A Broadside of Vertical Wires

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We often misunderstand the quest for more gain. The instant picture is a directional beam rotated by a heavy motor at the top of a large steel tower. That is only one version of robbing energy from unused directions and focusing it in the direction of our communications targets. Very often, we can do the required job with a bi-directional antenna. If we can limit our target areas, we can often do away with the tower and the rotator. Wire still works very well, especially in bi-directional arrays.

The set of options that we shall explore in these notes consists entirely of vertical arrays, which are especially apt to the lower HF and upper MF regions. All of the antennas that we shall examine are garden-variety arrays, with many variations in the literature. What may give this treatment a small bit of uniqueness is the fact that we shall level the playing field. To keep everything full size, we shall put every antenna on 40 meters--specifically 7.15 MHz. As well, each antenna will be above average ground, that is, ground with a conductivity of 0.005 S/m and a relative permittivity of 13. Once we examine some basic standards against which to measure array performance, all antennas will use AWG #12 copper wire. As a result, any changes of ground, frequency, and element size will apply roughly equally to all of the antenna types in the group.

In addition, we shall bypass the potential long list of monopole arrays and thereby evade questions surrounding ground radial systems and end-fire directional phasing schemes. We shall limit ourselves to antennas based on the vertical dipole and broadside arrays of dipoles that give us bi-directional patterns. The excluded antennas all are good candidates for service in amateur communications, but we have only limited space to conduct a review of some of the possibilities.

A Standard: the ½-Wavelength Vertical Dipole

The fundamental standard against which to measure the performance of all of the other related antennas on our incomplete list is the vertical dipole. **Fig. 1** provides a snapshot of the antenna's outline and both the elevation and azimuth patterns that emerge under the modeled test conditions. The sample antenna is a 1.25" diameter aluminum center-fed vertical that approximates what we might find in actual practice. Real antennas in amateur use might consist of anything from wire suspended from an overhanging limb to large well casings or even light tower sections.

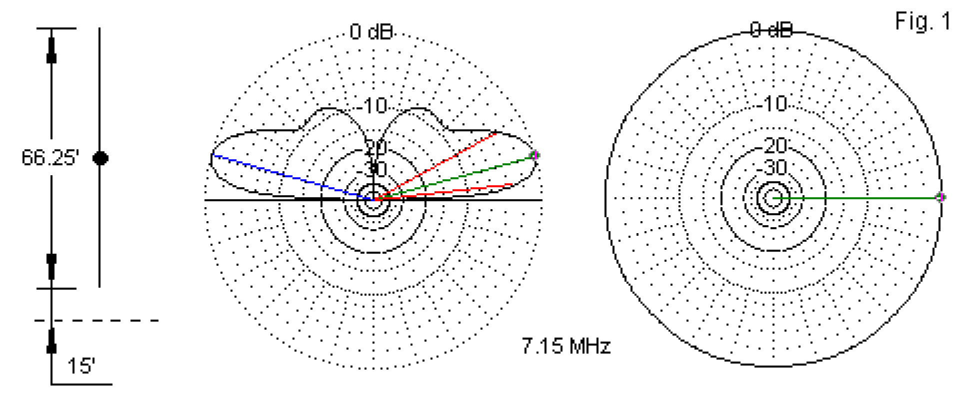


Fig. 1

Genral Outline and Elevation and Azimuth Plots
40-Meter Vertical Dipole

The base of the dipole is about 15' above ground. Since a wavelength at 7.15 MHz is just about 140' long, you can change the numbers in feet to a fraction of a wavelength. From that point, conversion to metric measures is simple. The importance of the base height shows up in the elevation pattern for the dipole. For any vertical antenna or array that we do not attached directly to ground and a radial system, two performance values interaction in opposite directions. As we raise the antenna, the elevation angle of maximum radiation (TO angle) decreases slowly and the gain increases. The same increase in height will also enlarge the higher-angle lobe. At a certain height--which varies with each array--all further energy will go into the second or higher elevation lobe. The heights that I have selected may not coincide with what your own physical conditions permit or with your preferences, so I recommend that you reproduce the exercise using your own set-ups.

My selections rest on several conditions. First, the base height must be at least 10'-12' above ground for safety. The outer end of any dipole or wire array holds an injurious voltage level. Lowering the base of the vertical dipole would require additional protection measures for people and animals. Second, the higher-angle lobe should be as small as practical to reduce sensitivity to higher angle signals. The resulting pattern disqualifies these antennas from NVIS service, but provides quieter background levels for the DX operator. Third, the combination of gain and TO angle must be optimal. This last condition is a judgment call and will vary with the needs and preferences of each operator. **Table 1** provides a summary of modeled performance data for my selections for all three vertical dipole antennas and arrays.

