The Quest for the Elusive TBWB4EQ
(The Tri-Band Wide-Band 4-Element Quad)

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Tri-band quads for 20, 15, and 10 meters have a long history--about as long as hams have used quads. A number of longer tri-banders have periodically appeared in the literature. In these notes, I shall be very interested in 4-element quads of planar design, that is, with the elements for each band on a vertically oriented support frame. These designs use the same spacing between elements for all bands.

In the course of our exploration, I shall examine beams in the 30- to 35-foot boom range. Our first stop will be to examine a long-standing *Antenna Book* design to understand its limitations, especially its narrow operating bandwidth on at least one of the 3 bands that it covers. The results of this small study will form the basis for seeking out a design with a broader operating bandwidth on all bands. The first stop will be the 1983 design from W6PU, a design that has held persistent interest for two decades. The designer used the central pair of elements to form phase-fed dual drivers. My interest in this design covers two long-standing expectations of phase-fed dual driver quads: their gain and their operating bandwidth.

Next, I shall turn to designing a modified W6PU-quad that virtually anyone can replicate in model form. The goal will be to obtain full-band coverage of 20, 15, and 10 meters, with adequate gain and front-to-back performance. I shall use a few techniques not easily available to the design originator in order to simplify the array and to overcome some of the problems with the original version. Finally, I shall set up a reasonably fair set of comparative beam designs to evaluate whether anyone should go to the effort of actually building a tri-band wide-band 4-element quad beam.

A Standard Tri-Band 4-Element Quad Design

Many quad builders prefer to by-pass the 3-element beam on their way up the ladder of performance. Odd numbers of elements tend to place the driver very close to the support mast and tower, resulting in a conflict between electrical and mechanical requirements. An even number of elements places the mast equally distant between the center two elements, freeing the builder from at least one potential interaction problem.

Traditionally, quad designers have used a somewhat arbitrary spacing of the elements. 4-element quads for multi-band service often use equal spacing between all elements, with 8' and 10' being the most common values. A few designs have used a combination of these values, so that we can find 4-element tri-band designs with boom-lengths ranging from 24' to about 30' or so. The premise behind the spacing selection stems from the use of planar element assemblies. In terms of wavelengths, a fixed spacing between elements results in a different spacing for each band. For example, fixed 10' spacing between elements is about 0.14-wavelength on 20, 0.21-wavelength on 15, and 0.28-wavelength on 10 meters.

The design of the quad then rests upon finding the element circumferences that will produce an acceptable combination of gain, front-to-back ratio, and feedpoint impedance, all with satisfactory operating bandwidths. Prior to the 1990s, the design effort was largely *empirical*, a term meaning trial and error. Indeed, most existing quad designs in amateur literature have their roots in the pre-computer-modeling period of antenna design.

One very interesting design appears in *The ARRL Antenna Book* for editions prior to the 19th. It appears in the table on page 12-2 of the 18th edition. The beam consists of 4 elements, each spaced 10' from the adjacent element. Hence, we have a total boom length of 30', plus whatever end lengths are necessary to handle the support-arm structures. **Fig. 1** supplies a basic outline of the quad's electrical structure. Throughout, the design of this quad, and the others that we shall examine, presumes separate feedlines for each band, with closed driver loops for each inactive band.

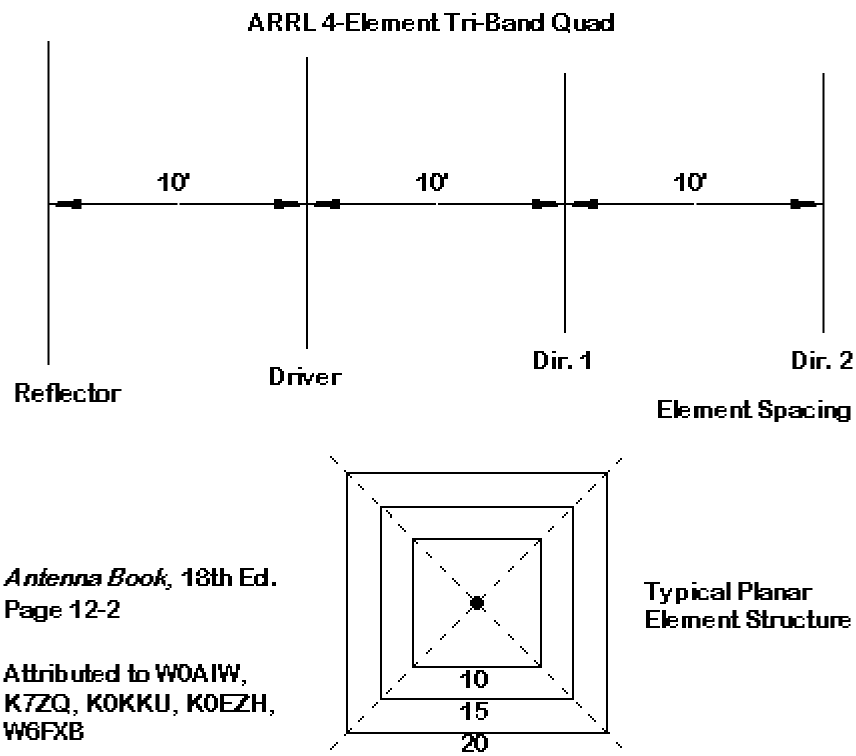


Fig. 1

Table 1. Dimensions of the ARRL *Antenna Book* 4-element, 30'-boom, tri-band quad

	Space from	Circumference in feet		
Element	Reflector in feet	20 Meters	15 Meters	10 Meters
Reflector	-----	72.42	48.67	35.70
Driver	10.0	70.42 (70.80*)	47.33	34.70 (35.20*)
Dir. 1	20.0	69.08	46.33	33.60
Dir. 2	30.0	69.08	46.33	33.60

* Dimensions in parentheses indicated modeling changes of the driver circumference to set the 50-Ohm SWR curve within the band limits. 20 and 15 meters use direct 50-Ohm coax connections; 10 meters uses a 1/4-wavelength 75-Ohm matching section to the 50-Ohm feedline.

Table 1 shows the element dimensions for the quad design. The antenna uses a direct feedline connection on 20 and 15 meters. However, 10 meters requires a quarter-wavelength

75-Ohm matching section to transform its higher feedpoint impedance (above 100 Ohms) down to the feedline's 50-Ohm characteristic impedance. The fixed element spacing creates a rising driver impedance as we move upwards through the HF bands. Although carefully choosing the element lengths can alter the impedance to some extent, there are severe limits to the range of adjustment. Trying to lower the 10-meter impedance for a direct 50-Ohm feed tends to degrade the other performance parameters on that band.

In trying to model this antenna in NEC-4 using AWG #12 copper wire, I had to alter the published length of the 20-meter and the 10-meter drivers--both upward--in order to place the 50-Ohm SWR curves within the band limits. 15 meters required no adjustment in the model. In part, this situation results from the fact that the 15-meter dimensions result from interaction between the elements for that band and the elements for both of the other bands. The 10-meter and 20-meter elements interact mainly with only one other band. Key variables for those bands also include methods of assembly. Attaching elements to the support arms is subject to a number of variations, some of which result in the creation of small 1-turn inductive loops at each corner. Together, they can have an effect upon the electrical length of a loop, with the most pronounced effect on the driver, where the relative current magnitude is highest. The fact that I had to increase both driver lengths--which make clean corners in the model--by similar amounts suggests that the empirically derived design may take such mounting loops into account.

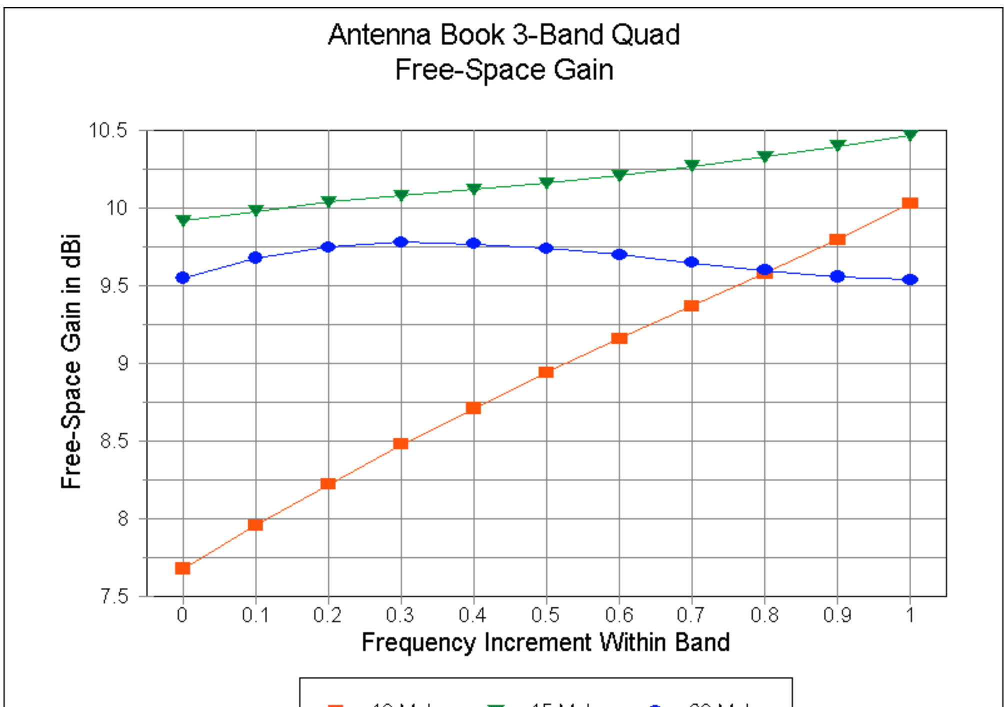


Fig. 2

I modeled this traditional design in free-space as simply a guide to its anticipated performance level. All other beam designs that we shall consider also use free-space models, thus allowing a direct comparison of performance among them. **Fig. 2** shows the modeled forward gain performance of the array. This and other performance graphs subdivide each amateur band into 10 parts to permit combined presentations. 10 meters covers the 28- to 29-MHz portion of the band.

To make sense of the graph, we should note a few benchmarks that emerge from monoband beams. A short-boom 3-element Yagi (about 16' on 20 meters) achieves a free-space gain of over 7 dBi, while a long boom version of the array (about 24' on 20 meters) is capable of just over 8 dBi. These values are approximate, since 3-element Yagis show a rising gain value across the operating bandwidth. An optimized 2-element monoband quad achieves 7 dBi or so. We may optimize 3-element models for the widest operating bandwidth and obtain just over 8.5 dBi or for maximum gain and reach about 9.1-dBi free-space gain. An optimized 4-element monoband quad that uses #12 copper wire--like the other quads cited--is capable of just about 10 dBi maximum.[1]

Since the boom length of the tri-band quad is considerably shorter than its monoband 4-element counterpart, we should not expect 4-element performance in the optimized monoband sense of the term. And we do not get it. However, we do obtain very respectable 20-meter performance in the 9.5-dBi range across the band. Helped by interactions with the surrounding elements for other bands and a longer boom as a percentage of a wavelength, the 15-meter gain performance does achieve the 10-dBi level. The 10-meter boom length is too long and thus shows a rising curve with a minimum value below 8 dBi. All in all, the quad design achieves quite good gain performance as a tri-band effort on a 30' boom.

Optimizing a monoband quad tends to bring the maximum 180-degree front-to-back ratio in close frequency-proximity to a desired gain level and the resonant feedpoint impedance of the array. Hence, these values are usually in excess of 20 dB and sometimes as high as 40 dB, although such a high peak front-to-back value is a narrow-band phenomenon. Most optimized monoband designs strive for relative equal band-edge values, and the exact band-edge front-to-back ratio will depend on the element diameter and the bandwidth of the passband as a function of its center frequency. A tri-band quad does not have the luxury of such techniques, as **Fig. 3** will reveal.

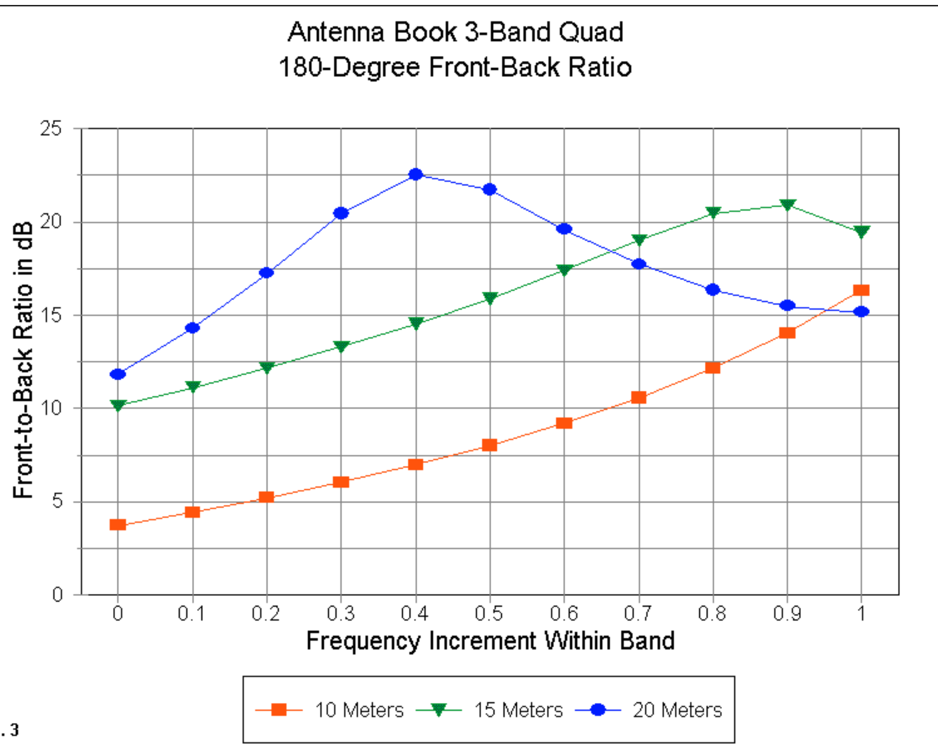


Fig. 3

Both 20 and 15 meters show very respectable front-to-back curves, with minimum values between 10 and 12 dB, both at the low end of the bands. 10 meters shows the most problematical curve, with extremely low values in the CW portion of the band, but much improved values higher up. The coincidence of the rising gain and front-to-back curves suggests that one might go some distance in further optimizing performance for 10 meters within the first MHz of the band. However, every change in the 10-meter loop dimensions will force a change in the adjacent 15-meter element, with consequences for the outer 20-meter element. Hence, optimizing the present 10-meter portion of the design--with the potential pitfalls of ruining the 15- or 20-meter performance--is a significant task. It falls outside our use of the design as a representative existing design for comparative purposes.

