Stacking Yagis: What can I Expect

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If you are contemplating stacking Yagis and feeding them both in and out of phase, you will need some reasonable expectations about stack performance as one element in the decision-making process. The following notes, drawn from modeling a number of kinds of stacks, may be useful in this regard. It is also recommended that you compare this modeling data with both the modeling and performance data obtained by N6BV and K1VR in 1994. [1]

Stacking and Modeling

Traditional wisdom of stacking suggests that for a stack of 2 Yagis, “BIP BOP BOT TOP” provides a way of accessing signals arriving at various skip angles. By switching among both antennas in phase (BIP), both antennas out of phase (BOP), bottom antenna only (BOT), and top antenna only (TOP), one might have access to different elevation angles to maximize signal strength as band conditions change. As the size of stacks increases, the number of options increases, as does switching complexity. How many of these options have any potential of improving operation?

The answer to this question involves many factors, including antenna and tower design, terrain, and location relative to one’s target station areas. No single study can provide definitive answers. Indeed, without some knowledge of skip elevations relevant to various paths and frequencies, one cannot assess whether any of the BIP BOP elevation angles are useful. However, modeling offers a means of establishing some reasonable initial expectations, which may contribute to the answer, which is correct for a particular station.

I modeled two different beams in various stacks. All models consisted of aluminum Yagis at a frequency of 14.175 MHz. The results are scalable to any of the upper HF bands if heights are read as fractions of a wavelength rather than as so many feet above ground. Modeling was done on NEC-4 (EZNEC Pro from W7EL) over average Sommerfeld-Norton ground (conductivity 0.005 S/m; dielectric constant 13). I used two Yagi models, both derived indirectly from K6STI. The smaller beam is a 3-element Yagi on a 24' boom with good gain and front-to-back ratio, along with a convenient native feedpoint impedance of 25 W. This antenna is a modification of a K6STI model included with a version of AO5. The larger beam is a 5-element Yagi designed by W3LPL on YO and has a resonant feedpoint impedance of about 36.7 W. **Figure 1** shows the contrast in the two beams.

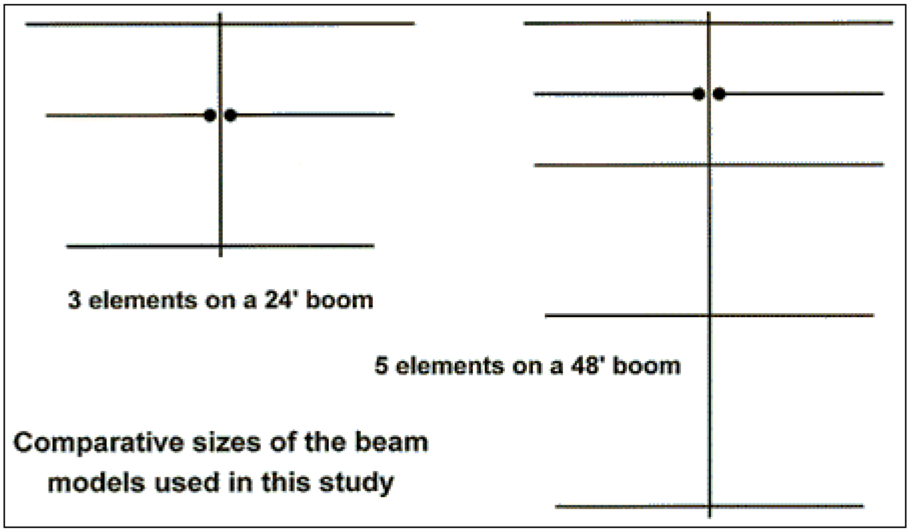

Fig 1—Comparative sizes of the beam models used in this study.

Since NEC transmission lines are mathematical models rather than physical models, phasing consisted of bringing two or more quarter wavelength transmission lines together, each calculated for the proper impedance transformation so that the parallel junction at a shorted wire yielded 50 □. Using this convenient ultimate feedpoint impedance provides a registration of variations in feedpoint impedance created by various antenna stack configurations.

NEC models are limited in the information they can provide. They presume level homogenous terrain. Nevertheless, within each group of antennas modeled, comparisons of various performance characteristics remain quite valid, even when extrapolated to other terrain and antenna farm clutter. The key is to compare stacked results with baseline data about the antennas in question.