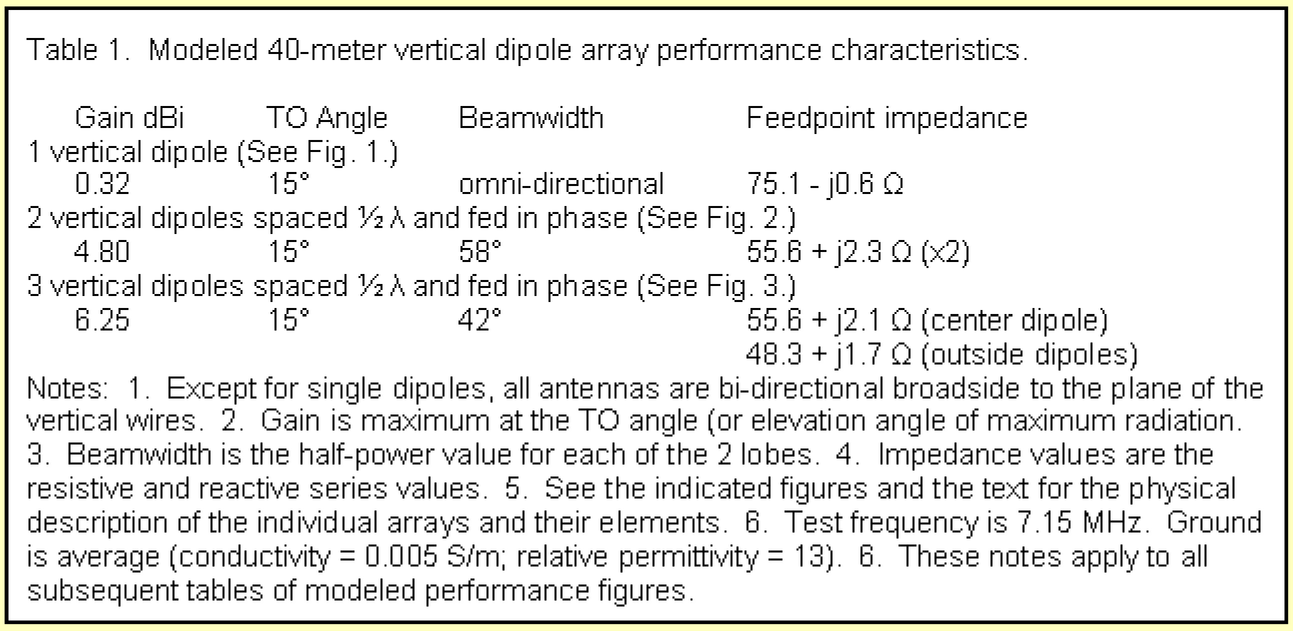


Table 1. Modeled 40-meter vertical dipole array performance characteristics.

Gain dBi	TO Angle	Beamwidth	Feedpoint impedance
1 vertical dipole (See Fig. 1.)			
0.32	15°	omni-directional	75.1 - j0.6 Ω
2 vertical dipoles spaced ½ λ and fed in phase (See Fig. 2.)			
4.80	15°	58°	55.6 + j2.3 Ω (x2)
3 vertical dipoles spaced ½ λ and fed in phase (See Fig. 3.)			
6.25	15°	42°	55.6 + j2.1 Ω (center dipole) 48.3 + j1.7 Ω (outside dipoles)

Notes: 1. Except for single dipoles, all antennas are bi-directional broadside to the plane of the vertical wires. 2. Gain is maximum at the TO angle (or elevation angle of maximum radiation. 3. Beamwidth is the half-power value for each of the 2 lobes. 4. Impedance values are the resistive and reactive series values. 5. See the indicated figures and the text for the physical description of the individual arrays and their elements. 6. Test frequency is 7.15 MHz. Ground is average (conductivity = 0.005 S/m; relative permittivity = 13). 6. These notes apply to all subsequent tables of modeled performance figures.

The vertical dipole itself is not yet a broadside array, since we have no plane of elements against which to measure the broadside directions. However, one simple array consists of two ½-wavelength vertical dipoles fed in phase. **Fig. 2** provides the outline and the patterns for the dipole pair. Note that mutual coupling requires that we lengthen the dipoles slightly to obtain resonance. For the test conditions, the bi-directional maximum gain at the 15° TO angle is about 4.5-dB greater than the gain of a single dipole. In exchange, the half-power beamwidth is 58° in each prime direction. Do not underestimate the importance of the beamwidth value in planning a broadside array. Feeding the array is simple in this case, since the dipole feedpoint values are close to 50 Ohms. Equal lengths of coax provide equal feedpoint currents. However, if we wish to have 50 Ohms at the junction of the two lines, then we must resort to ¾-wavelength 70-75-Ohm lines (since the velocity factor of ordinary coax lines will not allow electrical quarter-wavelength lines to reach a common junction).

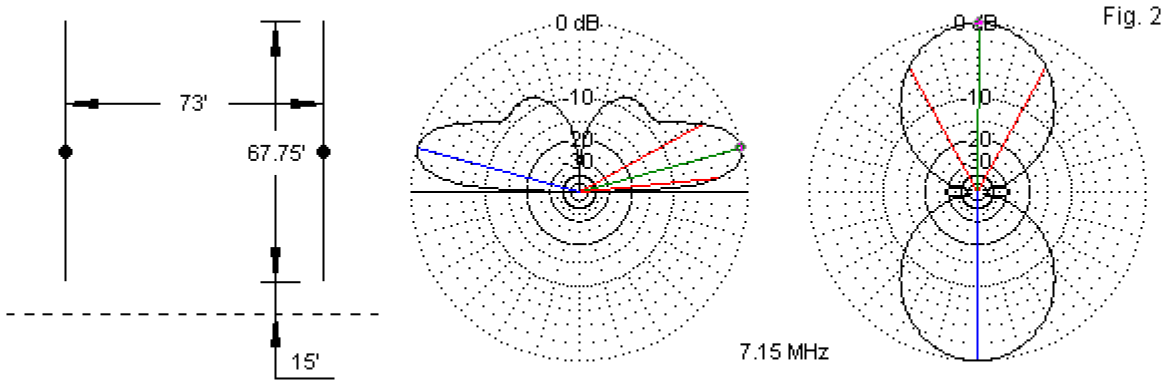


Fig. 2

General Outline and Elevation and Azimuth Plots
2 40-Meter Vertical Dipoles Fed In Phase

The azimuth pattern in **Fig. 2** shows another interesting fact about pairs of vertical dipoles fed in phase. The separation shown is 73', slightly greater than ½ wavelength. As we increase the spacing beyond ½ wavelength, the gain continues to increase, but we find sidelobes emerging. At what spacing we terminate the quest for gain because the sidelobes are too large is again a judgment call.

