4-Element Monoband Quad Design

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The most common designs of 4-element quads suffer from the urge to retain short booms and thin elements. Consequently, the average 4-element design fails to meet expectations or to match the performance of 4- and 5-element Yagis. A 4-element Yagi is capable of about 9 dBi gain with a good front-to-back ratio, although in practical designs, gain averages of 8.6 dBi (free space) are more typical in the HF bands using elements at 20 meters that average about 1" in diameter.

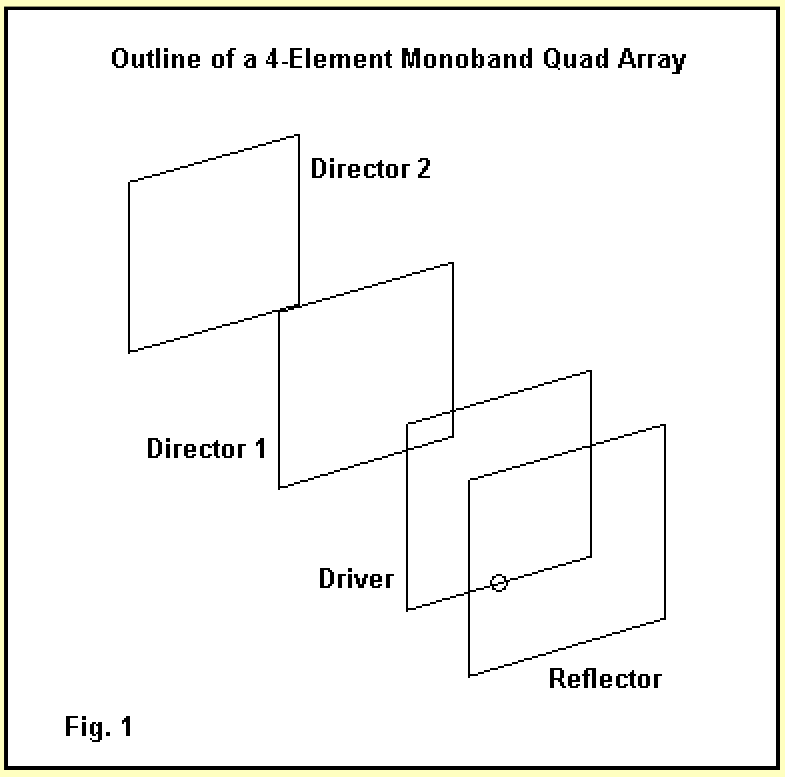

Outline of a 4-Element Monoband Quad Array

Fig. 1

The average monoband 4-element quad has the appearance of **Fig. 1**. As usual, the discussion limits itself to single feedpoint driver elements with square loops used throughout.

A Comparison of 3 Designs for 4-Element Quads

Let's begin with a comparison of three designs. The first is a standard design wire quad for 20 meters that has the following dimensions.

Design Data for a "Standard" 4-Element Quad

Element Diameter: #14 AWG
Reflector Circumference: 72.66'
Driver Circumference: 70.89'
Director 1 Circumference: 68.78'
Director 2 Circumference: 66.72'
Refl-Driver Spacing: 12.87'
Driver-Dir 1 Spacing: 10.59'
Dir 1-Dir 2 Spacing: 10.58'
Total Boom Length: 34.04'

The free-space gain of this array peaks just above 9.65 dBi at about 14.2 MHz. The front-to-back ratio peaks at about 23 dB at 14.25 MHz, but falls off to about 10 dB at the low end of the band. Indeed, the front-to-back ratio is above 20 dB for only about 150 kHz of the total width of 20 meters. The array has a 50-Ohm 2:1 SWR bandwidth that is just about 300 kHz, not enough to cover the entirety of 20 meters. In short, the array acts in an entirely normal way, with a front-to-back passband (using the 20 dB standard) that is just over half the overall 2:1 SWR passband.

If we are willing to use a much longer boom length to account for the higher level of inter-element coupling of loops compared to linear elements, we might arrive at the following design.

Design Data for an "Optimized" 4-Element Quad

Element Diameter: #14 AWG
Reflector Circumference: 72.91'
Driver Circumference: 70.50'
Director 1 Circumference: 67.29'
Director 2 Circumference: 65.78'
Refl-Driver Spacing: 11.37'
Driver-Dir 1 Spacing: 22.07'
Dir 1-Dir 2 Spacing: 25.27'
Total Boom Length: 58.71'

Although the "standard" short-boom design resulted from design "formulas," it is clear that no effort was made to make any of the performance peaks coincide in frequency. The present design was placed at 14.15 MHz in order to better equalized band edge performance.

This design retains the #14 AWG wire size, but extends the element spacing to the degree feasible before losing the desired antenna properties. Overall, gain is up by about 0.5 dB from the short-boom model, ranging from nearly 9.8 dBi to just under 10 dBi at mid-band. The front-to-back ratio peaks at about 40 dB, but drops to just under 15 dBi at the band edges. The beam is designed for a source impedance between 50 and 75 Ohms, where it misses full band coverage at under 2:1 by about 20 kHz or so. Although no single category of performance is so great as to dictate the longer boom design over the shorter version, the composite of all of the improvements in both gain and operating bandwidth strongly suggest the superiority of the longer-boom model.

As we have seen from designing quads with fewer elements, almost every category of performance benefits from enlarging the effective diameter of the elements. Consider the following design using 1" diameter elements. The 1" diameter elements can be synthesized from properly spaced pairs of wires in accord with principles enumerated at length in a past episode of this series.

Design Data for an "Optimized" 4-Element Quad

Element Diameter:	**1.0"**
Reflector Circumference:	**74.84'**
Driver Circumference:	**71.04'**
Director 1 Circumference:	**67.04'**
Director 2 Circumference:	**64.68'**
Refl-Driver Spacing:	**11.37'**
Driver-Dir 1 Spacing:	**22.07'**
Dir 1-Dir 2 Spacing:	**25.13'**
Total Boom Length:	**58.56'**

For our further efforts, we gain another half dB of gain over the #14 optimized design, with the free-space gain ranging from 10.3 to about 10.45 dBi. The front-to-back ratio peaks at a uselessly high 60 dB, but drops slightly below 20 dB at the band edges. Once more, the optimal feed cable is 75 Ohms, and the array easily holds the SWR below 2:1 across 20 meters.

