Improved Antenna Performance for VHF FM
Some Basics, Some Options, Some Hurdles

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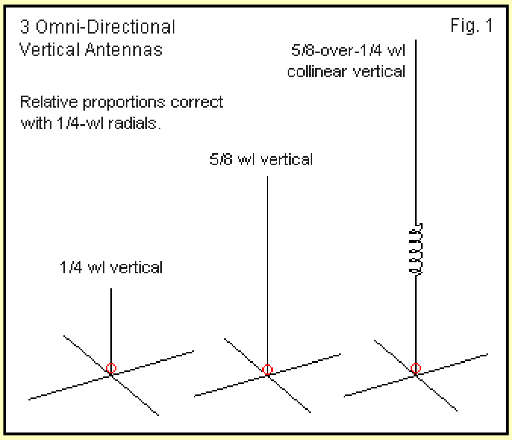
FM operations in the amateur VHF region principally use vertical polarization. The ever-enlarging FM repeater and related simplex operation in the upper 3 MHz of 6 meters and 2 meters has expanded operator goals. Once, amateurs were content to work only local stations and repeaters. However, time has increased the desired repeater range, but with due regard to not causing interference to repeaters operating on the same frequency pair or an adjacent pair. The solution has been less a matter of increased power--since that one factor does not help reception. Instead, the solution has been the use of better antennas. Rubber duckies and other simple antennas will always have a place on handheld units, but home stations require something better.

Let's look at a few options for better antenna systems for FM operations, beginning with some basic antennas and their limitations. Next, let's turn to ways in which we can increase gain and directivity to obtain full coverage of the horizon. Along the way, we shall examine some of the practical hurdles that we must overcome to achieve the goal.

Since we shall examine several different antenna options, let's place everything on a relatively level playing field. We shall use 6 meters--specifically, 51 to 54 MHz--for a band on which to do our sampling. Although we might place an antenna at virtually any height--the higher the better--let's limit ourselves to 1 wavelength. At 52 MHz, a wavelength is about 225" above ground. When we deal with a vertical antenna, its base, feedpoint, and ground plane radials will be at the 225" level. When we deal with vertically polarized directional antennas, the boom will be at that height.

Some Basics

FM and repeater operations normally begin with a vertical antenna of some sort. In most cases, operators replace the rubber ducky with a vertical monopole (and sometimes a vertical dipole). **Fig. 1** shows the outlines of three such antennas, ranging from the ubiquitous quarter-wavelength monopole and proceeding to more complex antennas. The 5/8-wavelength monopole is about 2.5 times longer than the quarter-wavelength version. The collinear on the right is only one of many similar phased vertical arrays that use a vertical element structure that does not spread in the X-Y plane.

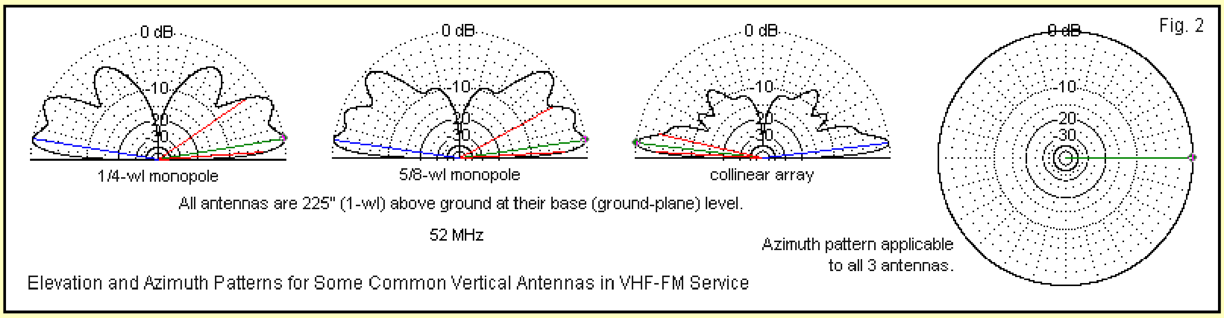


At 52 MHz, a quarter-wavelength monopole is about 57" long--nearly 5'. The longer 5/8-wavelength counterpart is about 142" long or nearly 12'. The collinear array in the illustration uses a 5/8-wavelength section over a 1/4-wavelength section, with an intervening phasing/matching inductor (or transmission line section). The total height is over 230" or about 19' tall. All of these heights are in addition to the 225" (18.75') base height that we stipulated at the beginning. At that height, the 3 antennas provide the performance shown in **Table 1**. Each antenna uses a 4-radial ground plane, and each radial is about 1/4-wavelength long.

