TABLE OF CONTENTS

**Chapter 12 —
CD-ROM Content**

Supplemental Articles

- "A Dipole Curtain for 15 and 10 Meters" by Mike Loukides, W1JQ
- "Bob Zepp: A Low Band, Low Cost, High Performance Antenna - Parts 1 and 2" by Robert Zavrel, W7SX
- "Curtains for You" by Jim Cain, K1TN (and Feedback)
- "Hands-On Radio Experiment #133 – Extended Double Zepp Antenna" by Ward Silver, NØAX
- "The Extended Double Zepp Revisited" by Jerry Haigwood, W5JH
- "The Extended Lazy H Antenna" by Walter Salmon VK2SA
- "The Multiband Extended Double Zepp and Derivative Designs" by Robert Zavrel, W7SX
- "The N4GG Array" by Hal Kennedy, N4GG
- "The W8JK Antenna: Recap and Update" by John Kraus, W8JK

Chapter 12

Broadside and End-Fire Arrays

12.1 BROADSIDE ARRAYS

Broadside arrays can be made up of collinear or parallel elements or combinations of the two. They can provide performance comparable to rotatable beams at very low cost if the amateur has the necessary supports. This chapter was originally contributed by Rudy Severns, N6LF, and is written from the perspective of using these antennas at HF. Much of the material translates easily to VHF and higher frequencies as well. The reader will find a number of projects for designing and constructing these antennas in the Bibliography and on the CD-ROM included with this book.

12.1.1 COLLINEAR ARRAYS

Collinear arrays are always operated with the elements in-phase. (If alternate elements in such an array are out-of-phase, the system simply becomes a harmonic type of antenna.) A collinear array is a broadside radiator, the direction of maximum radiation being at right angles to the line of the antenna.

Power Gain

Because of the nature of the mutual impedance between collinear elements, the feed point resistance (compared to a single element, which is ≈73 Ω) is increased as shown in the **Multielement Arrays** chapter. For this reason the power gain does not increase in direct proportion to the number of elements. The gain with two elements, as the spacing between them is varied, is shown by **Figure 12.1**. Although the gain is greatest when the end-to-end spacing is in the region of 0.4 to 0.6 λ, the use of spacings of this order is inconvenient to build and introduces problems in feeding the two elements. As a result, collinear elements are almost always operated with their ends quite close together — in wire antennas, usually with just a strain insulator between.

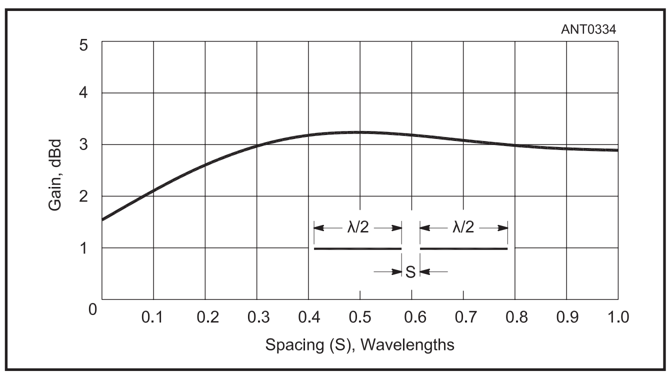

Figure 12.1 — Gain of two collinear λ/2 elements as a function of spacing between the adjacent ends.

With very small spacing between the ends of adjacent elements the theoretical power gain of collinear arrays, assuming the use of #12 AWG copper wire, is approximately as follows over a dipole in free space:

2 collinear elements — 1.6 dB
3 collinear elements — 3.1 dB
4 collinear elements — 3.9 dB

More than four elements are rarely used.

Directivity

The directivity of a collinear array, in a plane containing the axis of the array, increases with its length. Small secondary lobes appear in the pattern when more than two elements are used, but the amplitudes of these lobes are low enough so that they are usually not important. In a plane at right angles to the array the directive diagram is a circle, no matter what the number of elements. Collinear operation, therefore, affects only E-plane directivity, the plane containing the antenna.

When a collinear array is mounted with the elements vertical, the antenna radiates equally well in all geographical directions. An array of such stacked collinear elements tends to confine the radiation to low vertical angles. This configuration is common in base station antennas for VHF and UHF and is discussed in the **VHF and UHF Antenna Systems** chapter.

If a collinear array is mounted horizontally, the directive pattern in the vertical plane at right angles to the array is the same as the vertical pattern of a simple λ/2 antenna at the same height as discussed in the chapter **Effects of Ground**.

12.1.2 TWO-ELEMENT ARRAYS

The simplest and most popular collinear array is one using two elements, as shown in **Figure 12.2**. This system is commonly known as two half-waves in phase. The directive pattern in a plane containing the wire axis is shown in **Figure 12.3**, which shows superimposed patterns for a dipole and 2, 3 and 4-element collinear arrays. Depending on the conductor size, height, and similar factors, the impedance at the feed point can be expected to be in the range of 4 to 6 kΩ, for wire antennas. If the elements are made of tubing having a low λ/dia (wavelength to diameter) ratio, values as low as 1 kΩ are representative. The system can be fed through an open-wire tuned line with negligible loss for ordinary line lengths, or a matching section may be used if desired.

A number of arrangements for matching the feed line to this antenna are described in the chapter **Transmission Line System Techniques**. If elements somewhat shorter than λ/2 are used, then additional matching schemes can be employed at the expense of a slight reduction in gain. When the elements are shortened two things happen — the impedance at the feed point drops and the impedance has inductive reactance that can be tuned out with simple series capacitors, as shown in Figure 12.2B.

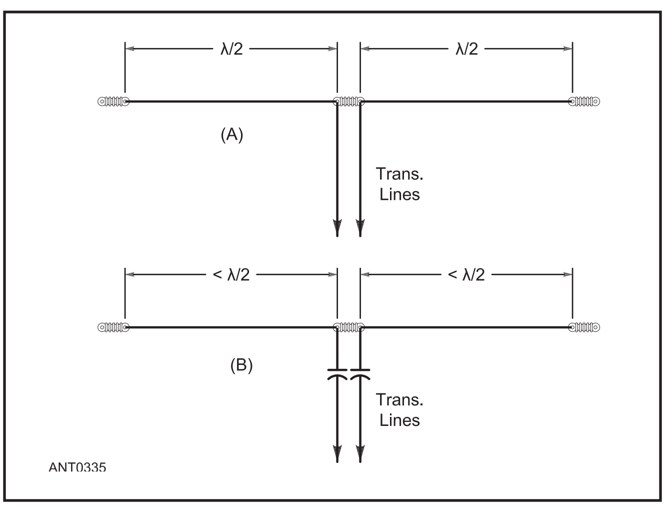

Figure 12.2 — At A, two-element collinear array (two half-waves in phase). The transmission line shown would operate as a tuned line. A matching section can be substituted and a nonresonant line used if desired, as shown at B, where the matching section is two series capacitors.

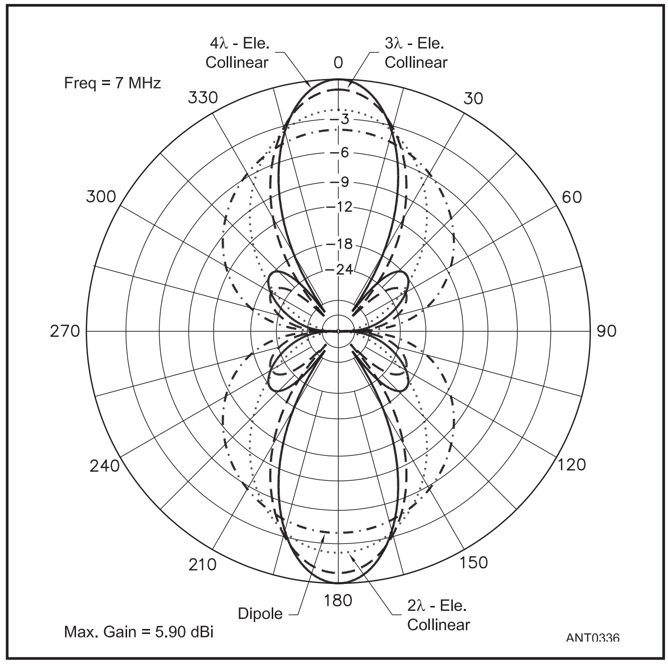

Figure 12.3 — Free-space E-plane directive diagram for dipole, 2, 3 and 4-element collinear arrays. The solid line is a 4-element collinear; the dashed line is for a 3-element collinear; the dotted line is for a 2-element collinear and the dashed-dotted line is for a λ/2 dipole.

Note that these capacitors must be suitable for the power level. Small doorknob capacitors, such as those frequently used in power amplifiers, are suitable. By way of an example, if each side of a 40 meter 2-element array is shortened from 67 to 58 feet, the feed point impedance drops from nearly 6000 Ω to about 1012 Ω with an inductive reactance of 1800 Ω. The reactance can be tuned out by inserting 25 pF capacitors at the feed point. The 1012 Ω resistance can be transformed to 200 Ω using a λ/4 matching section made of 450-Ω ladder line and then transformed to 50 Ω with a 4:1 balun. Shortening the array as suggested reduces the gain by about 0.5 dB.

Another scheme that preserves the gain is to use a 450-Ω λ/4 matching section and shorten the antenna only slightly to have a resistance of 4 kΩ. The impedance at the input of the matching section is then near 50 Ω and a simple 1:1 balun can be used. Many other schemes are possible. The free-space E-plane response for a 2-element collinear array is shown in Figure 12.3, compared with the responses for more elaborate collinear arrays described below.

12.1.3 THREE- AND FOUR-ELEMENT ARRAYS

In a long wire the direction of current flow reverses in each λ/2 section. Consequently, collinear elements cannot simply be connected end to end; there must be some means for making the current flow in the same direction in all elements. When more than two collinear elements are used it is necessary to connect phasing stubs between adjacent elements in order to bring the currents in all elements in-phase. In **Figure 12.4A** the direction of current flow is correct in the two left-hand elements because the shorted λ/4 transmission line (*stub*) is connected between them. This stub may be looked upon simply as the alternate λ/2 section of a long-wire antenna folded back on itself to cancel its radiation. In Figure 12.4A the part to the right of the transmission line has a total length of three half wavelengths, the center half wave being folded back to form a λ/4 phase-reversing stub. No data are available on the impedance at the feed point in this arrangement, but various considerations indicate that it should be over 1 kΩ.

An alternative method of feeding three collinear elements is shown in Figure 12.4B. In this case power is applied at the center of the middle element and phase-reversing stubs are used between this element and both of the outer elements. The impedance at the feed point in this case is somewhat over 300 Ω and provides a close match to 300 Ω line. The SWR will be less than 2:1 when 600-Ω line is used. Center feed of this type is somewhat preferable to the arrangement in Figure 12.4A because the system as a whole is balanced. This assures more uniform power distribution among the elements. In Figure 12.4A, the right-hand element is likely to receive somewhat less power than the other two because a portion of the input power is radiated by the middle element before it can reach the element located at the extreme right.

A four-element array is shown in Figure 12.4C. The system is symmetrical when fed between the two center elements as shown. As in the three-element case, no data are available on the impedance at the feed point. However, the SWR with a 600 Ω line should not be much over 2:1.

Figure 12.3 compares the directive patterns of 2, 3 and 4-element arrays. Collinear arrays can be extended to more than four elements. However, the simple 2-element collinear array is the type most frequently used, as it lends itself well to multiband operation. More than two collinear elements are seldom used because more gain can be obtained from other types of arrays.

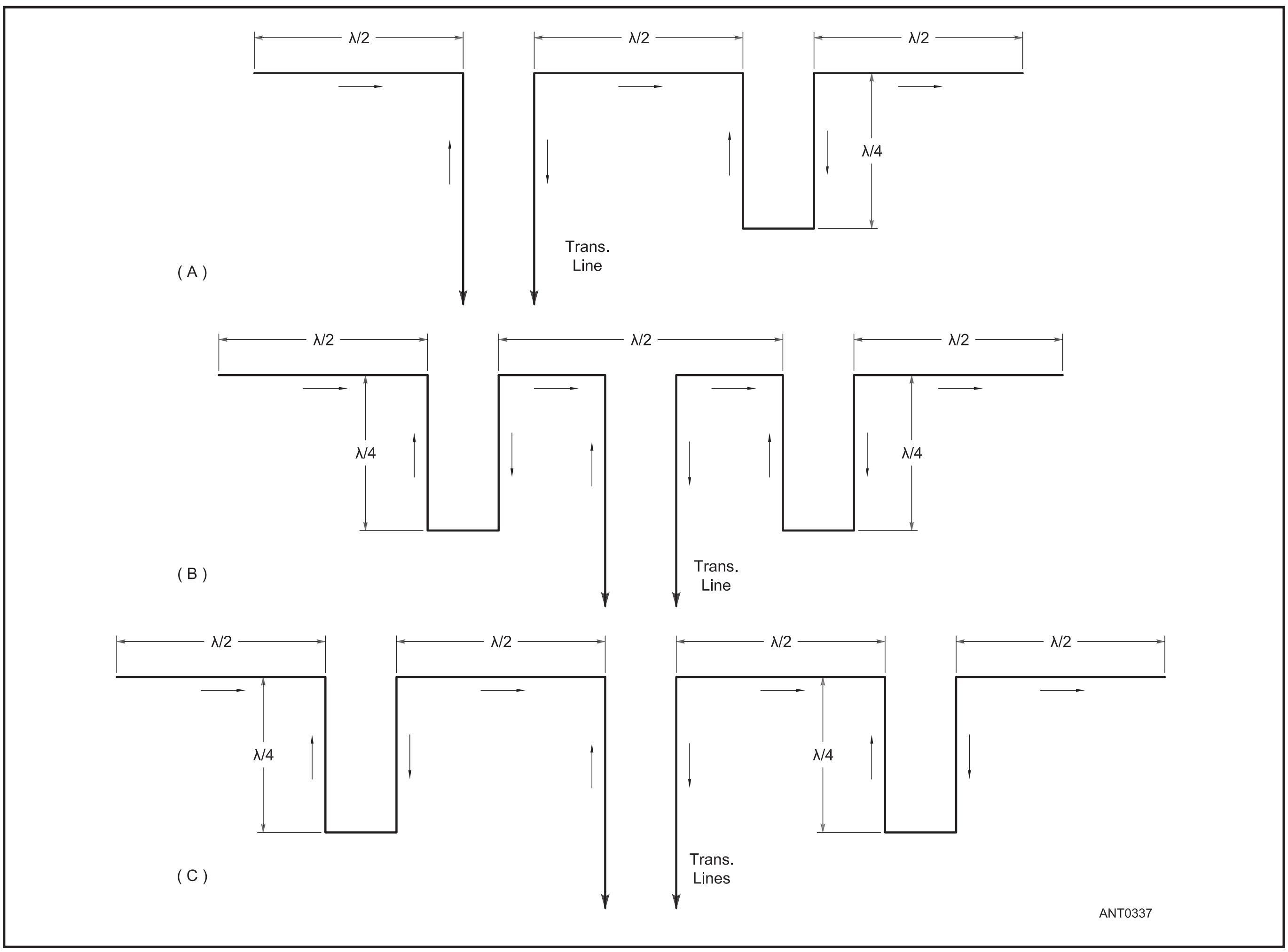

Figure 12.4 — Layouts for 3- and 4-element collinear arrays. Alternative methods of feeding a 3-element array are shown at A and B. These drawings also show the current distribution on the antenna elements and phasing stubs. A matched transmission line can be substituted for the tuned line by using a suitable matching section.

12.1.4 COLLINEAR ARRAY ADJUSTMENT

In any of the collinear systems described, the lengths of the radiating elements are the same as for λ/2 dipoles. The lengths of the phasing stubs can be found from the equations given in the chapter **Transmission Line System Techniques** for the type of line used. If the stub is open-wire line (500 to 600 Ω impedance) you may assume a velocity factor of 0.975 in the formula for a λ/4 line. On-site adjustment is, in general, an unnecessary refinement. If desired, however, the following procedure may be used when the system has more than two elements.

Disconnect all stubs and all elements except those directly connected to the transmission line (in the case of a feed such as is shown in Figure 12.4B leave only the center element connected to the line). Adjust the elements to resonance, using the still-connected element. When the proper length is determined, cut all other elements to the same length. Make the phasing stubs slightly long and use a shorting bar to adjust their length. Connect the elements to the stubs and adjust the stubs to resonance, as indicated by maximum current in the shorting bars or by the SWR on the transmission line. If more than three or four elements are used it is best to add elements two at a time (one at each end of the array), resonating the system each time before a new pair is added.

12.1.5 THE EXTENDED DOUBLE ZEPP

One method to obtain higher gain that goes with wider spacing in a simple system of two collinear elements is to make the elements somewhat longer than λ/2. As shown in **Figure 12.5**, this increases the spacing between the two in-phase λ/2 sections at the ends of the wires. The section in the center carries a current of opposite phase, but if this section is short the current will be small; it represents only the outer ends of a λ/2 antenna section. Because of the small current and short length, the radiation from the center is small. The optimum length for each element is 0.64 λ. At greater lengths the system tends to act as a long-wire antenna, and the gain decreases.

