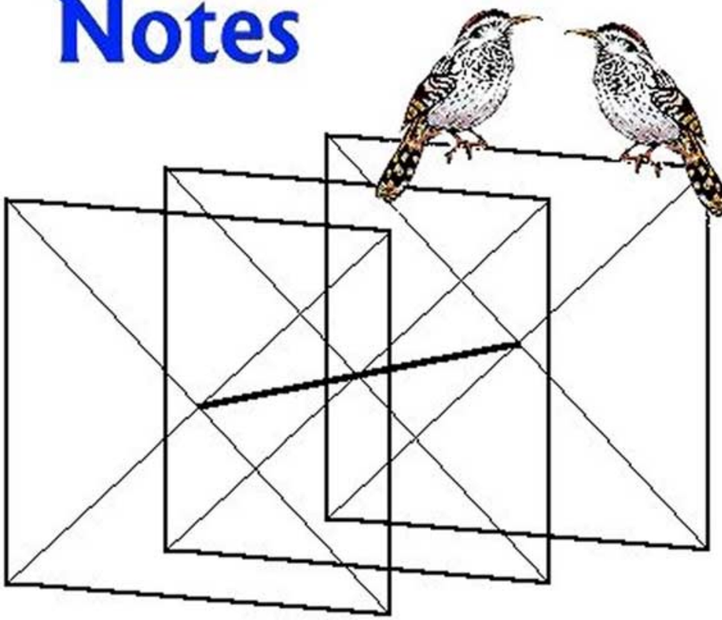
# Cubical Quad Notes



## Volume 2
## Rethinking the Quad Beam

L. B. Cebik, W4RNL

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***Published by***
***antenneX Online Magazine***
**http://www.antennex.com/**
**POB 72022**
**Corpus Christi, Texas 78472 USA**



ISBN: 1-877992-10-0

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## Dedication

This 2-volume study of cubical quads is dedicated to my wife, my friend, my supporter, and my colleague, all of whom are Jean. Her patience, understanding, and assistance gave me the confidence to retire early from academic life to undertake full-time the continued development of my website **http://www.cebik.com/**, which is devoted to providing as best I can information of use to radio amateurs and others—both beginning and experienced—on various antenna and related topics. These volumes are an outgrowth of that work—and hence, of Jean's help at every step.

## About the author

L. B. Cebik, W4RNL, has published over a dozen books, with works on antennas for both the beginner and the advanced student. Among his books are a basic tutorial in the use of NEC antenna modeling software and compilations of his many shorter pieces. His articles have appeared in virtually every amateur radio publication, with translations of some into several languages. A regular columnist for *antenneX*, *10-10 News*, *Low Down*, and others, LB also maintains a web site as a service to radio amateurs and others interested in antennas at http://www.cebik.com. Retired from academic life at the University of Tennessee, Knoxville, LB devotes himself to continuing education at his web site, in print, and as both Technical and Educational Advisor to the ARRL.

## Preface to Volume 2
## Rethinking the Quad Beam

In Volume 1 of this set, we reviewed a large number of existing quad array designs. Among the purposes of the review were these: to demonstrate the potentials and limitations of the designs explored; to provide a foundation for modeling quad arrays for analysis and design; and to discover whatever these quads might show us about the fundamental properties of quad arrays. Many of the designs examined were typical of what is in the field, and some were even the best of their type. From the mix of designs, we managed to extract a number of patterns.

1. Although quad arrays--especially 2-element quad beams--often have very wide bandwidths with respect to meeting a 2:1 VSWR limit, other properties of quads are rather narrow-banded. For many designs, the rate of gain change within a given ham band is quite high. As well, the front-to-back ratio exceeds 20 dB for only a small portion of an amateur band. In short, contrary to their past reputation, quads are not “low-Q” antennas, but instead, very high-Q as soon as we add operating characteristics other than SWR to our list of concerns. How to achieve a truly wide-band quad remains a significant challenge.

2. The typical quad array is a wire affair, and wire has a very small diameter relative to the length of an RF wave. If the typical 20-meter Yagi-Uda array uses elements that average 1" in diameter, the typical #14 AWG copper wire quad uses an element under 6.5% as large. Element diameter does make a difference in quad design and performance, a sizable difference. What remains to be developed is just how large a difference element diameter does make and whether that difference is sporadic or systematic.

3. When we compare seemingly similar parasitical beam designs for Yagis and quads, both of which have been optimized to the degree possible, the quad almost inevitably winds up with a longer boom length than the Yagi for the same number of elements. This fact suggests that there is a significant difference between the inter-element coupling for quad loop elements and for linear Yagi elements. The fact also is suggestive about the practice of striving for short-boom

quad designs when working with more than two elements. What ramifications these outcomes may have for quad design is yet to be seen.

4. Compared to the best of present Yagi-Uda designs, quads tend to show a much larger excursion of reactance at the feedpoint from one end of a given passband to the other. One critical question for quad design is whether this phenomenon can be overcome or whether it will continue to be a limiting factor on the bandwidth performance of quad arrays.

If we add together all of the questions so far raised, how do they combine to yield more adequate quad designs? In the combination there may be further surprises not revealed by the individual factors, and they remain to be discovered.

This volume attempts to rethink the quad, taking into account the role of element diameter, optimal element spacing for maximum performance across desired bandwidths, and the range of feedpoint reactance across a desired passband. In the course of our exploration, we shall discover that once certain critical factors are fully accounted for, the remaining elements of monoband quad design can be systematized into simple computer, spread sheet, or antenna modeling programs. Unlike past formula-laden methods of quad design, both element diameter and design frequency will have to be entered for a workable design to emerge.

Although the designs that emerge from these further studies are in one sense optimized, they do not constitute a set of ultimate quad designs. Rather, the designs represent the best composite of guiding parameters that I have been able to come up with so far. Not only are these design directions being investigated by others, but as well, there are many branch directions of design along the path that I have followed--too many directions for one person to fully explore in a short period of time. So at most, these notes present only the best that I have so far found. Much is left to be done, and the field of quad analysis and design remains wide open for the efforts of serious students of antenna properties.

Please use these notes as one kind of beginning--not as an end.

# Chapter 1
# Introduction and Reference Data

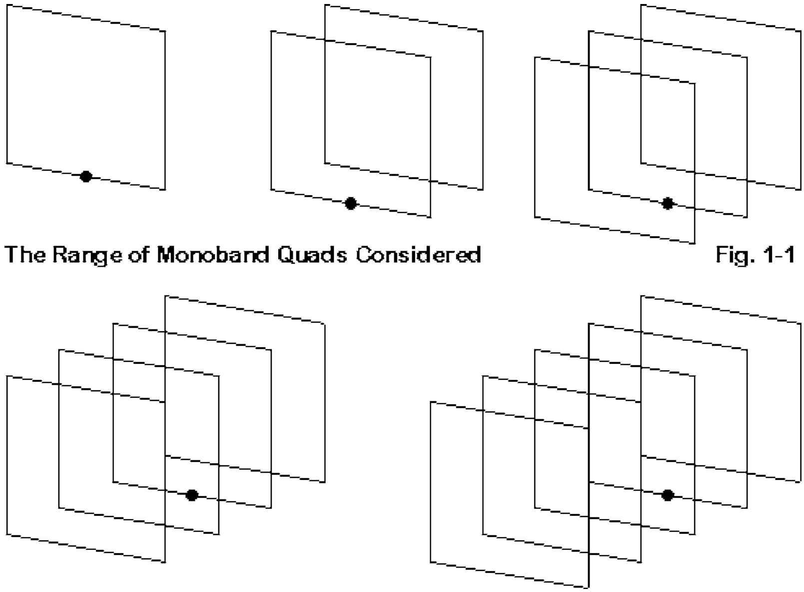
Rethinking the design of quad beams covers a vast territory--much more than any single individual can hope to cover in a single study. Therefore, we shall have to confine the scope of the study to a workable unit. As well, as in any study, the methods of analysis should be made plain so that anyone can replicate them--or go beyond them. Finally, there is some common data used throughout the study. Placing it here at the beginning seems most fitting and perhaps more useful than developing an appendix.

## Why Only Monoband Quads

The chapters ahead will look into only monoband quad design for a very basic reason: there is so much to learn about quad behavior with respect to element diameter and optimized spacing that trying to include multi-band arrays would be self-defeating. Virtually all multi-band quads involve compromise dimensions and compromise performance figures. What this volume hopes to accomplish is to discover what a quad might be able to do when it is designed without a compromise.

**Fig. 1** shows the range of quad that we shall work with in the course of the study. Essentially, any monoband quad between 1 and 5 elements will be our subject matter. Even within those limitations, we shall discover that the larger the number of elements, the more tentative the conclusions that we may draw about optimized quad behavior.

All quads will use a standard configuration. For an element count of 2 or more, there will be 1 reflector and a driven element, with the remaining elements (if any) being directors. Some design variants have included multiple reflectors. Others have attempted to use a phasing line between the driver and the reflector. However, these notes will stick to the more common design. In addition, each array will be fed at the bottom of the driver at a single, center location. All quad loops will be squares.



The Range of Monoband Quads Considered Fig. 1-1

**Design Standards: The Meaning of "Optimized"**

In many places, the arrays that we discuss will be referred to as "optimized." From the work in Volume 1, it should be clear that we may optimize a design for a single parameter--gain, for example--or for a "best compromise" among several factors. Because one of the chief drawbacks of present designs in the field is the operating passband, maximizing gain will be at most a secondary consideration, although for any design, we shall be concerned with the gain relative other quads with more or fewer elements, with longer or shorter booms, and with fatter or thinner elements. However, for all designs (subject to limitations imposed by the number of elements), we shall use the following general criteria in determining whether or not a design represents the best that can be obtained.

**1. Passband**: In general, for each additional element that we add to a quad array, we shall strive to obtain the widest possible operating passband. The dimensions of the passband are two. Most critical is the front-to-back ratio, for which we shall set a standard of 20 dB. The front-to-back ratio will use the 180° figure, although rear quadrants will be examined to discover if there are any problems in the quartering side lobes that are natural to quad radiation patterns.

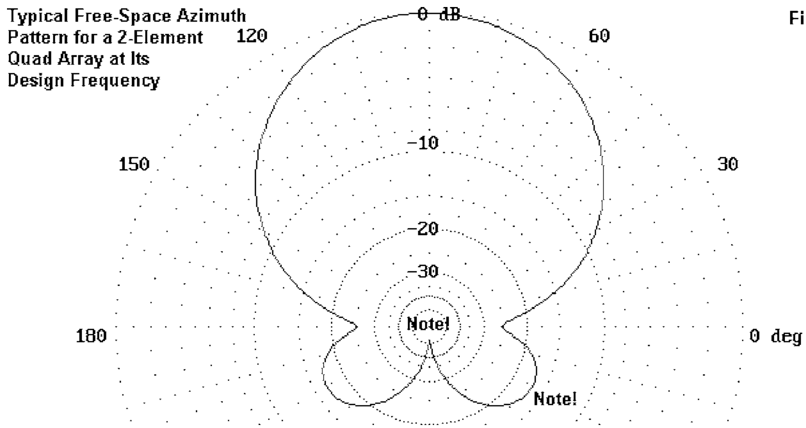


Fig. 1-2

**Fig. 1-2** shows a typical 2-element quad free space azimuth pattern. At the design frequency, the array has been optimized for a 180° front-to-back value of nearly 54 dB. However, the quartering side lobes are down by less than 17 dB. This latter figure is the worst-case front-to-back ratio and must be accounted for in evaluating the overall performance of an array.

The second dimension of passband performance is the VSWR curve. We shall use the common <2:1 SWR limit as marking the operating limits of the antenna's passband in this category. However, in most design cases, the SWR passband will be from 1.5 to nearly 2 times the front-to-back ratio passband. Therefore, once we have determined that the front-to-back ratio passband is satisfactory, the SWR curve will become largely a matter of simple interest and not a critical factor in design.

What shall count as satisfactory passband performance will very often be a matter of the width of an amateur band for which the array might be designed. A useful way to look at the ham bands is in terms of their bandwidth as a percentage of their center frequencies. For reference, the **Table 1-1** may be a useful guide.

**Table 1-1. Bandwidth as a Percentage of Band-Center Frequency**

| Band | Frequency Spread | Center Frequency | Bandwidth % | Notes |
|---|---|---|---|---|
| 160 | 1.8 - 2.0 | 1.9 | 10.53 | |
| 80 | 3.5 - 4.0 | 3.75 | 13.33 | |
| 40 | 7.0 - 7.3* | 7.15 | 4.26 | (*U.S. band) |
| 30 | 10.1 - 10.15 | 10.125 | 0.49 | |
| 20 | 14.0 - 14.35 | 14.175 | 2.47 | |
| 17 | 18.068 - 18.168 | 18.118 | 0.55 | |
| 15 | 21.0 - 21.45 | 21.225 | 2.12 | |
| 12 | 24.89 - 24.99 | 24.94 | 0.40 | |
| 10 | 28.0 - 29.7 | 28.85 | 5.89 | |
| (10A) | 28.0 - 29.0 | 28.5 | 3.51 | |
| 6 | 50.0 - 54.0 | 52.0 | 7.69 | |
| 2 | 144.0 - 148.0 | 146.0 | 2.74 | |

10 meters has two entries. One is for the entire band. However, since so many antennas are designed to cover only the first MHz of this wide HF band, entry “10A” is included. Clearly, for most of the work to be discussed, the non-harmonic (or WARC) HF bands are not of central interest, since almost any narrow-band array will more than adequately handle them. Of primary interest are the harmonically related HF bands and the two lowest VHF bands.

**2. Design-Frequency Considerations**: Besides trying to obtain the widest possible operating passband from a design--consistent with good gain performance--several facets of design involve the design frequency. First, the design frequency will normally be set at the center of a band. This position is not always the best for a practical design, since the SWR and front-to-back curves are rarely symmetrical above and below the design frequency. The curves below the design frequency are normally steeper. Hence, the best practical designs use a design frequency between 0.3 and 0.4 of the way from the low end of the band to the high end. This practice usually results in equalized front-to-back ratios and SWR values at the band edges. Nevertheless, using the band center as the design frequency does provide a good means of showing the level of asymmetry to the operating curves.

Second, the arrays will be designed for near resonance at the design frequency. Near resonance will be defined as a feedpoint impedance with under j1.0 Ω of reactance. In many generalized designs, the basic feedpoint impedance will show a larger variation in reactance as the frequency is varied significantly from the basic 30-MHz baseline. Even with perfect scaling of all element factors (circumference, spacing, and diameter), there will be some degree of variation due to skin effect. Skin effect does not vary at the same rate as the other factors involved in scaling an array from one frequency to another. In addition, the feedpoint reactance will vary according to the material chosen for the elements.

**Table 1-2** provides a short list of common materials often used in antenna construction. Some of the materials may be better known than others to hams who build their own antennas. For example, most hams buy antennas made from stainless steel rather than using the material for antenna construction. A few of the entries may be of predominantly historical interest, such as brass and phosphor bronze, although we still find them used in some home brew and commercial products. The value for "solder" on the list is an approximation for the value that might be found in a galvanized steel tower. Of the values in the list, copper and aluminum (especially 6063-T832 and 6061-T6) will be the most relevant to our efforts, although the remaining values provide a general context for understanding the merits of the most common antenna metals. Values are given for both resistivity--in Ohms/meter--and conductivity--in Siemens/meter (where the Siemen is the current name for what used to be called the "Mho"). The two values are, of course, simple reciprocals of each other. The listings are in "engineering" notation. 1.59E-08 equals 0.0000000159, while 6.2893E7 equals 62,893,000.

**Table 1-2. Conductivity and Resistivity of Common Materials**

| Material | Resistivity Ohms/meter | Conductivity Siemens/meter |
|---|---|---|
| Pure Silver | 1.59 E-08 | 6.2893 E7 |
| Copper | 1.7241 E-08 | 5.8001 E7 |
| Pure aluminum | 2.655 E-08 | 3.7665 E7 |
| 6063-T832 Aluminum alloy | 3.25 E-08 | 3.0769 E7 |
| 6061-T6 Aluminum alloy | 4.099 E-08 | 2.4938 E7 |
| Yellow brass (35% zinc) | 6.4E-08 | 1.5625 E7 |
| Phosphor bronze (5% tin) | 1.1E-07 | 9.0909 E6 |
| Solder | 1.42 E-07 | 7.0423 E6 |
| Stainless steel type 302 | 7.1999 E-07 | 1.3889 E6 |

In the range of materials from a perfect or lossless conductor through the aluminum entries in the table, the losses in the antenna due to the material can make a noticeable difference in performance for thin elements. Once an element reaches about 0.001 λ in diameter, the differences in performance attributable to the element material are largely marginal--and overall antenna performance approaches 99% efficiency, where efficiency is defined in terms of the ratio between power supplied to the antenna and power radiated from it.

**3. Element Diameter**: One the most fundamental variables in quad design will turn out to be element diameter. To a large degree, element diameter will determine for any size quad the required circumference for each loop and the spacing between the loops of multi-element arrays. In developing some automated design programs, the only two input values required will be the design frequency and the element diameter.

As a consequence, it is worthwhile to be familiar with the diameters of various wire sizes, especially those commonly used in quad construction. Above about 0.125" diameter, the common material is aluminum rod or tubing, so the sizes are self-revealing. However, there are also various wire gauge systems, the most common of which are the American Wire Gauge and the British Standard Wire Gauge. I shall assume that there may be readers for whom one or the other system is most relevant. As well, I shall presume that some readers are more comfortable using English units, while other are at home in metric measure. Therefore, **Table 1-3** and **Table 1-4** present the diameters of each gauge (from 1 to 40) in both systems of measurement.

**Table 1-3. Common AWG Wire Size Diameters in Inches and Millimeters**

| AWG Gauge# | Diameter Inches | Diameter Millimeters | AWG Gauge# | Diameter Inches | Diameter Millimeters |
|---|---|---|---|---|---|
| 1 | 0.2893 | 7.348 | 21 | 0.0285 | 0.723 |
| 2 | 0.2576 | 6.544 | 22 | 0.0253 | 0.644 |
| 3 | 0.2294 | 5.827 | 23 | 0.0226 | 0.573 |
| 4 | 0.2043 | 5.189 | 24 | 0.0201 | 0.511 |
| 5 | 0.1819 | 4.621 | 25 | 0.0179 | 0.455 |
| 6 | 0.1620 | 4.115 | 26 | 0.0159 | 0.405 |
| 7 | 0.1443 | 3.665 | 27 | 0.0142 | 0.361 |
| 8 | 0.1285 | 3.264 | 28 | 0.0126 | 0.321 |
| 9 | 0.1144 | 2.906 | 29 | 0.0113 | 0.286 |
| 10 | 0.1019 | 2.588 | 30 | 0.0100 | 0.255 |
| 11 | 0.0907 | 2.305 | 31 | 0.0089 | 0.227 |

| | | | | | |
|---|---|---|---|---|---|
| 12 | 0.0808 | 2.053 | 32 | 0.0080 | 0.202 |
| 13 | 0.0720 | 1.828 | 33 | 0.0071 | 0.180 |
| 14 | 0.0641 | 1.628 | 34 | 0.0063 | 0.160 |
| 15 | 0.0571 | 1.450 | 35 | 0.0056 | 0.143 |
| 16 | 0.0508 | 1.291 | 36 | 0.0050 | 0.127 |
| 17 | 0.0453 | 1.150 | 37 | 0.0045 | 0.113 |
| 18 | 0.0403 | 1.024 | 38 | 0.0040 | 0.101 |
| 19 | 0.0359 | 0.912 | 39 | 0.0035 | 0.090 |
| 20 | 0.0320 | 0.812 | 40 | 0.0031 | 0.080 |

There are equations for determining the diameter of any particular wire gauge--or the gauge from a given diameter. However, for most uses, the table is most apt. Note that in the AWG system, the wire diameter doubles with each 6-gauge decrease. Hence #12 AWG is twice the diameter of #18 AWG. Memorizing a few common gauge-diameter relationships is a useful exercise.

**Table 1-4. Common BSWG Wire Size Diameters in Inches and Millimeters**

| BSWG Gauge # | Diameter Inches | Diameter Millimeters | BSWG Gauge # | Diameter Inches | Diameter Millimeters |
|---|---|---|---|---|---|
| 1 | 0.3000 | 7.620 | 21 | 0.0320 | 0.813 |
| 2 | 0.2760 | 7.010 | 22 | 0.0280 | 0.711 |
| 3 | 0.2520 | 6.401 | 23 | 0.0240 | 0.610 |
| 4 | 0.2320 | 5.893 | 24 | 0.0220 | 0.559 |
| 5 | 0.2120 | 5.385 | 25 | 0.0200 | 0.508 |
| 6 | 0.1920 | 4.877 | 26 | 0.0180 | 0.457 |
| 7 | 0.1760 | 4.470 | 27 | 0.0164 | 0.417 |
| 8 | 0.1600 | 4.064 | 28 | 0.0148 | 0.376 |
| 9 | 0.1440 | 3.658 | 29 | 0.0136 | 0.345 |
| 10 | 0.1280 | 3.251 | 30 | 0.0124 | 0.315 |
| 11 | 0.1160 | 2.946 | 31 | 0.0116 | 0.295 |
| 12 | 0.1040 | 2.642 | 32 | 0.0108 | 0.274 |
| 13 | 0.0920 | 2.337 | 33 | 0.0100 | 0.254 |
| 14 | 0.0800 | 2.032 | 34 | 0.0092 | 0.234 |
| 15 | 0.0720 | 1.829 | 35 | 0.0084 | 0.213 |
| 16 | 0.0640 | 1.626 | 36 | 0.0076 | 0.193 |
| 17 | 0.0560 | 1.422 | 37 | 0.0068 | 0.173 |
| 18 | 0.0480 | 1.219 | 38 | 0.0060 | 0.152 |
| 19 | 0.0400 | 1.016 | 39 | 0.0052 | 0.132 |
| 20 | 0.0360 | 0.914 | 40 | 0.0048 | 0.122 |

In the BSWG system, wire diameter approximately triples for every 12-gauge decrease in number.

The ultimate treatment of element diameter will be in terms of fractions of a wavelength. #14 AWG (0.0641" diameter) represents a much fatter element at 2 meters than at 20 meters--10 times fatter, to be precise. When scaling an antenna from one frequency to another, it is crucial to scale not only the loop circumferences and spacing between elements, but as well the element diameter--if one is to replicate the performance at the new frequency that was obtained at the initial frequency.