For each model—whatever the height, number of beams, or phasing condition—there are several key parameters to note. Take-off angle indicates the elevation angle of maximum radiation in the favoured direction. All beams at heights of 1 λ or more show multiple elevation lobes of decreasing strength as the elevation increases. I have not noted these, but I have noted secondary lobes, especially where beams are fed out of phase to each other, since the lobe pattern is not standard to our usual expectations.

For comparative purposes, I have included numbers for gain (in dBi) and for front-to-back ratio (in dB). The latter figure is suggestive only, since it does not provide a clear picture of the radiation off the rear of the Yagis, especially under nonnormal stacking and phasing conditions. A few figures exceed 35 dB, which usually indicates a deep null immediately to the rear with an unspecified lower figure applicable to the remainder of the rearward 180° for the beam.

I have included bandwidth in degrees relative to the –3 dB points in forward gain. This number is useful as an indicator of when the normally anticipated forward oval pattern is distorted to a major degree. Feedpoint impedances of individual antennas and stacks under various phasing conditions provide an indication of the degree to which interactions provide acceptable or unacceptable conditions.

The 3-Element Beam and Some Common Stacks of Two

All the data will be presented in tables, without much commentary. Some unworthy options will be evident. Others may depend on two factors: (a) your own readout of experience or IONCAP results for paths from your QTH to your targets, and (b) what your operating activities and interests are and hence what your targets are. These are variables that the method of moments cannot model.

1-1. Baseline 3-element Yagi Characteristics: 1 antenna by height in wavelengths (where 70' equals about 1 □ at 20 meters):

Height	*TO angle*	*Gain*	*F-B*	*Beamwidth*	*Feedpoint Impedance*
in wl	*degrees*	*dBi*	*dB*	*degrees*	*R +/- jX ohms*
1/2	25	12.3	25.2	64	24.7 - 0.7
5/8	21	12.9	24.9	64	25.9 + 0.1
3/4	17	13.1	40.1	62	26.5 - 1.2
7/8	15	13.3	29.0	62	25.5 - 1.6
1	14	13.4	25.1	62	25.1 - 0.9
1.5	9	13.7	25.3	62	25.3 - 0.9
2	7	13.8	25.6	62	25.4 - 0.9
2.5	6	13.8	25.9	62	25.5 - 0.9

2-1. Two-beam stack, single feed at various spacings Abbreviations used in the following table are these "Both in" means both beams are fed phase; "Both out" means both beams are fed, but out of phase; "Top only" means that only the top beam is fed, but the lower beam is present in the stack; "Bot only" means that only the bottom beam is fed, although the upper beam is present in stack. A second line for an entry indicates a secondary elevation lobe worth noting.

2a1. 2 beams at 1 l and 1.5 l up

Stack	*TO angle*	*Gain*	*F-B*	*Beamwidth*	*Feedpoint Impedance*
set-up	*degrees*	*dBi*	*dB*	*degrees*	*R +/- jX ohms*
Both in	11	15.8	21.3	60	50.6 - 0.9
Both out	50	12.3	18.5	82	45.0 + 7.5
	25	11.5	28.8	66	
Top only	9	13.6	22.3	60	26.1 - 1.9
Bot only	14	13.3	22.1	62	26.0 - 1.9

2b1. 2 beams at 1 l and 1.63 l up:

Stack	*TO angle*	*Gain*	*F-B*	*Beamwidth*	*Feedpoint Impedance*
set-up	*degrees*	*dBi*	*dB*	*degrees*	*R +/- jX ohms*
Both in	10	16.2	17.6	62	51.4 - 1.7
Both out	47	12.7	23.1	76	49.0 + 6.5
	23	12.5	31.4	64	
Top only	9	13.9	18.6	62	22.1 - 1.1
Bot only	13	13.6	17.9	62	24.5 - 1.5

2c1. 2 beams at 1 l and 2 l up:

Stack	*TO angle*	*Gain*	*F-B*	*Beamwidth*	*Feedpoint Impedance*
set-up	*degrees*	*dBi*	*dB*	*degrees*	*R +/- jX ohms*
Both in	8	15.7	39.3	62	46.7 + 2.3
Both out	20	14.7	22.2	62	51.9 + 1.4
	39	12.9	26.6	70	
Top only	7	13.7	35.5	62	25.6 - 1.1
Bot only	14	13.4	26.7	62	25.3 - 1.1

2d1. 2 beams at 0.7 and 1.4 l up:

(This corresponds roughly to 50' lower and 100' upper on 20 meters, often recommended by various sources.)