This system is known as the *extended double Zepp* or *EDZ*, first described in *QST* in 1938 by Hugo Romander, W2NB. (See the Bibliography.) The gain over a λ/2 dipole is approximately 3 dB, as compared with about 1.6 dB for two collinear λ/2 dipoles. The directional pattern in the plane containing the axis of the antenna is shown in **Figure 12.6**. As in the case of all other collinear arrays, the free-space pattern in the plane at right angles to the antenna elements is the same as that of a λ/2 antenna — circular. The article "The Extended Double Zepp Revisited" by Jerry Haigwood, W5JH from September 2006 *QST* provides dimensions for the EDZ on 40 through 10 meters, along with building tips. (The article is also included on this book's CD-ROM. An analysis of the EDZ and related designs by Zavrel is listed in the Bibliography.)

This antenna is not resonant at the operating frequency so that the feed point impedance is complex (R ± *j*X). A typical example of the variation of the feed point impedance over the band for a 40 meter double-extended Zepp is shown in **Figure 12.7**. This antenna is normally fed with open-wire

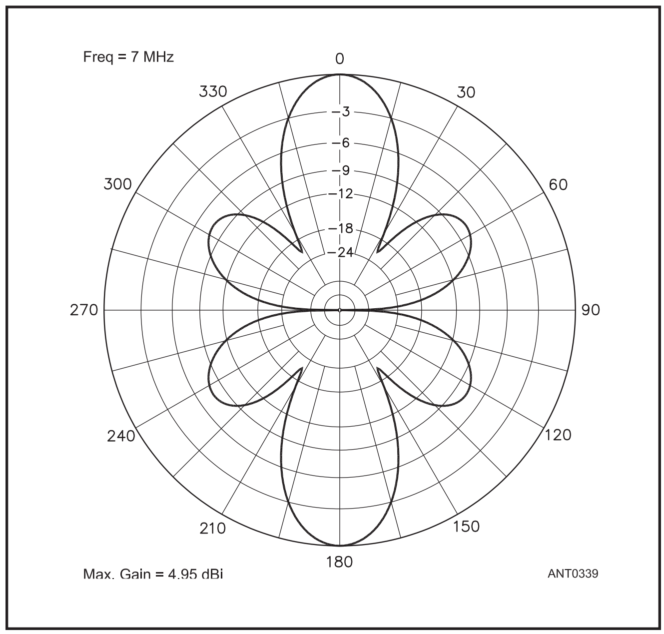

Figure 12.6 — E-plane pattern for the extended double Zepp of Figure 12.5. This is also the horizontal directional pattern when the elements are horizontal. The axis of the elements lies along the 90°-270° line. The free-space array gain is approximately 4.95 dBi.

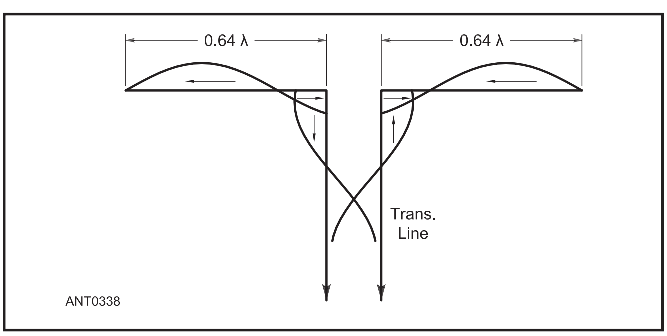

Figure 12.5 — The extended double Zepp. This system gives somewhat more gain than two λ-sized collinear elements.

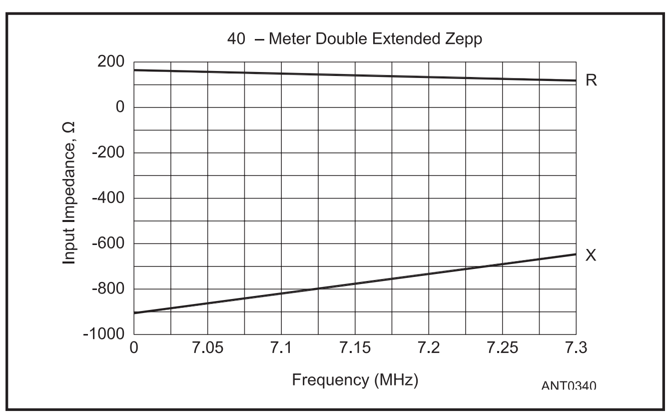

Figure 12.7 — Resistive and reactive feed point impedance of a 40 meter extended double Zepp in free space.

transmission line to an antenna tuner. This allows the antenna to be used on multiple bands, although SWR may be high on some bands. Impedance at the antenna tuner depends on the antenna's feed point impedance and the length of the feed line.

Variations on the Extended Double Zepp

By selecting the right length of feed line, the feed point impedance of the EDZ can be brought close to 50 Ω on the desired band. At that point, a choke balun can be used to create a transition to coaxial feed line. (See the **Transmission Line System Techniques** chapter regarding baluns.) The general design is shown in **Figure 12.8**.

Table 12.1 shows EDZ designs by W5JH including the length of the antenna (L_d) and 450-Ω window line (L_f) that result in approximately 50 Ω impedance at the end of the window line. (Note that the design also includes height above average ground which also affects feed point impedance.) The 50-Ω point is created only on the band shown in the table — SWR will be greatly different on other bands. (The original article by W5JH is provided on this book's CD-ROM.) The exact length of antenna which reproduces these impedances will depend on height above ground and type of ground. Be prepared to adjust antenna length and window line length.

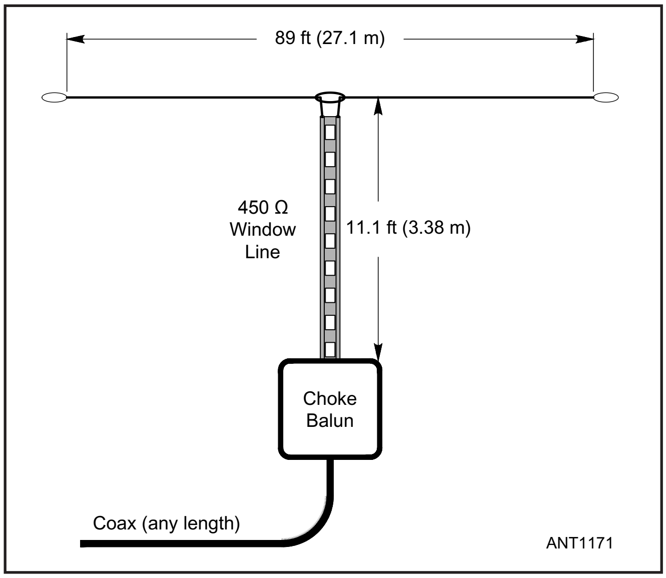

Figure 12.9 — The 20/15 meter EDZ with feed line length specified for low SWR on 20 and 15 meters.

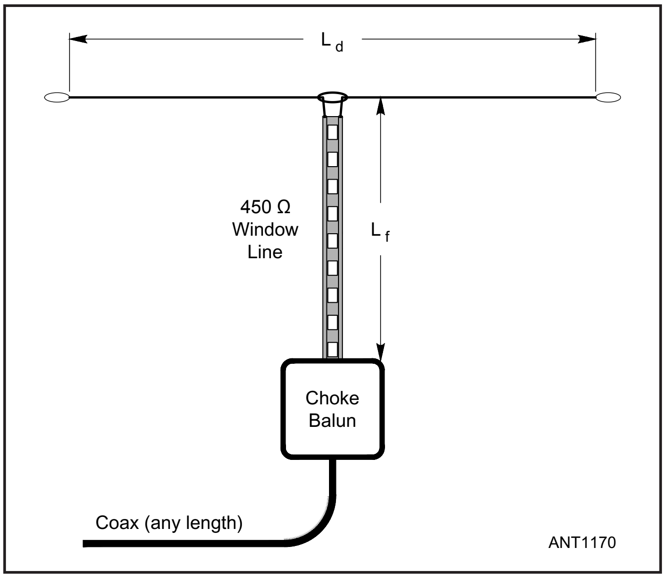

Figure 12.8 — A general design for Extended Double Zepp antennas by W5JH. Values for L_d (doublet length) and L_f (feed line length) are given in Table 12.1.

If it is desired to place the coax transition point farther from the antenna, add an integer number of λ/2 of feed line which will create a 50-Ω impedance at which the transition can be made. The transmission line software *TLW* can be used to calculate physical lengths for a variety of different types of parallel conductor feed lines.

Figure 12.9 is a 20/15 meter variation of the EDZ with low SWR on both bands through careful selection of the length of the 450-Ω feed line section. The pattern for 20 meters shown in **Figure 12.10** is similar to the classic EDZ of Figure 12.6 but because of the extra length on 15 meters,

Table 12.1
EDZ Antenna Dimensions for Different Bands

Freq (MHz)	*L_d (ft)*	*Min Height (ft)*	*Antenna Z (Ω)*	*Feed point Z (Ω)*	*L_f (ft)*	*SWR*
7.075	175.2	66	170.5 –*j*976.1	47.10 +*j*0.25	21.65	1.062:1
10.11	122.6	47	163.0 –*j*934.1	47.80 –*j*0.07	14.85	1.046:1
14.175	87.5	34	155.3 –*j*889.6	48.62 –*j*0.36	10.35	1.029:1
18.1	68.5	30	133.4 –*j*848.9	44.63 +*j*0.38	7.92	1.121:1
21.2	58.5	30	132.1 –*j*799.9	47.65 –*j*0.28	6.56	1.050:1
24.9	49.8	30	156.7 –*j*772.3	58.60 –*j*0.10	5.51	1.172:1
28.2	44	30	169.8 –*j*772.4	63.24 +*j*0.26	4.88	1.265:1

L_d is the antenna length, L_f is the length of the matching feed line the pattern takes on a clover-leaf shape as shown in **Figure 12.11**. A 74.7-foot section of 450-Ω window line (two λ/2 on 20 meters and 3λ/2 on 15 meters) brings the coax transition point to ground level and SWR is less than 1.5:1on both bands. (The original article, "Hands-On Radio, Experiment #133," is provided on this book's CD-ROM.)

A versatile antenna for 40, 80, and 160 meters, the "Bob Zepp" by Robert Zavrel, W7SX, is shown in **Figure 12.12**. This design uses traps to isolate sections of the antenna at 40 meters where it acts as a true EDZ. The antenna becomes an

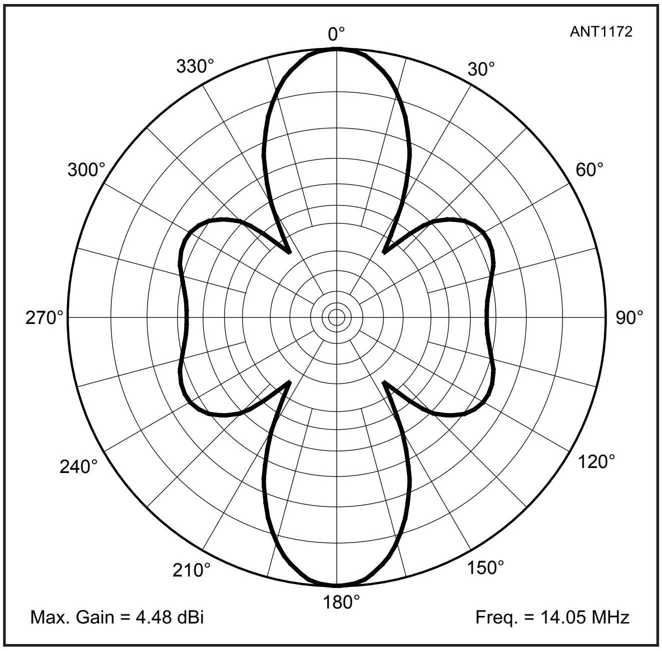

Figure 12.10 — The pattern of the 20/15 meter EDZ on 20 meters.

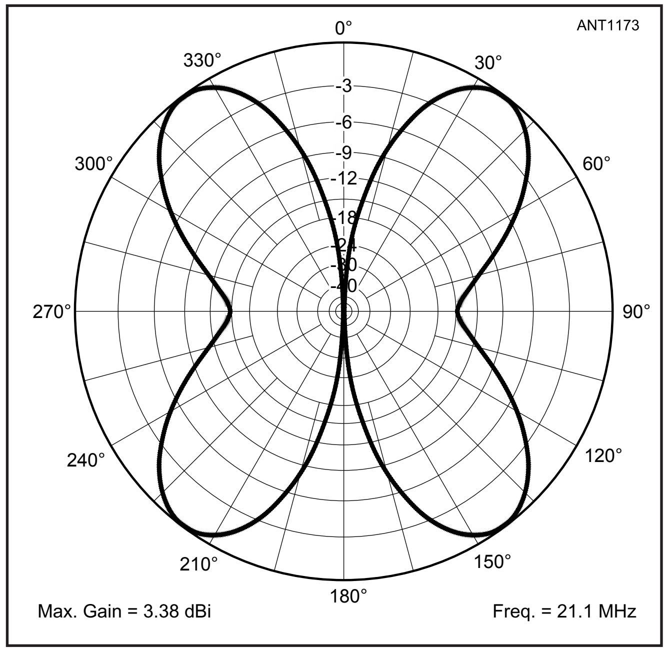

Figure 12.11 — The pattern of the 20/15 meter EDZ on 15 meters.

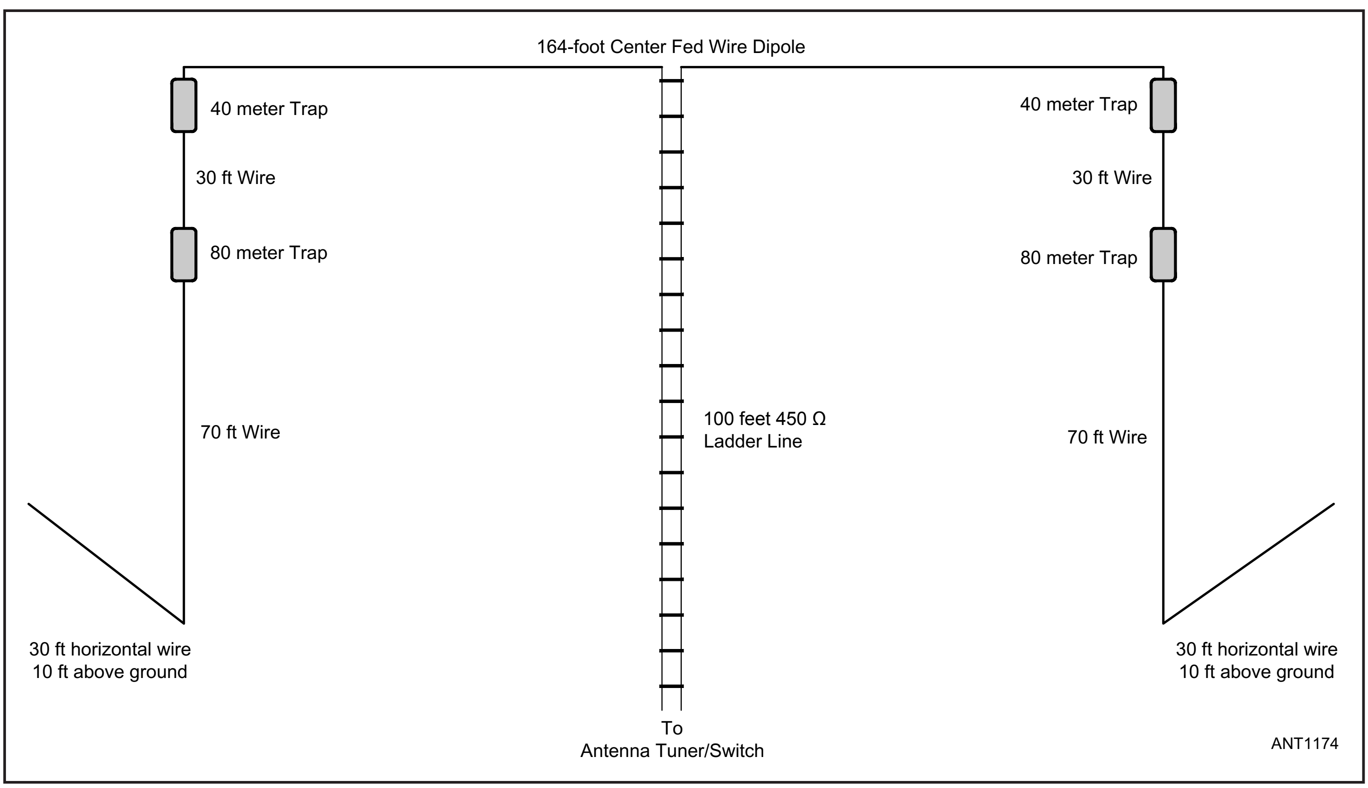

Figure 12.12 — The Bob-Zepp is an EDZ on 40 meters, an extended dipole on 80 meters, and a bi-directional array on 160 meters.

extended dipole on 80 meters and a two-vertical bidirectional, top-fed array on 160 meters. The antenna was designed for a height of around 110 feet. Significantly higher installation will affect the antenna's feed point impedance. The antenna can be installed at lower heights but the lower vertical sections and horizontal wires will have to be altered. See the original article, provided on this book's CD-ROM, for the complete design, including a full-power tuning unit and numerous construction drawings.

12.1.6 THE STERBA CURTAIN

Two collinear arrays can be combined to form the Sterba array, often called the Sterba curtain. An 8-element example of a Sterba array is shown in **Figure 12.13**. The four λ/4 elements joined on the ends are equivalent to two λ/2 elements. The two collinear arrays are spaced λ/2 and the λ/4 phasing lines connected together to provide λ/2 phasing lines. This arrangement has the advantage of increasing the gain for a given length and also increasing the E-plane directivity, which is no longer circular. An additional advantage of this array is that the wire forms a closed loop. For installations where icing is a problem a low voltage dc or low frequency (50 or 60 Hz) ac current can be passed through the wire to heat it for deicing. The heating current is isolated from RF by decoupling chokes. This is standard practice in commercial installations.

