

An OWA Family of 2-Meter Yagis From 6 to 12 Elements: Part 1: A Comparison of 12-Element Yagi Designs

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These notes present a family of Optimized Wide-band Antenna (OWA) Yagis developed as a simple design exercise and not necessarily intended to be implemented. The boom lengths range from 4.5 to 20 feet, with 6 to 12 elements. What differentiates these Yagis from a large collection of other excellent designs is not only the design principles (OWA) invoked, but as well the design specifications. Rather than aim solely for gain, front-to-back ratio, and feedpoint impedance, the designs also set specifications for control of secondary forward lobes. In this first part, we shall compare a 12-element 2-meter Yagi derived from DL6WU design to its corresponding OWA design to gather a perspective on what the use of OWA principles may gain and lose. In Part 2, we shall examine the entire set of OWA designs individually.

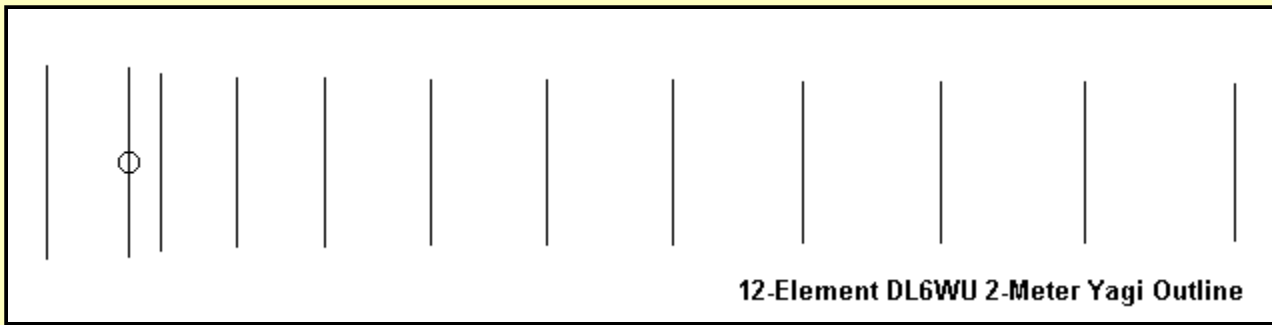
Background

In the quest for better long-boom Yagis for VHF, gain has been the leading criterion. Obtaining the most gain from the least number of elements on the shortest possible boom has been a hallmark of design efforts. Some writers, such as Zack Lau, W1VT, have set aside front-to-back ratio (unimportant to most operations) and feedpoint impedance (obtainable by a suitable match) in order to achieve maximum gain from minimum aluminum.

Other designers have taken a more balanced approach, combining calculated element lengths and placement with an easily matched feedpoint impedance (normally 50 Ohms). The work of pioneer Guenter Hoch, DL6WU, and Leif Asbrink, SM5BSZ, have contributed much to this effort. If the boom length is long enough, the front-to-back ratio tends to follow the gain, and the usual standard of a 20 dB front-to-back ratio has been part of the design.

We can illustrate the design conceptions involved with a 12-element Yagi based on work by DL6WU, whose designs are still the standard by which other efforts are measured. In principle, one may take a DL6WU design and cut it off anywhere among the set of directors and wind up with a usable Yagi with a gain that is close to the maximum for the resultant boom length. This principle is only partly correct by virtue of the broad operating bandwidth designed into the DL6WU array. If one removes one or more directors from a given design, the forward-most remaining director must be adjusted to reset the operating parameters. Since these parameters may individually peak anywhere within the broad limits of the design, further work is usually required to bring the peak gain, peak front-to-back ratio, and an acceptable feedpoint impedance range within the desired operating range. There are two easily used strategies in addition to modifying the forward-most director. One is to locate the desired set of parameters within the overall range of the array and then frequency scale them into the desired operating range. The second move is to adjust the driver length to set the balance of reactance around the center frequency of the desired operating range so as to yield the best 50-Ohm SWR curve for that range.

All of these maneuvers were applied to a shortened 12-element design from DL6WU's original work. My desire to use a 12-element array as the model is that the longest array in the set to be presented uses 12 elements. Hence, the potential for comparison is obvious. Moreover, 12 elements will easily fit on a 20' boom, a convenience for US builders. Whether the resulting revised DL6WU design is fair to the originator is a judgment for others to make. The outline of the array appears in below, followed by 2 charts: one provides the dimensions in inches of the array, while the other summarizes the NEC-4 modeled performance properties. The charts are followed by the 50-Ohm SWR curve across 2 meters and free-space azimuth patterns for the design. All of the values for this design and for all succeeding designs presume elements that are well insulated and isolated from the boom.