Table 1. Relative performance of 3 vertical antennas on 6 meters with a 1-wavelength base height

Antenna	Max. Gain dBi	TO Angle degrees
1/4-wavelength monopole	2.58	9.3
5/8-wavelength monopole	3.44	8.2
5/8-over-1/4 collinear	5.83	7.0

The gain of the antennas increases in small increments as we lengthen the array. The rising height of the maximum current portion of the antenna results in a gradual decrease in the take-off (TO) angle. **Fig. 2** shows the patterns for these three sample vertical antennas.



Elevation and Azimuth Patterns for Some Common Vertical Antennas in VHF-FM Service

At 1-wavelength above ground, we do not obtain the best elevation patterns possible for the two single-element monopoles. There is a higher-angle second lobe with considerable strength but limited utility. The collinear array overcomes this limitation to a considerable degree. However, its length is greater than the supporting mast that we have stipulated for our exercise.

On the far right of **Fig. 2**, we see the azimuth pattern that all of these vertical antennas share: an omni-direction pattern. The advantage of this pattern is that it simplifies the antenna structure. None of the antennas requires a rotator to point the antenna in a desired direction. That very property can be--under some circumstances--a disadvantage. Another repeater or station using the same or a nearby frequency (or frequency pair) may interfere with communications to a desired distant repeater or station, or you may interfere with the operation of that station or repeater. In such cases, a directional antenna is desirable or even necessary.

The moment we think of directional antennas, the Yagi comes to mind. However, a persistent misconception often accompanies the Yagi. Most of the patterns that we see for Yagi antennas are azimuth patterns of the Yagi when it is horizontally oriented. However, FM and repeater services call for vertically oriented antennas. Physically, the change is simple: we simply rotate the antenna 90 degrees around the axis formed by its boom. Unfortunately, many newer amateurs fail also to rotate the pattern.

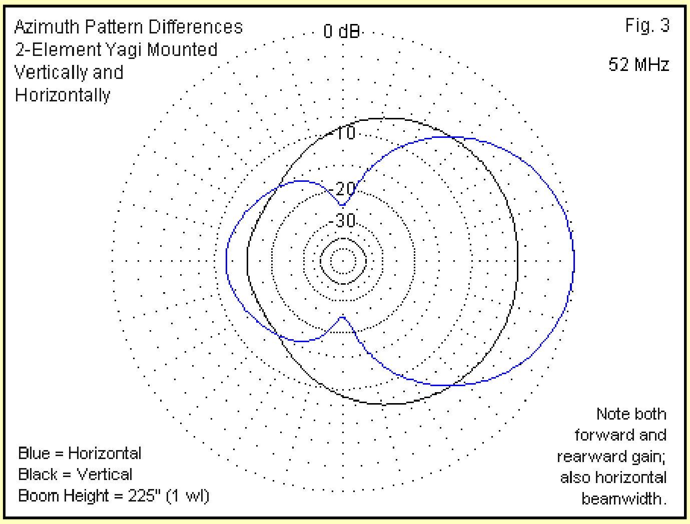


Fig. 3 shows the azimuth patterns of a simple 2-element reflector-driver Yagi for 6 meters. In both cases, the boom is 225" above ground. **Table 2** shows the data that goes with each of the patterns.

Table 2. Performance of a wide-band 2-element reflector-driver Yagi when oriented horizontally and vertically

Orientation	**Max. Gain dBi**	**TO Angle degrees**	**Front-to-Back Ratio dB**	**Beamwidth degrees**
Horizontal	**11.11**	**14**	**11.58**	**72**
Vertical	**6.41**	**10**	**10.28**	**153**

When horizontal, the Yagi shows about 4.5-dB higher gain than when oriented vertically. The difference lies to a considerable degree on the manner in which the ground-reflected radiation adds and subtracts from the direct radiation. Note that the maximum gain of the horizontal version is at 14 degrees elevation, but the vertical version has its maximum gain at only 10 degrees. A second important factor in determining the gain is the beamwidth. The vertical version has more than twice the half-power beamwidth of the horizontal version.

For those unfamiliar with reading radiation patterns, the similarity of the front-to-back ratio numbers may seem initially confusing. The pattern shows a considerable difference in the rearward gain lines. The front-to-back ratio is the difference between the maximum forward gain and the gain 180-degrees opposite. For a difference of 10 to 11 dB, the horizontal forward gain is higher than the vertical forward gain and so the rearward gain of the horizontal version must be similarly higher. Otherwise, the front-to-back ratios would be significantly different from each other.