The number of sections in a Sterba array can be extended as far as desired but more than four or five are rarely used because of the slow increase in gain with extra elements, the narrow H-plane directivity and the appearance of multiple sidelobes. When fed at the point indicated the impedance is about 600 Ω. The antenna can also be fed at the point marked X. The impedance at this point will be about 1 kΩ. The gain of the 8-element array in Figure 12.13 will be between 7 to 8 dB over a single element. A 10 meter Sterba curtain is described in the article, "Curtains for You," by Jim Cain, K1TN, that is included on this book's CD-ROM.

12.2 PARALLEL BROADSIDE ARRAYS

To obtain broadside directivity with parallel elements the currents in the elements must all be in-phase. At a distant point lying on a line perpendicular to the axis of the array and also perpendicular to the plane containing the elements, the fields from all elements add up in phase. The situation is similar to four parallel λ/2 dipoles fed together as a broadside array.

Broadside arrays of this type theoretically can have any number of elements. However, practical limitations of construction and available space usually limit the number of broadside parallel elements. These practical aspects of building a dipole curtain are illustrated in the article "A Dipole Curtain for 15 and 10 Meters" by Mike Loukides, W1JQ, in the Aug 2003 *QST* article on this book's CD-ROM.

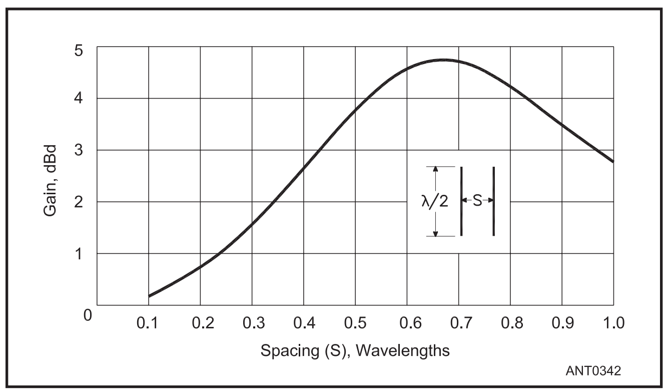

Figure 12.14 — Gain as a function of the spacing between two parallel elements operated in-phase (broadside).

12.2.1 POWER GAIN

The power gain of a parallel-element broadside array depends on the spacing between elements as well as on the number of elements. The way in which the gain of a two-element array varies with spacing is shown in **Figure 12.14**. The greatest gain is obtained when the spacing is in the vicinity of 0.67 λ.

The theoretical gains of broadside arrays having more than two elements are approximately as follows:

No. of Parallel Elements	*dB Gain with λ/2 Spacing*	*dB Gain with 3λ/4 Spacing*
3	5.7	7.2
4	7.1	8.5
5	8.1	9.4
6	8.9	10.4

The elements must, of course, all lie in the same plane and all must be fed in-phase.

12.2.2 DIRECTIVITY

The sharpness of the directive pattern depends on spacing between elements and number of elements. Larger element spacing will sharpen the main lobe, for a given number of elements, up to a point as was shown in Figure 12.1. The two-element array has no minor lobes when the spacing is λ/2, but small minor lobes appear at greater spacings. When three or more elements are used the pattern always has minor lobes.

12.3 OTHER FORMS OF BROADSIDE ARRAYS

For those who have the available room, multielement arrays based on the broadside concept have something to offer. The antennas are large but of simple design and non-critical dimensions; they are also very economical in terms of gain per unit of cost.

Large arrays can often be fed at several different points. However, the pattern symmetry may be sensitive to the choice of feed point within the array. Nonsymmetrical feed points will result in small asymmetries in the pattern but these are not usually of great concern.

Arrays of three and four elements are shown in **Figure 12.15**. In the 3-element array with λ/2 spacing at A, the array is fed at the center. This is the most desirable point in that it tends to keep the power distribution among the elements uniform. However, the transmission line could alternatively be connected at either point B or C of Figure 12.15A, with only slight skewing of the radiation pattern.

When the spacing is greater than λ/2, the phasing lines must be 1 λ long and are not transposed between elements. This is shown Figure 12.15B. With this arrangement, any element spacing up to 1 λ can be used, if the phasing lines can be folded as suggested in the drawing.

The 2-element array at C is fed at the center of the system to make the power distribution among elements as uniform as possible. However, the transmission line could be connected at either point B, C, D or E. In this case the section of phasing line between B and D must be transposed to make the currents flow in the same direction in all elements. The 4-element array at C and the 3-element array at B have approximately the same gain when the element spacing in the array at B is 3λ/4.

An alternative feeding method is shown in Figure 12.15D. This system can also be applied to the 3-element arrays, and will result in better symmetry in any case. It is necessary only to move the phasing line to the center of each element, making connection to both sides of the line instead of one only.

The free-space pattern for a 4-element array with λ/2 spacing is shown in **Figure 12.16**. This is also approximately the pattern for a 3-element array with 3λ/4 spacing.

Larger arrays can be designed and constructed by following the phasing principles shown in the drawings. No accurate figures are available for the impedances at the various feed points indicated in Figure 12.15. You can estimate it to be in the vicinity of 1 kΩ when the feed point is at a junction between the phasing line and a λ/2 element, becoming

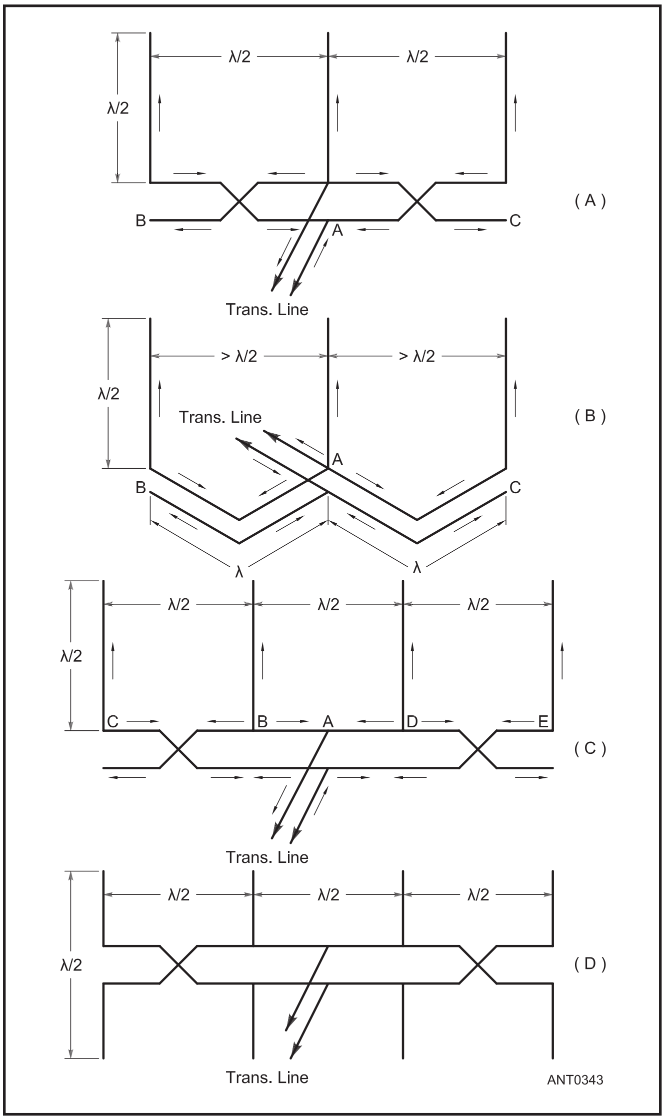

Figure 12.15 — Methods of feeding 3- and 4-element broadside arrays with parallel elements.

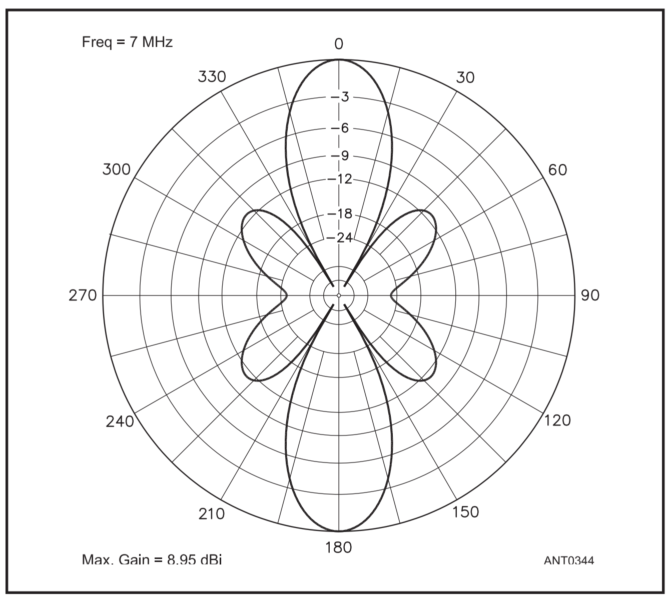

Figure 12.16 — Free-space E-plane pattern of a 4-element broadside array using parallel elements (Figure 12.15). This corresponds to the horizontal directive pattern at low wave angles for a vertically polarized array over ground. The axis of the elements lies along the 90°-270° line.

smaller as the number of elements in the array is increased. When the feed point is midway between end-fed elements as in Figure 12.15C, the feed point impedance of a 4-element array is in the vicinity of 200 to 300 Ω, with 600-Ω open-wire phasing lines. The impedance at the feed point with the antenna shown at D should be about 1.5 kΩ.

12.3.1 NON-UNIFORM ELEMENT CURRENTS

The pattern for a 4-element broadside array shown in Figure 12.16 has substantial sidelobes. This is typical for arrays more than λ/2 wide when equal currents flow in each element. Sidelobe amplitude can be reduced by using non-uniform current distribution among the elements. Many possible current amplitude distributions have been suggested. All of them have reduced current in the outer elements and greater current in the inner elements. This reduces the gain somewhat but can produce a more desirable pattern. One of the common current distributions is called binomial current grading. In this scheme the ratio of element currents is set equal to the coefficients of a polynomial. For example:

$$1\,x + 1, \Rightarrow 1, 1$$
$$(x+1)^2 = 1x^2 + 2x + 1, \;\Rightarrow 1, 2, 1$$
$$(x+1)^3 = 1x^3 + 3x^2 + 3x + 1, \;\Rightarrow 1, 3, 3, 1$$
$$(x+1)^4 = 1x^4 + 4x^3 + 6x^2 + 6x + 1, \;\Rightarrow 1, 4, 6, 4, 1$$

In a 2-element array the currents are equal, in a 3-element array the current in the center element is twice that in the outer elements, and so on.

12.3.2 HALF-SQUARE ANTENNA

On the low-frequency bands (40, 80 and 160 meters) it becomes increasingly difficult to use λ/2 elements because of their size. The half-square antenna is a 2-element broadside array with λ/4-high vertical elements and λ/2 horizontal spacing. See **Figure 12.17**. The free-space H-plane pattern for this array is shown in **Figure 12.18**. The antenna gives modest (4.2 dBi) but useful gain and has the advantage of only λ/4 height. Like all vertically polarized antennas, real-world performance depends directly on the characteristics of the ground surrounding it.

The half-square can be fed either at the point indicated or at the bottom end of one of the vertical elements using a voltage-feed scheme, such as for the Bobtail curtain described below. The feed point impedance is in the region of 50 Ω when fed at a corner as shown in Figure 12.17. The SWR bandwidth is typically quite narrow as shown in the following design examples.

Variations on the Half-Square Antenna

The following section was originally presented in *The ARRL Antenna Compendium Vol 5*, by Rudy Severns, N6LF.

A simple modification to a standard dipole is to add two λ/4 vertical wires, one at each end, as shown in **Figure 12.19**. This makes a *half-square antenna*. The antenna can be fed at one corner (low-impedance, current fed) or at the lower end of one of the vertical wires (high-impedance, voltage fed). Other feed arrangements are also possible.

The "classical" dimensions for this antenna are λ/2 (131 feet at 3.75 MHz) for the top wire and λ/4 (65.5 feet) for the vertical wires. However, there is nothing sacred

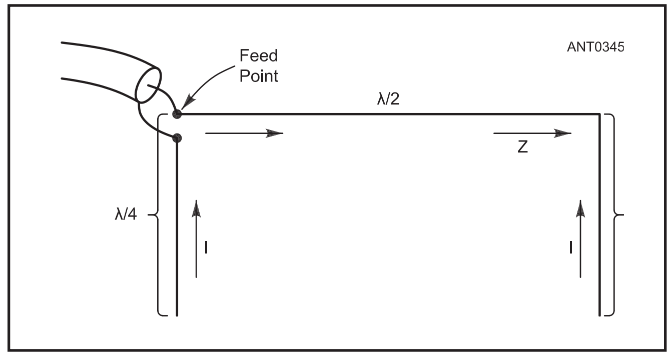

Figure 12.17 — Layout for the half-square antenna.

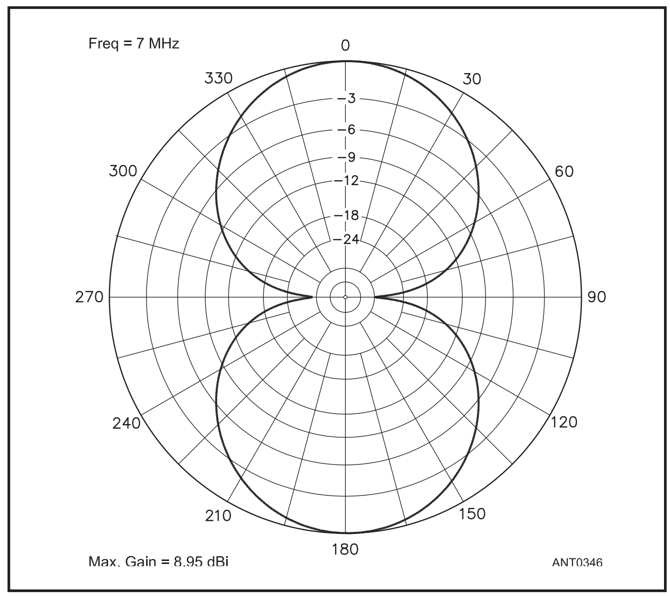

Figure 12.18 — Free-space E-plane directive pattern for the half-square antenna.

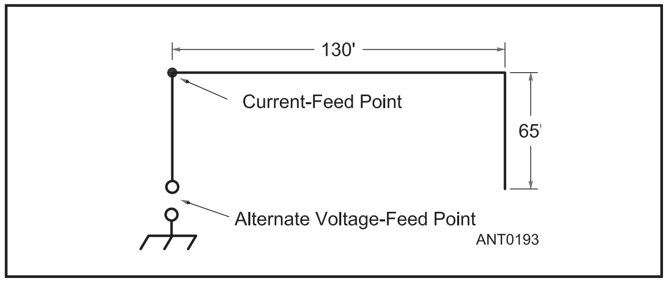

Figure 12.19 — Typical 80 meter half-square, with λ/4-high vertical legs and a λ/2-long horizontal leg. The antenna may be fed at the bottom or at a corner. When fed at a corner, the feed point is a low-impedance, current-feed. When fed at the bottom of one of the wires against a small ground counter-poise, the feed point is a high-impedance, voltage-feed.

about these dimensions! They can vary over a wide range and still obtain nearly the same performance.

This antenna is two λ/4 verticals, spaced λ/2, fed in-phase by the top wire. The current maximums are at the top corners. The theoretical gain over a single vertical is 3.8 dB. An important advantage of this antenna is that it does not require the extensive ground system and feed arrangements that a conventional pair of phased λ/4 verticals would.

Comparison to a Dipole

In the past, one of the things that has turned off potential users of the half-square on 80 and 160 meters is the perceived need for λ/4 vertical sections. This forces the height to be >65 feet on 80 meters and >130 feet on 160 meters. That's not really a problem. If you don't have the height there are several things you can do. For example, just fold the ends in, as shown in **Figure 12.20**. This compromises the performance surprisingly little.

It is helpful to compare the examples given in Figures 12.19 and 12.20 to dipoles at the same height. Two heights, 40 and 80 feet, and average, very good and sea water grounds, were used for this comparison. It is also assumed that the lower end of the vertical wires had to be a minimum of 5 feet above ground.

At 40 feet the half-square is really mangled, with only 35-foot long (≈ λ/8) vertical sections. The elevation-plane comparison between this antenna and a dipole of the same height is shown in **Figure 12.21**. Over average ground the half-square is superior below 32° and at 15° is almost 5 dB better. That is a worthwhile improvement. If you have very good soil conductivity, like parts of the lower Midwest and South, then the half-square will be superior below 38° and at 15° will be nearly 8 dB better. For those fortunate few with saltwater frontal property the advantage at 15° is 11 dB! Notice also that above 35°, the response drops off rapidly. This is great for DX but is not good for local work.

Figure 12.22 shows the azimuthal-plane pattern for the 80 meter half-square antenna in Figure 12.20, but this time compared with the response of a flattop horizontal dipole that is 100 feet high. These comparisons are for average ground and are for an elevation angle of 5°. The message here is that the lower your dipole and the better your ground, the more you have to gain by switching from a dipole to a half-square. The half-square antenna looks like a good bet for DXing.

Changing the Shape of the Half Square

Just how flexible is the shape? There are several common distortions of practical importance. Some have very little effect but a few are fatal to the gain. Suppose you have either more height and less width than called for in the standard version or more width and less height, as shown in **Figure 12.23A**.