DL6WU-Derived Design

No. of elements: 12
 Element diameter: 0.157" (4mm), except the driver: 0.197" (5mm)
 Boom length: 232.17" (19.35')
 Maximum 50-Ohm SWR: 1.28:1

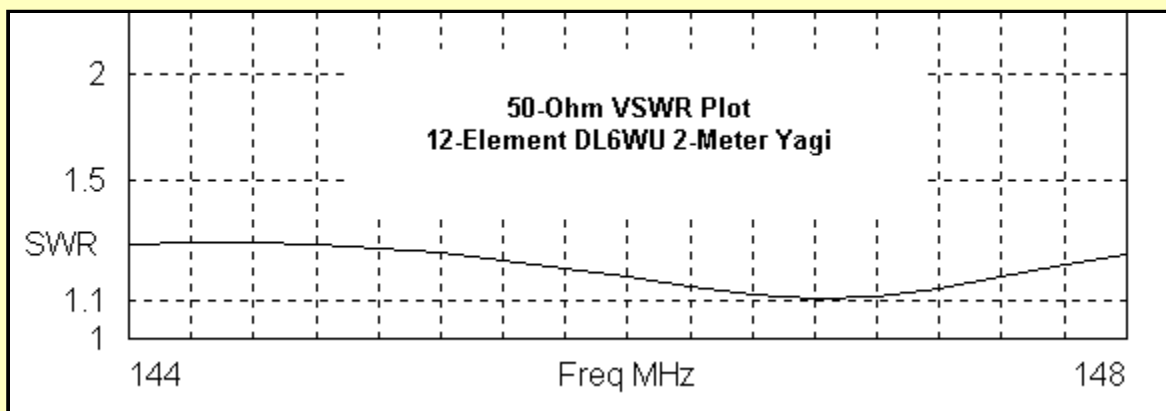
Dimensions (in inches):

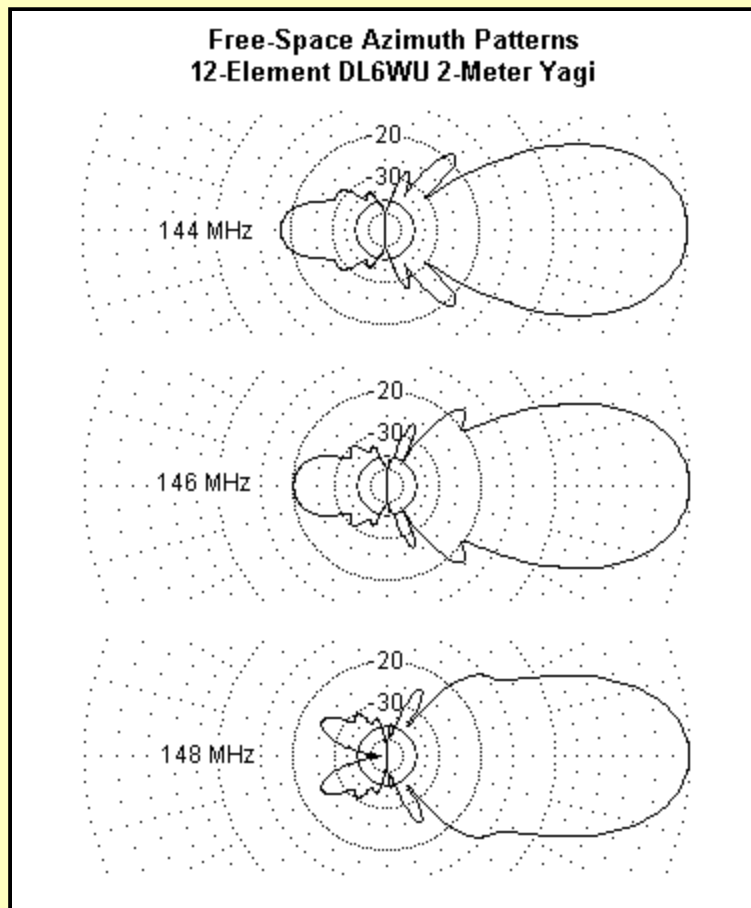
Element	Length	Space from Reflector
Reflector	40.34	----
Driver	38.74	15.24
Director 1	36.55	21.69
Director 2	36.35	36.35
Director 3	36.15	53.94
Director 4	35.96	74.46
Director 5	35.57	97.32
Director 6	35.18	121.95
Director 7	34.79	147.74
Director 8	34.59	174.71
Director 9	34.40	202.85
Director 10	32.38	232.17

