Multiple Reflectors for Long-Boom Yagis

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On occasion, I have received inquiries of the following type: How much will the gain of my Yagi for [VHF/UHF] improve if I just add some additional reflectors?

From the start, such inquiries have usually struck me as strange, since I do not generally think of a reflector as a key element in the improvement of an array's gain. The reflector, in concert with the driver--and in OWA designs, all in concert with the first director--tends to function so as to set the Yagi feedpoint impedance. In designs within which the first director is primarily a gain and directivity element, the length and spacing of the reflector, relative to the driven element, tends to set the impedance such that a wider spacing increases the impedance and vice versa.

As well, the reflector may play a variable role in setting the front-to-back ratio of a Yagi. In some designs, the reflector plays only a small role: in concert with the forward-most director, change the lengths of the two elements can smooth out (or peak) the font-to-back ratio across a given design passband. However, the directors themselves tend to control the level of the front-to-back ratio. In one design exercise for 12 meters, a set of phased drivers with an inherent front-to-back ratio barely above 7 dB returned a front-to-back ratio of well over 20 dB when a director was added to the array. In other cases, the reflector specifications may be crucial in obtaining a desired front-to-back level.

Adding reflectors, then, seems most apt to obtaining a desired driver impedance or to obtaining a desired front-to-back performance. Gain improvements would seem secondary from the perspective that I normally take. However, we might reformulate the question to see if some design work might give us something useful by way of answer.

Defining the Supplemental Reflector Question

Suppose that we start with a very reasonable Yagi design. Since the question of multiple reflectors arises most normally in the VHF and UHF region, let's use a 12-element Yagi with a boom length of about 2.94 wl. The design employs an OWA driver/reflector/first-director combination to provide a 50-Ohm impedance with an SWR under 1.2:1 across the 222-225-MHz spread. Hence, in the arena of setting the feedpoint impedance, there is little that additional reflectors could do to improve the situation.

As well, the array--ignoring any construction variables that might alter modeled specifications--shows better than 23 dB front-to-back ratio across the band--whether we take a 180-degree or worst-case slant on the front-to-back ratio. Although 20 dB is a typical radio amateur boundary between good performance and otherwise in this department, it is possible that further improvement might tweak a G/T (gain vs. thermal loss) calculation.

The array gain in free-space models runs between 14.24 dBi at the upper end of the band and 14.34 dBi at the lower end, with a peak of 14.36 dBi at band center. These figures have more precision than operationally useful, but do indicate the slope of the gain curve. Hence, we may retain them for this study.

Equally of note in the initial Yagi design is the secondary forward lobe performance. Many high gain designs have secondary forward lobes that are down by only 12-18 dB from the main forward lobe. The OWA-based design provides additional attenuation of these lobes to the -25 dB or better level.

To the existing array, we shall make no changes. Instead, we shall simply add a pair of reflector elements above and below the existing reflector. We shall seek out the length and position that optimizes performance best. Position here shall mean two things: the alignment of the reflectors with the original reflector and the vertical distance between the original and new reflectors. The general outline of the two arrays appears in **Fig. 1**.

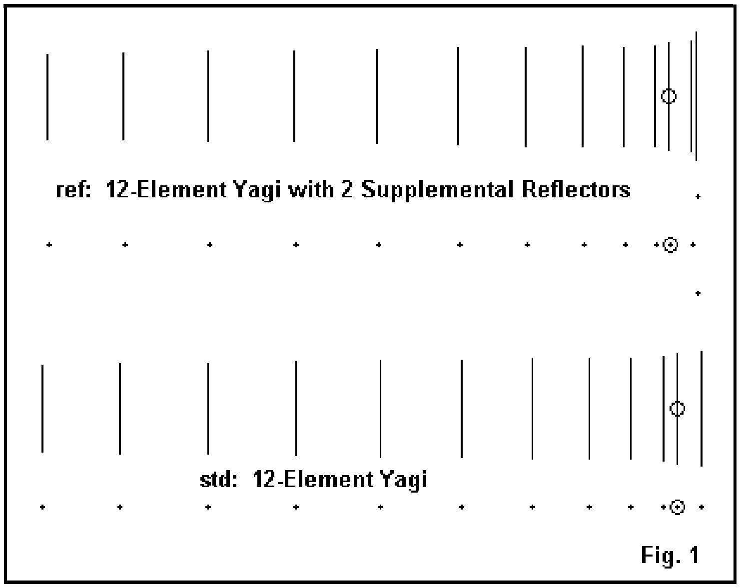


Fig. 1

Due to the graphing limitations in the software from which the outlines are taken, the "std" or original array does not line up exactly with the corresponding elements on the "ref" or supplemented array. However, the dimensions and positions of the original 12 elements have not changed.

Wires

Wire Other — Standard 12-Elements

Coord Entry Mode — Preserve Connections

Fig. 2

No.	End 1 X (in)	End 1 Y (in)	End 1 Z (in)	End 1 Conn	End 2 X (in)	End 2 Y (in)	End 2 Z (in)	End 2 Conn	Diameter (in)	Segs
1	-13.4491	0	0		13.4491	0	0		0.125	21
2	-12.9887	5.78212	0		12.9887	5.78212	0		0.125	21
3	-12.167	8.85899	0		12.167	8.85899	0		0.125	21
4	-11.9457	16.6905	0		11.9457	16.6905	0		0.125	21
5	-11.9686	26.7813	0		11.9686	26.7813	0		0.125	21
6	-11.9075	40.3681	0		11.9075	40.3681	0		0.125	21
7	-11.5748	56.8802	0		11.5748	56.8802	0		0.125	21
8	-11.2788	76.2883	0		11.2788	76.2883	0		0.125	21
9	-11.0487	96.4126	0		11.0487	96.4126	0		0.125	21
10	-10.8185	117.326	0		10.8185	117.326	0		0.125	21
11	-10.5883	138.108	0		10.5883	138.108	0		0.125	21
12	-10.2595	156.523	0		10.2595	156.523	0		0.125	21

Fig. 2 provides an EZNEC Pro wire table for the original array, with all dimensions in inches. This wire structure, using 1/8" aluminum elements, is the basis for what follows.