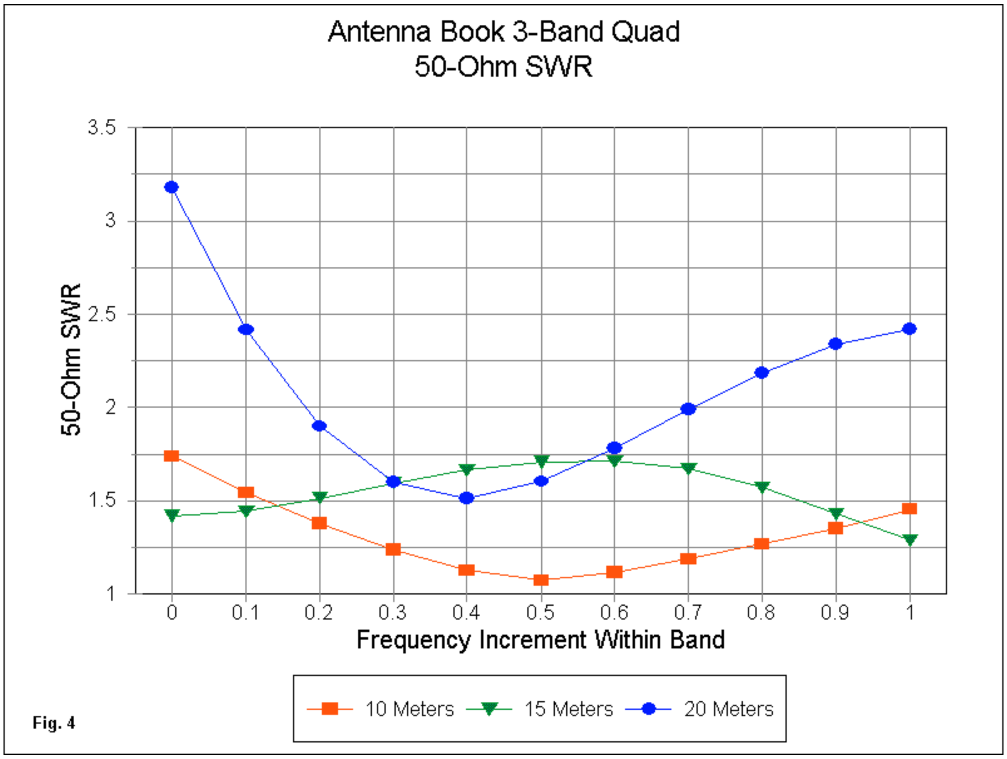


Fig. 4

The 50-Ohm SWR curves appear in **Fig. 4**. Both 10 and 15 meters achieve less than 2:1 SWR across the bands. However, remember that the 10-meter driver includes a quarter-wavelength matching section that the model includes. Only the 20-meter SWR curve falls short of the mark, largely due to the fact the both the feedpoint resistance and reactance show large excursions. The resistance changes by 44 Ohms across the band, while the reactance changes by 81 Ohms. For comparison, the feedpoint resistance on 15 meters changes by just 6 Ohms, while the reactance changes by 20 Ohms. The 20-meter curve is a function of the fact that the loops for that band have no further lower-band loops with which to interact. Hence, they tend to show more normal monoband properties for the boom length and the element spacing than do the higher-band elements. Despite slight interactions with the 15-meter elements, the 20-meter elements display the narrow SWR bandwidth typical of monoband 20-meter quads on the same boom. The original tables for the ARRL quad design show separate dimensions for the CW and the SSB portions of the band.

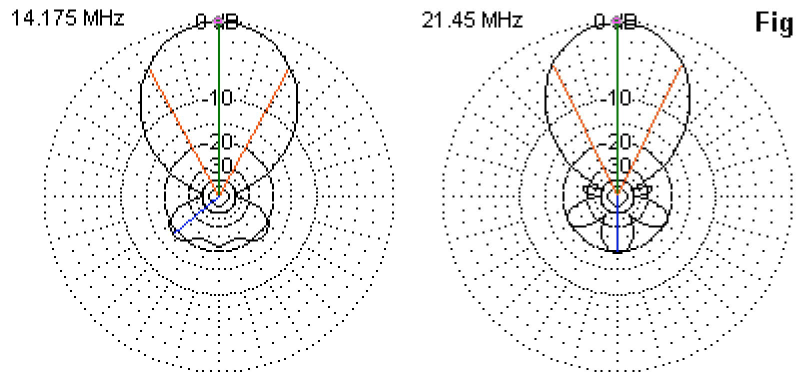


Fig. 5

Broad Rear Lobes **Extra Lobes**

Some Typical Multi-Band Quad Pattern Characteristics

Multi-band quads have a few other idiosyncrasies that do not show up readily in tables. Pattern shape is one of them, and **Fig. 5** displays some of them. However, the ARRL quad design is remarkably free of extreme pattern, and so the figures only modestly represent what we often see in more extreme forms. The pattern to the left shows a typical multi-band quad fantail. The rear lobes on multi-band quads often show considerable strength in rear quartering directions, resulting in worst-case front-to-back ratios that are considerably lower than the 180-degree front-to-back ratio. Inadequately designed LPDAs with too few elements for the frequency span covered tend to show a similar problem. It is likely that the fantail effect is a product of interactions with supposedly inert elements for other bands. Some have attributed the spread to the fact that there is a small vertically polarized component to the pattern, but this component does not result in forward beamwidths significantly wider than those we achieve from Yagis of similar gain potential. With respect to the relatively modest fantail shown in **Fig. 5**, the only function of the vertical radiation component is to reduce the deep side nulls that we might find for a Yagi.

The other pattern anomaly that accompanies multi-band design is the appearance of extra lobes, as shown by the 15-meter pattern in **Fig. 5**. In monoband design, it is possible to suppress secondary or forward side lobes through at least 6-element arrays. However, multi-band quads tend to show some extraneous lobes, even with only 3-4 elements per band. The most likely source of them is from the inactive elements for the other bands. As we increase loop size above about 1.5 wavelengths or decrease it below about 0.75-wavelength, the radiation tends to move from the desired broadside orientation toward the loop edges. Even low-level, induced activity in the supposedly inert loops can yield small lobes, such as the pair of side lobes shown in **Fig. 5**.

Nonetheless, the patterns of the ARRL quad show the anomalies only in small and relatively harmless ways. Moreover, the array shows very adequate levels of gain and front-to-back ratio. The 10-meter performance might withstand further optimizing, assuming one could achieve this goal without unduly disrupting the performance on 20 and 15 meters. Still, the task is one internal to the basic 4-element design itself.

We came to the ARRL 4-element, tri-band quad with the idea of using it as a comparator for reportedly improved designs. However, there are perhaps only two reasons for changing the basic design of the quad. One is to improve the operating bandwidth across 20 meters. The other is to see if we cannot achieve higher levels of gain and front-to-back ratio from a similar boom length. The next step in our exploration is to review an old design that seems to promise both.

The Original W6PU Dual Driver 4-Element Tri-Band Quad

In the December, 1983, issue of *CQ*, Robert Martinez, W6PU, presented "The Evolution of the Four-Element Double-Driven Quad Antenna" (pp. 30-36). The article is absolutely typical of the period relative to antenna design. Without the benefit of well-calibrated computer calculation of antenna performance potentials, the era was filled with countless writers who handled decibels without due care.[2] Perhaps the most important of the W6PU claims are an improvement of 5.5 to 6.0 dB in forward gain and a 30-dB front-to-back ratio. Since the author refers to 2-element and 4-element quads for 40 through 10 meters, it is unclear over what the new antenna showed the higher gain. However, we can model the W6PU 4-element, tri-band, dual-driver quad and see what we get. Since we have just reviewed a comparable model of a reasonably competent 4-element single-driver quad, we shall be able to tell if the builder effected any improvements by using dual drivers.

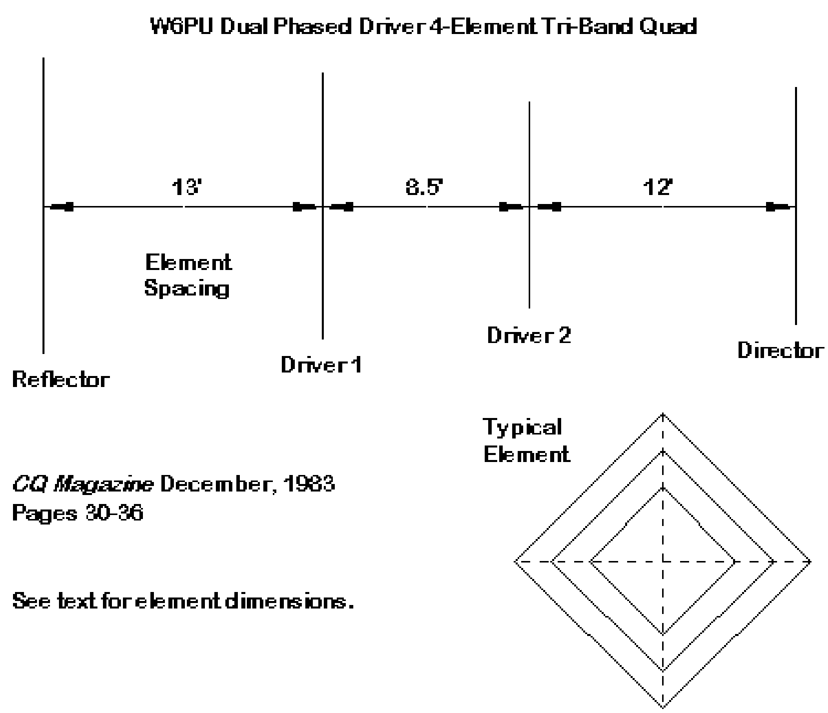


Fig. 6

Fig. 6 shows the general outlines of the W6PU quad. The total boom length is 33.5' (plus the usual end additions for hardware). **Table 2** supplies the element loop circumferences used to construct the test model from the article description. The original reflector loop specifications called for loops identical in circumference to the ones used for driver 1. However, each reflector had a specified shorted transmission line stub with a trimmer capacitor across the short to tune the stub. See **Table 3** for the values involved and **Fig. 7** for the layout given in the article. Unfortunately, the text gives the builder the alternative of using 300-Ohm line or home-crafted lines spaced 1.5" apart. A stub made from AWG #12 copper wire and spaced 1.5" will have a characteristic impedance of about 435 Ohms. Hence, for modeling purposes, it became impossible to know what sort of stub lengths and trimmer settings might have been used. The simpler method of proceeding was to use full size reflectors that are electrically equivalent to the stubbed and trimmed elements used in the original model. The values shown in **Table 2** resulted in the best gain and front-to-back performance across the band--without altering the other element sizes.

Table 2. Dimensions of the W6PU dual-driver, 4-element, 33.5'-boom, tri-band quad

	Space from		Circumference in feet	
Element	Reflector in feet	20 Meters	15 Meters	10 Meters
Reflector	-----	75.42*	50.30*	37.24*
Driver 1	13.0	71.75	47.83	35.92
Driver 2	21.5	68.17	45.42	34.08
Dir. 1	33.5	68.67	45.83	34.42

*From Robert Martinez, W6PU, "The Evolution of the Four-Element Double-Driven Quad Antenna," *CQ* (December, 1983), pp. 30-36. Original specifications call for reflectors using the same circumference as the first driver, but with shorted transmission-line stubs and trimmer capacitors. The NEC-4 models use electrically equivalent full-size reflector loops, with the circumferences listed in the table.

Table 3. Dimensions of the reflector stubs of the original W6PU quad.

Band	Stub Impedance In Ohms (see text)	Stub Length in feet	Trimmer Capacitor in pF
20	300	4.50	150
15	300	3.50	100
10	300	2.25	75

Note: article specifies 300-Ohm or 1.5" wide stub line. Reflector circumference for each band is identical to the listed value for the first driver circumference in Table 2.