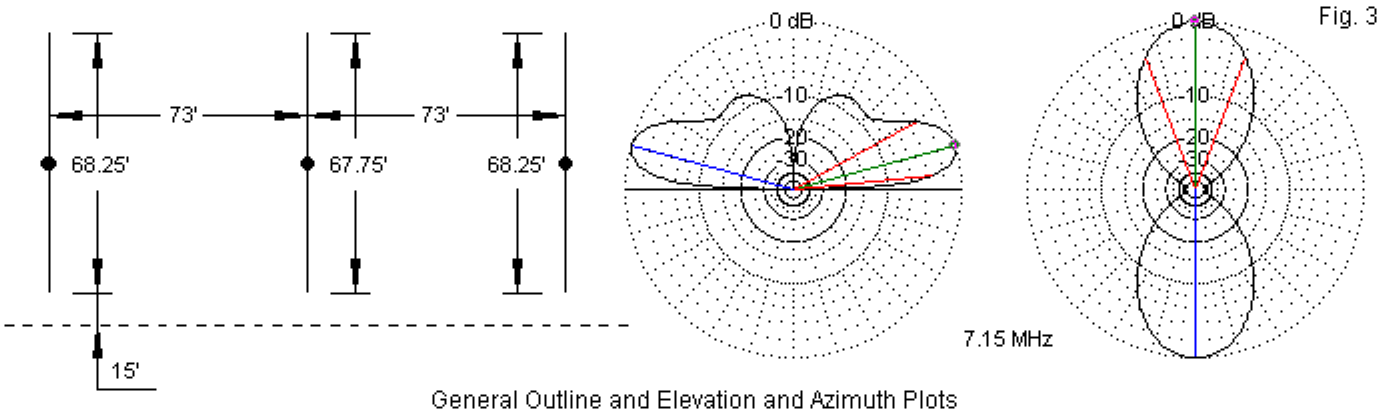


Fig. 3

General Outline and Elevation and Azimuth Plots
3 40-Meter Vertical Dipoles Fed In Phase

Fig. 3 shows what we can obtain from 3 vertical dipoles in phase. We obtain nearly 1.5-dB additional gain, but with a beam that is over 15° narrower. To achieve near resonance at the feedpoints, we must make the outer dipoles slightly longer than the center dipole. However, the factor that hinders most antenna builders from implementing a 3-dipole array (besides space) is the need for binomial current distribution. To produce the desired pattern, the center dipole must show twice the feedpoint current as each of the outside dipole feedpoints. One advantage that accrues to the wire arrays that we shall sample is the use of a single feedpoint for the entire array.

Hatted Dipoles

Before we look at the wire arrays, we should examine a technique that can overcome to some degree the height requirements of the simple vertical dipole. We can add hats to each end of each dipole and reduce the vertical length without jeopardizing the performance by very much. The hats can be any symmetrical wire extensions at right angles to the vertical. The extensions permit the antenna to reach a resonant length, but the symmetry of the extensions tends to cancel the horizontal component of the far fields. **Fig. 4** shows the outline (and patterns) of a 1.25" diameter vertical dipole shortened to 32'. Each AWG #12 hat wire is 16' long. The hat in this case takes the form of a T with the wires in the plane of the dipoles. Hence, we may lash the extension wires to a pair of non-conductive lines at the top and bottom of the dipoles to simplify overall construction. If we raise the feedpoint level above ground to nearly the same height as the full dipole feedpoints, we obtain close to the same TO angle and very close to full gain. However, we significantly reduce the near-resonant feedpoint impedance. The same considerations would apply to all-wire hatted dipoles, although the vertical dimensions would be somewhat longer. See **Table 2** for the modeled performance data for all three hatted arrays.

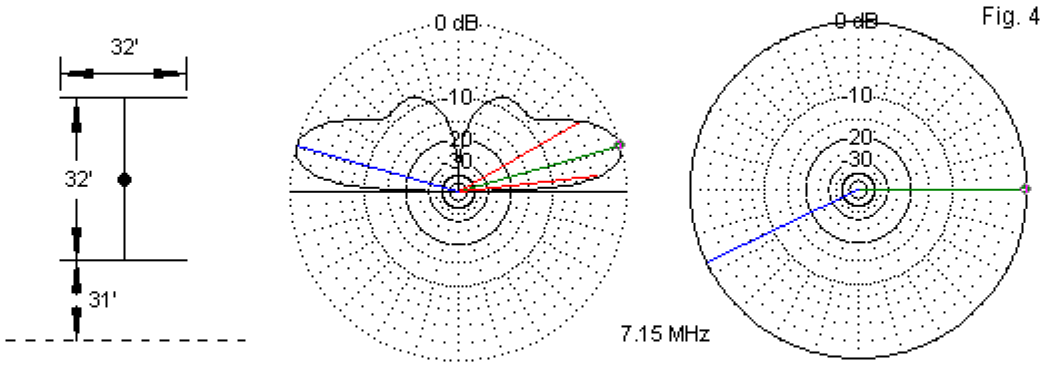


Fig. 4

General Outline and Elevation and Azimuth Plots
40-Meter Hatted Vertical Dipole

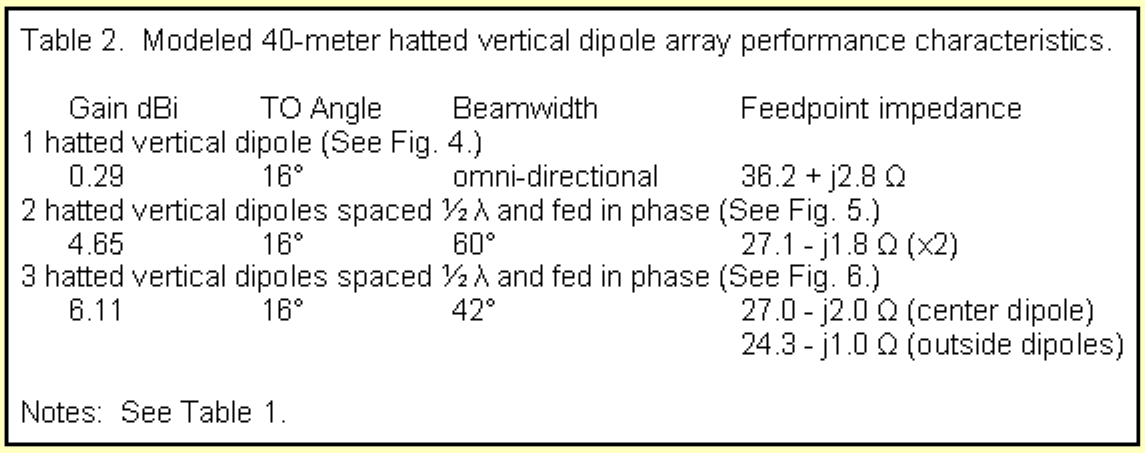


Table 2. Modeled 40-meter hatted vertical dipole array performance characteristics.

Gain dBi	TO Angle	Beamwidth	Feedpoint impedance
1 hatted vertical dipole (See Fig. 4.)			
0.29	16°	omni-directional	36.2 + j2.8 Ω
2 hatted vertical dipoles spaced ½ λ and fed in phase (See Fig. 5.)			
4.65	16°	60°	27.1 - j1.8 Ω (x2)
3 hatted vertical dipoles spaced ½ λ and fed in phase (See Fig. 6.)			
6.11	16°	42°	27.0 - j2.0 Ω (center dipole) 24.3 - j1.0 Ω (outside dipoles)

Notes: See Table 1.