Wires

Wire Other

12-Elements Plus 2 Offset Reflectors

Coord Entry Mode Preserve Connections

Fig. 3

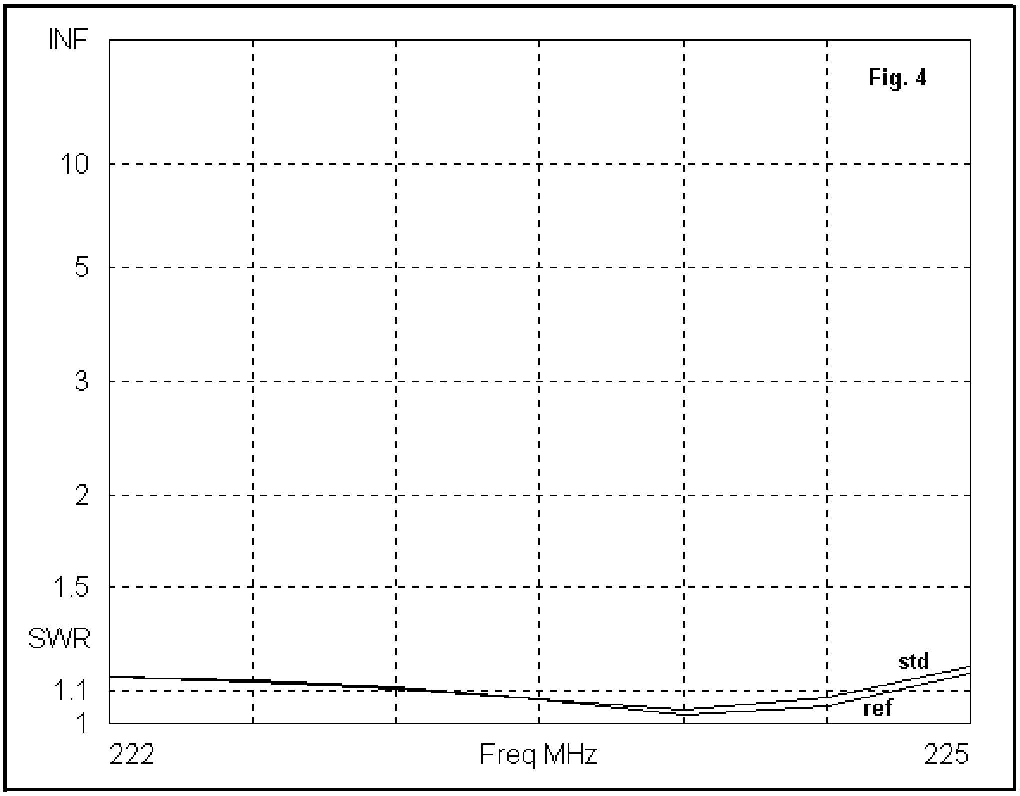
No.	End 1				End 2				Diameter	Segs
	X (in)	Y (in)	Z (in)	Conn	X (in)	Y (in)	Z (in)	Conn	(in)	
1	-15.3543	-1.1811	11.811		15.3543	-1.1811	11.811		0.125	21
2	-15.3543	-1.1811	-11.811		15.3543	-1.1811	-11.811		0.125	21
3	-13.4491	0	0		13.4491	0	0		0.125	21
4	-12.9887	5.78212	0		12.9887	5.78212	0		0.125	21
5	-12.167	8.85899	0		12.167	8.85899	0		0.125	21
6	-11.9457	16.6905	0		11.9457	16.6905	0		0.125	21
7	-11.9686	26.7813	0		11.9686	26.7813	0		0.125	21
8	-11.9075	40.3681	0		11.9075	40.3681	0		0.125	21
9	-11.5748	56.8802	0		11.5748	56.8802	0		0.125	21
10	-11.2788	76.2883	0		11.2788	76.2883	0		0.125	21
11	-11.0487	96.4126	0		11.0487	96.4126	0		0.125	21
12	-10.8185	117.326	0		10.8185	117.326	0		0.125	21
13	-10.5883	138.108	0		10.5883	138.108	0		0.125	21
14	-10.2595	156.523	0		10.2595	156.523	0		0.125	21

Fig. 3 shows the corresponding wire table for the 14-element array, with the 2 new reflectors listed as wires 1 and 2. Notice that they are slightly behind the original reflector and considerably separated from it vertically. The 13' long Yagi now becomes nearly 2' high as a result of adding the reflectors.

Besides their positions, also note the length of the added reflectors, which are significantly longer than the original reflector. I adjusted the position and length of the reflectors to obtain the best combination of gain, front-to-back ratio, and feedpoint impedance possible. In their present positions, changes of new reflector length shows a slight drop in gain. However, it might also be possible to continue working with the reflector specifications to obtain further increases in performance. These notes are a preliminary investigation and the results are suggestive, but in no way final. However, see the added notes near the end.

Potential Performance Comparisons

One critical factor remained a constant: the added reflectors should result in a feedpoint impedance range that resulted in a 50-Ohm SWR curve no worse than that of the original array. **Fig. 4** shows the remarkably coincident curves that resulted.



The following table compares the impedance and SWR values at the band edges and center.

Antenna	STD		REF	
Frequency	R+/-jX Ohms	SWR	R+/-jX Ohms	SWR
222	47.5 + j 6.1	1.14	49.5 + j 6.8	1.15
223.5	48.9 + j 3.3	1.07	51.2 + j 3.4	1.07
225	43.6 - j 4.2	1.18	45.5 - j 5.3	1.16

Then what, if anything, did we obtain for our trouble? To answer this question, let's look at the relevant data in both tabular and graphical formats.

In the following table, the following column headings will apply: GN = free-space forward gain in dBi; B/W = -3 dB horizontal beamwidth in degrees; FB 180 = 180-degree front-to-back ratio in dB; FB W-C = worst case front-to-back ratio in dB; S/L = front-to-(forward)-side-lobe ratio in dB.

Parameter	GN	B/W	F-B 180	F-B W-C	S/L
STD					
222	14.34	36.8	24.65	24.53	27.85
223.5	14.36	36.2	24.59	24.12	26.57
225	14.24	35.4	23.08	23.08	24.97
REF					
222	14.44	36.8	31.25	31.25	28.09
223.5	14.46	36.2	34.73	34.16	26.64
225	14.34	35.6	34.21	31.41	24.88

The constant gain increase resulting from placing and optimizing the 2 new reflectors is 0.10 dB. As expected, the gain increase is itself not significant enough to call for the additional two elements. Likewise, the beamwidth does not change at all (0.2 degrees at 225 MHz). Moreover, the forward side lobe performance also fails to change significantly.

However, the front-to-back ratio shows a more dramatic increase with the addition of the new elements. The average increase in the 180-degree ratio is 9.3 dB, while the average improvement of the worst-case value is nearly 8.4 dB. (It may be useful to note that in optimizing the front-to-back ratio, the worst-case value was equalized to the degree possible at the band edges.)

