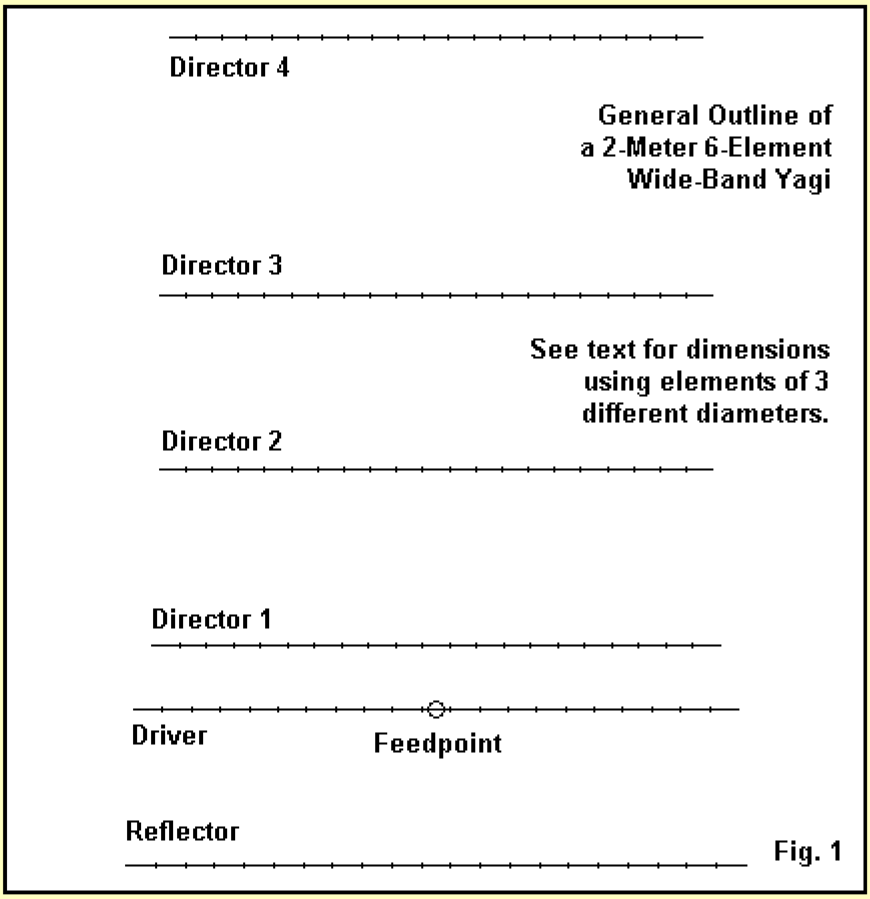
Notes on 6-Element Wide-Band 2-Meter Yagis

L. B. Cebik, W4RNL (SK)

I have in several past notes discussed a VHF antenna to which I must confess some partiality. The antenna is a 6-element Yagi that covers all of 2-meters with at least 10 dBi free-space gain, at least 20 dB 180- degree front-to-back ratio, and better than 1.2:1 50-Ohm SWR from 144 to 148 MHz. The antenna boom length is less than 56" (1.4 m), which lends itself to the use of a non-conductive boom, for which the element lengths and spacings are designed. The use of a direct 50-Ohm feed reduces the number of mechanical connections in the path between cable and element, thus reducing the number of potential loss sources. (However, a common-mode current suppression "choke" is advisable.) **Fig. 1** shows the general outline of the array.



The design is an adaptation of Optimized Wide-band Antenna (OWA) principles used at HF by a series of HF antennas designed by NW3Z and WA3FET. For a given boom length and gain level, the design requires one extra director that has the main function of controlling--in concert with the reflector--the impedance of the array over a wide frequency span. One may design OWA arrays for almost any reasonable feedpoint impedance. The main difference among such designs is that the space required by the reflector, driver, and first director tends to increase with increases in the design feedpoint impedance.

OWA designs also tend to have second and third directors that are the same length. However, in some designs, the third director may be slightly longer than the second. The fourth or final director is the shortest. Changing its length will alter performance at one or the other end of the design passband, with some alteration of the SWR curve as well.