Stack	*TO angle*	*Gain*	*F-B*	*Beamwidth*	*Feedpoint Impedance*
set-up	*degrees*	*dBi*	*dB*	*degrees*	*R +/- jX ohms*
Both in	11	15.7	15.0	64	50.7 - 5.7
Both out	28	13.8	25.8	64	49.7 + 7.1
	58	9.1	18.6	86	
Top only	10	13.9	16.4	64	24.4 - 0.8
Bot only	18	13.2	18.9	64	25.5 - 0.2

To illustrate the various options, I have included Figures **2**, **3**, **4** and **5**, which are elevation plots for each feed option with the antennas at 1 and 1.63λ up. You may want to look at both the plots and the tables when evaluating the trends that emerge.

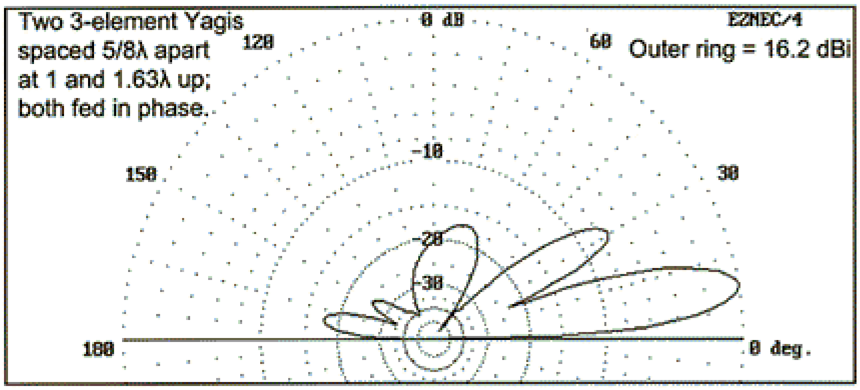

Fig. 2

Fig 2—3-element Yagis spaced 5/8 λ apart: both in phase

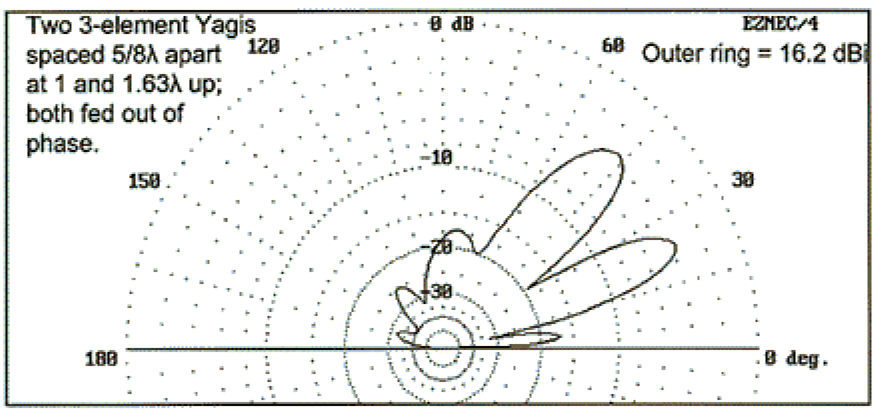

Fig. 3

Fig 3—3-element Yagis spaced 5/8 λ apart: both out of phase

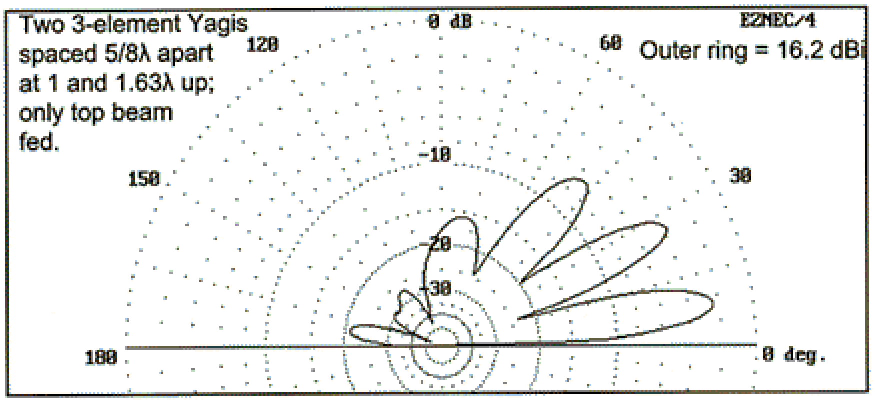

Fig. 4

Fig 4—3-element Yagis spaced $^5/_8$ λ apart: only top beam fed

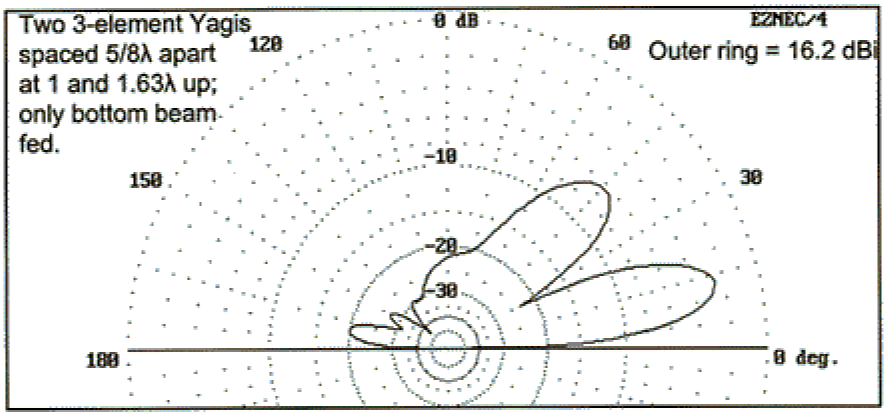

Fig. 5

Fig 5—3-element Yagis spaced $^5/_8$ λ apart: only bottom beam fed

A number of notable trends appear in this progression of ever widening distances between the stack of two beams. Maximum gain from the stack occurs when spaced about $^5/_8$ λ apart. At spacing less than 1 λ, when the antennas are fed together in phase, the front-to-back ratio decreases relative to the performance of a single antenna of this design. This reduction also applies to feeding either