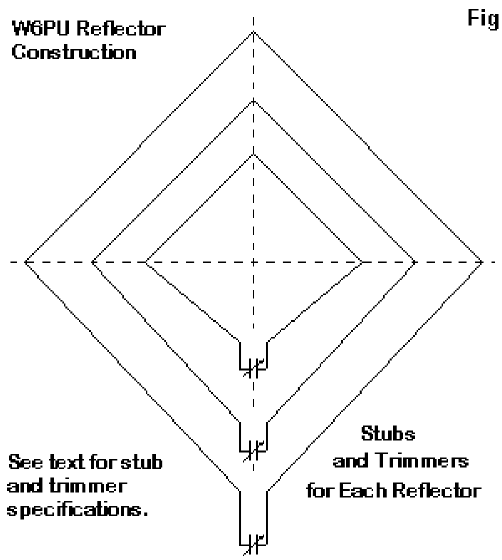
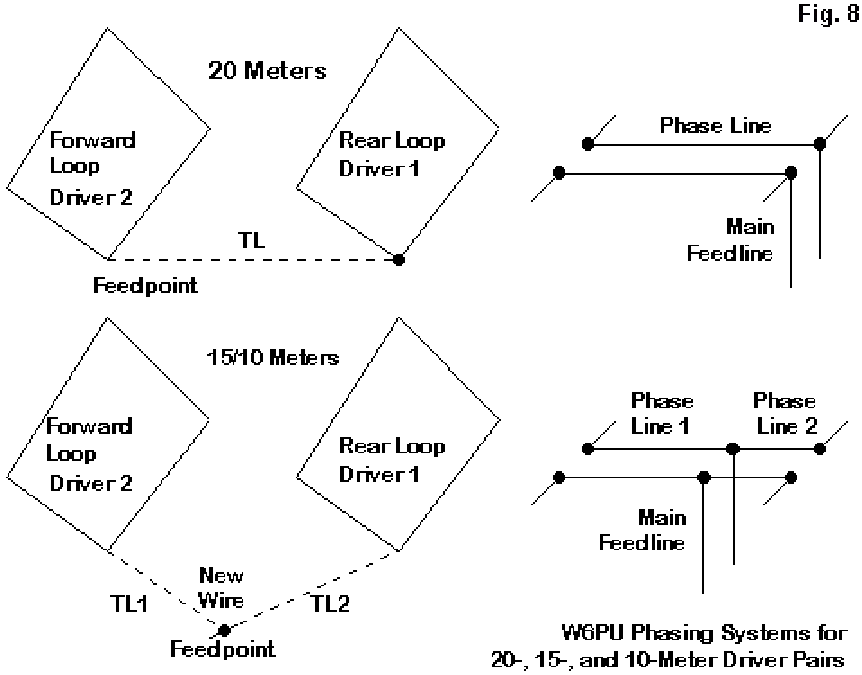


Fig. 7

Fig. 8



W6PU Phasing Systems for 20-, 15-, and 10-Meter Driver Pairs

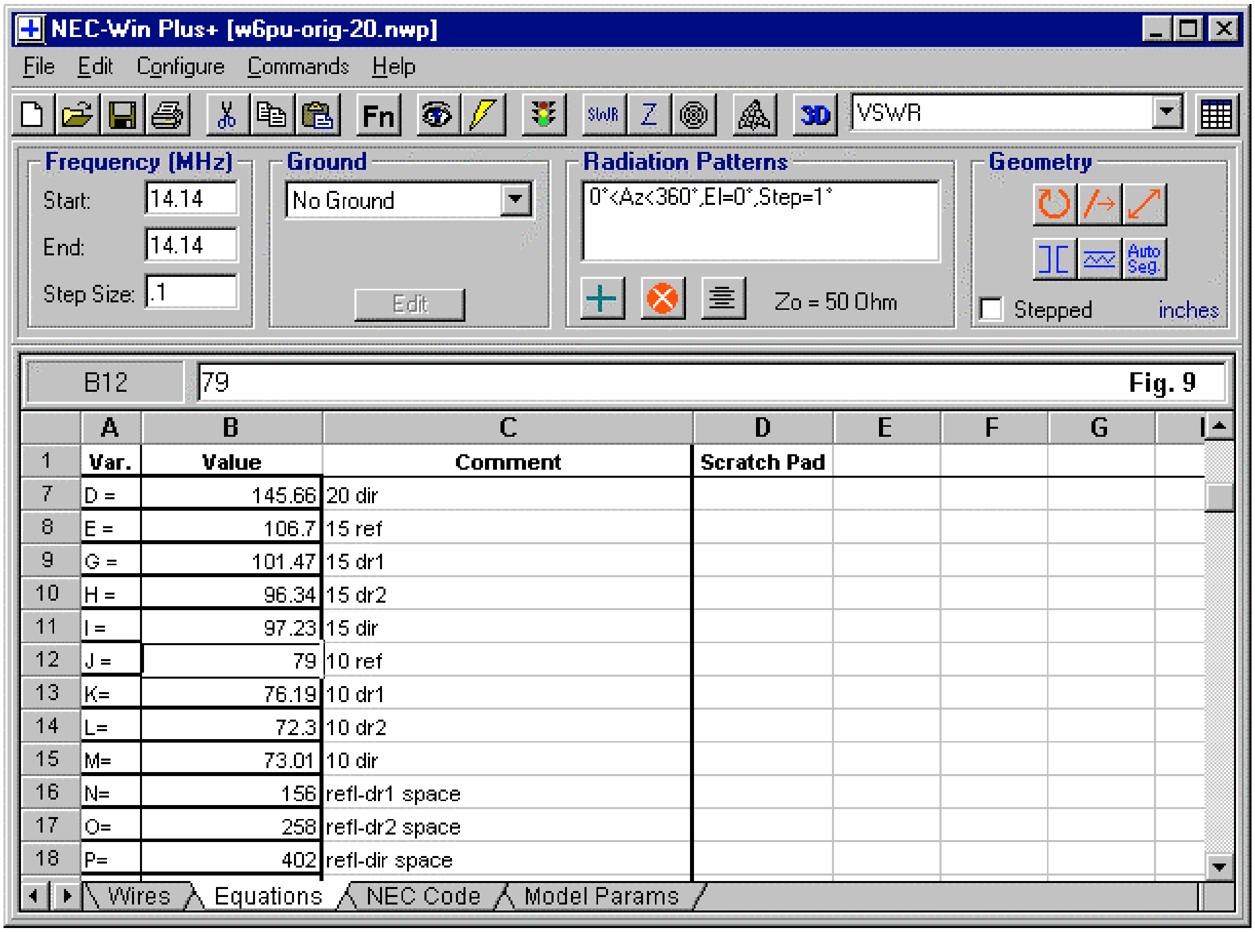
Note that the driver closest to the reflector is designated as driver 1, while the one closer to the director is called driver 2. This orientation is necessary to fully appreciate the sketch in **Fig. 8**. The right-hand side shows the phase-line arrangement between drivers for the 20-meter band--which uses a single line--and the 10- and 15-meter bands--which use a split-line phasing system. The feedpoint, contrary to most phase-line systems used in horizontal arrays, is at or closer to the rear driver (driver 1). **Table 4** provides data on the specified line lengths. The original article carefully notes the use of 50-Ohm (RG-8A/U) line with a velocity factor of 0.66. The electrical lengths used in the model of the antenna are the equivalent lengths for a velocity factor of 1.0.

Table 4. Phase-line lengths for each band for the W6PU quad.

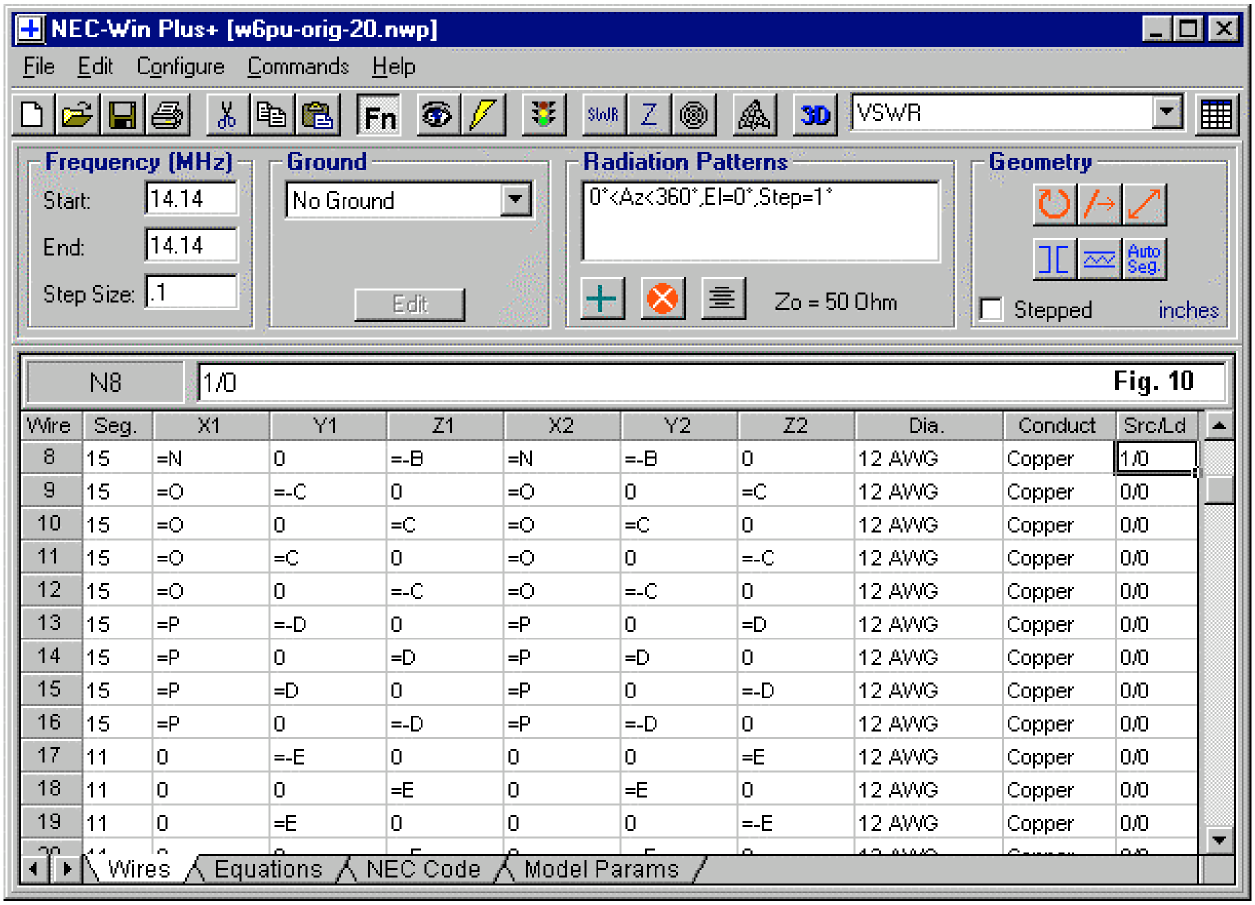
Band	Line Route	Physical Length	Electrical Length	Feedpoint
20	Driver 2 to Driver 1	8.50'	12.88'	Driver 1
15	Driver 1 to Junction	7.17'	10.86'	Junction
	Driver 2 to Junction	14.58'	22.10'	Junction
10	Driver 1 to Junction	5.33'	8.08'	Junction
	Driver 2 to Junction	9.67'	14.65'	Junction

Note: All phase lines 50-Ohm, VF 0.66 coaxial cables. Driver 1 is the element closest to the reflector--that is, the rear driver.

Modeling a multi-band quad in NEC requires attention to a number of factors. First, the antenna wires require a bit more than minimal segmentation at the highest frequency. The model uses 7 segments per side or 28 segments per loop at 10 meters. Since the segment length should be relatively constant throughout the assembly, the 15-meters elements used 11 segments per side and the 20-meter elements used 15 segments per side. Second, the split phase lines require a junction segment to use for the antenna feedpoint. The technique appears in the left-hand side of **Fig. 8**. All wires are AWG #12 copper.

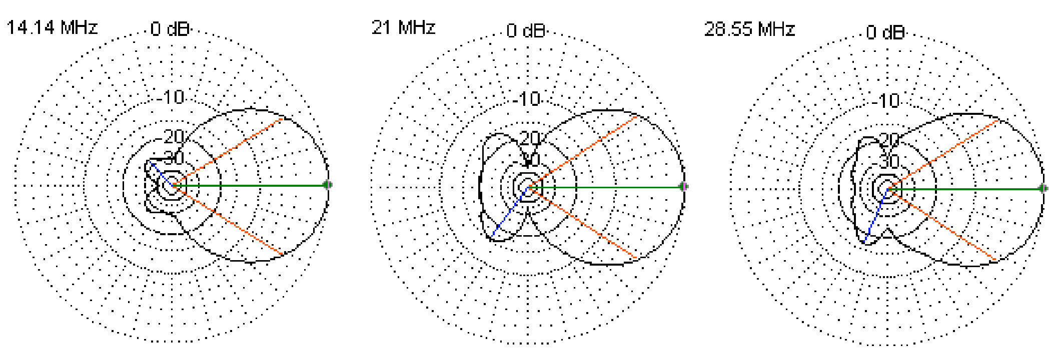


The structure is a diamond. Setting coordinates around the system involves calculating the support-arm length for each circumference loop. For square loops, the corner coordinates are each simply the circumference divided by 8, so that each side is 1/4 of the circumference. For diamond loops, the arm length is the circumference divided by 4 square roots of 2 or 5.6569. To avoid having to make multiple adjustments to change any loop size, I used software (in this case, NEC-Win Plus) with variables. **Fig. 9** shows part of the set-up of the page on which I assigned variables. **Fig. 10** presents a portion of the page on which I set up the wires by using variables instead of constants. An alternative view of the same program page would show the numbers created by the assignment of variables. Changing a loop size thus requires only one revised entry in the model. Since NEC-Win Plus uses NEC-2, I crosschecked the results of each run using NEC-4 software. The results are the same.



Wire	Seg.	X1	Y1	Z1	X2	Y2	Z2	Dia.	Conduct	Src/Ld
8	15	=N	0	=-B	=N	=-B	0	12 AWG	Copper	1/0
9	15	=O	=-C	0	=O	0	=C	12 AWG	Copper	0/0
10	15	=O	0	=C	=O	=C	0	12 AWG	Copper	0/0
11	15	=O	=C	0	=O	0	=-C	12 AWG	Copper	0/0
12	15	=O	0	=-C	=O	=-C	0	12 AWG	Copper	0/0
13	15	=P	=-D	0	=P	0	=D	12 AWG	Copper	0/0
14	15	=P	0	=D	=P	=D	0	12 AWG	Copper	0/0
15	15	=P	=D	0	=P	0	=-D	12 AWG	Copper	0/0
16	15	=P	0	=-D	=P	=-D	0	12 AWG	Copper	0/0
17	11	0	=-E	0	0	0	=E	12 AWG	Copper	0/0
18	11	0	0	=E	0	=E	0	12 AWG	Copper	0/0
19	11	0	=E	0	0	0	=-E	12 AWG	Copper	0/0

Running the model on each of the bands produced the free-space E-plane patterns shown in **Fig. 11**. Each pattern represents my judgment of the best pattern on the band, with a record of the frequency at which it occurred. Besides the anticipated fantailed rear lobes on the upper two bands, they are all well behaved. The question is whether we achieved anything with these well-shaped patterns.



Original W6PU Dual-Driver 4-Element Tri-Band Quad
Best Free-Space E-Plane Patterns

Fig. 11

Fig. 12 graphs the free space gain of the array across each of the bands, using the same graphing scale that we applied to the single-driver ARRL quad beam. The 10-meter gain curve is very similar to the one obtained from the ARRL quad. The 15-meter curve is similar in its evenness, but at a level that is below that we obtained from the single-driver beam. The 20-meter curve peaks at mid-band. It descends very slowly above the peak frequency, but drops precipitously at the low end of the band.