In other places, I have published notes on the design of a family of OWA-type Yagis for 2 meters. The sizes ranged from 6 to 12 elements, with boom lengths running from 4.5' to 20'. Among the advantages that accrue to the family is the excellent control of secondary forward lobes, which remain generally better than 20 dB below the level of the main lobe. The result is a naturally wider horizontal beamwidth without gain loss, relative to designs in which the secondary forward lobes are down from the main lobe by only 12 to 18 dB.

My return to the 6-element version of the OWA Yagi results from inquiries that I have received on this useful utility design. Similar questions have arisen concerning other antenna designs that I have published. The question runs something like the following: I cannot obtain the specified diameter material at the local hardware store. Can I use the alternative size material that they carry?

The answer to this question carries us in two directions. The first kind of answer involves learning what sources there are for various materials used in constructing good antennas. For example, there are several outlets, such as Texas Towers (http://www.texastowers.com) from which we can order many basic antenna element materials. One advantage of using these sources is that they carry 6061 and 6063 rods and tubes, generally the best aluminum types to use for antenna elements. The material obtainable from hardware outlets rarely has the aluminum type specified on the label. The other advantage is the availability of a wide range of rod and tubing diameters.

The second kind of answer involves adapting a given antenna design to a new diameter material. Suppose that a designers specifies 0.1875" (3/16" or 4.76 mm) elements. The builder has a stock of either 0.125" (1/8" or 3.18 mm) rods or 0.25" (1/4" or 6.35 mm) rods. Will he or she need to adjust the element lengths of spacings?

The answer is "yes." In fact, without making such adjustments, the antenna will not perform as originally designed. There are two major reasons for this result. In general and first, both driver and parasitic elements lengths require adjustment with every change of diameter. The general goal is to arrive at elements whose self-resonant frequencies are the same as in the original array. Second, the inter-element coupling changes for a given spacing of two elements if we change the element diameter. Element spacing does not change as rapidly as the element length for a given level of coupling when we change element diameter. However, it changes enough so that we cannot ignore the effects.

One of the simplest ways to accommodate a revised element diameter is to resort to a Yagi optimizing program. We simply plug into the program the existing design and specify the new element diameter. The program then churns out the revised design.

More antenna builders have general antenna modeling programs than have optimizing programs. There is a procedure that we can use to re-optimize a design for a new element diameter, although it has a pitfall from which we must guard ourselves. Here is how the procedure works.

1. Create a model of the original design and establish its operational characteristics.

2. Revise the model to use the new element diameter.

3. Find the frequency at which the new model shows the same operating characteristics as the original model did at its initial design frequency. If we are moving to a larger-diameter element, the new frequency will be lower than the old one. If we are moving to a smaller-diameter element, the new frequency will be higher than the old one.

4. Frequency scale the revised antenna model from the new design center to the original design center. Retain the new element diameter: the amount of performance change occasioned by the small frequency movement will usually not require a reiteration of this step. However, when enlarging or shrinking elements by more than a factor of 2, it may pay to make the change in two steps of scaling and checking.

At this stage, check the performance of the antenna across the passband used by the original design. In many instances, the model will suggest that we need not make any further changes. However, in some cases, we may need to adjust some element lengths to center the gain, front-to-back, and SWR curves as closely as possible to their original form (assuming that the original curves are the most desirable ones for our application). The driver length will have the greatest effect upon the SWR curve. Juggling the reflector length and the most forward director lengths can smooth out the performance across the passband, although rechecking the SWR curve may be necessary. For a given band-edge adjustment, alter the element that moves gain and/or front-to-back performance values in the desired direction with least adverse affect on the SWR curve. Finally, when reducing element diameters, you may need to increase the reflector spacing from the driver to raise the general impedance level back to that of the larger elements with which you began.

The pitfall in this procedure involves stopping at this point. Although the initial detection of the revised design center frequency and scaling that back to the original center produced element lengths that are very close to optimum, the element spacing moved in the wrong direction. The thin-element model increased element spacing, while the fat element model decreased the spacing. However, as element diameter increases, element spacing must increase to maintain the same level of coupling. Because we have adjusted element lengths, the spacing adjustments may not be dramatic, but they will be noticeable. Therefore, we need one more step.

5. If increasing element diameter, increase the spacing among elements by about twice the amount that the initial scaling decreased them. If decreasing the element diameter, do the opposite. Do not use a simple additive method, but instead find a multiplier based on the scaling ratio used in step 4. Take into account any revised positioning of the reflector in step 4. As well, check the driver, reflector, and most forward director lengths to re-establish the performance curves for the array.