If we carry in our heads only the pattern of the horizontally oriented Yagi, then the use of a Yagi immediately brings to mind a collection of associated machinery to direct the antenna. Among that gear is a rotator, a control cable, a control box, and some way to mount the rotator to the support mast (or tower). This equipment may cost many times more than the antenna that it turns, especially if we use relatively simple directional antennas. The rotator motor assembly may weigh many times as much as the antenna, sometimes forcing us to use a sturdier central support--for example, a tower instead of a mast. The motor also has moving parts that require periodic preventive maintenance as they undergo alternative periods of baking and freezing.

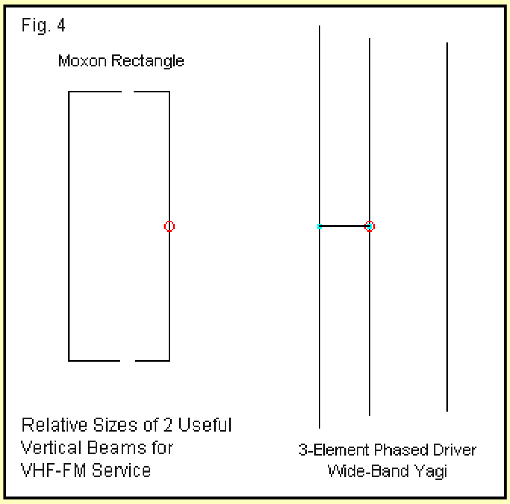
On the other hand, if we stare intently at the radiation pattern for the same antenna when vertically oriented, other options may come to mind. The beamwidth is especially attractive. As we increase the overall boomlength and gain of a Yagi, both the beamwidth values shown for the 2-element antenna will shrink, and as the boom gets very long and the number of elements grows to a high order, the two values will almost (but never quite) come together. The element tips will confine the E-plane beamwidth of the antenna to a slightly tighter value than the flat surfaces that we see when the beam is vertically oriented. Nevertheless, for small, low-gain Yagis and similar arrays, the beamwidth of the vertical version will be much greater than the beamwidth of a corresponding horizontal version. This is a useful property for many installations.

Covering the Horizon with Multiple Vertically Oriented Directional Antennas

One way to cover the horizon with directional antennas without using a rotator is to mount multiple antennas at a given height and to switch from one to the next. This technique is most apt to VHF FM service where we meet several conditions.

- 1. The individual antennas are fairly small and light and therefore do not load the support arms.
- 2. The size of the antennas lets us mount each one a distance away from the central support mast.
- 3. The beamwidth of each antenna is large to reduce the number necessary for full horizon coverage.

One reason for choosing 6 meters as our sampling band is that it falls near the limit of practical construction for such a system. In fact, it will show us some of the limitations and hurdles that we must overcome to put such a system in place. To illustrate the technique, I have selected two small directional beams that might be serviceable on this band. **Fig. 4** shows their outlines and relative sizes.

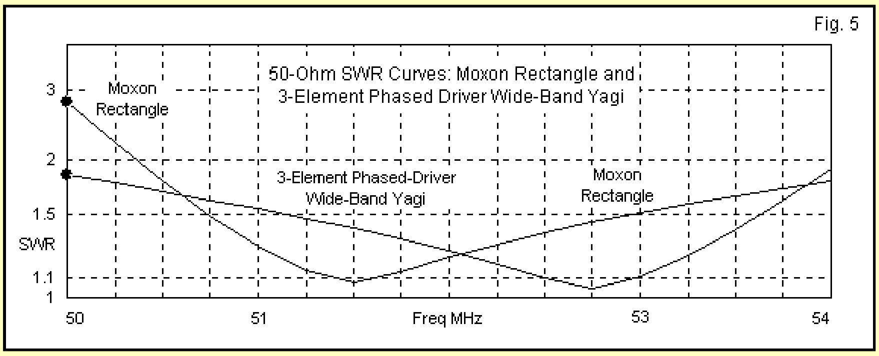


The antenna on the left is a Moxon rectangle, a parasitic 2-element array with a driver and a reflector. The beam to the right is a 3-element Yagi that uses a pair of phased drivers and a director. The driver pair uses a 250-Ohm phase line with a single half twist. Since the elements of the 3-element Yagi do not fold back, the antenna is slightly larger than the Moxon and has slightly more gain. **Table 3** provides some data for 52 MHz for versions of both beams when using 0.5"-diameter elements.

