supports a counterweight, which must clear the tower as the counterweight is raised and lowered. An additional three feet between pulley and tower is advisable.

Unlike a Yagi, whose beamwidth may be anywhere from 40 to 60 degrees, the eight-wavelength rhombic will have a beamwidth of only 8 degrees. Therefore, accuracy in determining both the true bearing to the desired reception area and the physical positioning of the four towers supporting this antenna is especially important. Check all measurements and calculations carefully. (See references 1 and 2 for how to determine bearings.)

To determine the bearing of my antenna, and to set the ground posts properly, I borrowed a transit and stood where the fixed-antenna tower was to be erected. I sighted Polaris – the North Star – while KA4ECM, my wife Millie, stood about 400 feet away, shining a flashlight toward me. I lowered the transit, to a point parallel to the ground still keeping it pointed squarely in the direction of Polaris, while KA4ECM walked slowly in an east-west direction. As soon as I spotted her light in the transit viewfinder, I signaled for her to stop. She then planted a ground post at that point.

The following day we reset the transit to align on that ground post, and swung it 46.8 degrees from North, *inserting a second post at the distant point.* (Accuracy of ±1 degree is recommended.)

By Henry G. Elwell, Jr., N4UH, Route 2, Box 20G, Cleveland, North Carolina 27013

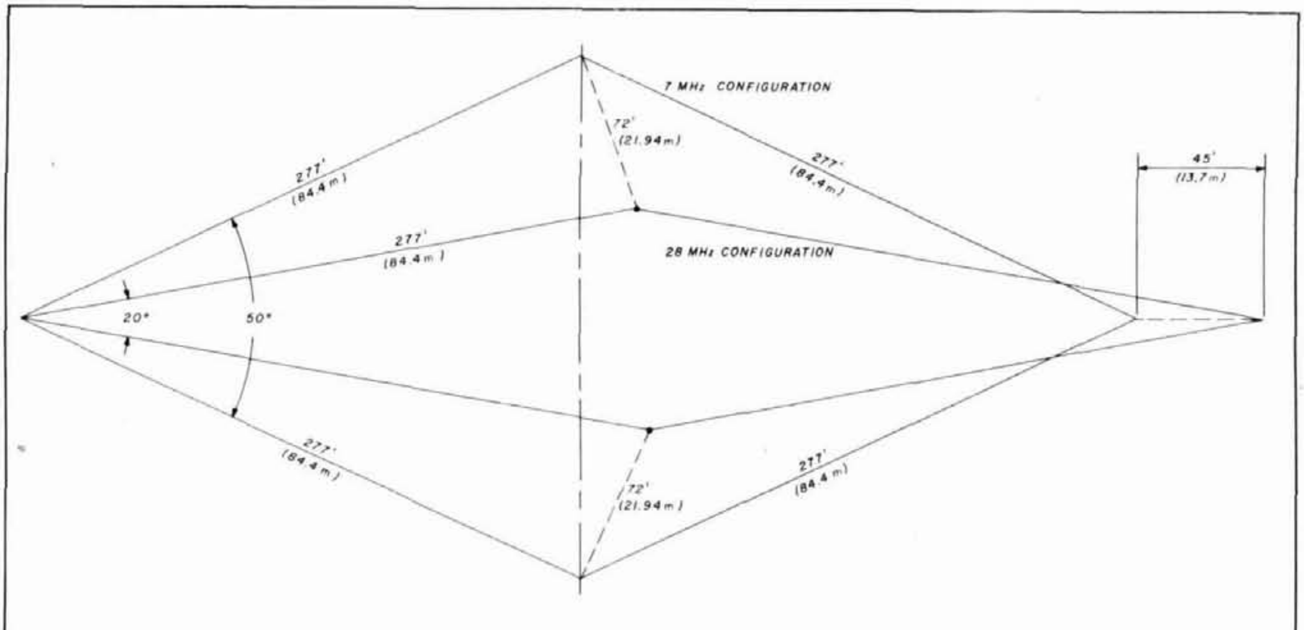
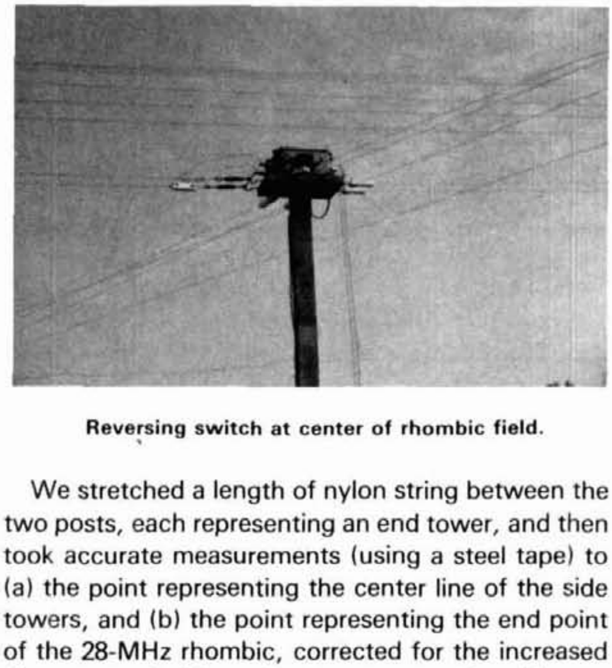


