Do I Need More Gain?

L. B. Cebik, W4RNL (SK)

On 2 meters, we find both horizontally polarized and vertically polarized antennas in keeping with the 2 main activity clusters on that band. At the lower end of the band, point-to-point communication dominates, along with some E-M-E reflected-wave communication. In the main, these activities use horizontal polarization. In the upper part of the band, repeater and related mobile activities dominate, with a reliance on vertically polarized antennas. Near the middle of the band, we find a narrow frequency spread used for satellite communications. The variety of antennas used for this service tends to be a mixture, with some circularly polarized antennas. Similar patterns apply to most of the amateur VHF and UHF bands.

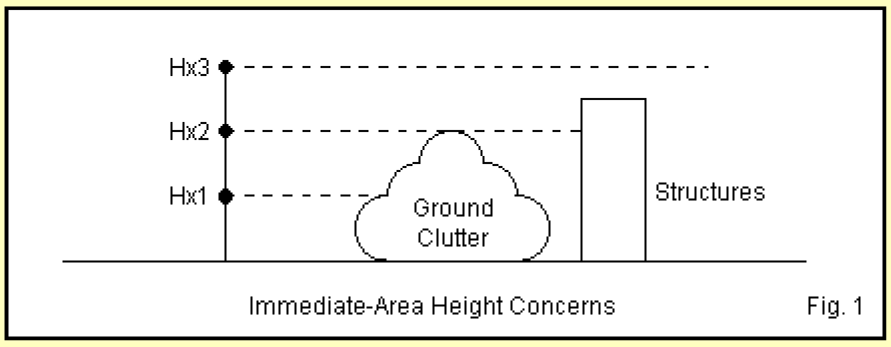
Unfortunately, many amateurs carry over HF antenna experiences into the VHF and UHF bands. Hence, there seems to be only one question that dominates poor results with an existing antenna: how do I obtain more gain? Longer Yagis and exotic antennas come to mind as the sure fire answers to all inadequate communications problems. (We shall bypass the "more power" answer to the same question.)

For some situations, an antenna with more forward gain might be the answer. But higher gain may not always imply a longer Yagi with more elements. For many cases, the answer to our need for effective communication may lie elsewhere. In these notes, we shall review some information that is readily available but scattered. In the end, we may opt for more antenna gain, but only as a secondary feature of other antenna properties that we too often overlook. We shall confine ourselves to ordinary communication on 2 meters--as a band on which we can focus attention and make comparisons. Extreme terrestrial DX and E-M-E communications will have to be topics for another day.

Height

Sometimes the answer to an antenna problem is not gain but height. There are two immediate clusters of reasons for needing more height.

Local Clutter: Local clutter consists of all objects that may block, absorb, refract, and reflect RF energy so that it cannot reach its target. **Fig. 1** provides a simplified sketch of the situation. Both organic and inorganic structures can get in the way of RF energy that we want to reach a certain station, regardless of whether we are using a vertically or horizontally polarized antenna. Trees and shrubs vary in their energy deflection abilities, depending on local weather, type of flora, and the season. Wet wood is usually more ionized than dry wood. Some species of trees have a higher metallic content than others.



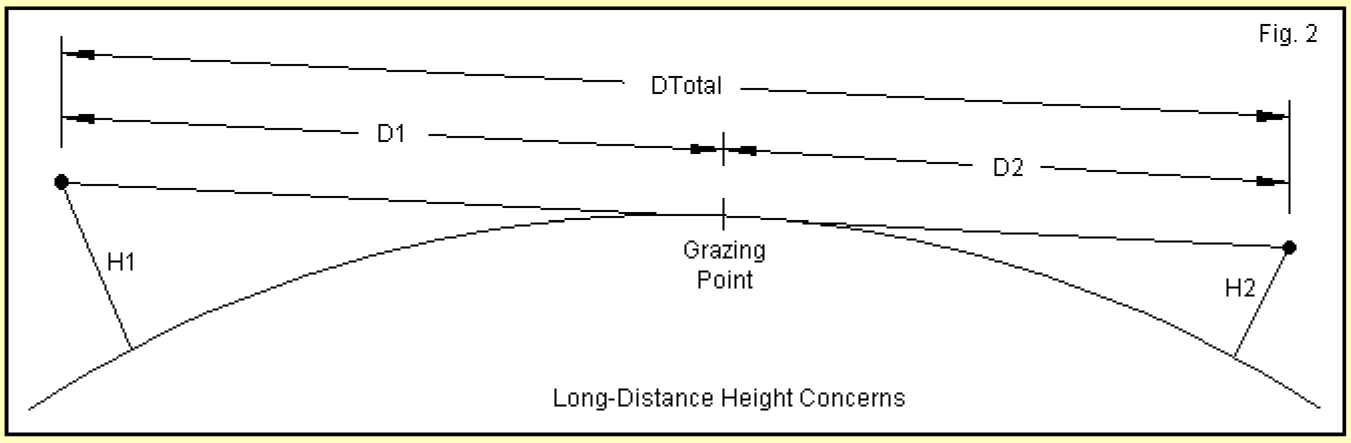
Immediate-Area Height Concerns Fig. 1

The more modern a human-built structure, the more likely it is to have more metal that can block our communications attempts. On old Victorian mansion might have a single AC circuit and wires in the floor of the upper story. A modern house has computer, telephone, TV, and other cables adding to extensive house wiring that likely comes down the walls from an attic area. As well, foil-lined attic insulation is common. Finally, structural steel is working its way into the modern home, not only as support beams, but also as a replacement for the traditional 2-by-4. We do not have to move to a high-rise apartment structure to be surrounded by metal.

In these kinds of situations, raw antenna gain may not help us much at all. As the figure suggests, we need to place our antenna above the clutter. If the clutter is at a moderate distance from our antenna location, we can sometimes move the antenna site laterally to clear most of the problematical signal deflections. However, in most cases, nothing succeeds like height. We shall return to the local-area height question, but first, we should note the second category of concerns.

The Horizon: How close the radio horizon is to us often surprises newer VHF and UHF operators. Since VHF and UHF communication normally is line of sight (and just a little more), the height of the antennas at both ends of the line determines how far apart we may be and still effectively communicate. **Fig. 2** shows the most basic outline of the situation.

Fig. 2



Long-Distance Height Concerns

If the 2 antennas have different heights, each will have a different distance to the grazing point, that is, the point at which the RF energy encounters the ground. We can estimate either D1 or D2 from a standard equation (shown in *The ARRL Antenna Book*, 20th Ed., p. 23-6).

$$D_{mi} = 1.415\sqrt{H_{ft}}$$

The equation shown is actually a short form of a slightly more complex equation, a version of which appears in *Reference Data for Engineers*, 8th Ed., p.33-14.

$$D_{mi} = \sqrt{1.5\,K H_{ft}}$$

The equations are easily converted from miles of distance and feet of height to kilometers and meters. However, let's look more closely at the new element in the second version of the equation. K is the effective earth radius. The value is about 1.333 for the temperate latitudes, but may vary from 0.6 to 5.0 depending on where in the world we may be. The simplified equation produces accurate results only for the latitudes in which the value of K is 4/3.

We may easily turn the equation around to see how high an antenna must be for a given distance to the radio horizon.