Modeled Performance

Parameter	144 MHz	146 MHz	148 MHz
Gain dBi	14.46	14.67	14.54
Max. 2ndary Lobe	-18.60	-17.76	(-24.03)*
180-deg F-B	18.21	20.22	46.63
-3dB Beamwidth	35.6	33.8	32.4
Impedance (R+/-jX)	55.5 - j 11.3	47.1 - j 7.0	53.4 + j 10.5
50-Ohm SWR	1.27	1.17	1.24

*Value is for the 2nd secondary lobe.





The design revision strove to place both the maximum gain peak and the maximum front-to-back ratio within the operating passband (144-148 MHz) with only partial success, since the front-to-back ratio peaks at the upper band edge. The front-to-back ratio exceeds 20 dB over at least half of the band, with the 144-MHz value being the worst case.

The SWR curve would be deemed acceptable for almost all applications. In fact, many of the broadband VHF and UHF Yagi designs from the 1970s forward have employed an intuitive OWA arrangement of the reflector, driver, and first director. As the SWR curve shows, the SWR value meanders at a low level, with a dip in the upper portion of the band. There is a peak inside the lower band edge, indicating a second dip just below the usable band.

The final graphic shows the modeled free-space azimuth patterns for the array. The progression of patterns is typical for a Yagi with its gain peak within the operating passband. The normal "oval" forward lobe gradually becomes a more "bullet-shaped" lobe. The transition brings with it a narrowing of the -3 dB beamwidth.

The change of shape of the forward lobe is due to the devolution of the first secondary forward lobe. Although this lobe is clearly evident in the patterns for 144 and 146 MHz, it is only a "swelling" of the main lobe at 148 MHz. For this reason, the modeling software did not detect it as a lobe and identified the second secondary lobe as the main one. The DL6WU design used in this illustration has a fairly good set of figures for secondary forward lobes. Many other designs that I have explored have had much worse--from -17 dB to -11 dB.

All-in-all, the DL6WU design represents a very fine array of its type relative to a comparison of the boom length and number of elements with the modeled performance figures. For US builders, the array presents some practical problems, since 4 mm rod is not only not available, but as well is almost the arithmetic mean between available sizes (0.125" and 0.1875"). Therefore, some redesign would be necessary to obtain the performance promised by the array. Nevertheless, the result would have the same number of elements and still fit a 20' boom.

An Expanded Set of Specifications

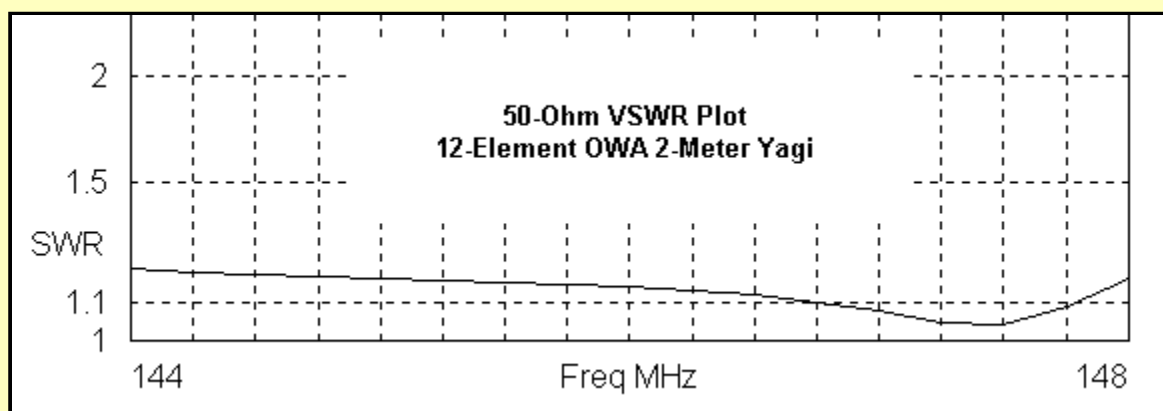
The DL6WU-derived design presents a sufficient number of theoretical problems to occasion a new set of specifications for 2-meter Yagi design. Rather than leading with gain, we shall lead with pattern control in an effort to eliminate to the degree possible secondary lobes. As it turns out, the same technique that gives us an increased measure of pattern control also provides a means for obtaining the lowest possible 50-Ohm SWR across the band. OWA techniques provide the basis for both achievements. A high front-to-back ratio will also be a part of the specifications, while gain will be simply peaked within the band. This specification set requires more detailed discussion.