fig. 1. Horizontal layout of controlled vertical radiation rhombic at the lowest frequency (7 MHz) and the highest design frequency (28 MHz band).



Reversing switch at center of rhombic field.

table 1. Correlation between amount of "let-out" and antenna height.

side tower let-out, feet	antenna height feet
0	65.00
10	61.75
20	59.00
30	57.00
40	55.00
50	53.75
60	53.50
70	52.25

We stretched a length of nylon string between the two posts, each representing an end tower, and then took accurate measurements (using a steel tape) to (a) the point representing the center line of the side towers, and (b) the point representing the end point of the 28-MHz rhombic, corrected for the increased distance needed for pulley-tower separation. (Plan on installing a pulley on the fixed end so that the whole array can be dropped to the ground when necessary.)

We then placed the transit on the nylon string at the point representing the side tower's centerline. Ninety-degree right and left bearings were made and posts temporarily set at distances of approximately 120 feet. We strung nylon cord between these posts, took accurate measurements along the cord, and then drove stakes representing the two side towers into the ground.

Even though Polaris is easy to spot with the naked eye, it may be difficult to locate with the transit or telescope. Because of its great distance from Earth, its light reaches the telescope in parallel rays, making magnification difficult. Taking your bearings on a clear, windless – and not too cold – night minimizes the discomfort of an already difficult task.

The terrain over which my rhombic had to be erected was generally level but fell off quite sharply to the east. Various tower heights were necessary to produce an antenna that would be parallel to sea level. Two were 70 feet; a side tower had to be 80 feet; and the far end tower was 100 feet. The necessary tower heights were determined from topographical maps.

If the rhombic is to be erected on ground with a uniform slope extending for at least 1000 yards in front table 2. Control of the vertical angle of radiation is by paying out the side tower cables.

let-out distance (feet)	angle 2A (degrees)	vertical angle of radiation — degrees 7.2 MHz	10.1 MHz	14.2 MHz	21.3 MHz	28.6 MHz
0	50.0	26	16.0	5	beam splits	
10	45.8	28	20.0	11	beam splits	
20	41.6	30	22.5	16	beam splits	
30	37.6	31	24.0	18	6.0	beam splits
40	33.4	32	26.0	21	10.0	7
50	29.2	33	27.0	22	14.0	11
60	25.0	34	27.5	23	16.0	13
70	21.0	35	28.0	24	17.5	15

of the antenna, the practice is to make the front and rear poles approximately equal in height in order to bring the major axis of the antenna parallel to the average ground slope.

The erection of towers has been well covered in the literature. Substantial towers, well guyed in three directions according to the manufacturer's specifications, are necessary. One point to remember is that one guy set should be directly behind the vector force of the antenna at each tower.