In order to familiarize yourself with how large the diameter of a certain element is at a given frequency, **Table 1-5** provides some sample values of wire diameter in wavelengths and the corresponding element diameter in inches. In parentheses, where applicable, is the nearest AWG wire gauge to the listed diameter.

**Table 1-5. Some Wire Diameters in Wavelengths and Inches**

| Dia. in WL | Physical Diameter in Inches (Closest AWG Gauge) | | | |
|---|---|---|---|---|
| | 3.5 MHz | 14 MHz | 30 MHz | 144 MHz |
| 0.00001 | 0.0337 (20) | 0.0084 (32) | 0.0039 (38) | 0.00082 |
| 0.0000316 | 0.1066 (10) | 0.0267 (24) | 0.0124 (29) | 0.0026 (40) |
| 0.0001 | 0.3372 | 0.0843 (12) | 0.0393 (18) | 0.0082 (32) |
| 0.000316 | 1.0664 | 0.2666 (2) | 0.1244 (8) | 0.0259 (22) |
| 0.001 | 3.372 | 0.841 | 0.3934 | 0.0820 (12) |
| 0.00316 | 10.664 | 2.666 | 1.244 | 0.2592 (2) |
| 0.01 | 33.722 | 8.431 | 3.934 | 0.8964 |

For the largest diameters listed, there are unlikely to be corresponding quad arrays. However, as we shall see, it is possible to simulate very large diameter elements using multiple strands of thinner wire. So using a 0.01 wavelength element diameter at 80 meters is not impossible, however improbable. Even less probable is the use of a 0.00001 (1E-5) wavelength diameter element at 2 meters. However, a 0.9" diameter element (or something close) is certainly feasible at 144 MHz.

The entries in **Table 1-5** are divided in increments such that the corresponding common logarithms of the wire size progress from -5.0 through -2.0. The entries containing “316” represent wire diameter values whose common logarithm is X.5. (The more precise value of wire diameter would use “31622777,” but that fussiness would yield spurious precision in most cases.) It will turn out that most of the dimensions and performance figures for quads, when varied by element diameter, yield more usable curves when related to the common logarithms of the various element diameters. Hence, every wire diameter--whether given in inches, in millimeters, or as a wire gauge--will end up converted to the corresponding wire size as a fraction of a wavelength and from there to the appropriate common logarithm.

## Development Methods

The optimized designs presented in subsequent chapters emerge from patient antenna modeling in NEC-2. The primary software used in the process was NEC-Win Plus, with cross checks using GNEC (NEC-4). Both are products of Nittany-Scientific, Inc. The advantages of NEC-Win Plus for this particular application are two, and both involve the model-by-equation facility.

In developing a precise quad model that meets the criteria set for the design and that uses progressively thicker (or thinner) element diameters (with consequential changes in loop circumferences and element spacings), it is easier to set up the basic model so that the coordinates of the wires for each loop and the wire diameter are variables. The numeric values of each variable can be changed with a single entry which will result in several changes to the array dimensions.

For any given wire size, when the array is declared optimized, the resulting values may be recorded or saved. The progression of value sets can then be manipulated to arrive at equations for the resulting curves. Regression analysis will be the main tool for translating the curves into equations of an order (4th order equations will be most commonly used) that provides suitable design guidance.

Several of the quad designs shown in succeeding chapters will demonstrate the process in various levels of detail. However, **Fig. 1-3** will provide a sample of the process. In this case--the reflector circumference for a 4-element quad--the data from optimized samples is entered. The smooth curve represents the continuous output values that emerge from the 4th order equation having the form noted in the inset. The precise values for a, b, c, d, and e will be given in Chapter 9. The only difference among these equations in the many applications of them in this study will be the numerical values generated for the constants.

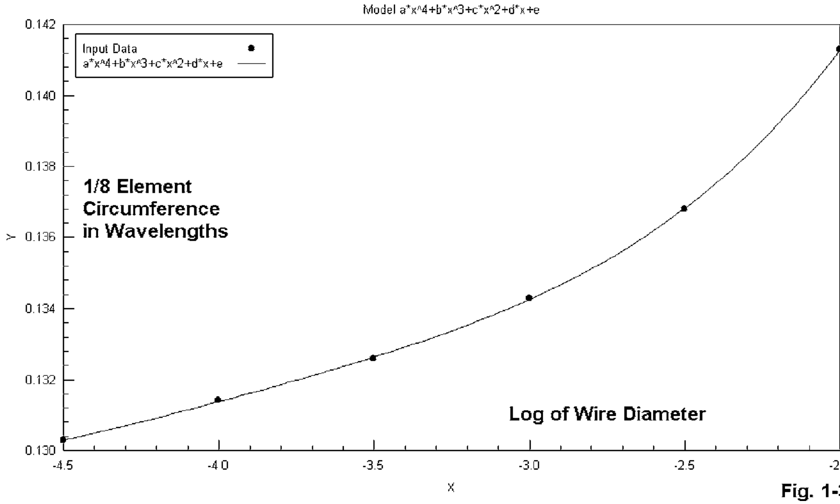



**Fig. 1-3**

Regression analysis equations are simple curve fitting exercises and have no foundation in an electronics or antenna theory. They are useful calculating tools within the context of this study. No attempt will be made to integrate these equations with any facet of antenna theory. They will have served their purpose if they allow us to design the dimensions of a given quad array type and to have some relevant indications of its performance.

When inserted into an independent programming medium, such as GW Basic or a spreadsheet, the analyses will provide estimates of certain performance parameters. Exactly which ones are supplied will vary with the quad type. However, the results of the regression analysis may be placed into a NEC-2 model in NEC-Win Plus using once more the model-by-equation facility. This application is the second major reason for using the selected software. When applied to antenna modeling software, only the dimensional equations are inserted, since the software itself becomes a superior means of obtain data on performance parameters, both at the design frequency and over a user-selected passband. In both cases, the user need only supply a value for the element diameter and for the design frequency to obtain full results.

The GW Basic versions of the design equations are available in the suite of utility programs called HAMCALC. The suite of well over 200 programs comes on a CD-ROM that includes a copy of GW Basic. It is available for $7 (US) from George Murphy, VE3ERP, 77 McKenzie Street, Orillia, ON L3V 6A6, Canada. The fee covers the cost of the disk and air mail postage (anywhere in the world), with excess proceeds over costs being donated to the amateur radio program of the Canadian National Institute for the Blind.

The model-by-equation versions of the program are available at the Nittany Scientific web site (http://www.nittany-scientific.com). They come as .NWP input spreadsheet files. For export to other NEC programs or cores, the results of a given set of input selections can be saved as a .NEC file. Such files can be run in any almost NEC program, such as GNEC or EZNEC Professional.

In all cases, the design results are offered tentatively. They represent the best that I have so far been able to develop. Further developmental work in the future by me or by others may well result in superior designs as the dynamics of quad operation gain a better and more systematic understanding. My only reason for reporting on these interim results is that, even if imperfect, they represent some interesting and useful directions in monoband quad array design. Moreover, the volume of such results has reached the level of forming a relatively coherent progressive treatment.

However, we shall not know how far short of the goal these notes end up if we do not get started. The proper place to start the investigation of quads is with the single quad loop.

# Chapter 2
# Calculating the Length of a Resonant Square Quad Loop

I have received numerous inquiries about calculating the length of wire needed to form the circumference of a single resonant square quad loop at various frequencies. Everybody seems to "know" that such a loop in the HF range requires use of the old formula

$$L_{ft} = \frac{1005}{f_{MHz}}$$

Folks also seem to know that this equation does not work at VHF.

In fact, this old formula does not work at HF either. It has been, is, and always will be wrong for common sizes of bare wire. I have heard by the unreliable grapevine that it is the formula to use at HF for insulated wire, where we have a shortening effect or velocity factor. However, being over 4% short, the formula exceeds the velocity factor effects of most wire insulations with which I am familiar.

#12 AWG bare copper wire requires a calculation constant of about 1043 at 28.5 MHz and a constant of about 1065 at 146 MHz. However, each of these numbers is good for only one wire size at only one frequency. There should be a more general solution that will get quad loop builders into the ballpark at any frequency and wire size. Therefore, let's look at the problem of figuring the wire length for a single resonant quad loop all over again.

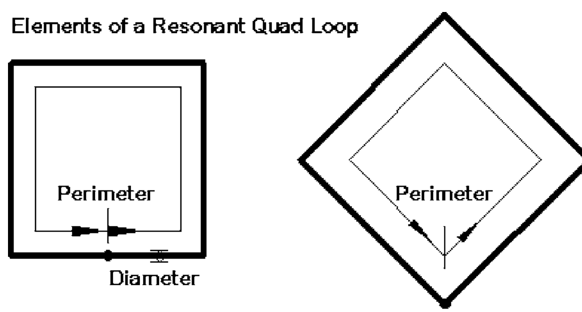


Fig. 2-1

**Fig. 2-1** shows us the basic ingredients for what we need. A single quad loop in free space has only two directly related dimensions: wire diameter and circumference length. If we express both measures in terms of wavelengths (or fractions of a wavelength), then the required perimeter length of the loop at resonance for lossless wire will be a direct function of the wire diameter. Remember that a fixed wire diameter, like #12 AWG wire (0.0808"), becomes a larger fraction of a wavelength as we increase the frequency. As we increase the wire diameter as a function of a wavelength, the loop circumference will also increase in terms of wavelengths. Perhaps Bob Haviland, W4MB, was the first to note this phenomenon and to understand its import.

The only reason we also need to know the frequency is so that we can translate the input wire diameter from a common unit of measure, such as inches or millimeters, into a fraction of a wavelength. If we use feet and/or inches, then a wavelength, L, becomes

$$L_{ft} = \frac{983.5592}{f_{MHz}} \quad \text{and} \quad L_{in} = \frac{11802.71}{f_{MHz}}$$

and, for meters and millimeters,

$$L_{ft} = \frac{983.5592}{f_{MHz}} \quad \text{and} \quad L_{in} = \frac{11802.71}{f_{MHz}}$$

You can apply the length of a wave at your desired frequency to the wire diameter you select to get its diameter as a fraction of a wavelength. Use the reference tables in Chapter 1 to find the diameter of any wire whose size is listed by gauge.

Once we have converted our wire diameter into a fraction of a wavelength, we can determine how long the perimeter of a single resonant quad loop must be in terms of a wavelength.

To find the relationship between the wire diameter and the perimeter length, I modeled a large number of quad loops and brought them to resonance, where resonance is defined as a feedpoint impedance with less than +/-0.1 Ohm of reactance. The process was considerably eased by using the model-by-equation facilities of NEC-Win Plus. Once I had placed variables for the wire dimensions and the wire diameter, a new model required only that I change two values on the equations page. Using this facility is how I came to realize that no matter what frequency I plugged into the model, the impedance did not change if I defined the variables in terms of a wavelength.

The restriction on this result is the use of lossless or perfect wire and a free space model. However, changing any model's material into copper or aluminum yields no significant adjustments to the result. The effects of material losses will be greater with very thin wire (as a fraction of a wavelength) than for think wire. The resistive component of the impedance grew to reflect the wire losses (an Ohm or two), and the remnant reactance near resonance remained less than +/-1 Ohm.

Of course, placing an antenna over ground, especially at a height that is under 1 wavelength, may show a pattern of changing resistance and reactance at the feedpoint. Expressed in other terms, the required length for resonance of the loop will vary with height--and the impedance will not be a constant value. However, quad loops are relatively less sensitive to changes in height above ground than dipoles with free ends. So the problem is not likely to be excessively significant.

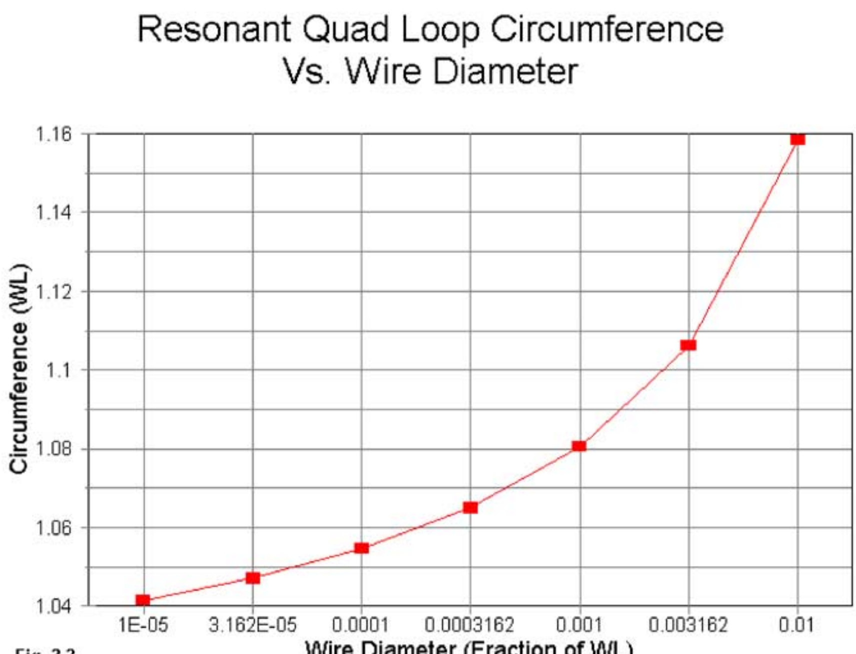



Fig. 2-2

Nevertheless, ground effects will vary from application to application and must be the responsibility of the builder and user of the antenna.

**Fig. 2-2** shows the relationship between the wire diameter and the perimeter length, when both are expressed in terms of a wavelength. Note that the wire diameter axis is a log scale, and the "3162" steps are points at which the common log has a value of x.5. The graph is limited to wires sizes from 1.0E-05 to 1.0E-2, which covers the range of #18 on 80 meters to small tubing at VHF. As is evident, the relationship is not at all linear.

While doodling with the values for wire diameter and loop circumference, I evolved following equation is a first order approximation of the curve in the graph.

$$QL_{wl} = 1.0413 + (\log^2(d_{wl} * 1E5) * 0.0128)$$

where QL is the perimeter length of the quad loop and d is the wire diameter, both in wavelengths.

The approximation is satisfactory for most amateur building projects, since the maximum error is about 2%, relative to the NEC models from which the algorithm was generated. Nevertheless, I was not satisfied with the results. Therefore, I turned to regression analysis to see if a more adequate fit might be obtained between the modeled data and the results of a calculation. If one has enough data points that vary along relatively smooth curves, regression analysis can provide equations that permit very accurate interpolations between the data points. The sample curve in Chapter 1 is typical of the results. Programs such as Datafit automate the process, while allowing the user to select the degree of equation best suited to the job. For the loop circumference and for the feedpoint impedance at resonance, 4th order equations proved sufficient.

I shall not parade the equations at this point for reasons of economy of space and because they appear later in a utility program. The general form of the equation will suffice:

$$y = a x^4 + b x^3 + c x^2 + d x + e$$

where x is the common logarithm of the wire size expressed as a fraction of a wavelength and y is the parameter being related to x, in this case, either the circumference length (as a fraction of a wavelength) or the resonant feedpoint resistance.

(The form of the equation, of course, will change if one selects other than a 4th order version.) The circumference dimension can be the full circumference, the length of one side, or half the length of one side, since all three of these measures are related to each other by simple multipliers or dividers. The modeler tends to prefer 1/8 the circumference, which is half the side length, a convenient number to plug into a model that is centered along one of the axes.

The constants a through e emerge from the regression analysis and are generally carried out to the available space in the cell in which they are recorded. Because they are constants, my own preference is to use them to the full level of precision given, saving all rounding operations until the last move in a calculation. For hand calculator work, this procedure is fraught with problems, but when placing such values into a calculating program on a spreadsheet or in Basic, they work very well. They also relieve one from the task of determining if a deviation from the baseline data is a function of the equation itself or of some one or more rounding steps along the way.

The regression analysis provided equations that much more closely fit the data than the original approximation, even though the approximation might well suffice for amateur construction. Models based on the calculated outputs from both schemes were created and then checked for the amount of feedpoint reactance. The deviation from precise results is shown in **Table 2-1**. The table lists a span of wire sizes (in terms of a fraction of a wavelength) and then lists the reactance of quad loops modeled on the results of each algorithm.

**Table 2-1. Feedpoint Reactance of Calculated Models**

| Wire Size | Reactance of the Calculated Loop | |
|---|---|---|
| in WL | Approximation | Regression |
| .00001 | - 1.1 | + 0.6 |
| .00003162 | - 7.9 | + 1.2 |
| .0001 | - 1.3 | - 0.4 |
| .0003162 | +11.4 | + 1.2 |
| .001 | +21.0 | + 1.1 |
| .003162 | - 0.1 | + 4.7 |
| .01 | - 1.7 | - 1.0 |

For the initial approximation, the maximum error occurs at a wire size of about 0.001 wl. For larger and smaller wire sizes, the error in the algorithm is far less than

1%. For the equation yielded by regression analysis, the maximum error occurs with the next-to-largest wire size listed and is the only figure to exceed 2 Ohms. The modeled resonant resistance of the baseline models ranges from 121.6 Ohms for the thinnest wire model (0.000001 wavelengths) to 141.4 Ohms for the largest diameter element (0.01 wavelengths). A reactance of 20 Ohms would not produce an objectional SWR value.

The superiority of the regression equation over the initial approximation is perhaps even more graphic in **Fig. 2-3**. The graph plots the original baseline modeled dimensions, which appear as the circumference and the element diameter as fractions of a wavelength. As well, there are curves that show the results of using the original approximation and the regression equation. The original approximation was calibrated to a minimum wire diameter of 1E-5, so the results approaching 1E-6 move rapidly away from the baseline data. In contrast, the regression equation shows a close overlap with the baseline, with the exception of the next-to-largest wire diameter for which the data is correlated.

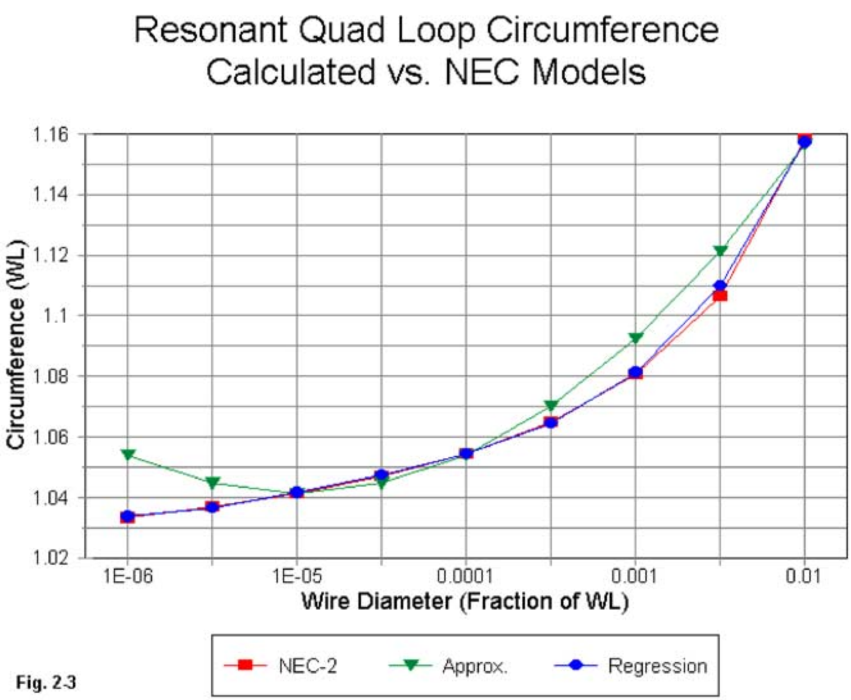



Fig. 2-3

The end values for the correlations were selected for quite different reasons. At the smallest diameter end of the scale, values less than 1E-6 wavelengths are impractical at any frequency for which radio amateurs would build a quad loop. The cut-off at wire sizes approaching 0.01 wavelength was a function of the segment length-to-diameter ratio of the element. Larger diameters would have required a shift to fewer segments per quad loop side, which in turn would have disrupted the smoothness of the baseline curve.

Translating the results in wavelengths into normal units of measure is simply a second exercise in applying the relationships in the earlier given equations. The required perimeter length can be transformed into any common unit for the frequency specified at the beginning of the exercise.

### A Utility in GW Basic

To save you the trouble of doing the transformation and algorithm calculations for each possible quad you may wish to build, I have put the basics of the discussion above into a simple utility program. The listing of the GW Basic program follows.

```
10 CLS:PRINT “Program to calculate the perimeter length of a
   resonant square  quad loop.”
20 PRINT “All equations correlated to NEC antenna modeling
   software for wire  diameters”
30 PRINT “     from 1E-6 to 1E-2 wavelengths.”
40 PRINT “L. B. Cebik, W4RNL”
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):D1=.4342945*LOG(D)
150 IF D1<-6 THEN 160 ELSE 170
160 PRINT “Wire diameter less than 1E-6 wavelengths:  results
    uncertain.”
```

```
170 IF D1>-2 THEN 180 ELSE 190
180 PRINT "Wire diameter greater than 1E-2 wavelengths:  results
    uncertain."
190 AV=.0001386272922#:BV=.002677872933#:CV=.01955406057#:
    DV=.06540532144#:EV=.2164538128#
200 L1=(AV*(D1^4))+(BV*(D1^3))+(CV*(D1^2))+(DV*D1)+EV
230 A2=.3131933:B2=5.694978593#:C2=38.65184274#:D2=118.05237#:
    E2=262.9477727#
240 L2=(A2*(D1^4))+(B2*(D1^3))+(C2*(D1^2))+(D2*D1)+E2
250 PRINT "Perimeter Length in Wavelengths:";L1*8
300 PRINT "Dimensions:"
310 WL=299.7925/F:PRINT "Wavelength in Meters =";WL
320 PM=L1*WL:PRINT "Perimeter Length in Meters =";PM*8
330 WF=983.5592/F:PRINT "Wavelength in Feet =";WF
340 PF=L1*WF:PFI=PF*12:PRINT "Perimeter Length =";PF*8;" Feet or
    ";PFI*8;" Inches"
341 PRINT"Resonant Impedance in Ohms =";L2
350 INPUT "Another Value = 1, Stop = 2: ";P
360 IF P=1 THEN 10 ELSE 370
370 END
```

The program let's you enter the wire diameter in either inches or millimeters. Anyone so inclined can add an AWG wire table module for direct entry of wire gauges. However, the table of diameters in Chapter 1 should satisfy most needs.