The effect on gain from this type of dimensional variation is given in **Table 12.2**. For a top length (L_T) varying between 110 and 150 feet, where the vertical wire lengths (L_V)

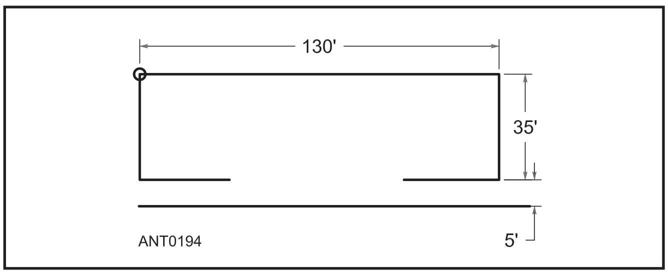

Figure 12.20 — An 80 meter half-square configured for 40-foot high supports. The ends have been bent inward to reresonate the antenna. The performance is compromised surprisingly little.

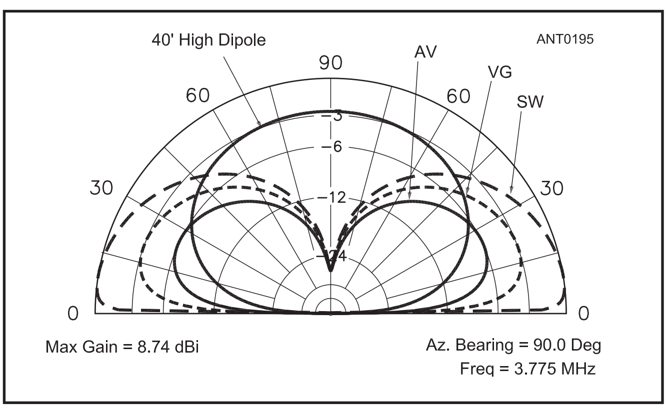

Figure 12.21 — Comparison of 80 meter elevation response of 40-foot high, horizontally polarized dipole over average ground and a 40-foot high, vertically polarized half-square, over three types of ground: average (conductivity σ = 5 mS/m, dielectric constant ε = 13), very good (σ = 30 mS/m, ε = 20) and salt water (σ = 5000 mS/m, ε = 80). The quality of the ground clearly has a profound effect on the low-angle performance of the half-square. Even over average ground, the half-square outperforms the low dipole below about 32°.

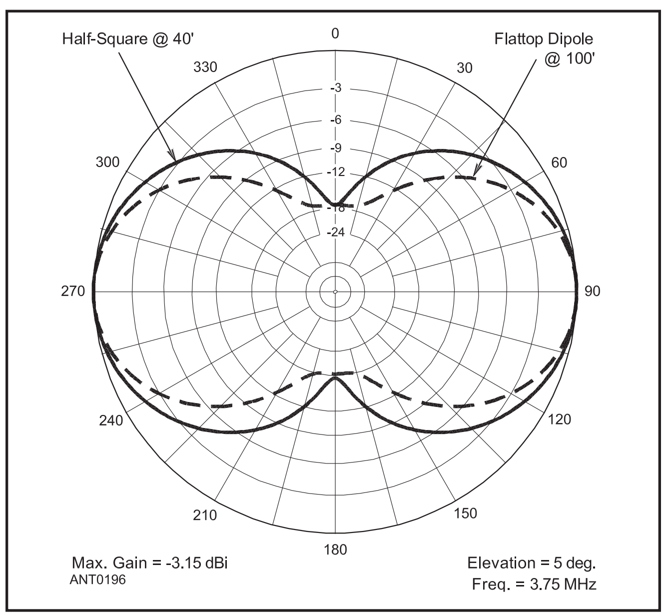

Figure 12.22 — 80 meter azimuth patterns for shortened half-square antenna (solid line) compared with flattop dipole (dashed line) at 100 feet height. Average ground is assumed for these cases.

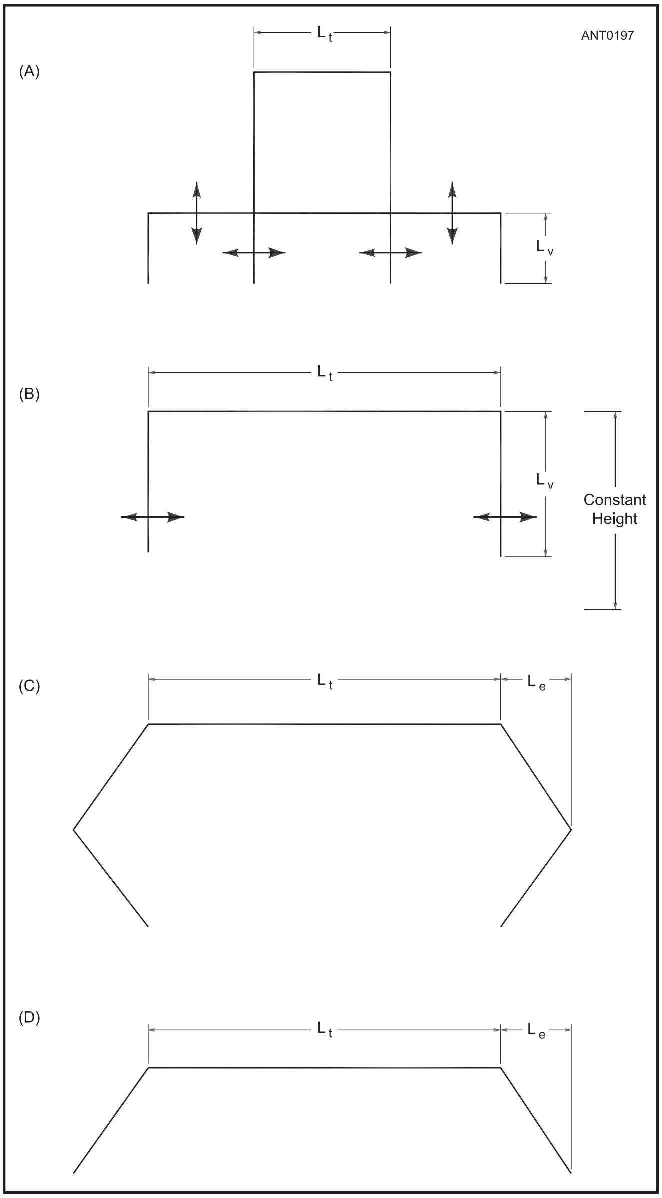

Figure 12.23 — Varying the horizontal and vertical lengths of a half-square. At A, both the horizontal and vertical legs are varied, while keeping the antenna resonant. At B, the height of the horizontal wire is kept constant, while its length and that of the vertical legs is varied to keep the antenna resonant. At C, the length of the horizontal wire is varied and the legs are bent inwards in the shape of "vees." At D, the ends are sloped outward and the length of the flattop portion is varied. All these symmetrical forms of distortion of the basic half-square shape result in small performance losses.

readjusted to resonate the antenna, the gain changes only by 0.6 dB. For a 1-dB change the range of L_T is 100 to 155 feet, a pretty wide range.

Another variation results if we vary the length of the horizontal top wire and readjust the vertical wires for resonance, while keeping the top at a constant height. See Figure 12.23B. Table 12.2 shows the effect of this variation on the peak gain. For a range of L_T = 110 to 145 feet, the gain changes only 0.65 dB.

The effect of bending the ends into a V shape, as shown

Table 12.2
Variation in Gain with Change in Horizontal Length
Vertical Height Readjusted for Resonance (Figure 12.23A)

L_T (feet)	*L_V (feet)*	*Gain (dBi)*
100	85.4	2.65
110	79.5	3.15
120	73.7	3.55
130	67.8	3.75
140	61.8	3.65
150	56	3.05
155	53	2.65

Vertical Length Readjusted for Resonance, but Horizontal Wire Kept at Constant Height (Figure 12.23B)

L_T (feet)	*L_V (feet)*	*Gain (dBi)*
110	78.7	3.15
120	73.9	3.55
130	68	3.75
140	63	3.35
145	60.7	3.05

Table 12.3
Gain for Half-Square Antenna, Where Ends Are Bent Into V-Shape (see Figure 12.23C)

Height ⇒	*H=40 feet*	*H=40 feet*	*H=60 feet*	*H=60 feet*
L_T (feet)	*L_V (feet)*	*Gain (dBi)*	*L_e (feet)*	*Gain (dBi)*
40	57.6	3.25	52.0	2.75
60	51.4	3.75	45.4	3.35
80	45.2	3.95	76.4	3.65
100	38.6	3.75	61.4	3.85
120	31.7	3.05	44.4	3.65
140	—	—	23	3.05

in Figure 12.23C, is given in **Table 12.3**. The bottom of the antenna is kept at a height of 5 feet and the top height (H) is either 40 or 60 feet. Even this gross deformation has only a relatively small effect on the gain. Sloping the ends outward as shown in Figure 12.23D and varying the top length also has only a small effect on the gain. While this is good news because it allows you dimension the antenna to fit different QTHs, not all distortions are so benign.

Suppose the two ends are not of the same height, as illustrated in **Figure 12.24**, where one end of the half-square is 20 feet higher than the other. The elevation-plane radiation pattern for this antenna is shown in **Figure 12.25** compared to a dipole at 50 feet. This type of distortion does affect the pattern. The gain drops somewhat and the zenith null goes away. The nulls off the end of the antenna also go away, so that there is some end-fire radiation. In this example the difference in height is fairly extreme at 20 feet. Small differences of 1 to 5 feet do not affect the pattern seriously.

If the top height is the same at both ends but the length

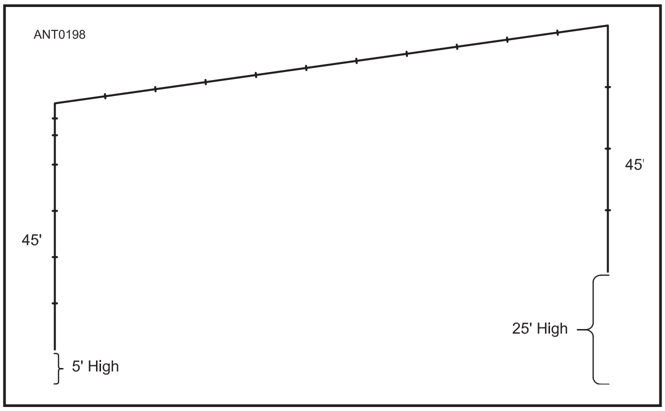

Figure 12.24 — An asymmetrical distortion of the half-square antenna, where the bottom of one leg is purposely made 20 feet higher than the other. This type of distortion does affect the pattern!

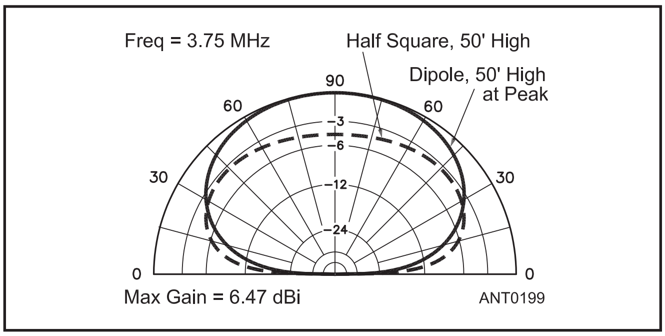

Figure 12.25 — Elevation pattern for the asymmetrical half-square compared with pattern for a 50-foot high dipole. This is over average ground, with a conductivity of 5 mS/m and a dielectric constant of 13. Note that the zenith-angle null has filled in and the peak gain is lower compared to conventional half-square over the same kind of ground.

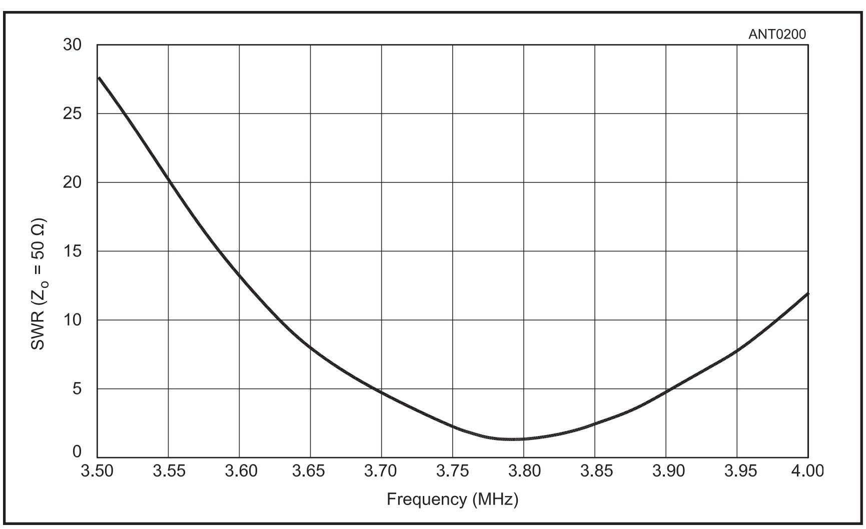

Figure 12.26 — Variation of SWR with frequency for current-fed half-square antenna. The SWR band- width is quite narrow.

of the vertical wires is not the same, then a similar pattern distortion can occur. The antenna is very tolerant of symmetrical distortions but it is much less accepting of asymmetrical distortion.

What if the length of the wires is such that the antenna is not resonant? Depending on the feed arrangement, that may or may not matter. We will look at that issue later on, in the section on patterns versus frequency. The half-square antenna, like the dipole, is very flexible in its proportions.

Half-Square Feed Point Impedance

There are many different ways to feed the half-square. Traditionally the antenna has been fed either at the end of one of the vertical sections, against ground, or at one of the upper corners as shown in Figure 12.19.

For voltage feed at the bottom against ground, the impedance is very high, on the order of several thousand ohms. For current feed at a corner, the impedance is much lower and is usually close to 50 Ω. This is very convenient for direct feed with coax.

The half-square is a relatively high-Q antenna (Q ≈ 17). **Figure 12.26** shows the SWR variation with frequency for this feed arrangement. An 80 meter dipole is not particularly wideband either, but a dipole will have less extreme variation in SWR than the half-square.

Patterns Versus Frequency

Impedance is not the only issue when defining the bandwidth of an antenna. The effect on the radiation pattern of changing frequency is also a concern. For a voltage-fed half-square, the current distribution changes with frequency. For an antenna resonant near 3.75 MHz, the current distribution is nearly symmetrical. However, above and below resonance the current distribution increasingly becomes asymmetrical. In effect, the open end of the antenna is constrained to be a voltage maximum but the feed point can behave less as a voltage point and more like a current maximum. This allows the current distribution to become asymmetrical.

The effect is to reduce the gain by –0.4 dB at 3.5 MHz and by –0.6 dB at 4 MHz. The depth of the zenith null is reduced from –20 dB to –10 dB. The side nulls are also reduced. Note that this is exactly what happened when the antenna was made physically asymmetrical. Whether the asymmetry is due to current distribution or mechanical arrangements, the antenna pattern will suffer.

When current feed at a corner is used, the asymmetry introduced by off-resonance operation is much less, since both ends of the antenna are open circuits and constrained to be voltage maximums. The resulting gain reduction is only –0.1 dB. It is interesting that the sensitivity of the pattern to changing frequency depends on the feed scheme used.

Of more concern for corner feed is the effect of the transmission line. The usual instruction is to simply feed the antenna using coax, with the shield connected to vertical wire and the center conductor to the top wire. Since the shield of the coax is a conductor, more or less parallel with the radiator, and is in the immediate field of the antenna, you might expect the pattern to be seriously distorted by this practice. This arrangement seems to have very little effect on the pattern. The greatest effect is when the feed line length was near a multiple of λ/2. Such lengths should be avoided.

Of course, you may use a choke balun at the feed point if you desire. This might reduce the coupling to the feed line even further but it doesn't appear to be worth the trouble. In fact, if you use an antenna tuner in the shack to operate away from resonance with a very high SWR on the transmission line, a balun at the feed point would take a beating.

Voltage-Feed at One End of Antenna: Matching Schemes

Several straightforward means are available for narrowband matching. However, broadband matching over the full 80 meter band is much more challenging. Voltage feed with a parallel-resonant circuit and a modest local ground, as shown in **Figure 12.27**, is the traditional matching scheme for this antenna. Matching is achieved by resonating the circuit at the desired frequency and tapping down on the inductor in Figure 12.27A or using a capacitive divider (Figure 12.27B). It is also possible to use a λ/4 transmission-line matching scheme, as shown in Figure 12.27C.

If the matching network shown in Figure 12.27B is used, typical values for the components would be: L = 15 µH, C1 = 125 pF and C2 = 855 pF. At any single point the SWR can be made very close to 1:1 but the bandwidth for SWR < 2:1 will be very narrow at <100 kHz. Altering the L-C ratio doesn't make very much difference. The half-square antenna has a well-earned reputation for being narrowband.

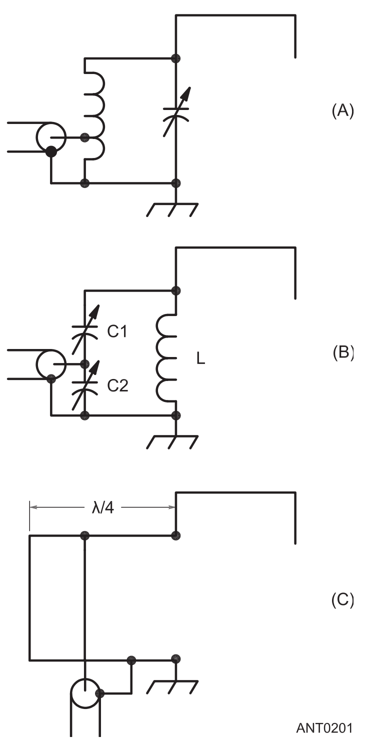

Figure 12.27 — Typical matching networks used for voltage-feeding a half-square antenna.