1. Pattern control: Secondary forward lobes generally obtain their power by a reduction in the -3 dB beamwidth of the main forward lobe. For example, a roughly comparable array with secondary lobes reduced to the -24 dB level will have a nearly 3 degrees wider beamwidth than the example just shown. The beamwidth advantage is even greater compared to Yagis of the same size and gain with even stronger secondary forward lobes. Note that this increase in beamwidth does not come at the expense of main lobe forward gain--although designs that use pattern control as a primary specification may for other reasons end up with slightly less gain--perhaps 1/3 dB less than an array designed expressly for gain within the wide-band category of designs.

Therefore, a specification for the present design exercise is a series of arrays with all secondary forward lobes at -22 dB or more relative to the main forward lobe. There may be other Yagi design techniques available to permit further reduction of the secondary lobes without appreciable detriment to other operating parameters. However, as a start, the application of an OWA drive set for the array has permitted a considerable improvement over common designs.

2. Feedpoint Impedance: The OWA techniques refined by NW3Z and WA3FET for HF use are equally applicable to VHF and UHF arrays. As noted, they are almost implicit in a number of the classic 50-Ohm long-boom designs. In fact, the DL6WU design uses a wider than optimal spacing of the reflector from the driver for OWA purposes. The result is that the reflector tends to control the impedance level more than the combination of the reflector and first director, resulting in a larger than desired swing in reactance. The 2-meter band is an excellent place to use them, since the bandwidth as a percentage of the center frequency (2.74%) is almost the same as the bandwidth of 20 meters (2.47%) for which the initial OWA designs were developed.

Obtaining a very low 50-Ohm SWR across a considerable bandwidth requires careful sizing and placement of the reflector, driver, and first director elements. The exact element lengths and the spacing between them are a function of the element diameters. However, in long boom arrays, once these elements have been set, only the forward-most elements need juggling to obtain virtually the same SWR profile across the band. The SWR curve of the OWA 12-element design to be discussed further on is an example of the desired curve.



Note the general similarity of the curve to that of the DL6WU design. Although not apparent in this curve, many OWA SWR curves show a second dip just at the lower edge of the band (or just below that). However, the SWR curve itself does not tell the entire story. Part of the OWA benefit lies in the reduced reactance excursion across the band. For the 12-element design, the reactance changes by a total of less than 10 Ohms, compared to the DL6WU net change of nearly 22 Ohms.

(Other 50-Ohm Yagi designs do considerably worse than the DL6WU design used as an illustration here.)

The relative size and space among the reflector, driver, and first director do not complete the OWA picture. Wide band Yagi designs can be obtained with 3, 4, and 5 elements, but the OWA design becomes most stable with 6 or 7 elements. Director 3 is often the same length as or slightly longer than director 2--as a matter of course. This feature is not possible to implement on a true DL6WU design in which the directors are all tapered according to a formula.

As a sample--but not the only possible one, the following dimensional chart shows the first 5 elements of the longer-boom models to come. There may be slight changes made in some array designs to polish the curves, but the set illustrates both the reflector-driver-first-director arrangement, as well as the amount by which the 3rd director may exceed the 2nd in length.

Element Diameter: 0.1875"

Element	Length	Space from Reflector
Reflector	40.90	----
Driver	39.50	8.79
Director 1	37.00	13.47
Director 2	36.33	25.38
Director 3	36.40	40.72
Director 4	36.21	61.38
Director 5	35.20	86.49

For this particular situation, where the element diameter is 3/16" (0.0023 wavelength) and the design frequency is 146 MHz, the reflector is 0.109 wavelengths behind the driver, while the first director is 0.058 wavelengths in front. The element lengths from reflector to first director are 0.506, 0.489, and 0.458 wavelengths. To date, I have arrived at no single equation set that will settle all cases where OWA drive sets are desired.