antenna alone with the other still in the stack. For stacks of beams less than 0.7 λ apart, when fed together, but out of phase, the higher of the two main elevation lobes dominate. Moreover, the impedance of the junction of the phasing lines departs somewhat from the 50-λ ideal. All of these characteristics are relevant to assessing the utility of the various options for feeding the stack antennas.

The 5-Element Beam and Some Common Stacks of Two

Whether the characteristics of 3-element Yagis in a stack can be reliably extrapolated to longer Yagis is an important question, since antennas with 4 to 7 elements are common choices among DXers and contesters. Therefore, I repeated the exercise with the 5-element, 48'-boom Yagi model.

1-2. Baseline 5-element Yagi Characteristics:

1 antenna by height in wavelengths:

Height in wl	*TO angle degrees*	*Gain dBi*	*F-B dB*	*Beamwidth degrees*	*Feedpoint Impedance R +/- jX ohms*
1	13	15.4	23.3	52	36.7 + 0.2
1.5	9	15.8	23.4	52	36.7 + 0.2
2	7	15.9	23.4	52	36.7 + 0.3
2.5	6	16.0	23.4	52	36.7 + 0.3

2-2. Two-beam stack, single feed at various spacings:

2a2. 2 beams at 1 l and 1.5 l up:

Stack set-up	TO angle degrees	Gain dBi	F-B dB	Beamwidth degrees	Feedpoint Impedance R +/- *j*X ohms
Both in	10	17.2	18.0	50	48.4 + 2.3
Both out	24	14.0	26.0	56	54.6 + 3.1
	49	12.5	16.4	62	
Top only	9	14.7	19.4	50	36.0 - 2.0
Bot only	15	14.4	21.0	50	36.0 - 2.0