Lest we think that achieving a significantly greater distance to the radio horizon is a linear matter of raising the antenna by so many feet, notice the fact that the equation uses the square root of height in finding the distance. Doubling the antenna height will only increase the distance to the radio horizon by a factor of 1.4. **Table 1** correlates some common antenna heights and the distance to the radio horizon.

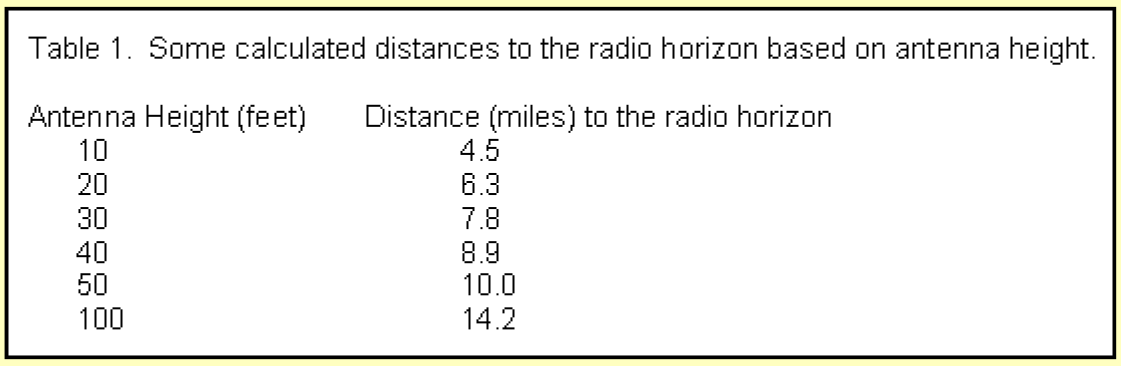


Table 1. Some calculated distances to the radio horizon based on antenna height.

Antenna Height (feet)	Distance (miles) to the radio horizon
10	4.5
20	6.3
30	7.8
40	8.9
50	10.0
100	14.2

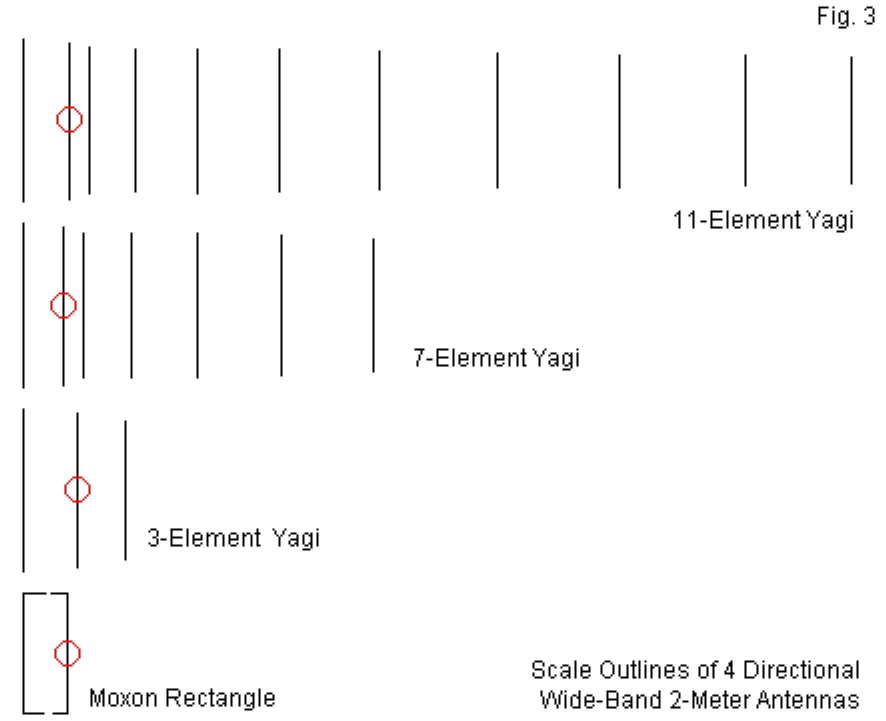
Of course, the distance to the horizon (D1) is not the distance to the most remote distant station that we can contact. That station will also have an antenna height and resulting distance (D2) to its radio horizon. So the actual communications distance is D1 + D2. Atmospheric bending of signals may add perhaps 10% to the raw calculation. However, broadcast antennas (for example, FM or television) usually add a factor to their height plans so that station signals clear the Fresnel zone, the region in which diffraction from objects in the signal path may yield interfering waves. Nevertheless, for point-to-point communications, the average amateur is severely limited in efforts to increase the communications range by adding more tower sections. Little wonder that FM repeater work relies heavily on placing the repeater antennas on the highest tower with space for rent or donation.

In most cases, achieving enough antenna height to clear most local clutter takes precedence over adding to the antenna gain. Only if we can establish at least marginal communications with the desired target station will added antenna gain provide significant signal strength to convert marginal signals into reliable ones.

Gain and Beamwidth

We often overlook an important property of antennas in our quest for maximum gain and front-to-back ratio. Antennas also exhibit a beamwidth that can be very useful to us in obtaining the coverage that we desire and the blocking of signals from undesired directions. We shall deal eventually with all four of the antennas in **Fig. 3**, but initially we shall look most intently at the 3 Yagis in the group. The outlines are to scale. **Table 2** lists the dimensions for the Yagi antennas in inches. The dimensions assume that the beams use either a nonconductive boom or that the elements are well insulated and isolated from a conductive boom. The EZNEC models of these antennas are available from the ARRL web site. The models use a free-space environment and the elements will form a horizontally polarized antenna if we place them over ground. However, you may rotate the elements to create a vertically polarized antenna and adjust the array height as desired.