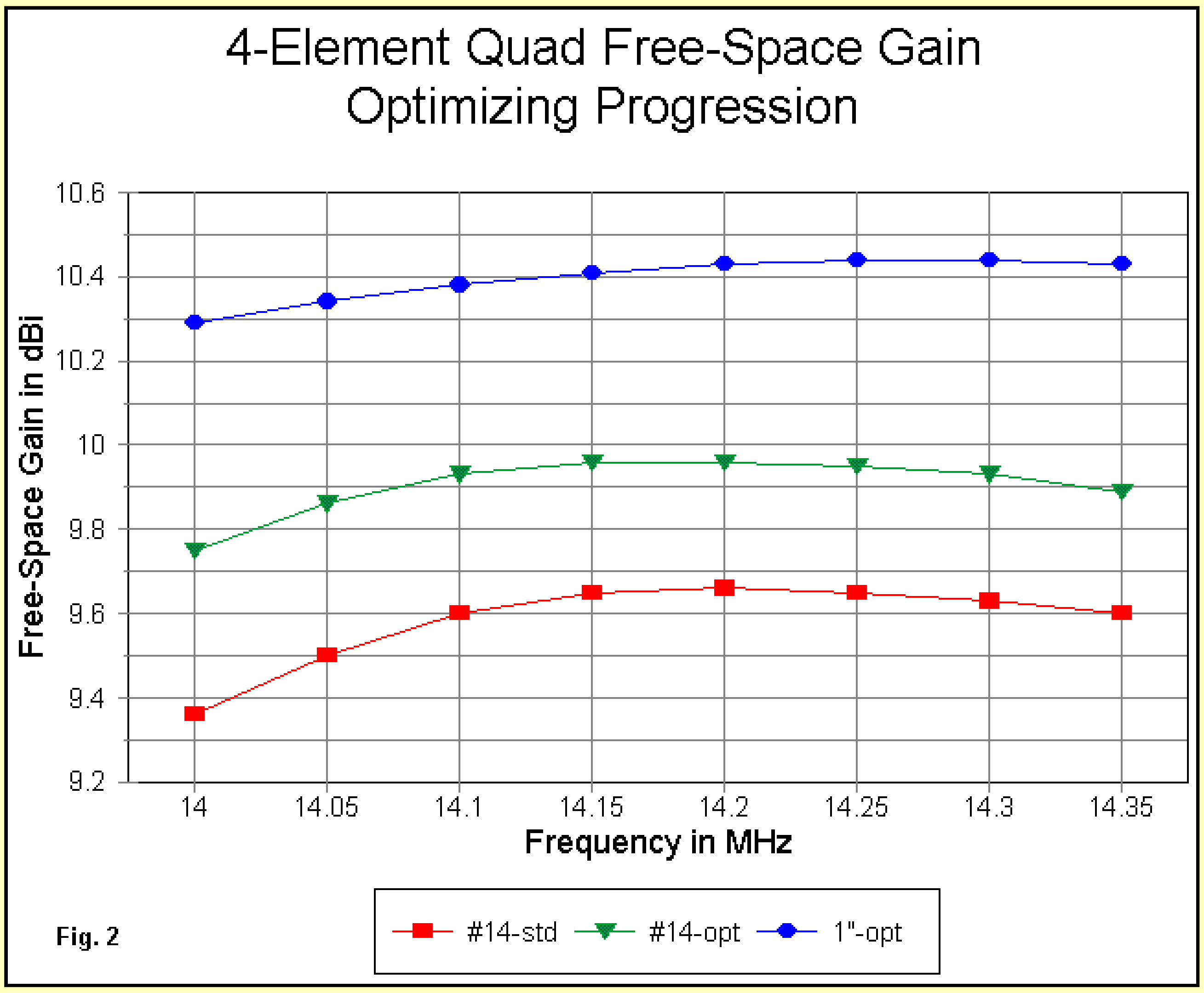


Fig. 2

A graphical comparison of the 3 designs can perhaps portray the performance better than words. **Fig. 2** shows the free-space gain curves of the 3 arrays. Note that all three arrays place the peak gain within the passband, a mark of having achieved the highest gain feasible from the general design. However, also note that both wire designs show a sharper drop in gain at the low end of the band compared to the gain curve for the 1" model.