2b2. 2 beams at 1 l and 1.63 l up:

Stack set-up	*TO angle degrees*	*Gain dBi*	*F-B dB*	*Beamwidth degrees*	*Feedpoint Impedance R +/- jX ohms*
Both in	10	17.4	15.6	50	51.0 + 0.1
Both out	23	14.7	33.8	54	54.5 - 0.5
	45	12.7	21.6	58	
Top only	8	15.1	16.4	50	35.1 + 0.1
Bot only	14	14.8	18.0	52	35.5 - 0.1

2c2. 2 beams at 1 l and 2 l up:

Stack set-up	*TO angle degrees*	*Gain dBi*	*F-B dB*	*Beamwidth degrees*	*Feedpoint Impedance R +/- jX ohms*
Both in	8	17.9	25.1	52	50.3 + 0.5
Both out	20	16.4	21.2	52	50.6 - 1.1
	38	12.9	19.6	54	
Top only	7	16.0	25.4	52	36.9 + 0.1
Bot only	13	15.4	24.4	52	36.9 + 0.1

2d2. 2 beams at 0.7 and 1.4 l up:

Stack set-up	*TO angle degrees*	*Gain dBi*	*F-B dB*	*Beamwidth degrees*	*Feedpoint Impedance R +/- jX ohms*
Both in	11	17.0	14.3	52	51.3 - 1.4
Both out	27	15.6	44.5	54	53.3 - 2.1
	55	7.0	15.6	62	
Top only	9	15.3	16.7	52	35.7 + 0.9
Bot only	19	14.5	18.0	52	35.4 + 1.2

Although the in-phase-fed 5-element stack has more gain than the 3-element stack, it is by no more than the advantage of one 5-element beam over one 3-element beam—about 2 dB or less. The 5-element Yagis appear to interact more strongly at spacings less than 1 λ, as evidenced by not only the larger reduction in front-to-back ratio for stacked beams fed in phase, but as well by the reduced performance figures of both the top and bottom beams when fed alone compared to single beams at the same height. Note also that the maximum in-phase-fed stack gain occurs at 1 λ separation, not at the

0.63 □ separation of the 3-element stack. On the other hand, the 5-element beams, when fed out of phase, yielded dominant lobes at lower elevation angles than the 3-element counterparts.

Two models do not make an assured conclusion. However, it is at least safe to say that long Yagis do not necessarily perform in stacks in a way identical to shorter Yagis.

Stacks of 3 and 4

Despite the warning that 3-element and 5-element Yagis do not perform identically in stacks, I can do no more than sample stacks of 3 and 4 beams in this space. I shall use the 3-element beam to tabulate performance characteristics of the various options available on these tall stacks.

3. 3 beams stacked at 1, 1.5, and 2 l: Added abbreviations: “Top out” means that the top beam is out of phase with the other two; “Mid out” means that the middle beam is out of phase with the other two; “Bot out” means that the bottom beam is out of phase with the other two; “Mid only” means that only the middle beam is fed, but with the other two present.

Stack set-up	*TO angle degrees*	*Gain dBi*	*F-B dB*	*Beamwidth degrees*	*Feedpoint Impedance R +/- jX ohms*
All in phase	9	17.2	22.3	60	50.3 - 0.9
Top out	17	13.4	22.1	62	51.4 + 3.6
	36	13.2	30.8	68	
Mid out	55	13.3	14.3	88	41.3 + 12.9
	32	8.9	18.5	68	
Bot out	22	14.3	22.1	64	51.9 + 3.3
	7	10.3	19.7	60	
Top only	7	13.6	24.5	60	26.2 - 2.1
Mid only	9	13.6	19.0	60	26.7 - 3.2
Bot only	14	13.3	23.1	62	25.8 - 2.0

3-beam stacks offer many more options than 2-beam stacks with respect to switching for optimal elevation angles. However, some options offer potentially troublesome feedpoint impedances, for example, the "Mid out" arrangement. Others repeat some of the elevation lobes offered by other options: it is dubious that one would want both the “All in phase” and the “Top only” options. Nevertheless, only a full analysis of terrain, operating aims, and likely skip paths could settle the final switching decisions for any given station.