Fig. 3



Scale Outlines of 4 Directional Wide-Band 2-Meter Antennas

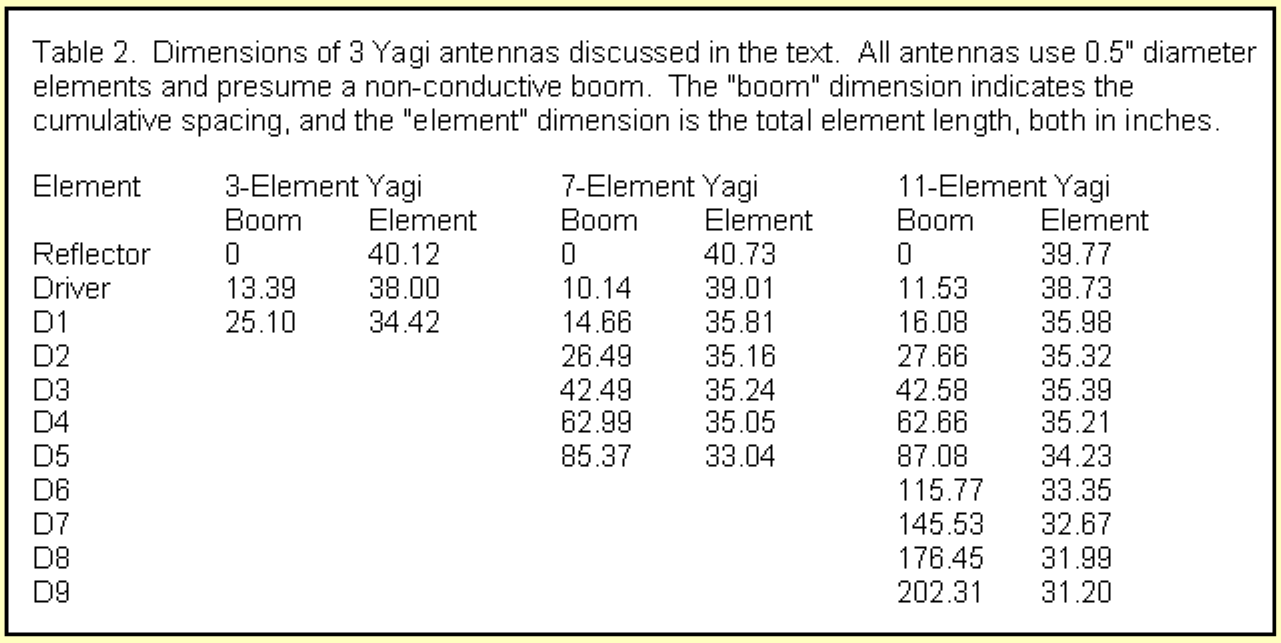


Table 2. Dimensions of 3 Yagi antennas discussed in the text. All antennas use 0.5" diameter elements and presume a non-conductive boom. The "boom" dimension indicates the cumulative spacing, and the "element" dimension is the total element length, both in inches.

Element	3-Element Yagi		7-Element Yagi		11-Element Yagi	
	Boom	Element	Boom	Element	Boom	Element
Reflector	0	40.12	0	40.73	0	39.77
Driver	13.39	38.00	10.14	39.01	11.53	38.73
D1	25.10	34.42	14.66	35.81	16.08	35.98
D2			26.49	35.16	27.66	35.32
D3			42.49	35.24	42.58	35.39
D4			62.99	35.05	62.66	35.21
D5			85.37	33.04	87.08	34.23
D6					115.77	33.35
D7					145.53	32.67
D8					176.45	31.99
D9					202.31	31.20

All three Yagis are credible performers for their boomlengths and number of elements, and all use ½" diameter elements for uniformity. I have selected Yagis that cover the entire 2-meter band so the comparisons are fair throughout. The change of gain across the band is minimized, and the front-to-back ratio is at least 20 dB for all models at all frequencies sampled. The two larger Yagis have feedpoint impedance values very close to 50 O. The 3-element version has a natural driver resonance between 25 and 30 O. The model uses a ¼-wavelength matching section to bring the model source impedance above 40 O at the design frequency (146 MHz). The 36-O transmission line can be composed of parallel sections of 72-O coax cable. Should you wish actually to construction the antenna, you may also shorten the driver and add a beta (hairpin) matching component. In all cases, the beams cover the band with under 2:1 50-O SWR. **Table 3** lists the modeled performance of the Yagis at 144, 146, and 148 MHz in free space to provide some fundamental data.

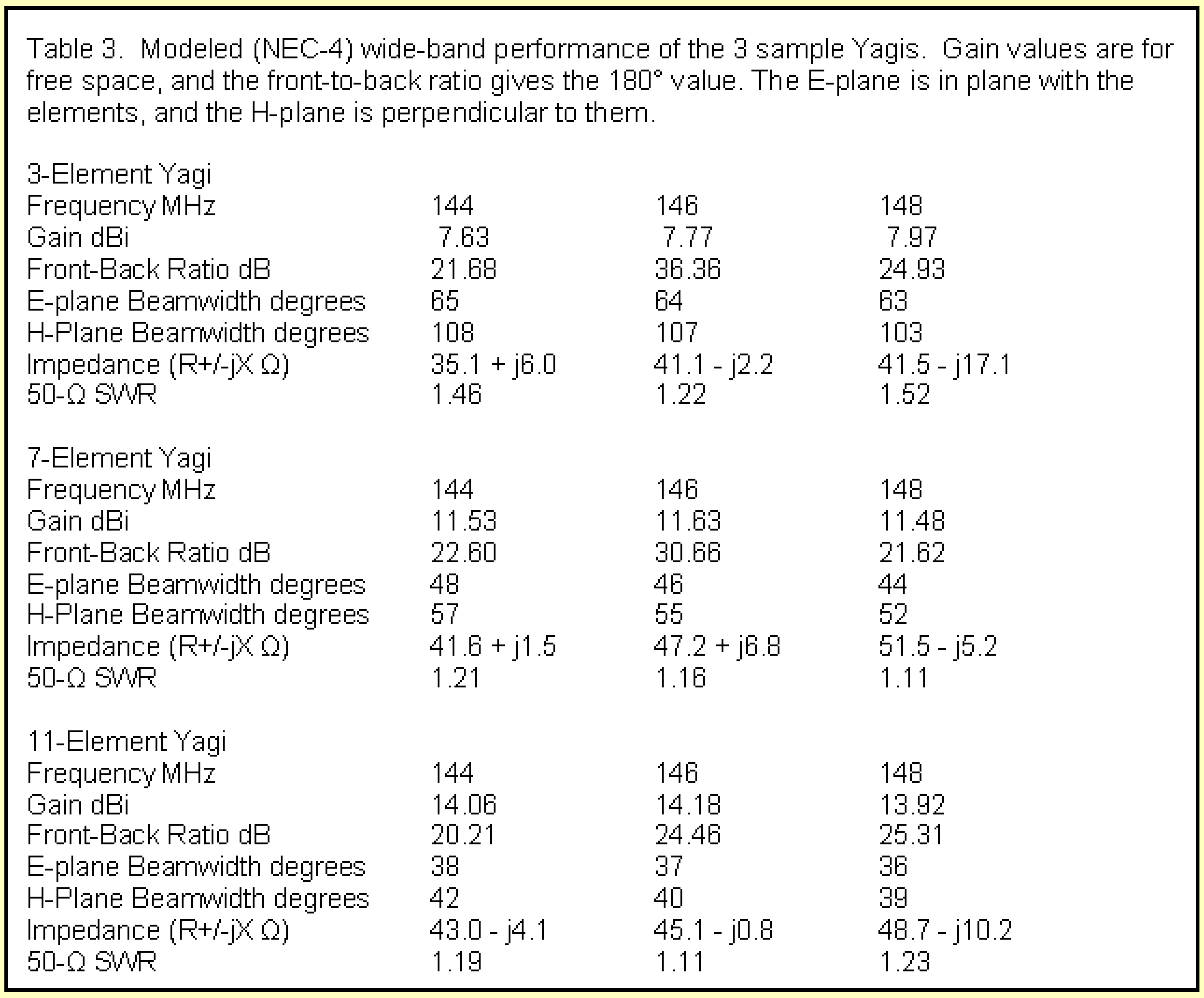


Table 3. Modeled (NEC-4) wide-band performance of the 3 sample Yagis. Gain values are for free space, and the front-to-back ratio gives the 180° value. The E-plane is in plane with the elements, and the H-plane is perpendicular to them.