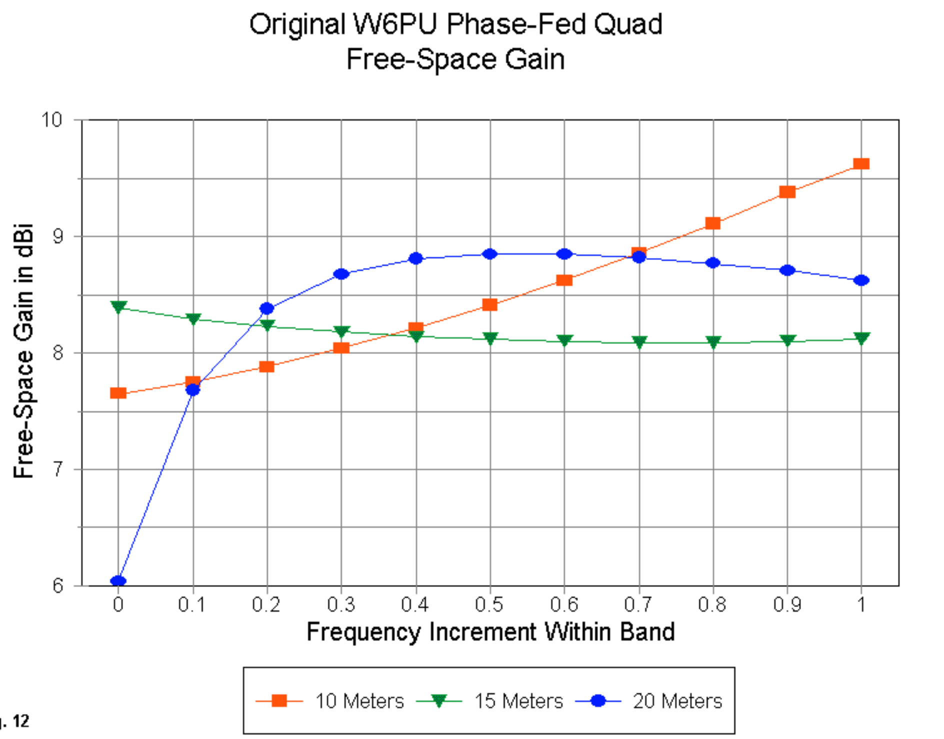


Fig. 12

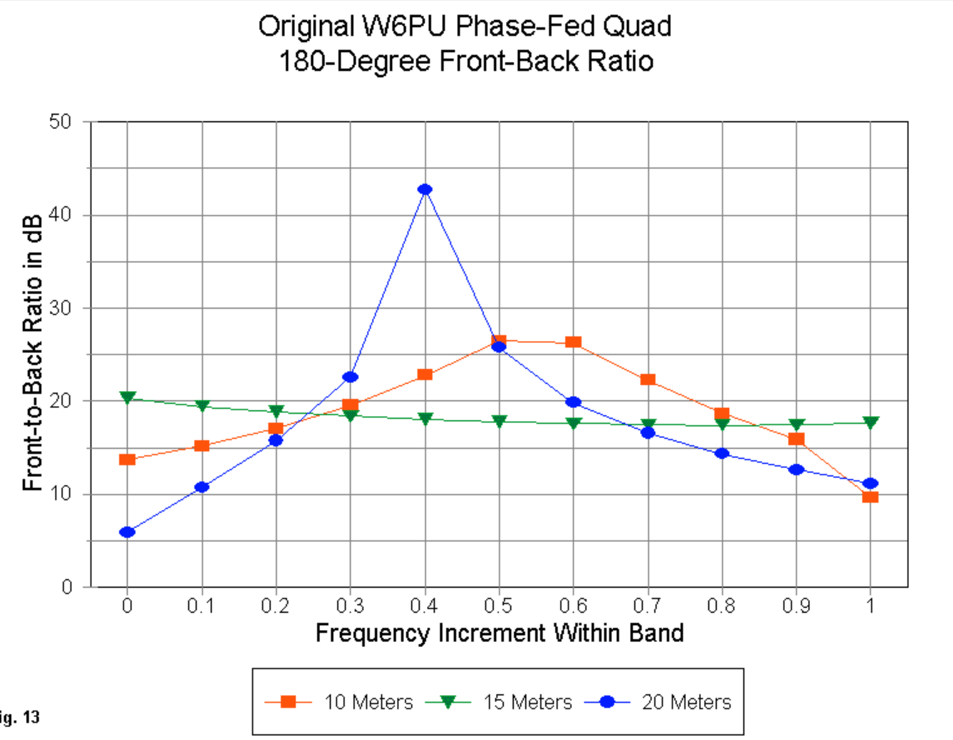


Fig. 13

We can see the results for the 180-degree front-to-back values in **Fig. 13**. The values are not significantly different overall from those obtained from the single-driver array. Perhaps the one major difference lies in the very high peak value on 20 meters near 14.14 MHz. The pattern shape in **Fig. 11** reveals that the antenna has almost no rear lobes at all--just enough to recognize the deep 180-degree dimple. Accompanying this remarkable front-to-back value is a severe decrease in the front-to-back ratio at the low end of the band, corresponding to the great decrease in forward gain in the same frequency region.

One might surmise that W6PU created the antenna to obtain a coincidence of maximum gain and maximum front-to-back ratio for a small portion of the 20-meter spectrum. 10 meters also shows a mid-band front-to-back ratio peak, but of much smaller proportions. 15-meters is flat. However, the array design using phase-fed drivers fails to produce any gain over the single driver quad explored earlier in these notes. Since we do not know the design of the quad against which he made his gain comparisons, any further conclusions than this one would be speculative.

We need not speculate about the feedpoint impedances obtained with the model of the W6PU array. They are all too low to graph against a 50-Ohm standard. All of the reported impedances have a very low reactive component, with the maximum range over the 3 bands going from -j8 Ohms up to +j11 Ohms. However, the resistive component is problematical. On 10 meters, it runs from 9 to 20 Ohms. On 15, the range is 9 to 11 Ohms. On 20, it runs from 1.5 to 15.5 Ohms. The diagrams all show a direct connection to a 50-Ohm feed line. However, the model suggests that a 1:4 transformer would be necessary to achieve a 50-Ohm impedance across even part of the bands. With such a transformer, 15 meters would show under 2:1 50-Ohm SWR across the band. 10-meters might provide about 800 kHz of coverage, since the feedpoint resistance rises very slowly across the first half of the band and much more rapidly thereafter. On 20, the SWR would be satisfactory only over the upper or SSB portion of the band. Of course, this speculation assumes the use of a 1:4 transformer with high efficiency.

The number of times that the W6PU dual-driver array has been brought to my attention suggests that numerous antenna planners are using the beam as a potential foundation for their own antenna work. Yet, we are left with a quandary. If the dual-driver system aimed to increase gain over a single driver, it failed. If it aimed to produce a wider passband than the single driver array, it also failed.

In arrays using phase-fed dual drivers, the constraints of phase feeding the drivers make maximum gain and a wide passband virtually contradictory. It is possible to set the current magnitude and phase on the two elements so that they yield very high gain--over 7 dBi in free-space models of 2-element phased horizontal arrays--over a very narrow passband and at a very low impedance. It is also possible to set the driver current magnitudes and phases to achieve maximum front-to-back ratio, but only at a lesser gain, perhaps just below 6 dBi. The required current magnitudes and phases for a given pair of elements are very different for the two conditions. In phase-fed Yagi studies, I have used the high-gain setting with a director to achieve further gain and a very good front-to-back ratio--but only at the cost of a low feedpoint impedance and a bandwidth only suited to the so-called WARC bands.[3]

Obtaining a wide operating bandwidth tends to require a set of current magnitude and phase conditions that fall in between those needed for the extremes of gain and of front-to-back ratio. The improvement in horizontal arrays using linear elements tends to be only marginal, usually to the front-to-back ratio over the entire passband, relative to Yagis with similar spacing and the same number of elements. The gain remains at or just under the levels achieved by a well-designed Yagi of the same boom length and the same number of elements.[4]

Since it is unlikely that the phase-fed dual driver system can achieve any gain advantage over the single-driver ARRL quad array, perhaps the rightful place for the W6PU array lies in providing full band coverage with good gain and front-to-back values for all of the bands--including 20 meters. However, if we hope to achieve a wide-band, 50-Ohm feed system, the array will have to undergo considerable redesign.

A Modified W6PU Dual Driver 4-Element Tri-Band Quad

Designing a simple 2-driver log-cell Yagi begins with the design of the phased drivers. When we add parasitic elements to the driver set, we ordinarily do not disturb the drivers. Instead, we set the length and spacing of each parasitic element for a desired set of performance curves over the selected passband. Finally, we either accept the feedpoint conditions presented by the phased drivers, or we take the entire array through a number of iterations attempting to preserve the performance curve while attaining a desired feedpoint impedance curve. In theory, designing a dual-driver monoband quad would follow the same scenario.

Our subject antenna, however, is not a monoband quad, but rather a tri-band quad with preset element spacing. Our goal is to discover if we can adapt the basic design to a reasonably high performance array, using the ARRL quad as an initial measuring stick. As well, the goal is to find out if we can extend the passband so that we obtain full band coverage on 20 and 15 meters and full coverage from 28 to 29 MHz on 10 meters. The task has some limiting factors. First, the element spacing, even between drivers, varies from one band to the next as a function of a wavelength. Second, the interactions among the active elements and the passive ones may complicate not only the sizing of the parasitic loops, but as well, the phase line for the active band. Indeed, because changes in the phase line length on one band will affect the activity of the elements when passive, we have an additional variable that will affect the outcomes. Hence, we shall require a considerable number of iterations to assure that we attain the project goals.

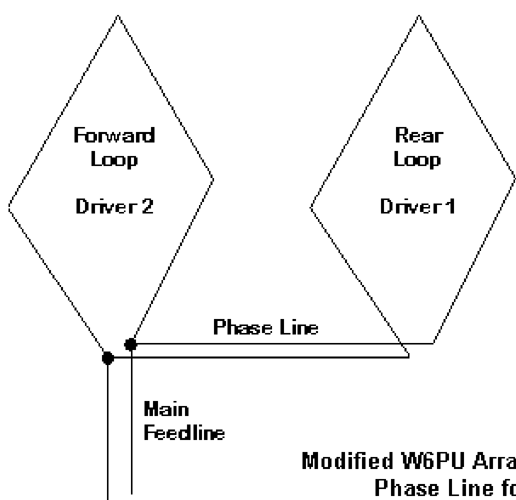


Fig. 14

Modified W6PU Array
Phase Line for
Forward Driver Feed

Refer to **Fig. 5** for the general outline of the modified W6PU phased-driver array. The elements of that sketch do not change in the process of modification. However, we do change the phase-line scheme to a more conventional one that uses a single line between drivers for each band. As well, we feed the forward driver, as shown in **Fig. 14**. These moves are for convenience of design and do not invalidate the use of split lines to effect the desired phasing. The goal is to find a ratio of current magnitude on the drivers and a set of relative phase angles that will yield acceptable performance.

A phased pair of drivers requires relative current magnitudes and phase angles of certain orders for any given performance curve. The current magnitudes are normally close to but hardly ever precisely equal. The current phase angle between the two elements varies with the spacing, with the rear element showing a positive angle relative to the forward element. The wider the spacing, the larger the phase-difference required for a given result.

At the same time, we wish the feedpoint to exhibit an acceptable impedance. In our test case, the target is 50 Ohms resistive, with slow variations of both resistance and reactance as we move away from the design frequency. For a system that uses a single line between the drivers, we may presume a constant voltage at the junction of the forward element and the phase-line end. The parallel connection forms a current divider. The forward element feedpoint impedance sets the current level and phase angle for the forward element. However, the impedance of the rear element, as transformed along the phase line, determines the impedance on the phase-line side. Hence, the phase-line characteristic impedance and length play a role in determining what impedance appears at the junction. This impedance, in parallel with the forward element impedance, determines the current division. The transformation of the current and its phase angle working back toward the rear element determine the current magnitude and phase angle at that point. The parallel combination of the phase-line forward-end impedance and the forward element impedance yield the feedpoint impedance of the array.[5] If we use a split pair of phase lines, with a length forward to the front element and another length back to the rear element, we only complicate the situation by one more set of transformations along an added transmission line.

The presence of parasitic elements and of interactive undriven elements for inactive bands assures that the simple calculations will not yield usable results. Therefore, when all else fails, one uses the method of experimental iteration, also known as trial and error. By a series of trial phase-line lengths and characteristic impedances, accompanied by judicious re-sizing of some element circumferences, one can see trends in performance, as well as the limits of improvement made by further changes of the same type. The initial stage involved finding setting for the individual bands, followed by re-adjustments occasioned by the fact that changes to one band required additional changes to the other bands.

Table 5. Dimensions of the W6PU dual-driver, 4-element, 33.5'-boom, tri-band quad

	Space from	Circumference in feet		
Element	Reflector in feet	20 Meters	15 Meters	10 Meters
Reflector	-----	73.07	50.30	37.24
Driver 1	13.0	72.12	49.97	36.06
Driver 2	21.5	67.41	46.20	33.00
Dir. 1	33.5	67.88	45.83	34.42

Table 5 provides the dimensions of the final model for the modified W6PU array. The most notable changes are the enlargement of the rear drivers and the shrinkage of the 20-meter

and 10-meter forward drivers. The 15-meter forward driver is actually larger than in the original array. Changes to the circumferences of reflectors and directors tweak performance or the position of performance peaks within the passband.

A 50-Ohm phase line proved satisfactory for all bands, but its length is not what we expect of a 2-element phase-line. We are used to the trick of reversing the connections of a short phase line to accrue the impedance transformation of a longer line, for example, giving a half twist to a 45-degree line to effect a 135-degree line. Because early principles in amateur circles stressed the impedance transformation rather than the current transformation in the phase line, we have mis-labeled the effect of the half twist. A 45-degree line with a half twist does not transform to 135 degrees, but instead to -45 degrees--or 315 degrees, if counting always in a positive direction. Of course, the current transformation is only 45 degrees if the rear element has an impedance that matches the characteristic impedance of the phase-line.