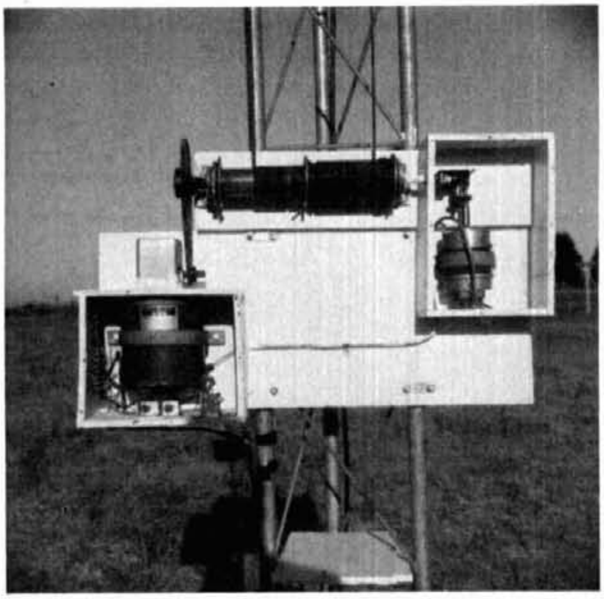
In private communications, Marshall Etter, W2ER, who was chief engineer at the old RCA overseas receiving station in Riverhead, Long Island, stated that tests showed it was not necessary to interrupt the guy wires with insulators for rhombic arrays. However, if the towers are also to be used for mounting Yagis, the use of guy insulators should be considered.

As to choice of antenna wire, the military specifies high strength, 40 percent conductance, using three strands of No. 12 AWG copperweld wire, with a rated breaking point of 2433 pounds. Other wire, such as No. 6 AWG (0.162 inch), 40 percent conductance copperweld, may also be used. W2ER stated that seven-strand No. 16 AWG bronze wire was used in the RCA Rocky Point installations. He advises against the use of solid wire, which tends to vibrate in long spans. I used a special stranded steel core, wrapped with copper, used for aircraft trailing-wire antennas.*

For maximum strength, treat the rhombic as four long-wire antennas. Terminate each leg at an insulator. At the side tower, terminate both the left and right legs on the same insulator holes, connecting the two legs with a flexible jumper soldered to each leg for a good electrical circuit (see **fig. 2**). The flexible jumper provides slack when changing the tilt angle for different bands or propagation conditions.

The end tower antenna legs are terminated in insulators, and two insulators connected to a pear ring (see **fig. 3**). The pear ring provides a strong, easy way of connecting the three forces: two antenna legs, and the opposing force of the restraining cable.

*Marshall Etter, W2ER, has a limited supply of wire, insulators, and other rhombic antenna construction materials. Inquiries (enclose SASE) should be addressed to W2ER at 16 Fairline Drive, East Quogue, New York 11942.



Side tower drive system. Motor drive is at left; take-up spindle, center; synchro position transmitter, right. Note the chain drive from motor to spindle to provide increased torque.

standing wave ratio

Once the complete system was operational, SWR was measured. **Figure 4** shows the average overall SWR from 160 meters through 10 meters. The increase in SWR in the 160-meter band may be expected because the exponential lines were designed for a minimum frequency of 3.5 MHz and the 4:1 balun cannot be expected to operate properly over such a wide frequency range. Although the big rise in SWR in the 21-MHz band is not understood, it is believed to be associated in some way with the balun. Operation in the 15-meter band is excellent, and with all open wire lines, losses due to a 3:1 SWR are minimal.