To illustrate these steps, I took my original 6-element OWA Yagi, designed for 3/16" elements, and revised it for more commonly available 1/8" and 1/4" element materials. First, however, I tweaked the design for slightly better optimized performance.

I next used the steps above to obtain the best possible performance in NEC-4 models for the thinner and thicker elements. The design criteria remained constant throughout the exercise:

Gain: greater than 10 dBi free-space gain from 144-148 MHz with a maximum range of about 0.1 dB between maximum and minimum gain;

Front-to-back ratio: greater than 20 dB 180-degree front-to-back ratio with worst-case front-to-back ratios also greater than 20 dB;

50-Ohm VSWR: less than 1.2:1 50-Ohm VSWR from 144 to 148 MHz.

The design work--being hand-done--does not necessarily represent the absolute best that one might obtain from the design. Still, the designs meet all of the performance criteria with ease. The following table presents the resulting design dimension, first in inches.

Dimensions of 3 6-element Wide-Band Yagis (Inches)

Note: All elements aluminum and are presumed well insulated and isolated from a conductive boom or mounted on a non-conductive boom. The driver will be split for a direct feed with 50-Ohm coaxial cable. The separation of the feedpoint ends is included in the overall element length shown, and the split is non-critical between 1/8" and 3/4".

Dimension	**1/8" el.**	**3/16" el.**	**1/4" el.**
Element Length in Inches			
Refl.	**40.80**	**40.67**	**40.38**
Driver	**40.10**	**39.92**	**39.47**
Dir. 1	**37.63**	**37.38**	**36.99**

Dir. 2	**36.56**	**36.31**	**36.10**
Dir. 3	**36.56**	**36.31**	**36.10**
Dir. 4	**35.20**	**34.96**	**34.50**
Spacing from Reflector in Inches			
Driver	**10.20**	**10.18**	**10.25**
Dir. 1	**14.27**	**14.39**	**14.48**
Dir. 2	**25.95**	**26.06**	**26.22**
Dir. 3	**37.39**	**37.47**	**37.70**
Dir. 4	**54.44**	**54.49**	**54.82**

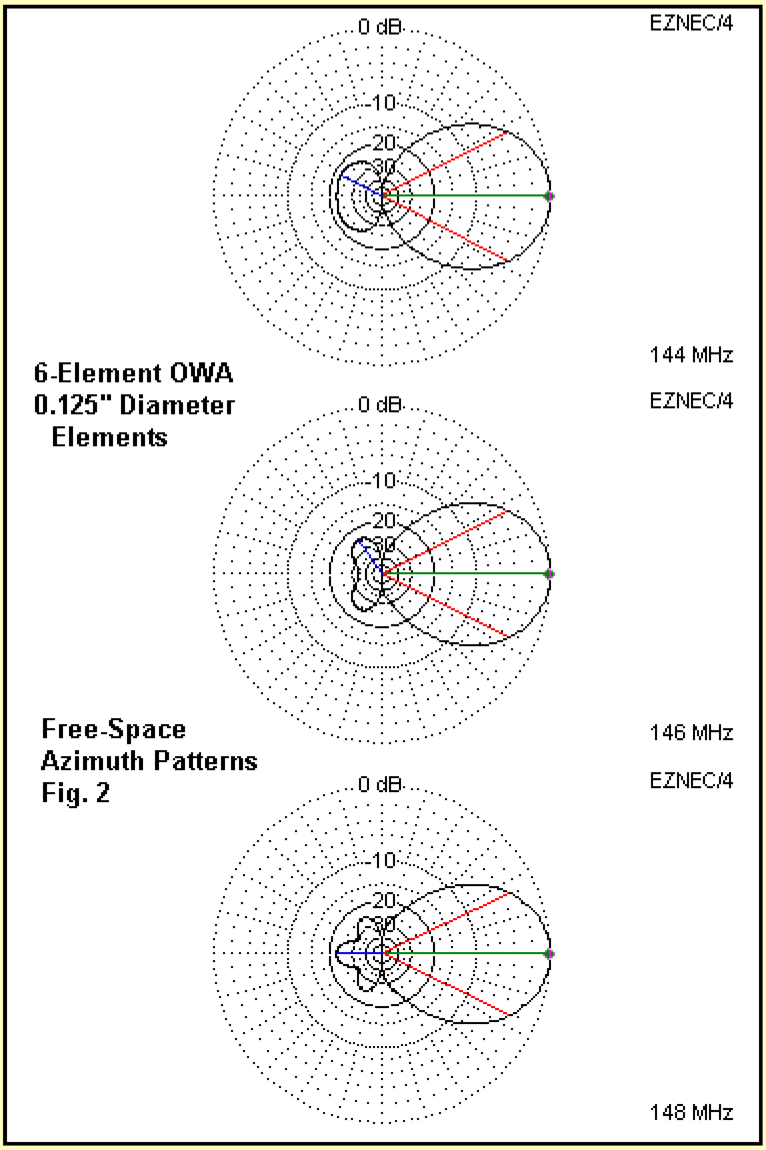
Because the design has drawn interest from a few individuals who work in the metric system, the following table repeats the dimensions in millimeters. The most common European 2-meter element diameter appears to be 4 mm (0.1575"). Although I did not optimize a 4-mm version of the antenna, the differences between the 1/8" and 3/16" versions should provide reasonably close guidance.