Lines 190 through 230 do most of the calculating, with each algorithm broken into steps. One line lists the constants, while the next calculates the result. Two outputs are calculated: the perimeter of the loop and the anticipated resonant impedance.

You can repackage the equations into almost any form and calculating medium. The program was written in GW Basic, which only recognizes log-base e (natural logs). But then, GW Basic was a product of the 1980s (my edition is dated 1987). Hence, the log functions contain a conversion factor to change the natural logs into log-base 10 (common logs). You can expand the 0.4343 multiplier indefinitely for greater precision of calculation (say, to 0.4342945), but the common conversion factor is precise enough for virtually all applications. If you translate the program into another medium that recognizes both common (LOGx) and natural (LNx) logs, you should remove the conversion factor if you retain the "log" notation. Current spreadsheets—a common substitute for Basic—tend to have both functions.

Outputs (to screen only) include the input data, the wire size in terms of a wavelength, and the resulting perimeter length, also in terms of a wavelength. In addition, the outputs include the length of a wave in feet and in meters, along with the perimeter lengths in these units. At the bottom is the resonant impedance. I shall assume that conversion to inches, millimeters, or centimeters is a routine hand calculator job. However, you can feel free to doctor the utility program to include these outputs as well.

I tend to prefer working up utilities in GW Basic, since the listing makes all of the arithmetic transparent, both for error detection and for transferring the information to other media. For example, all of the constants required for the regression equations are clearly apparent in the listing.

### Some Examples and Some General Quad Loop Properties

Let's run a few examples through the calculating utility and see what they might reveal about quad loop properties in general. First, we shall use #12 wire on 20, 10, 6, and 2 meters, as shown in **Table 2-2**.

**Table 2-2. Sample Quad Loops of #12 AWG Wire**

| Frequency | Wire Diameter | | Perimeter | | Feedpoint Impedance (R+/-jX) | |
|---|---|---|---|---|---|---|
| MHz | in. | wl | wl | feet | Perfect Wire | Copper Wire |
| 14.1 | 0.0808 | 9.652E-5 | 1.0542 | 73.537 | 124.7 - j 0.3 | 126.5 + j 1.3 |
| 28.5 | 0.0808 | 1.951E-4 | 1.0597 | 36.573 | 125.4 - j 1.1 | 126.7 - j 0.0 |
| 51.0 | 0.0808 | 3.491E-4 | 1.0656 | 20.551 | 126.3 - j 1.1 | 127.2 - j 0.3 |
| 146.0 | 0.0808 | 9.995E-4 | 1.0812 | 7.284 | 128.7 + j 1.1 | 129.3 + j 1.6 |

The series of #12 examples shows the "growth" in the wire diameter as a function of a wavelength. We can also see that as the loop circumference grows, so too does the feedpoint impedance. However, as the wire diameter grows as a function of a wavelength, the losses reduce, as evidenced by the smaller differential between the resistive components of the perfect-wire and the copper wire impedances.

To get a more global perspective on effects of element material on the quad loop feedpoint impedance with different wire sizes, **Table 2-3** surveys the entire span of calibrated wire sizes from 1E-6 to 1E-2 for perfect, copper, and 6063-T832 aluminum.

**Table 2-3. Element Size vs. Material Relative to Feedpoint Impedance**

| Diameter | Feedpoint Impedance (R +/- jX Ohms) | | |
|---|---|---|---|
| in WL | Perfect Wire | Copper | Aluminum |
| 1E-6 | 121.8 _ j 1.8 | 1086 - j152 | 1523 - j483 |
| 1E-5 | 122.9 + j 0.6 | 150.6 + j22.8 | 162.5 + j30.6 |
| 1E-4 | 124.7 - j 0.4 | 127.3 + j 1.9 | 128.2 + j 2.7 |
| 1E-3 | 128.7 + j 1.1 | 129.0 + j 1.3 | 129.1 + j 1.4 |
| 1E-2 | 140.8 - j 1.0 | 140.9 - j 1.0 | 140.9 - j 1.0 |

For practical purposes, by the time the element reaches a diameter of 1E-4 wavelengths, the differential between a perfect wire and the most common materials used in quad loop construction becomes insignificant. At a diameter of 1E-3 wavelengths, the differentials are negligible. As a practical example, we might have added to the list in **Table 2-3** the following quad loop for 146 MHz using a 0.25" element.

| Frequency | Wire Diameter | | Perimeter | | Feedpoint Impedance (R+/-jX) | |
|---|---|---|---|---|---|---|
| MHz | in. | wl | wl | feet | Perfect Wire | Copper Wire |
| 146.0 | 0.25 | 3.092E-3 | 1.1091 | 7.472 | 133.5 + j 4.7 | 133.7 + j 4.8 |

Note that the element diameter is about mid-range between the 1E-3 and the 1E-2 entries in **Table 2-3**. So, too, is the impedance, which shows negligible change in the transition from perfect to copper wire.

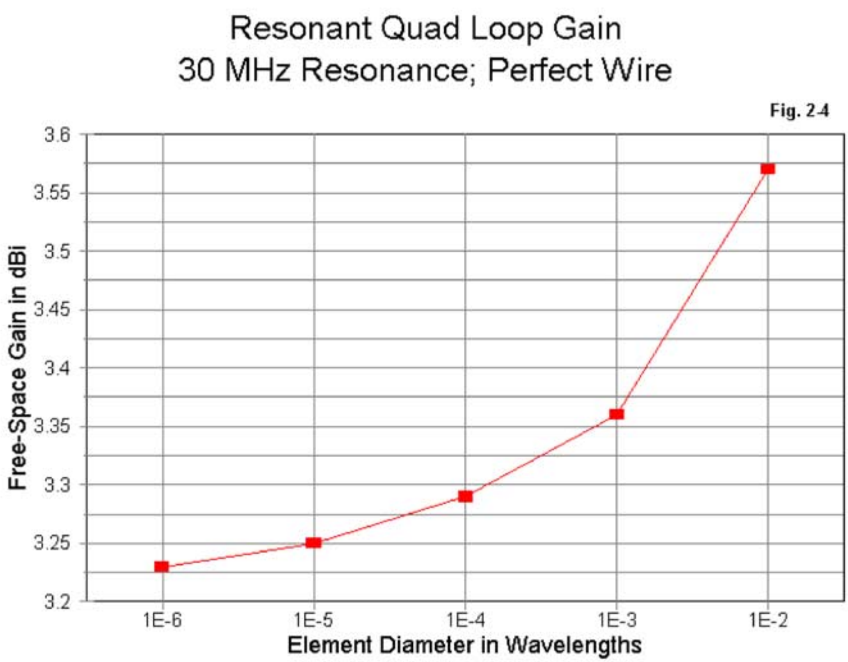
To see the effects of real ground on our calculated loop sizes, let's model the #12 28.5 MHz copper wire loop at various heights above average ground (conductivity 0.005 S/m; dielectric constant 13). **Table 2-4** provides some interesting data.

**Table 2-4. A #12 Quad Loop at 28.5 MHz Above Ground**

| Height | Feedpoint Impedance | VSWR Relative |
|---|---|---|
| Wavelengths | R +/- j Ohms | 125.4 Ohms |
| Free Space | 125.4 - j 1.1 | 1.01 |
| 0.5 | 124.1 - j12.4 | 1.11 |
| 0.75 | 126.3 + j 6.5 | 1.05 |
| 1.0 | 124.8 - j 6.9 | 1.06 |
| 1.25 | 126.0 + j 3.5 | 1.03 |

The lesson contained in this table is that calculating the single quad loop via the algorithm will result in usable dimensions for any common antenna height. The antenna impedance will slowly stabilize near its free space value as we further increase the height. The range of variation in feedpoint impedance for heights from 0.5 to 1.0 wavelengths is somewhat less than we find for linear dipoles. Thus, the quad loop acquires a reasonably justified reputation for being relatively immune to the effects of nearby objects, including the ground.

While we are cataloging general quad loop properties as we change the element diameter, we should pay heed to the changes in gain from a loop. The quad loop (in free space) presents a figure-8 pattern broadside to the plane of the loop. As we move from very thin wire (1E-6 wavelengths) to very fat wire (1E-2 wavelengths), even with perfect wire, we shall see considerable change in the free-space gain of the quad loop.



The total change in gain runs from about 3.23 dBi for the thinnest element to about 3.57 dBi for the fattest element. Although the differential would not be operationally significant for a single quad loop, the effects of this phenomenon are cumulative as we add loops to form complex quad arrays. As shown in **Fig. 2-4**, the increase in gain (not to be confused with the gain itself) nearly doubles for each additional order of magnitude in the element diameter.

The consequence of this pattern of gain increase, especially when applied to multi-element quad arrays, is that quads with the largest diameter elements not only show the highest gain, but as well by a considerable margin. We shall see this principle in action in future chapters of this study.

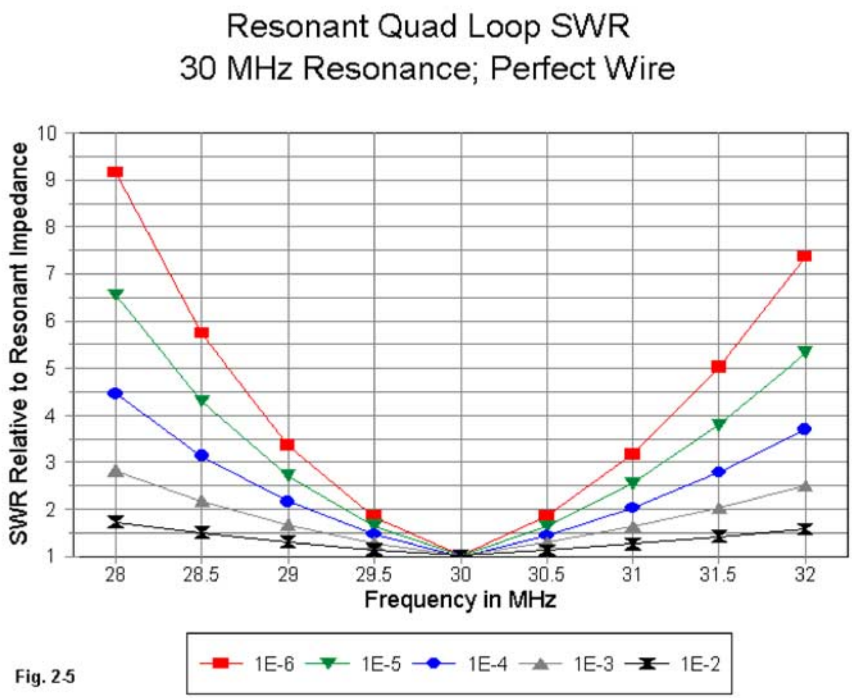


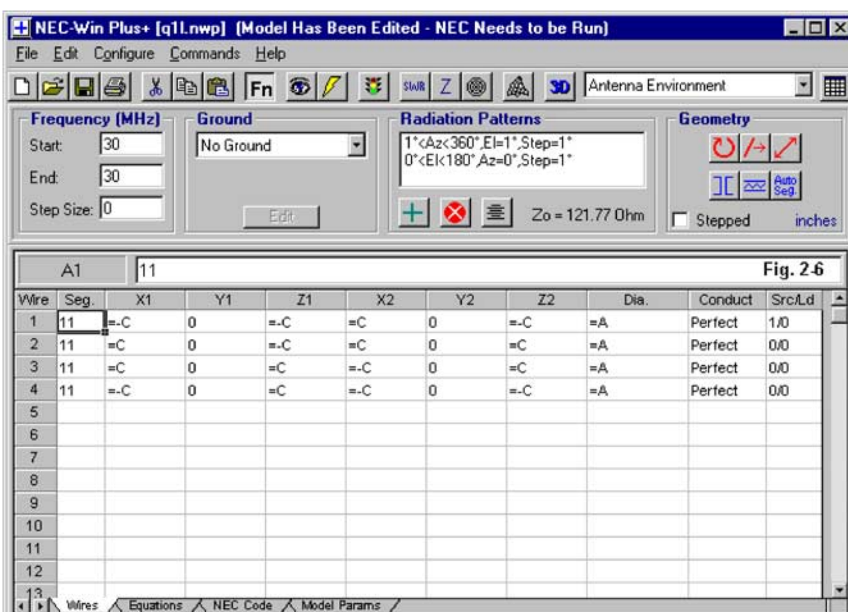

Fig. 2-5

Single quad loops also display the classic SWR curves that are commonplace with more complex quad arrays. As shown in **Fig. 2-5**, Each curve in the set rises more steeply below the design frequency than above it. In this example, element diameters from 1E-6 through 1E-2 wavelengths were used to create quad loops at 30 MHz. Each loop was referenced to its own resonant impedance for VSWR curves from 28 to 32 MHz.

As one might well expect, the versions with the largest diameter elements showed the shallowest SWR curves, while the steepest curve belongs to the thinnest element. However, regardless of the element diameter, the VSWR ratio rises more rapidly below the design frequency. As we shall see in future chapters, adding elements to form a complex array sometimes makes the differential more dramatic.

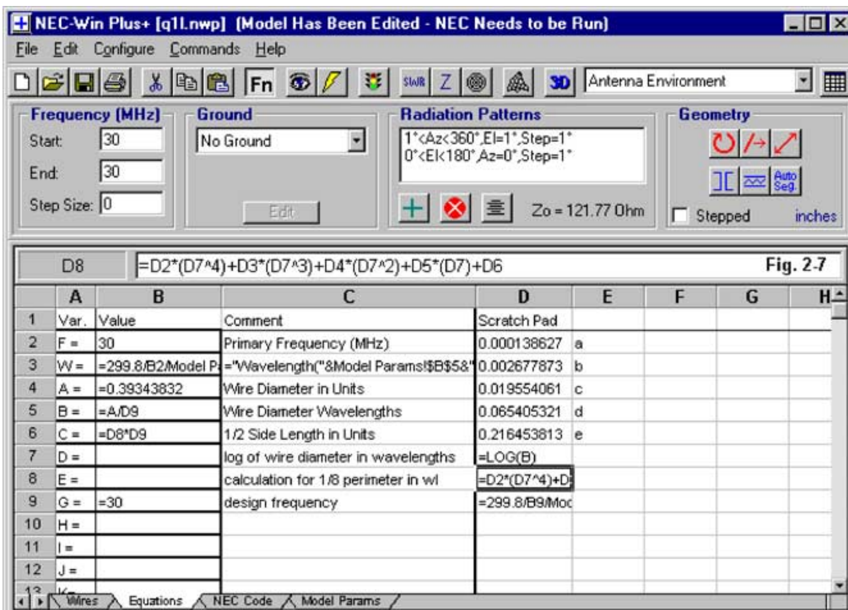
### A Design Model

As earlier noted, the dimension equation for the single square quad loop can be placed into a NEC-2 model, so long as the modeling software has a design-by-equation facility. NEC-Win Plus has such a facility, so I wrote a model that automatically sets the dimensions for a quad loop at resonance. The user need only enter the design frequency and the wire diameter in the units to which the program is currently set.



However, the process requires that the wires and geometric coordinates be set up as variables. **Fig. 2-6** illustrates the process (although the black and white illustration blanks out a bit of the detail, for example, the dividing lines of the spread sheet cell structure).

+C and -C have been chosen as the dimensional variables, where C represents half the length of the quad side. A represents the wire diameter in the selected units, in this case inches. The model has been set for a single frequency run at 30 MHz in free space. In NEC-Win Plus, toggling the FN button alternately shows the wires page in terms of variables and in terms of numerical values.




The second step is to set up the equations page. For this design project, **Fig. 2-7** shows the various parts of one method of accomplishing this task. Column D contains the constants (a through e) produced by the regression analysis. Cell D8 is highlighted so that the 4th order equation appears in the working space above the cells. Since the user can add any number of equations, whether or not used in creating the quad dimensions on the wires page, I have added cell D7. Note that the spreadsheet treats "LOG" as a common logarithm, so no correction is required (such as the one needed in GW Basic).

The user specifies two variables in this spreadsheet. Variable A in cell B4 is the wire diameter. Note the required entry format (=0.3934. . .). As well, the user specifies the design frequency in cell B9 as variable G. Cell D9 converts this frequency to its corresponding wavelength value. This step is necessary so that the antenna can be stepped from frequencies below the design frequency to frequencies above it. (If the automatically produced variables F and W had been used, the model would be dimensionally defined by the "Start" frequency in the upper left corner of **Fig. 2-7**).

The results of entering a design frequency of 30 MHz and a wire diameter of 0.3934. . . inches produces the design dimensions shown in **Fig. 2-8**.

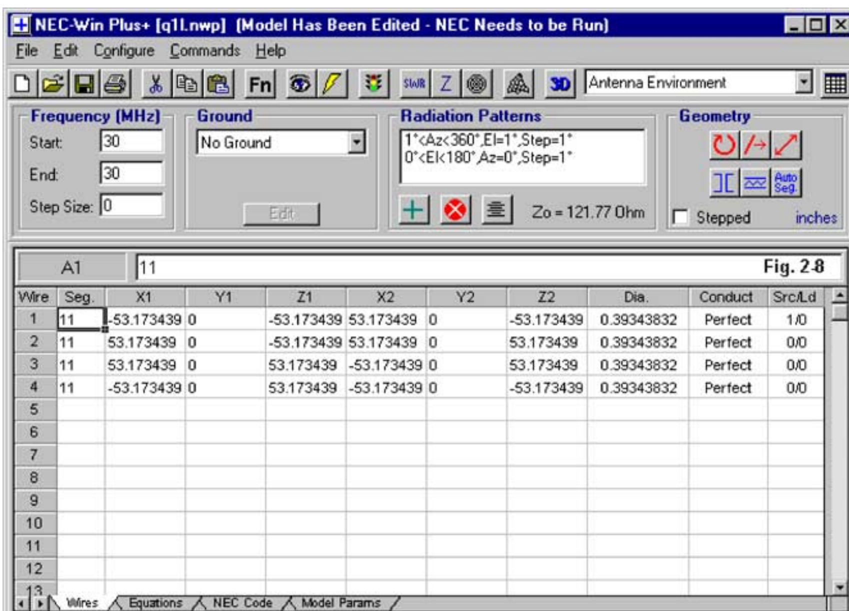


**Fig. 2-8**

Each side of the quad loop is twice the value shown in each cell of the X and Z columns. At this point, the modeler can run the program as is or alter other model parameters, such as the frequency sweep or the conductivity of the model wires. All normal tabular and graphical outputs will be available for analysis.

The comparative data shown in the graphs in this chapter were produced by running the design model through each wire diameter increment. The exception, of course, is data for the baseline models, which consisted of individual models optimized for resonance at selected wire sizes. The model results and the GW Basic program results, of course, agree, since they both use the same equations to determine the dimensions, given any frequency and element diameter entry.

One of the conveniences of using the design model is that one can select any desired frequency sweep parameters. The curves shown earlier used the span from 28 to 32 MHz in 0.5 MHz steps. However, for most amateur design projects, the frequency span is likely to be an HF or VHF ham band, with the steps selected so that the sweep starts and stops at the desired band edges. For single designs, it is convenient to use the built-in SWR plot button. As well, we shall find occasion to use the Z button to plot the change in resistance and reactance across a desired passband. The change in reactance will be, in some cases, of special interest.

The set-up shown for NEC-Win Plus will apply in general terms to any other program having a design-by-equation facility. However, there may be differences of detail related to the order of the set-up and the manner in which variables and equations are entered.

## Conclusions

It is certainly legitimate to ask why I have gone to such fussy levels of explanation and correlation with NEC models in the presentation of the simple BASIC program to calculate quad loop circumferences. The answer has two parts.

1. We began with a traditional wire cutting formula from sources that actually were intended only for use with thin wire multi-element quad arrays. That formula has always simply been presented as if it were correct, and it has become embedded in the minds of antenna builders. I did not wish this presentation merely to present an alternative “formula” in equally simple terms, trusting only to the belief potential of readers.

Instead, my aim has been to show both the method and the rationale for generating a usable design program that is adequate to virtually all applications for single quad loops. Correlating the program to NEC-2 models of quads loops--which are themselves very accurate relative to such antennas in the real world--provides a degree of confidence in the adequacy of the result.

2. The circumference of a single resonant quad loop turns out not to be amenable to a simple cutting formula at all. The required perimeter length is a direct consequence of the wire diameter selected for the loop. Of equal or greater importance than the design program is an appreciation of the fundamental properties of the quad loop, especially as it forms the basis for increasingly complex quad arrays. We have been able to survey those properties rapidly partly because of the ease with which the design program provides us with resonant quad loops of any wire diameter and at any desired frequency.

It will be useful to keep in mind the general properties and patterns relating to quad loop gain, SWR, and feedpoint impedance as we move from the single quad loop to multi-element arrays. One of the questions that we shall keep in the back of our mind is this: which properties of quad arrays emerge from the quad loop itself and which arise from the parasitic assembly that we create by combining quad loops? Just as understanding a Yagi is impossible without an understanding of the dipole, so, too, understanding a quad beam requires a preliminary understanding of the simple 1-wavelength loop.

The design program that we have developed, of course, even within the limits of its accuracy, applies only to square and diamond loops that are individually resonant. The required dimensions of the loops within a quad beam using 2 or more elements will differ from the dimensions of a single quad loop, just as do the linear elements of a Yagi relative to a single resonant dipole.

Moreover, the calculations will also require alteration for rectangular loops developed to achieve enhanced gain and a reduction of

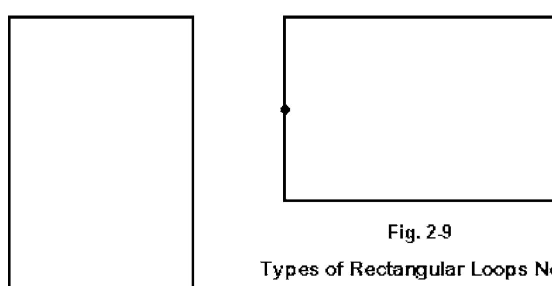


Fig. 2-9

Types of Rectangular Loops Not Covered by the Algorithm the feedpoint impedance to something closer to 50 Ohms. In general, the perimeter of such rectangular loops, when fed on the short horizontal elements shown in **Fig. 2-9**, will be somewhat longer than the circumference of a resonant square loop. Nevertheless, since squares are the most common form of loops, owing to the greater ease of construction, the little utility program in these notes should be serviceable for many antenna builders. Moreover, the techniques used to produce it will prove applicable to developing design programs for more complex arrays.