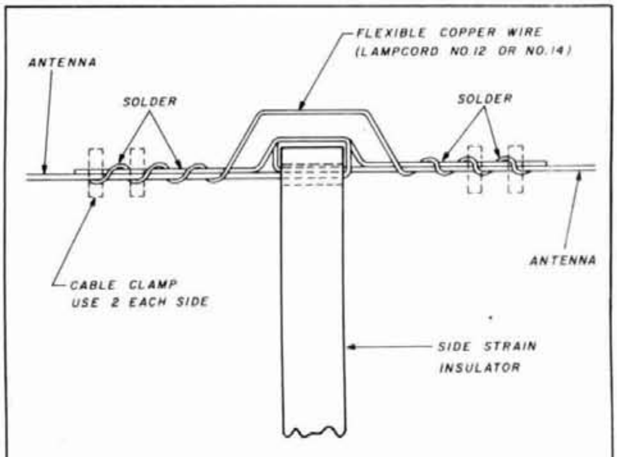
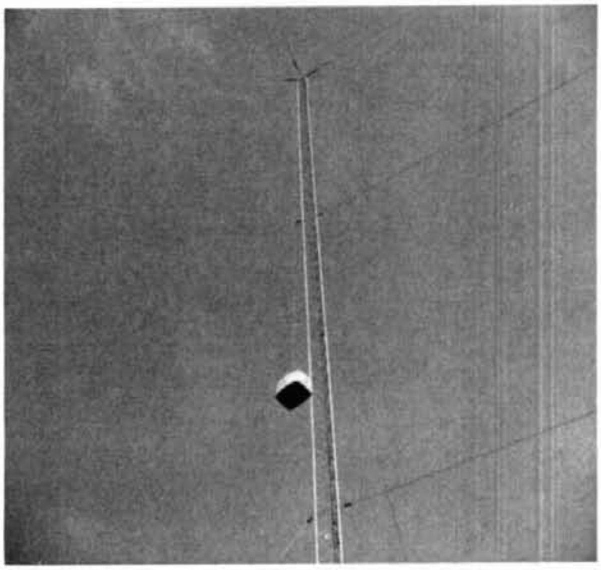


fig. 2. Connection of antenna leg at side towers to obtain antenna strength and good electrical connection between antenna legs.



End tower; 220-pound weight is shown in 40-meter position.

I have long believed in using tubes, which are very forgiving on SWR excursions, in the output amplifier stages. Use of solid-state outputs would require investigation and correction for SWRs greater than 2:1 or suffer the reduction in output levels which such transceivers automatically provide.

report on results

It will take many more months of operation and evaluation to explore fully all the capabilities of the CVR rhombic. After almost a year's operation during its development period, results can be reported in qualitative terms. Additional testing with data on the effects of changing the configuration for operation on a specific band as well as other details may be the subject of another article.

The rhombic has been used on all current Amateur bands from 160 through the 10-meter band. Foster graphs[3] determined the expected results to be as shown in **table 2**. A report on its actual performance, band by band, follows.

• **160 meters.** The rhombic has a constant 3:1 SWR over the entire band. Using an FT102, phone contacts were made from this QTH to the Virgin Islands, to Canada, and west to Texas. Definite front-to-back response was noticed when reversing direction of fire. Comparisons were made against an 80-foot W2LL vertical with apparent advantages going to the vertical for longer distances, and to the rhombic for shorter distances.

• **80 meters.** The rhombic, 1 wavelength on a leg, has an SWR less than 2.5:1 over the entire band. It exhibits definite gain over a W2LL vertical (60-foot tower with TH7DX Tribander on top) for DX. Friends in the New York City area said the rhombic's signal was stronger than that of any other antenna I've ever used. One of the first contacts was with VK6HD, long path at 2157Z. There is about a 15-dB front-to-back difference when reversing antenna fire direction. The beamwidth is noticeable, ZL4PO/C, within the beamwidth, gave me a 58 when all other East Coast stations were getting 56 to 57. However, Australian stations, which are outside the beamwidth by 23 degrees, give me reports comparable to other East Coast stations.

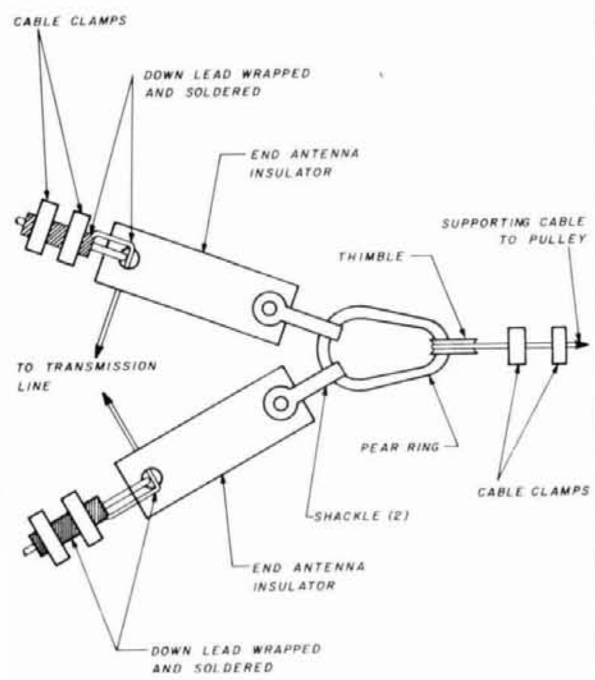


fig. 3. Pear ring used for terminating antenna and supporting cables.