Before commenting further on these results, let's examine them as annotated free-space azimuth (E-plane) patterns. Comparing the std and ref patterns may provide additional insight into what has happened as a result of adding the new reflectors.

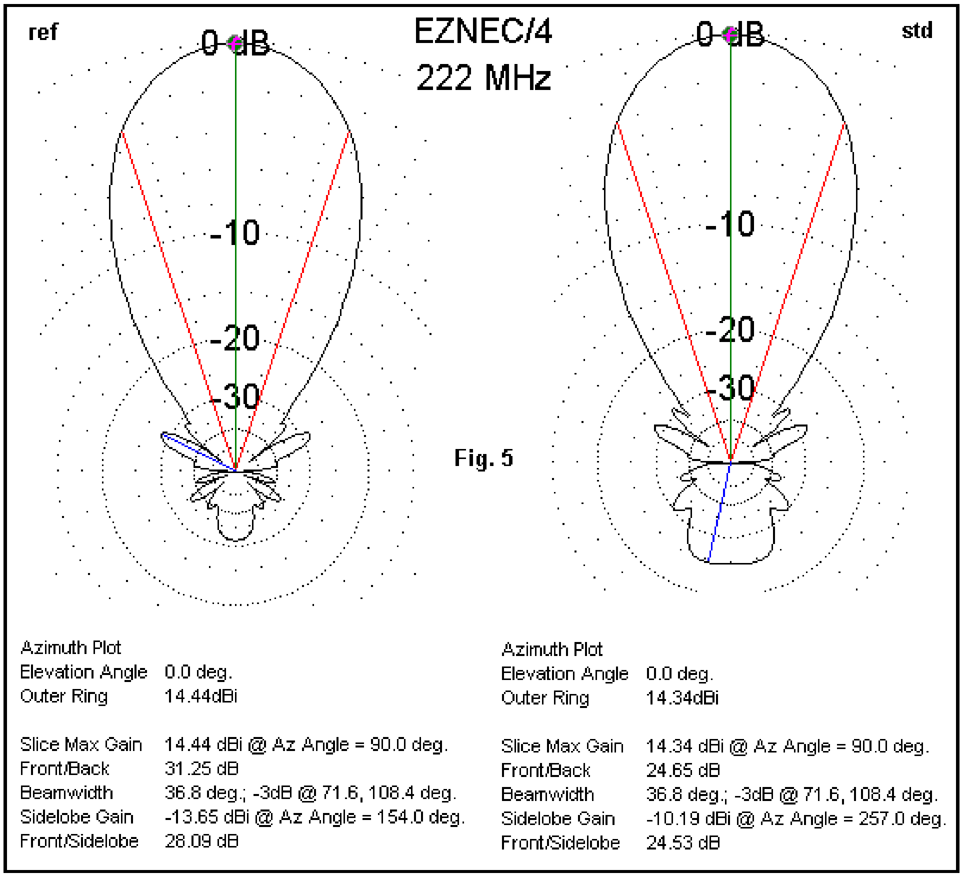


Fig. 5 shows the corresponding patterns at 222 MHz. Most notable is the shrinkage of the main rear lobe, but without significant effect on the rear side lobes. The strongest rear side lobes remain virtually as strong in both patterns, although the main lobe shrinkage makes those lobes more vivid for the ref model. In fact, a new set of rear side lobes, swallowed by the main lobe in std, becomes evident in ref.

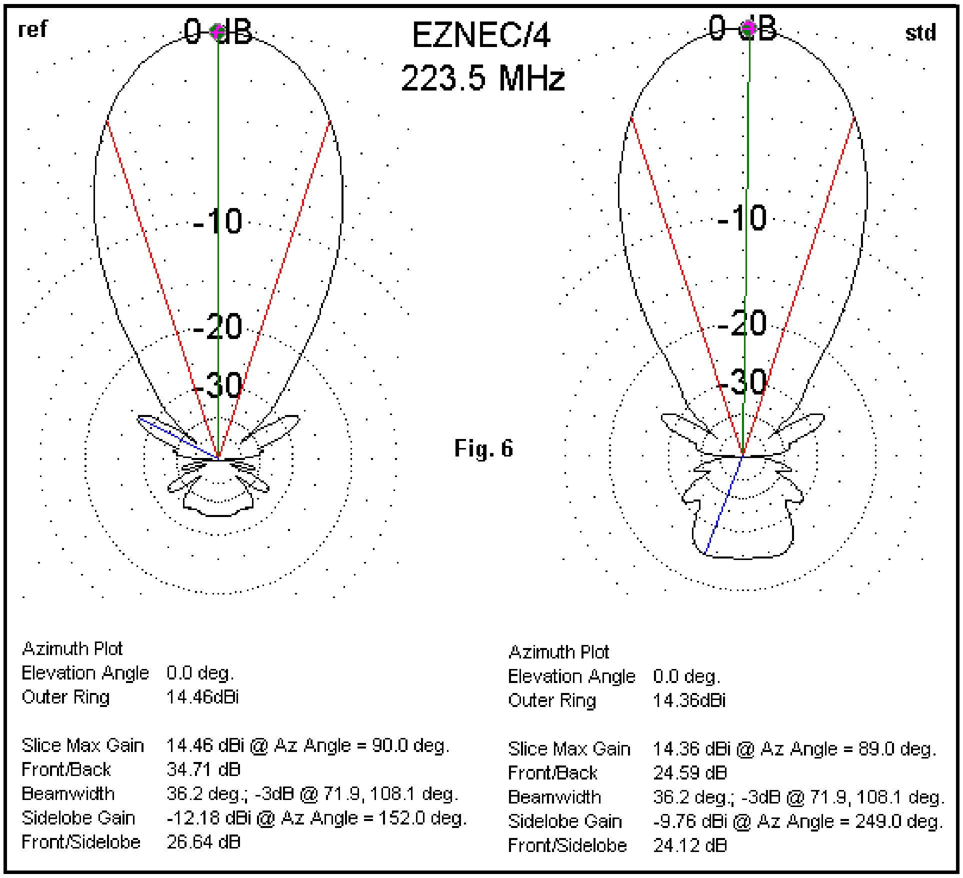


Fig. 6 reveals something about the main rear lobe of both models. The seemingly insignificant spread of the main rear lobe for std turns out to have some importance, as revealed by the "fan" shape of the main rear lobe in ref. At 223.5 MHz, the ref array reaches peak performance in both forward and rearward directions. Hence, the secondary rearward lobes also show some noticeable improvement--however marginal the exact numbers--relative to those same lobes in std. However, there is virtually no change on the forward lobe structure of the array.