Dimensions of 3 6-element Wide-Band Yagis (Millimeters)

Dimension	**3.175 mm el.**	**4.763 mm el.**	**6.35 mm el.**
Element Length in Millimeters			
Refl.	**1036**	**1033**	**1026**
Driver	**1019**	**1014**	**1003**
Dir. 1	**956**	**949**	**940**
Dir. 2	**929**	**922**	**917**
Dir. 3	**929**	**922**	**917**
Dir. 4	**894**	**888**	**876**
Spacing from Reflector in Inches			
Driver	**259**	**259**	**260**
Dir. 1	**362**	**366**	**368**
Dir. 2	**659**	**662**	**666**
Dir. 3	**950**	**952**	**958**
Dir. 4	**1383**	**1384**	**1392**

Note that all element lengths shrink as the element diameter increases. The total element length difference between 1/8" and 1/4" elements approaches 0.5" (12 mm). Between steps, the 0.25" (6 mm) difference will make a difference in performance, displacing the performance curve significantly. As well, all but 1 of the element spacings increase as diameter increases. The exception is the 1/8" reflector, which I moved back to raise overall impedance of the array closer to 50 Ohms. Increasing the element spacing to a near optimal level allows the array to yield its maximum gain while providing the least difference in gain within the operating passband.

The 1/8" Model



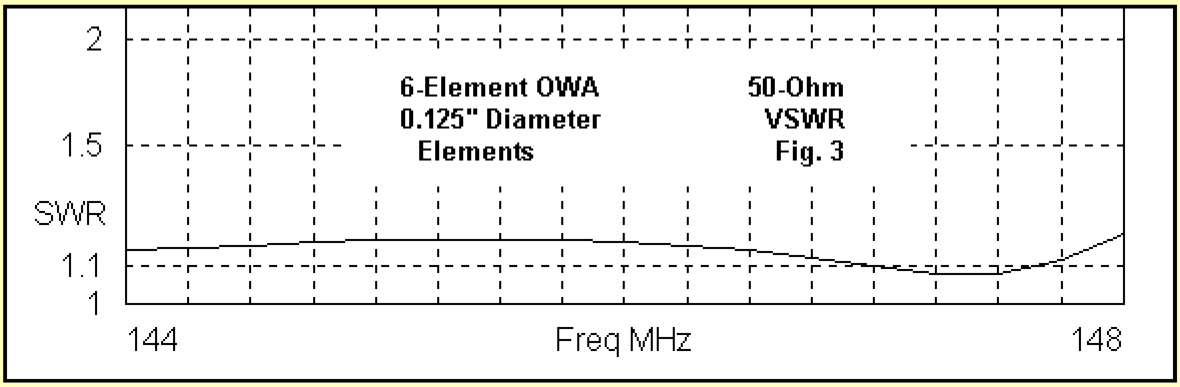
Free-Space Azimuth Patterns
Fig. 2

Fig. 2 provides spot checks on the free-space azimuth patterns of the array with 1/8" elements--with the antenna horizontally positioned. The following table presents performance values across the band, as reported by NEC-4.