12.3.3 BOBTAIL CURTAIN

The antenna system in **Figure 12.28**, called a Bobtail curtain, was originally described by Woodrow Smith, W6BCX, in 1948 (see Bibliography for this and other articles on the Bobtail.) It uses the principles of co-phased verticals to produce a broadside, bidirectional pattern providing approximately 5.1 dB of gain over a single λ/4 element. The antenna performs as three in-phase, top-fed vertical radiators approximately λ/4 in height and spaced approximately λ/2. It is most effective for low-angle signals and makes an excellent long-distance antenna for 1.8, 3.5 or 7 MHz.

The three vertical sections are the actual radiating components, but only the center element is fed directly. The two horizontal parts, A, act as phasing lines and contribute very little to the radiation pattern. Because the current in the center element must be divided between the end sections, the current distribution approaches a binomial 1:2:1 ratio. The radiation pattern is shown in **Figure 12.29**.

The vertical elements should be as vertical as possible. The height for the horizontal portion should be slightly greater than B, as shown in Figure 12.28. The tuning network is resonant at the operating frequency. The L/C ratio should be fairly low to provide good loading characteristics. As a starting point, a maximum capacitor value of 75 to 150 pF is recommended, and the inductor value is determined by C and the operating frequency. The network is first tuned to resonance and then the tap point is adjusted for the best match.

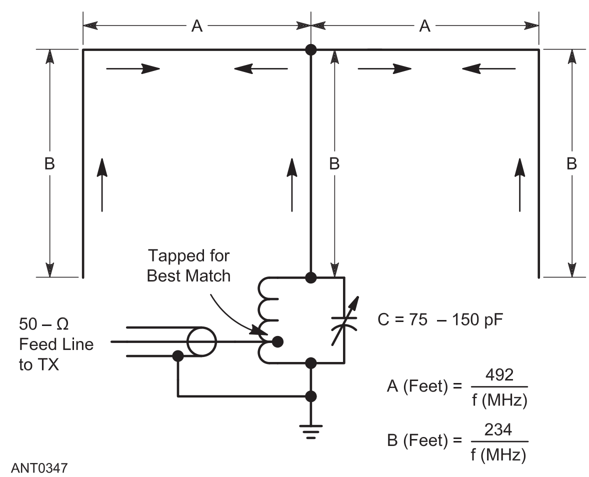

Figure 12.28 — The Bobtail curtain is an excellent low-angle radiator having broadside bidirectional characteristics. Current distribution is represented by the arrows. Dimensions A and B (in feet, for wire antennas) can be determined from the equations.

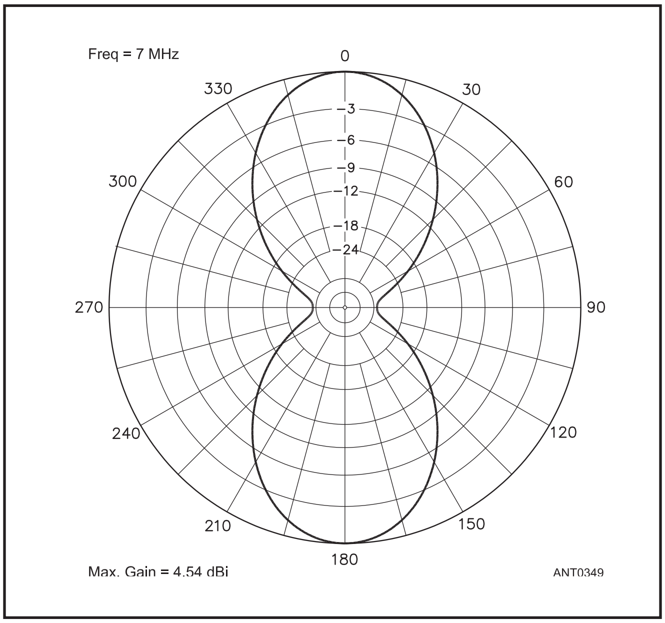

Figure 12.29 — Calculated free-space E-plane directive diagram of the Bobtail curtain shown in Figure 12.28. The array lies along the 90°-270° axis.

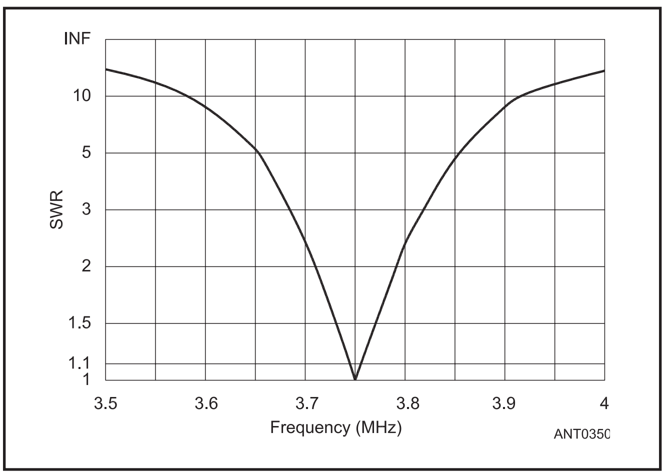

Figure 12.30 — Typical SWR plot for an 80 meter Bobtail curtain in free space. This is a narrow-band antenna.

A slight readjustment of C may be necessary. A link coil consisting of a few turns can also be used to feed the antenna.

A feeling for the matching bandwidth of this antenna can be obtained by looking at a feed point located at the top end of the center element. The impedance at this point will be approximately 32 Ω. An SWR plot (for Z_0 = 32 Ω) for an 80 meter Bobtail curtain at this feed point is shown in **Figure 12.30**. However, it is not advisable to actually connect a feed line at this point since it would detune the array and alter the pattern. This antenna is relatively narrow band. When fed at the bottom of the center element as shown in Figure 12.28, the SWR can be adjusted to be 1:1 at one frequency but the operating bandwidth for SWR less than 2:1 may be even narrower than Figure 12.30 shows. For 80 meters, where operation is often desired in the CW DX portion (3.510 MHz) and in the phone DX portion (3.790 MHz), it will be necessary to retune the matching network as you change frequency. This can be done by switching a capacitor in or out, manually or remotely with a relay.

While the match bandwidth is quite narrow, the radiation pattern changes more slowly with frequency. **Figure 12.31** shows the variation in the pattern over the entire band (3.5 to 4.0 MHz). As would be expected, the gain increases with frequency because the antenna is larger in terms of wavelengths. The general shape of the pattern, however, is quite stable.

A variation of the Bobtail for multiple bands, the N4GG Array, is described in a July 2002 *QST* article that is included on this book's CD-ROM. The antenna covers multiple bands using parallel wires similarly to a fan dipole and with vertical wires acting as they do in the Bobtail curtain.

12.3.4 THE BRUCE ARRAY

Four variations of the Bruce array are shown in **Figure 12.32**. The Bruce is simply a wire folded so that the vertical sections carry large in-phase currents, while the horizontal sections carry small currents flowing in opposite directions with respect to the center of a section (indicated by dots). The radiation is vertically polarized. The gain is proportional to the length of the array but is somewhat smaller than you can obtain from a broadside array of λ/2 elements of the same length. This is because the radiating portion of the elements is only λ/4.

The Bruce array has a number of advantages:

1) The array is only λ/4 high. This is especially helpful on 80 and 160 meters, where the height of λ/2 supports becomes impractical for most amateurs.

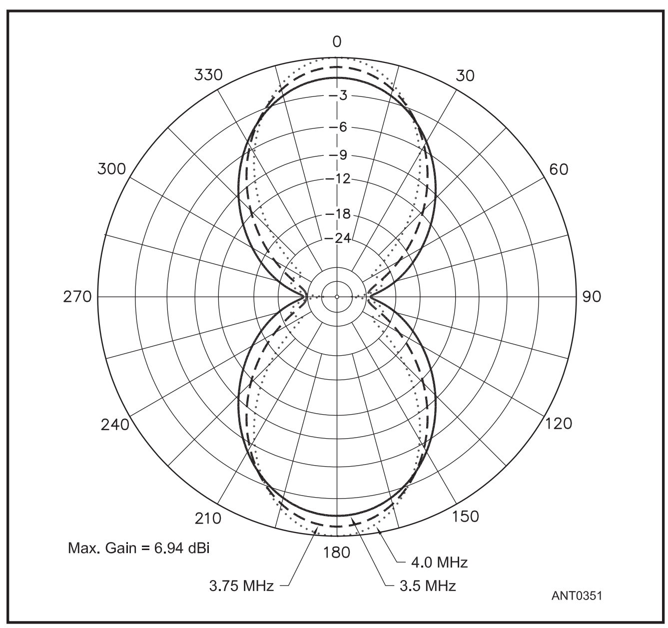

Figure 12.31 — 80 meter Bobtail curtain's free-space E-plane pattern variation over the 80 meter band.

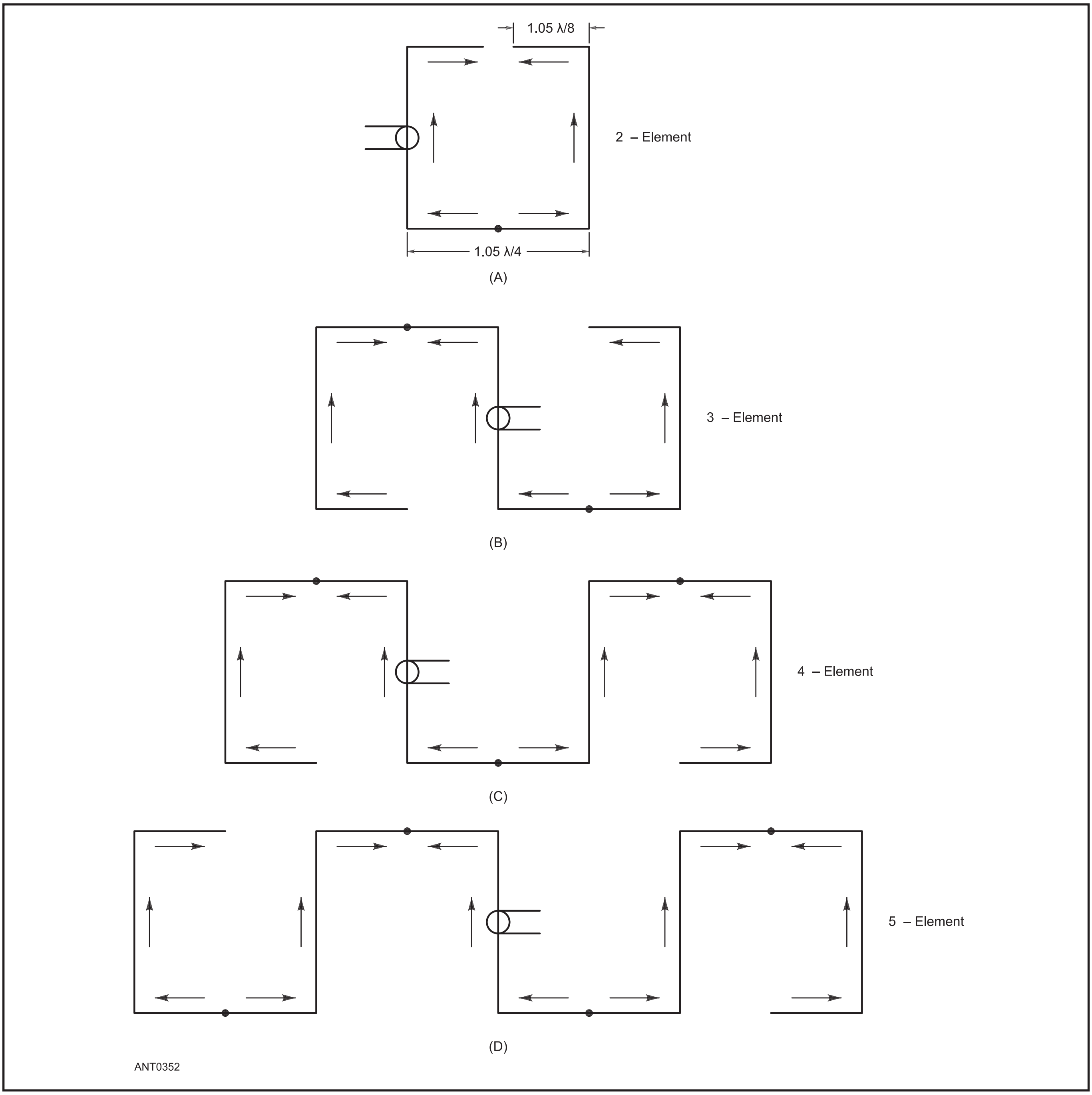

Figure 12.32 — Various Bruce arrays: 2, 3, 4 and 5-element versions.

2) The array is very simple. It is just a single piece of wire folded to form the array.

3) The dimensions of the array are very flexible. Depending on the available distance between supports, any number of elements can be used. The longer the array, the greater the gain.

4) The shape of the array does not have to be exactly 1.05 $\lambda/4$ squares. If the available height is short but the array can be made longer, then shorter vertical sections and longer horizontal sections can be used to maintain gain and resonance. Conversely, if more height is available but width is restricted then longer vertical sections can be used with shorter horizontal sections.

5) The array can be fed at other points more convenient for a particular installation.

6) The antenna is relatively low Q, so that the feed point impedance changes slowly with frequency. This is very helpful on 80 meters, for example, where the antenna can be relatively broadband.

7) The radiation pattern and gain is stable over the width of an amateur band.

Note that the nominal dimensions of the array in

Table 12.4
Bruce Array Length, Impedance and Gain as a Function of Number of Elements

Number Elements	*Gain Over λ/2 Vertical Dipole*	*Gain over λ/4 Ground-Plane*	*Array Length Wavelengths*	*Approx. Feed Z, Ω*
2	1.2 dB	1.9 dB	¼	130
3	2.8 dB	3.6 dB	½	200
4	4.3 dB	5.1 dB	¾	250
5	5.3 dB	6.1 dB	1	300

Figure 12.32 call for section lengths = 1.05 λ/4. The need to use slightly longer elements to achieve resonance is common in large wire arrays. A quad loop behaves in the same manner. This is quite different from wire dipoles, which are typically shortened by 2-5% to achieve resonance.

Figure 12.33 shows the variations in gain and pattern for 2 to 5-element 80 meter Bruce arrays. **Table 12.4** lists the gain over a vertical λ/2 dipole, a 4-radial ground-plane vertical and the size of the array. The gain and impedance parameters listed are for free space. Over real ground the patterns and gain will depend on the height above ground and the ground characteristics. Copper loss using #12 AWG conductors is included.

Worthwhile gain can be obtained from these arrays, especially on 80 and 160 meters, where any gain is hard to come by. The feed point impedance is for the center of a vertical section. From the patterns in Figure 12.33 you can see that sidelobes start to appear as the length of the array is increased beyond 3λ/4. This is typical for arrays using equal

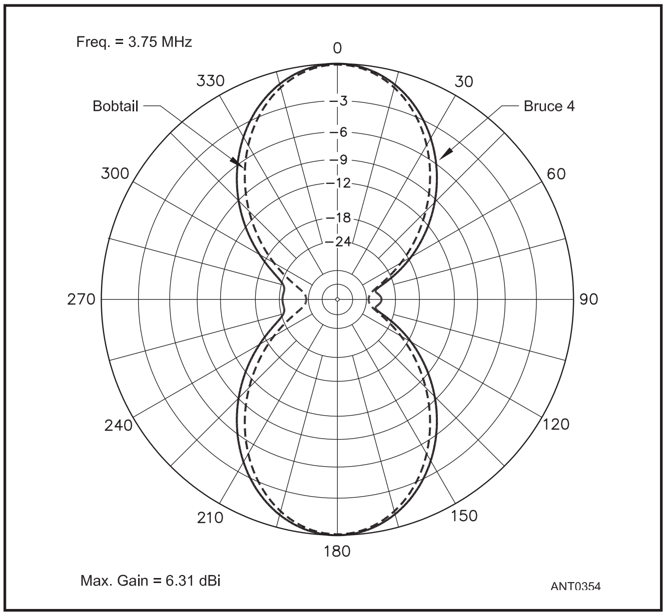

Figure 12.34 — Comparison of free space patterns of a 4-element Bruce array (solid line) and a 3-element Bobtail curtain (dashed line).

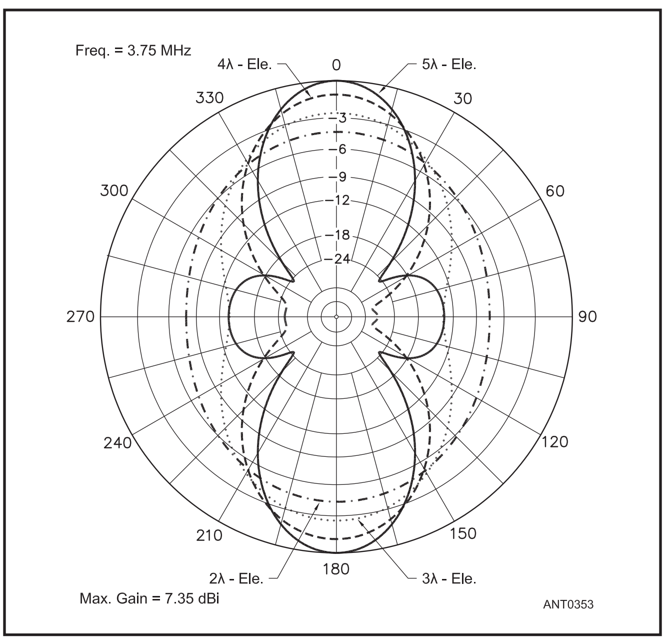

Figure 12.33 — 80 meter free-space E-plane directive patterns for the Bruce arrays shown in Figure 12.32. The 5-element's pattern is a solid line; the 4-element is a dashed line; the 3-element is a dotted line, and the 2-element version is a dashed-dotted line.