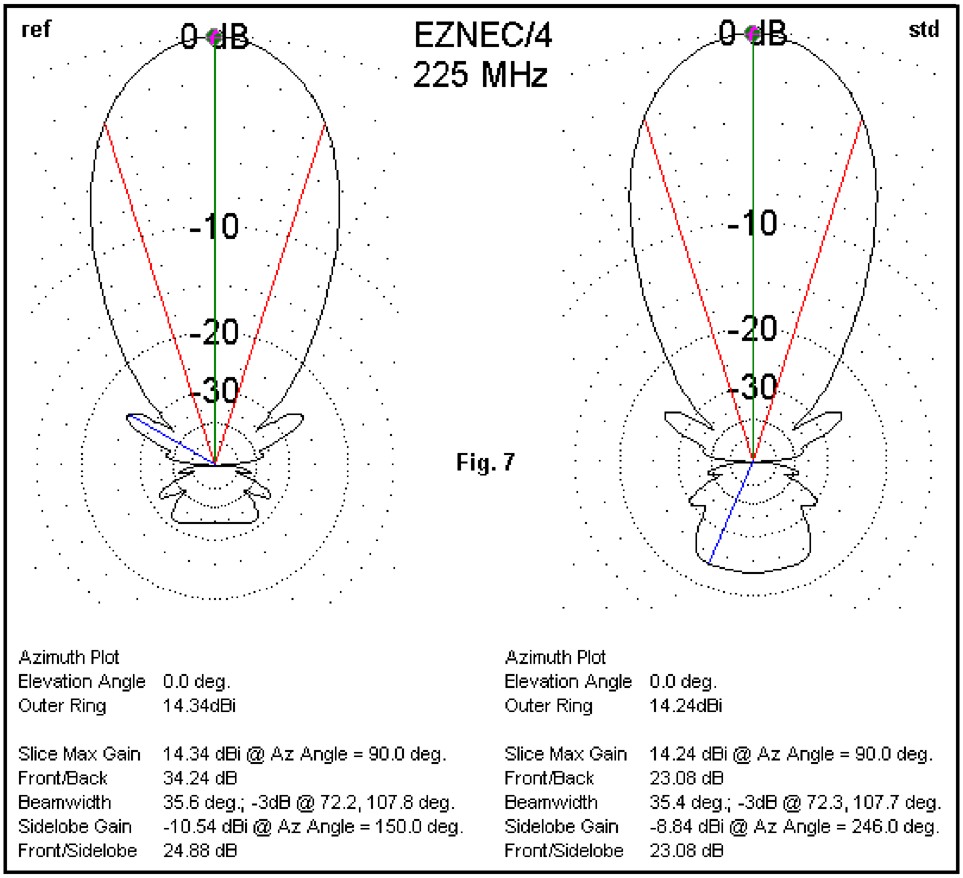


Fig. 7, the comparison at 225 MHz, shows a continuation of the features so far noted. The rear quadrants show considerably less energy in ref than in std, despite an absence of change to the forward lobe structure. One reason--subject to full analysis of a 3-dimensional pattern set--that so little gain is added to the forward lobe is that the original rear lobes initially had so little energy. At well over 20 dB down from the main lobe, a further increase in front-to-back ratio of 10 dB leaves little energy to add to the array's forward gain.

Indeed, even had the new reflectors reduced all side lobes to near-zero values, the array would still have shown little further forward gain. The key to adding such gain would be a further reduction in the -3 dB beamwidth, which seems beyond the powers of new reflector elements to influence. Essentially, only the director structure of the array might accomplish that feat.

However, for some possible applications, the absence of a significant increase in forward gain may not be sufficient reason to ignore the addition (and further perfection) of the new reflector elements. To the degree that the best weak signal reception performance requires us to minimize all pattern lobes except the main forward lobe, the improvements in front-to-back ratio may be operationally significant. Indeed, the rear lobe structure of ref suggests that some further reductions may be possible without jeopardizing other performance factors.

Exploring Supplemental Reflector Performance With Model Variables

Perhaps the simplest way to accomplish this task as an initial modeling design effort is to transfer the model to a program accepting variables and equations. Despite the graphical representation of results in EZNEC Pro, I actually did the design revisions using NEC-Win Plus, using the model-by-equation facility.