# Chapter 3
# 2-Element Quads as a Function of Wire Diameter: Understanding Some Quad Properties

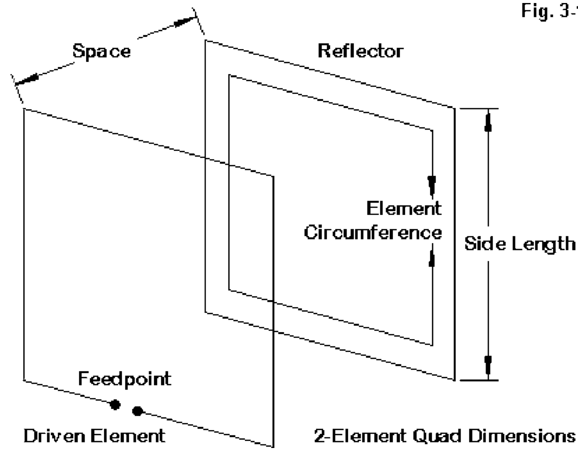
There are some very old formulas for cutting the lengths of 2-element (and larger) quad beam elements, formulas that have persisted since at least the 70s, if not before. The driven element should be 1005/f(MHz) feet long, while the reflector should be 1030/f(MHz) feet long. Spacing should be between 0.14 and 0.2 wavelengths. (See, for example, *The ARRL Antenna Book*, p. 12-1, in most recent editions.) Moreover, the quad has been called a very "low-Q" antenna, meaning that it is wide-banded compared to other beam antennas, presumably including Yagis.

Unfortunately, using the formulas will result in a relatively poor 2-element quad at any spacing. As well, we should not be too attracted by the so-called low Q of the quad, because that feature has very restricted application to SWR. A quad, as we saw in Volume 1, is not a low-Q antenna when it comes to other operating bandwidth considerations

In fact, we should very likely start all over again, beginning with the one piece of information that early quad builders thought was too insignificant to notice: the wire size. In this and the next two chapters, we shall examine the properties of 2-element quad beams using a driver and reflector based on the wire size we select for the elements. In this chapter, we shall look at quad properties based on very careful modeling with NEC. In the next chapter, we shall provide a way of automating the design process. In the final part of our work with 2-element monoband quads, we shall look at a way to improve the operating performance bandwidth of wire quads.

There are many operating specifications that we might emphasize for the design frequency we choose. For this exercise, I shall pick two, letting the others become what they will in the designs. First, the driven element will be resonant at the design frequency. Before we are done, we shall show how and why to vary that parameter without significantly affecting the reflector. Second, we shall select a spacing between elements and a reflector length that provides maximum 180-degree front-to-back ratio at the design frequency. These choices are consistent with fundamental work done on VHF models by Dan Handelsman, N2DT, and David Jefferies, G6GPR, and generally provide the widest operating bandwidth for most of the quad beam's other parameters.

Fig. 3-1




2-Element Quad Dimensions

**Fig. 3-1** shows the critical 2-element quad dimensions for our work. In order to generalize the results, we shall deal with the wire size, element lengths, and element spacing in terms of fractions of a wavelength. This procedure will allow us later to develop a general set of design equations that will be accurate to within 0.5% for wire sizes greater than 0.0003 wavelength and within about 1% for wires down to about 0.00003 wavelength, with the calculated resonance and peak front-to-back ratio occurring within about 10 kHz of actual detailed models.

The range of wire sizes that we shall examine will run from 1E-5 to 1E-2 wavelengths. Refer to charts in Chapter 1 for detailed correlations with standard wire gauges. By way of review, 1E-5 (0.00001) wavelengths is about #20 AWG at 80 meters and successively smaller in physical diameter as the frequency increases. 1E-3 (0.001) wavelengths is about #12 at 2 meters and increasingly fatter physically as the frequency goes down. Although the single quad loop exercises in Chapter 2 used wire sizes down to 1E-6, such wire sizes are impractical at any HF or VHF frequency and have been omitted. As well, as we shall discover, these wires sizes result in impractical arrays with respect to performance.

We shall follow the same procedure that we used for the 1-element quad loop in the preceding chapter and check not only the rounded values (for example, 1E-4) but as well intermediate values of an order that yields -x.5 as common logarithms. Not only for single element quads, but for virtually all quad designs, we may more easily track dimension and performance curves using the common logarithm of the wire diameter expressed in wavelengths than by using the wire diameter itself.

Models for each wire diameter were developed to obtain element lengths and spacing to resonate with driver within +/-j1 Ohm of remnant reactance. As well, the front-to-back peak value had to exceed 50 dB. NEC-2 or -4 are equally adept at this task, since the quad presents no pressure on either core's limitations until the wire size exceeds 0.01 wavelength. The models used 21 segments per side to ensure good convergence. 11 segments per side would have yielded equally valid modeling results. However, in examining a sequence of models from which curves and other generalized data are to be drawn, it is important to retain a single segmentation if it is satisfactory. Changes in segmentation will result is operationally insignificant differences in output values, but the resulting curves will be displaced a noticeable amount numerically at the point of a significant change in segmentation.

The models were calibrated for the most common material used in quad beam construction: copper. Test aluminum models showed little change in characteristics relative to the baseline copper models, but the slightly higher wire losses can add roughly an Ohm to the feedpoint impedance—less than 1% of the actual value. The test frequency was 28.5 MHz, about the geometric mean for the combined HF and VHF frequency range.

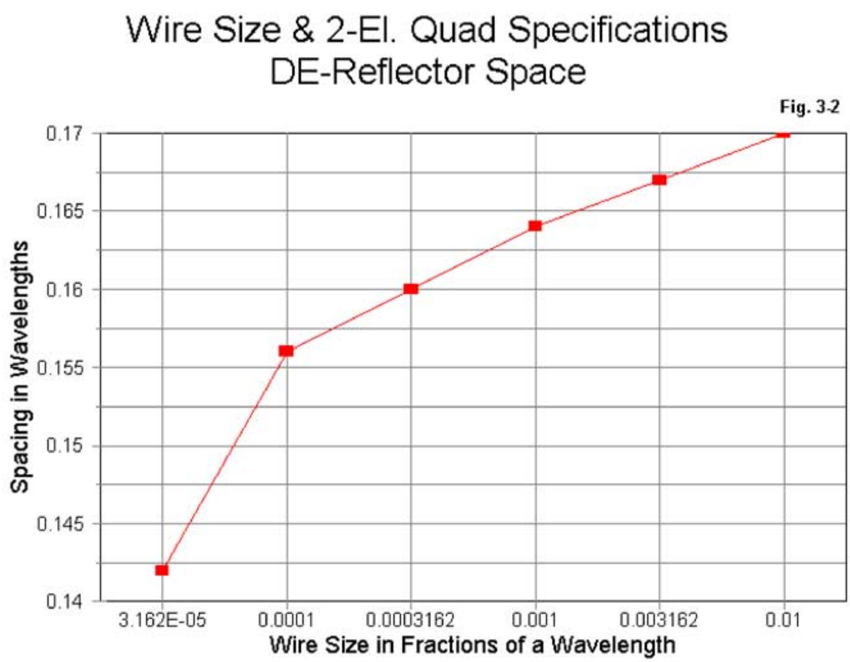
Since copper wire material losses vary with frequency, but at a rate that differs from the changes in wire diameter, there will be slight variations from the results to be shown at the extremes of the frequency range. At very low HF frequencies, the gain will be higher, but only by a maximum of a few tenths of a dB. Since the gain increase results from lower material losses, the source impedance will be lower—perhaps as much a 5 Ohms at 80 meters. Conversely, gain at VHF for a given wire size will be very slightly lower than at 28.5 MHz, while the feedpoint impedance will be correspondingly higher. However, these slight variations occasion no significant changes in the physical dimensions of the quad as a function of a wavelength.

Before examining the properties of 2-element quad beams in detail, let's take a summary view of the modeling results in the form of **Table 3-1**. All sizes and lengths are in wavelengths. We shall use our shorthand notation for wire sizes. Gain is the free-space value.

**Table 3-1. Summary 2-Element Quad Performance Results**

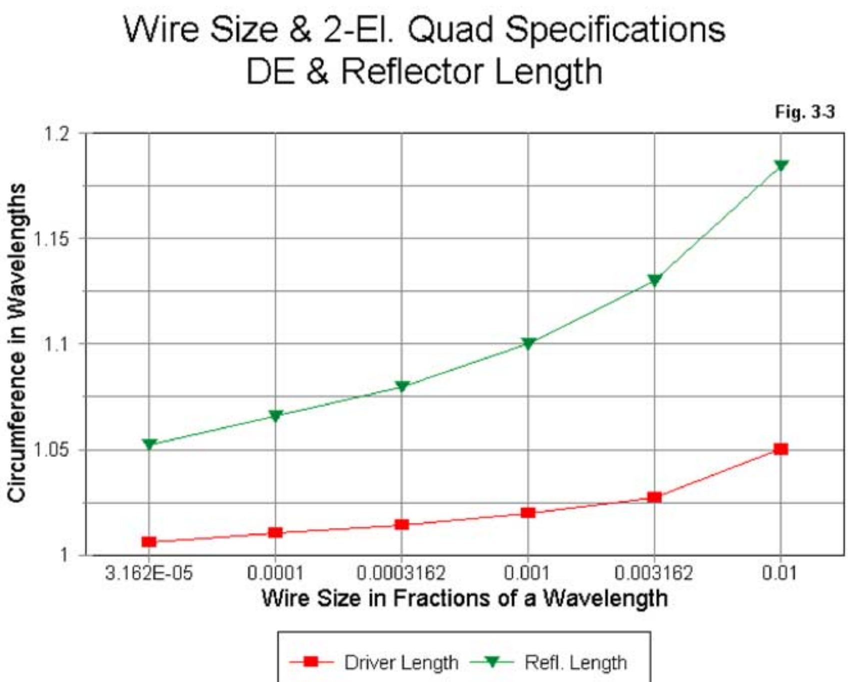
| Wire dia. | DE-Ref Space | DE Length | Ref Length | Gain dBi |
|---|---|---|---|---|
| 1E-5 | 0.650 | 0.99920 | 1.02248 | 2.95 |
| 3.16E-5 | 0.142 | 1.00600 | 1.05224 | 6.67 |
| 1E-4 | 0.156 | 1.01060 | 1.06560 | 6.99 |
| 3.16E-4 | 0.160 | 1.01424 | 1.07976 | 7.08 |
| 1E-3 | 0.164 | 1.01984 | 1.10000 | 7.11 |
| 3.16E-3 | 0.167 | 1.02744 | 1.12992 | 7.16 |
| 1E-2 | 0.170 | 1.05016 | 1.18432 | 7.21 |

The key element in this table is the value set for the thinnest wire. Notice the gain associated with this wire size. As the wire size increases—given our design criteria of resonance and peak front-to-back value—the frequency at which peak gain occurs decreases. For a wire size of about 3.16E-5, the maximum front-to-back value and the peak gain value occur at about the same frequency. For all wire sizes greater than 3.16E-5, the peak gain frequency is below the design frequency and grows more distant from it with increasing wire size.



In contrast, for wire sizes below 3.16E-5, the peak gain value occurs at a frequency higher than the design frequency. At the design frequency the gain value may be quite low, since the gain decreases more rapidly at frequencies below that at which peak gain occurs. The result is that 2-element quad beams with any performance potential at all and designed to the criteria used in this exercise are not feasible in wire sizes below 3.16E-5. As a result, model results for the thinnest wire in the table have been removed from the graphs to follow.

The first significant feature appears in **Fig. 3-2**, which plots the required element spacing for maximum front-to-back ratio against the wire sizes. The thinner the wire, the closer that spacing must be to achieve maximum front-to-back values at the design frequency. Notice that the curve becomes nearly linear with wire sizes above 1E-4, which is thinner than #14 at 10 meters. The shallowness of the curve above this value indicates that for most practical monoband beam designs, 0.17 wavelength spacing represents a limit. However, since tuning a 2-element quad for



peak front-to-back also tends to result in the widest operating bandwidth for most parameters, it becomes advisable to use the spacing that is correct for the selected wire size.

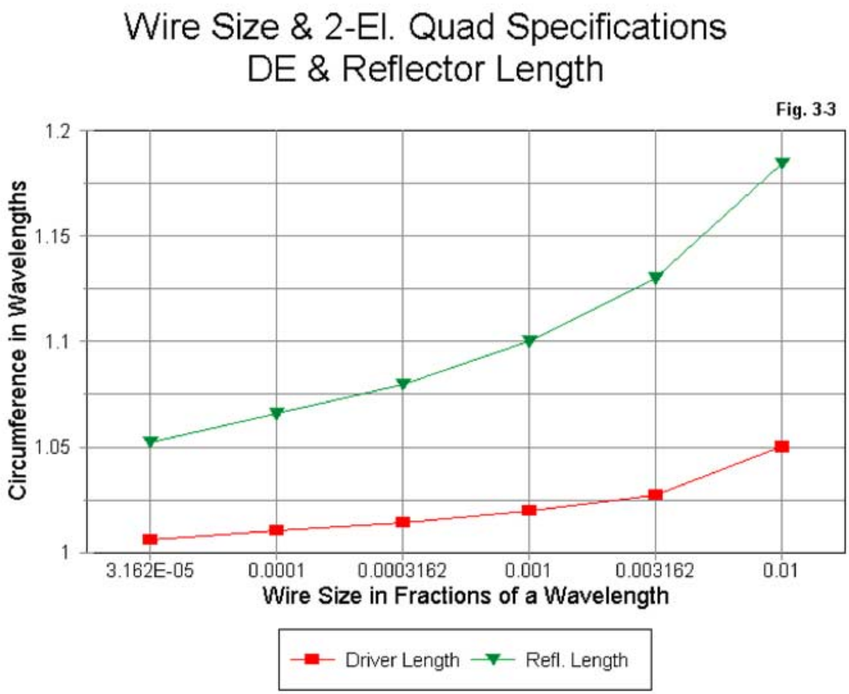
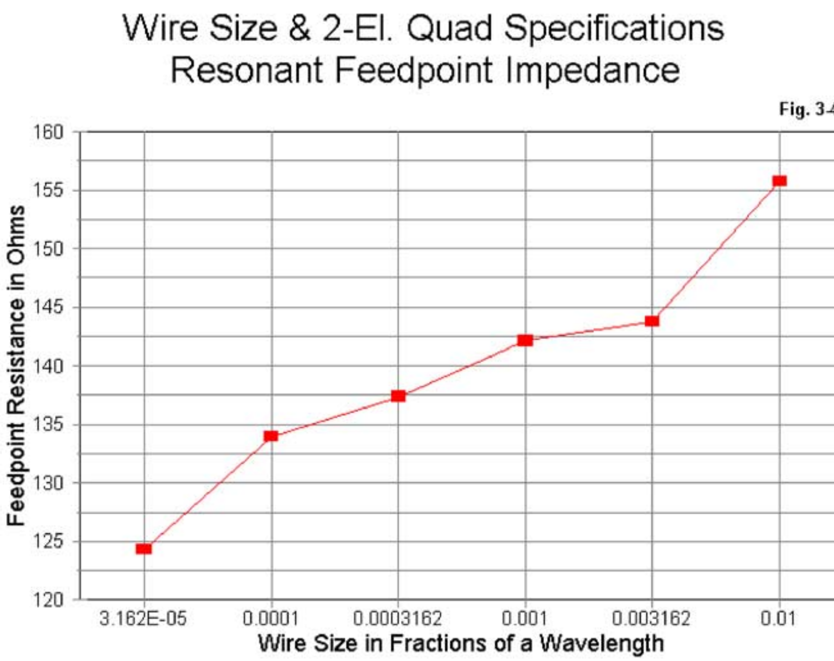


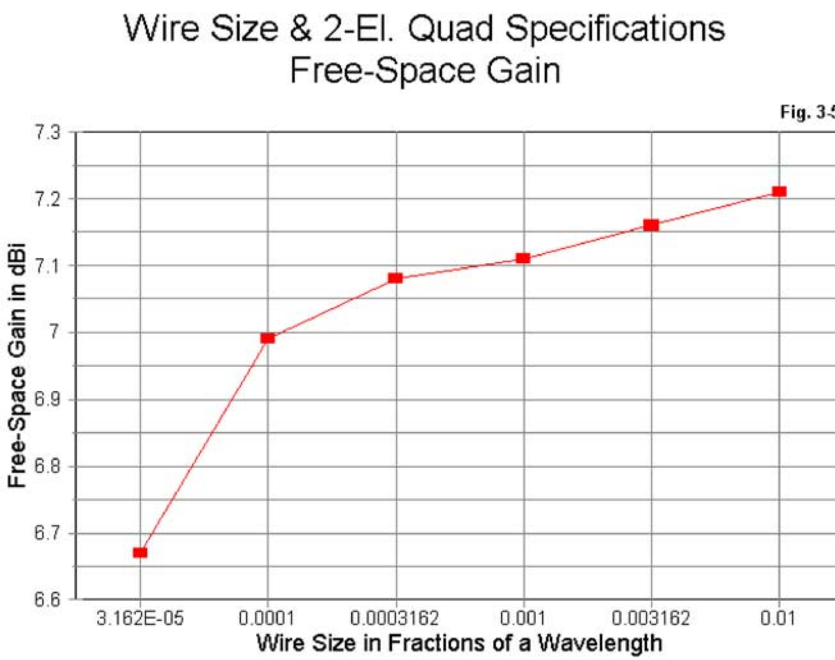

**Fig. 3-3** presents the driver and reflector element circumference lengths. Of special note is the fact that the reflector length increases at a faster rate than the driver length. In practical terms, the fatter the wire, the more the length of the reflector must exceed the length of the driver for peak performance.

Combining the results for spacing and element length yields the conclusion that inter-element coupling increases with wire size. Arriving at the correct value for a given wire size involves both element length and spacing so that the parasitic element currents have the correct magnitude and phase for maximum front-to-back performance. This performance will only be achieved if both the upper and lower wires of the reflector have close to optimal currents at their centers—and thus an optimal current distribution along their length. Part of the reflector sizing curve is a result of this function.

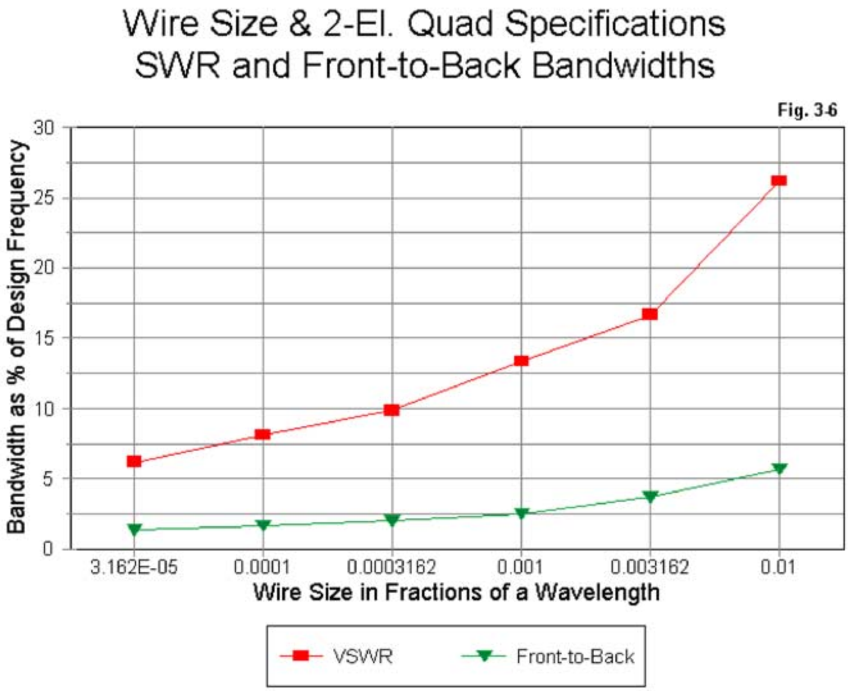
In **Fig. 3-4** we have the resonant feedpoint impedances of the modeled quads. The general increase in value is apparent. Part of the stair-step nature of the curve results from the fact that close to resonance, the resistive component of the impedance can show significant changes as we change the remnant reactance from close to j-1 Ohm to +j1 Ohm. In the value range of the graph (125-155 Ohms), the stair-step result is visually apparent, but not operationally significant. However, the overall difference between the thinnest and the fattest wire values may be significant for the method chosen to match an optimized quad beam to a given main feed line.




The change of gain with respect to wire size, shown in **Fig. 3-5**, must be read with great care. For wire sizes greater than 1E-4, the gain increase with additional wire thickness would not itself justify using a larger wire size. However, remember that as the wire thickness increases, the frequency of maximum gain becomes increasing lower than the design frequency. One consequence of this fact is that for thicker wires, the amount of gain change across a given amateur band will be less than for thinner wires. For example, consider a 2-element quad at 10 meters with a 28.5 MHz design frequency. Using #14 wire, the gain at 29 MHz will drop to under 6.5 dB, despite the 7+ dB value at the design frequency. With 0.5" elements, the gain at 29 MHz will be above 6.7 dB. In general, fatter elements provide both better and smoother performance across the ham bands.




There are other dimensions to operating bandwidth that are worth noticing. Two are included in **Fig. 3-6**. The graph shows clearly the VSWR bandwidth as a percentage of the design frequency. Even the thinnest wire on the graph shows a 6.2% operating bandwidth, while the span from 28 to 29 MHz is only about 3.5% of the design frequency. It is the wide SWR range that has given the 2-element quad beam the illusion of being a low-Q antenna.