0.125"-Diameter 6-Element OWA Yagi Performance

Frequency MHz	Gain dBi	Front-to-Back Ratio dB	Feedpoint Impedance R +/- j X Ohms	50-Ohm VSWR
144	**10.06**	**22.62**	**47.9 + j 6.3**	**1.14**
145	**10.12**	**28.35**	**49.4 + j 7.9**	**1.17**
146	**10.17**	**32.85**	**50.7 + j 7.9**	**1.17**
147	**10.17**	**26.48**	**49.8 + j 4.8**	**1.10**
148	**10.12**	**22.44**	**42.0 + j 0.2**	**1.19**

Although the 1/8" model proved easy to tame with respect to roughly equal front-to-back performance at both edges of the passband, gain equalization proved more difficult. For those unfamiliar with a typical OWA SWR curve, **Fig. 3** shows the anticipated performance of the 1/8" model. Note that there is a peak value near 145.5 MHz, with lower values above and below that frequency. The typical OWA SWR curve tends to show two minima, with the rise in SWR becoming steep above the null at the higher frequency.



The 3/16" Model

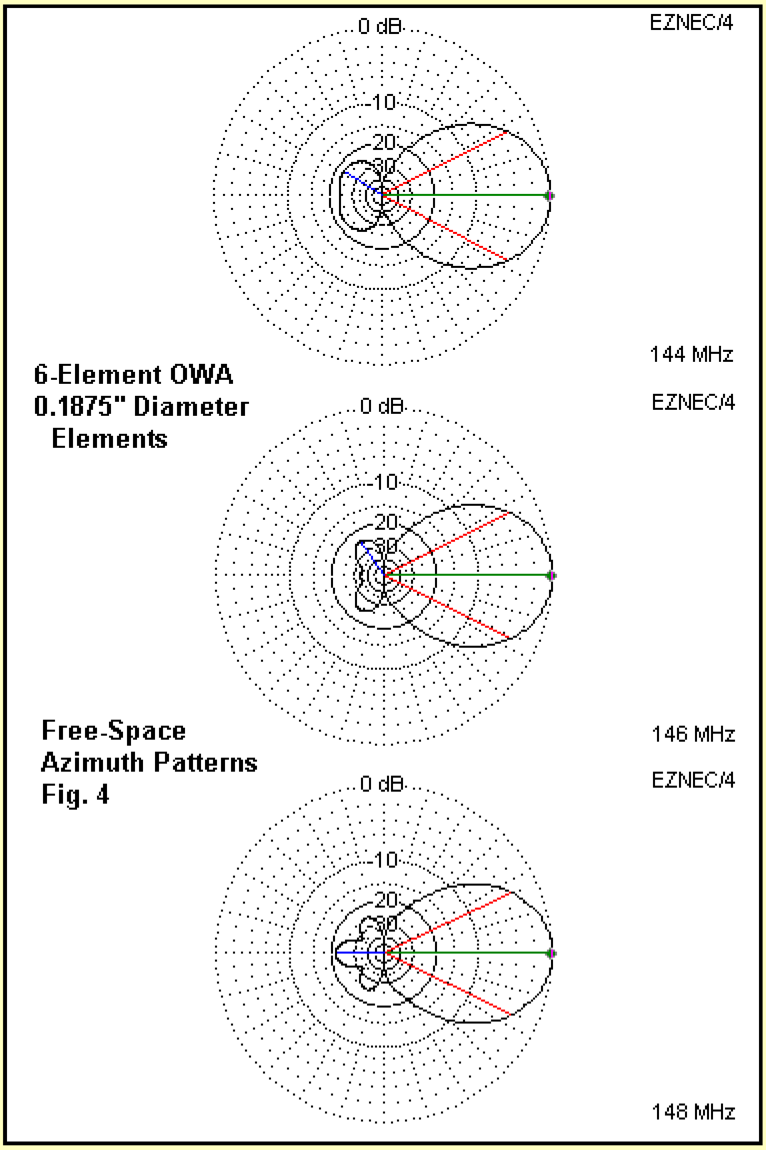


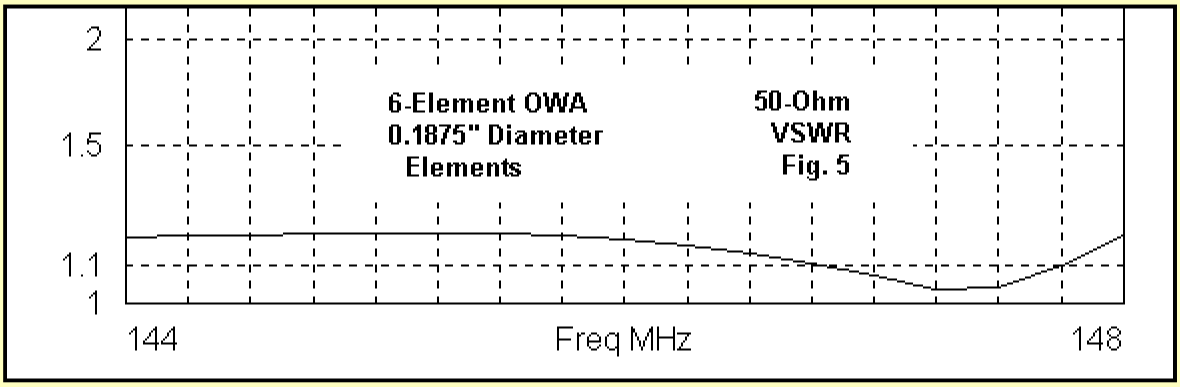
Fig. 4 shows sample free-space azimuth patterns for the mid-size model. As element diameter increases, the deep front-to-back rear null may vary above or below the design center frequency, although the gain increases smoothly. The following table shows the anticipated performance of this version of the array.

0.1875"-Diameter 6-Element OWA Yagi Performance

Frequency MHz	Gain dBi	Front-to-Back Ratio dB	Feedpoint Impedance R +/- j X Ohms	50-Ohm VSWR
144	10.15	23.77	45.3 + j 6.5	1.18
145	10.20	31.03	47.6 + j 8.4	1.19

146	**10.24**	**32.41**	**50.3 + j 8.0**	**1.17**
147	**10.23**	**25.04**	**50.7 + j 3.4**	**1.07**
148	**10.17**	**21.30**	**42.7 - j 3.2**	**1.19**

Although the performance advantages would not be detectable in operation, we would not have obtained performance even equal to that of the 1/8" model had we not at least adjusted the element lengths. For most utility purposes, adjustments to the element spacing might be superfluous effort. However, unless we in fact perform the necessary modeling, we could not make such a judgment. Although the judgment holds in this case, it might not hold in others. **Fig. 5** shows the VSWR curve across 2 meters.