As we add elements to the array, returning to the basic SWR curve and the reducing the reactance excursion to a minimum requires an added design step beyond those required by DL6WU and similar designs. Terminating a DL6WU design required only that we adjust the forward-most director--normally shorter than its length as part of a longer array. For an OWA design, the 2 forward-most directors require adjustment of both length and spacing to refine performance and re-establish the SWR curve.

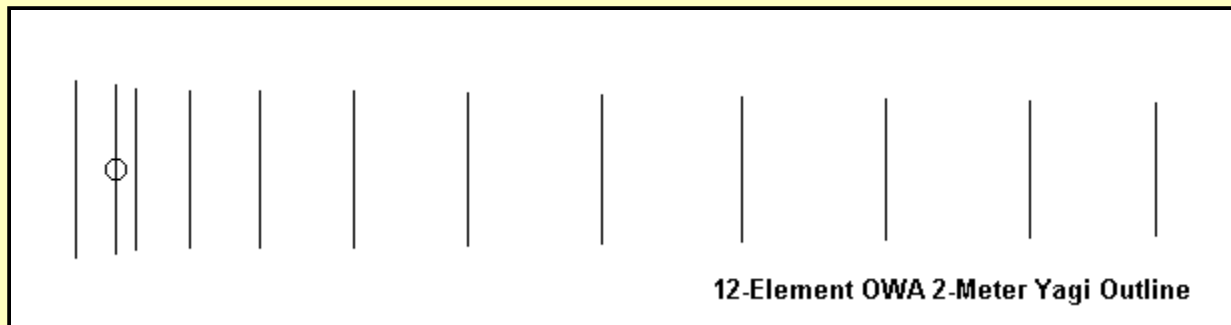
3. Front-to-back ratio: For this set of Yagis, a 20-dB worst-case front-to-back ratio was set as a requirement for all versions at all frequencies within the operating passband. In fact, it is possible to achieve higher overall values of front-to-back ratio (whether taken as the 180-degree, worst-case, or averaged value) than those within the designs to be examined. However, this move comes at the expense of either the forward gain, the desired SWR curve, or both.

4. Gain: Within the boundaries of this exercise, the gain value was not a primary objective. In many instances, the gain value was balanced against the front-to-back performance of the array. However, the resulting difference from the maximum obtainable gain was not great--perhaps 0.1 to 0.2 dB at most.

More significance was placed on centering the gain peak within the operating passband. This placement is normal for OWA designs and has the benefit of reducing the variation of gain from one end of the band to the other. Maximum gain excursions of under 0.3 dB are normal for the beams within this collection.

Applying the specification set roughly in the order given in the list yielded a range of 7 Yagis from 6 to 12 elements, all with similar characteristics. The dimensions cannot be simply summarized because of the need to adjust multiple elements as one moves from one size to the next. However, we can provide a view of the peak performance obtained by looking at the final Yagi in the sequence, the 12-element OWA design.

The 12-Element OWA 2-Meter Yagi As with the DL6WU design, we begin with the array outline, followed by the dimensions and modeled performance of the array. We have already examined the SWR curve, so the final graphic will complete the picture with free-space azimuth patterns for the design.