3-Element Yagi			
Frequency MHz	144	146	148
Gain dBi	7.63	7.77	7.97
Front-Back Ratio dB	21.68	36.36	24.93
E-plane Beamwidth degrees	65	64	63
H-Plane Beamwidth degrees	108	107	103
Impedance (R+/-jX Ω)	35.1 + j6.0	41.1 - j2.2	41.5 - j17.1
50-Ω SWR	1.46	1.22	1.52
7-Element Yagi			
Frequency MHz	144	146	148
Gain dBi	11.53	11.63	11.48
Front-Back Ratio dB	22.60	30.66	21.62
E-plane Beamwidth degrees	48	46	44
H-Plane Beamwidth degrees	57	55	52
Impedance (R+/-jX Ω)	41.6 + j1.5	47.2 + j6.8	51.5 - j5.2
50-Ω SWR	1.21	1.16	1.11
11-Element Yagi			
Frequency MHz	144	146	148
Gain dBi	14.06	14.18	13.92
Front-Back Ratio dB	20.21	24.46	25.31
E-plane Beamwidth degrees	38	37	36
H-Plane Beamwidth degrees	42	40	39
Impedance (R+/-jX Ω)	43.0 - j4.1	45.1 - j0.8	48.7 - j10.2
50-Ω SWR	1.19	1.11	1.23

We should first review some common information about Yagis with different lengths. The most significant physical fact is that the boomlength tends to increase faster than the element count. The 7-element Yagi has 2.3 times the number of elements as the 3-element Yagi, but the boom is 3.4 times longer. The 11-element Yagi has 3.7 times the elements of the 3-element Yagi, but on a boom 8.1 times longer. Gain does not keep pace with the increases in either the element count or boomlength. Moving from 3 to 7 elements nets us a 3.9-dB gain increase, but adding a similar number of elements to wind up with 11 nets us only about 2.6-dB additional gain.

Next, let's examine some data that many VHF Yagi users overlook. The data tables include the E-plane and H-plane beamwidth values, that is the number of degrees between the half-power points on the radiation pattern. The E-plane beamwidth is very close to what we would obtain operating the beam horizontally over the ground, while the H-plane value is close to what we can expect for beamwidth when operating the antenna vertically over ground.

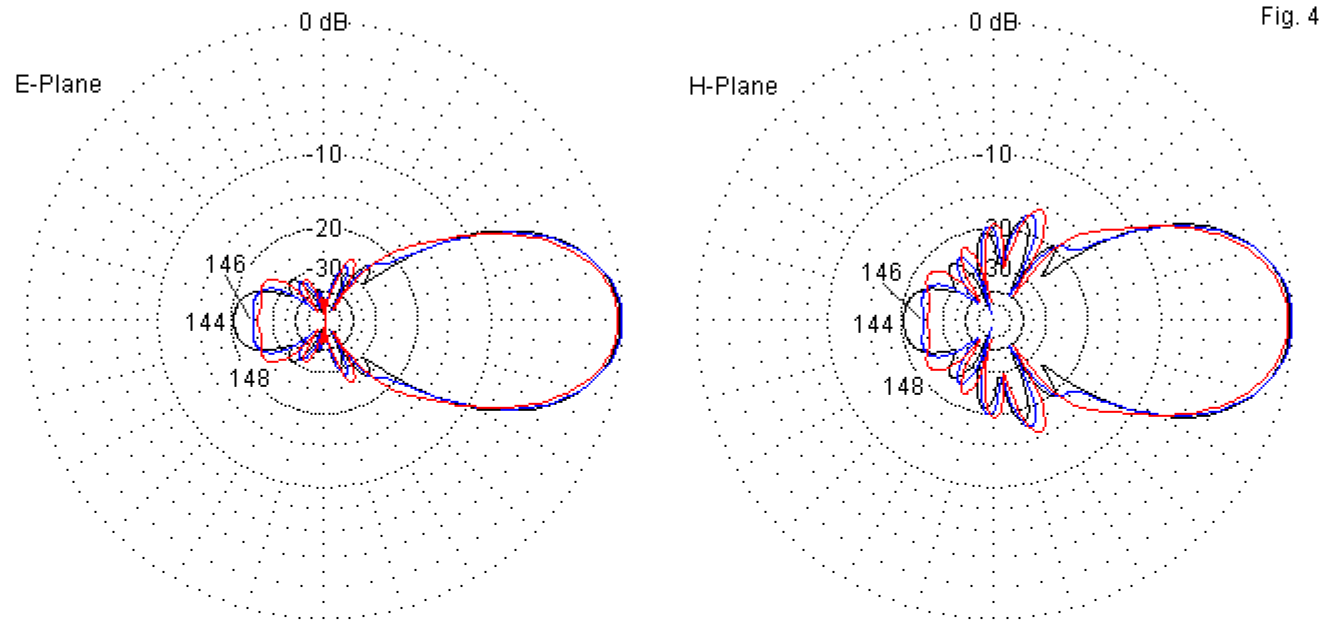


Fig. 4

Free-Space E-Plane and H-Plane Patterns: 11-Element Yagi: 144-146-148 MHz

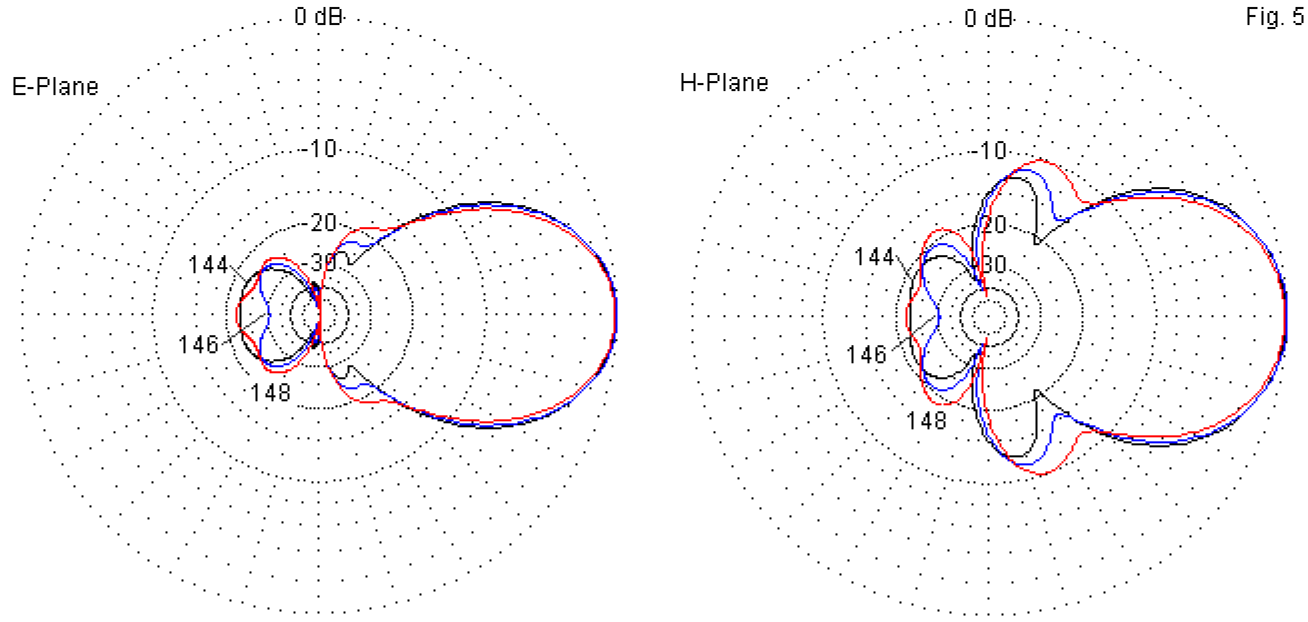


Fig. 5

Free-Space E-Plane and H-Plane Patterns: 7-Element Yagi: 144-146-148 MHz

If we begin with the 11-element Yagi, shown in **Fig. 4** for all three sampled frequencies in both planes, we find no great difference between the E-plane and H-plane beamwidth values--about 3°. However, if we shorten the beam to 7 elements, as shown in the overlaid patterns of **Fig. 5**, the beamwidth difference grows to 9°. When we clip 4 more elements from the Yagi, as in the patterns in **Fig. 6**, the difference between the E-plane and H-plane beamwidth values climbs to about 43°.