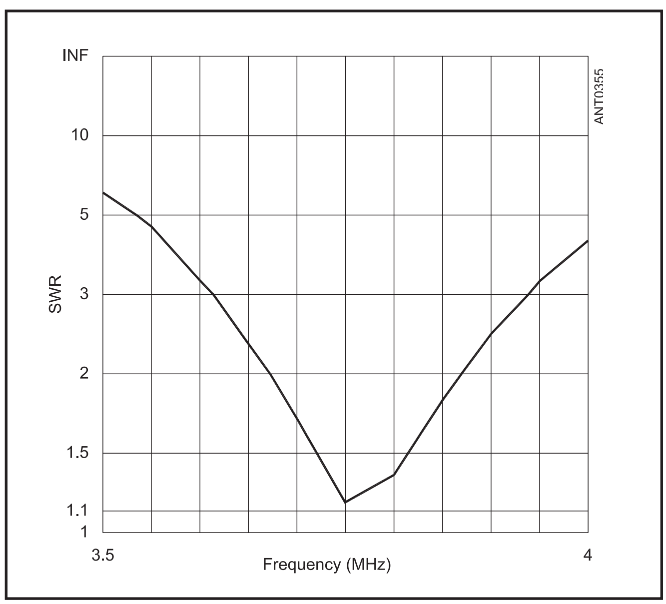

Figure 12.35 — Typical SWR curve for a 4-element 80 meter Bruce array.

currents in the elements.

It is interesting to compare the Bobtail curtain (Figure 12.28) with a 4-element Bruce array. **Figure 12.34** compares the radiation patterns for these two antennas. Even though the Bruce is shorter (3λ/4) than the Bobtail (1 λ), it has slightly more gain. The matching bandwidth is illustrated by the SWR curve in **Figure 12.35**. The 4-element Bruce has over twice the match bandwidth (200 kHz) than does the Bobtail (75 kHz in Figure 12.30). Part of the gain difference is due to the binomial current distribution — the center element has twice the current as the outer elements in the Bobtail. This reduces the gain slightly so that the 4-element Bruce becomes competitive. This is a good example of using more than the minimum number of elements to improve performance or to reduce size. On 160 meters the 4-element Bruce will be 140 feet shorter than the Bobtail, a significant reduction. If additional space is available for the Bobtail (1 λ) then a 5-element Bruce could be used, with a small increase in gain but also introducing some sidelobes.

The 2-element Bruce and the half-square antennas are both 2-element arrays. However, since the spacing between radiators is greater in the half-square (λ/2) the gain of the half-square is about 1 dB greater. If space is available, the half-square would be a better choice. If there is not room for a half-square then the Bruce, which is only half as long (λ/4), may be a good alternative. The 3-element Bruce, which has the same length (λ/2) as the half-square, has about 0.6 dB more gain than the half-square and will have a wider match bandwidth.

The Bruce antenna can be fed at many different points and in different ways. In addition to the feed points indicated in Figure 12.32, you may connect the feed line at the center of any of the vertical sections. In longer Bruce arrays, feeding at one end will result in some current imbalance among the elements but the resulting pattern distortion is small. Actually, the feed point can be anywhere along a vertical section. One very convenient point is at an outside corner. The feed point impedance will be higher (about 600 Ω). A good match for 450-Ω ladder-line can usually be found somewhere on the vertical section. It is important to recognize that feeding the antenna at a voltage node (dots in Figure 12.32) by breaking the wire and inserting an insulator, completely changes the current distribution. This will be discussed in the section on end-fire arrays.

A Bruce can be fed unbalanced against ground or against a counterpoise as shown in **Figure 12.36**. Because it is a vertically polarized antenna, the better the ground system, the better the performance. As few as two elevated radials can be used as shown in Figure 12.36B, but more radials can also be used to improve the performance, depending on local ground constants. The original development of the Bruce array in the late 1920s used this feed arrangement.

12.3.5 FOUR-ELEMENT BROADSIDE ARRAY

The 4-element array shown in **Figure 12.37** is commonly known as the Lazy H. It consists of a set of two collinear elements and a set of two parallel elements, all operated in-phase to give broadside directivity. The gain and directivity will depend on the spacing, as in the case of a simple parallel-element broadside array. The spacing may be chosen between the limits shown on the drawing, but spacings below 3λ/8 are

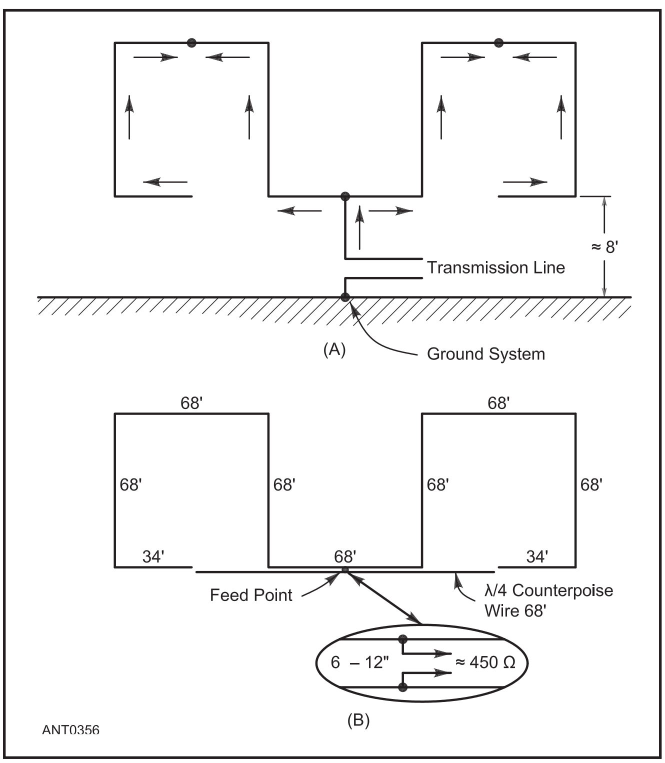

Figure 12.36 — Alternate feed arrangements for the Bruce array. At A, the antenna is driven against a ground system and at B, it uses a two-wire counterpoise.

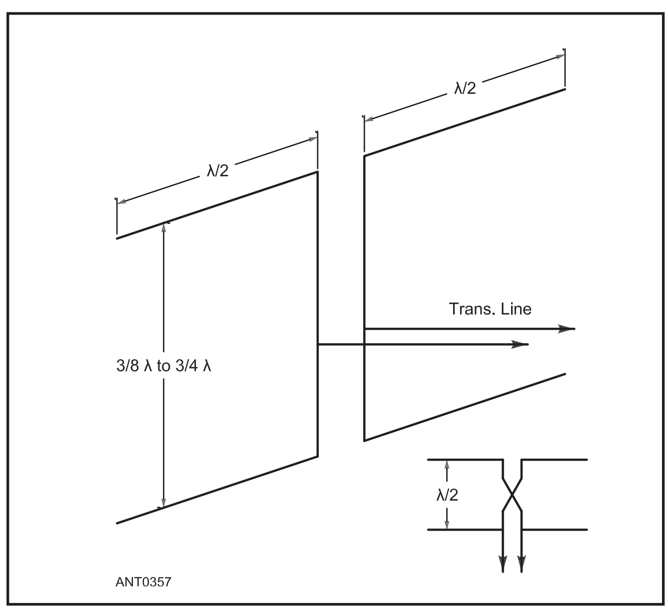

Figure 12.37 — Four-element broadside array ("lazy H") using collinear and parallel elements.

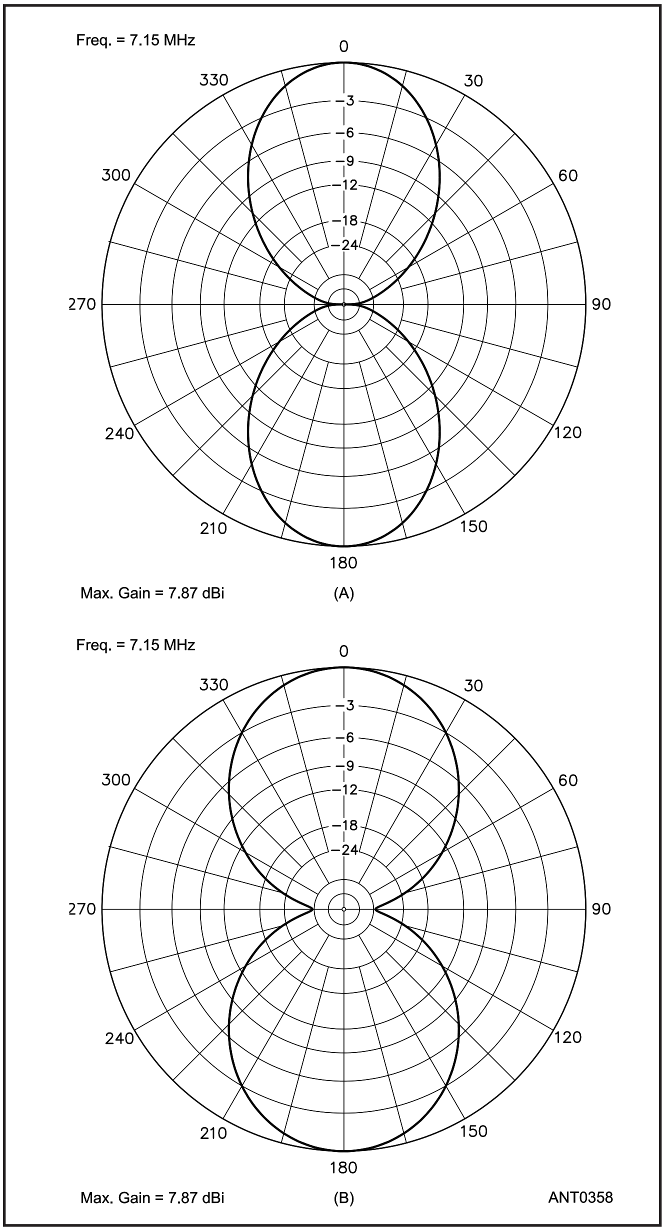

Figure 12.38 — Free-space directive diagrams of the 4-element antenna shown in Figure 12.37. At A is the E-plane pattern. The axis of the elements lies along the 90°-270° line. At B is the free-space H-plane pattern, viewed as if one set of elements is above the other from the ends of the elements.

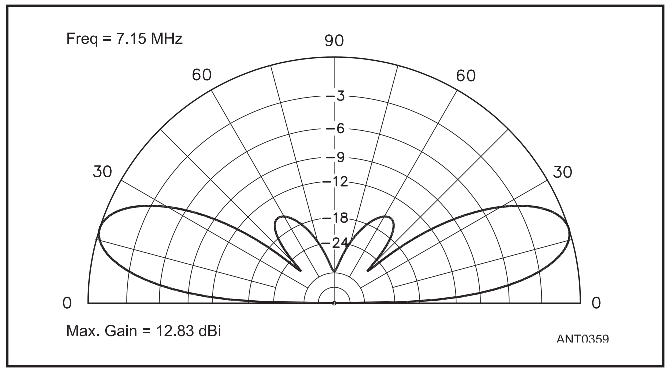

Figure 12.39 — Vertical pattern of the 4-element broadside antenna of Figure 12.37, when mounted with the elements horizontal and the lower set λ/4 above flat ground. Stacked arrays of this type give best results when the lowest elements are at least λ/2 high. The gain is reduced and the wave angle raised if the lowest elements are too close to ground.

not worthwhile because the gain is small. Estimated gains compared to a single element are:

3λ/8 spacing — 4.2 dB
λ/2 spacing — 5.8 dB
5λ/8 spacing — 6.7 dB
3λ/4 spacing — 6.3 dB

Half-wave spacing is generally used. Directive patterns for this spacing are given in **Figures 12.38** and **12.39**. With λ/2 spacing between parallel elements, the impedance at the junction of the phasing line and transmission line is resistive and in the vicinity of 100 Ω. With larger or smaller spacing the impedance at this junction will be reactive as well as resistive. Matching stubs are recommended in cases where a non-resonant line is to be used. They may be calculated and adjusted as described in the **Transmission Line System Techniques** chapter.

The system shown in Figure 12.37 may be used on two bands having a 2-to-1 frequency relationship. It should be designed for the higher of the two frequencies, using 3λ/4 spacing between parallel elements. It will then operate on the lower frequency as a simple broadside array with 3λ/8 spacing.

An alternative method of feeding is shown in the small diagram in Figure 12.37. In this case the elements and the phasing line must be adjusted exactly to an electrical half wavelength. The impedance at the feed point will be resistive and on the order of 2 kΩ.

A variation of this antenna called the "extended Lazy H" makes an effective broadside antenna on its fundamental and several higher bands. It is a good Field Day antenna if the supports are available for the lower elements to be at least λ/4 above the ground. It can be used with a tuner on all HF bands and as a top-loaded vertical by connecting the feed line conductors together and driving it against a ground system. A version for 7, 14, and 21 MHz is described in "The Extended Lazy H Antenna," by Walter Salmon in Oct 1955 *QST* and included on this book's CD-ROM.

12.3.6 THE BI-SQUARE ANTENNA

A development of the lazy H, known as the bi-square antenna, is shown in **Figure 12.40**. The gain of the bi-square is somewhat less than that of the lazy-H, but this array is attractive because it can be supported from a single pole. It has a circumference of 2 λ at the operating frequency, and is horizontally polarized.

The bi-square antenna consists of two 1 λ radiators, fed 180° out-of-phase at the bottom of the array. The radiation resistance is 300 Ω, so it can be fed with either 300- or 600-Ω line. The free space gain of the antenna is about

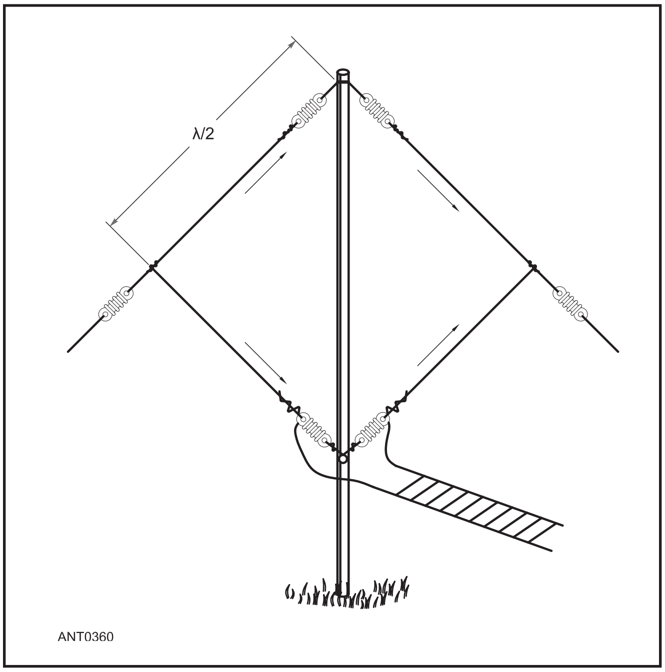

Figure 12.40 — The bi-square array. It has the appearance of a loop, but is not a true loop because the conductor is open at the top. The length of each side, in feet, is 480/f (MHz).

5.8 dBi, which is 3.7 dB more than a single dipole element. Gain may be increased by adding a parasitic reflector or director. Two bi-square arrays can be mounted at right angles and switched to provide omnidirectional coverage. In this way, the antenna wires may be used as part of the guying system for the pole.

Although it resembles a loop antenna, the bi-square is not a true loop because the ends opposite the feed point are open. However, identical construction techniques can be used for the two antenna types. Indeed, with a means of remotely closing the connection at the top for lower frequency operation, the antenna can be operated on two harmonically related bands. As an example, an array with 17 feet per side can be operated as a bi-square at 28 MHz and as a full-wave loop at 14 MHz. For two-band operation in this manner, the side length should favor the higher frequency. The length of a closed loop is not as critical.

12.4 END-FIRE ARRAYS

The term end-fire covers a number of different methods of operation, all having in common the fact that the maximum radiation takes place along the array axis, and that the array consists of a number of parallel elements in one plane. End-fire arrays can be either bidirectional or unidirectional. In the bidirectional type commonly used by amateurs there are only two elements, and these are operated with currents 180° out-of-phase. Even though adjustment tends to be complicated, unidirectional end-fire driven arrays have also seen amateur use, primarily as a pair of phased, ground-mounted λ/4 vertical elements. Extensive discussion of this array is contained in the **Multielement Arrays** chapter.

Horizontally polarized unidirectional end-fire arrays see little amateur use except in log-periodic arrays (described in the **Log-Periodic Dipole Arrays** chapter). Instead, horizontally polarized unidirectional arrays usually have parasitic elements (described in the **HF Yagi and Quad Antennas** chapter) and are called Yagis.