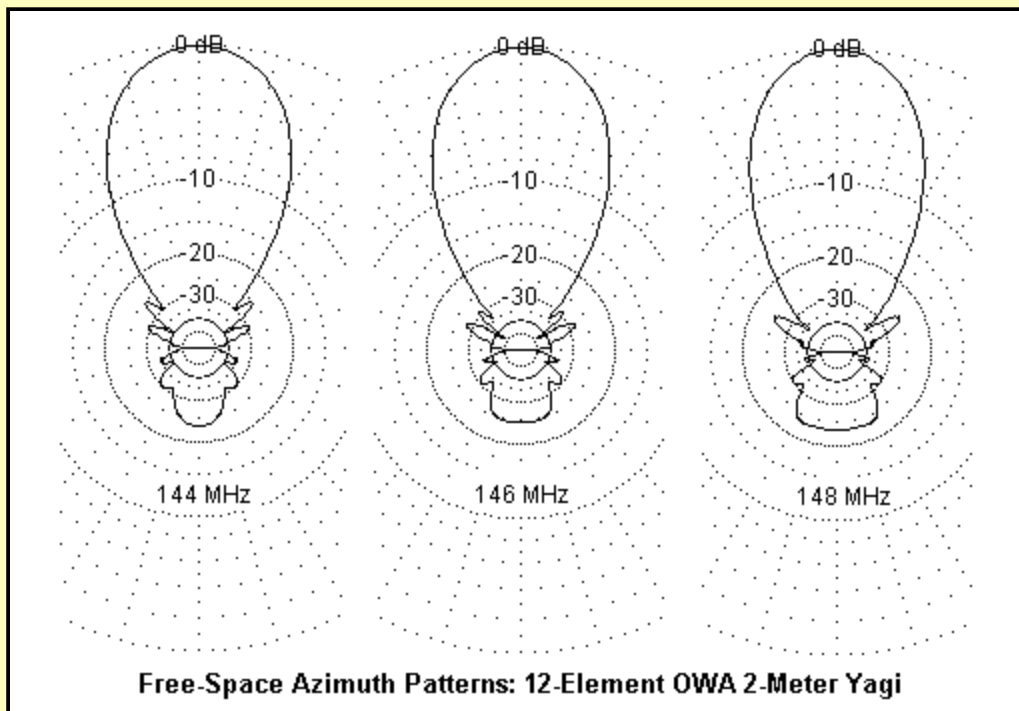
No. of elements: 12
 Element diameter: 0.1875" (3/16")
 Boom length: 238.00" (19.67')
 Maximum 50-Ohm SWR: 1.20:1

Dimensions (in inches):

Element	Length	Space from Reflector
Reflector	40.90	----
Driver	39.50	8.79
Director 1	37.00	13.47
Director 2	36.33	25.38
Director 3	36.40	40.72
Director 4	36.21	61.38
Director 5	35.20	86.49
Director 6	34.30	116.00
Director 7	33.60	146.60
Director 8	32.90	178.40
Director 9	32.20	210.00
Director 10	31.20	238.00

Modeled Performance

Parameter	144 MHz	146 MHz	148 MHz
Gain dBi	14.07	14.35	14.27
Max. 2ndary Lobe	-25.15	-28.04	-25.04
180-deg F-B	23.22	24.66	23.17
-3dB Beamwidth	38.4	36.8	35.6
Impedance (R+/-jX)	43.1 + j 4.8	47.4 + j 6.1	43.9 - j 3.9
50-Ohm SWR	1.20	1.15	1.17



The gain deficit of this array relative to the DL6WU ranges from 0.27 to 0.32 dB. In exchange for this small deficit, we obtain a 20-dB front-to-back ratio or better as the worst-case value across the band. The feedpoint impedance undergoes less change of reactance for a lower overall shift in the 50-Ohm SWR value. However, the improvement in this category relative to the DL6WU is, at best, marginal.

The free-space azimuth pattern graphic shows perhaps the greatest advantage of the present design: a better than 7 dB improvement in the suppression of forward side lobes to a worst-case value of -25.04 dB. All three patterns show a "normal" shape, with little or no tendency toward a bullet shape. The beamwidth is an average of 3 degrees wider than the standard long-boom Yagi design.

It perhaps would be foolhardy to make any claims to the effect that the increased beamwidth offered by better pattern control would yield significant operational benefits. It is the goal of a design exercise to explore what is possible, not to try to convert the possible into the operationally necessary.

An ideal Yagi would show no secondary lobes at all, either forward or rearward. In a survey of some 40 designs in my collection, I found the following pattern of lobe formation on each side of the main forward lobe to be generally, but not exclusively, true.