Table 3. Performance of a Moxon rectangle and a wide-band 3-element phased-driver Yagi at 52 MHz at 225" above ground

Antenna	Length inches	Width inches	Max. Gain dBi	TO Angle degrees	Front-to-Back Ratio dB	Beamwidth degrees
Moxon Rectangle	82.3	30.6	6.46	9.8	20.92	151
3-Element Yagi	108.9	34.8	7.65	9.5	20.03	123

Both antennas will provide a 50-Ohm SWR below 2:1 across the 51-54-MHz span for FM operation. However, the two SWR curves, shown in **Fig. 5** have quite different curves. Phased drivers tend to have a more equal growth of SWR above and below the design frequency (or lowest SWR frequency). In contrast, a single driver tends to show more rapid changes in SWR on one or the other side of the design frequency. Hence, the Yagi places its design frequency a little above the band center. In contrast, the Moxon design frequency is below mid-band so that the SWR is acceptable across the desired spectrum, even though it rises rapidly toward 50.0 MHz.



Each antenna uses a single parasitic element. The Moxon uses a reflector. Therefore, its gain decreases as the operating frequency increases. The 3-element Yagi uses a director, so its gain increases as the operating frequency increases. (Standard design Yagis using both a reflector and one or more directors show the rising gain feature, indicating that the directors tend to control the array gain more than the reflector.) **Fig. 6** provides graphical verification of the gain situation for both antennas.

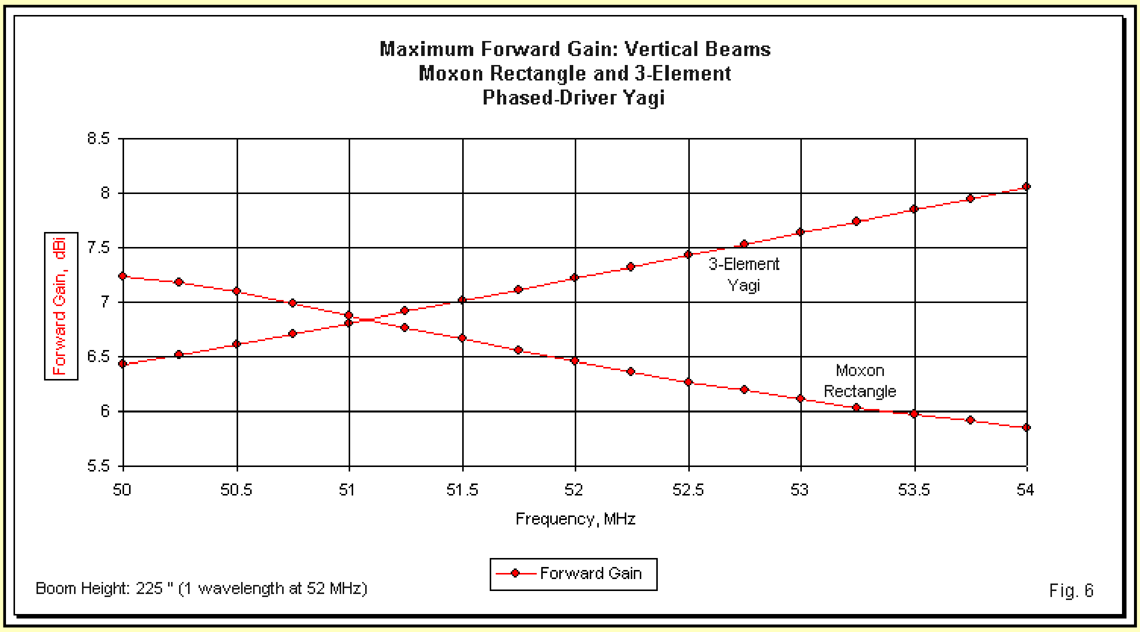


Fig. 6

Before we become too enamored with the rising gain characteristic of the 3-element Yagi, we need to evaluate the antennas in the type of service that we intend. We shall create a symmetrical arrangement of the antennas around and away from a central support mast. The beamwidth of the individual antennas suggests that we only need 3 arrays, equally spaced at 120-degree intervals to cover the horizon. (Of course, we shall switch from one antenna to the next, since operating them all together would give us a single lumpy pattern with no gain advantage over a vertical monopole or dipole. Remember that the goal is to obtain some gain and some directivity, and operating the 3 antennas at the same time would defeat both goals.)

One key question is how far out on a support boom or arm each antenna must be for effective operation. The answer partly depends on the antenna design. However, 1/4-wavelength appears to be an approximate minimum distance. As we shall see, this minimum will not work for every design, but it does give us a starting point. If the antennas are any closer together on shorter arms, the interactions between them can ruin their performance, since they are all the same in any given installation. Hence, they are more susceptible to interaction than antenna designs for different frequency ranges.

1/4-wavelength is nearly 60" (5') on 6 meters. Hence, the support booms must be a total of over 90" for the Moxon and over 95" for the Yagi. 8' booms are equivalent to each half-element of a 10-meter beam, so the project is not implausible by any means. Before we close, we shall look at some construction cautions to observe. If we move the operating frequency to 2 meters or higher, then we can use a separation from the mast that is greater than 1/4 wavelength with virtually no stress on the support arms. The individual antennas are smaller and lighter. We shall also see that some designs require greater spacing from the mast.