The spacing between the two drivers in our array does not permit the use of a very short line. Hence, we need to use longer lines without the twist for our phase lines. The shortest line must be at least 8.5' long, plus a small addition to clear the supporting mast for the array. On 20 meters and 15 meters, the required 50-Ohm lines are considerably longer. In this exercise, I shall pass over the difficulties of physically controlling the route taken by the longer lines.

Table 6. Phase-line lengths for each band for the modified W6PU quad.

Band	Driver Spacing		Line Electrical	Physical Length	
	Wavelengths	Degrees	Length feet	VF=.66	VF=.80
20 (14.175)	0.1225	44.10	31.25'	20.63'	25.00'
15 (21.225)	0.1834	66.02	25.83'	17.05'	20.67'
10 (28.5)	0.2463	88.67	13.33'	8.79'	10.67'
10 (alt)*	0.2463	88.67	30.59'	20.19'	24.47'

Note: All lines are 50-Ohm without reversal, except 10 (alt)*, which uses a reversed 50-Ohm line. For all lines, the route is from Driver 1 (rear) to driver 2 (forward), with the feedpoint at driver 2.

Table 6 presents the required line lengths for the phase lines for all 3 bands. On 10 meters, the 8.79' line may be too short for routing around the mast. Therefore, I have included its reversed counterpart, which is similar in length to the 20-meter line. The table also contains some other useful information, such as the spacing between drivers for each band measured as a function of a wavelength and in electrical degrees--both at the middle of each band. As well, I have shown the physical lengths of the lines assuming velocity factors of 0.66 and 0.80 as a rough guide to the actual line lengths a builder might encounter. Anyone contemplating building this or any other phased array is well advised not to trust the published velocity factor values, but to measure the velocity factor of the actual material being used.

Table 7. Current phasing data.

Freq.	Differentials Between Rear Driver and Forward Driver		Line Length
MHz	Current Magnitude Ratio Rear-to-Forward	Relative Current Phase Rear (Forward = 1.0)	Degrees
14.175	1.365:1	103.2	162.1
21.225	0.779:1	131.3	200.7
28.5	0.856:1	150.3	139.1

One more table completes the data necessary to understand something of the complexity of a multi-band, dual-driver quad array. **Table 7** provides information on the modeled mid-band differentials between the two drivers in terms of their current magnitudes and phase angles. The data may provide some appreciation of how element interactions complicate matters in tri-band phased arrays. The lines for 20 and 15 meters are considerably longer than we might expect for the spacing between driver, while the 10-meter line is shorter. (These expectations are based on the erroneous rule of thumb that a spacing of 0.125-wavelength requires a phase line of 135 electrical degrees.) Indeed, the 15-meter line, under the influence of both the 10- and 20-meter inactive elements, is longer than 1/2 wavelength (180 degrees).

The current ratios initially look to be well off of any ideal ratio, where something close to 1:1 might be expected. However, I experimented extensively with the 20-meter drivers and obtained peak performance with exactly equal currents and a phase difference of 110 degrees. The improvement was exactly 0.01-dB increase in gain and 3 dB in front-to-back ratio. Since the front-to-back ratio at the center of 20 meters already exceeds 23 dB and since the added gain is not obtainable with a commonly available transmission line, I concluded the tests.

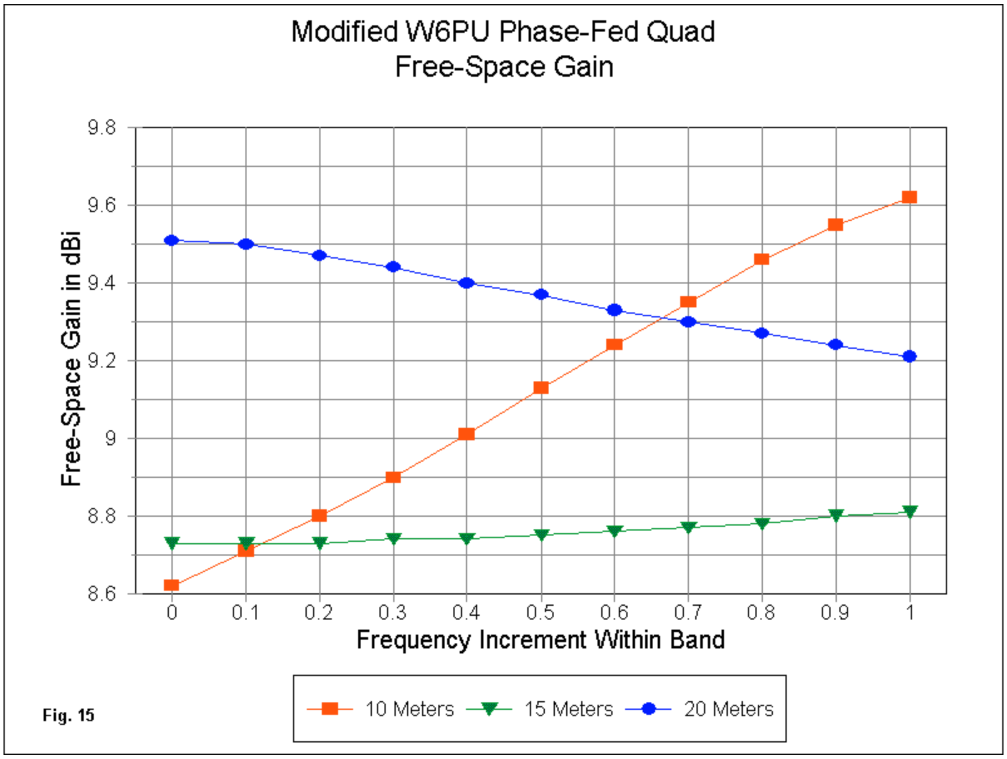


Fig. 15

The question that follows this foray into the design parameters for a multi-band, phase-fed quad array is what we obtained for our efforts. In terms of free-space gain, **Fig. 15** provides the results. Relative to the original W6PU design, we obtain higher gain across each of the three bands. 20 meters shows a smooth gain curve, with no major drop-off at either band edge. 10 meters shows the cross-band rise that we saw in the original design, but at a high average level. 15-meter gain is flat across the band and slightly greater than in the original design.

If we compare array gain with the ARRL quad with which we started this investigation, we find the 20-meter results to be very comparable, with the ARRL single-driver quad having an average 0.1-dB advantage. However, the ARRL quad shows an average advantage of about

1.3 dB advantage over the dual-driven array on 15 meters. The 10-meter gain curve largely offsets that advantage, since the ARRL version is much steeper. It has about a full dB less gain at the low end of the band and only just exceeds the modified W6PU array at the top end. In essence, this result establishes that a phase-fed quad array has no particular gain advantage over a more conventional single-driver array of about the same boom length and using the same number of elements.

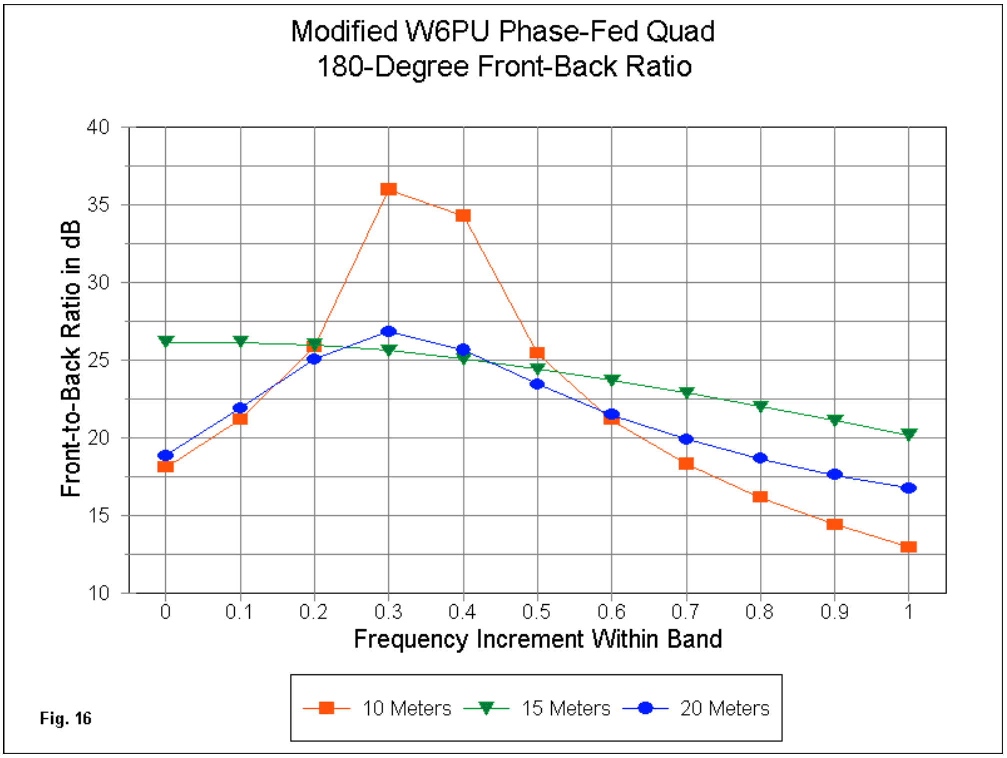


Fig. 16

The 180-degree front-to-back ratio results appear in **Fig. 16**. The original W6PU array has a very sharply peaked 20-meter front-to-back curve with very poor values at the low end of the band. In contrast, the ARRL quad 20-meter front-to-back curve almost parallels the modified array curve, although the latter has somewhat better low-end values. On 15 meters, the modified array shows a value above 20 dB all across the band. The original W6PU array was several dB lower at all points in a parallel curve. The ARRL front-to-back curve rises from 10 dB to 22 dB across the band, in contrast to the smooth results for the modified phase-fed design.

On 10 meters, the modified and original W6PU designs again show parallel curves. However, the modified design manages to increase the front-to-back ratio by at least 3 dB everywhere in the band. Unfortunately, the ARRL array requires significant improvement in its 10-meter front-to-back performance, with a curve that runs from 4 dB at the low end of the band to only 14 dB at 29 MHz. Although the gain differentials among the designs may be operationally moot in most cases, the modified phase-fed array has superior performance in the front-to-back category over both of the other arrays.

Since the motivation for this design exercise was to determine if phase-feeding a quad array could improve the operating bandwidth, especially on 20 meters, we should examine **Fig. 17**. The graph settles the question immediately. On 20 and 15 meters, the 50-Ohm SWR curve is 1.5:1 or lower everywhere on each band. Although the 10-meter SWR curve remains below 2:1 across the first MHz of the band, it does not match the corresponding 10-meter SWR curve of the ARRL quad. However, that single-drive quad does not match the phase-fed array on either 20 or 15 meters, with 20 meters being very deficient in coverage.

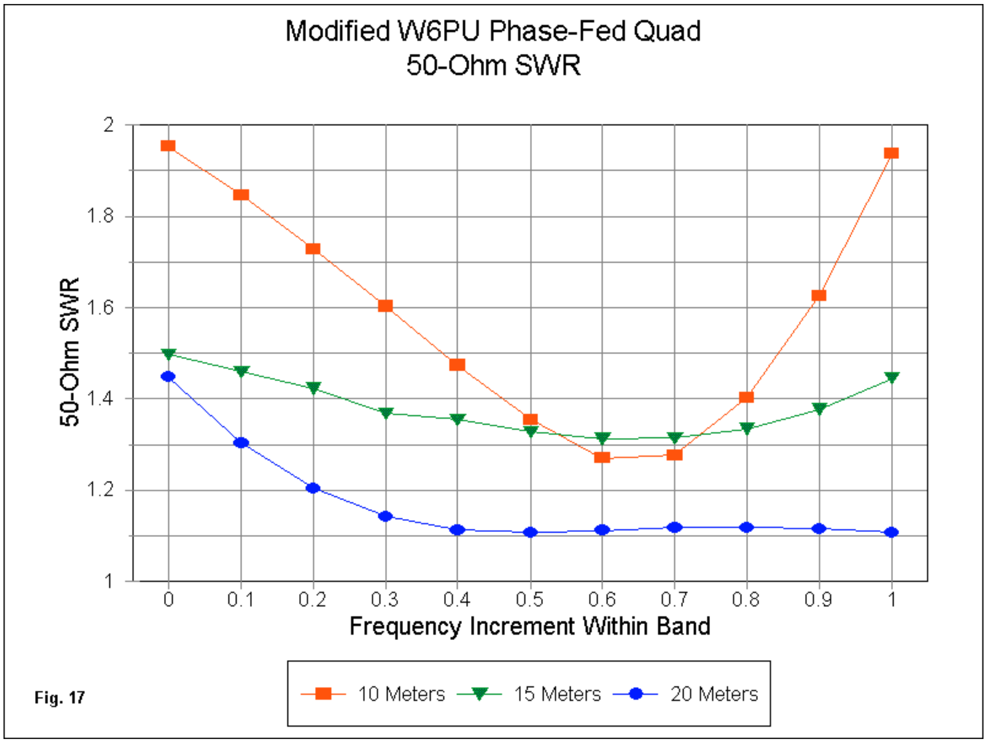
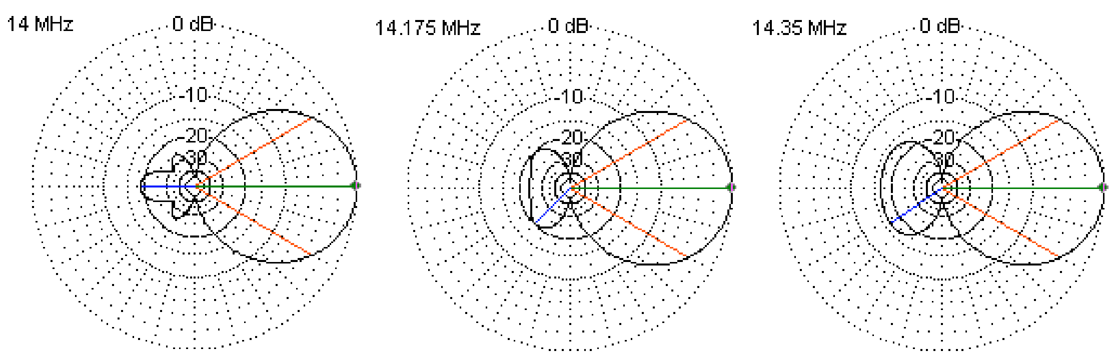