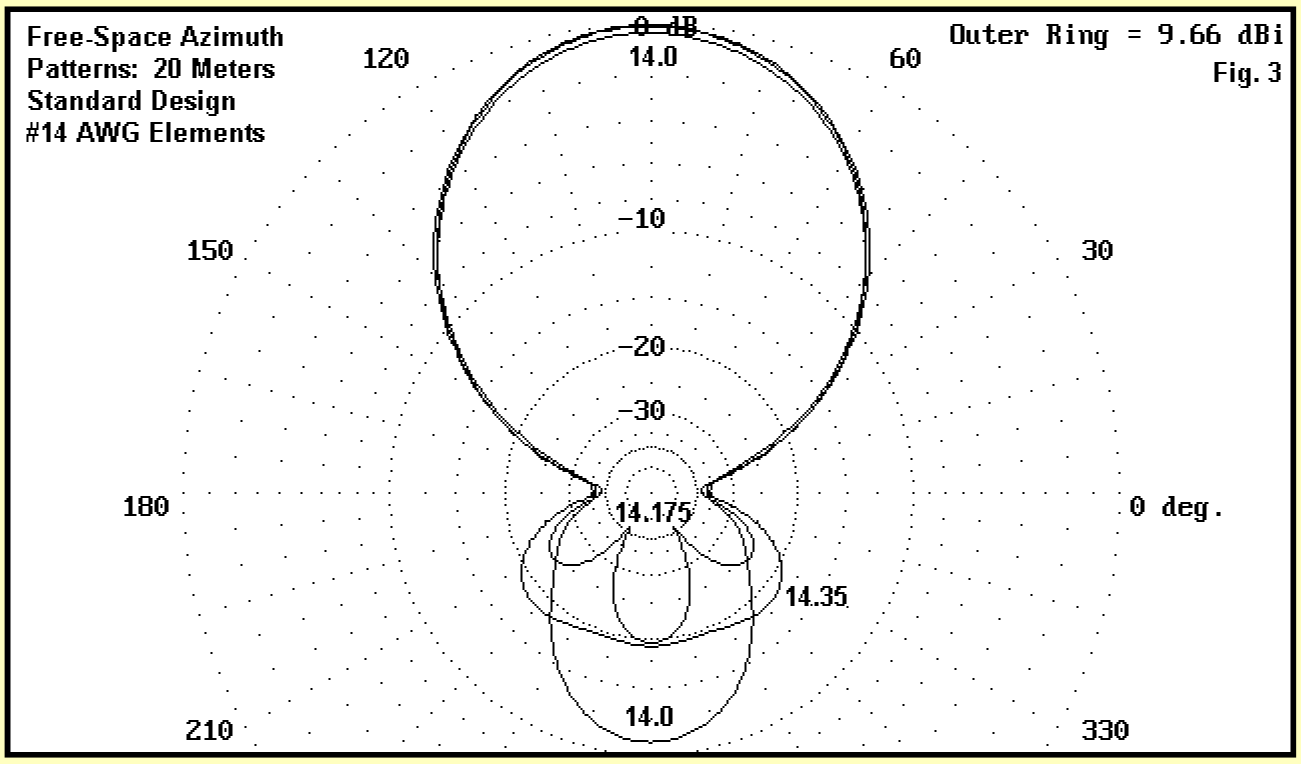


Fig. 3

Often, a series of strategically taken azimuth plots can show the strengths and weakness of designs even better than graphed curves. **Fig. 3** shows the azimuth plots for the 20-meter band edges and middle for the short-boom design. Clearly the design has been optimized for the upper end of the 20-meter band, although it is