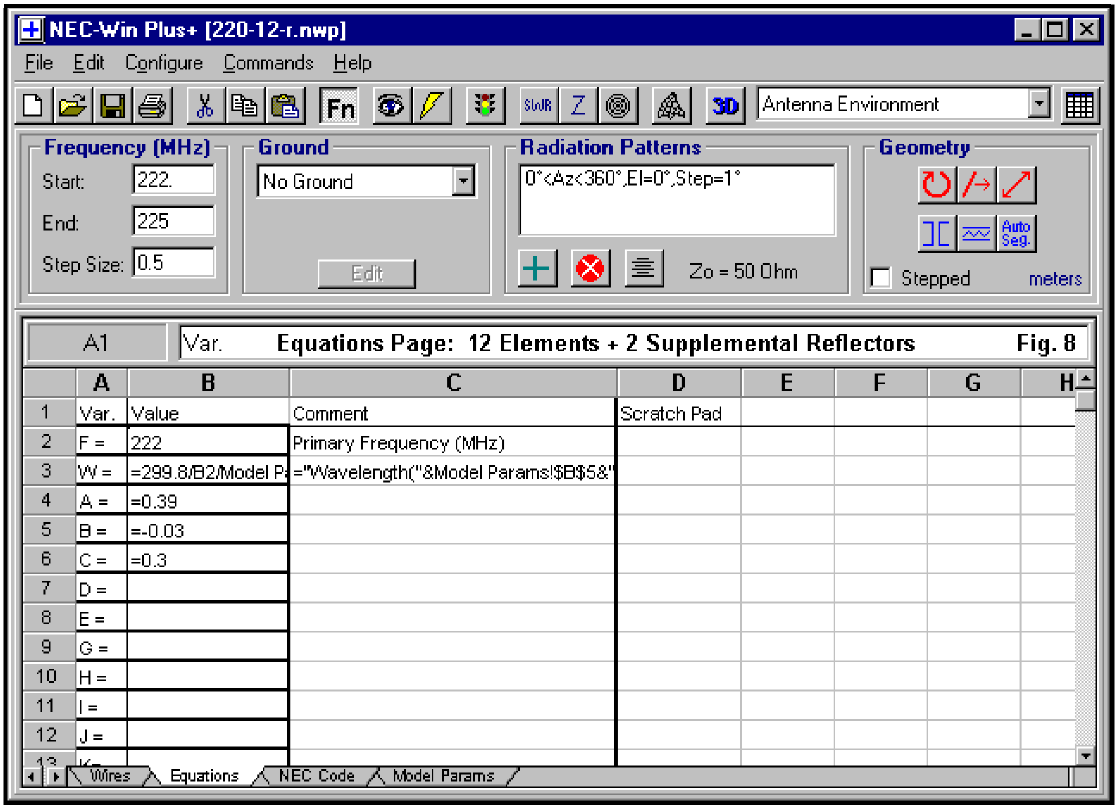
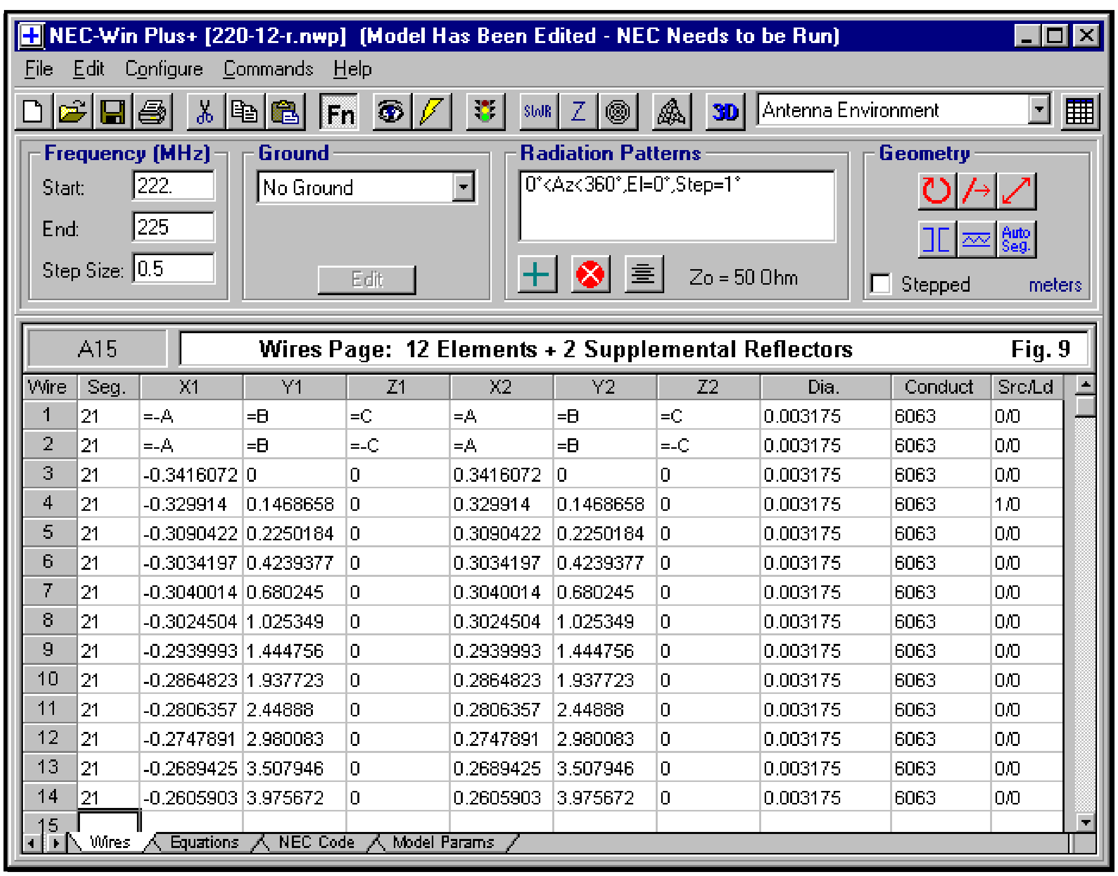


Fig. 8 shows the very simply equations page, with 3 variables, A, B, and C. A is the element half length in meters (the default unit of .NEC-format conversion from EZNEC to NEC-Win). B is the distance along the Y-axis, where a value of zero would align the new reflectors with the old. C is the vertical separation of each reflector above and below the plane of the other elements.



The wires page, **Fig. 9**, shows the variable placement for the two new elements. The element length coordinates appears as A and -A. Likewise, the upper and lower new reflectors are at C and -C. Note that in this initial exercise, I did not alter the placement of length of the original reflector. In a full scale study, one might wish to convert this element to a set of variables and adjust its specifications. (Since the original reflector was crucial to obtaining the impedance curves across the passband, I left it unchanged as the simplest means of sustaining those curves.)

Since NEC-Win Plus uses NEC-2, I transferred the final optimized dimensions back to EZNEC Pro, using NEC-4, so that all numbers would emerge from the same calculating engine.

The Performance of a Single Added Reflector

Although the improvements to the front-to-back ratio are directly attributable to the added reflectors forming a roughly vertical plane with the original reflector, the question arose as to whether we might obtain similar results with a single new in-plane reflector. I therefore simplified the model in NEC-Win and tried to optimize a single reflector placed immediately behind the original. **Fig. 10** shows the resulting wire table.