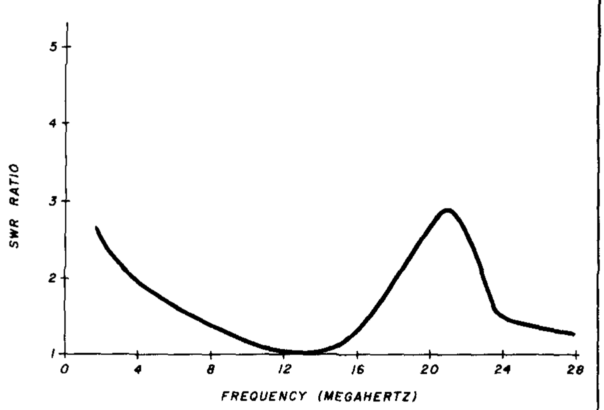


fig. 4. Graph illustrates *smoothed* SWR ratio versus frequency.

• **40 meters.** The rhombic exhibits a sharp change in SWR over this band: 3:1 from 7.0 MHz, dropping to 1.5:1 at 7.2 MHz and remaining there over the rest of the band. These SWR changes are peculiar to my particular setup. Being terminated, the SWR should be reasonably flat over the entire band. The rhombic is 2 wavelengths on a leg on this band. Reversing the direction of fire results in a 30 dB change in signal strength.

I've used the rhombic on this band mainly in contests, with phone results being the most informative. Because contest signal reports are meaningless, antenna effectiveness has been judged by the fact that, except for a single exception, my station received the first reply when a European stood by for Stateside calls on a stated frequency. No other 40-meter antenna was available during this evaluation period to supply comparative reports. However, the "feel" is that the rhombic, in its favored directions, is equal to or better than 3- or 4-element Yagis.

• **30 meters.** The rhombic, 3 wavelengths on a leg, has an SWR of approximately 1.5:1 across the band, and a front-to-back ratio of about 30 dB. Its signal really shines on this band because most of the antennas in competition with the rhombic are relatively simple. In the 40-meter configuration (on the 30-meter band) the rhombic's vertical angle of radiation (VAR) is at its lowest angle — 16 degrees — so ground reinforcement on this band (30-meter) has not been of major significance.

• **20 meters.** The rhombic, 4 wavelengths on a leg, has an SWR practically flat over the entire band; that is, 1.2:1 or less. Operation is with the side insulators 30 feet from the side towers for open-band operation into Europe where its vertical angle of radiation is about 18 degrees. Experience has shown that for band opening, long-path operation, and band closing operation, a 40-meter configuration with a VAR of 5 degrees on 20 meters provides very impressive signals. My first CQ on this band with the FT102 during band-opened conditions was a sufficient reward for all the effort put into siting and construction of the rhombic.

The comparison antenna on this band is a Hy-Gain TH7DX at 60 feet; this is a tribander beam on a 24-foot boom with two driven elements, a director, and a reflector. It is an excellent antenna that puts me among the top callers in most pileups.

The results of comparisons with European stations show a 1-1/2 to 2 S-unit advantage of the rhombic over the TH7. Front-to-back ratio is about 25 dB. The narrow beamwidth of the rhombic is noticeable on this band; thus, signals into Australia are superior on the TH7, as expected, because Australia is off the 3-dB edge of the main lobe by almost 30 degrees.

• **16 meters.** No operation has been accomplished on this band, although a quick SWR check indicated an SWR of 1.7:1.

• **15 meters.** The rhombic is 6 wavelengths on a leg on this band and for some unknown reason, not investigated, the antenna system has an SWR ranging from 3:1 to 2.2:1 over the band.