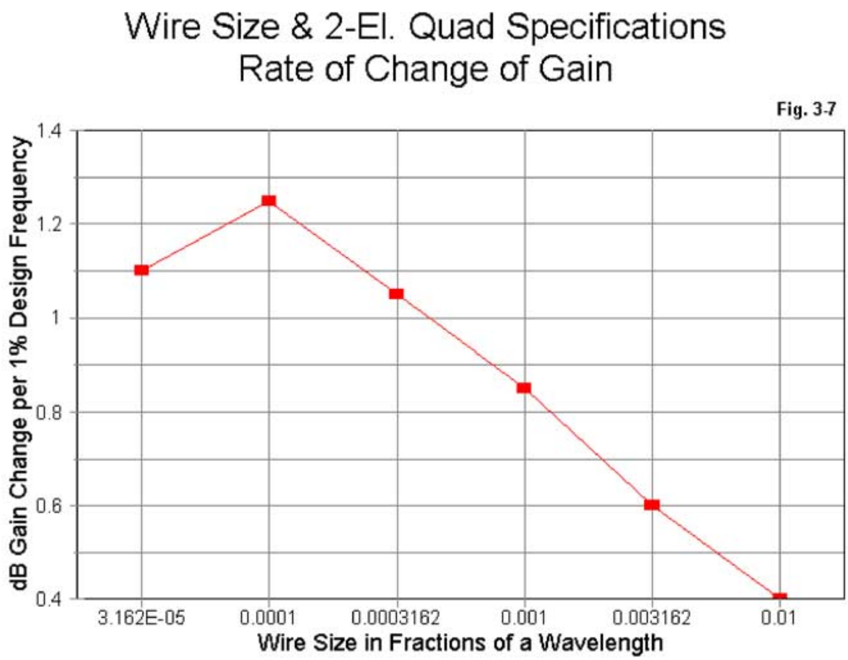

However, notice the second curve on the graph, which provides the front-to-back operating bandwidth. Because a 20-dB front-to-back ratio can be commonly achieved with Yagi design across a relatively wide frequency range—that is, a range covering all or almost all of a ham band—the operating bandwidth was defined as the percentage of design frequency over which the model had a front-to-back ratio in excess of 20 dB. These percentages are very low and do not reach the 3.5% level until we have a wire size of about 3.16E-3. This value represents a wire over 1" in diameter at 10 meters. Since quads are rarely made from wires this thick at HF, the quad user will generally have to be content with front-to-back performance at the band edges that is inferior to that which a well-designed Yagi may provide.

The narrowness of the operating bandwidth relative to front-to-back performance for the 2-element quad beam demonstrates a number of cautions. First, VSWR operating bandwidth is often a misleading indicator of the operating bandwidth of other antenna properties. The 2-element quad beam is in fact a high-Q (or narrow-band) antenna with respect to its front-to-back performance. Essentially, the loop construction of 2 1/2-wavelength elements connected at the ends makes the inter-relationship of the driver and the reflector more frequency critical in terms of arriving at the correct current magnitude, phase, and distribution on the reflector for high front-to-back performance—relative to the linear elements of the Yagi.

(Note: this comparison only suggests that the rate of change of a 2-element driver-reflector Yagi optimally spaced for maximum front-to-back ratio will be less than for a 2-element quad. However, such a Yagi may have a peak front-to-back ratio of only about 12 dB, with lesser values away from the design frequency. As well, the 2-element Yagi will have a lower gain—with a considerable variance across a band as wide as 10 meters. Hence, the 2-element quad will generally outperform a 2-element Yagi when both are designed to the same criteria. The point of these notes about quad performance is not to assess the overall superiority of one antenna type over the other. Instead, these notes call attention to the specific properties of the quad that must be taken into account when designing one or when reaching an overall evaluation of the quad's performance—especially, when considering options within quad design factors.)

When we initially examined the gain of quads relative to wire size, we noted the frequency position of the gain peak and its influence on the rate of change of gain across an intended band of operation. **Fig. 3-7** formalizes those notes by showing the rate of gain change per 1% of design frequency in terms of dB. Let us use the 1E-4 wire size as a marker, since it is the first data point where peak gain is significantly lower in frequency that the maximum front-to-back frequency. The curve is nearly linear from that point through 1E-2 wire sizes. In fact, for each decrease of wire size by a factor of 10, the rate of gain change across a working passband increases by nearly 1/2 dB. Wherever stable gain is required across a passband, the fattest element diameter feasible is the order of the day.

Although the graphs based on element wire size have much to teach us about the performance of 2-element quads, they cannot teach everything. For example, once one has designed a 2-element quad for a chosen wire size, it is usually a good procedure to reresonate the driver from the mid-band design frequency to a lower frequency—somewhere between 1/4 and 1/3 the way up from the lower limit of the passband. The obvious questions is this: how do we arrive at such a recommendation?




The answer can be found by performing a frequency sweep of a given design and looking at selected properties. For an example, let's take one of our 28.5 MHz designs using 3.16E-4 wavelength wire (about 0.12" in diameter, between #10 and #8 AWG) and sweep it between 27.8 and 30.8 MHz. Then, let's record the results for VSWR and front-to-back ratio on a graph, such as **Fig. 3-8**.

The design frequency values can be easily identified. Let's begin with the VSWR curve. Note that the SWR value increases much more rapidly below the design frequency than above it. If we wish to have roughly equal SWR values at the band edges of a chosen operating passband, then it will be necessary to reduce the resonant frequency of the driver. In fact, the small change in element size needed to effect this change will have negligible effect on the performance of the reflector or the frequency of maximum front-to-back. For example, reducing the resonant driver frequency to about 28.3 MHz will move the front-to-back ratio peak by only a few kHz.

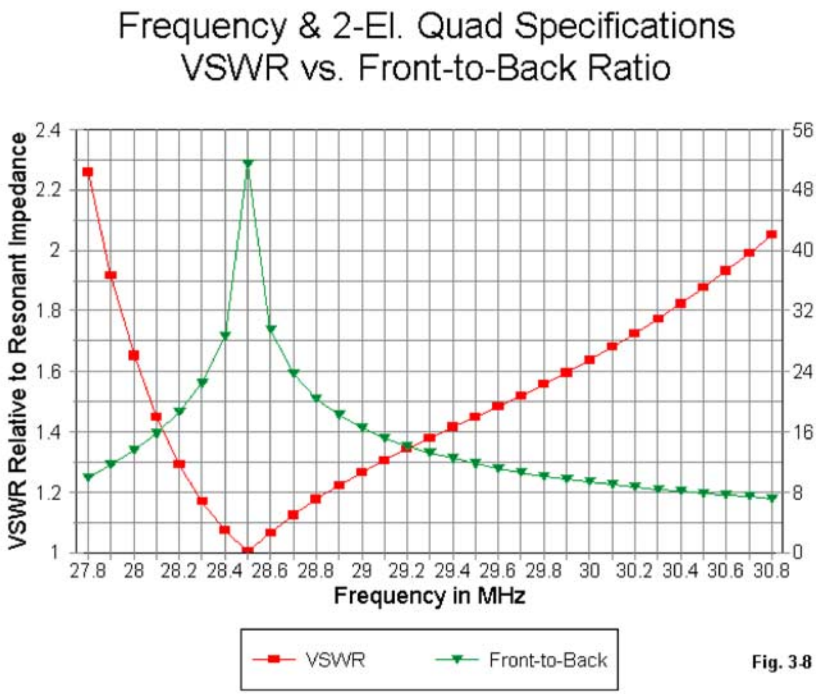



Fig. 3-8

Such a move will likely be beneficial (although minimally so) to the overall front-to-back performance within the passband—for example 28 to 29 MHz. Similarly to the SWR performance, but to a lesser degree, the front-to-back value changes more slowly above the design frequency than below it. From the graph, you may determine that 0.3 MHz above design frequency, the front-to-back ratio is above 20 dB, while 0.3 MHz below design frequency, the value is only about 18.5 dB. In fact, using the span from 28 to 29 MHz as a passband definition, there is a 3 dB difference in the front-to-back ratios at the passband edges.

It is possible from the graph in **Fig. 3-8** to create an illusion—namely, that there is good performance to be had from the antenna above 29 MHz. However, remember that across the passband, the antenna gain is steadily decreasing, and it continues to decrease as we raise the frequency further. By the frequency at which the SWR approaches 2:1 on the high side of the design frequency, the gain has dropped to about 5.5 dBi, and the front-to-back ratio is only about 7.4 dB. At 29.7 MHz, the gain is down to 6 dB, with a front-to-back ratio of about 10.6 dB. Although usable for some purposes, these figures are down considerably from the design frequency values.

The point of the exercise has been to demonstrate the changes in 2-element quad performance as we change wire size. I noted early on that one would have to make some adjustments as we change frequency, since the graphs are calibrated to copper wire. For a better sense of the degree of change, let's sample our 3.16E-4 wavelength diameter wire quad at a number of frequencies. Note that 28.5 MHz is the original design frequency. All of the quads use the same length elements and spacing in terms of fractions of a wavelength.

**Table 3-2. 2-Element Quads at Different Frequencies**

| Frequency MHz | Gain dBi | Front-to-Back Ratio dB | Feedpoint Z R +/- jX Ohms |
|---|---|---|---|
| 3.5 | 7.12 | 45.37 | 136.7 + j 0.4 |
| 28.5 | 7.08 | 51.33 | 137.4 + j 0.2 |
| 144.0 | 7.02 | 47.67 | 138.6 - j 0.1 |
| 223.0 | 6.99 | 43.33 | 139.2 - j 0.3 |

For thinner wire sizes, the variance will be greater, while fatter wires will show less variance.

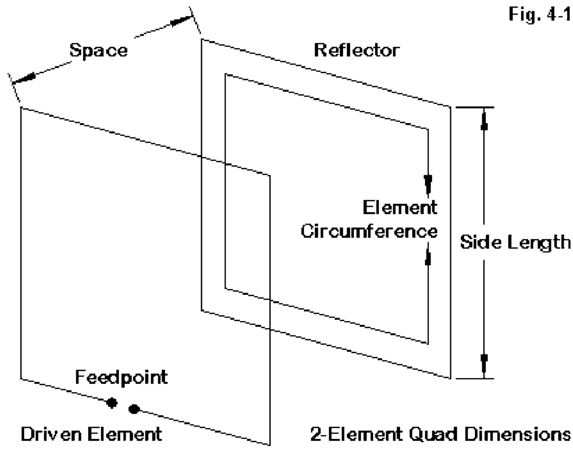
The small range of the variance should tell us two things. First, the general properties of 2-element quads are indeed largely a function of the diameter of the wire we use for the elements. In general, performance—especially the operating bandwidth of most essential performance specifications—improves with the use of larger diameter elements. Unfortunately, this fact is at odds with the conventional ways in which we construct quads. The supporting structure for quad elements will handle thinner wire but certainly not aluminum tubing. However, there are alternative ways of simulating fat elements that make use of wire. Remember that the inter-element coupling is the key contribution of thicker elements. Material losses are secondary. Hence, if we can increase the coupling through the use of light-weight simulated fat elements, we may generally ignore their slightly higher material losses. We shall defer that task to the third part of the chapters on 2-element quads.

Second, the general reliability of the modeling results as we alter frequency gives rise to the possibility of automating the design process. Suppose that we could simply specify a wire size and a design frequency and have a program that will complete all of the remaining electrical design steps. That will be our project for the next chapter.

# Chapter 4
# 2-Element Quads as a Function of Wire Diameter: Automating the Design Process

In Chapter 3, we examined some of the properties of the 2-element monoband quad beam as they emerged from the wire size. For that exercise, we used a series of graphs based on selected models. The models used wire diameters from 3.16E-5 through 1E-2 wavelengths in diameter so that the X-axis of each graph would follow a linear pattern according to the common logarithm. The Y axes of the graphs explored various properties of the beam. The design specification for each model was that the driver should be resonant within +/-1 Ohm of remnant reactance and that the wire dimensions and element spacing should produce a maximum value of 180-degree front-to-back ratio. **Fig. 4-1** shows the salient quad dimensions.

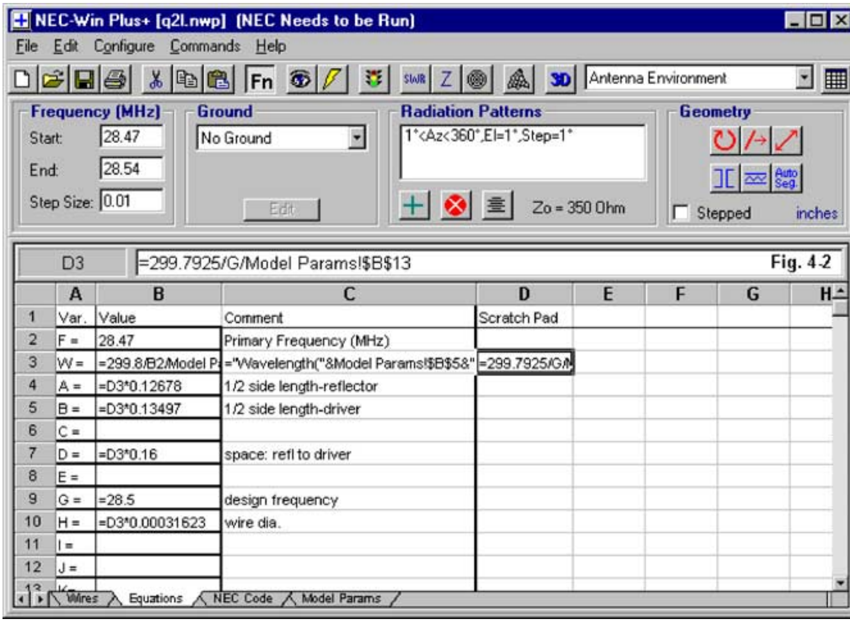
Fig. 4-1




2-Element Quad Dimensions

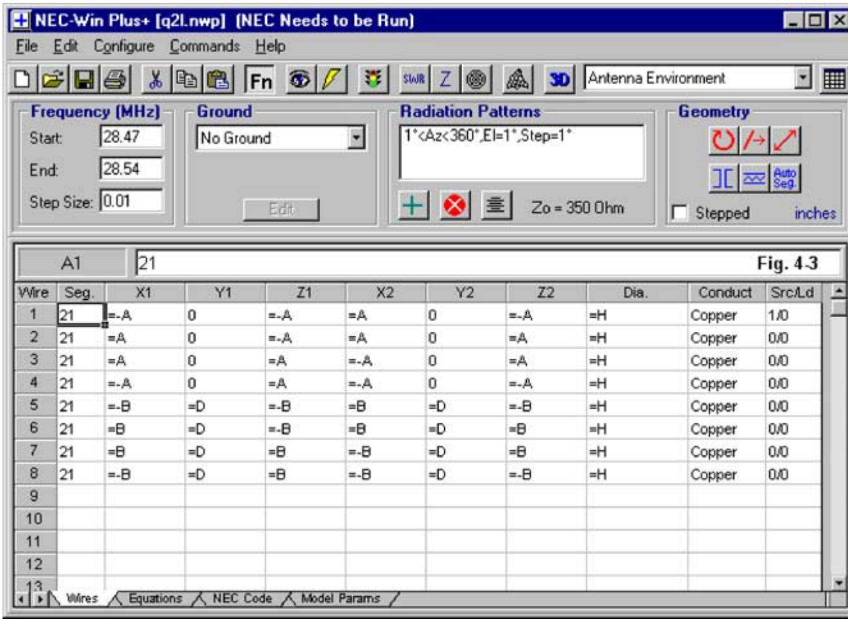
The task of finding suitable beam dimensions was considerably eased by the use of “modeling by equation” techniques. The program used was NEC-Win Plus, but any other NEC-2 or NEC-4 program with a similar facility would work as well. All models used copper wire and were in free space.

**Fig. 4-2** shows the equations page of the model used to explore quad properties. The standard design frequency (variable G) is 28.5 MHz, which is roughly the geometric mean between the lowest HF frequency for which a 2-element quad might be built and the high VHF frequency to be used. By moving the design frequency down from a more perfect 30 MHz, the resulting model beams could be compared more easily to physical beams built for the 10-meter amateur band.




For each wire size selected for variable H (multiplied by the wavelength in cell D3 to provide physical dimensions for the program), it became necessary only to vary three values. A is 1/8 of the driver circumference, while B is 1/8 of the reflector circumference. D is the spacing between elements. As a matter of course, I examined spacing in 0.005 wavelength increments to find highest front-to-back peak and then refined the spacing.

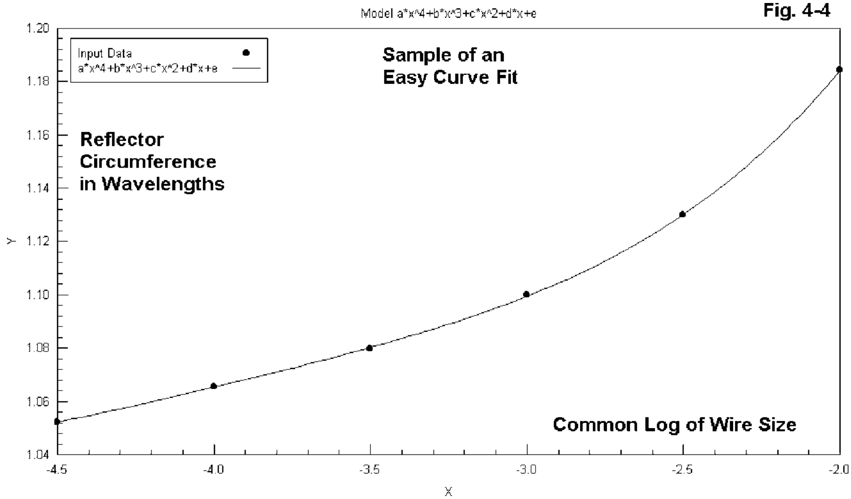
**Fig. 4-3** shows the equations version of the wires page. The wires corresponding to the variables are clear enough. Each model was swept in 0.01 MHz (10 kHz) increments to track the pattern of both resonance and the maximum front-to-back ratio. The closer to resonance, the smaller the change to the driver length variable A. The closer to maximum front-to-back ratio, the smaller the changes to the reflector length variable B. Then the spacing would be changed, with a further zeroing-in exercise until no further improvements could be made.




Note the Radiation Pattern entry. The gain and front-to-back ratio were obtained from a tabular readout. Since I needed only the 90-degree mark for gain and the 270-degree mark for rearward gain, I set the parameters for the radiation pattern to produce only 4 values. This set-up will not yield any usable graphical patterns, but it does simplify scanning the output tables.

From this preliminary work, which one might replicate either in greater detail or for other antennas, I obtained the data points for the graphs in Chapter 3. These graphs are simple "connect-the-dot" constructions that are useful for seeing patterns. However, they do not provide any basis for calculating 2-element quads for other design frequencies.

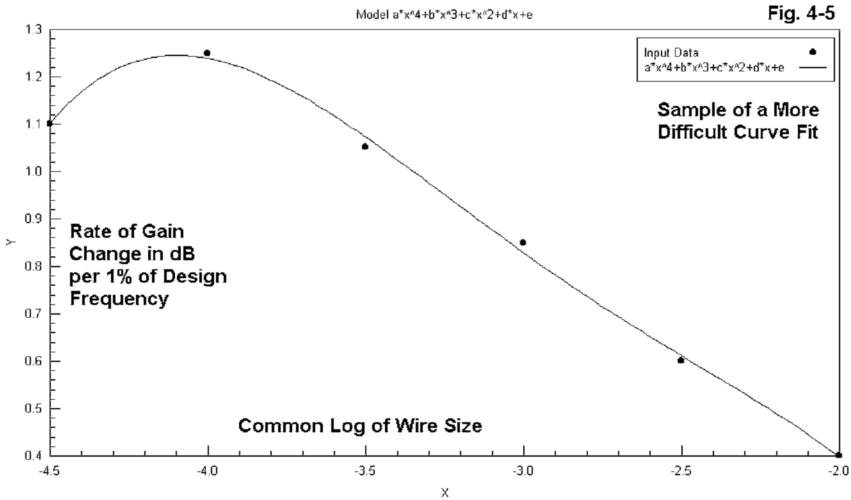
**Fig. 4-4**




I subjected the data obtained from the systematic modeling exercise to regression analysis. At one time, such analysis was painstakingly slow. However, programs like DataFit automate the process, providing both tabular and graphical outputs to test the equations that result. For the 2-element quad, 4th-order equations yielded results that fell within about 0.5% of optimized models throughout the physical wire size limits and the frequency limits of the project, with the exception of very thin wires. Where the common log of the wire diameter in wavelengths was -4 or less, the error rate increases slightly. In all test cases, the resulting model had its resonant frequency and its maximum front-to-back frequency within about 10 kHz of the requested design frequency. These results were judged to be well within the construction variables for most antenna-building situations.

There is a limit to how well regression analysis can track data points. Higher-order equations tend usually (but not always) to provide a better track than lower-order equations. 4th-order equations were the maximum possible with the limited number of data points used. Some data point sequences make easy curve fits for regression analysis. **Fig. 4-4** shows the reflector circumference curve produced by the analysis along with the original data points. A more exacting fit is hard to imagine. However, **Fig. 4-5** shows a more difficult fit between the curve and the data points for the rate of gain change. Although the curve comes close to the data points, the reversal of direction for the thinnest wire makes the shape of the curve peak more open to question. Remember that with the thinnest wire used, the 2-element quad reaches a coincidence between the frequency of maximum gain and the frequency of maximum front-to-back ratio. Hence, the rate of change is less than the next thinnest wire sized used. From 0.0001 wavelength wire diameters onward, the frequency of maximum gain is always lower than the frequency of maximum front-to-back ratio. For the purposes of the advisory approximation, the curve and the regression equation is perfectly adequate.

**Fig. 4-5**




The equations produced by regression analysis are perfectly adequate for calculating all of the data we examined in Part 1 for all points between the listed data points. However, the equations have no inherent theoretic import for electronics or antennas beyond their ability to calculate.