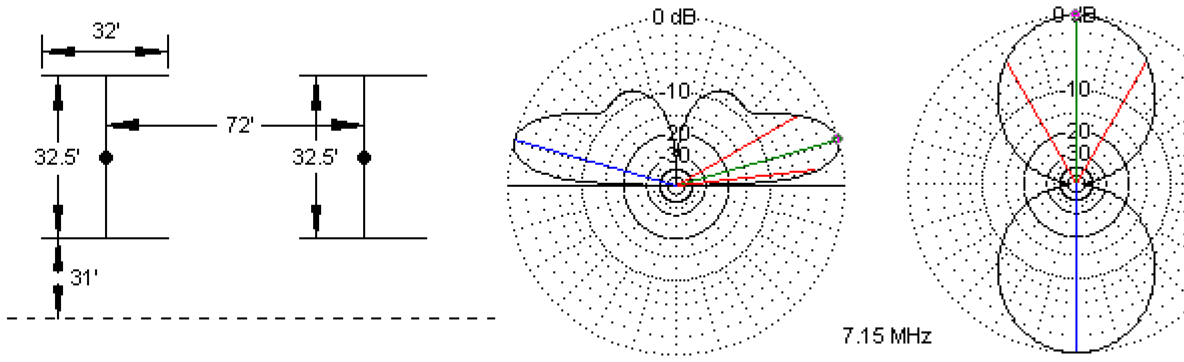


Fig. 5

General Outline and elevation and Azimuth Plots
2 40-Meter Hatted Vertical Dipoles Fed In Phase

Fig. 5 demonstrates the hatting technique applied to a pair of dipoles fed in phase. 50-Ohm ¾-wavelength lines would satisfactorily transform the impedances for a common-junction match to a 50-Ohm main feedline. The gain, TO angle, and beamwidth are comparable to the values for full-size dipoles in the same arrangement. The azimuth pattern shows the consequences of closing the spacing slightly: the sidelobes have virtually disappeared. By holding the hat extension wires at a constant 16', we can see the consequence of mutual coupling in the vertical section of the two dipoles. Like the full-size dipole array, the individual elements require lengthening to restore a near-resonant condition.

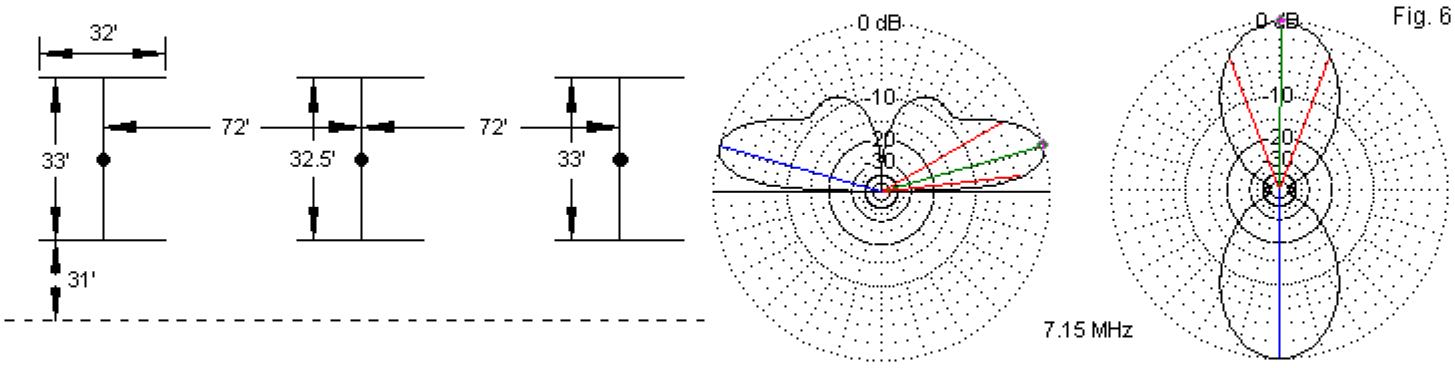


Fig. 6

General Outline and elevation and Azimuth Plots
3 40-Meter Hatted Vertical Dipoles Fed In Phase

A 3-hatted-dipole array appears in **Fig. 6**. It uses the same spacing (72') as used in the 2-dipole array to reduce sidelobes. The results once more are very similar to those for full-size dipoles. However, this array requires binomial feeding, just like the full-size counterpart, with the feedpoint current at the center element reaching twice the value of the feedpoint currents on the outer elements. I have included the 3-dipole arrays not as a recommendation for construction, but instead to provide performance standards against which we may compare the performance of wire arrays that simulate 3-dipole arrays.

Wire Arrays

Almost any antenna handbook contains the names of vertically polarized wire arrays that do not and need not touch the ground: half-squares, bobtail curtains, deltas, and rectangles. Physical constraints often dictate which among the candidates that we can implement. How we categorize the entire collection depends on the perspective from which we approach them. I once called the entire group "self-contained verticals" or SCVs, since they do not require ground radial systems. We may also view them from the feedpoint perspective. Each antenna has one feedpoint but presents vertical wires in phase. Hence, we might call them "self-phasing arrays." By bending and connecting parts of each dipole element so that they touch, we create lines that change the phase of both the voltage and the current to leave the vertical wire sections essentially in phase with each other at close to optimal spacing.