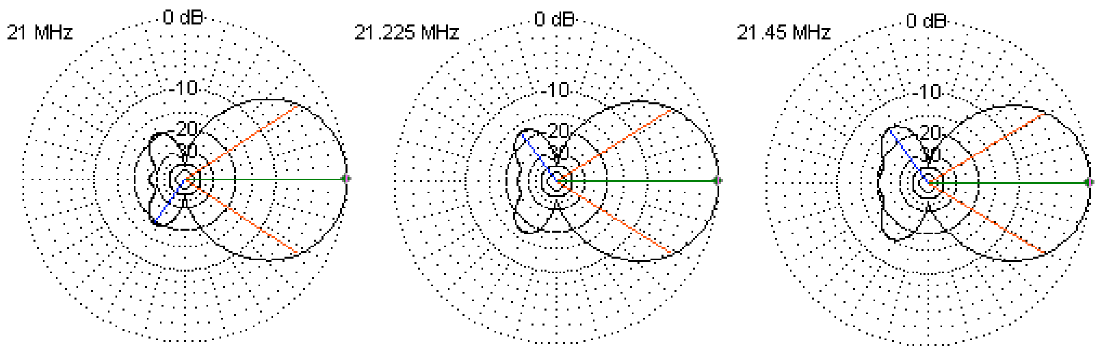
Fig. 17



Modeled 20-Meter Free-Space Azimuth Patterns
Modified W6PU Quad Array

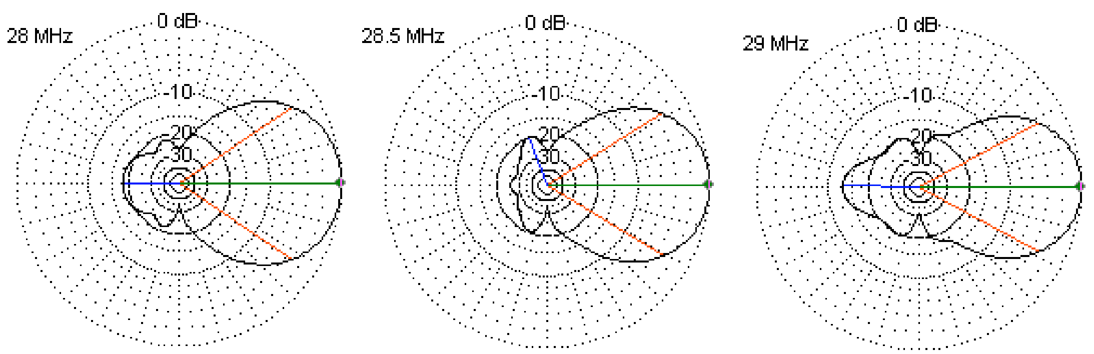
Fig. 18

As I indicated early on in the investigation, multi-band quads require attention not only to levels of performance, but as well to pattern shape. Therefore, I am including some modeled free-space E-plane patterns that will closely resemble the azimuth patterns one might achieve with such an antenna at least 1 wavelength above real ground. **Fig. 18** samples the 20-meter patterns at the band edges and in the middle of the band. Perhaps the only way to describe these patterns, relative to our expectations from a comparable monoband Yagi, is that they are clean and well behaved.



Modeled 15-Meter Free-Space Azimuth Patterns
Modified W6PU Quad Array
Fig. 19

In **Fig. 19**, we find the corresponding patterns for 15 meters. The forward lobes are once more clean. The rear lobes show a minor tendency toward fan-tailing as we increase the frequency within the band, so that the worst-case front-to-back ratio is about 15 dB at the high end of the band. Compared to many multi-band quad designs, the 10-meters patterns in **Fig. 20** are quite free from anticipated abnormalities. The rear lobes, while not as diminutive as we might like from a monoband Yagi, are free from quartering sidelobes that would yield a ratio of under 20 dB. From 28.5 MHz to 29 MHz, the forward lobe barely shows small bulges, indicating an incipient but undeveloped secondary forward lobe.



Modeled 10-Meter Free-Space Azimuth Patterns
Modified W6PU Quad Array
Fig. 20

All-in-all, then, the modified W6PU phase-fed driver multi-band quad offers in principle reasonably good performance on all three of the wide upper HF amateur bands. It is broadband in its full coverage of each band, and its gain and front-to-back levels are very respectable for quad arrays with a 33.5' boom. The modified version overcomes the shortcomings that appeared in models of the original W6PU design, while generally equaling or bettering the performance curves for the ARRL design (except for 15-meter gain).

In the final analysis--and apart from prejudices for or against quads--the design leaves us with a final question: how does the anticipated phase-fed quad performance stack up over and against the performance of a comparable multi-band Yagi design?

The Modified Phase-Fed Quad vs. 2 Multi-Band Yagis

The modified W6PU phase-fed quad uses 12 elements in 4 groups of three on a 33.5' boom. To evaluate its performance fairly, we need to compare the figures that appear in the graphs (**Fig. 15**, **16**, and **17**) with those from an array with which the quad might be competitive as a design of similar complexity, similar coverage, and similar size. Hence, monoband quads and Yagis are not suitable comparators in the evaluation. The potential gain figures for the monoband antennas, cited at the beginning of this study, serve only to reveal to what extent the multi-band quad (or other multi-band antennas) achieves (or fails to achieve) monoband performance.

A more suitable comparator for a first-order competitive comparison would be a multi-band Yagi having a similar boom length to the one used in the quad, something in the range from 30' to 35'. Over the years, I have developed models of at least two possible designs. Although the models have roots in the measurement of dimensions of actual antennas, they are not models of the antennas themselves. Instead, they are modeling idealizations, using uniform-diameter elements, in contrast to the normal stepped-diameter element structures used in upper-HF horizontal arrays. Hence, the element lengths do not coincide with those of actual antennas. As well, both models use complex feeding systems so that the user requires only one feedpoint and cable. All such systems depend for the impedance transformations on not only the element lengths and spacing, but as well on the element diameter. The idealization of the model to uniform-diameter elements requires alterations in the feed structure to simulate the actual one. As a consequence, the performance curves that emerge from the models may differ in detail from those obtained with real antennas of roughly similar outlines. These cautions result in a disclaimer: for true models of any antenna, commercial or otherwise, one needs to consult the maker or the maker's literature.

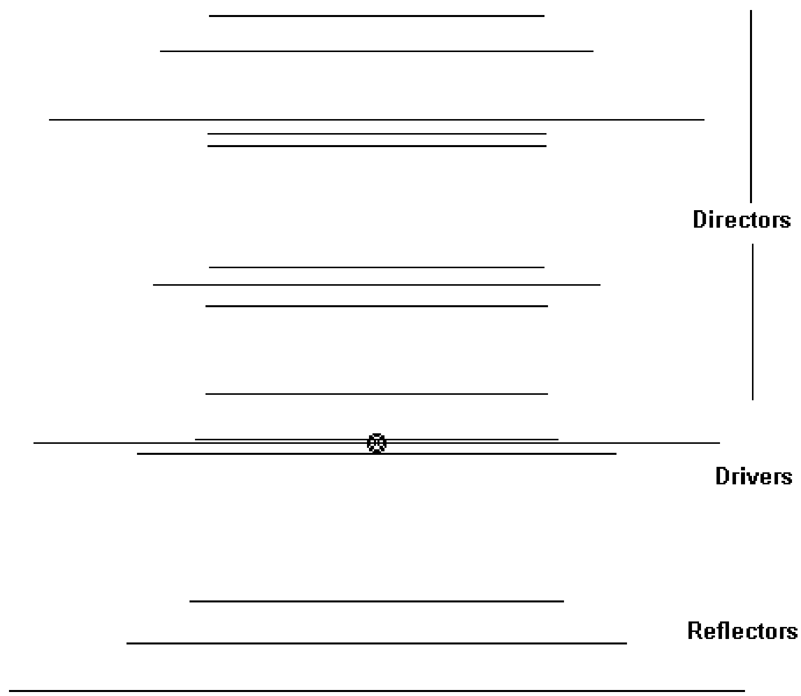
In addition, various antenna makers use different methods and test set-ups for obtaining performance results that eventually appear in one or another form of print. The modeling results that I shall present stem from simple free-space models. Hence, they may not coincide with numbers that may appear for similar-looking antennas. As well, makers modify and improve designs with time, and the models used here may be dated relative to their roots.

Nevertheless, we may use these idealized models for a limited purpose: to gather basic data on the potential performance of multi-band Yagis in the 30-35-foot category. We shall limit the use of the data to seeing how the modified quad design stacks up with these modeled Yagis. The comparison may tell us whether the quad design is roughly competitive, vastly superior, or embarrassingly inferior. If one needs finer shades of evaluation, one must build all of the arrays and test them on a rated range.

One question that the evaluation will not tell us is whether the quad enjoys in fact its reputation as a band opener and closer. Such a study involves more than the basic modeled performance of the antenna, since it likely depends on propagation phenomena as well as on radiation pattern phenomena. Consequently, these notes will remain silent on that perennial issue in the Yagi-vs.-quad discussion.

A 15-element tri-band Yagi using a master driver and two slaved drivers: The first of our multi-band Yagis uses a boom just over 31.5' long, plus such end extensions as may be needed to mount the element-to-boom hardware. The general outline appears in **Fig. 21**, with the model dimensions shown in **Table 8**. The design uses 3 20-meter elements, 4 15-meter elements, and 8 10-meter elements. This type of listing is conventional and based on the length of the elements. However, as in all multi-band Yagi designs, the elements for inactive bands relative to one being used are active to some degree.

Fig. 21



15-Element Tri-Band Yagi Using a Master and 2 Slaved Drivers

Table 8. General dimensions of a 15-element, master+2 slaved drivers, tri-band Yagi

El. #	Function	Length (feet) (feet)	Diameter (inches)	Distance from Reflector (feet)
1	20-m reflector	34.50	0.625	-----
2	15-m reflector	23.33	0.50	2.17
3	10-m reflector	17.50	0.40	4.17
4	15-m slaved driver	22.33	0.50	11.09
5	20-m master driver	32.17	0.625	11.60
6	10-m slaved driver	16.97	0.40	11.79
7	10-m director 1	16.00	0.40	13.92
8	10-m director 2	15.92	0.40	18.00
9	15-m director 1	20.92	0.50	19.00
10	10-m director 3	15.58	0.40	19.83
11	10-m director 4	15.83	0.40	25.50
12	10-m director 5	15.83	0.40	26.08
13	20-m director 1	30.67	0.625	26.75
14	15-m director 2	20.33	0.50	30.00
15	10-m director 6	15.67	0.40	31.58

20-meter elements are particularly troublesome to 10-meter operation, since they can be not only active, but may control 10-meter performance. The length of a 20-meter element as it approaches a full wavelength on 10 meters tends to be long in terms of what the 10-meter portion of the array requires, even from a full-wave element. The effect is to drag the performance curves lower in frequency, preventing full high-band coverage. The normal compensation is to add a 10-meter director immediately to the driver side of the 20-meter director. As well, one usually needs to place a further 10-meter director on the other side of the 20-meter director. Although less of a burden in this respect, similar treatment usually accompanies the placement of 15-meter directors, as these elements can also affect 10-meter performance. Signs of such design maneuvers appear in **Fig. 21**.

A second reason for surrounding lower-band directors with high-band directors is the fact that in developing a design, directors for different bands--especially for 10 and 20 meters--seem to "want" to be in the same place. The design at hand does not use traps to resolve the placement issue. Instead, the fore-and-aft high-band director treatment settles the issue.

The driver section of the antenna employs a master 20-meter driver. Closely spaced slaved drivers for 15 meters and 10 meters require no connection to the master driver to perform their function. Such systems depend upon the mutual coupling between elements--all of which are highly dependent upon element length and spacing of the slaved drivers relative to the master driver--to provide the higher-band energy for the array and to show a suitable impedance at the master driver on all three bands.

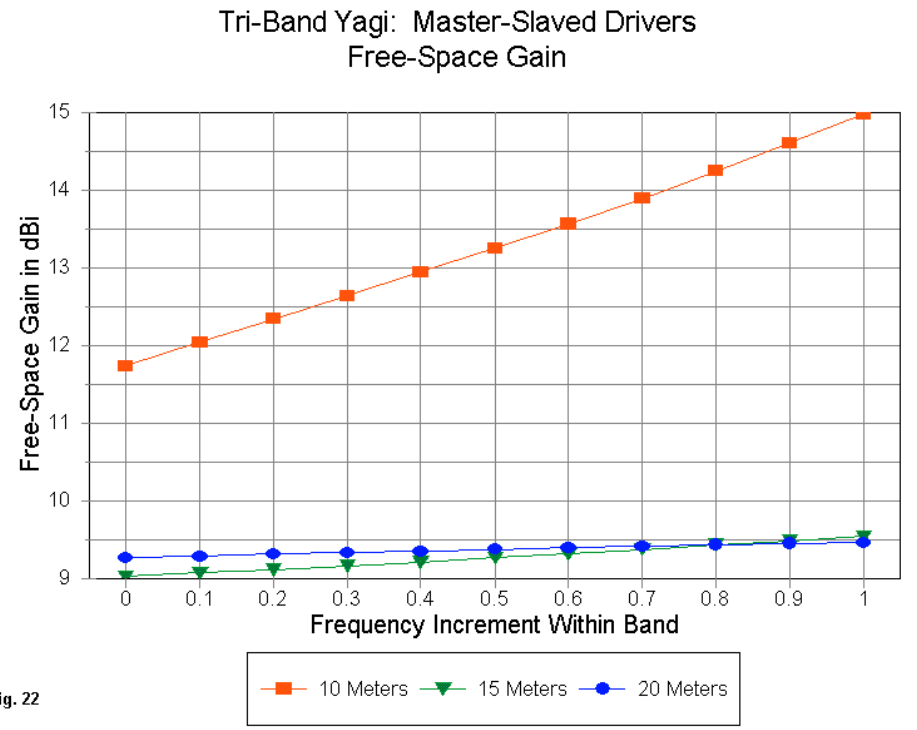


Fig. 22

Such a design is capable of high levels of performance on all three upper-HF bands. **Fig. 22** shows the modeled free-space gain of the array. The values for 20 and 15 meters form smooth curves and range from just above 9 dBi to about 9.5 dBi. The boom length is long for 10 meters and is filled with directors that increase gain in addition to compensating for interactions with elements for other bands. Hence, 10-meter gain is considerable higher than for the lower bands, ranging from about 11.7 dBi to nearly 15 dBi across the first MHz of the band.