The production of a set of calculating equations does have the merit of allowing one to create a small program in any number of media to automate the design process for 2-element quads that meet the basic specifications (resonance and maximum front-to-back ratio on the design frequency). By specifying the wire size and the design frequency, we can let the program generate the remaining data. Therefore, I produced the following little GW Basic program to do just this task.

```
10 CLS:PRINT “Program to calculate the dimensions of a resonant
   square 2-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”
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 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=.00336#:BD=.04966518519#:CD=.2731955556#:DD=.6716364021#:
ED=1.644147937#
200 DE=(AD*(D1^4))+(BD*(D1^3))+(CD*(D1^2))+(DD*D1)+ED
210 AR=.003173333333#:BR=.0508237037#:CR=.3081977778#:
DR=.8663851852#:ER=2.040064444#
220 RE=(AR*(D1^4))+(BR*(D1^3))+(CR*(D1^2))+(DR*D1)+ER
230 AS=-.003#:BS=-.03551851852#:CS=-.1553055556#:DS=-.2902116402#:
   ES=-.02540079365#
240  SP=(AS*(D1^4))+(BS*(D1^3))+(CS*(D1^2))+(DS*D1)+ES
250  AZ=1.976333333#:BZ=30.84751852#:CZ=172.4909722#:DZ=
   419.5162831#: EZ=519.8747579#
260 ZR=(AZ*(D1^4))+(BZ*(D1^3))+(CZ*(D1^2))+(DZ*D1)+EZ
270 AG=-.06333333333#:BG=-.7203703704#:CG=-3.010277778#: DG=-
   5.381375661#:EG=3.738769841#
280 GN=(AG*(D1^4))+(BG*(D1^3))+(CG*(D1^2))+(DG*D1)+EG
290 AW=1.688666667#:BW=23.76837037#:CW=124.9339444#:
   DW=295.8872328#:EW=281.2755159#
```

```
300 SW=(AW*(D1^4))+(BW*(D1^3))+(CW*(D1^2))+(DW*D1)+EW

310 AF=-.00266666667#:BF=.388#:CF=4.790666667#:DF=19.55485714#:
   EF=28.76628571#
320 FB=(AF*(D1^4))+(BF*(D1^3))+(CF*(D1^2))+(DF*D1)+EF
330 AN=-.08333333333#:BN=-.9462962963#:CN=-3.943055556#: DN=-
   7.582671958#:EN=-5.23234127#
340 DG=(AN*(D1^4))+(BN*(D1^3))+(CN*(D1^2))+(DN*D1)+EN
350 WL=299.7925/F:PRINT "Wavelength in Meters =";WL
360 WF=983.5592/F:PRINT "Wavelength in Feet =";WF
370 PRINT "Quad Dimensions in Wavelengths, Feet, and Meters:"
380 PRINT "Driver Side =";(DE/4);" WL or";(DE/4)*WF;"Feet or";(DE/
   4)*WL;"Meters"
390 PRINT "Driver Circumference =";DE;" WL or";DE*WF;"Feet
   or";DE*WL;"Meters"
400 PRINT "Reflector Side =";(RE/4);" WL or";(RE/4)*WF;"Feet
   or";(RE/4)*WL;"Meters"
410 PRINT "Reflector Circumference =";RE;" WL or";RE*WF;"Feet
   or";RE*WL;"Meters"
420 PRINT "Reflector-Driver Space =";SP;" WL or";SP*WF;"Feet
   or";SP*WL;"Meters"
430 PRINT "Approximate Resonant Feedpoint Impedance =";ZR;"Ohms"
440 PRINT "Approximate Free-Space Gain =";GN;"dBi"
450 PRINT "Approximate 2:1 VSWR Bandwidth =";SW;"% of Design
   Frequency"
460 PRINT "Approximate >20 dB F-B Ratio Bandwidth =";FB;"% of
   Design Frequency"
470 PRINT "Approximate Rate of Gain Change =";DG;"dB per 1% of
   Design Frequency"
480 INPUT "Another Value = 1, Stop = 2: ";P
490 IF P=1 THEN 10 ELSE 500
500 END
```

Line 140 contains something peculiar to GW Basic. "LOG" in GW Basic always mean the natural logarithm. Hence, a conversion factor is necessary to convert the natural log to a common log. 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 does not contain a module to convert AWG wires gauges into physical diameters, so **Table 4-1** may be useful as a set of checkpoints. See Chapter 1 for a full set of values for wires gauges from 1 to 40.

**Table 4-1. Some Common AWG Wires Sizes and Diameters**

| AWG Gauge | Dia. Inches | Dia. mm |
|---|---|---|
| 18 | 0.0403 | 1.0236 |
| 16 | 0.0508 | 1.2903 |
| 14 | 0.0641 | 1.6281 |
| 12 | 0.0808 | 2.0523 |
| 10 | 0.1019 | 2.5883 |
| 8 | 0.1285 | 3.2640 |

**Fig. 4-6** provides a truncated view of the screen data produced by the program. The test case is a 28.5 MHz quad using wire just slightly larger than #18 AWG. Conveniently, the selected wire size is 0.0001 wavelength in diameter. The remaining entries show the calculated data.

2-Element Quad Utility Report (truncated) Fig. 4-6

Desired Frequency: 28.5 MHZ
Wire Diameter in Inches: .04141302"
Wire Diameter in Wavelengths: 0.0001
Driver Side Length: .2526 WL or 8.717 feet or 2.657 meters
Driver Circumference: 1.0103 WL or 34.867 feet or 10.628 meters
Reflector Side Length: .2663 WL or 9.191 feet or 2.802 meters
Reflector Circumference: 1.0653 WL or 36.766 feet or 11.206 meters
Refl-Driver Space: .1557 WL or 5.375 feet or 1.638 meters
Approx. Resonant Feedpoint Impedance: 133.4 Ohms
Approx. Free-Space Gain: 6.99 dBi
Approx. 2:1 VSWR Bandwidth: 7.8% of Design Frequency
Approx. >20 dB Front-to-Back Ratio Bandwidth: 1.7% of Design Frequency
Approx Rate of Gain Change: 1.24 dB per 1% of Design Frequency

The following table parallels the data from the program and from the 28.5 MHz test model that served as the 0.0001 data point. ("DF" means "design frequency.")

**Table 4-2. A Comparison of Calculated and Modeled Data**

| Data | Calculated | Modeled |
|---|---|---|
| Wire dia. in WL | 0.0001(input) | 0.0001(input) |
| Driver circumference in WL | 1.0103 | 1.0106 |
| Refl. circumference in WL | 1.0653 | 1.0656 |
| DE-Refl. Space in WL | 0.1557 | 0.156 |
| Resonant Feedpoint Z in Ohms | 133.4 | 133.9 |
| Free Space Gain in dBi | 6.99 | 6.99 |
| 2:1 VSWR Bandwidth in % of DF | 7.8 | 8.1 |
| >20 dB F-B Ratio Bandwidth in % of DF | 1.71 | 1.67 |
| Rate of Gain Change in dB per 1% of DF | 1.24 | 1.25 |

There are some cautions to be observed in using the program or its equations. At the frequency extremities of the program, that is, at low HF or middle to upper VHF, certain systematic variations will appear between the calculations and actual models of the antenna. They are best illustrated by reference to **Table 4-3** . The 28.5 MHz reference frequency corresponds to the program design frequency and was used in **Table 4-2** above.

**Table 4-3. Variations in Results According to Frequency**

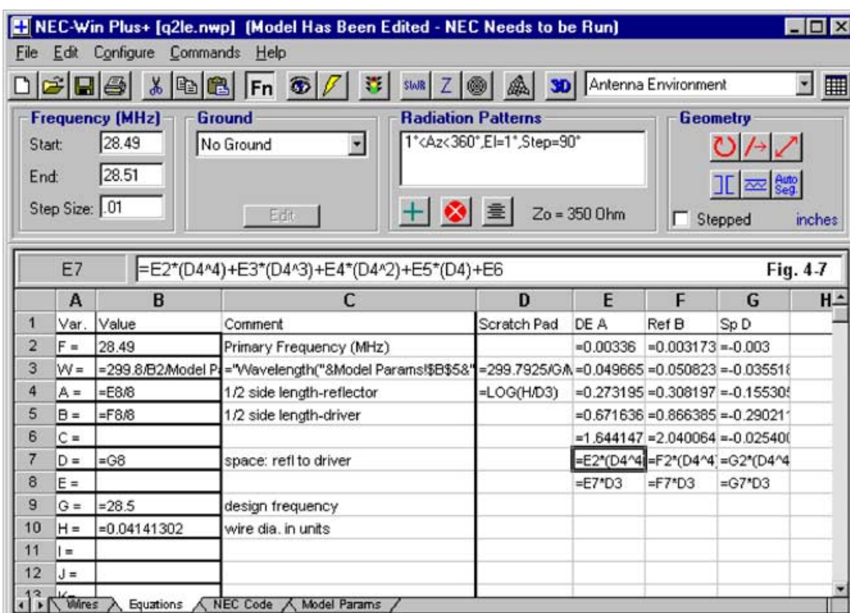
| Frequency MHz | Wire WL | Size Dia. inches | Gain dBi | Feed Z Ohms | Efficiency % |
|---|---|---|---|---|---|
| 3.5 | 0.0001 | 3.372" | 7.12 | 131.3 | 98.82 |
| 28.5 | 0.0001 | 0.414" | 6.99 | 133.4 | 96.69 |
| 144.0 | 0.0001 | 0.0082" | 6.79 | 137.8 | 92.85 |

The rate of change of material losses in real materials does not occur at the same rate as the change in inter-element coupling. NEC calculates efficiency solely on the basis of material losses, which the table shows to increase with frequency if the wire diameter is held constant as a function of a wavelength. Increased material or resistive losses also appear as increases in the source impedance, not to mention small reductions in the antenna gain. Conversely, well below the design frequency, efficiency increases, gain increases, and the source impedance decreases.

Had the program been calibrated for lossless wire, there would have been no difference in the results at any of these frequencies. However, calibrating the program in terms of copper wire provides a more realistic basis for planning. The differences between copper and aluminum will be minimal. It is probably useful to note also that few amateur quads for 80 meters will be constructed from 3.37" diameter wires, and equally few built for 2 meters will use 0.0082" wire (about #32 AWG). Nonetheless, the advice given in Part 1 to use the fattest element diameter possible—or a simulation of a fat wire--remains valid.

For those using a NEC program with a "model by equation" facility, such as NEC-Win Plus, the equations in the GW Basic program can be entered directly into the model itself.

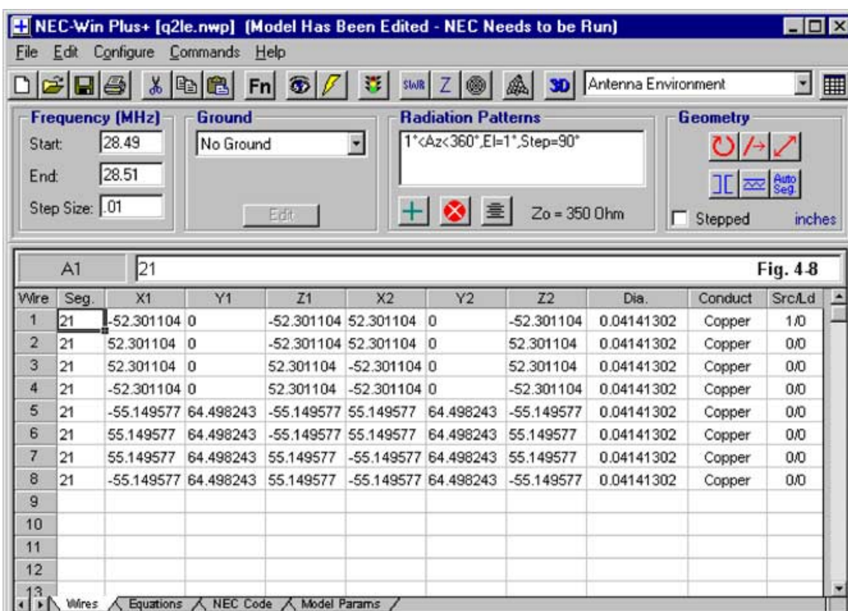
**Fig. 4-7** shows the equations page for such a model. Columns E, F, and G contain the constants and equations for determining variables A, B, and C. Since each final equation (line 7) produces a value for the driver, reflector, and spacing in wavelengths, line 8 converts these values to physical values using the current dimensional units (inches in the figure). Of course, the values for the driver and reflector are for the total circumference, so the required values for A and B are 1/8 of the line 8 numbers.



Although this model has only the dimensional equations entered, there is no reason why one cannot also enter the other equations. The spread sheet is fully functional and has sufficient columns (out of sight to the right) to handle the supplemental calculations. One need only enter the design frequency and the wire size (in current dimensional units) to obtain results for both the model and the supplemental information. (Note that the spreadsheet here does know a LOG from a LN, so the conversion factor has been omitted in column D, line 4.)

Of course, one also needs to attend to the frequency or frequencies for the model, as noted in the upper left corner of the figure. In this case, a sweep of 0.01 MHz each side of the design frequency provides sufficient data to determine the resonant frequency and the frequency of peak front-to-back ratio. The radiation pattern can be modified for a full azimuth pattern, if one needs it.

The model itself appears in dimensional form in **Fig. 4-8**. The dimensions correspond precisely to the output from the Basic program, once one moves from feet to inches or back the other way.




| Wire | Seg. | X1 | Y1 | Z1 | X2 | Y2 | Z2 | Dia. | Conduct | Src/Ld |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 21 | -52.301104 | 0 | -52.301104 | 52.301104 | 0 | -52.301104 | 0.04141302 | Copper | 1/0 |
| 2 | 21 | 52.301104 | 0 | -52.301104 | 52.301104 | 0 | 52.301104 | 0.04141302 | Copper | 0/0 |
| 3 | 21 | 52.301104 | 0 | 52.301104 | -52.301104 | 0 | 52.301104 | 0.04141302 | Copper | 0/0 |
| 4 | 21 | -52.301104 | 0 | 52.301104 | -52.301104 | 0 | -52.301104 | 0.04141302 | Copper | 0/0 |
| 5 | 21 | -55.149577 | 64.498243 | -55.149577 | 55.149577 | 64.498243 | -55.149577 | 0.04141302 | Copper | 0/0 |
| 6 | 21 | 55.149577 | 64.498243 | -55.149577 | 55.149577 | 64.498243 | 55.149577 | 0.04141302 | Copper | 0/0 |
| 7 | 21 | 55.149577 | 64.498243 | 55.149577 | -55.149577 | 64.498243 | 55.149577 | 0.04141302 | Copper | 0/0 |
| 8 | 21 | -55.149577 | 64.498243 | 55.149577 | -55.149577 | 64.498243 | -55.149577 | 0.04141302 | Copper | 0/0 |
| 9 | | | | | | | | | | |
| 10 | | | | | | | | | | |
| 11 | | | | | | | | | | |
| 12 | | | | | | | | | | |
| 13 | | | | | | | | | | |

The model in the figure has been set in order to correspond to our initial design case. However, let's survey a few designs using material that may be more likely at the chosen frequency than the constant 0.0001 wavelength wire we have so far used. In **Table 4-4** below, C means calculated by the program and M means modeled results. In all cases, the reference models on which the program is based show a front-to-back ratio that is greater than 50 dB. Hence, the Front-to-Back column may be used as an indication of program accuracy, understanding that values change very rapidly near the peak. Hence, values of about 40 dB or so indicate a peak within about 10 kHz of the design frequency.

**Table 4-4. Sample Calculated Designs**

| Wire Size (and log) | Frequency MHz | Gain dBi | Feed Z Ohms | F-B Ratio dB |
|---|---|---|---|---|
| 1. #12 20-meters | | | | |
| C 0.0808 (-4.0) | 14.175 | 6.99 | 133.2 | —- |
| M 0.0808 | 14.175 | 7.05 | 132.3 | 41.0 |
| 2. #14 20-meters | | | | |
| C 0.0641 (-4.1) | 14.175 | 6.95 | 131.6 | —- |
| M 0.0641 | 14.175 | 7.04 | 130.3 | 38.1 |
| 3. #14 40-meters | | | | |
| C 0.0641 (-4.4) | 7.15 | 6.76 | 126.2 | —- |
| M 0.0641 | 7.15 | 7.03 | 121.2 | 31.1 |
| 4. #14 6-meters | | | | |
| C 0.0641 (-3.6) | 50.5 | 7.07 | 138.1 | —- |
| M 0.0641 | 50.5 | 7.04 | 138.7 | 47.6 |
| 5. 0.5" 2-meters | | | | |
| C 0.5 (-2.2) | 144 | 7.19 | 149.3 | —- |
| M 0.5 | 144 | 7.18 | 150.0 | 59.6 |

The limitations noted earlier have appeared in full force. Thin wire models tend to show up to 1 to 1.5% errors in some data, while fat wire models come very close to calculated values. The break point falls at about the wire size where the log of the diameter in wavelengths reaches -4. However, the actual frequencies of peak front-to-back ratio are within 10 to 15 kHz of the calculated value. Thin wire models tend to show more rapid decreases in front-to-back ratio relative to the peak value for smaller changes in frequency. Consequently, the calculated values for antenna dimensions would easily fall within construction variables.

Because of the number of variables—especially compared to the one dimensional variable needed for a single quad loop—we cannot expect quite the same precision of result for 2-element quad beams. However, the program can go a long way toward easing the guesswork involved in the construction of these antennas. Given the need for field adjustment and in many cases the likely need to change the resonant frequency to place the SWR curve where we want it, the program should provide more adequate guidance to the 2-element quad builder than almost anything else around.

Before we leave our 2-element bandwidth-optimized quads, let's tackle one more question: can we improve the operating bandwidth of 2-element quads (especially the front-to-back ratio bandwidth) and avoid large, heavy, tubular elements, especially in the HF range? That will be our task in Chapter 5.

# Chapter 5
# 2-Element Quads as a Function of Wire Diameter: Fatter Elements from "Mere Wire"

In Chapter 3, I suggested that there might be a way to simulate large diameter elements in 2-element quads by using wire. The object of the substitution would be to allow the same performance as a thick tubular element without the very high increase in weight associated with such elements. Quad support structures are rarely designed to handle anything but wire.

In this chapter, let's re-examine the reasons for wanting to use fat elements in our quads. Then let's perform a modeling test to see if we can get the simulation to work well.

## Why a Fat-Element Quad?

The simplest way to get a handle on why fatter elements are beneficial to 2-element quads is to examine the performance of a couple of optimized designs. The design frequency will be 28.5 MHz. The design passband will be 28-29 MHz: we shall be interested in performance across that span, and not just at the design frequency.

The element diameters chosen are 0.0641" and 0.5". The thinner wire corresponds to #14 AWG copper wire, perhaps the most popular quad element material used in the U.S. The half-inch size is arbitrary, but sufficiently larger to show major performance differences—differences that can make a difference in operation across the designated passband.

Each beam was designed using the automated program and model presented in Chapter 4. The #14 version uses a spacing of 0.158 wavelength. The driver circumference is 1.012 wavelength long, while the reflector length is 1.071 wavelength. The design frequency resonant impedance is 136.1 Ohms. The 0.5" diameter version requires a spacing of 0.164 wavelength. The driver is 1.020 wavelength long, while the reflector is 1.103 wavelength long. The resonant impedance at the design frequency is 141.1 Ohms.

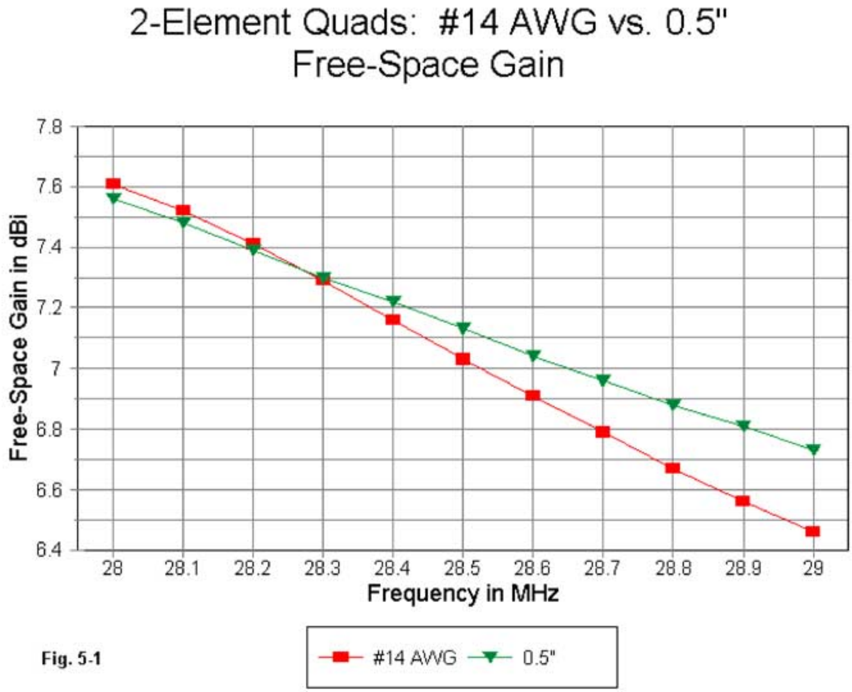



Fig. 5-1

**Fig. 5-1** shows the gain curves for the two quads. As we have noted, the thinner the wire size for a 2-element quad, the closer in frequency are the maximum front-to-back and the maximum gain points. Hence, the #14 quad starts at a higher gain, being closer to the gain peak. However, the gain of the #14 version decreases more rapidly across the passband of interest in this exercise. In contrast, the 0.5" version has a lower rate of change across the band, which tends to even up gain performance between band edges.

If gain were the only parameter in question, then there would likely be no reason to work with fatter elements. However, we should also look carefully at the front-to-back curve, shown in **Fig. 5-2**.