4. 4 beams stacked at 1, 1.5, 2, 2.5 l up: Beams are designated “Top,” “2nd,” “3rd,” and “Bot” from top to bottom in the stack of 4

Stack set-up	*TO angle degrees*	*Gain dBi*	*F-B dB*	*Beamwidth degrees*	*Feedpoint Impedance R +/- jX ohms*
All in phase	7	18.3	21.3	60	49.8 - 2.6
Top out	12	15.1	21.8	60	49.5 + 2.8
	28	12.2	24.5	64	
2nd out	40	13.5	28.2	71	48.9 + 8.6
	9	11.3	22.2	60	
3rd out	6	12.3	20.6	60	48.6 + 7.8
	30	12.0	22.2	66	
Bot out	20	14.9	22.3	62	49.4 + 2.9
	6	14.1	20.4	60	
Top 2 out	17	16.0	20.6	62	52.1 - 0.6
	32	13.3	21.8	66	
Mid 2 out	26	14.4	24.8	64	52.2 + 2.3
	43	13.7	29.8	74	
Top/3rd out	57	14.0	12.8	91	38.5 + 16.7
Top only6	13.7	21.3	60		25.5 - 0.3
2nd only	7	13.5	20.2	60	26.5 - 3.4
3rd only	9	13.4	21.4	60	26.5 - 3.2
Bot only	14	13.2	23.8	62	25.8 - 2.0

Note: In terms of resultant far field plots, “Top 2 out” above is equivalent to “Bot 2 out” and “Top/3rd” out is equivalent to “2nd/Bot out.”

Although the number of options available for switching feed schemes multiplies as we increase the number of beams in a stack, there are many repetitions and near repetitions in the list. It is unlikely that one could make use of more than a 4-way switch in optimizing the elevation angle for the antenna array. In looking at the options, consider the beamwidth and the impedance offered by each arrangement, as well as gain, front-to-back ratio, and elevation angle.

Horizontal Separation

Beams separated horizontally but fed either in phase or out of phase exhibit characteristics quite different from vertically stacked beams. In-phase fed pairs of our 3-element Yagis have ear lobes, similar to those developed by extended double Zepp antennas. When fed out of phase, the beam’s forward centerline is a very deep null, with strong main lobes on either side. Figures **6** and **7** illustrate the phenomena, which vary according to the degree of separation.