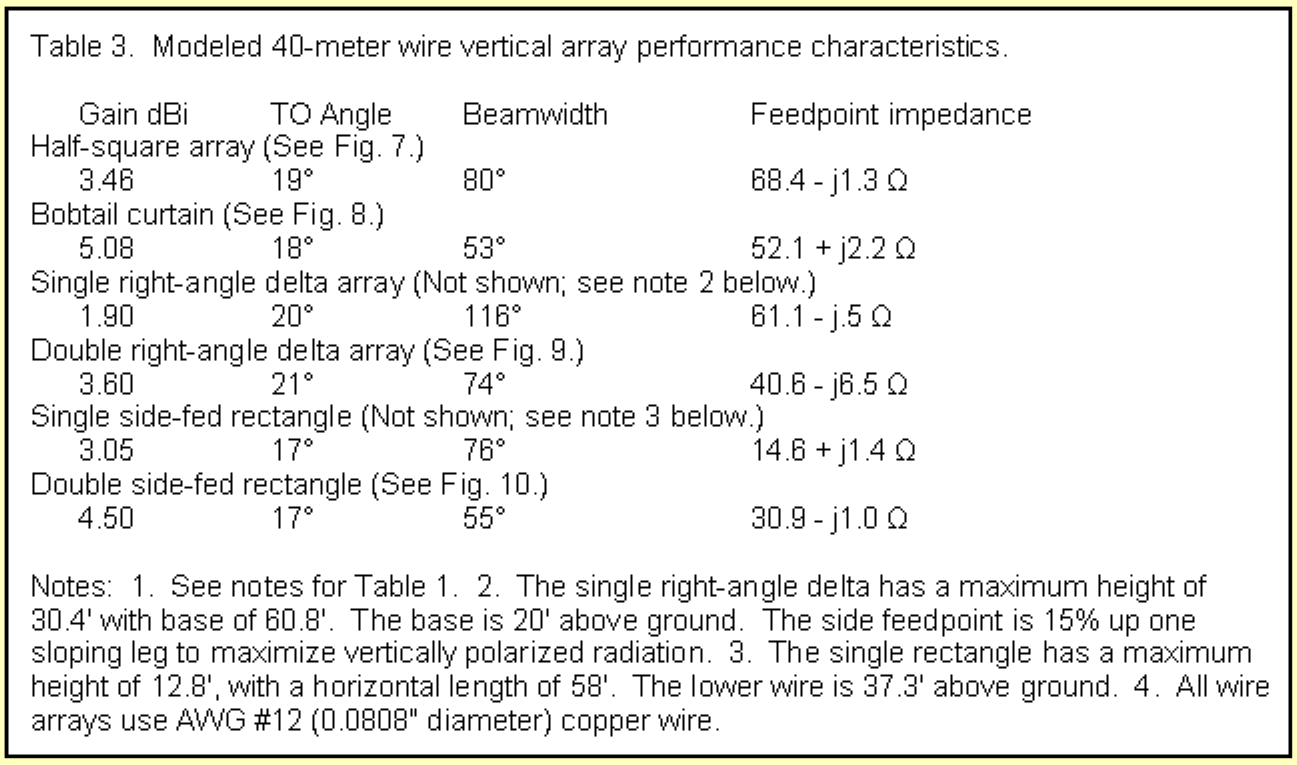
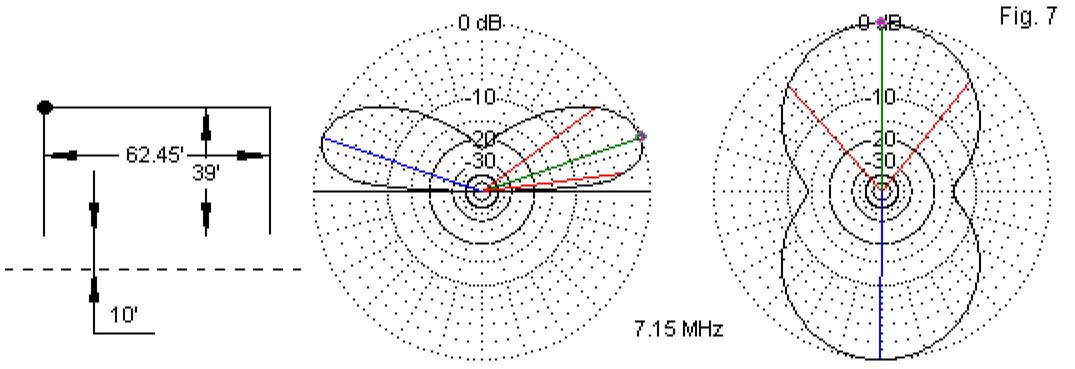


Table 3. Modeled 40-meter wire vertical array performance characteristics.

	Gain dBi	TO Angle	Beamwidth	Feedpoint impedance
Half-square array (See Fig. 7.)	3.46	19°	80°	68.4 - j1.3 Ω
Bobtail curtain (See Fig. 8.)	5.08	18°	53°	52.1 + j2.2 Ω
Single right-angle delta array (Not shown; see note 2 below.)	1.90	20°	116°	61.1 - j.5 Ω
Double right-angle delta array (See Fig. 9.)	3.60	21°	74°	40.6 - j6.5 Ω
Single side-fed rectangle (Not shown; see note 3 below.)	3.05	17°	76°	14.6 + j1.4 Ω
Double side-fed rectangle (See Fig. 10.)	4.50	17°	55°	30.9 - j1.0 Ω

Notes: 1. See notes for Table 1. 2. The single right-angle delta has a maximum height of 30.4' with base of 60.8'. The base is 20' above ground. The side feedpoint is 15% up one sloping leg to maximize vertically polarized radiation. 3. The single rectangle has a maximum height of 12.8', with a horizontal length of 58'. The lower wire is 37.3' above ground. 4. All wire arrays use AWG #12 (0.0808" diameter) copper wire.

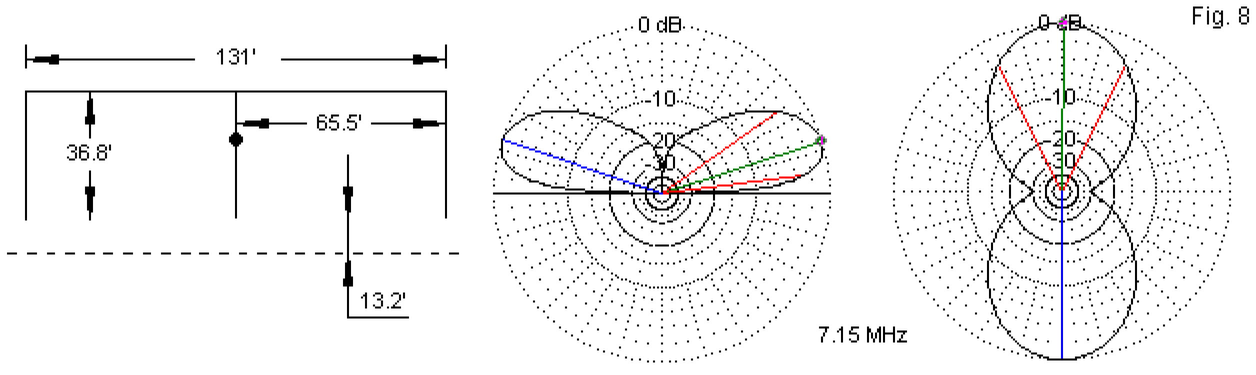
In our effort to create a level field for comparisons, all of the wire arrays that we shall explore use AWG #12 copper wire at 7.15 MHz over average ground. The heights will aim at maximum gain commensurate with a reasonable TO angle, but in no case will the top height exceed 50'. **Table 3** provides the modeled performance data for