The 1/4" Model

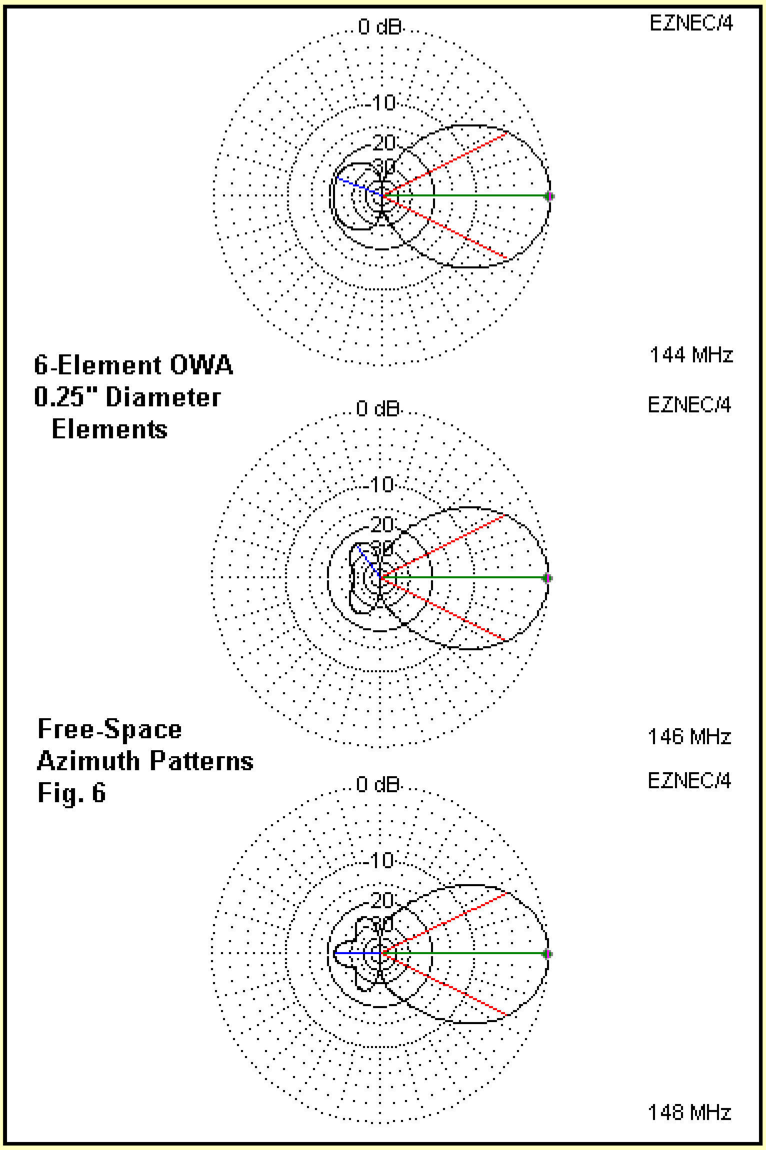
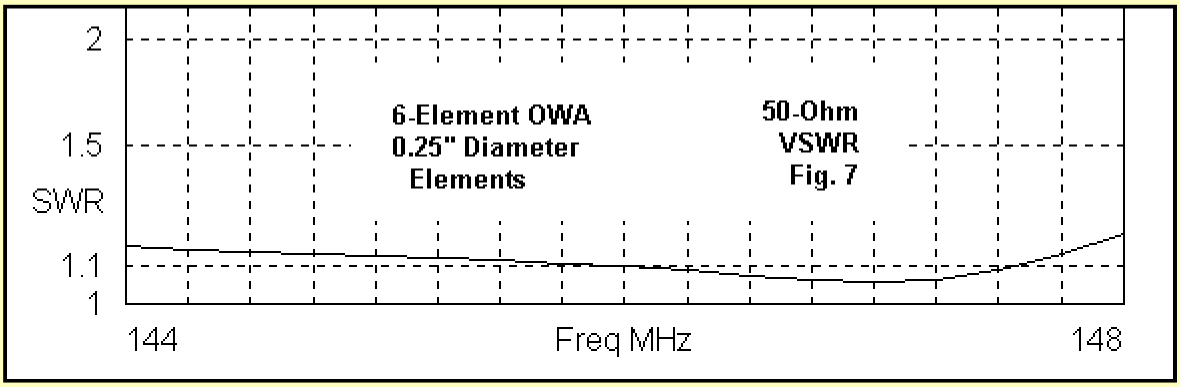


Fig. 6 shows the free-space azimuth patterns for the 1/4" version of the array. The differences of these patterns from the preceding sets are subtle and not of great operational performance. However, as the following table of anticipated performance figures shows, the largest diameter model in this sequence also shows the least relative gain change across the passband.

0.25"-Diameter 6-Element OWA Yagi Performance

Frequency MHz	Gain dBi	Front-to-Back Ratio dB	Feedpoint Impedance R +/- j X Ohms	50-Ohm VSWR
144	10.19	21.85	44.2 + j 3.4	1.16
145	10.24	26.59	47.6 + j 5.4	1.13
146	10.27	29.63	51.2 + j 4.6	1.10
147	10.25	25.64	52.8 - j 0.4	1.06
148	10.18	22.05	47.0 - j 8.0	1.19

Fig. 7 shows the SWR curve for this version of the array, perhaps the shallowest of the entire lot. Indeed, the numerical progressions displayed by this design exercise illustrate the principles of array redesign, although for the limited set of element diameters, they do not produce operationally detectable differences in results. However, I cannot stress enough that the element length adjustments are absolutely necessary to obtain the basic performance level of the 1/8" model, with adjustments to other elements to center the performance curves and assure satisfactory SWR performance.



Optimizing vs. Changing Designs

Let's begin with an observation about OWA SWR curves. For a given passband, the higher frequency minimum is normally a prelude to a steep rise in SWR. The designer normally positions the minimum close to the upper edge of the design passband. For the two thinner models, the minimum occurs at about 147.5 MHz. For the 1/4" version, the minimum is set at 147 MHz. That difference is a larger difference than we might think at first sight.