Wires

Wire Other

12-Elements Plus 1 In-Line Reflector

Coord Entry Mode Preserve Connections

Fig. 10

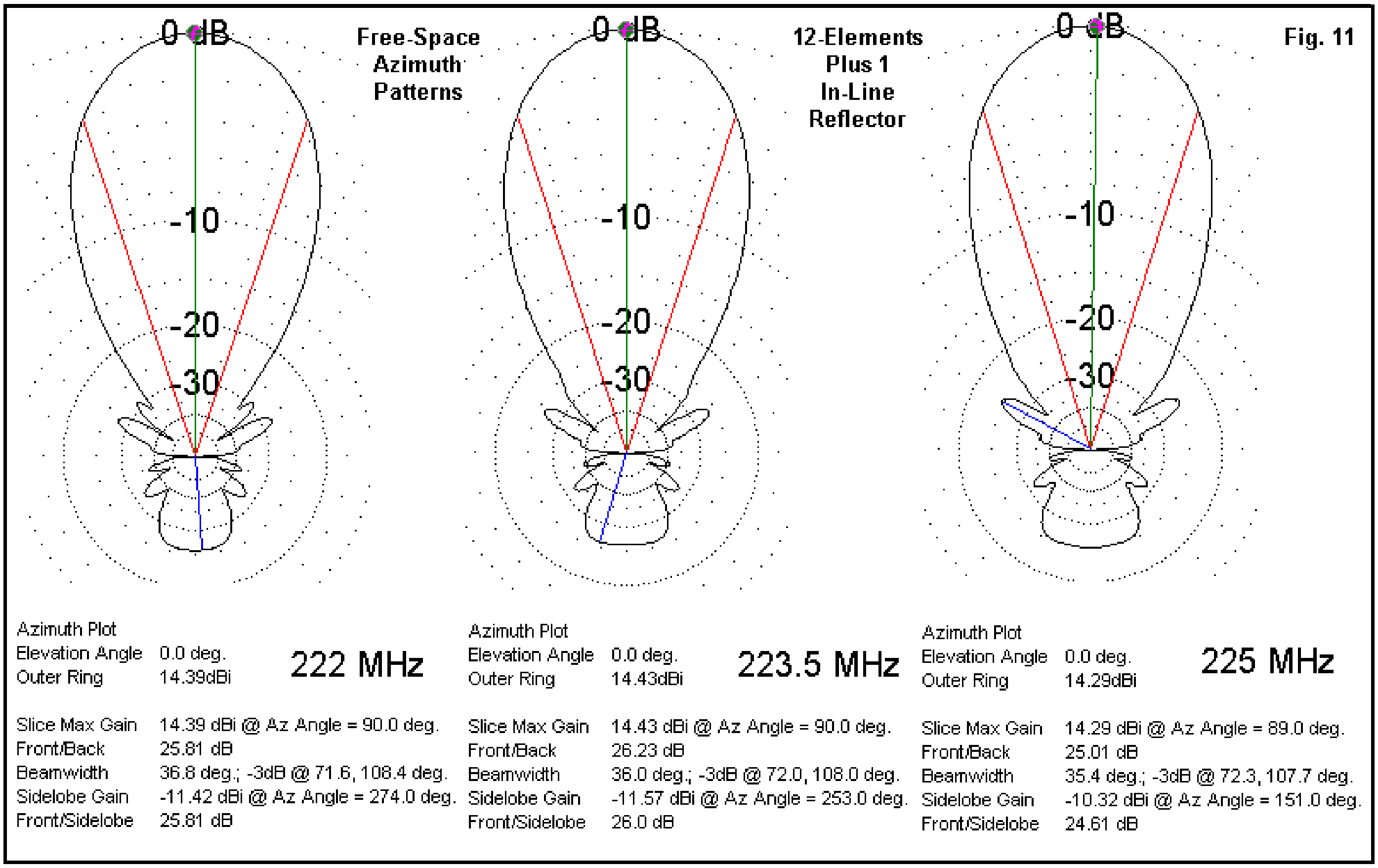
Wires

No.	End 1				End 2				Diameter	Segs
	X (in)	Y (in)	Z (in)	Conn	X (in)	Y (in)	Z (in)	Conn	(in)	
1	-13.189	-9.44882	0		13.189	-9.44882	0		0.125	21
2	-13.4491	0	0		13.4491	0	0		0.125	21
3	-12.9887	5.78212	0		12.9887	5.78212	0		0.125	21
4	-12.167	8.85899	0		12.167	8.85899	0		0.125	21
5	-11.9457	16.6905	0		11.9457	16.6905	0		0.125	21
6	-11.9686	26.7813	0		11.9686	26.7813	0		0.125	21
7	-11.9075	40.3681	0		11.9075	40.3681	0		0.125	21
8	-11.5748	56.8802	0		11.5748	56.8802	0		0.125	21
9	-11.2788	76.2883	0		11.2788	76.2883	0		0.125	21
10	-11.0487	96.4126	0		11.0487	96.4126	0		0.125	21
11	-10.8185	117.326	0		10.8185	117.326	0		0.125	21
12	-10.5883	138.108	0		10.5883	138.108	0		0.125	21
13	-10.2595	156.523	0		10.2595	156.523	0		0.125	21
*										

Wire 1 is the new reflector. Note that it is shorter than the original. As well, it is at a considerable distance from the original reflector, lengthening the boom by over 9". The position and length of the new reflector were the best obtainable without modifying the original reflector. The following table summarizes the data from the model (omitting the impedance and SWR data, which did not change).

Parameter	**GN**	**B/W**	**F-B 180**	**F-B W-C**	**S/L**
1-REF					
222	**14.39**	**36.8**	**25.81**	**25.81**	**27.61**
223.5	**14.43**	**36.2**	**26.23**	**26.00**	**26.28**
225	**14.29**	**35.4**	**25.01**	**25.01**	**24.61**

Once more, gain does not change by much--0.05 dB above std. As well, the beamwidth and side-lobe performance remain constant with std. The average 180-degree front-to-back ratio improves by only 1.6 dB, while the average worst-case front-to-back ratio improves by 1.7 dB. In short, the addition of an in-plane reflector provides little improvement in overall performance while lengthening the array weight and length. **Fig. 11** provides E-plane patterns for comparison with the one marked std and ref.



No fixed and final conclusions emerge from this preliminary study of adding reflectors to long VHF and UHF Yagis. The work does suggest that relative to reasonably well-designed single-reflector in-plane Yagis, added vertical plane reflectors offer little to improve gain, beamwidth, side-lobes, or impedance concerns. Some of the illusion that they might create notable improvements in any of these areas certainly stems from lack of complete information on the part of inquirers. However, some of the impression may also result from comparing lesser in-plane designs with perfected designs using added reflectors.

At this juncture, subject to change with time and further investigation, the real contribution of added reflectors appears in the reduction of rear lobe radiation. In many single-reflector designs, the interests of maximizing gain has resulted in relatively poor rearward performance. Even the design called std in these notes can use improvement if employed in the most demanding weak signal applications. to this end, the addition of vertical-plane reflectors can improve the antenna performance without detracting from other performance goals of the design. And it is here that added vertical-plane reflectors may have their best use.

Supplemental Notes on "Ultimate Front-to-Back" Performance

It struck me that the data presented in the above notes is incomplete. We have not explored the H-plane (or free-space elevation) pattern results of adding the supplemental reflectors. At the same time, the failure to reach something close to ultimate front-to-back performance also bothered me (or my sense of orderliness in bringing the small and provisional test to completion).

Therefore, I returned to the NEC-Win model and its variables, seeking the maximum front-to-back performance that I could generate with 2 supplemental reflectors--without jeopardizing the improvements, such as they are, in forward performance. **Fig. 12** provides a wire table (in EZNEC format) for the results of these attempts to "perfect" the model.