not clear whether this is intentional or accidental. The formulas were applied for a midband frequency of

14.175 MHz. Fatter wire with no change in dimensions would have moved the operating peaks higher in the band, while thinner wire would have narrowed the operating bandwidth of the array.

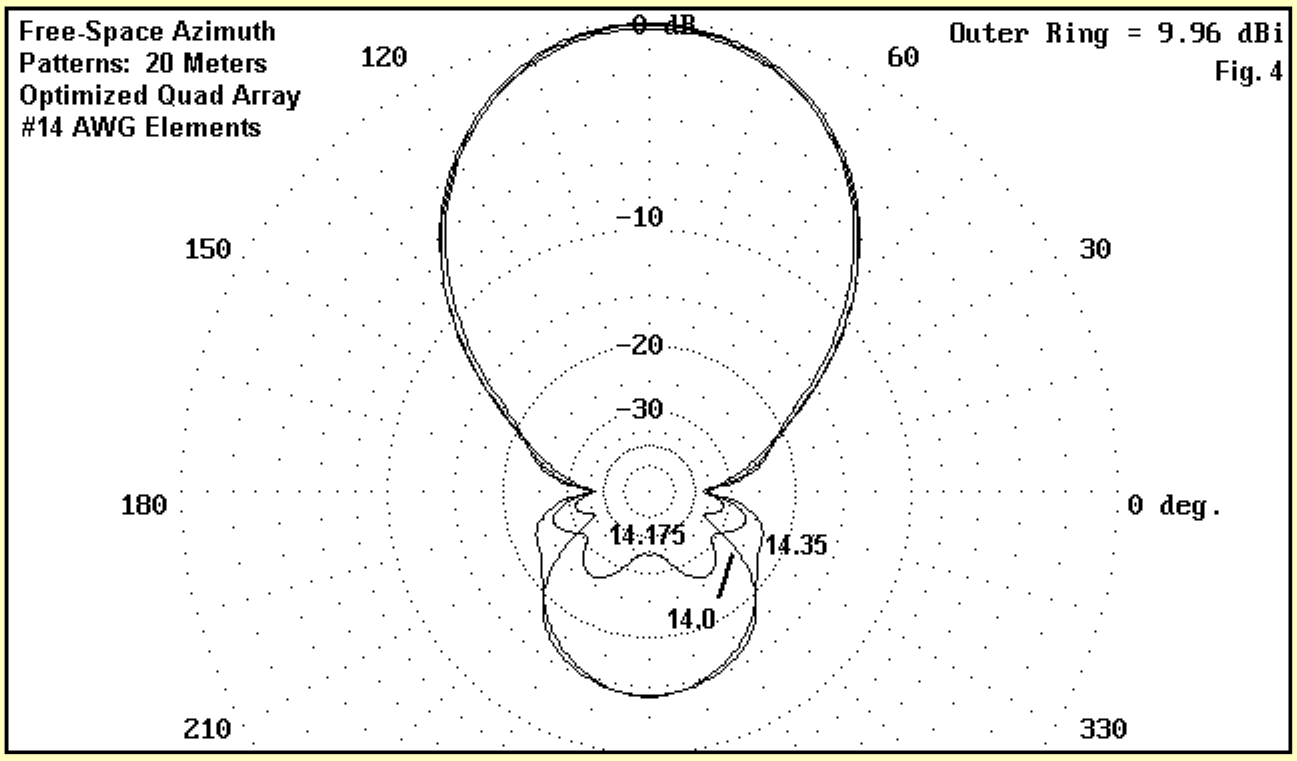
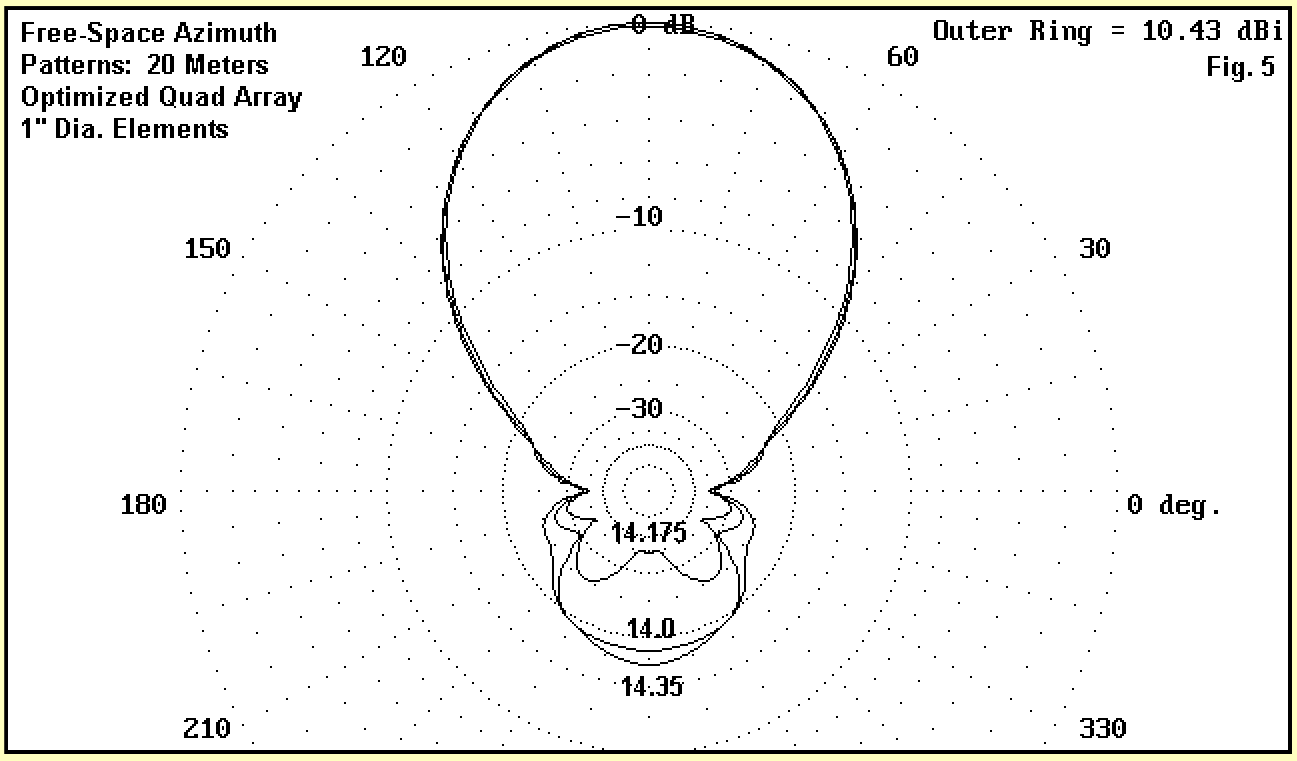