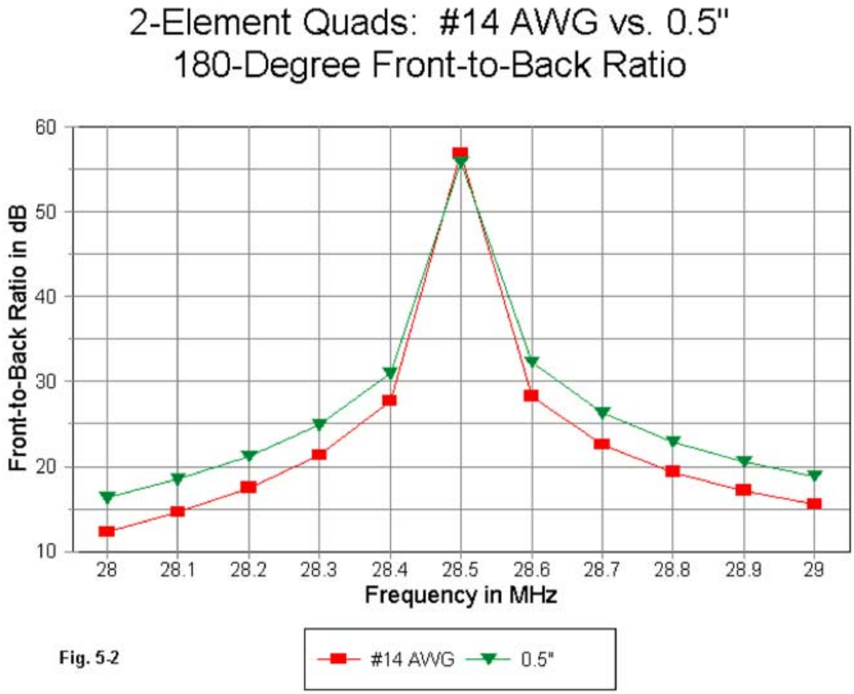



**Fig. 5-2**

It is tempting to focus on the front-to-back peak, which is the same for both antennas. However, of much greater importance is the front-to-back ratio toward the band edges. The front-to-back ratio of the #14 antenna is barely 12 dB at 28 MHz and 16 dB at 29 MHz. 20 dB front-to-back ratio is a common amateur standard. For the #14 version, we achieve this goal only between 28.26 and 28.78 MHz. In contrast, the 0.5" version of the antenna shows better than 20 dB front-to-back ratio between 28.15 and 28.94 MHz, a 50% improvement in bandwidth between the 20-dB markers. At 28 MHz, the 0.5" antenna improves the front-to-back ratio by 4 dB over the #14 version, while at 29 MHz, the improvement is 5 dB.

The operational improvements are sufficiently large to encourage us to try to obtain them. We may not want to go to exceptional lengths mechanically to acquire the improved performance, but if we could modify the standard quad support structure in minor ways, the modifications might be worth the work.

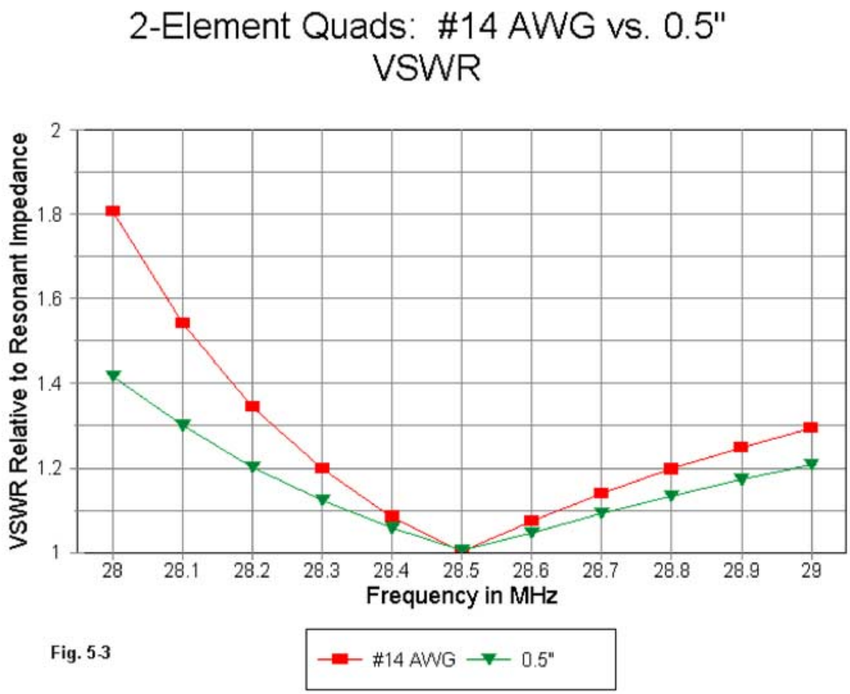



Fig. 5-3

To complete the record, **Fig. 5-3** shows the comparative SWR curves of the two antennas, each referenced to its own resonant feedpoint impedance. Once more, we see the more rapid increase in SWR below design frequency than above it. Since the SWR never reaches 2:1, we might be satisfied with either curve. However, for very long coax runs, the 0.5" curve is superior in reducing line losses.

### How Can We Obtain Fat Element Performance from Wire?

For a "fat" element, we may construct an equivalent element from 2 wires spaced by a distance that is not at all arbitrary. When using relatively thin wire to simulate very thick elements, a three wire scheme may be required, but the transition from #14 to 0.5" on 10 meters is far from needing the added wire.

For linear elements, such as used in Yagis, the technique is simple. We may take each element and find its resonant frequency. Then we construct a wire pair (shorted at the ends and the center) of the same length as the tubular element. We adjust the spacing until we arrive at the same resonant frequency. For most simple arrays of linear elements, the wire spacing used for one element will generally suffice for all of them.

The dual wire element will have a higher material loss than the original tubular element, since its surface area is smaller. However, the performance of a parasitic array depends more upon the inter-element coupling than on material loss (within limits, of course). The dual wire element restores the level of coupling that is reduced in the move from a fat to a thin element. Hence, the modeled performance of Yagis using thick tubular elements and their dual wire equivalents is generally within 0.1 dB gain and indistinguishable with respect to the front-to-back ratio and the impedance curve. These factors apply not only to the design frequency, but as well across the passband.

For 2-element quads, with their closed element geometry, the construction of a 2-wire equivalent requires a different procedure—more of a trial and error technique. Constructing a 2-wire element for each of the quad's elements requires a trial spacing of the wires and then adjustment of the overall loop sizes to bring the antenna to resonance and to maximum front-to-back ratio at the design frequency. The feedpoint impedance at resonance is a good indicator that the wire spacing is correct: it should be about the same as the fat-element antenna being simulated.

There are two main ways to construct dual-wire elements, shown in **Fig. 5-4**.

One method, shown on the left, involves placing a cross-piece at the loop support point—a sort of Tee-configuration. Then, for each element, identical loops are built, spaced by the desired amount. At each corner (minimally), bridge wires between loops are required to ensure that each loop in the element has the same current distribution. The mid-point between loops in each element—where the support arm is—represents the point for measuring the spacing between elements.

The second method is to construct loops in the same plane. This method is illustrated on the right in **Fig. 5-4**. The two loops for each element will have different circumferences, one larger and one smaller than the reference length used to calculate them. Once more, bridge wires are necessary at the corners (at least) to ensure equal current distribution along the wires of each loop. In this planar construction method, each element is a constant distance from the other.

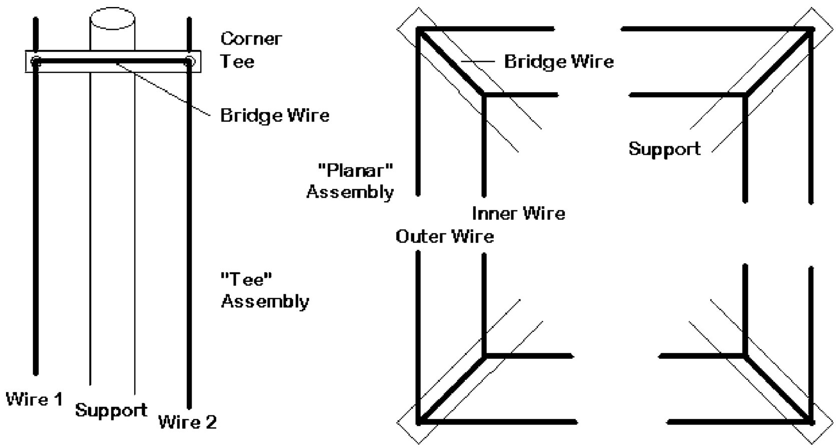



Fig. 5-4

For our test antenna, I finally settled on a wire spacing of 5" for both the Tee and the planar models. To see what is necessary in quad element adjustment for the simulated fat elements, **Table 5-1** may be useful.

**Table 5-1. 2-Wire Quad Dimensions**

| Antenna | #14 Single | 0.5" Single | #14 Tee | #14 Planar |
|---|---|---|---|---|
| Element Spacing | 0.158 wl | 0.164 wl | 0.164 wl | 0.164 wl |
| Driver Length | 1.012 wl | 1.020 wl | 1.003 wl | 1.003 wl |
| Refl. Length | 1.071 wl | 1.103 wl | 1.107 wl | 1.107 wl |
| Res. Impedance | 136.1 Ohms | 141.1 Ohms | 142.1 Ohms | 141.8 Ohms |

For the Tee configuration, the actual spacing is +/- 2.5" for each of the loops. For the planar configuration, the actual loop lengths are 4 x +/- 2.5" for each loop. From the perspective of resonance and maximum front-to-back ratio at the design frequency, it makes no difference whether one uses the Tee or the planar configuration. The results are the same to 4 significant figures, with differences only in the 5th digit for numerical fussiness on my part.

More interesting at this point is the fact that each of the dual-wire antennas requires a smaller driver and a larger reflector than the 0.5" antenna which they simulate. In fact, the dual-wire driver is even smaller than that required for the more closely spaced single #14 antenna. Whether these loop size adjustments will affect performance remains to be seen.

Modeling dual wire elements involves great care. The 5" spacing at 10 meters presses the limits of NEC-2. To ensure equal current distribution in the driver, one must model a single wire of at least three segments, with the source placed at the center. Then, 1-segment wires move at right angles to the center feed wire to the required spacing limit. For 5" spacing, these wires were each 2.5" long. Since NEC prefers that wires meeting at angles have similar segment lengths, 2.5" became the standard segment length for the entire model. The planar model required different levels of segmentation for the inner and outer loops in order to keep the segment junctions parallel with each other. In the end, the models required between 645 and 670 segments. This level of segmentation still provided a large segment length-to-wire diameter ratio, also desirable for accuracy.

Even with such care, the NEC-2 models pressed the core limits for the close spacing of wires. Initial NEC-2 models showed a systematic 0.3 dB gain deficit relative to the 0.5" model. Applying the average gain test in NEC-Win Plus to all of the models produced values of 1.002 for both of the single wire models. However, the dual-wire models yield values 0.969. Values close to 1.000 indicate a precise model within the limits of the test (which is a necessary, but not a sufficient condition of model adequacy). For many general purposes, values as low as 0.96 and as high as 1.04 are considered very good. However, for correlating models, especially when one design is a proposed substitute for the other, the average gain test values were considered inadequate.

The models were reconstructed in NEC-4, which is, while not perfect, considerably better than NEC-2 with respect to close wire situations. Unfortunately, the average gain test was not available in the version of NEC-4 used. However, the gain deficit dropped to 0.1 dB. I suspect, but cannot prove, that the remaining deficit is a function of the core and not a real difference between antennas. (Proof will have to await the next generation of modeling cores.) Part of my suspicion arises from the fact that the dual wire models virtually eliminate material loss as a source of reduced gain. The single #14 wire quad has an efficiency of 97.9% as a function of wire composition, including skin effect. The 0.5" model has an efficiency of 99.7%. Both dial-wire antennas have efficiencies of 99.0%.

We shall look separately at the performance of the Tee and the planar versions of the dual-wire 2-element quad. The reason for separate treatment will become apparent before we are done.

### The Dual-Wire Tee Model

**Fig. 5-5** presents a sketch of the elements of the dual-wire quad in the Tee

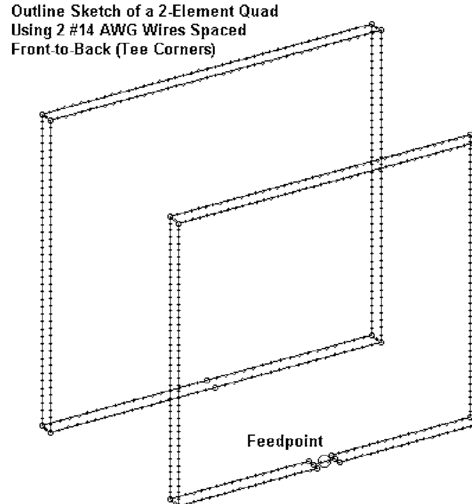



Fig. 5-5

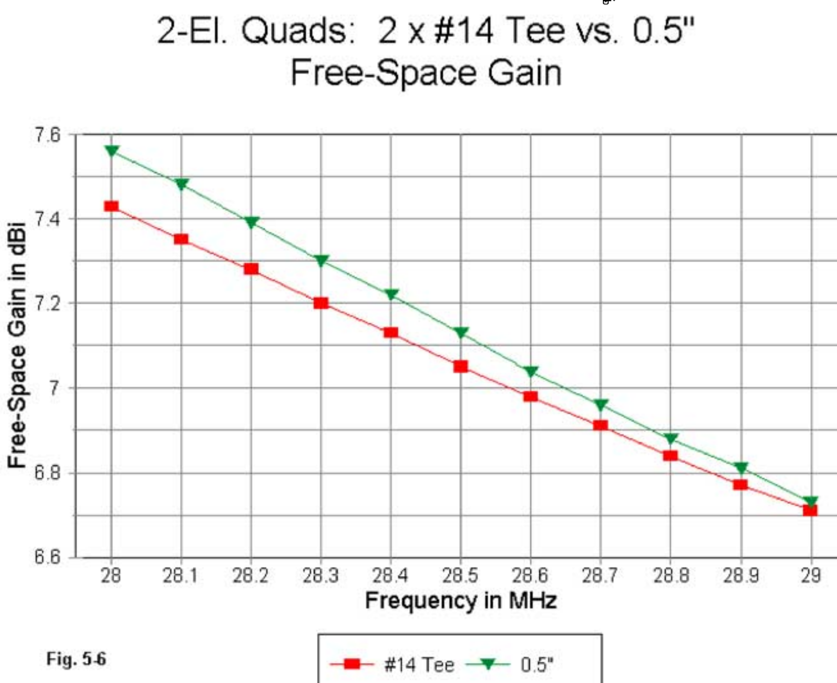



Fig. 5-6

configuration (where "Tee" refers to the unseen supporting structure). The structure, including the feedpoint modeling, is apparent from the sketch.

Since the SWR curve is relatively unimportant to the antenna's performance, we may by-pass that consideration and focus upon gain and front-to-back ratio, compared to the 0.5" antenna which the new version simulates.

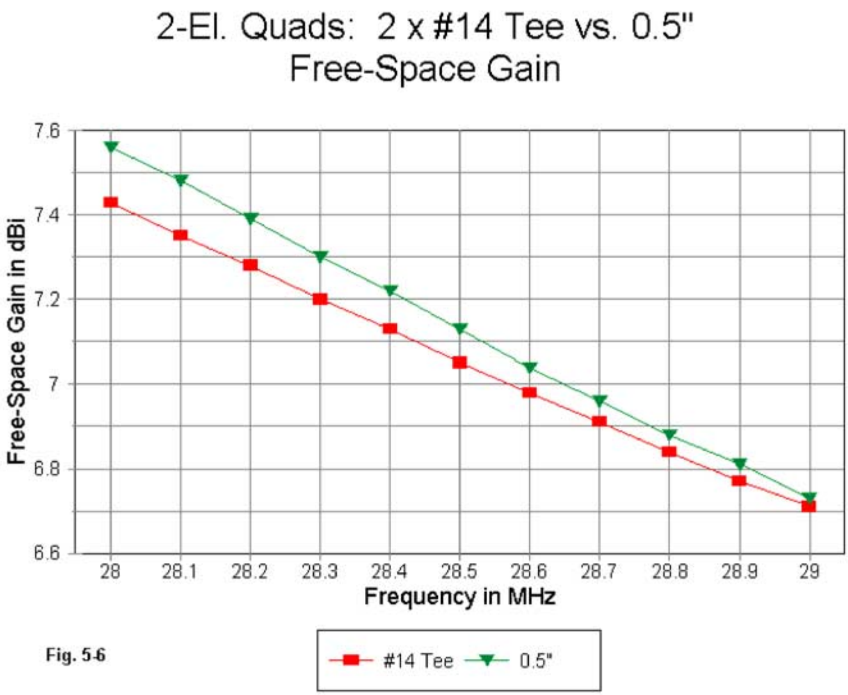



Fig. 5-6

**Fig. 5-6** presents the gain curves across the first MHz of 10 meters for the 0.5" antenna and its counterpart. Of note is the NEC-4 deficit of about 0.1 dB average that we have previously noted. More important however is the shallower curve for the dual wire antenna. The lower rate of change in gain tends to indicate that the 5" spacing between wires is actually simulating a wire somewhat fatter than 0.5".

The impression given by the gain curve in **Fig. 5-6** is confirmed in the front-to-back curve in **Fig. 5-7**. The dual-wire version of the antenna actually increases the passband for better than 20 dB front-to-back ratio from 28.1 to 29.0 MHz. This operating bandwidth is not a function of the very slightly lower peak front-to-back ratio at the design frequency. That difference only indicates that the 0.5" curve is better centered at 28.5 MHz.

With respect to gain and front-to-back ratio, then, there is little to choose between the dual thin-wire and the single fat wire models.

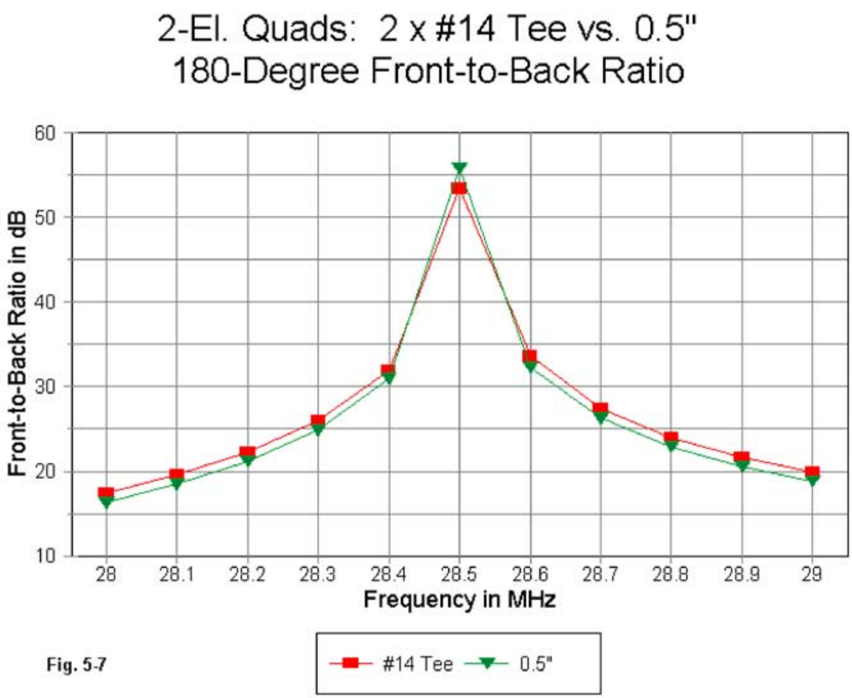



Fig. 5-7

## The Dual-Wire Planar Model

The model construction of the planar configuration of the dual-wire quad appears in **Fig. 5-8**. The construction of an actual planar antenna using the dual wire

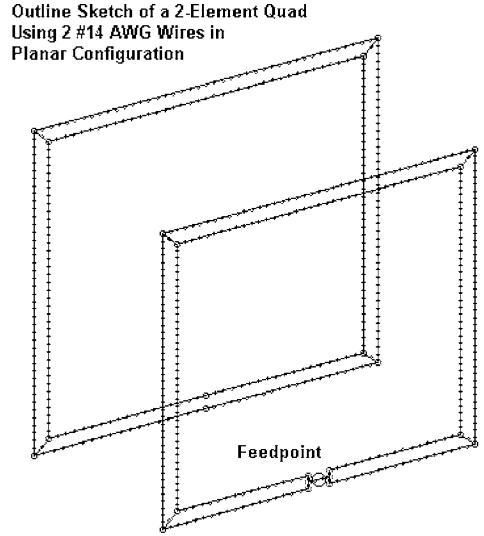


Fig. 5-8

technique should parallel the model closely, especially with respect to the use of bridge wires and the feedpoint area of the driver.

Once more, we shall by-pass the SWR curves and focus our attention on gain and front-to-back performance bandwidths. Graphing these two curves give us a much better view of the array's operating bandwidth than graphing the feedpoint VSWR curve.

**Fig. 5-9** shows the gain curves of the planar model and the 0.5" standard. The planar model shows the same tendency toward a shallower rate of gain decrease across the band than the single 0.5" element model. Interestingly, the planar model begins 0.03 dB lower than the Tee model at 28 MHz, but ends up at the same gain value at 29 MHz.

The front-to-back curve in **Fig. 5-10** shows the same performance spread as the equivalent curve for the Tee—a 28.1 to 29 MHz passband for better than 20 dB front-to-back ratio. By now, it should be apparent why I have presented the Tee and planar curves separately: placed on the same graph, we could not see one through the other.

To illustrate this point, **Fig. 5-11** presents the SWR curves for both dual-wire antennas, along with the curve for the 0.5" model. The Tee and planar curves overlie each other so closely that they are indistinguishable. In fact, for every operating parameter about which we might have concerns, the two versions of the dual-wire antenna are indistinguishable. Moreover, the curves also suggest one more time that the dual-wire antennas have a broader operating bandwidth in every important way than the 0.5" model for which they are a substitute.

Finding the exact wire spacing to be a precise substitute for the 0.5" element model would have been an exercise in unwarranted fussiness. 5" is a nice round number and convenient for modeling. #12 AWG wire (.0808" diameter) would have yielded a different dual-wire spacing for the same equivalence to a 0.5" single element. However, the more likely course of further experimentation should be to find the spacing (in easy-to-handle numbers) that yields a true minimum front-to-back ratio of 20 dB across the entire 1 MHz span of 10 meters.