Wires

Wire Other

☐ Coord Entry Mode ☐ Preserve Connections

2 Supplemental Reflectors
"Ultimate F-B"
Fig. 12

No.	End 1 X (in)	End 1 Y (in)	End 1 Z (in)	End 1 Conn	End 2 X (in)	End 2 Y (in)	End 2 Z (in)	End 2 Conn	Diameter (in)	Segs
1	-1.1811	15.1575	14.5669		-1.1811	-15.1575	14.5669		0.125	21
2	-1.1811	15.1575	-14.5669		-1.1811	-15.1575	-14.5669		0.125	21
3	0	13.4491	0		0	-13.4491	0		0.125	21
4	5.78213	12.9887	0		5.78213	-12.9887	0		0.125	21
5	8.85898	12.167	0		8.85898	-12.167	0		0.125	21
6	16.6905	11.9457	0		16.6905	-11.9457	0		0.125	21
7	26.7813	11.9685	0		26.7813	-11.9685	0		0.125	21
8	40.3681	11.9075	0		40.3681	-11.9075	0		0.125	21
9	56.8802	11.5748	0		56.8802	-11.5748	0		0.125	21
10	76.2883	11.2788	0		76.2883	-11.2788	0		0.125	21
11	96.4126	11.0487	0		96.4126	-11.0487	0		0.125	21
12	117.326	10.8185	0		117.326	-10.8185	0		0.125	21
13	138.108	10.5883	0		138.108	-10.5883	0		0.125	21
14	156.523	10.2595	0		156.523	-10.2595	0		0.125	21
*										

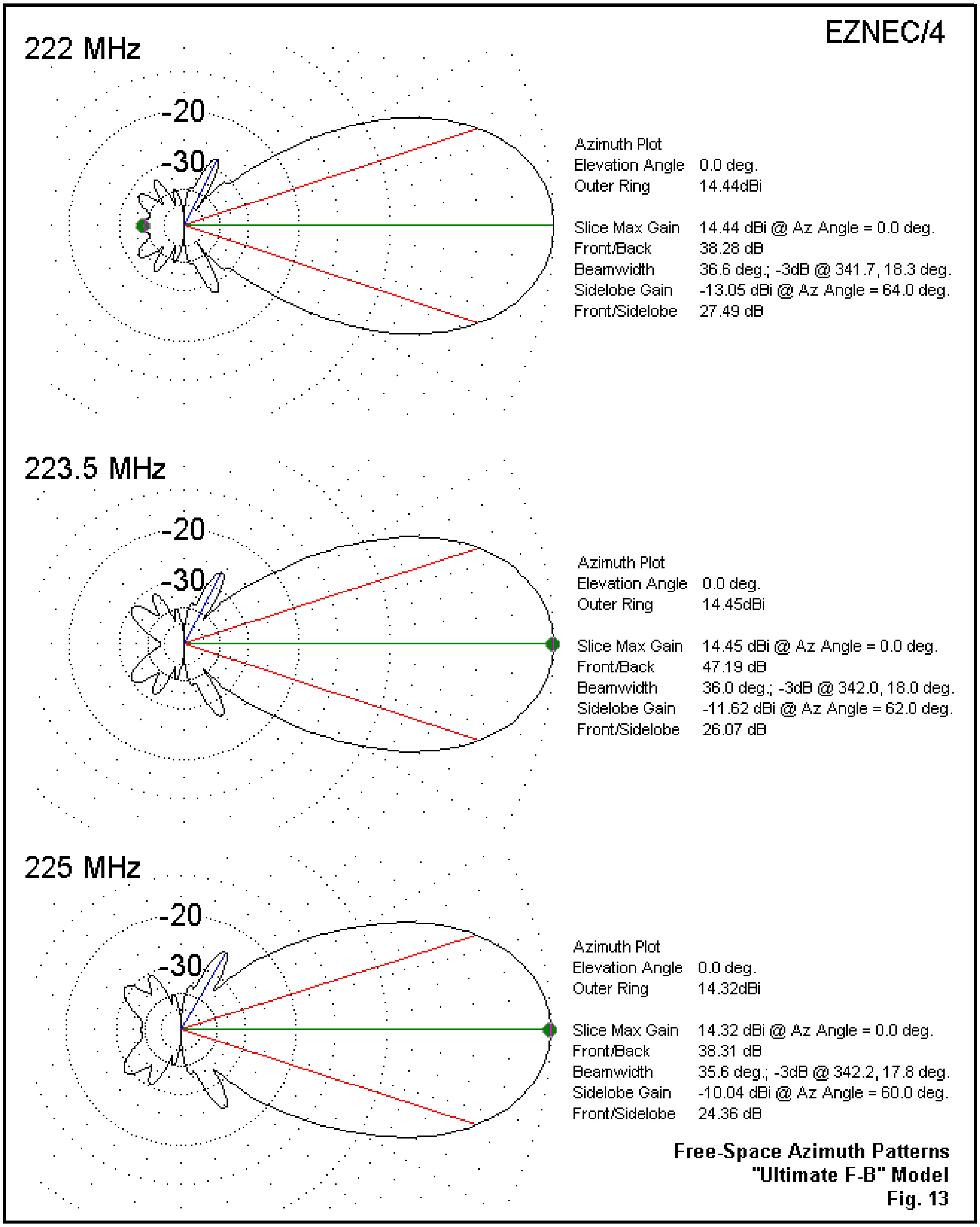
If you compare this model with the earlier provisional supplemental reflector model, you will discover that only one parameter has changed: the vertical distance between each new reflector and the plane of the standard Yagi. The increase is nearly 25%. The reflector lengths remain within 1% of their previous values. Also constant is the distance from the original reflector in the array plane, although this distance is less sensitive to change than the element length.

The resulting SWR curve is well within the project specifications, as revealed by the following table (where STD represents the original Yagi and ULT refers to the freshly modified version).

Antenna	STD		ULT	
Frequency	**R+/-jX Ohms**	**SWR**	**R+/-jX Ohms**	**SWR**
222	**47.5 + j 6.1**	**1.14**	**49.4 + j 5.9**	**1.12**
223.5	**48.9 + j 3.3**	**1.07**	**50.8 + j 2.5**	**1.05**
225	**43.6 - j 4.2**	**1.18**	**44.8 - j 5.8**	**1.18**

The following table compares the performance values of all 3 arrays, with STD giving us a reference baseline, while REF and ULT let us see what further improvements we may make and where the limits may lie.