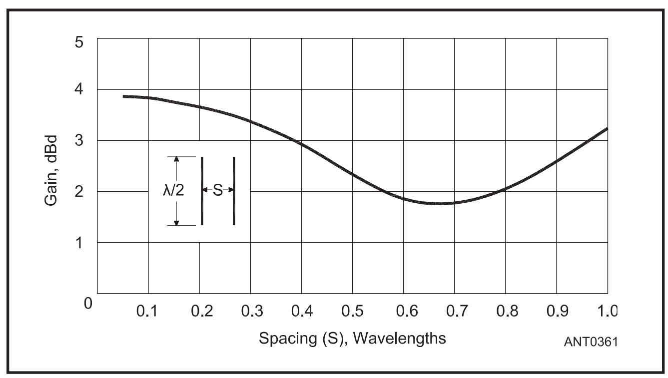

Figure 12.41 — Gain of an end-fire array consisting of two elements fed 180° out-of-phase, as a function of the spacing between elements. Maximum radiation is in the plane of the elements and at right angles to them at spacings up to λ/2, but the direction changes at greater spacings.

12.4.1 TWO-ELEMENT END-FIRE ARRAY

In a 2-element array with equal currents out-of-phase, the gain varies with the spacing between elements as shown in **Figure 12.41**. The maximum gain occurs in the neighborhood of 0.1 λ spacing. Below that the gain drops rapidly due to conductor loss resistance.

The feed point resistance for either element is very low at the spacings giving greatest gain, as shown in the **Multielement Arrays** chapter. The spacings most frequently used are λ/8 and λ/4, at which the resistances of center-fed λ/2 elements are about 9 and 32 Ω, respectively.

The effect of conductor resistance on gain for various spacings is shown in **Figure 12.42**. Because current along the element is not constant (it is approximately sinusoidal), the resistance shown is the equivalent resistance (R_{eq}) inserted at the center of the element to account for the loss distributed along the element.

The equivalent resistance of a λ/2 element is one half the

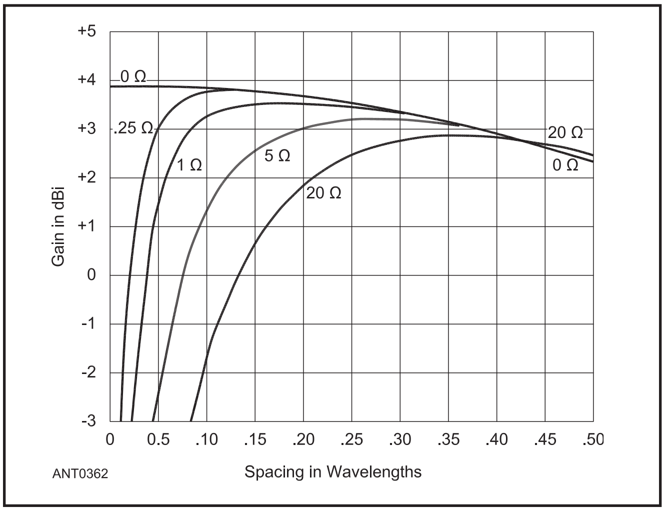

Figure 12.42 — Gain over a single element of two out-of-phase elements in free space as a function of spacing for various loss resistances.

ac resistance (R_{ac}) of the complete element. R_{ac} is usually >> R_{dc} due to skin effect. For example, a 1.84 MHz dipole using #12 AWG copper wire will have the following R_{eq}:

Wire length = 267 feet

R_{dc} = 0.00159 [Ω/foot] × 267 [feet] = 0.42 Ω

$F_r = R_{ac}/R_{dc} = 10.8$

$R_{eq} = (R_{dc}/2) \times F_r = 2.29\ \Omega$

For a 3.75 MHz dipole made with #12 AWG wire, R_{eq} = 1.59 Ω. In Figure 12.42, it is clear that end-fire antennas made with #12 AWG or smaller wire will limit the attainable gain because of losses. There is no point in using spacings much less than λ/4 if you use wire elements. If instead you use elements made of aluminum tubing then smaller spacings can be used to increase gain. However, as the spacing is reduced below λ/4 the increase in gain is quite small even with good conductors. Closer spacings give little gain increase but can drastically reduce the operating bandwidth due to the rapidly increasing Q of the array.

Unidirectional End-Fire Arrays

Two parallel elements spaced λ/4 apart and fed equal currents 90° out-of-phase will have a directional pattern in the plane at right angles to the plane of the array. See **Figure 12.43**. The maximum radiation is in the direction of the element in which the current lags. In the opposite direction the fields from the two elements cancel.

When the currents in the elements are neither in-phase nor 180° out-of-phase, the feed point resistances of the elements are not equal. This complicates the problem of feeding equal currents to the elements, as discussed in the **Multielement Arrays** chapter.

More than two elements can be used in a unidirectional end-fire array. The requirement for unidirectivity is that there must be a progressive phase shift in the element currents equal to the spacing, in electrical degrees, between the elements. The amplitudes of the currents in the various elements also must be properly related. This requires binomial current distribution. In the case of three elements, this requires that the current in the center element be twice that in the two outside elements, for 90° (λ/4) spacing and element current phasing. This antenna has an overall length of λ/2. The directive diagram is shown in **Figure 12.44**. The pattern is similar to that

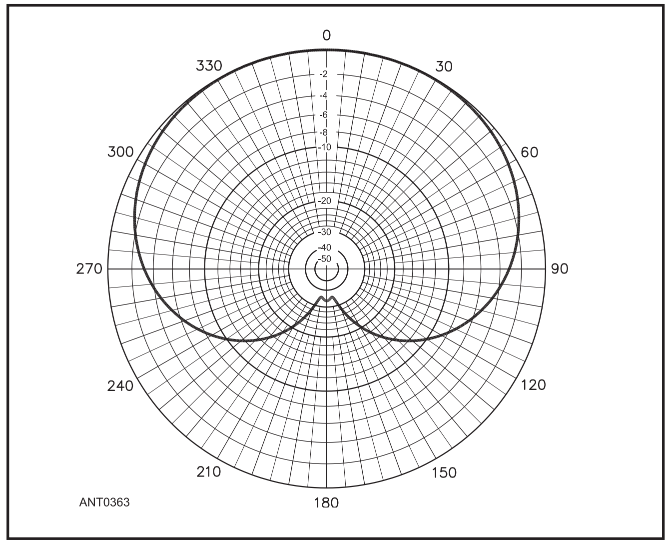

Figure 12.43 — Representative H-plane pattern for a 2-element end-fire array with 90° spacing and phasing. The elements lie along the vertical axis, with the uppermost element the one of lagging phase. Dissimilar current distributions are taken into account.

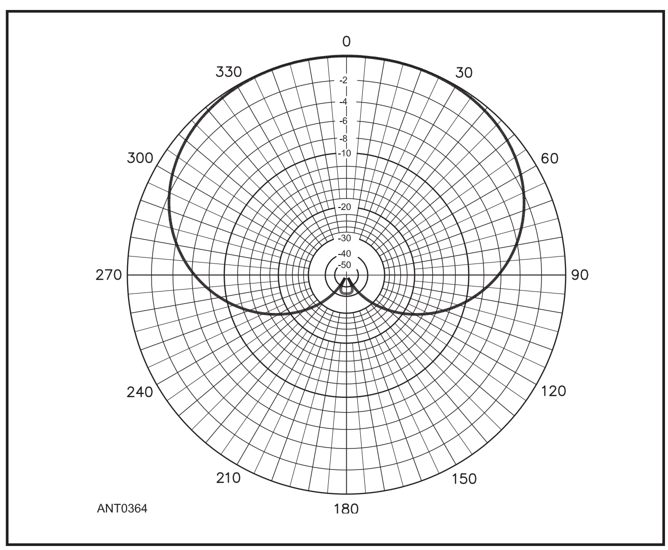

Figure 12.44 — H-plane pattern for a 3-element end-fire array with binomial current distribution (the current in the center element is twice that in each end element). The elements are spaced λ/4 apart along the 0°-180° axis. The center element lags the lower element by 90°, while the upper element lags the lower element by 180° in phase. Dissimilar current distributions are taken into account.

of Figure 12.43, but the 3-element binomial array has greater directivity, evidenced by the narrower half-power beamwidth (146° versus 176°). Its gain is 1.0 dB greater.

12.4.2 THE W8JK ARRAY

John Kraus, W8JK (SK), described his bidirectional flat-top W8JK beam antenna in 1940. See **Figure 12.45**. (His June 1982 *QST* article "The W8JK Recap and Update" is included on the CD-ROM for this book.) Two λ/2 elements are spaced λ/8 to λ/4 and driven 180° out-of-phase. The free-space radiation pattern for this antenna, using #12 AWG copper wire, is given in **Figure 12.46**. The pattern is representative of spacings between λ/8 and λ/4 where the gain varies less than 0.5 dB. The gain over a dipole is about 3.3 dB (5.4 dBi referenced to an isotropic radiator), a worthwhile improvement. The feed point impedance (including wire resistance) of each element is about 11 Ω for λ/8 spacing and 33 Ω for λ/4 spacing. The feed point impedance at the center connection will depend on the length and Z_0 of the connecting transmission line.

Kraus gave a number of other variations for end-fire arrays, some of which are shown in **Figure 12.47**. The ones fed at the center (A, C and E) are usually horizontally polarized flat-top beams. The end-fed versions (B, D and F) are usually

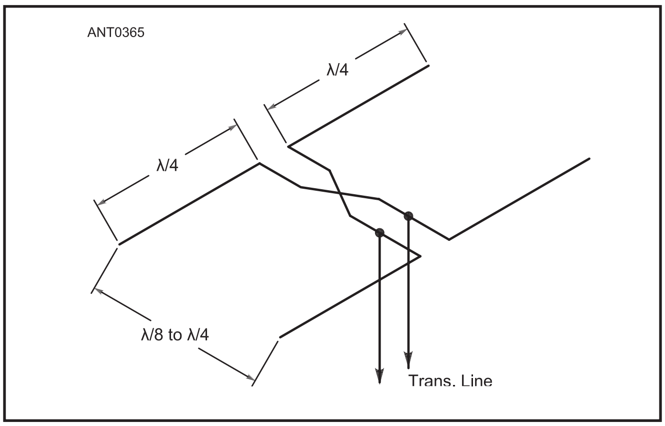

Figure 12.45 — A 2-element W8JK array.

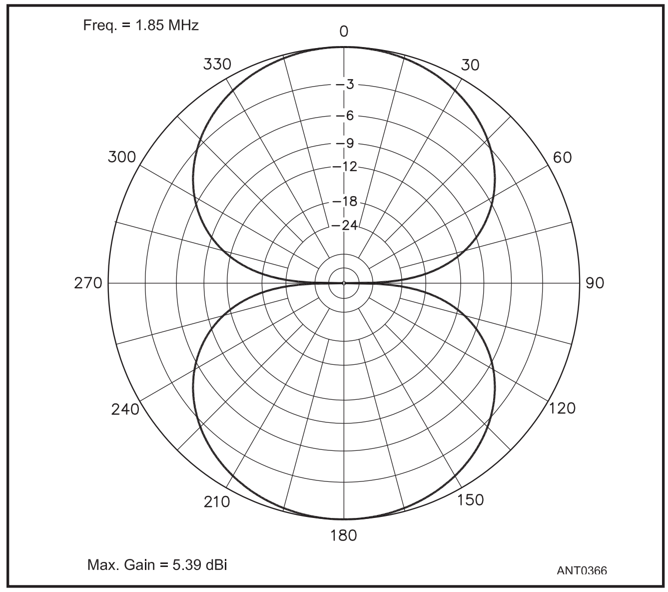

Figure 12.46 — Free-space E-plane pattern for the 2-element W8JK array.

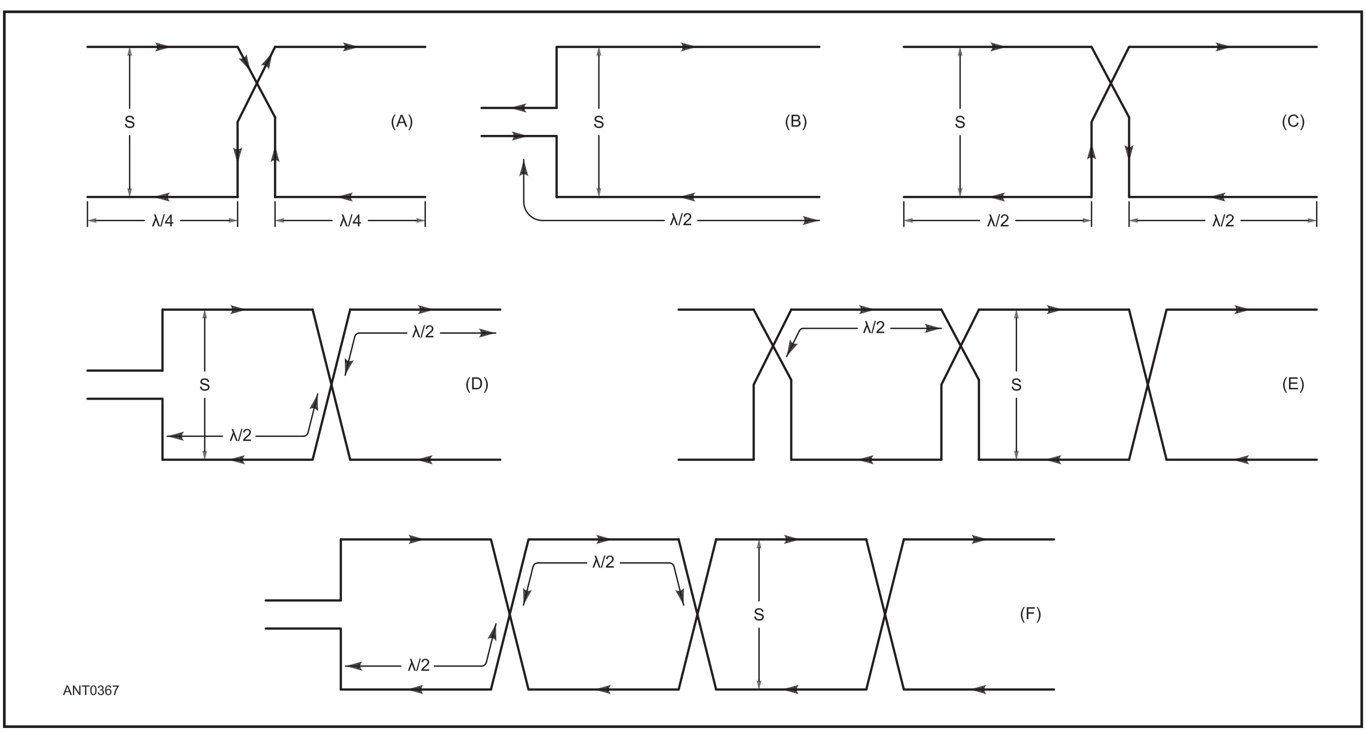

Figure 12.47 — Six other variations of W8JK "flat-top beam" antennas.

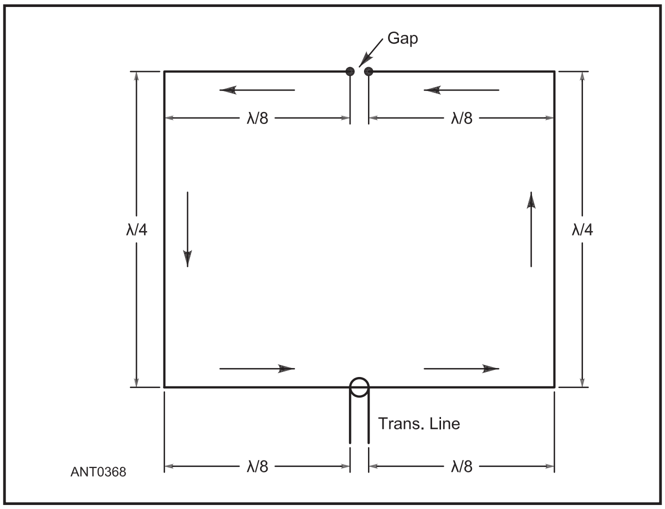

Figure 12.48 — A 2-element end-fire array with reduced height.

vertically polarized, where the feed point can be conveniently near ground.

A practical variation of Figure 12.47B is given in **Figure 12.48**. In this example, the height is limited to λ/4 so the ends can be bent over as shown, producing a 2-element Bruce array. This reduces the gain somewhat but allows much shorter supports, an important consideration on the low bands. If additional height is available, then you can achieve some additional gain. The upper ends can be bent over to fit the available height. The feed point impedance will greater than 1 kΩ.

The article "Building the W8JK" by Suggs (see Bibliography) shows how to build a W8JK beam that covers 20 through 6 meters.

12.4.3 FOUR-ELEMENT END-FIRE AND COLLINEAR ARRAYS

The array shown in **Figure 12.49** combines collinear in-phase elements with parallel out-of-phase elements to give

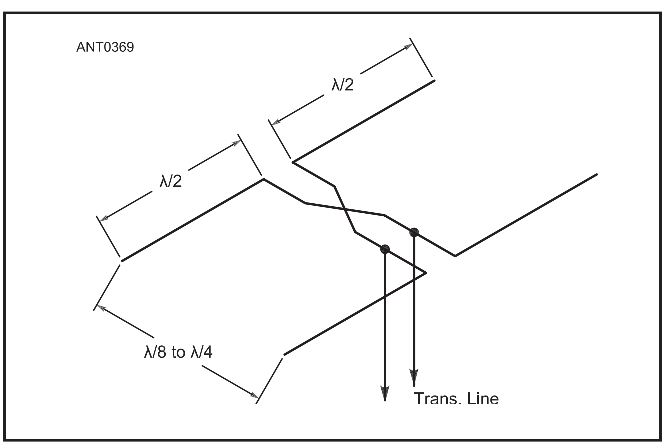

Figure 12.49 — A 4-element array combining collinear broadside elements and parallel end-fire elements, popularly known as a two-section W8JK array.