Preliminary controlled vertical radiation operation was accomplished over the entire configuration change of the rhombic, — that is, with side insulators at zero feet to 70 feet. Because it takes about 30 seconds for a 10-foot increment change of the side insulators, I thought it best to take qualitative measurements on a broadcast station. Radio Berlin at 21.6 MHz was used for the test. A 25-dB change in signal strength was noted between zero feet and 40-50 feet, with a buildup of 5 dB from that point to 60 feet and 70 feet. Much more work has to be done in this area.

• **12 meters.** Again, no operation is permitted on this band, although a quick SWR check indicated a 1.2:1 SWR ratio.

• **10 meters.** On this band the rhombic is 8 wavelengths on a leg and its operation is truly awesome to someone like me, whose biggest 10-meter antenna was a 5-element Yagi at 55 feet. I first operated on this band in February, 1983, with the rhombic in a 40-meter configuration. At that time I had not yet fully explored the beamwidth of the rhombic. But I foolishly asked Roger, N4ZC, with his large antenna farm to work VKs and ZLs with me to see how our signals compared. In both countries his 6-element Yagi at 90 feet was 2 S-units better than my rhombic.

Since that time I've realized that even ZL is too far beyond the 8-degree beamwidth of the rhombic on 10 meters, and the 40-meter configuration simply does not operate properly on 10 meters.

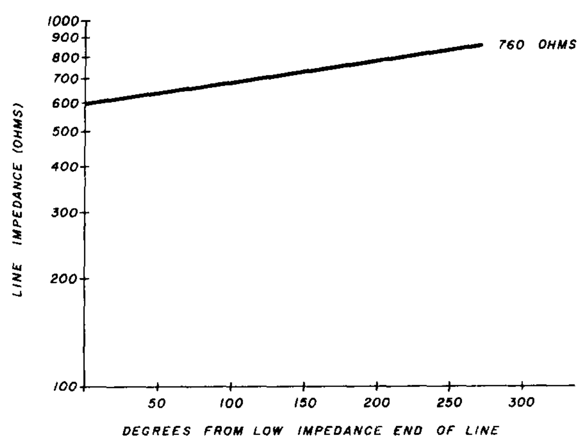


fig. A1. An exponential transmission line is used to transform impedances.

Ten meters opened again in the Fall after I had gained more experience with the rhombic and adjusted it to operate on this band. In the RSGB 10/15 meter contest in October, although not noted for my speedy contest operation, I worked 61 UK stations in 25 minutes because of the strength of the signal I was putting into Europe; "First W heard this morning," and "Loudest signal on the band," were pleasant to hear.

The general opinion appeared to be that the rhombic was 3-4 S-units stronger than the TH7. However, the narrow beamwidth is very noticeable on this band. With 45 ARRL countries within the beamwidth of the rhombic, the population density of Europe was being saturated, which was the original objective of the project.

acknowledgements

A project of this size cannot be accomplished without help and I wish to thank W2ER, WD4KJZ, WD4FFX, W2IRC, W2KXD, Alan Sielke, K1AA, W2LL, and my wife Millie, KA4ECM, whose contributions made it all possible.

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1. Jerry Hall, K1PLP, "Bearing and Distance Calculations by Sleight of Hand," *QST*, August, 1973, page 24.
2. Chester H. Brent, WB4GVE "Aim Your Beam Right," *73*, June, 1976, page 122.
3. Donald Foster, "Radiation of FM Rhombic Antennas," *Proceedings of the I.R.E.*, Volume 25, October, 1937, page 1327.

appendix

determination of an exponential line

Exponential transmission lines are useful in transforming impedances. The values at any point along the line can be determined using graphical or mathematical approach.[A1,A2] Since these references may not be available to everyone, a description of their method follows.

graphical method

This method uses a minimum transmission-line dimension of one-half wavelength drawn on semi-log paper.