Fig. 4 provides the comparable set of patterns for the #14 optimized long-boom array. In this design exercise, the design frequency of 14.15 MHz provides well-balanced band-edge performance, although the rear lobes become significant at both 14.0 and 14.35 MHz.



The rear lobes of **Fig. 5** show that the 1" diameter model belongs to the same design sequence as the optimized #14 model. However, the band-edge rearward performance is considerably improved over the thin-wire model. The rear lobe aligned 180-degrees from the forward lobe at 14.175 MHz shows how steep the front-to-back curve is, since the peak occurs at 14.15 MHz. The mid-band front-to-back ratio is about 35 dB compared to the peak 60 dB figure 25 kHz away.

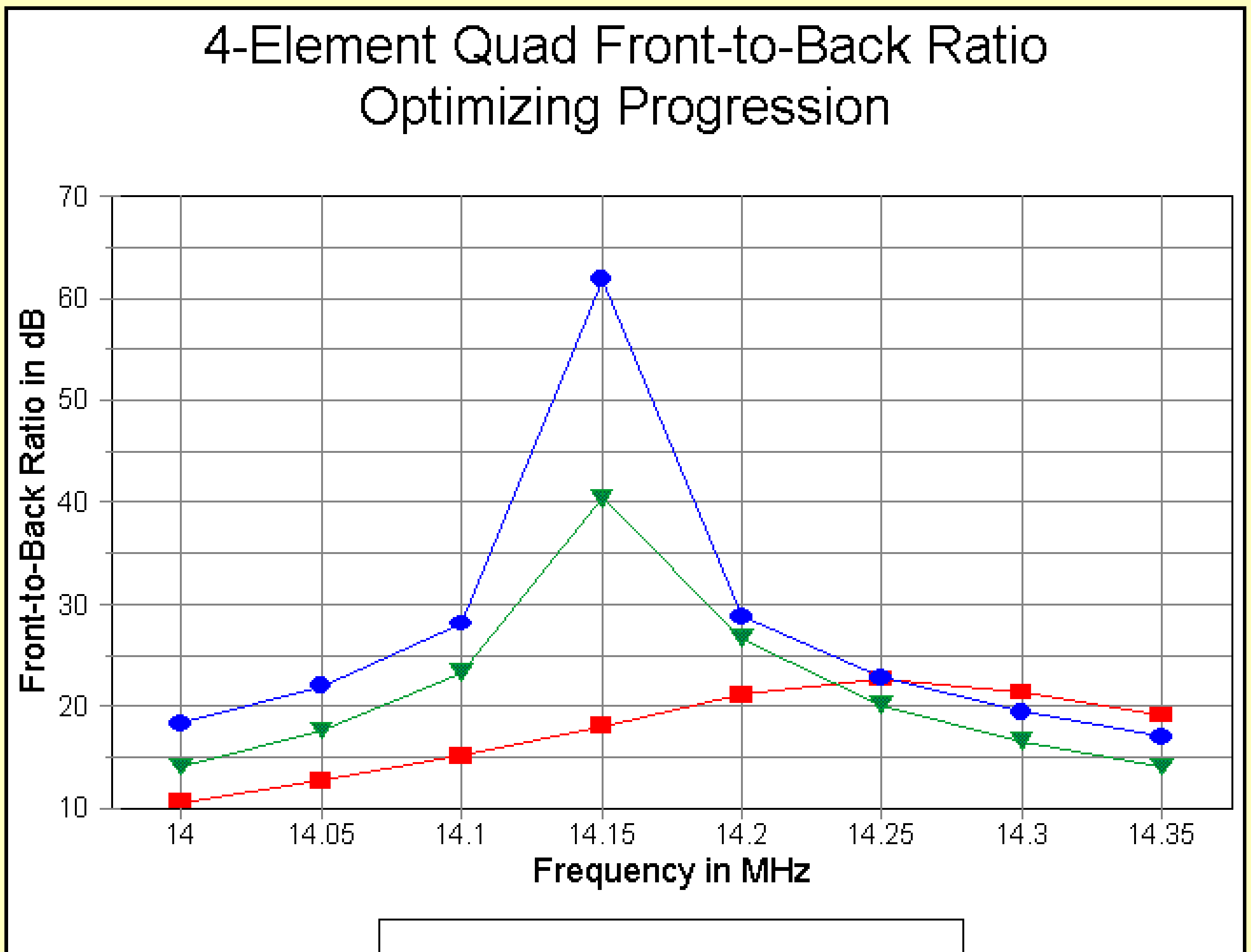


Fig. 6

In fact. **Fig. 6** reveals that same information about front-to-back performance in a different form. The peak front-to-back frequency for the #14 optimized model is just below 14.175 MHz and exceeds 40 dB. Also of note is the fact that the short-boom model achieved such gain as it could at the expense of front-to-back ratio.

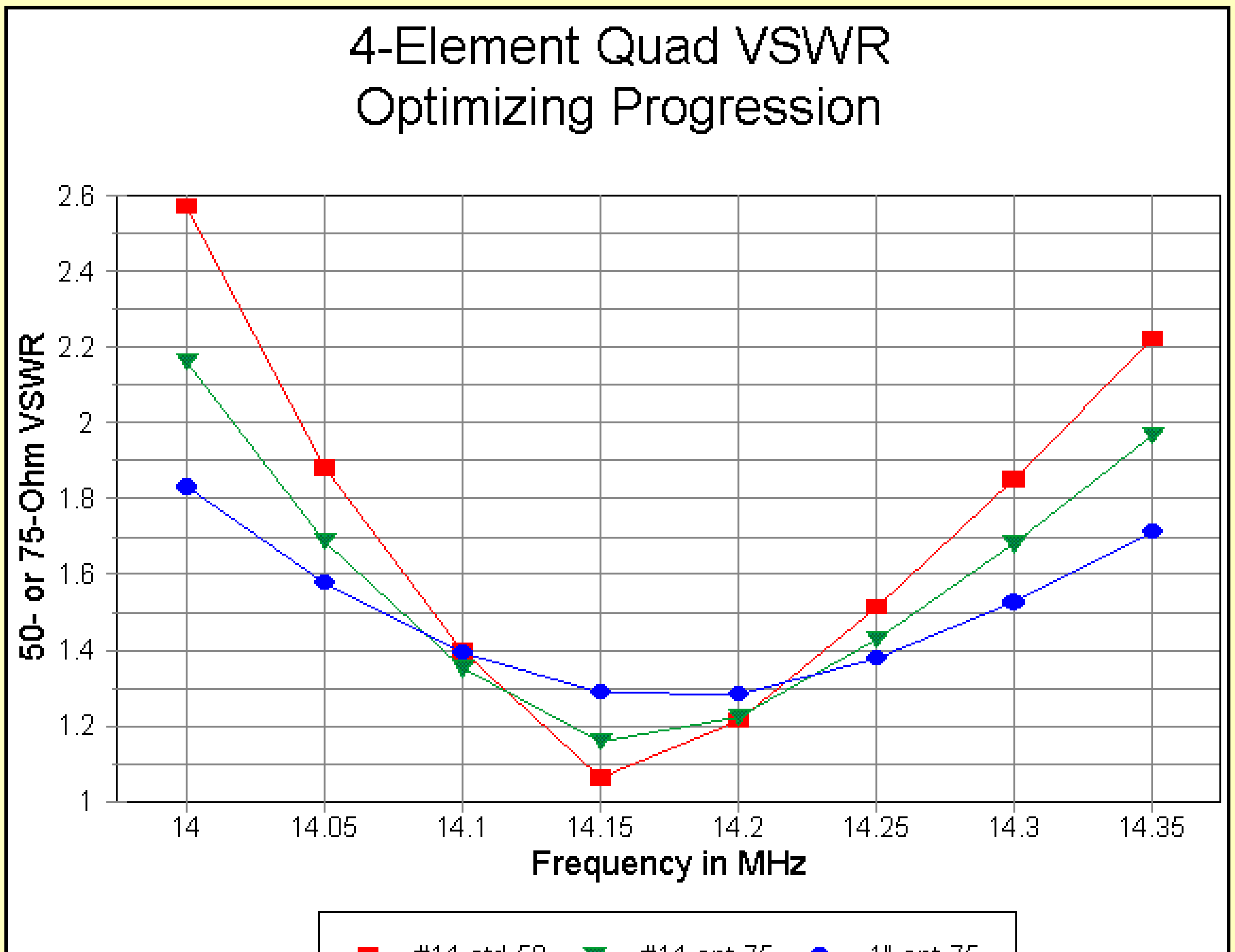


Fig. 7

In **Fig. 7**, we have the SWR curves, although we must remember which one represents a 50-Ohm value and which ones represent a 75-Ohm value. In large measure, the bandwidth quality of any array--with special attention to quads--is a function as much of the range of feedpoint reactance across a band as it is a matter of the range of the resistive component of the feedpoint impedance. Moreover, the ratio of total change of reactance to the average resistance (or to the desired feed cable) will indicate loosely whether or not a 2:1 ratio can be maintained across the band. The short-boom model has a median resistive component of 48.8 Ohms with a total change of reactance of 85.8 Ohms--a ratio of about 1.76:1. The long- boom wire model has a reactance range that is higher: 96.5 Ohms. However, the median resistance is 66 Ohms, for a 1.46:1 ratio. The 1" model shows a change in reactance of 67 Ohms with median resistance of 59 Ohms, for a 1.13:1 ratio. Although the ratios are not precise indicators of SWR performance, it is clear that a low ratio is a good indicator of better bandwidth. More precise equations can be developed, but the complexity of the SWR formulas make the exercise--already less than precise--somewhat superfluous. A good indicator is sufficient to alert the quad designer to desired directions of improvement.