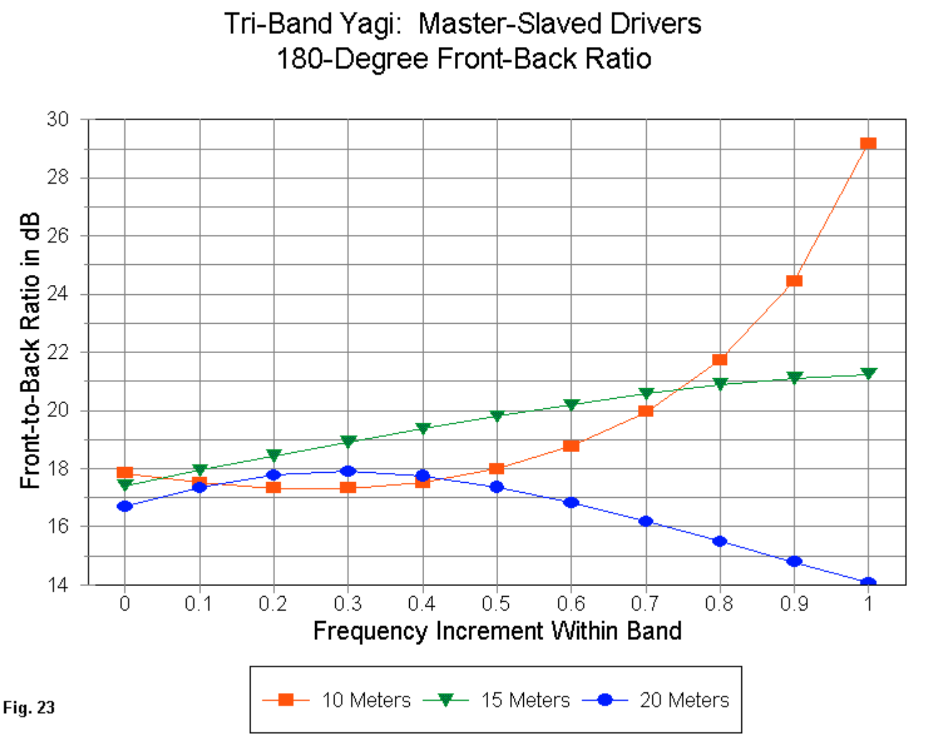


Fig. 23

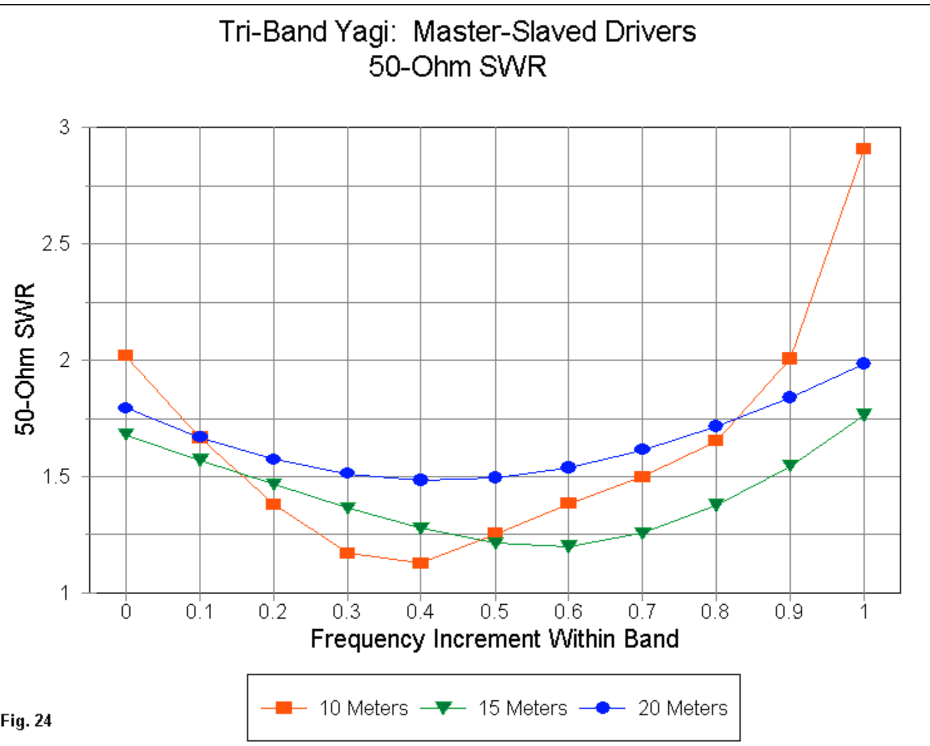
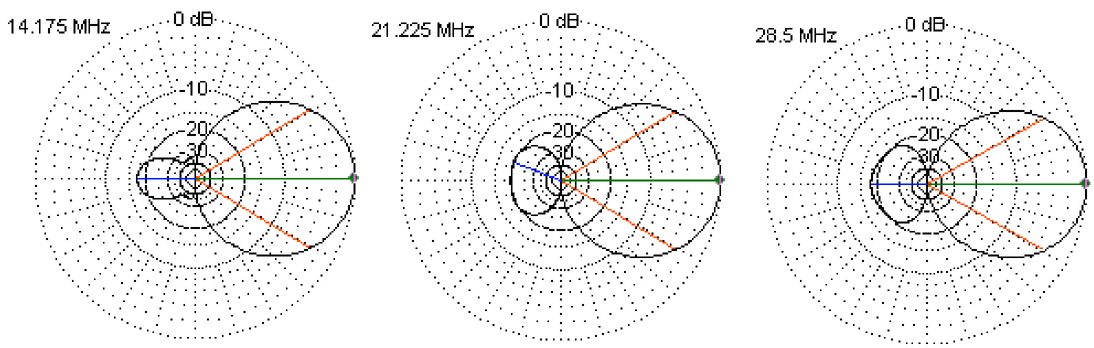


Fig. 24

Fig. 23 shows the modeled 180-degree front-to-back performance of the array. From monoband beams, we expect to see values above 20 dB everywhere within the band covered. Although the front-to-back ratio of a tri-band beam may peak over the 20-dB marker level, the average front-to-back ratio averages in the range between 17 and 20 dB. In the test model, the 20-meter ratio drops to just above 14 dB at the high end of the band, while the 10-meter ratio appears headed for a sharp peak just beyond 29 MHz. Nonetheless, the curves are important also for what they do not show: the extremely low values at one or another band edge that often attach to some conventional multi-band quad designs. For example, the lowest value on 20 meters--where the array uses 3 elements--is well above what we might obtain from a 2-element driver-reflector Yagi design.

The 50-Ohm SWR performance appears in **Fig. 24**. On 20 and 15 meters, the array achieves an SWR well below the conventional standard of 2:1 at the antenna feedpoint. The antenna also manages to cover all but the last 100 kHz of the 10-meters, as defined in terms of its first MHz. Some improvement in the 10-meter curve may be possible by judicious adjustments to the length and spacing of the 10-meter slaved driver relative to the master 20-meter driver. However, my experience with 2-band antennas using the same type of driving system suggests that without beneficial element interactions that broaden an operating curve, reduced coverage is natural. The means taken to isolate 10-meter gain and front-to-back performance from problematical interactions with lower-band elements also limits the SWR passband. All multi-band antennas ultimately demand compromises and decisions as to which properties receive priority.

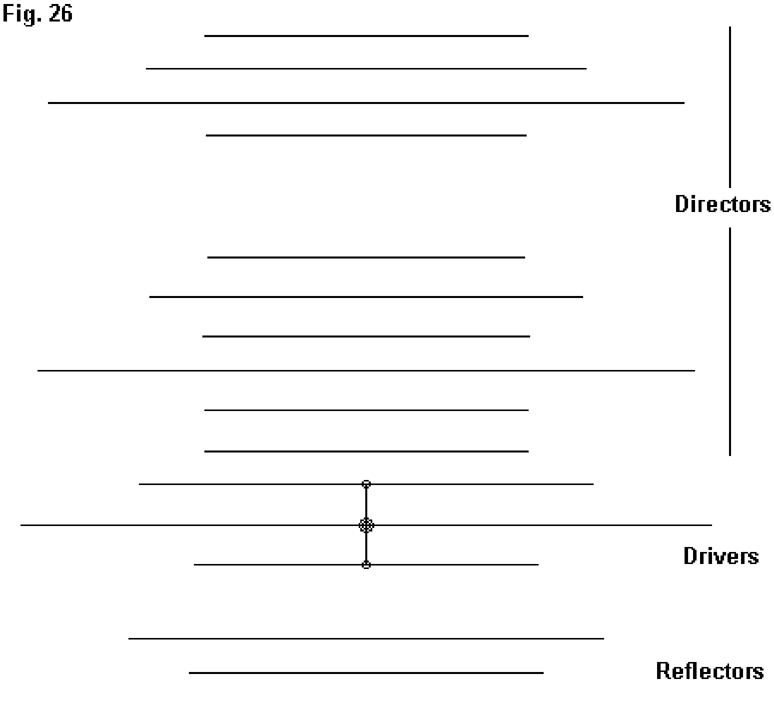


15-Element Tri-Band Yagi Using a Master and 2 Slaved Drivers
Representative Free-Space E-Plane Patterns **Fig. 25**

Multi-band Yagi designers are as concerned with pattern shape as with the basic performance numbers. **Fig. 25** provides a sample pattern from each band--taken at the band center frequency--to create a quick check on this property. In all cases, the patterns are clean, that is, typical Yagi patterns for the level of gain and front-to-back ratio.

A 16-element tri-band Yagi using directly coupled drivers: A single multi-band Yagi design might be an aberration from the norm, so I am including a second tri-bander using a boom nearly 33' long. It employs 16 elements: 4 for 20 meters, 4 for 15 meters, and 8 for 10 meters. Lest one think that the design is a clone of the 15-element Yagi, a comparison of **Fig. 26** with **Fig. 21** will reveal that the element placement is quite different throughout. What this array shares in common with the first one are two major design features. One is the use of surrounding 10-meter directors for the 20- and 15-meter directors. The other is the general progression of elements, which is a factor controlled by the frequencies covered more than a simple decision of the designer.

Fig. 26



16-Element Tri-Band Yagi Using 3 Directly Coupled Drivers

Table 9. General dimensions of a 16-element, directly coupled drivers, tri-band Yagi

El. #	Function	Length (feet) (feet)	Diameter (inches)	Distance from Reflector (feet)
1	20-m reflector	34.68	0.70	-----
2	10-m reflector	17.29	0.55	1.64
3	15-m reflector	23.24	0.625	3.28
4	10-m driver	16.77	0.55	6.89
5	20-m driver	33.74	0.70	8.86
6	15-m driver	22.16	0.625	10.83
7	10-m director 1	15.73	0.55	12.47
8	10-m director 2	15.73	0.55	14.44
9	20-m director 1	32.17	0.70	16.40
10	10-m director 3	15.99	0.55	18.04
11	15-m director 1	21.27	0.625	20.01
12	10-m director 4	15.47	0.55	21.98
13	10-m director 5	15.66	0.55	27.89
14	20-m director 2	31.17	0.70	29.53
15	15-m director 2	21.58	0.625	31.17
16	10-m director 6	15.73	0.55	32.81

The 16-element array differs from the 15-element Yagi in several important ways. The 4th 20-meter element changes the relationships among all of the directors, allowing a wider spacing between the 10-meter directors and the lower-band directors. As well, the array places the 10-meter driver behind the 20-meter driver, with the 15-meter driver in front. The result is a slight reduction in 10-meter gain and an enhancement of 15-meter gain, relative to what would be possible had one reversed the drivers.

The positions of the drivers also result from the feed system, which directly couples energy from the master driver's feedpoint to each of the other two drivers via a low-impedance transmission line. This system uses close driver spacing, but not as close as in the master-slaved driver system. Nonetheless, the higher-band drivers receive both direct energy and mutually coupled energy from the 20-meter driver. Hence, the higher-band driver lengths and spacing are critical to the success of the feed system. **Table 9** provides the dimensions of the model that uses uniform-diameter elements. Compared to the 15-element array, the 16-element Yagi uses much fatter elements, especially on the upper bands.

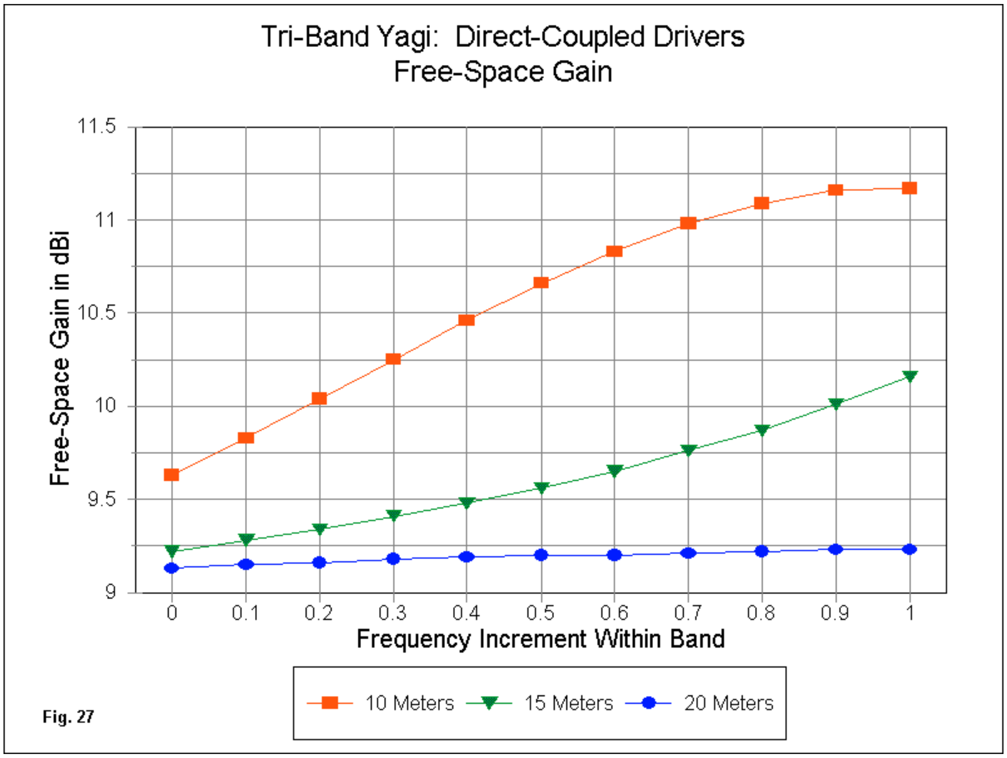


Fig. 27

The gain that we obtain from the model of the 16-element array appears in **Fig. 27**. The 10-meter gain shows the steeply rising curve common to most multi-band designs, but at a somewhat lower level than for the 15-element design. In contrast, the 15-meter curve is slightly higher. 20-meter gain levels are comparable within about 0.2 dB.