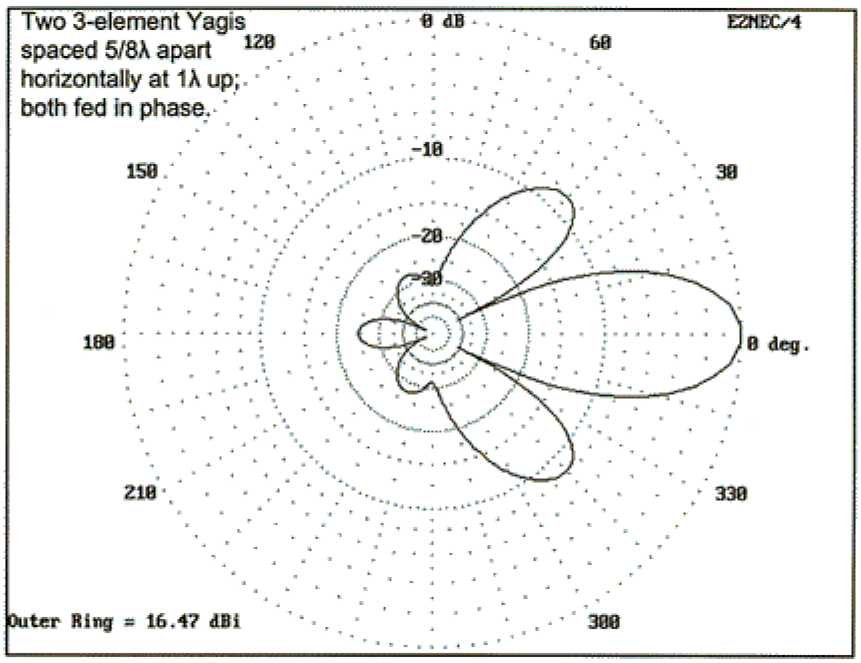

Fig. 6

Fig 6—3-element Yagis horizontally spaced $^5/_8$ λ: both in phase

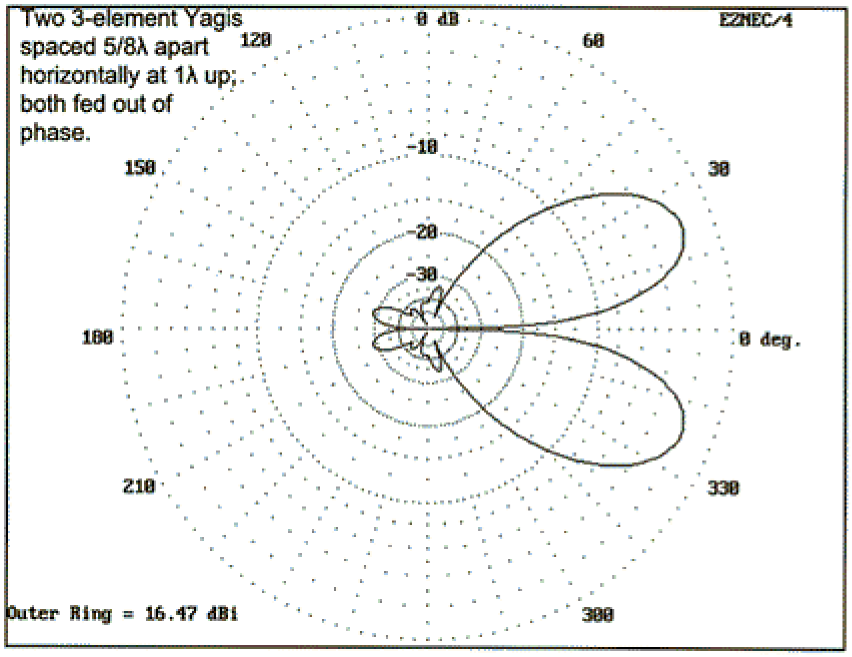

Fig. 7

Fig 7—3-element Yagis horizontally spaced $^5/_8$ λ: both out of phase

5. 2 beams at 1 l height, horizontally spaced, where spacing is given in wavelength fractions from tip to tip of the elements. (Add 1/2 λ for boom-to-boom spacing.) Side ear gain only is given. For out-of-phase fed pairs, "Split" means the number of degrees each side of center line of the lobes.

Stack set-up	*TO angle degrees*	*Gain dBi*	*F-B dB*	*Beamwidth degrees*	*Feedpoint Impedance R +/- jX ohms*
5a. $^1/_4$ l spacing					
In phase	13	16.1	22.8	32	50.3 - 0.6
side ears		-2.9			
Out of phase	13	13.4	39.8		48.2 + 4.2
split		28			
5b. $^1/_2$ l spacing					
In phase	14	16.5	22.3	26	49.6 + 0.1
side ears		5.8			
Out of phase	13	14.2	30.8		50.1 + 3.0
split		24			
5c. $^5/_8$ l spacing					
In phase	13	16.5	24.3	24	49.0 + 0.6
side ears		8.2			
Out of phase	13	14.6	27.9		50.4 + 2.4
split		22			
5d. 1 l spacing					
In phase	13	16.4	26.5	18	49.3 + 1.9
side ears		11.7			
Out of phase	13	15.4	25.1		50.1 + 1.3
split		18			

Note that as the spacing grows wider, the out-of-phase forward lobe split grows narrower, but the "ears" grow larger. Eliminating the ears requires that the beams be very close, side-to-side. However, the undesired consequences are a loss in gain and a disruption of the feedpoint impedance due to close coupling of the elements.

These results only sample the possibilities for stacking. A myriad of other arrangements and heights are possible. However, I hope that these systematic modeling notes form a beginning step in having reasonable expectations of stacks.

[1]R. Dean Straw, N6BV, and Fred Hopengarten, K1VR, "Stacking Tribanders: A Super Station—Sorta," *QST* 78 (February, 1994), 38-44. The information is summarized in 17th Edition of *The ARRL Antenna Book* (Newington: ARRL, 1994), pp. 11-24 - 11-30.