Automating 4-Element Quad Design

Both optimized designs emerge from the same sequence of designs that will allow for automated design after regression analysis of the baseline models that spanned wire diameters from 3.16E-5 to 1E-2 wavelengths. As we have added elements to the designs, it has become harder to maintain a wide operating bandwidth with decreasing wire sizes. 4-element design, when applied to HF arrays that typically use wire, significantly benefits from the development of thick-wire substitutes in order to achieve maximum gain, a high front-to-back ratio over the entire chosen band, and an SWR of less than 2:1 across the band. In general, a wire size of 0.005 wavelengths is desirable, which is in the vicinity of 5" at 20 meters.

Obviously, a 2-wire--or preferably a 3-wire--substitute is called for. (Narrow-band applications, of course, are immune from this requirement, except for achieving maximum gain and adequate front-to-back ratio.)

The selection of a design sequence also calls for some comment. The baseline arrays in the sequence must, of course, be part of a sequence and not merely a set of random spot designs, each of which uses the prescribed wire size. Each array was designed so that, to the degree possible, maximum gain occurred within 1.5% of the design frequency. The maximum front-to-back ratio was set on the design frequency, as was array resonance. Wire size was change in increments that resulted in a sequence of the common logarithms of the wire size in wavelengths of 0.5 increments. This interval ensured a regression analysis that could be carried out to the 4th order.

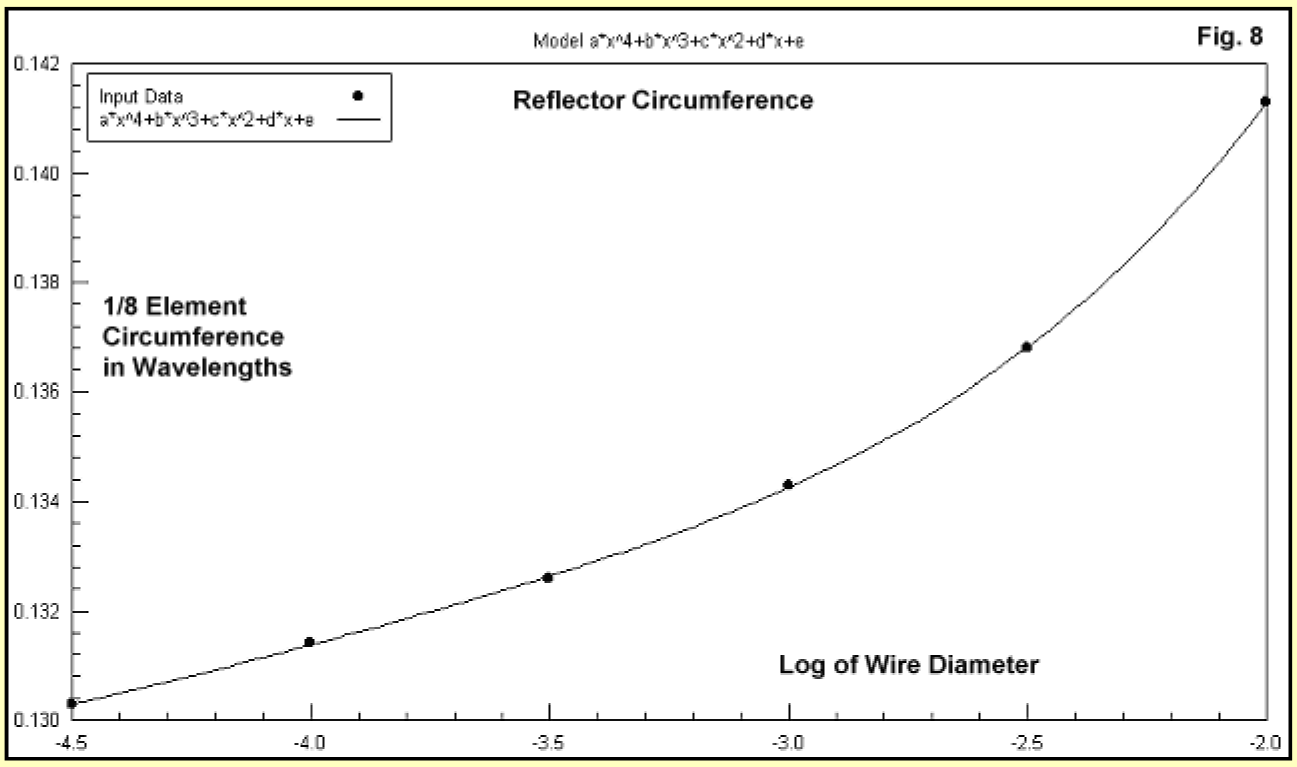


Fig. 8 shows the reflector circumference (more correctly, the value of 1/8 of the reflector circumference) curve developed via regression analysis. Similar curves, not all so precisely fitted as the example, emerged for the other parameters of the 4-element quad design.

In practice, the number of true variables in the analysis turned out not to exceed those used for the 3-element quads shown in preceding episodes. The spacing needed between the reflector and driver and between the driver and the first director required very large changes before they resulted in a significant change in array properties. In contrast, each of the other dimensions of the array were quite sensitive to small changes. (These dimensions included all element circumferences and the spacing between director 1 and director 2.) Therefore, the spacing between the driver and its adjacent elements was allowed to stand as a pair of constants (in terms of wavelengths).

An additional factor involved in the selection of the model sequence to form the basis for automated design involved the rate of change of the reactance range from the lower to the upper limits of a defined frequency span. Each model in a sequence will show a range of reactance change across an assigned frequency span such that the thinner the wire, the higher the reactance range. The rate of change of this range from one wire size to the next plays a role in the selection of the design sequence: the lowest rate of change with wire size decrease is the most desired sequence. This rate ensures that thinner wire designs--while not matching the performance of thick-element designs in the same sequence--at least provide useful performance.