The Moxon Rectangle Triangle

Let's create a set of 3 Moxon rectangles at 120-degree intervals, with each Moxon reflector 60" (5') from a central support mast. The top of the mast in the design models is at the boom level (225"). The left side of **Fig. 7** shows the layout of the array.

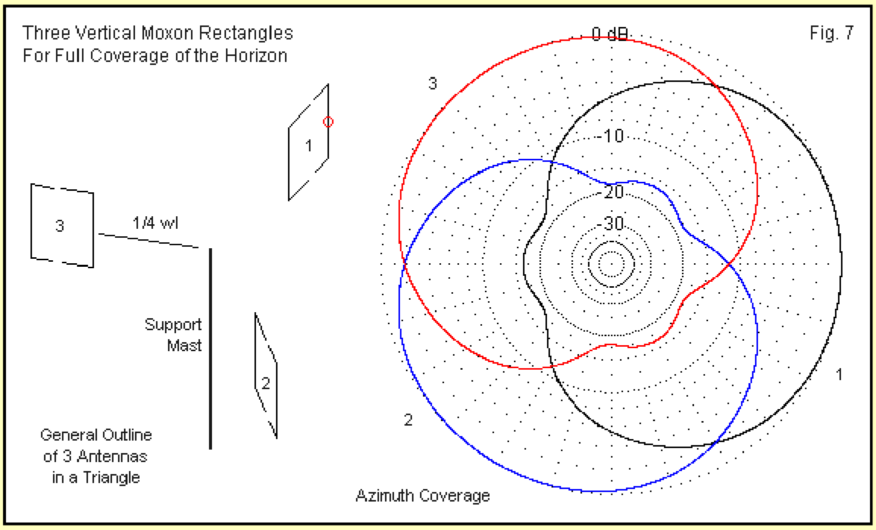


Fig. 7

The right side of **Fig. 7** shows the patterns that result from each antenna in this configuration. The maximum gain of each antenna is about 6.6 dBi. At the points where we switch from one antenna to the next, the drop in gain is under 2 dB. Two data points relative to the system show us that we are using the bare minimum of separation of the antenna from the center point. One feature is the front-to-back ratio. It has dropped from nearly 21 dB down to between 16 and 17 dB. For this type of service, the drop is not serious, but it does indicate that there is still some interaction between the antennas, even when two of the three are unfed. There is a second indicator of interaction among the antennas. The beamwidth has dropped from over 150 degrees down to about 143 degrees. Again, the decrease in beamwidth is not serious enough to defeat the goal of full horizon coverage with acceptable directivity. However, it strongly suggests that where feasible, the individual antennas should be more than 1/4-wavelength away from the centerpoint.

In general, even at 6 meters, a triangle of Moxon rectangles can provide directional coverage of the horizon with a good front-to-back ratio as a safeguard against interference.

The Triangle of 3-Element Phased-Driver Yagis

The Yagi that we have selected for our design test has a beamwidth of 123 degrees when used in isolation, but at the same height as a triangle of beams. We may set up a symmetrical arrangement of 3 such antennas using the same scheme that we used with the Moxon rectangles. The booms are at 225" above ground, and the rear elements are 60" from the center point or support mast. **Fig. 8** shows the general layout in the left portion of the graphic.