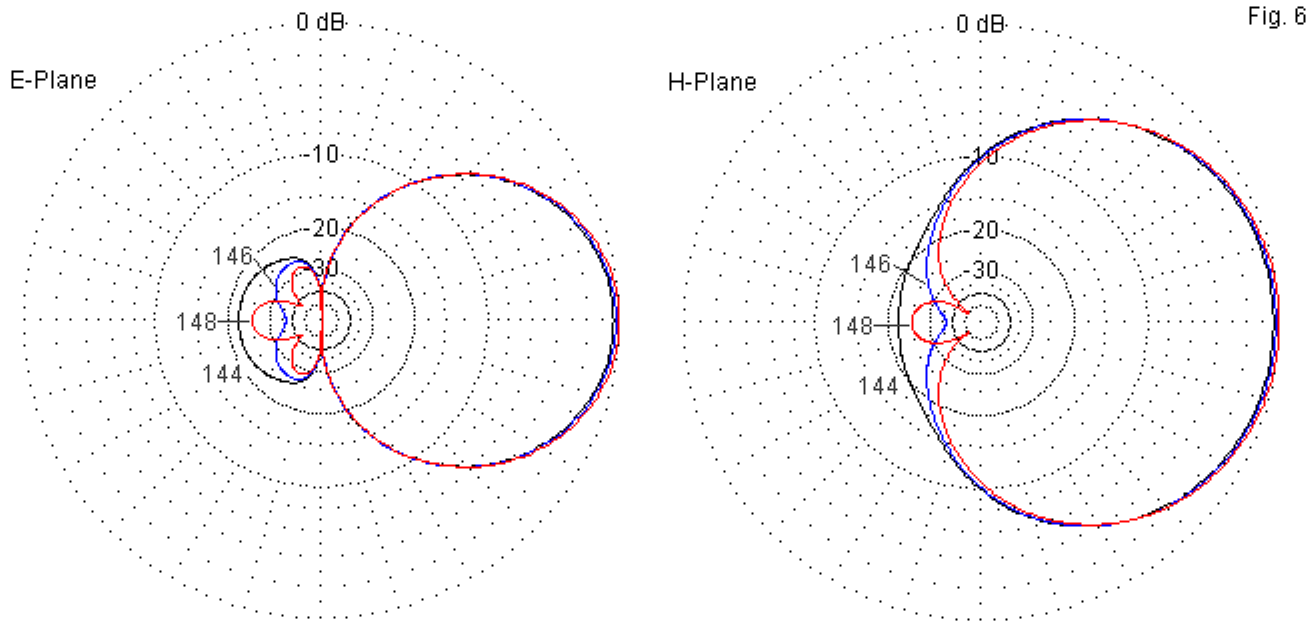
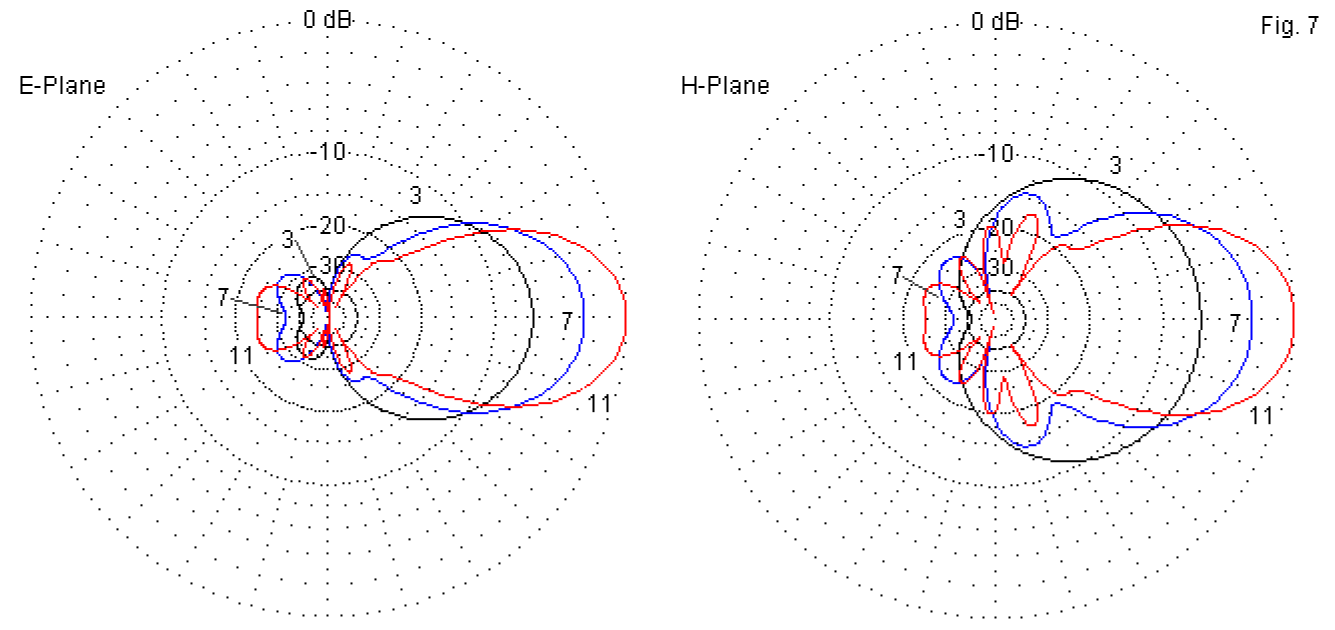


Fig. 6

Free-Space E-Plane and H-Plane Patterns: 3-Element Yagi: 144-146-148 MHz

Fig. 7



Free-Space E-Plane and H-Plane Patterns: 3-7-11-Element Yagis: 146 MHz

To make the information even more graphic, **Fig. 7** overlays all 3 beam patterns in each plane for 146 MHz. The E-plane patterns show the gain increases with boomlength. However, the beamwidth decreases by only 27° as we move from 3 to 11 elements. In the H-plane, the differential in beamwidth values is 67°. When using the Yagis over ground in the horizontal position, the change in beamwidth usually signals only greater ease or difficulty in aiming a rotatable installation. In contrast, the much larger change in beamwidth presents us with some interesting potentials for vertically oriented Yagis over ground, even if we create a fixed installation.

Table 4. Dimensions of a 2-meter Moxon rectangle using ¼" diameter elements. See text for an explanation of the dimension letter designations. Dimensions are in inches.