Fig. 28 shows the modeled 180-degree front-to-back ratio results. Overall, the front-to-back ratio fluctuates within the 14 to 22 dB range. No sharp peaks appear in the graph, although one might exist between 21.36 and 21.45 MHz in the last tenth of the 15-meter band.

The advantages of the directly coupled drivers--used by more than one maker these days--appear in **Fig. 29**. Although the graph indicates a few 50-Ohm SWR values above 1.5:1, the curve shapes strongly suggest that with judicious adjustment of the drivers, all of the curves would settle in with band-edge values well below 1.5:1. To go with the performance curves, the

16-element array patterns all classify as clean and well behaved, as revealed by the samples in **Fig. 30**.

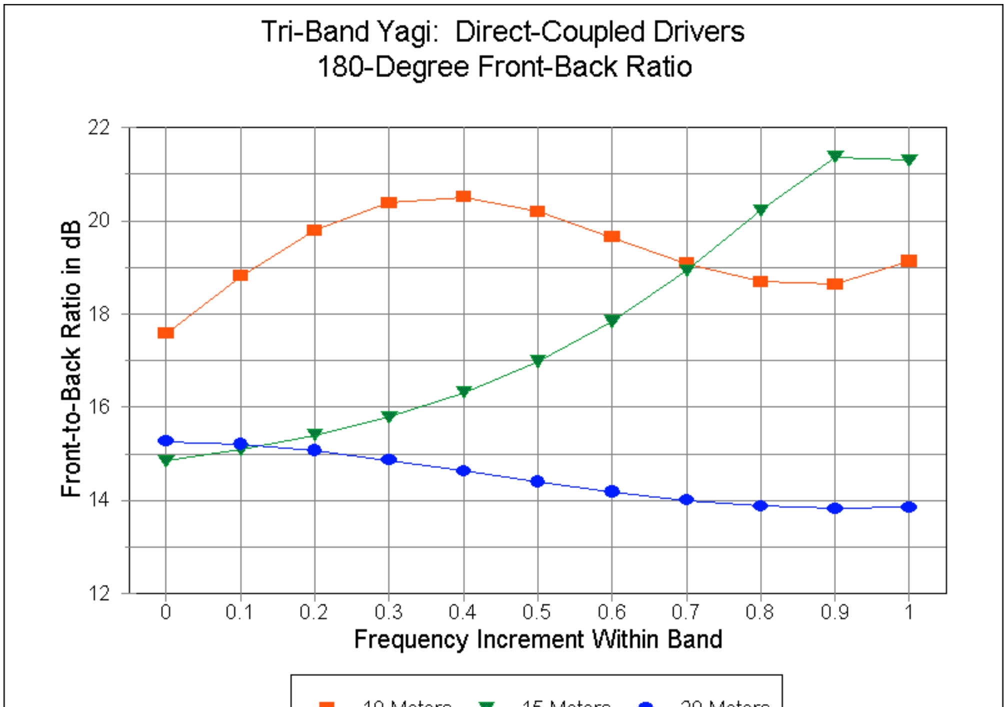


Fig. 28

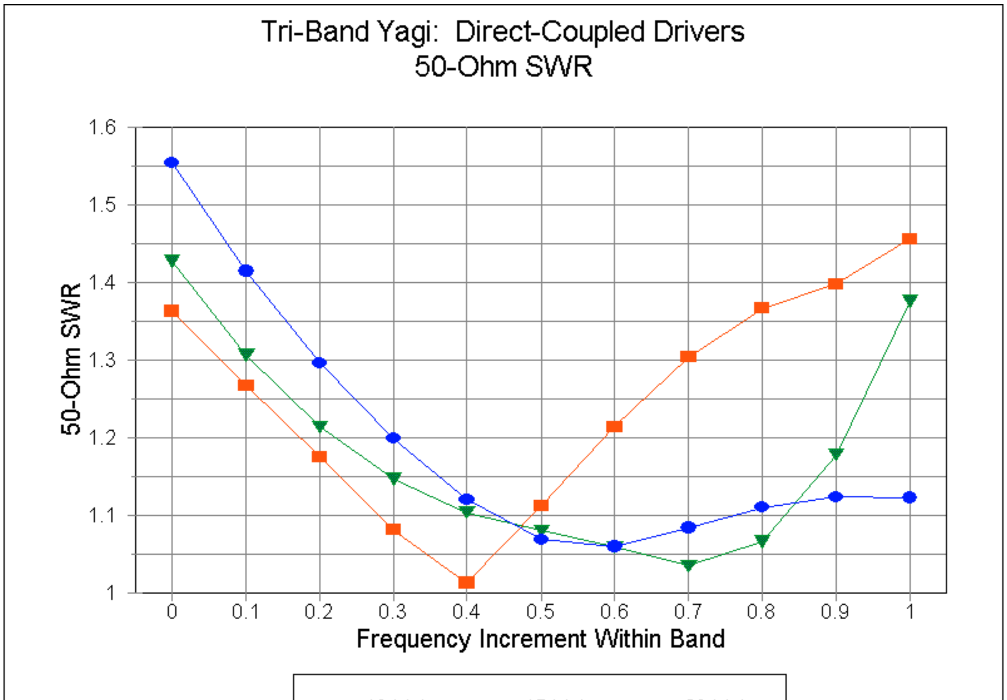
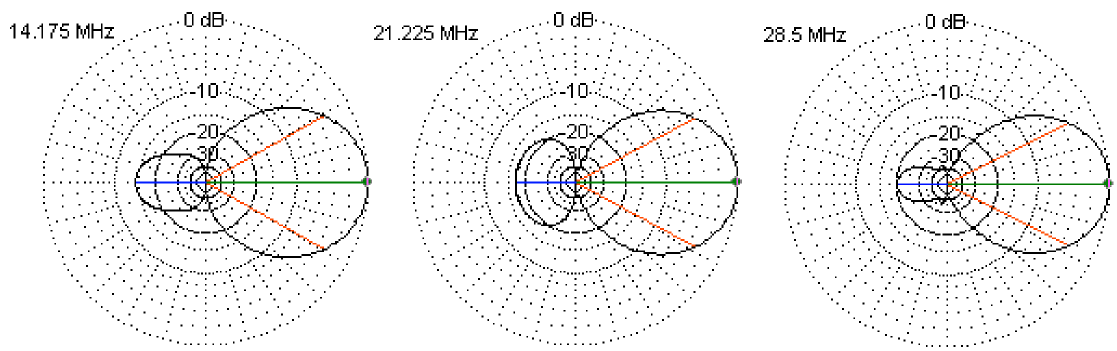


Fig. 29



16-Element Tri-Band Yagi Using 3 Directly Coupled Drivers
Representative Free-Space E-Plane Patterns

Fig. 30

The comparison and conclusion: The two multi-band Yagi designs, as modeled here, are sufficiently similar to form a basis for evaluating whether the modified W6PU phase-fed quad array is competitive. By competitive, I simply mean that it is capable of sufficient performance to warrant a move from abstract modeling design to planning a physical implementation. A review of the performance curves for all three antennas is necessary for detailed evaluation, but we can gain something of value by summarizing the average performance figures. **Table 10** provides the averaged data for free-space gain, 180-degree front-to-back ratio, worst-case front-to-back ratio, and 50-Ohm SWR. The insertion of the worst-case figure provides for the tendency of the quad to show a fantail rear lobe structure on some bands, such as 15 meters.

Table 10. Some average values of performance parameters by bands: modified W6PU quad array and 2 tri-band Yagis

Band	Free-Space Gain dBi	180-Degree/Wost-Case Front-to-Back Ratio dB	50-Ohm SWR
Modified W6PU 4-element phase-fed Quad			
10	9.13	22.17 / 18.28	1.59
15	8.76	23.94 / 16.95	1.38
20	9.37	21.48 / 19.74	1.17
15-element, master+2 slaved drivers, tri-band Yagi			
10	13.29	19.97 / 18.68	1.64
15	9.27	19.62 / 19.18	1.43
20	9.37	16.56 / 16.56	1.66
16-element, directly coupled drivers, tri-band Yagi			
10	10.55	19.32 / 19.32	1.25
15	9.61	17.64 / 17.17	1.18
20	9.19	14.47 / 14.47	1.20

Clearly, the Yagis win the gain contest on 10 meters by a wide margin, due to the ability to add the extra directors on a 30-35-foot boom. On 15 meters, the Yagis hold a slight gain margin--about 0.5 dB--but 20 meters is a dead heat. In the 180-degree front-to-back category, the quad is superior by a margin that ranges from slight--that is, a fraction of a dB--to a margin that might be operationally significant--5 dB. When it comes to worst-case front-to-back ratios, the field is split, with each antenna in the table taking top honors once. All of the arrays cover all bands with less than 2:1 50-Ohm SWR, with the exception for one Yagi of the top 100 kHz of the first MHz of 10 meters.

Although it is dangerous to make decisions based on such summary figures, the averages do indicate that the phase-fed 4-element quad is sufficiently competitive with tri-band Yagis of similar boom length to rank as neither vastly superior nor embarrassingly inferior. Hence, quad aficionados might be attracted to the design or to some offshoot of it. A myriad of mechanical features that may influence such a decision go uncovered in this study. Certainly, quad hardware is readily available. However, even some seemingly minor construction details can affect performance. For example, the creation of loops at the fastening points of the loops to the support arms can detune a loop from its modeled dimensions. In addition, one would need to carefully handle the long phasing lines between the drivers. For many operators contemplating a new antenna in the size range that we have been considering, one final fact may prove decisive. A quad design of the sort investigated here is a home-brew effort, whereas the Yagi models have commercial counterparts that require only assembly in accord with detailed instructions.

This investigation began with an evaluation of the ARRL quad as a well-designed single-driver quad in order to establish two things: whether it has limited band coverage and whether the use of phase-fed dual drivers would provide any gain or band-coverage advantages over a single-driver quad. The initial modeling of the most prominent dual-driver 4-element quad developed by W6PU failed to provide the promised 50-Ohm feedpoint impedance, although the general design showed promise in other operating categories. Some judicious redesign of the phasing system and the element dimensions yielded a promising design with full-band coverage on 20 through 10 meters. However, the exercise laid to rest the old claim that driver-phasing significantly increases array gain. The truer function of driver phasing is to obtain a wider operating bandwidth while sustaining other performance figures, such as the front-to-back ratio.

Our final question was whether or not the resulting quad design is electrically competitive with multi-band Yagis of similar boom length. The general answer is affirmative, although specific properties of one or another type of array may tip the balance. Since all multi-band arrays are filled with compromises occasioned by element interaction, the quad is neither decisively superior nor decisively inferior to comparable Yagi designs from a strictly electrical perspective.

About the intangibles that form both the quad and the Yagi mystiques, I must close with a prudent "no comment."

Notes

1. See L. B. Cebik, *Cubical Quad Notes*, Vol. 2 (*antenneX*, 2001), for background on the optimized monoband quads used as benchmarks.

2. Without casting a single aspersion on the antenna that W6PU created, we may note that he gives the basic quad loop a 2 to 2.5 dB advantage over the a dipole. (The actual advantage when using the same element wire-diameter is 1.0 to 1.1 dB.) He attributes a much lower radiation elevation angle to the quad over a Yagi, when both are mounted at the same height. (The effective height of a quad is about two-thirds of the distance upward from the lowest point to the highest, a net increase in effective height that fails to lower the radiation angle significantly relative to the Yagi.) W6PU gives the diamond shaped quad loop a gain advantage

over the square loop. (The differential is negligible in electrical terms, although some builders prefer the diamond for its support of feed cables along its arms and its ability to withstand winter weather.) Finally, he tends to add up all of the small gains to reach a value for his antenna that is their simple sum.

If any problematical tendency has remained from the early 1980s in antenna work, it is the temptation to sum up the theoretic gains from individual modifications to a basic antenna and then to claim that the gain of the new antenna is that sum. In most instances, the new antenna will not achieve the performance level of the claims derived from simple summing. In some cases, a basic modification will dominate the performance, negating the gains of other modifications. In other cases, modifications will cancel each other rather than re-enforcing each other. The only way to have confidence in performance levels is to create the entire new antenna structure and then to test it. Accurate modeling is one route to testing antenna ideas before building and, equally important, before making claims about the design.

3. For fuller information on phase-fed horizontal arrays, see the 4-part series " Some Notes on Two-Element Horizontal Phased Arrays," in *The National Contest Journal*, beginning in Nov/Dec, 2001 and concluding in May/Jun, 2002.

4. For further background on antennas using phase-fed driver cells and linear elements, see L. B. Cebik, "Some Aspects of Long-Boom, Monoband Log-Cell Yagi Design," *QEX* (Jul/Aug, 2001), pp. 11-22.

5. See L. B. Cebik, "Modeling and Understanding Small Beams: Part 5, The ZL Special," *Communications Quarterly* (Winter, 1997), pp. 72-90, for some of the equations relevant to an analysis of action along an array phase line.