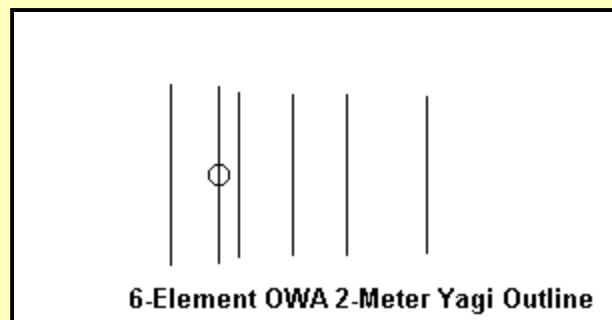
No. of Elements	No. of Secondary Forward Lobes
3-6	0
7-10	1
11-12	2
13-16	3
17-19	4
20-21	5
22-25	6
26-28	7
>28	9 or more

The table does not tell the entire story, since some designs showed as many as 4 additional side lobes relative to the numbers in the chart. As well, some designs displayed many small lobes, while others showed fewer wider lobes. In some cases, the lobes flowed into each other rather than being separately identifiable by intervening nulls. Nevertheless, of all of the original and modified

designs in my collection of models, the best values of secondary lobe suppression ran 18.5 dB and lower--usually considerably lower.

The "Extra Element" OWA Question

The fact that the 12-element OWA Yagi comes as close as it does to the gain of a standard wide-band Yagi raises one question about the foundations of OWA design as practiced in the HF region. The NW3Z/WA3FET designs for 20 meters use a 48' boom with 6 elements to achieve the gain and front-to-back values inherent in better 5-element designs of the same boom length. The OWA advantage lies in its control of the feedpoint impedance across the entirety of the 20-meter band, along with some smoothing of the gain and front-to-back values. In fact, the basic 6-element design can be scaled to 2 meters and then adjusted for the use of the (relatively) fatter 3/16" elements used throughout this series of Yagis. The results of this work appear in the graphics and tables that follow. We may note in passing that this 4.5' long Yagi is ripe for construction using a non-metallic boom.



No. of elements: 6
 Element diameter: 0.1875" (3/16")
 Boom length: 54.22 (4.52')
 Maximum 50-Ohm SWR: 1.23:1

Dimensions (in inches):

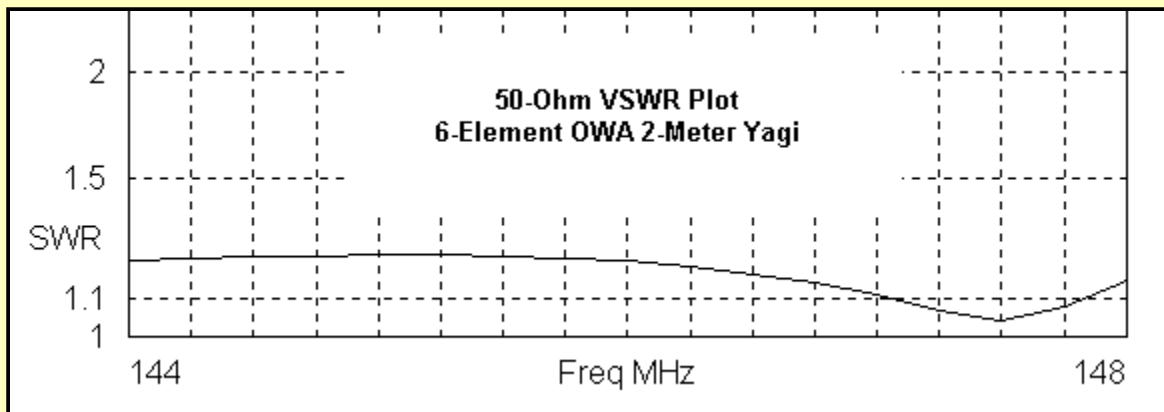
Element	Length	Space from Reflector
Reflector	40.52	----
Driver	39.96	10.13
Director 1	37.38	14.32
Director 2	36.31	25.93
Director 3	36.31	37.28
Director 4	34.96	54.22