General Outline and Elevation and Azimuth Plots
40-Meter Half Square Array

Perhaps the purest form of SCV is the half-square array. Interestingly, this antenna emerged later than its doubled big brother, the bobtail curtain. (See Woodrow Smith, W6BCX, "Bet My Money on the Bobtail Beam," *CQ* (March, 1948), 21-23 and 92-95, and Ben Vester, K3BC, "The Half Square Antenna," *QST* (March, 1974), 11-14, for the seminal articles on each antenna.) However, the half square is electrically more fundamental, corresponding roughly to a pair of vertical dipoles fed in phase. **Fig. 7** shows the general outline and the plots for a half square at roughly the optimal operating height. We can picture two vertical dipoles. The upper halves of each dipole bend toward each other until they just touch. These touching lines not only complete each dipole, but also form a phasing line between the two corner points. At the center, the voltage and current undergo a phase reversal, so the two vertical wires remain in phase. Hence, we need only a single feedpoint at one of the two upper corners. (We can also extend one vertical leg to the ground and use voltage-feeding techniques).

For best performance the horizontal wire must be shorter than ½ wavelength, while the vertical wires are longer than one-half of a resonant vertical dipole. For common copper wire sizes, the ratio of vertical to horizontal is about 5:8. Because the resulting array does not use full ½-wavelength spacing (about 70') and only half of the virtual dipoles contribute to the effective far field, the gain is about a dB shy of the gain of two vertical dipoles fed in phase. At maximum gain, the TO angle is slightly higher, since the bottom ends of the elements are closer to ground. These factors also contribute to the 80° beamwidth of the array.

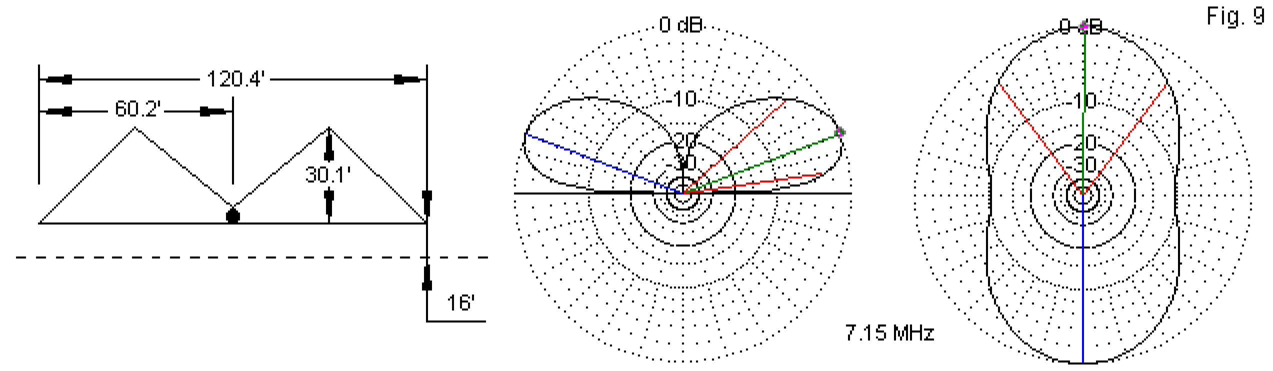


General Outline and Elevation and Azimuth Plots
40-Meter Bobtail Curtain

The bobtail curtain appeared earlier, but is electrically the double of the half-square array. **Fig. 8** presents the outline and the patterns for a roughly optimized bobtail curtain. The dimensions closely correspond to those worked out empirically by SM4CAN. The vertical elements are shorter than those of the half square, but the phase lines in each of the 2 sections are longer. To obtain a 50-Ohm impedance, the feedpoint is about 60% of the way up the center element. However, bringing the center element to the ground and using voltage-feeding techniques is very common. Still, we lack the radiation from the upper portions of the vertical dipoles and the spacing remains shy of a more ideal ½ wavelength. Hence, the maximum gain is lower than for 3 half-wavelength dipoles in phase, and the beamwidth is greater. In fact, the bobtail curtain performance figures more closely resemble the values associated with 2 half-wavelengths in phase. Nevertheless, the bobtail's single feedpoint produces a very close approximation of binomial feed with its 1-2-1 current magnitude ratios at the upper corners of the array.

There are two configurations that many hams use largely to overcome site constraints. One is the delta and the double delta. **Table 3** provides data on the single right-angle delta, when we feed it about 15% up one side to maximize the vertical component of the far-field pattern. This compact form that requires only a single upper support falls short of the ideal vertical element spacing and hence shows the lowest gain of any of the wire arrays. Its cousin, the double delta, appears in **Fig. 9**. We feed the array across the upper and lower (or base) wires at the center for vertical polarization. Although the feedpoint impedance is close to ideal, the gain is less than the gain of 2 vertical dipoles in phase--with a corresponding increase in beamwidth.