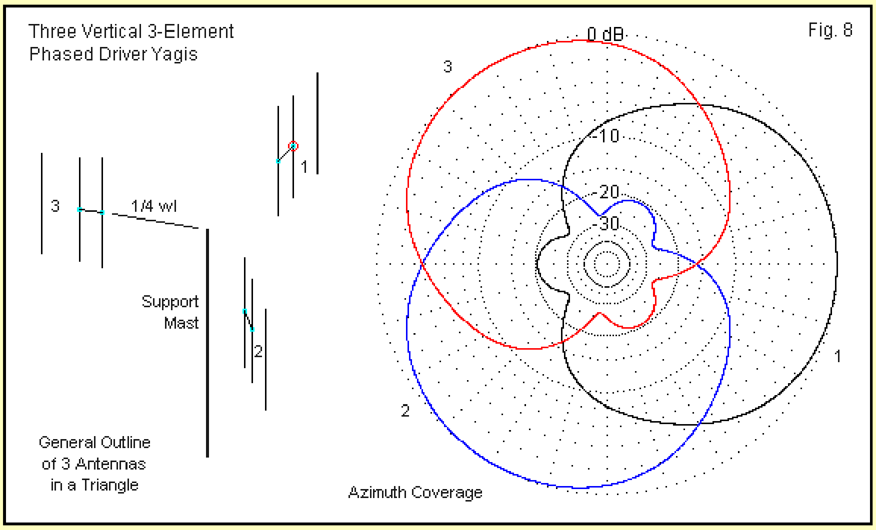


Fig. 8

If we successively feed one Yagi at a time, we obtain the coverage shown by the patterns at the right. The forward gain of each antenna has risen by a small amount to just about 8 dBi. The front-to-back ratio holds at about 20 dB. Hence, we must ask where the extra gain comes from. Part of the answer is a reduction in the beamwidth for each antenna in the array. The beamwidth has decreased from 123 degrees to about 109 degrees. That decrease is sufficient to affect the gain where the patterns overlap. Relative to each antenna's maximum gain, the crossover points show nearly 5 dB lower gain. For some installations, the crossover points may not be significant, especially if they are not directed toward desired communications targets. However, relative to full horizon coverage, the drop is significant.

The Square of 3-Element Phased-Driver Yagis

When the beamwidth is not sufficient to cover an area, we have two choices. One is to extend the antenna support booms and move each antenna further out from the feedpoint. That action is certainly feasible at 2 meters and above. However, let's assume that we have reached our physical limit (60") on 6 meters. The second course of action is to add additional antennas. Some cellular and wireless services use this technique with many high-gain Yagis in the UHF range. We shall be modest and add a single antenna to create a square of 4 Yagis, each 60" from the center point and support mast. The left side of **Fig. 9** shows the revised arrangement.

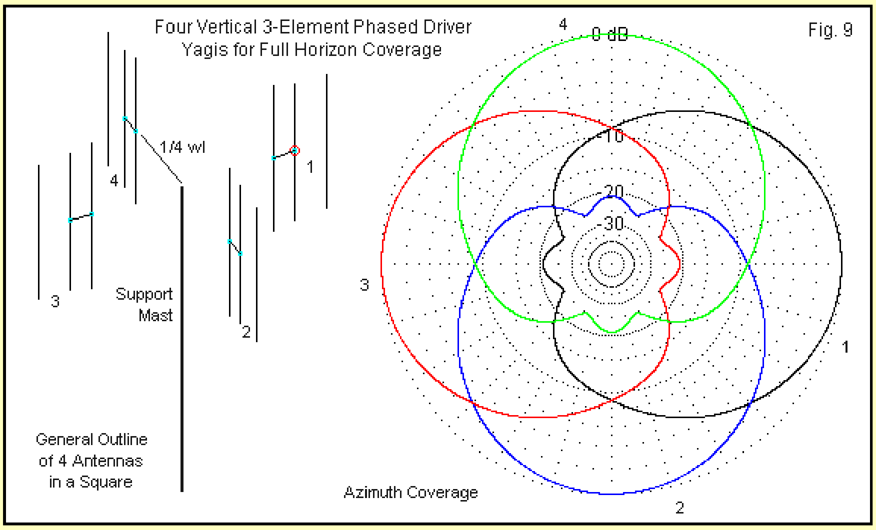


Fig. 9

The front-to-back ratio of the square array holds at just above 20 dB. However, the gain of each antenna has increased by another half-dB. The primary source of the added gain is a further reduction in the beamwidth of each pattern. The beamwidth has dropped to about 95 degrees (down from 109 degrees in the triangle and from 123 degrees for an isolated Yagi of this design). As a result, we do not obtain the seamless coverage of the horizon that we might have expected. Rather, as shown on the right in **Fig. 9**, the cross-over points for the patterns are between 3.5 and 4 dB lower in gain than the maximum forward gain values.

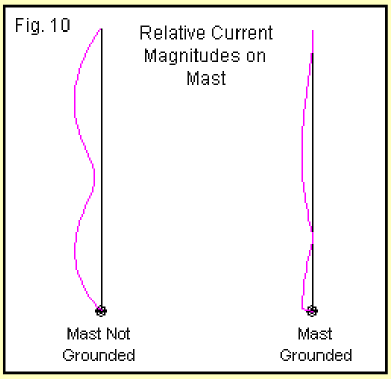
In setting up this exercise, we did not create a limit on the decrease in gain that we would accept for any switched arrangement of vertically oriented antennas. Therefore, we can only note that the crossover gain-decrease for the Yagi square is between the values obtained for the Yagi triangle and for the Moxon rectangles. From the gain increases shown by the Yagis, it is clear that these antennas interact to a greater degree than we found in the Moxon rectangles. One notable feature of the Moxon rectangle is its highly effective reflector. That element limits interaction between a given rectangle and others facing in different directions. In contrast, the rearmost element of the Yagi is one of the drivers. Hence, structures similar to one of the antennas and beside or behind it are likely to serve as distant reflectors and couple with the active antenna. The result is a slight increase in gain and an attendant reduction in beamwidth.