Modeled Performance

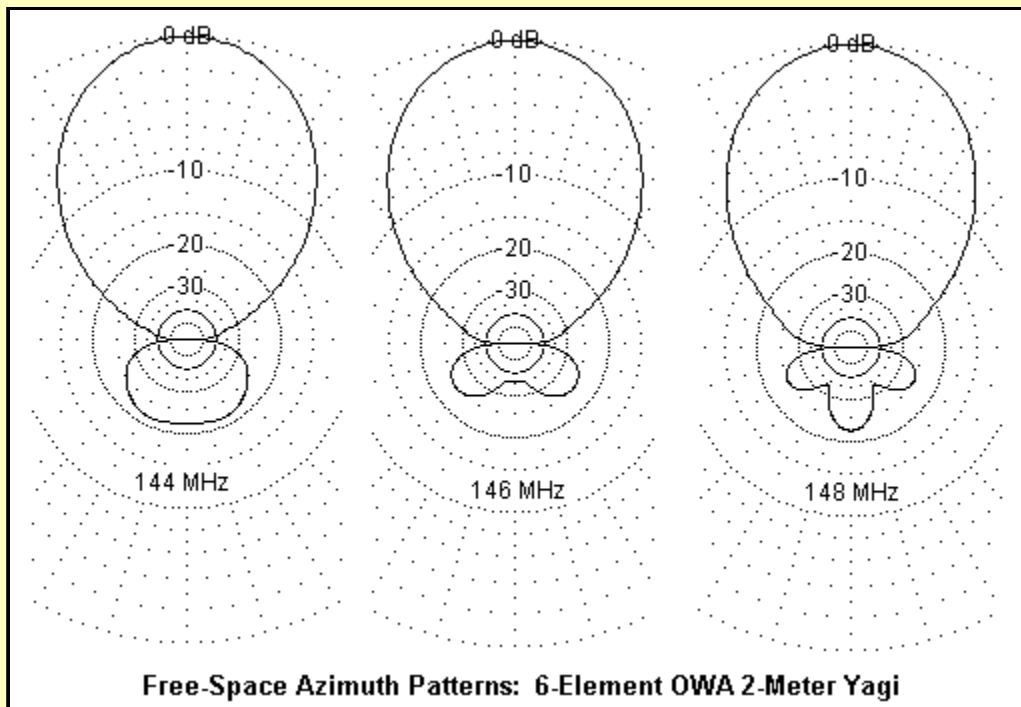
Parameter	144 MHz	146 MHz	148 MHz
Gain dBi	10.13	10.23	10.16
180-deg F-B	22.01	35.36	22.19
-3dB Beamwidth	54.0	52.6	51.4
Impedance (R+/-jX)	44.8 + j 7.6	50.0 + j 9.6	43.8 - j 1.6
50-Ohm SWR	1.22	1.21	1.15

If we compare the dimensions of the 6-element OWA Yagi with those of the "core" of the present series, we shall see differences that go beyond detail. The reflector is further back--0.125 wavelength behind the driver, while the first director is closer--0.052 wavelength in front. The element lengths also differ. The reflector is shorter (0.501 wavelength); the driver and first director are longer (0.494 and 0.467 wavelength, respectively). As well, the second and third directors are of equal length, in contrast to the longer second director of the long-Yagi core.

The difference in design lowers the overall gain of the array to what one might achieve in standard designs with 5 elements. However, the 6-element array decreases the gain change across the band to about 0.1 dB. The remaining values are comparable to those yielded by the selected core, as illustrated by the SWR curve.



The free-space azimuth patterns for the 6-element array do not directly reveal anything about the suppression of secondary lobes, since a 6-element Yagi does not ordinarily show any development in this direction. However, it may be well to keep these patterns at hand as we examine in Part 2 the full family of Yagis in the sequence headed by the 12-element version. Note that the 6-element patterns show no tendency toward a "bullet-shaped" pattern at the high end of the band. As a result, the -3 dB beamwidth changes by only 2.6 degrees across the 2-meter band.



We shall see in the next section of these notes that the 7-element Yagi that forms the foundation of the sequence has an inordinate gain improvement over the 6-element OWA Yagi we have just examined. We shall also see that achieving this extra gain--which obviates the need for an extra element--also pushes the pattern shape across the band toward a "bullet" pattern at the high end. As we add more elements, the bullet gradually diminishes so that by the time we reach the 12-element array at the head of the line, the pattern has returned to a well-behaved shape resembling that of the pattern at the low end of the band.

The question that remains--but which will not be addressed in these notes--is whether we might have obtained even better pattern control by using the 6-element Yagi as the foundation and holding the resulting arrays to normal or non-bullet patterns altogether. The decision to use the core that we examined earlier was based on the very significant improvement it offered. Further improvements using OWA techniques can be developed by other designers.

Thus, we have the rationale for the present exercise: to discover to what degree at least one OWA technique enables us to further suppress secondary lobes and "clean up" the typical long-boom Yagi pattern. In Part 2, we shall survey the entire set of Yagis for two purposes. First, we shall see

to what degree the technique works at each Yagi size. Second, we shall look at some designs that may be suited to those who cannot go the entire route toward a 20' boom.



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