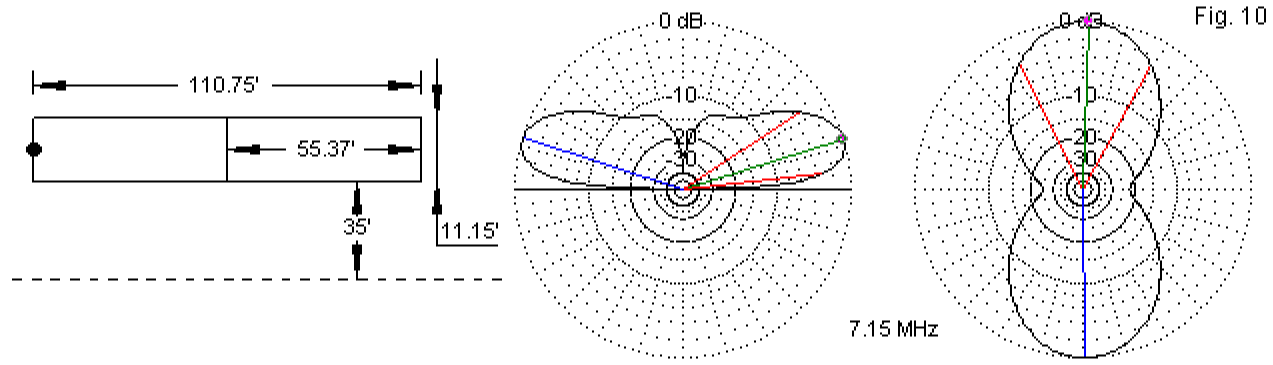
Fig. 9



General Outline and Elevation and Azimuth Plots
40-Meter Double-Right-Angle-Delta Array

The side-fed rectangle and double rectangle provide higher gain than single and double deltas largely because the end elements are vertical and closer to ½ wavelength apart. **Table 3** provides data on the single rectangle. It optimum dimensions represent a compromise between spacing and the required length of the end elements. Element spacing dominates the equation until the vertical end elements become too short to provide a strong far field pattern. The low feedpoint impedance of a single rectangle tends to reduce the utility of this version of the antenna despite the fact that the spacing of the horizontal wires is relatively small. The double rectangle, shown in **Fig. 10**, is more practical, despite its greater horizontal dimension. The gain and beamwidth approximate the values for 2 ideal vertical dipoles fed in phase although the antenna only requires 2 50' tall non-conductive end supports. The diagram shows the array fed at the center of one end. The 31-Ohm impedance is far more workable than would be the very low impedance at the middle of the center vertical wire, on which we find twice the current magnitude of the end vertical wires.

Fig. 10



General Outline and Elevation and Azimuth Plots
40-Meter Double-Rectangle Array

Of the double arrays, the bobtail curtain and the dual rectangle may be the most popular for those with the required space. The double rectangle is a bit shorter and presents the fewest safety problems. However, the bobtail curtain has a bit more gain and its loose ends provide a means for voltage-feeding techniques. (Bringing the bobtail center wire to ground and using a tank circuit for impedance matching does not alter the position of the high current point at the corner with the two horizontal phase lines. Nor does it alter the required current magnitudes and phase angles at each of the array's outer corners.) Half squares and single deltas remain popular among those with more limited space. With a change of feedpoint, each antenna is adaptable to use as a general all-band wire.

The Bruce Array

The Bruce array or curtain derives its name from Edmond Bruce, one of the legends of antenna developments in the late 1920s and through the 1930s. The array that bears his name is not, according to reports traced to John Kraus, W8JK, the antenna that he would have preferred to bear his name. The preferred antenna is the rhombic (originally named the diamond by Bruce). In fact, the Bruce-type curtain fell out of favor among wire-fans in the amateur community until resurrected by Rudy Severns, N6LF, and given prominence in Chapter 8 of the 20th edition of the *ARRL Antenna Book*. We shall briefly examine two forms of the Bruce array: a 5-element "innie" and a 7-element "outie." A Bruce array requires 1/8-wavelength end sections, and the navel reference refers to how we handle them. **Table 4** provides the modeled data for the two sample arrays.

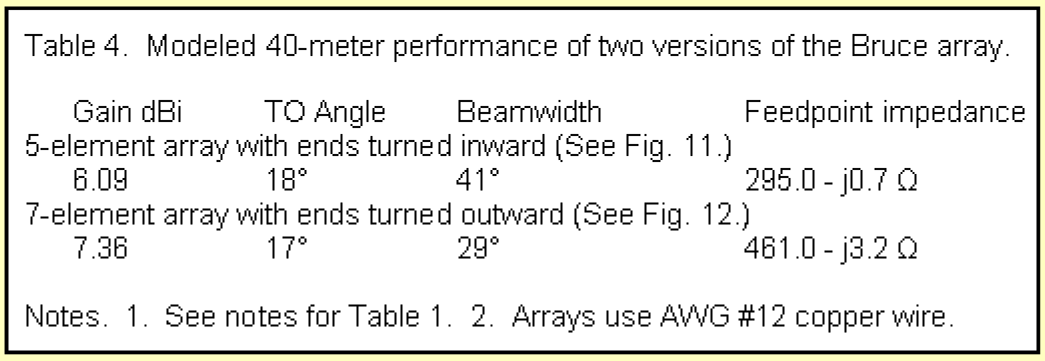


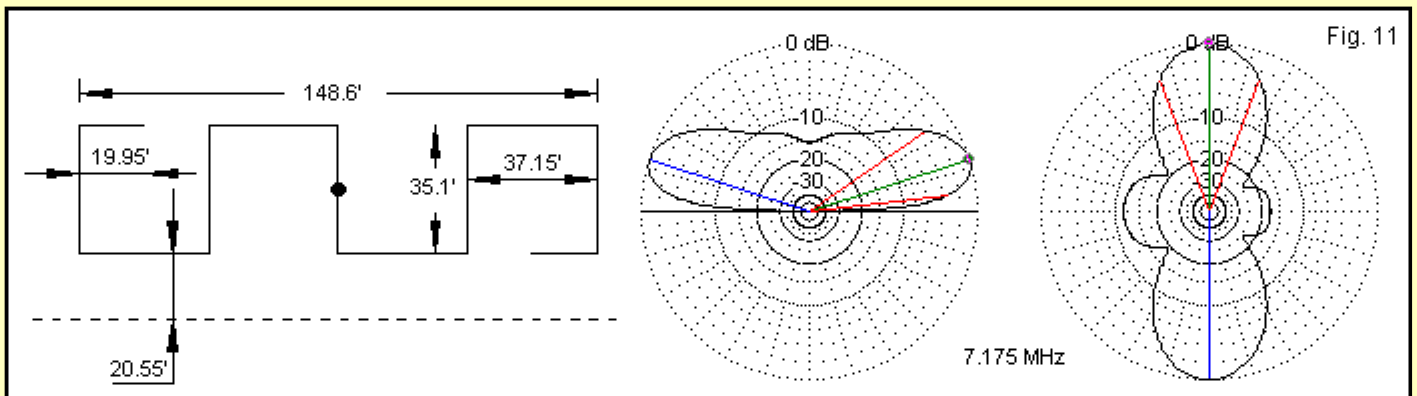
Table 4. Modeled 40-meter performance of two versions of the Bruce array.