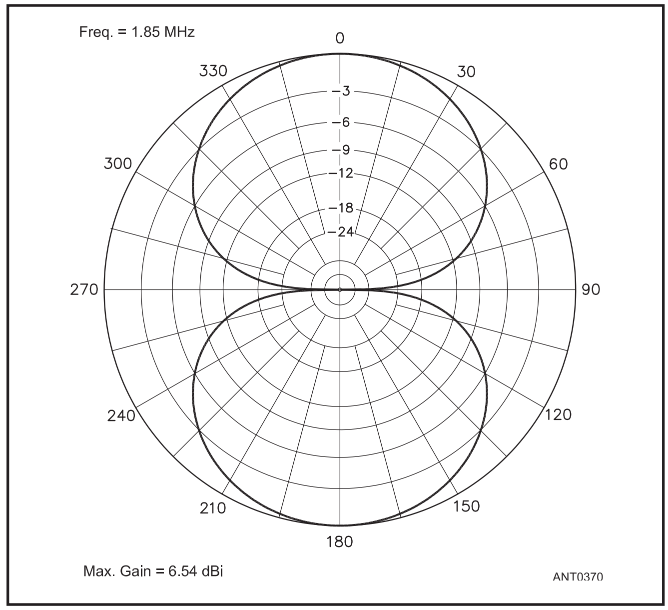

Figure 12.50 — Free-space E-plane pattern for the antenna shown in Figure 12.49, with λ/8 spacing. The elements are parallel to the 90°-270° line in this diagram. Less than a 1° change in half-power beamwidth results when the spacing is changed from λ/8 to λ/4.

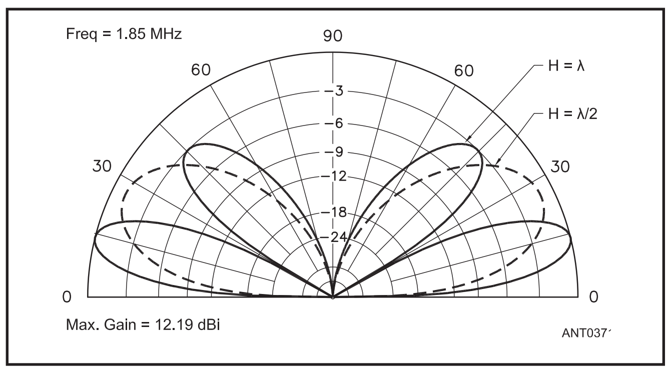

Figure 12.51 — Elevation-plane pattern for the 4-element antenna of Figure 12.49 when mounted horizontally at two heights over flat ground. Solid line = 1 λ high; dashed line = λ/2 high.

both broadside and end-fire directivity. It is a two-section W8JK. The approximate free-space gain using #12 AWG copper wire is 4.9 dBi with λ/8 spacing and 5.4 dBi with λ/4 spacing. Directive patterns are given in **Figure 12.50** for free space, and in **Figure 12.51** for heights of 1 λ and λ/2 above flat ground.

The impedance between elements at the point where the phasing line is connected is of the order of several thousand ohms. The SWR with an unmatched line consequently is quite high, and this system should be constructed with open-wire line (500 or 600 Ω) if the line is to be resonant. With λ/4 element spacing the SWR on a 600 Ω line is estimated to be in the vicinity of 3 or 4:1.

To use a matched line, you could connect a closed stub 3λ/16 long at the transmission-line junction shown in Figure 12.49. The transmission line itself can then be tapped on this matching section at the point resulting in the lowest line SWR. This point can be determined by trial.

This type of antenna can be operated on two bands having a frequency ratio of 2 to 1, if a resonant feed line is used. For example, if you design for 28 MHz with λ/4 spacing between elements, you can also operate on 14 MHz as a simple 2-element end-fire array having λ/8 spacing.

Combination Driven Arrays

You can readily combine broadside, end-fire and collinear elements to increase gain and directivity, and this is in fact usually done when more than two elements are used in an array. Combinations of this type give more gain, in a given amount of space, than plain arrays of the types just described. Since the combinations that can be worked out are almost endless, this section describes only a few of the simpler types.

The accurate calculation of the power gain of a multi-element array requires a knowledge of the mutual impedances between all elements, as discussed in earlier sections. For approximate purposes it is sufficient to assume that each set (collinear, broadside, end-fire) will have the gains as given earlier, and then simply add up the gains for the combination. This neglects the effects of cross-coupling between sets of elements. However, the array configurations are such that the mutual impedances from cross-coupling should be relatively small, particularly when the spacings are λ/4 or more, so the estimated gain should be reasonably close to the actual gain. Alternatively, an antenna modeling program, such as *EZNEC*, can give good estimates of all parameters for a real-world antenna, providing that you take care to model all applicable parameters.

12.4.4 FOUR-ELEMENT DRIVEN ARRAYS

The array shown in **Figure 12.52** combines parallel elements with broadside and end-fire directivity. The smallest array (physically) — 3λ/8 spacing between broadside and λ/8 spacing between end-fire elements — has an estimated gain of 6.5 dBi and the largest — 3λ/4 and λ/4 spacing, respectively — about 8.4 dBi. Typical directive patterns for a λ/4 × λ/2 array are given in **Figures 12.53** and **12.54**.

The impedance at the feed point will not be purely resistive unless the element lengths are correct and the phasing lines are exactly λ/2 long. (This requires somewhat less than λ/2 spacing between broadside elements.) In this case the impedance at the junction is estimated to be over 10 kΩ. With other element spacings the impedance at the junction will be reactive as well as resistive, but in any event the SWR will be quite large. An open-wire line can be used as a resonant line, or a matching section may be used for non-resonant operation.

12.4.5 EIGHT-ELEMENT DRIVEN ARRAYS

The array shown in **Figure 12.55** is a combination of collinear and parallel elements in broadside and end-fire directivity. Common practice in a wire antenna is to use λ/2

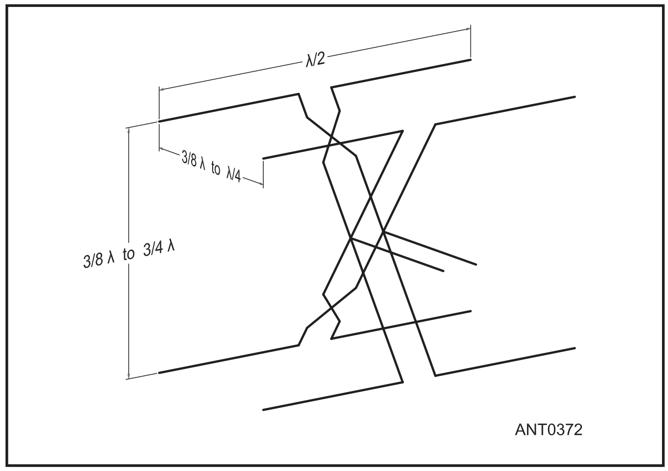

Figure 12.52 — Four-element array combining both broadside and end-fire elements.

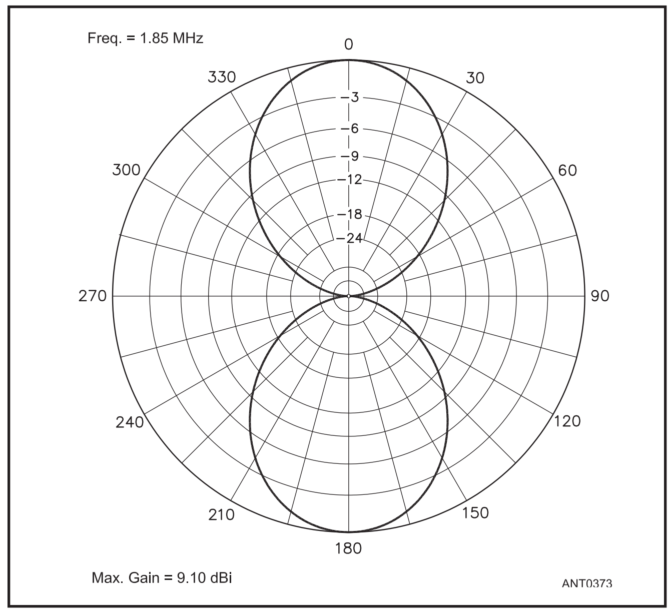

Figure 12.53 — Free-space H-plane pattern of the 4-element antenna shown in Figure 12.52.

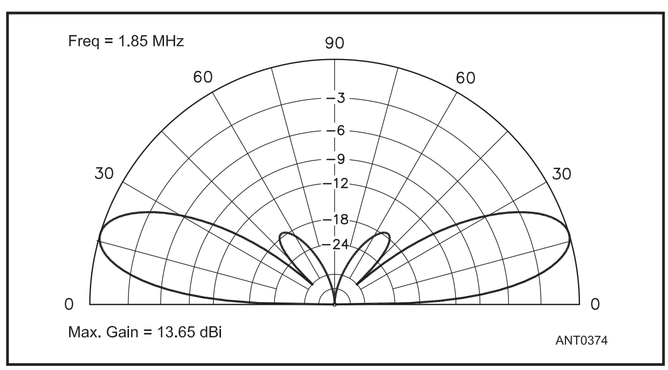

Figure 12.54 — Vertical pattern of the antenna shown in Figure 12.52 at a mean height of 3λ/4 (lowest elements λ/2 above flat ground) when the antenna is horizontally polarized. For optimum gain and low wave angle the mean height should be at least 3λ/4.

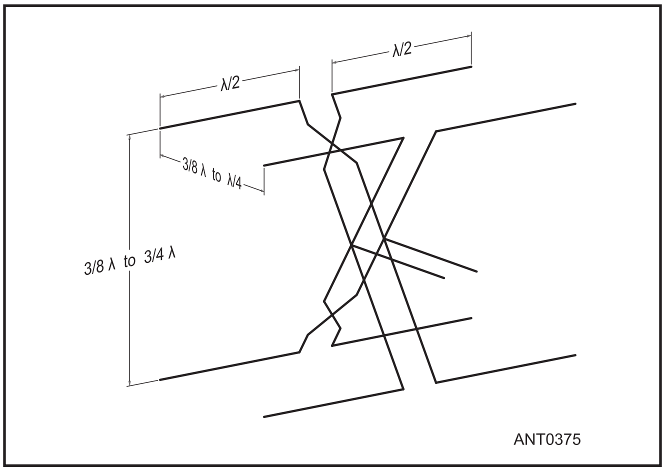

Figure 12.55 — Eight-element driven array combining collinear and parallel elements for broadside and end-fire directivity.

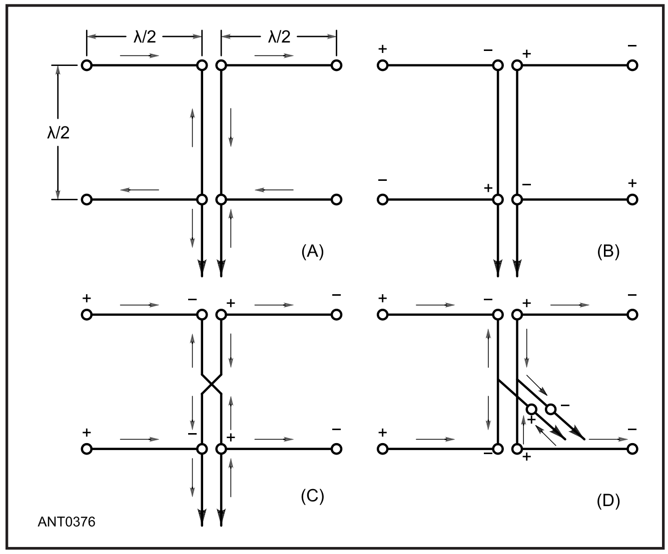

Figure 12.56 — Methods of checking the phase of currents in elements and phasing lines.

spacing for the parallel broadside elements and λ/4 spacing for the end-fire elements. This gives a free-space gain of about 9.1 dBi. Directive patterns for an array using these spacings are similar to those of Figures 12.53 and 12.54, but are somewhat sharper.

The SWR with this arrangement will be high. Matching stubs are recommended for making the lines non-resonant. Their position and length can be determined as described in the chapter **Transmission Line System Techniques**.

This system can be used on two bands related in frequency by a 2-to-1 ratio, providing it is designed for the higher of the two, with 3λ/4 spacing between the parallel broadside elements and λ/4 spacing between the end-fire elements. On the lower frequency it will then operate as a 4-element antenna of the type shown in Figure 12.52, with 3λ/8 broadside spacing and λ/8 end-fire spacing. For two-band operation a resonant transmission line must be used.

12.4.6 PHASING ARROWS IN ARRAY ELEMENTS

In the antenna diagrams of preceding sections, the relative direction of current flow in the various antenna elements and connecting lines was shown by arrows. In laying out any antenna system it is necessary to know that the phasing lines are properly connected; otherwise the antenna may have entirely different characteristics than anticipated. The phasing may be checked either on the basis of current direction or polarity of voltages. There are two rules to remember:

1) In every λ/2 section of wire, starting from an open end, the current directions reverse. In terms of voltage, the polarity reverses at each λ/2 point, starting from an open end.

2) Currents in transmission lines always must flow in opposite directions in adjacent wires. In terms of voltage, polarities always must be opposite.

Examples of the use of current direction and voltage polarity are given at A and B, respectively, in **Figure 12.56**. The λ/2 points in the system are marked by small circles. When current in one section flows toward a circle, the current in the next section must also flow toward it, and vice versa. In the 4-element antenna shown at A, the current in the upper right-hand element cannot flow toward the transmission line because then the current in the right-hand section of the phasing line would have to flow upward and thus would be flowing in the same direction as the current in the left-hand wire. The phasing line would simply act like two wires in parallel in such a case. Of course, all arrows in the drawing could be reversed, and the net effect would be unchanged.

C shows the effect of transposing the phasing line. This transposition reverses the direction of current flow in the lower pair of elements, as compared with A, and thus changes the array from a combination collinear and end-fire arrangement into a collinear-broadside array.

The drawing at D shows what happens when the transmission line is connected at the center of a section of phasing line. Viewed from the main transmission line, the two parts of the phasing line are simply in parallel, so the half wavelength is measured from the antenna element along the upper section of phasing line and thence along the transmission line. The distance from the lower elements is measured in the same way. Obviously, the two sections of phasing line should be the same length. If they are not, the current distribution becomes quite complicated; the element currents are neither in-phase nor 180° out-of-phase, and the elements at opposite ends of the lines do not receive the same current. To change the element current phasing at D into the phasing at A, simply transpose the wires in one section of the phasing line. This reverses the direction of current flow in the antenna elements connected to that section of phasing line.

12.5 BIBLIOGRAPHY

J. Cain, "Curtains for You," *QST*, Oct 1991, pp 26-30. See also Feedback in Dec 1991 *QST*, p 73. This article also appears in *ARRL's Wire Antenna Classics*.

L.B. Cebik, "Some Notes on Two-Element Horizontal Phased Arrays," in four parts, *NCJ*, Nov/Dec 2001, pp 4-10; Jan/Feb 2002, pp 4-9; Mar/Apr 2002, pp 3-8; and May/Jun 2002, pp 3-8.

D. Cooper, "The Bi-Square Array," *Ham Radio*, May 1990, pp 42-44.

J. Haigwood, "The Extended Double Zepp Revisited," *QST*, Sep 2006, pp 35-36.

H. Jasik, *Antenna Engineering Handbook*, 1st ed. (New York: McGraw-Hill, 1961). Later editions are edited by Richard C. Johnson.

H. Kennedy, "The N4GG Array", *QST*, Jul 2002, pp 35-39.

J. D. Kraus, *Antennas*, 2nd ed. (New York: McGraw-Hill Book Co., 1988).

J. D. Kraus, "The W8JK Antenna Recap and Update," *QST*, Jun 1982, pp 11-14.

R. Johnson, *Antenna Engineering Handbook*, 3rd ed. (New York: McGraw-Hill Inc., 1993). This is a later edition of the volume by the same name edited by H. Jasik.

E. A. Laport, *Radio Antenna Engineering* (New York: McGraw-Hill Book Co, 1952).

M. Loukides, "A Dipole Curtain for 15 and 10 Meters," *QST*, Aug 2003, pp 34-38.

H. Romander, "The Extended Double-Zepp Antenna," *QST*, Jun 1938, pp 12-16. This article also appears in *More Wire Antenna Classics*, published by ARRL.

W. Salmon, "The Extended Lazy H Antenna," *QST*, Oct 1955, p 20.

W. Smith, "Bet My Money on a Bobtail Beam," *CQ*, Mar 1948, pp 21-23.

W. Smith, "The Bobtail Curtain and Inverted Ground Plane, Part One," *Ham Radio*, Feb 1983, pp 82-86.

W. Smith, "Bobtail Curtain Follow-Up: Practical DX Signal Gain" *Ham Radio*, Mar 1983, pp 28-30.

D. Suggs, "Building the W8JK Beam," *QST*, Sep 2005, pp 31-35.

R. Zavrel, "The Multiband Extended Double Zepp and Derivative Designs," *QEX*, Jul/Aug 1999, pp 34-40.

R. Zimmerman, "A Simple 50-Ohm Feed for W8JK Beams," *QST*, Jun 1999, pp 41-42, 47. See also Feedback in Jul 1999 *QST*, p 63.