There are, in fact, spot designs that will outperform the models in this sequence, some of which have shorter booms. Dan Handelsman provided me with one such design for 2 meters using a 0.5" diameter element. The design data are as follows:

Design Data for an N2DT 4-Element Quad

Design Frequency: 146 MHz
Element Diameter: 0.5"
Reflector Circumference: 92.36"
Driver Circumference: 84.64"
Director 1 Circumference: 83.20"
Director 2 Circumference: 78.80"
Refl-Driver Spacing: 17.50"
Driver-Dir 1 Spacing: 17.50'
Dir 1-Dir 2 Spacing: 18.00'
Total Boom Length: 53.00'

The dimensions for the corresponding 0.5" diameter model from the selected sequence are these:

Design Data for a 4-Element Quad from the Sequence

Design Frequency: 146 MHz
Element Diameter: 0.5"
Reflector Circumference: 89.98"
Driver Circumference: 83.42"
Director 1 Circumference: 77.76"
Director 2 Circumference: 74.35"
Refl-Driver Spacing: 13.22"
Driver-Dir 1 Spacing: 25.67'
Dir 1-Dir 2 Spacing: 28.07'
Total Boom Length: 66.96'

The N2DT quad actually outperforms the sequenced quad by a small margin, despite the 14" reduction in boom length. The gain is 0.15 dB higher (10.76 vs. 10.61 dBi) at the design frequency. The 20-dB bandwidth is close to 2.8% in contrast to the sequence design's 2.75% value. (The bandwidth of 2 meters is about 2.78%.) Both arrays have a 50-Ohm SWR under 2:1 across the band. (For the VHF range, with large diameter elements whose logs are between -2.5 and -2.0, the feedpoint impedances of the sequenced designs are closer to 50 Ohms than to 75 Ohms.) The natural question is why the N2DT design was not chosen as the basis for the design sequence.

The answer lies in the rate of change of the span of reactance with decreasing wire sizes. For the span of wire sizes whose diameters in wavelengths result in common logs of -2.0 to -2.5, the reactance range increased 54% for the N2DT design, but only by 33% for the chosen sequence. Although the rate of change is not a linear curve in all cases, it does provide an indication of the most promising design sequence that is usable over a wide span of wire diameters.

Neither the N2DT design nor the sequence design provides the highest possible gain for a 4-element quad. The following dimensions are for a high-gain 4-element quad that also uses 0.5" diameter elements and a design frequency of 146 MHz.

Design Data for a High-Gain 4-Element Quad

Element Diameter: 0.5"
Reflector Circumference: 89.120"
Driver Circumference: 83.760"
Director 1 Circumference: 77.760"
Director 2 Circumference: 74.080"
Refl-Driver Spacing: 13.200"
Driver-Dir 1 Spacing: 25.937"
Dir 1-Dir 2 Spacing: 30.715"
Total Boom Length: 69.840"

This design will meet the less than 2:1 SWR standard (50 Ohms), but the front-to-back ratio holds above the 20 dB level for only about 3/4 of the 2-meter band. As well, the gain varies about 0.4 dB across the band. The two most prominent factors in the design are its free-space gain, which reaches 11.0 dBi, and its length, which is about 2" short of 6'. It did not exhibit a sufficient bandwidth or a sufficiently low rate of reactance-span change to qualify for the sequence.

The Automated Design Program

Perhaps the only significant claim that can be made for the sequence of designs that resulted in the automated design program is that they yield close to the widest bandwidth in the listed operating categories, along with the best gain potential as a secondary criterion, of any sequence that I have so far uncovered. Obviously, there may well be other sequences awaiting discovery. Therefore, the program should be used with due appreciation of the tentative nature of its presentation.

However, what the program does do is to give due place to element diameter and to quad- loop inter-element coupling in its development. As with the other programs in this sequence, one enters the desired element diameter in a specified unit of measure. The program contains no provision for entering AWG wire sizes. As well, one enters the design frequency. For wide bands, such as the harmonically related HF amateur bands, it may be best to select a design frequency between 0.35 to 0.4 of the way from the lower band edge in order to achieve roughly similar front-to-back and SWR values at both band edges.

As with past programs, the listing is for GW Basic, since that format makes all of the mathematics visible to the user.