Dimension	Length
A	28.98
B	3.71
C	1.48
D	5.60

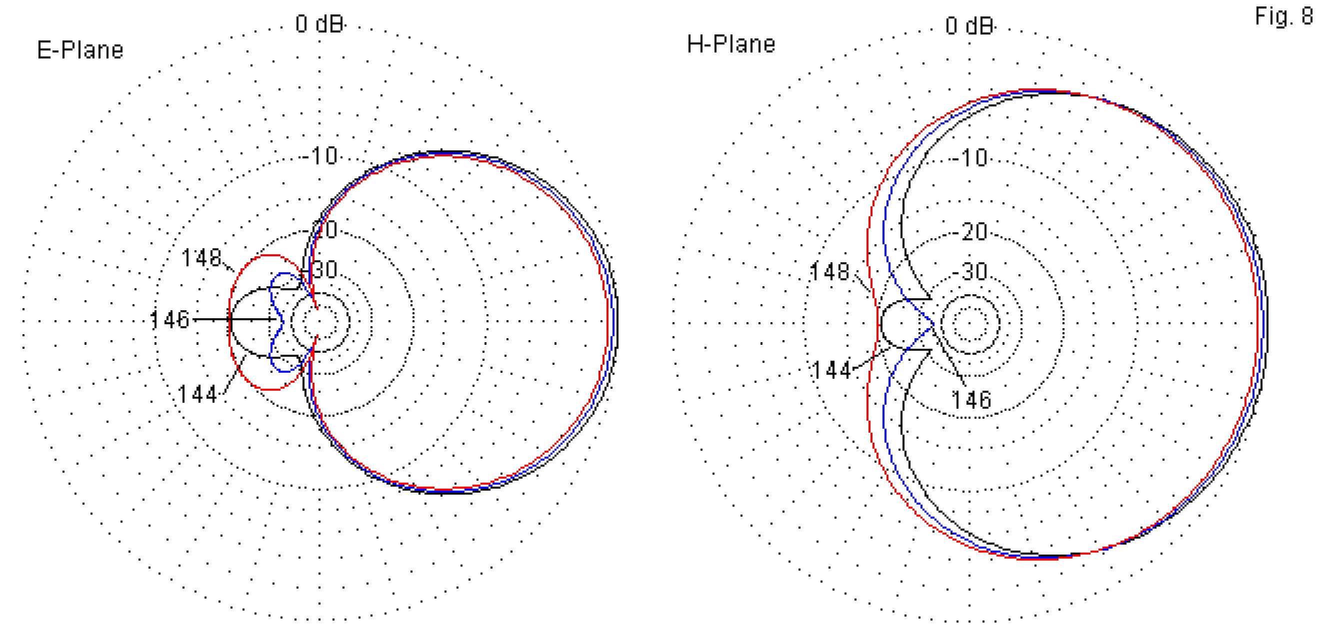
Before we explore that potential, let's add one more beam to the collection, the Moxon rectangle. This compact 2-element array has some interesting properties in conjunction with the Yagis in our collection. **Table 4** lists the dimensions, with reference back to **Fig. 3**, which shows the outline of the beam. Dimension A represents the two parallel long element sections. B is the driver tail length, while D is the reflector tail, where "tail indicates the portion of the elements that point toward each other. Dimension C is the gap between tails. The sample Moxon uses ¼" diameter elements.

Table 5. Modeled (NEC-4) wide-band performance of the Moxon rectangle. Gain values are for free space, and the front-to-back ratio gives the 180° value. The E-plane is in plane with the elements, and the H-plane is perpendicular to them.

Frequency MHz	144	146	148
Gain dBi	6.26	5.94	5.64
Front-Back Ratio dB	20.54	35.18	19.55
E-plane Beamwidth degrees	78	79	79
H-Plane Beamwidth degrees	134	144	153
Impedance (R+/-jX Ω)	41.9 - j11.6	53.2 - j1.7	62.9 + j5.8
50-Ω SWR	1.36	1.07	1.29

Table 5 provides the modeled performance data for the Moxon rectangle. The gain is modest, but the front-to-back ratio is very high for a 2-element wide-band beam. The direct 50-O feedpoint covers the entire 2-meter band easily. More significant perhaps are the patterns in **Fig. 8**. The E-plane beamwidth is 79° at mid-band, about 13° wider than for the 3-element Yagi. However, the greatest growth in beamwidth occurs in the H-plane pattern, which is 34° wider than the corresponding 3-element Yagi pattern. The cardioidal pattern provides a 144° beamwidth at 146 MHz.

Fig. 8



Free-Space E-Plane and H-Plane Patterns: Moxon Rectangle: 144-146-148 MHz

Where we do not require much gain, the Moxon rectangle provides some very promising potentials. Horizontally, the antenna makes a good field unit that we might hand-steer without much difficulty. However, the final promise for the antenna may well lie in its service as a fixed vertically polarized antenna for certain types of home-station repeater operations.

Beamwidth as a Primary Property

At many locations, omni-directional antennas for repeater operations may be the wrong choice. **Fig. 9** presents only two such scenarios. The left portion of the figure shows a situation in which there may be a repeater station to the east that either causes interference or which we simply do not wish to access while working with one or more of the repeaters to the west. The situation calls for a directional antenna with a reasonably good front-to-back ratio to reduce signals to and from the east. At the same time, the beamwidth of the antenna should be wide enough to permit contact with the entire set of repeater stations to the west.

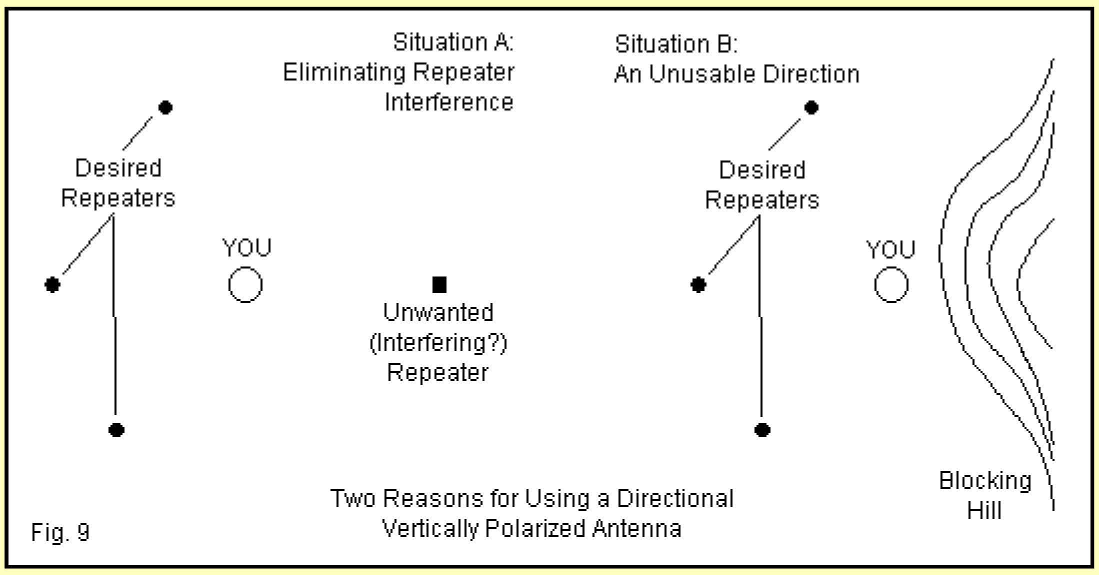


Fig. 9

Two Reasons for Using a Directional Vertically Polarized Antenna

On the right, we have a hill or other major terrain obstruction that prevents operation to the east. In this case, we might use an omni-directional antenna. However, such an antenna will provide lower gain. As well, reflections from the hill may create interference patterns. The use of a directional antenna with the proper pattern shape would permit us to control the reflections in a useful way.