Gain dBi	TO Angle	Beamwidth	Feedpoint impedance
5-element array with ends turned inward (See Fig. 11.)			
6.09	18°	41°	295.0 - j0.7 Ω
7-element array with ends turned outward (See Fig. 12.)			
7.36	17°	29°	461.0 - j3.2 Ω

Notes. 1. See notes for Table 1. 2. Arrays use AWG #12 copper wire.

As suggested in **Fig. 11**, a Bruce array consists of a set of parallel vertical dipoles with a vertical height of about ¼ wavelength. The separation between vertical sections is also about ¼ wavelength. Hence, each horizontal wire represents the completion of a vertical dipole. Unlike the half square and the bobtail curtain, the Bruce verticals presume a high current region at the center of the vertical wire sections. Unlike the rectangle, the bottom wire does not return to the position of the top wire, but extends in the opposite direction to connect to the next vertical dipole. The ideal length both vertically and horizontally for wire sections (excluding the shorter end sections) is actually about 1.05 times a quarter wavelength, although the antenna admits of considerable variation. The 5-element version represents an attempt to squeeze out the maximum gain from the number of elements, which required slightly more spacing horizontally and slightly less vertical length. However, the benefits are very small for the exercise.

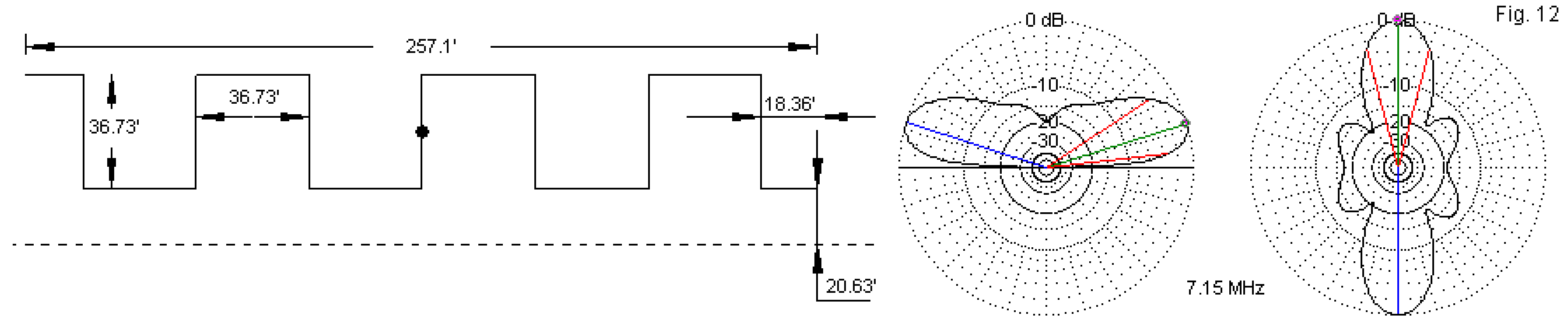
Fig. 11



General Outline and Elevation and Azimuth Plots
5-Element Bruce Array with In-Turned Ends

The most interesting fact about the 5-element version is the inward turn of the end sections. The resulting array is 148' long, only slightly longer than longest of the doubled wire arrays. Using a centered feedpoint on the center wire (other feedpoint positions are possible), the array produces just over 6 dBi gain, close to the maximum that we can encourage from 3 vertical dipoles fed in phase. The modeled feedpoint impedance is close to 300 Ohms, a handy value for available transmission lines. The one major difference from other arrays occurs in the azimuth pattern. It shows uneliminable sidelobes that result from spacing vertical elements at ¼-wavelength intervals. The differential in the sidelobe sizes results from one end section occurring at the array top and the other existing at the array bottom.

Fig. 12



General Outline and Elevation and Azimuth Plots
7-Element Bruce Array with Out-Turned Ends

The alternative form of the Bruce array--shown mostly in college texts such as Kraus' Antennas--points the end sections outward. The seven-element version of the array appears in **Fig. 12** and requires the horizontal span that the inward turn version would need for 8 sections. Using 7 elements allows a central wire for the feedpoint. It uses a more conventional set of element dimensions, with equal vertical and horizontal lengths. Nevertheless, adding 2 more sections has two consequences. First, the impedance is close to 460 Ohms, another convenient impedance for available transmission lines. Second, the larger version shows increased gain over the smaller version. The increase is about 1.25 dB, with a commensurate shrinking of the beamwidth. The progression of gain-vs.-beamwidth ratios provides a glimpse at the original use for curtain-type arrays. In the 1930s, point-to-point communications with specific cities across the ocean comprised a significant set of commercial enterprises. Hence, both Bell Labs and RCA gave high emphasis to more directive wire arrays. Unless one is very favorably positioned between two major target areas 180° apart, it is possible to set up a wire array with too much gain and too little beamwidth. The azimuth pattern for the 7-element Bruce array shows the diminishing beamwidth when compared to other azimuth patterns in the series.

An Interim Conclusion

We have not examined every vertically polarized wire array that we might use on 40 meters, indeed, not even every wire array based on the vertical dipole. However, we have subjected enough types to comparable modeling conditions to allow some evaluation of performance potential vs. mechanical requirements for installation. All of our samples except the original full-size vertical dipoles might easily suspend from sturdy ropes between non-conductive 60' end support posts, trees, or even surplus telephone poles. Scaling the arrays to 80/75-meter size would likely require lower bottom wires or elements ends in addition to taller posts. The results would include increased TO angles and slightly lower maximum gain levels. Even so, vertically polarized wire arrays offer a large number of options for bi-directional lower-band antennas.

These notes have omitted the many bi-directional horizontal arrays of use to radio amateurs. I shall partially fill the void next time. In the meantime, be sure to obtain for your library not only a current edition of *The ARRL Antenna Book*, but as well a copy of ON4UN's compendious **Low-Band DXing**.

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