The solution to the problem is to increase the separation of the antennas from each other by increasing the distance from the centerpoint. At higher frequencies, this solution is relatively easy to implement. However, we set that solution aside at 6 meters for an important reason: we needed to see that some antenna designs are inherently more interactive in this type of service than other designs. As a result, the simple "trick" of creating a triangle of antennas to cover the FM and repeater horizon turns out to be somewhat less than an automatic or easy design exercise.

The Question of the Mast

If some antenna designs are more sensitive than others with respect to interactions, we may also be able to detect that sensitivity in terms of the influence of the support mast on the performance of our arrays. Therefore, I simulated three mast conditions. One case uses no mast in the models, which simulates a non-conductive mast. The actual mast need not be totally non-conductive, but might use PVC or similar materials in the top section from the lower tips of the antenna elements upward.

The second and third cases use 1.25"-doameter masts with only one difference between them. In one case, the mast goes all the way to ground. In the other case, the mast terminates 1" above ground to simulate either an insulated base or one that is highly resistive. The important difference between these two cases shows up in **Fig. 10**.



On the two masts, the peak relative current magnitude is less important than the pattern of current distribution. With the mast isolated from ground, and nearly 1 wavelength long, the current shows 2 distinct peaks and three nulls. However, if we ground the mast, one current peak occurs at ground level, reducing the current magnitude at the top of the mast in the vicinity of the antenna elements. The lower current level should show up as a difference in the modification of antenna performance relative to an isolated antenna. In all of the cases that we shall examine, the top of the mast is at boom height, that is, 225" above ground.

The Moxon Rectangle Triangle

We can summarize the relevant information concerning the triangle of Moxon rectangles in tabular form. See **Table 4**.

Table 4. Performance of a Moxon rectangle triangle with and without a center mast.

Antenna/Mast	Max. Gain dBi	TO Angle degrees	Front-to-Back Ratio dB	Beamwidth degrees
Isolated Moxon	6.46	9.8	20.92	151
No or non-conductive mast	6.56	10.3	16.91	143
Grounded mast	6.58	10.1	16.38	143
Ungrounded mast	6.38	10.1	16.84	146

The differences in performance are very small among the options. The similarity in performance of the 3 triangles suggests that the key factor in Moxon triangular performance is the presence of the insert antennas and not the mast. However, the ungrounded mast with a current peak higher up on the mast does appear to be the source of the slightly lower gain and the accompanying increase in beamwidth.

The Triangle of 3-Element Phased-Driver Yagis

The absence of a reflector element in the 3-element phase-fed Yagi might lead us to suspect that we would find greater differentials among the three trial models of a triangle of Yagis. To see if reality matches our suspicions, we may examine the data in **Table 5**.

Table 5. Performance of a triangle of 3-element phase-fed Yagis with and without a center mast.

Antenna/Mast	Max. Gain dBi	TO Angle degrees	Front-to-Back Ratio dB	Beamwidth degrees
Isolated Yagi	7.65	9.5	20.03	123
No or non-conductive mast	8.00	9.8	19.44	105
Grounded mast	7.97	9.8	20.60	109
Ungrounded mast	7.49	9.8	21.63	119

The gain range among the 3 mast scenarios is over 0.5 dB (compared to the 0.2-dB range for the Moxon rectangles). The similarity between the values for a non-conductive mast and for a ground mast is suggestive that the upper grounded-mast current levels are not high enough to seriously change antenna behavior within the triangle of Yagis. However, the ungrounded mast yields a lower gain and a wider beamwidth in noticeable amounts.

The Square of 3-Element Phased-Driver Yagis

Whether the behavior of the Yagi square is similar to the Yagi triangle requires another data table, namely, **Table 6**.

Table 6. Performance of a square of 3-element phase-fed Yagis with and without a center mast.

Antenna/Mast	Max. Gain dBi	TO Angle degrees	Front-to-Back Ratio dB	Beamwidth degrees
Isolated Yagi	7.65	9.5	20.03	123
No or non-conductive mast	8.48	9.6	21.73	95
Grounded mast	8.52	9.6	20.91	95
Ungrounded mast	8.43	9.7	21.45	96