4 Repeater Scenarios: 4 Antenna Solutions

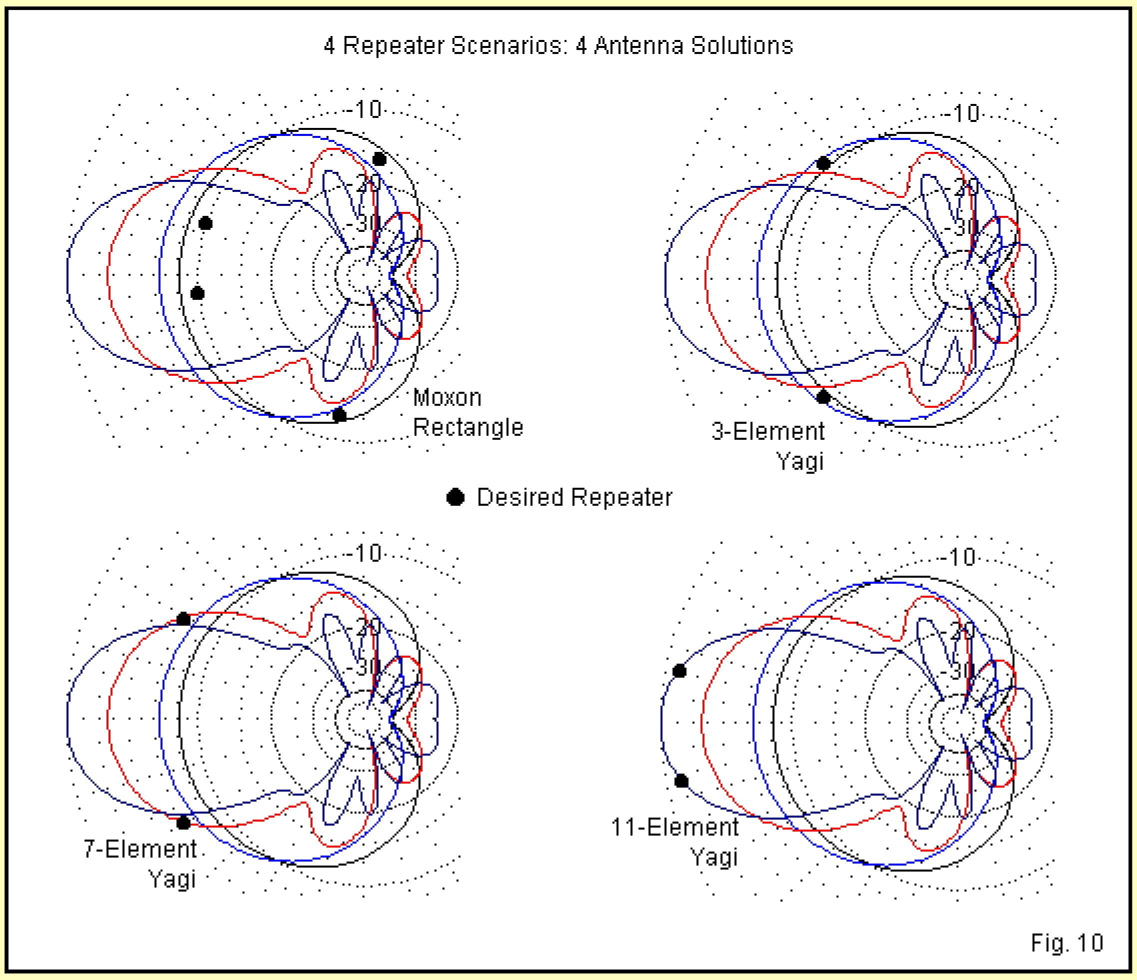


Fig. 10

We have surveyed 4 different antennas in terms of the H-plane beamwidth. Which one will serve best in a given application depends on the operational needs. **Fig. 10** presents overlaid H-plane patterns for all 4 antennas at 146 MHz. There are 4 different sets of needs indicated by the dots or locations of the desired repeater stations. (Note that, although I am working in terms of repeaters, any vertically polarized station within the active field may be included.)

The upper left situation shows 4 widely spaced stations, two of which fall outside the beamwidth of any of the Yagis. If gain is not a major consideration, then the Moxon rectangle may best fulfill this need. Indeed, one need not use this antenna design only when there is a need for a very wide beamwidth. The upper right portion suggests a situation calling for somewhat more gain but a lesser demand on beamwidth. Hence, the 3-element Yagi may be the antenna of choice. The two lower scenes present calls for still higher gain and decreasing beamwidth requirements. The 7- or 11-element Yagis may best fill these roles.

The lessons from this exercise are two. First, for any proposed antenna, we should understand not only the potentials for gain and front-to-back ratio. We should also understand both the E-plane and H-plane beamwidths. Second, once we understand the beamwidth capabilities of antennas, we may select one that will provide us with designer-coverage for a given communications situation. In many cases, we may avoid the expense and maintenance worries of using a rotator by selecting the right antenna for the desired field of coverage.

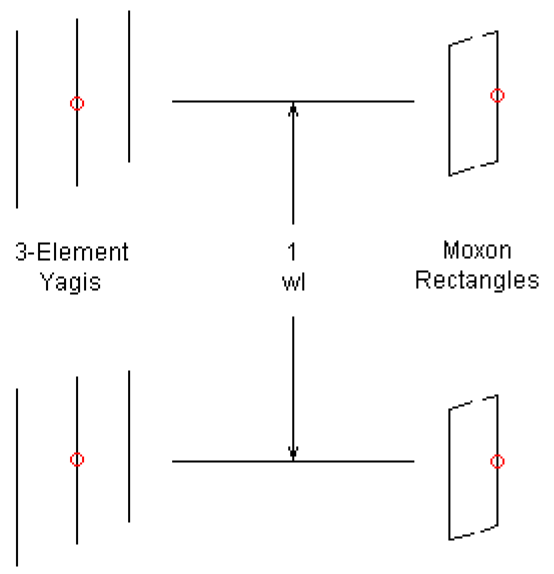
More Gain, Same Beamwidth

So far, we have resolved antenna issues by relying on antenna properties other than forward gain. There may be cases in which we need height, beamwidth, and additional gain. As we saw in comparing the Yagis, the higher the gain potential, the narrower the beamwidth. Suppose we need to meet the demands of one of the top two scenes in **Fig. 10**, but with more gain than we can obtain from a single Moxon rectangle or 3-element Yagi.

The answer does not lie in making a longer Yagi. For every increment of boomlength that we add, we lose a proportional amount of beamwidth. For vertically polarized Yagis, the rate of decreasing beamwidth is greater than for horizontally polarized Yagis. Of course, we can accept the narrower beamwidth and resort to the rotator. However, we should first explore a strategy that allows us to enjoy the simplicity of a fixed installation.

One effective strategy is to use a 2-stack of whichever antenna we select. The mechanical trade-offs between a longer-boom Yagis with 3-dB higher gain and a stack of 2 shorter Yagis are about even at 2-meters and above. To create a stack, we shall have to extend the mast by about 7' (1 wavelength), but the individual antennas will place less stress on the mast than a single Yagi with a boom perhaps 3 times as long. Since we would have to rotate the longer Yagi to cover the same field, let's try the stacking route.