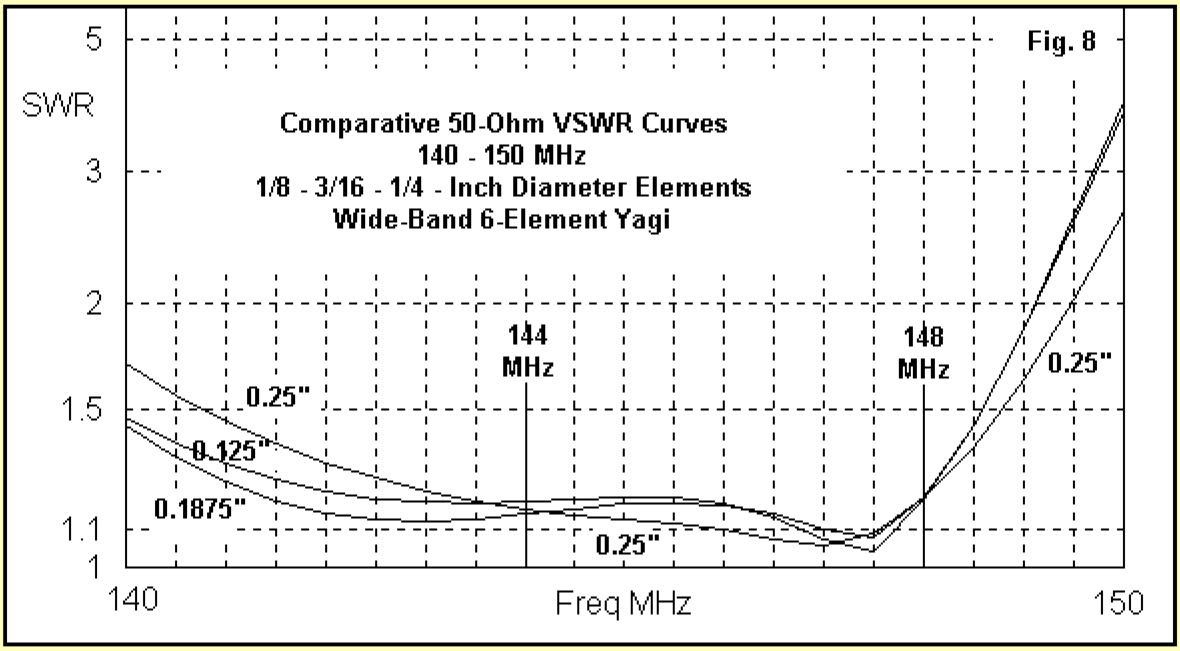


Fig. 8 presents the SWR curves for all three versions of the array from 140 to 150 MHz. Although the gain and front-to-back performance fall off below the design limits of this exercise, the antenna is still usable 4 MHz below the design limit. One use we might make of this information is the following: should we wish to cover the 2 MHz region above the 148-MHz design limit, we might scale the antenna or readjust the elements most affecting the impedance performance of the OWA Yagi.

The relative similarity of the 1/8" and 3/16" curves--when added to the performance tables for these arrays--generally establishes that each is an optimized version relative to its element diameter. However, note the slight difference in the shape of the SWR curve for the 1/4" version. Its upper-end rate of increase is shallower than we might expect based on the other two curves. As well, the lower minimum is not so much a null as it is simply a decrease in the rate of SWR increase as the frequency goes below the 2-meter band edge.

To achieve an SWR curve that is truly congruent with the 1/8" and 3/16" curves, we would need to do some further design work. As it stands, one might well consider the 1/4" version of the antenna a slightly revised design rather than simply an optimization of the other designs for the new diameter of material.

Perhaps the most evident consequence of the differences in the curves is that fact that the exercise cannot provide any convenient formulas for adjusting element lengths and spacings. The element diameter ratios were 3/2 (3/16:1/8) and 4/3 (1/4:3/16). The element length decreases with increasing diameter were about 1% per step, with special attention given to advisable further adjustments to the reflector, driver, and most forward director. The spacing adjustments amount to about 0.5% per step, again with special attention to the reflector-drive space and the position of the most forward director.

At best, then, this design exercise has yielded only a small catalog of matters on which to use care when changing the diameter of an element while retaining the performance of the original design. However, a catalog is usually better than a mere guess.

Go to Main Index