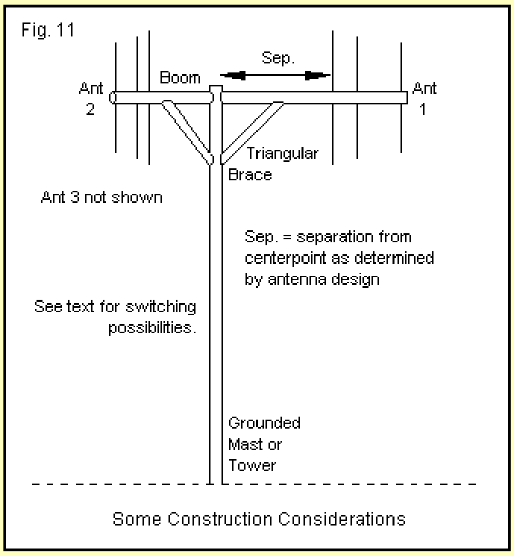
Once more, the values for the non-conductive mast and the grounded mast are very similar. However, when we leave the mast ungrounded, the values for the square of Yagis change much less than they did in the triangle. In fact, the gain changes by less than 0.1 dB, and the beamwidth changes by only 1 degree across the three tested cases. The most likely source of the difference between the triangle and the square is the closer proximity of the Yagis within a square of 4 antennas. As a result, the interaction between antenna structures tends to override any effects of even an ungrounded mast.

Since we did find some significant differences of mast-to-antenna interactions between the Moxon rectangles and the Yagis, the lesson is simple. These notes are not usable as a design document. Rather, they establish the need to carefully model the actual antennas and mast to be used in a horizon-covering switched array at the height to be used and at the distance from the support mast to be used.

A Few Construction Hurdles

The basic idea of an array of directional vertical antennas symmetrically placed around a central mast is not new by any means. The number of antennas required for full horizon coverage depends on the antenna design, the spacing of the antenna from the centerpoint, and the degree of reduced gain that is acceptable at the pattern cross-over points. For most amateur applications, an array of three--perhaps four--antennas is about the maximum array size before a rotator becomes the more attractive option. Part of the reason lies in the cost of numerous antennas, and part of the reason lies in the growing complexity of construction as the number of antennas increases.

Fig. 11



Some Construction Considerations

Fig. 11 summarizes a few of the most rudimentary construction considerations. The support mast should be well grounded, if for no other reason than lightning safety. However, if antennas use the minimal 1/4-wavelength spacing between the rearmost element and the array centerpoint, a grounded or a non-conductive upper mast may have significant influence upon the performance of the individual antennas in the collection.

For the lower VHF region, especially 6 meters, the booms may require a triangular brace to reduce the stress moment along the horizontal support. For all-metal construction, the braces may be straps or L-stock, depending on the actual antenna weight and its distance from the mast. Upper VHF assemblies may be able to omit the bracing. Indeed, as the frequency increases, the use of UV-protected PVC (or similar) boom materials becomes attractive.

These notes are not so much a guide to construction as they are a reminder that the physical assembly requires as much planning as the electrical performance of the antennas in the array. Equally important is the switching method. Here we have at least three alternatives.

- 1. We may run separate feedlines from each antenna into the shack for convenient switching. This option is perhaps most attractive for its simplicity and is most applicable where the coax runs are fairly short. A basic coaxial-cable switch near the equipment position allows the operator to select the favored direction with the fewest mechanical complexities.

- 2. We may run short feedlines to a single position at the centerpoint of the array. At that position, we may install a remote coaxial-cable switch. This system requires only one long cable run from the antennas to the shack. The savings in cable may also allow us to purchase the lowest-loss coax that we can find. The system is likely most applicable where the distance between the operating position and the antennas is fairly long. The system has two disadvantages to weigh in the balance.

One is the placement of a remote electro-mechanical device at the antenna site, where it will require suitable weather protection. The second disadvantage is the need to run a power line to the remote switching unit.

- 3. Those who are very adept in electrical circuitry may create a polling system out of the array. Essentially, in the receiving mode, the system continuously scans at a given frequency until its receives the strongest signal. It locks upon this signal with the antenna that yields the highest signal strength. Such systems are most applicable at repeater installations. Normally, they are used only for receiving, with the transmitted signal on its own channel going to an omni-directional antenna (since the receiving station for the repeated signal may be in any direction and may involve multiple directions for a round-table discussion). With suitable time constants, the system may capture signals with no interruption, even from a mobile station that passes from the field of one antenna to the next.

Essentially, a switched FM-repeater service antenna system can be as simple or complex as our skills, ingenuity, and inclinations dictate. With the correct antennas properly spaced from the centerpoint of the array, it provides an alternative to the rotator. In some circumstances, it may prove to be superior, since we do not need to wait on the slow-moving rotator in order to communicate. Although we have explored 6 meters as a kind of worst-case scenario in terms of the support vs. antenna interaction equation, the use of a triangle of vertically polarized directional antennas may be easier to implement at higher VHF and UHF ranges for full horizon coverage.

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