Fig. 11



Outlines of Vertical 2-Stacks of 3-Element Yagis and Moxon Rectangles

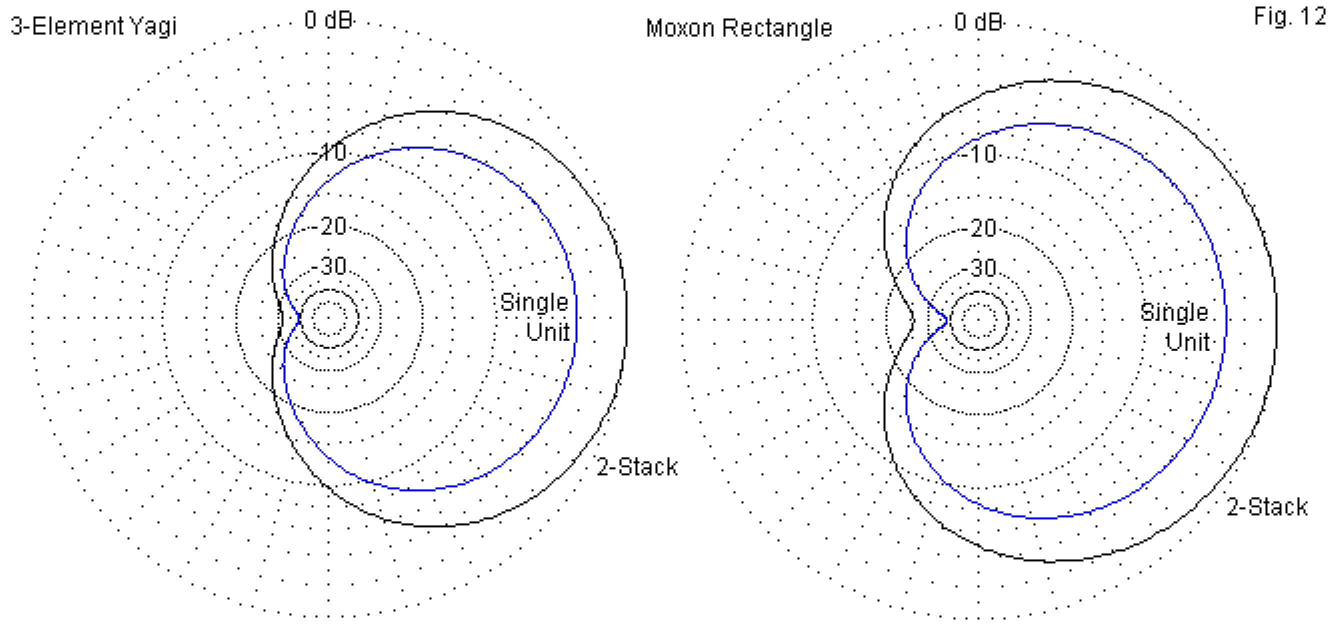
A good separation between vertically polarized stacked beams is about 1 wavelength, center-to-center (or, for reference, feedpoint-to-feedpoint), as shown in the outlines in **Fig. 11**. Since all of the feedpoint impedances are 50 O, you may use a pair of 75-O cables, one from each feedpoint to the midpoint between them. Each line should be an odd multiple of ¼ wavelength at about 146 MHz (taking the velocity factor of the line into account). The two resulting 100-O impedances in parallel match the main 50-O cable. Other schemes are possible, but this one is time-tested. Phase-line losses require the use of the best quality coax that you can afford.

Table 6. Comparative performance at 146 MHz of a single unit and of a 2-stack, using vertically polarized 3-element Yagis and 2-element Moxon rectangles. 2-stacks are separated by 1λ center-to-center. Base height is 20', with the second antenna 7' higher.

3-Element Yagi	Single Unit	2-Stack
Gain dBi	11.46	14.64
TO angle degrees	4.2°	3.6°
Front-Back Ratio dB	36.04	31.63
H-Plane Beamwidth degrees	107°	108°
Impedance (R+/-jX Ω)	41.1 - j2.2	40.8 - j3.2 (x2)
Moxon Rectangle	Single Unit	2-Stack
Gain dBi	9.64	12.90
TO angle degrees	4.3°	3.7°
Front-Back Ratio dB	34.58	25.90
H-Plane Beamwidth degrees	144°	147°
Impedance (R+/-jX Ω)	53.3 - j1.6	54.5 - j3.5 (x2)

Table 6 provides comparative information on the modeled performance of the two types of antennas, with information on single-unit and 2-stack versions. With a 1-wavelength separation between the two antennas in each stack, we net about 3.2-dB of added gain over single-units at the lower height. As well, the 2-stack has a slightly lower TO angle, and that fact has positive implications for point-to-point use of the array. The antennas are each far enough above ground and far enough apart that the feedpoint impedance values for the 2-stack do not significantly change relative to the impedance of a single unit.

Fig. 12



Single-Unit and 2-Stack Azimuth Patterns at a 20' Base Height Vertically Polarized 3-Element Yagi and Moxon Rectangle

For the present discussion, perhaps the most important fact is that neither beam loses any horizontal beamwidth when placed in the 2-stack just described. **Fig. 12** compares the single-unit and 2-stack azimuth patterns for each antenna type. 2-stack gain in each case marks the outer limit of the patterns. Hence, the Yagi may give the illusion of showing a pattern that is smaller in area. However, the real difference lies in the narrower beamwidth for the higher-gain Yagi, relative to the Moxon rectangle.

Our exercise presumed that we needed vertical polarization for the desired communications. It also set up scenarios in which we wanted to null out a general direction and direct our transmitted energy (and our receiving sensitivity) over part or all of the remaining horizon. The techniques that emerged gave priority to the H-plane beamwidth of the antenna candidates in devising a way to meet the need. Gain became a secondary property. Within the limits of the scenario, attaining more gain required methods other than simply making a longer Yagi with more gain.

Conclusions

At VHF and UHF, there are numerous communications activities that call for the highest gain possible. Long-distance point-to-point work may call for stacks and squares of the longest-boom antennas feasible installed as high as possible. E-M-E work may call for similar antennas, but height is less of a problem, since we shall point the antennas upward. Still, the quest for gain rules these activities.

However, we may fail to meet most basic communication needs if we only think of gain, and especially, if we think of gain only in terms of longer Yagis with more elements. The first task is to employ all of the ingenuity at our disposal in raising the antenna above the local ground clutter. The next step is raising the antenna to a height that places our signal above the radio horizon relative to our targets.

As we move into special needs--such as those presented by home-station contacts via repeaters--gain may once more take a back seat to other antenna performance parameters. In the sample case, the horizontal beamwidth of various antennas proved to be more important than raw gain in developing a solution. Even when we needed more gain, a longer antenna was not the best route to achieving it.

These notes are not in any way final answers to the questions that we have explored. Instead, they are initial options designed to expand thinking about point-to-point communications. For example, Yagis and Moxon rectangles are not the only antenna types that might meet our needs. Planar and corner reflector arrays are available and might allow easier construction, especially at 432 and 1296 MHz. Even the broadband batwing dipole array might meet some needs.

The first step in choosing the option that is correct for a given situation is an analysis of the situation itself. The second step is a full understanding of the antenna performance properties relevant to the needs of the situation. The more complete our understanding of available antenna designs, the more likely that we shall be to select a workable option as a solution.

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