- Mark the vertical scale with the desired impedance range. All cases will probably be from 100 to 1000 ohms.
- Mark the horizontal scale in wavelengths or electrical degrees.
- Mark a point at the 0 degree location with the desired input impedance.
- Mark a point corresponding to the desired output impedance and degrees point. The separation between these two points should be at least one-half wavelength (180 degrees).
- Draw a line between the two impedance points.
- The required characteristic impedance can now be read from the graph at all intermediate points along the line.
- Determine the necessary line configuration from each impedance point from the formula:

$$a = P\ 10^{Z/276}\ \text{2-wire line} \qquad \textbf{(A1)}$$

$$a = \frac{P}{\sqrt{2}}\ 10^{Z/138}\ \text{4-wire line side-connected} \qquad \textbf{(A2)}$$

$$a = \sqrt{2}\ P\ 10^{Z/138}\ \text{4-wire line, cross-connected} \qquad \textbf{(A3)}$$

where a = distance between wires of transmission line, in inches
P = radius of wire, in inches
Z = desired line impedance

Table A1 lists wire radius for various size wires. **Table A2** shows impedance variation along an exponential transmission line as a function of location and line spacing.

Example: Design an exponential 2-wire line to go from 760 ohms to 600 ohms using No. 14 bare copper wire, 3/4 wavelength (270 degrees). **Figure A1** is first drawn and then a table set up to show distance from the 600-ohm point, the impedance representing that distance, and (from the above equations) the line spacing required; see **table A2**. For greater accuracy, use the second method.

mathematical method

The impedance, Z, at any point on an exponential transmission line can be mathematically described as:

$$Z = Z_S\, e^{2s\theta} \qquad \textbf{(A4)}$$

where Z_S = the input or sending end impedance in ohms
s = line length in wavelengths (1 wavelength = 360 degrees)
θ = is a transformation function

The transformation function can be determined from the desired characteristics of the transmission line; i.e., input impedance, Z_S, and desired output impedance, Z, at the end of the line of s wavelengths. Its equation is:

$$\theta = \frac{1}{2s}\ ln\ \frac{Z}{Z_S} \qquad \textbf{(A5)}$$

To solve, determine:

- input and output impedance; Z_S and Z.
- line length; (minimum of 1/2-wavelength at lowest operating frequency); s.
- solve for θ.
- solve for Z for each selected value of s; let s be no greater than 20 degrees; 10 degrees preferably.
- determine the necessary line configuration for each value of Z using line spacing formulas shown in **graphical method**.

Example: Design an exponential 2-wire line to go from 600 ohms to 760 ohms using No. 14 bare copper wire, 3/4-wavelength long (270 degrees).

table A1. Radius of common wire gauges.

wire size	radius (inches)
8	0.0642
10	0.0509
12	0.0406
14	0.0320
16	0.0254
18	0.0200

table A2. Impedance variations along an exponential transmission as a function of location and line spacing.

distance from 600-ohm point (degrees)	characteristic impedance (ohms)	line spacing (inches)
0	600	4.78
20	611	5.23
40	620	5.64
—	—	—
250	750	16.69
270	760	18.14

table A3. Mathematical and graphical method results compared.

distance from 600-ohm point (degrees)	characteristic impedance (ohms)	line spacing inches
0	600.0	4.78
20	610.6	5.22
40	621.4	5.71
—	—	—
250	747.2	16.31
270	760.0	18.14

Steps 1 and **2** have already been determined. It is then necessary to solve for θ, which will become a constant for this example; Z_s is also a constant.

$$\theta = \frac{1}{2 \cdot 0.75} \ln \frac{760}{600} = 0.158$$

Then solve for Z at 10 or 20-degree intervals and tabulate. Twenty-degree intervals are shown in **table A3**.

$$Z = 600\, e^{(2 \cdot \frac{20}{360} \cdot 0.158)} = 610.6$$

Line spacing is then determined:

$$a = 0.032\,(10^{600/276}) = 4.78 \text{ inches}$$

It will be seen that a slight discrepancy exists between the values of Z obtained from the graphical method and from the mathematical method because of difficulty in reading the curve.

For a given spacing, a four-wire line will give a much lower impedance than a two-wire line, and a cross-connected four-wire line will give an even lower impedance (than the same dimensioned side-connected four-wire line). Also the larger the wire-diameter wire, the lower the impedance for a given line separation. These factors may be used to arrive at your design of an open wire exponential line.

references

1. Edmund Laporte, *Radio Antenna Engineering*, Chapter 3, figure 3.81 and Chapter 4, page 422.
2. John D. Ryder, *Networks and Fields*, Prentice-Hall Inc., Chapter 6, Section 6-13.

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