A GW Basic Program to Calculate Dimensions of a Wide-Band 4-Element Quad Beam

```
10 CLS:PRINT "Program to calculate the dimensions of a resonant square 4-element quad beam."
20 PRINT "All equations calibrated to NEC antenna modeling software for wire diameters"
30 PRINT "     from 3.16E-5 to 1E-2 wavelengths within about 0.5% from 3.5 - 250 MHz."
40 PRINT "L. B. Cebik, W4RNL (SK)"
50 INPUT "Enter Desired Frequency in MHz:";F
60 PRINT "Select Units for Wire Diameter in 1. Inches, 2. Millimeters, 3. Wavelengths"
70 INPUT "Choose 1. or 2. or 3.";U
80 IF U>3 THEN 60
90 INPUT "Enter Wire Diameter in your Selected Units";WD
100 IF U=1 THEN WLI=11802.71/F:D=WD/WLI
110 IF U=2 THEN WLI=299792.5/F:D=WD/WLI
120 IF U=3 THEN D=WD
130 PRINT "Wire Diameter in Wavelengths:";D
140 L=.4342945*LOG(D*10^5):LL=L^2:LM=LL*.0128:LN=LM+1.0413:D1=.4342945*LOG(D)
150 IF D1<-4.5 then 160 else 170
160 print "Wire diameter less than 3E-5 wavelengths:  results uncertain."
170 if d1>-2 THEN 180 ELSE 190
180 PRINT "Wire diameter greater than 1E-2 wavelengths:  results uncertain."
190 AD=-.00018:BD=-.002359259259#:CD=-.01090277778#:DD=-.01971296296#:ED=.1174938889#
200 DE=(AD*(D1^4))+(BD*(D1^3))+(CD*(D1^2))+(DD*D1)+ED:DE=DE*8
210 AR=.0002666666667#:BR=.004237037037#:CR=.02554444444#:DR=.07158756614#:ER=.2119230159#
220 RE=(AR*(D1^4))+(BR*(D1^3))+(CR*(D1^2))+(DR*D1)+ER:RE=RE*8
230 AI=-.0002#:BI=-.002525925926#:CI=-.01182777778#:DI=-.02473915344#:EI=.1008246032#
240 IR=(AI*(D1^4))+(BI*(D1^3))+(CI*(D1^2))+(DI*D1)+EI:IR=IR*8
250 AT=-.0006#:BT=-.009059259259#:CT=-.04912777778#:DT=-.1152343915#:ET=.01678174603#
260 TT=(AT*(D1^4))+(BT*(D1^3))+(CT*(D1^2))+(DT*D1)+ET:TT=TT*8
270 SP=.1635:IP=.481
280 ATT=.0026666666667#:BTT=.036888888889#:CTT=.177#:DTT=.3386587302#:ETT=1.046738095#
290 TTP=(ATT*(D1^4))+(BTT*(D1^3))+(CTT*(D1^2))+(DTT*D1)+ETT
300 AZ=1.2#:BZ=13.92592593#:CZ=60.777777778#:DZ=113.9177249#:EZ=132.618254#
310 ZR=(AZ*(D1^4))+(BZ*(D1^3))+(CZ*(D1^2))+(DZ*D1)+EZ
320 AG=-.1#:BG=-1.184444444#:CG=-5.228333333#:DG=-9.831507937#:EG=4.045238095#
330 GN=(AG*(D1^4))+(BG*(D1^3))+(CG*(D1^2))+(DG*D1)+EG
340 AW=.07#:BW=1.048518519#:CW=6.173055556#:DW=17.12092593#:EW=21.34722222#
350 SW=(AW*(D1^4))+(BW*(D1^3))+(CW*(D1^2))+(DW*D1)+EW
360 AF=-.03#:BF=-.27666667#:CF=-.4475#:DF=2.348809524#:EF=7.853214286#
370 FB=(AF*(D1^4))+(BF*(D1^3))+(CF*(D1^2))+(DF*D1)+EF
380 WL=299.7925/F:PRINT "Wavelength in Meters =";WL;"    ";
390 WF=983.5592/F:PRINT "Wavelength in Feet =";WF
400 PRINT "Quad Dimensions in Wavelengths, Feet, and Meters:"
410 PRINT "Driver Side =";(DE/4);" WL or";(DE/4)*WF;"Feet or";(DE/4)*WL;"Meters"
420 PRINT "Driver Circumference =";DE;" WL or";DE*WF;"Feet or";DE*WL;"Meters"
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430 PRINT "Reflector Side =";(RE/4);" WL or";(RE/4)*WF;"Feet or";(RE/4)*WL;"Meters"
440 PRINT "Reflector Circumference =";RE;" WL or";RE*WF;"Feet or";RE*WL;"Meters"
450 PRINT "Reflector-Driver Space =";SP;" WL or";SP*WF;"Feet or";SP*WL;"Meters"
460 PRINT "Director 1 Side =";(IR/4);" WL or";(IR/4)*WF;"Feet or";(IR/4)*WL;"Meters"
470 PRINT "Director 1 Circumference =";IR;" WL or";IR*WF;"Feet or";IR*WL;"Meters"
480 PRINT "Director 1-Reflector Space =";IP;" WL or";IP*WF;"Feet or";IP*WL;"Meters"
490 PRINT "Director 2 Side =";(TT/4);" WL or";(TT/4)*WF;"Feet or";(TT/4)*WL;"Meters"
500 PRINT "Director 2 Circumference =";TT;" WL or";TT*WF;"Feet or";TT*WL;"Meters"
510 PRINT "Director 2-Reflector Space =";TTP;" WL or";TTP*WF;"Feet or";TTP*WL;"Meters"
520 PRINT "Approx. Feedpoint Impedance =";ZR;"Ohms   ";
530 PRINT "Free-Space Gain =";GN;"dBi"
540 PRINT "Approximate 2:1 VSWR Bandwidth =";SW;"% of Design Frequency"
550 PRINT "Approximate >20 dB F-B Ratio Bandwidth =";FB;"% of Design Frequency"
560 INPUT "Another Value = 1, Stop = 2: ";P
570 IF P=1 THEN 10 ELSE 580
580 END
```

Note: "LOG" in GW Basic always mean the natural logarithm. Hence, a conversion factor is necessary to convert the natural log to the common log required by the program. If the medium to which this program may be transferred already knows the difference between "LOG" and "LN," the conversion factor can be dropped.

The program provides supplemental data on the approximate feedpoint impedance at resonance, the free-space gain at the design frequency, the under 2:1 SWR bandwidth as a percentage of the design frequency, and the greater than 20 dB front-to-back ratio bandwidth also as a percentage of the design frequency. Since the latter two curves are not symmetrical on both sides of the design frequency, careful selection of the design frequency is important.

A version of this program appears in the HAMCALC suite of GW Basic utility programs available from VE3ERP. As well, a version appears at the Nittany-Scientific web site (now defunct) in the form of a NEC-Win Plus model set up in equations (**http://www.nittany-scientific.com**). The supplemental data do not appear in that program, since running a model through a frequency sweep is a superior method of determining passband performance and selecting the optimal design frequency. The following links will take you to a download page where you may download the program as a. **a NEC-Win Plus model file**, b. **a GW Basic program**, or c. **a VB script** generously made available by Randy Frum, AC4FD. Randy notes that the script will run natively on Windows ME and Windows 2000 and above and will run on other Windows operating systems (95, 98 and NT) if the Windows Scripting Host is installed (normally installed with IE 5 and above). Simply run the script from the "Run" command on your main screen.

Some Foreshadowing

The level of inter-element coupling among quad loops requires greater spacing, in general, than comparable linear dipole/Yagi elements in order to optimize array gain. To obtain high gain with a good bandwidth for other operating parameters, the multi-element monoband quad becomes longer faster than potentially competing Yagi-Uda designs. At 4 optimally spaced elements, even with thick element diameters, the quad approaches a possible limit on its ability to provide higher gain with a shorter boom length.

Yagi designs are only one alternative to the potential 5- and 6-element quad. Dan Handelsman has been working with asymmetrical and symmetrical double rectangles (ADRs and SDRs) as alternatives both to the entire set of simple quad loops and to the reflector and driven elements of such arrays. These designs show promise of adding gain and a very wide operating bandwidth for any given number of elements and boom length. However, the cost appears at present to be greater complexity in the mechanical design of the ADR and SDR elements. The feasibility of such designs may eventually be different for potential HF and VHF applications.

In short, these design exercises are only a beginning to the process of more fully understanding both the potentials and the limitations of quad designs in all of their forms--some of which we have yet to see.

Go to Main Index