Parameter	GN	B/W	F-B 180	F-B W-C	S/L
STD					
222	**14.34**	**36.8**	**24.65**	**24.53**	**27.85**
223.5	**14.36**	**36.2**	**24.59**	**24.12**	**26.57**
225	**14.24**	**35.4**	**23.08**	**23.08**	**24.97**
REF					
222	**14.44**	**36.8**	**31.25**	**31.25**	**28.09**
223.5	**14.46**	**36.2**	**34.73**	**34.16**	**26.64**
225	**14.34**	**35.6**	**34.21**	**31.41**	**24.88**
ULT					
222	**14.44**	**36.6**	**38.28**	**32.96**	**27.49**
223.5	**14.45**	**36.0**	**47.19**	**30.31**	**26.07**
225	**14.32**	**35.6**	**38.31**	**28.50**	**24.36**



Free-Space Azimuth Patterns
"Ultimate F-B" Model
Fig. 13

Fig. 13 provides sample free-space azimuth (E-plane) patterns for the array at each frequency. Of special note with respect to our project of increasing the front-to-back ratio is the fact that, although we indeed significantly increased the 180-degree front-to-back ratio, we did not improve the worst-case value. In fact, above 222 MHz, the worst-case value actually goes down. However, the total energy to the real remains lower, as may be evident from comparing the rearward quadrants of ULT and REF in their respective azimuth patterns.

Whatever the improvement, it comes at a cost. First, the forward gain shows signs of a decrease--as yet imperceptible in operation, but numerically significant in terms of optimizing an array. Second, the sidelobe performance is beginning to deteriorate slightly, as revealed by a comparison of the side-lobe values in REF and ULT. In the ULT model, neither of these decreases has yet reached a level that would count against carrying the supplemental reflector design process to the ULT values.

The supplemental reflectors also have a benefit for the free-space elevation (or H-plane) pattern of the array. **Fig. 14** shows that benefit.

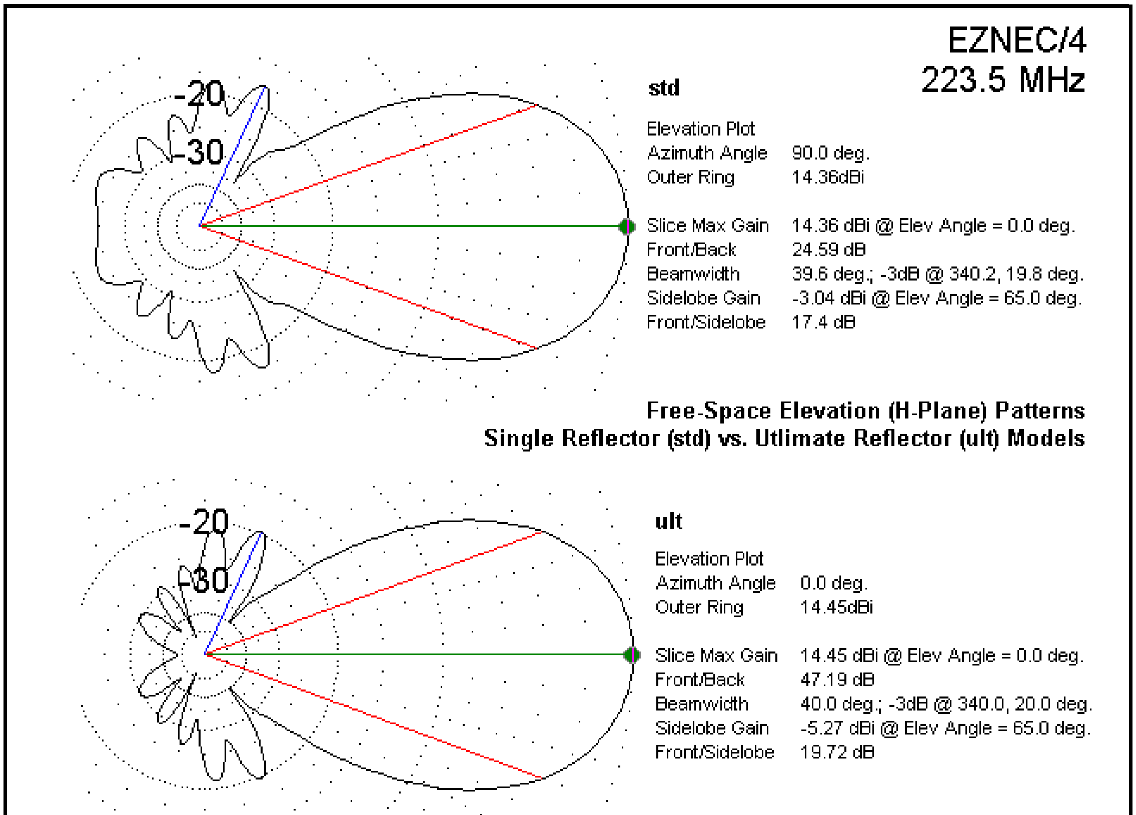


Fig. 14

The figure compares the 223.5-MHz elevation patterns for STD and ULT. The improvement in the rear-most portion of the pattern is clear, as the large main rear lobe of STD devolves into a collection of smaller lobes. However, we should also attend to the secondary forward lobes in the H plane--a pair above and below the plane of the array. Each member of the set shows at least 2-dB improvement due to the presence of the added reflectors. At the same time, the main forward lobe shows a slight increase in beamwidth. Yagi design has, to a very large measure, tended to ignore H-plane performance, since it has been viewed as somewhat beyond effective control. The element ends in the E-plane constitute the chief controls in forming the azimuth pattern. To the degree that the azimuth pattern shows a stronger forward lobe, the beamwidth and the side lobes in the H plane follow suit, although imperfectly, if the evidence of the STD pattern is any indicator. The supplemental reflectors outside the main array plane provide some added control of the H-plane side lobes. However, it remains to the future to see what other steps might be taken to reduce the vertical side-lobes even further. The Yagi has been traditionally viewed as a 2-dimensional array, and modern long-boom Yagi design is approaching the limits of what can be obtained by varying only element lengths and spaces. The addition of supplemental reflectors has shown some promise of improved front-to-back performance, but only up to a limit. Perhaps the key break in past Yagi thinking lies in the potential of supplemental elements above and below the plane of the directors to improve both vertical side-lobe performance. What form Yagi-Uda arrays may someday take lies in future design efforts as we begin to think of the parasitic array as a 3-dimensional antenna.