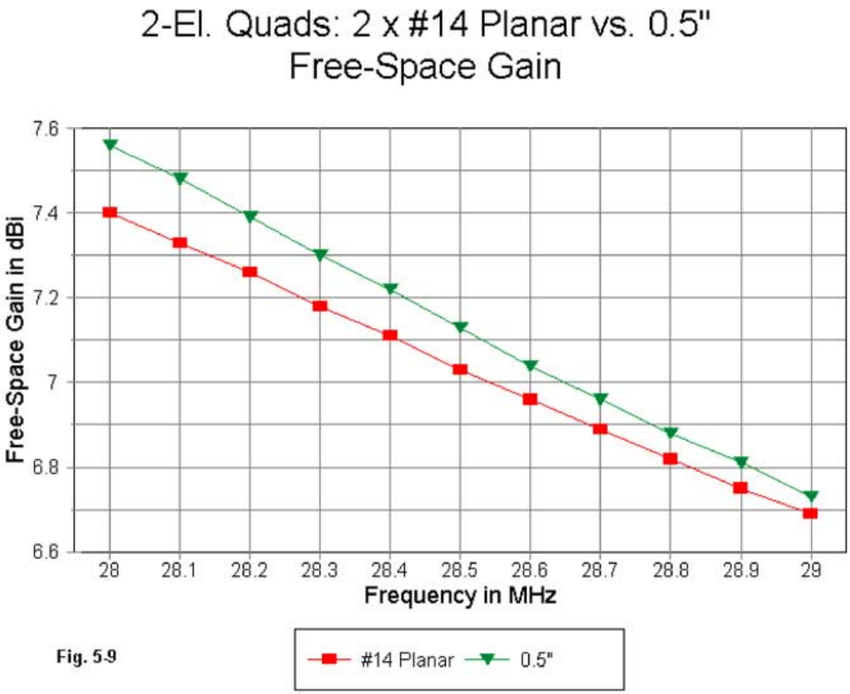



Fig. 5.9

The present exercise has been aimed at establishing the principles of dual-wire simulation of fat-wire elements in the optimized 2-element quad. I suspect that the wider bandwidth of performance with the 5" spacing suggests that a slightly wider element spacing might show further gains. However, that increase would be of the order of 0.001 wavelength for a total spacing of 0.165 wl at the design frequency. Such differences would likely be lost in the variables of actual antenna construction.

More significant to antenna construction are the physical consideration of choosing the planar or Tee models. Initially, the planar version seems more appealing, since it requires fewer parts. There is no need for fixing the Tee support to the main support arm. The absence of any significant difference between the Tee and planar model performance suggests that the planar model would perform equally well on either of the two main types of quad construction: the use of a spider hub and slanting support arms or the use of a boom with flat-plane support arm structures. The only possible deficit for the planar model is the need to have loops for each element that have different circumferences.

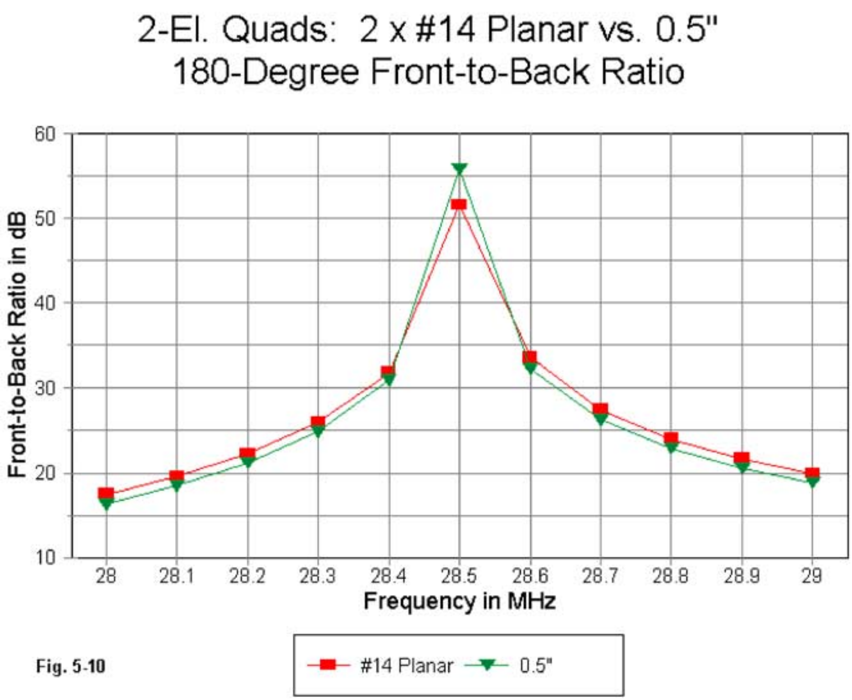



Fig. 5-10

With proper construction, the dual-wire antennas—especially the planar model—can strengthen the overall assembly for each element by providing dual tensioning of the arms relative to each other. However, by using 2 wires for each element (relative to a narrow banded single #14 wire), we have increased the available wire for ice and snow loading. How the strengthening and the loading potentials balance, one cannot say in the abstract.

The dual-wire technique is not restricted to monoband 2-element quads. It is adaptable to 3-band and 5-band quads. I would suspect that single wire elements would satisfy the needs of the narrower bands—17 and 12 meters. However, the use of dual wire techniques might overcome the fall-off of performance on the wider bands—20, 15, and 10 meters. As well, the inherently wider SWR curve for the dual-wire configuration might overcome some of the interaction between bands that makes a shallow SWR curve difficult to obtain on some bands in some multi-band designs.

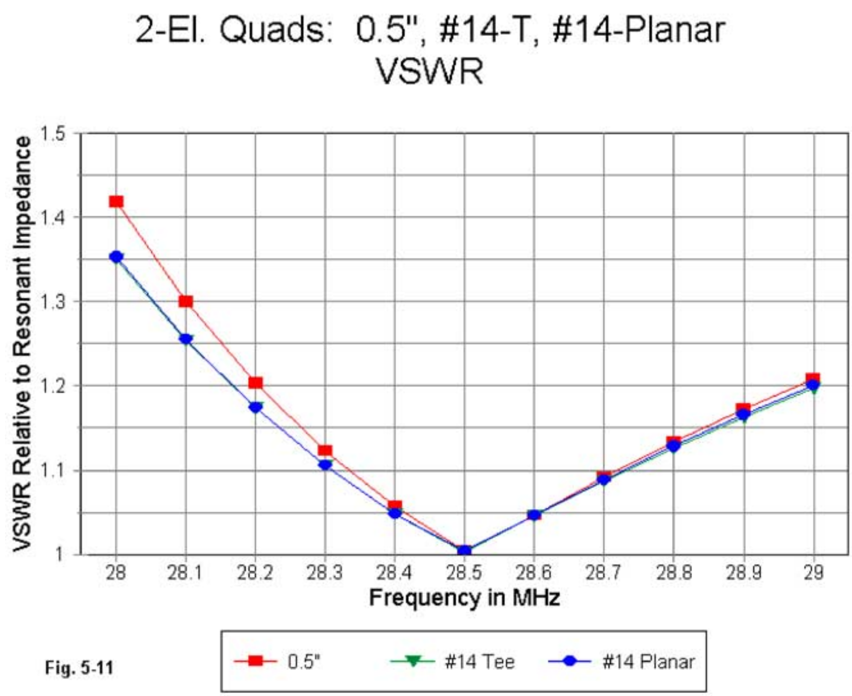



**Fig. 5-11**

The key to a good multi-band 2-element quad employing dual-wire techniques for the wider bands lies in the balance of the support arm strength and the potential for winter loading. The wire weight would be about 60% greater than for single wire designs, with an equal increase in surface area. Hence, before tackling such a task, one would do well to assess the adequacy of the support structure.

In addition, the design of a multi-band 2-element quad using dual wire elements for some bands requires a total redesign of the elements relative to conventional values. Not only must the wire spacing be selected so that the coverage on each band meets design specifications, but as well, the driver and loop sizes must be refigured for the element spacing selected—along with the spacing between elements.

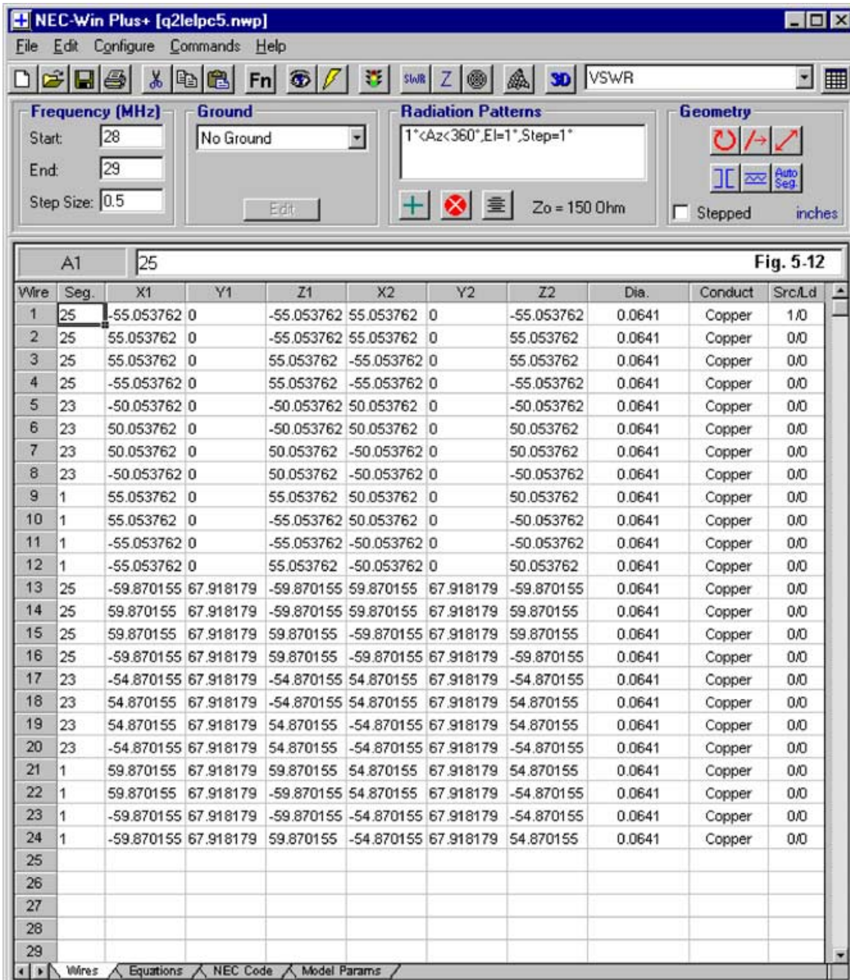
The design task is far from simple. However, it is feasible and may be one way to bring quad design from the 1960s into the new millennium. There is no good reason why quads should not enjoy the same high front-to-back ratios across the ham bands as the Yagis with which they compete.

### An Additional Note on Dual-Wire Gain

The matter of the gain deficit that appeared in NEC-2 models of the dual-wire wider-band 2-element quads continued to disturb me. Even though the final deficit was small in NEC-4 models, I still wondered if there was a way of rebuilding the dual-wire models to eliminate any question of whether the deficit was real or a product of core limitations.

I rebuilt the planar model in the following way: I eliminated the driven element section for the feedpoint and ran both wires continuously from corner to corner. I then placed a source at the center of each lower driver wire to simulate a parallel feed of the two loops. The resulting model could use fewer segments, since the minimum segment size was now about 5" to keep the segment junctions parallel between the inner and outer loops of each element. Slight adjustments of driver and reflector brought the model to the optimal conditions of resonance and maximum front-to-back value. The Average Gain Test in NEC-2 registered 0.9996, a value considered to indicate a highly accurate model.

The resulting frequency sweep with the model on both NEC-2 and NEC-4 yielded an average gain differential of 0.025 dB between cores. At 28.5 MHz, the NEC-2 dual wire model gain is now within 0.06 dB of the 0.5" single wire model. There are no significant differences in the front-to-back and the SWR curves.




| Wire | Seg. | X1 | Y1 | Z1 | X2 | Y2 | Z2 | Dia. | Conduct | Src/Ld |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 25 | -55.053762 | 0 | -55.053762 | 55.053762 | 0 | -55.053762 | 0.0641 | Copper | 1/0 |
| 2 | 25 | 55.053762 | 0 | -55.053762 | 55.053762 | 0 | 55.053762 | 0.0641 | Copper | 0/0 |
| 3 | 25 | 55.053762 | 0 | 55.053762 | -55.053762 | 0 | 55.053762 | 0.0641 | Copper | 0/0 |
| 4 | 25 | -55.053762 | 0 | 55.053762 | -55.053762 | 0 | -55.053762 | 0.0641 | Copper | 0/0 |
| 5 | 23 | -50.053762 | 0 | -50.053762 | 50.053762 | 0 | -50.053762 | 0.0641 | Copper | 0/0 |
| 6 | 23 | 50.053762 | 0 | -50.053762 | 50.053762 | 0 | 50.053762 | 0.0641 | Copper | 0/0 |
| 7 | 23 | 50.053762 | 0 | 50.053762 | -50.053762 | 0 | 50.053762 | 0.0641 | Copper | 0/0 |
| 8 | 23 | -50.053762 | 0 | 50.053762 | -50.053762 | 0 | -50.053762 | 0.0641 | Copper | 0/0 |
| 9 | 1 | 55.053762 | 0 | 55.053762 | 50.053762 | 0 | 50.053762 | 0.0641 | Copper | 0/0 |
| 10 | 1 | 55.053762 | 0 | -55.053762 | 50.053762 | 0 | -50.053762 | 0.0641 | Copper | 0/0 |
| 11 | 1 | -55.053762 | 0 | -55.053762 | -50.053762 | 0 | -50.053762 | 0.0641 | Copper | 0/0 |
| 12 | 1 | -55.053762 | 0 | 55.053762 | -50.053762 | 0 | 50.053762 | 0.0641 | Copper | 0/0 |
| 13 | 25 | -59.870155 | 67.918179 | -59.870155 | 59.870155 | 67.918179 | -59.870155 | 0.0641 | Copper | 0/0 |
| 14 | 25 | 59.870155 | 67.918179 | -59.870155 | 59.870155 | 67.918179 | 59.870155 | 0.0641 | Copper | 0/0 |
| 15 | 25 | 59.870155 | 67.918179 | 59.870155 | -59.870155 | 67.918179 | 59.870155 | 0.0641 | Copper | 0/0 |
| 16 | 25 | -59.870155 | 67.918179 | 59.870155 | -59.870155 | 67.918179 | -59.870155 | 0.0641 | Copper | 0/0 |
| 17 | 23 | -54.870155 | 67.918179 | -54.870155 | 54.870155 | 67.918179 | -54.870155 | 0.0641 | Copper | 0/0 |
| 18 | 23 | 54.870155 | 67.918179 | -54.870155 | 54.870155 | 67.918179 | 54.870155 | 0.0641 | Copper | 0/0 |
| 19 | 23 | 54.870155 | 67.918179 | 54.870155 | -54.870155 | 67.918179 | 54.870155 | 0.0641 | Copper | 0/0 |
| 20 | 23 | -54.870155 | 67.918179 | 54.870155 | -54.870155 | 67.918179 | -54.870155 | 0.0641 | Copper | 0/0 |
| 21 | 1 | 59.870155 | 67.918179 | 59.870155 | 54.870155 | 67.918179 | 54.870155 | 0.0641 | Copper | 0/0 |
| 22 | 1 | 59.870155 | 67.918179 | -59.870155 | 54.870155 | 67.918179 | -54.870155 | 0.0641 | Copper | 0/0 |
| 23 | 1 | -59.870155 | 67.918179 | -59.870155 | -54.870155 | 67.918179 | -54.870155 | 0.0641 | Copper | 0/0 |
| 24 | 1 | -59.870155 | 67.918179 | 59.870155 | -54.870155 | 67.918179 | 54.870155 | 0.0641 | Copper | 0/0 |
| 25 | | | | | | | | | | |
| 26 | | | | | | | | | | |
| 27 | | | | | | | | | | |
| 28 | | | | | | | | | | |
| 29 | | | | | | | | | | |

**Fig. 5-12** shows the wire geometry of the final model. Wires 1-8 and 13-20 are the element loops, with wires 9-12 and 21-24 being the corner links. These links are crucial to maintaining symmetrical currents in the elements, both in the model and in a physical quad built to these specifications. In fact, additional interloop links would be in order for a physical quad.

The source can be handled in one of two ways. One may place two sources on the model, one at the center segment of each bottom driver loop wire. The impedance for the array then becomes the solution to a parallel impedance problem. Treating the resistive and reactive components separately, one may take the reciprocal of each resistive value and add them, finally taking the reciprocal of the result. Do the same for the reactive components.

Alternatively, you may connect a very short (for example, 1") transmission line with a characteristic impedance close to the value on one of the parallel sources (for example, 300 Ohms in this case) between the two parallel source segments. Then, eliminate one of the original parallel sources. The single reported impedance will be within 0.5% of the value calculated from the dual sources.

The **Table 5-2** summarizes the differences between the original and the alternative models at the design frequency. NEC-2 performance figures are shown.

**Table 5-2. Planar 2-Wire Design Differences**

| Model | Original Planar | Alternate Planar | 0.5" |
|---|---|---|---|
| Free-space gain | 6.92 dBi | 7.07 dBi | 7.13 dBi |
| Max. front-to-back | 51.56 dB | 49.44 dB | 55.82 dB |
| Feedpoint impedance | 141.8 + j0.5Ω | 141.7 - j0.2Ω | 141.1 - j0.5Ω |
| Driver Length | 1.003 wl | 1.015 wl | 1.020 wl |
| Reflector Length | 1.107 wl | 1.108 wl | 1.103 wl |
| Spacing | 0.164 wl | 0.164 wl | 0.164 wl |

The differential in reflector length is under 0.1% and makes no difference in operation. The driver length difference between the original and alternate models is about 1.2%, but falls within the range of field adjustments, since the builder may wish to alter the frequency of resonance within the passband. The feedpoint impedances are identical well beyond any possibility of measuring a difference.

The disadvantage of using the alternate model is the requirement to calculate the parallel combination of series R+/-jX impedances for the two loops or to use the transmission-line connector between the sources. However, the simplification of the model, the higher AGT rating, and the far better agreement with NEC-4 models all recommend the alternative. The alternative technique also holds some promise of allowing dual wire versions of long boom quad models, since the segmentation per loop is halved relative to the original planar model.

Of course, the alternative model tends to confirm the earlier noted suspicion that there is no significant gain difference—by even minuscule amounts—between the dual-wire quads and the 0.5" single element quad.

## Scaling and Limiting 2-Wire Quads

Scaling a 2-wire design follows the same rules as scaling a design for a 1-wire design. One cannot simply apply the 5" wire spacing used at 10 meters to a 20-meter design and expect it to replicate a scaled version of the 0.5" 10-meter quad. First on the list of problems is that a correctly scaled 20-meter version of the half-inch 10-meter quad would have 1.0" diameter elements.

A correctly scaled 2-wire version of the 10-meter quad would end up with (roughly) double the element lengths, double the spacing between elements, double the spacing between wires, and double the wire diameter. The resulting wire diameter (0.1282") is #8 AWG, a wire size not in general use in quad construction. It weighs about 4 times as much as the more common #14, although much of the weight differential can be eliminated by the use of aluminum wire.

A trial 20-meter quad perfectly scaled for 14.25 MHz covered 14.0 to 14.5 MHz with the same properties as its 10-meter original. The natural tendency is then to see if the same quad can be developed for something like #14 wire, perhaps by spreading the wires further apart. If success includes a peak front-to-back ratio that approaches 50 dB (one of the markers in developing a sequence of maximum band-width 2-element quads), then success will be elusive.

Trial quads using decreasing wires sizes from #10 through #14 showed two tendencies. Initially, a #10 version of the antenna using 13" spacing showed a performance peak at the design frequency (14.25 MHz). However, the maximum attainable front-to-back ratio was only 35.5 dB. The passband edges showed decreases in gain relative to the #8 scaled model. Further decreases in wire size showed additional performance reductions and a decrease in the frequency of peak performance--down to 14.1 MHz for #14 AWG wire, even with optimized spacings that peaked at about 16".

Essentially, the 2-wire technique is limited by a combination of spacing and wire size such that spacing cannot compensate beyond a certain point for decreasing wire surface area. The inter-element coupling becomes insufficient to simulate the original 1" modeled elements. When the designer reaches this point, he has two general options. One is to return to a fatter wire. The other is to model a potential 3-wire substitute for the tubular element.

Despite such limitations, the 2-wire simulation of much fatter and heavier single elements shows some potential for developing quads that have wider operating passbands than traditional single-wire models. Since gain and operating bandwidth are both functions of element diameter in 2-element quads, and since quads are mechanically designed for thin-wire elements, obtaining the highest gain and the widest bandwidth may call for such techniques.

However, these notes have only scratched the surface of the work needed to make such designs routine. Much remains to be done, especially in the area of developing substitute elements using 2, 3, and possibly 4 wires for the mid-to lower HF region. As well, codifying the limitations of each substitute in terms of usable wire size relative to the frequency and basic element diameter of interest remains a task for the future. It is a field for the combined efforts of both experimenters and modelers.

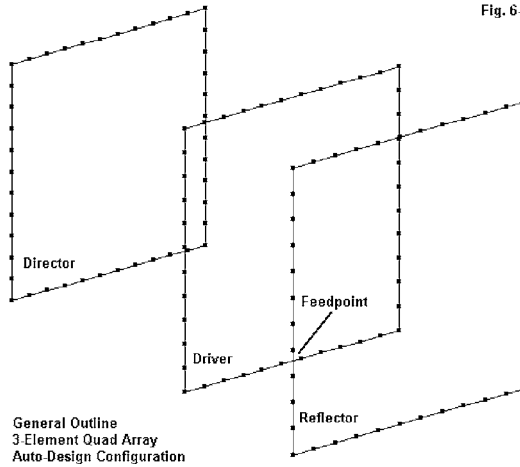
# Chapter 6
# Automating the Design of 3-Element Monoband Quad Beams: A Wide-Band Model

The exercise of automating the design of 2-element quads raised the question of whether a similar technique might be applied to 3-element quads. One answer is in this set of notes. A second answer appears in the next chapter.

For all quads, from 1 to *n* elements, performance depends in large measure upon the diameter of the loop wire as measured in terms of wavelength. Indeed, performance varies with the common logarithm of the wire diameter.

When we automated the design of 2-element quads, we chose as the primary parameter the spacing between elements such that it yielded the highest front-to-back ratio when the array was resonant. The design equations for 3-element quads retain the same feature, using the same progression of spacings between the reflector and the driven element. This selected spacing not only yields the highest front-to-back ratio, but as well it tends to yield the widest operating bandwidth. As we noted in the discussion of 2-element quads, quad array bandwidth is less a matter of the 2:1 SWR bandwidth and more a matter of the >20 dB front-to-back ratio bandwidth.

The director was sized and spaced to yield a good gain with a resonant feedpoint impedance between 70 and 80 Ohms. In general, this procedure does not yield the very highest possible gain or the shortest possible boom length. However, it does produce a very good gain (as judged in quad terms) with the widest possible operating bandwidth. These results are consistent with the conclusions reached in Volume 1 as we explored spot designs of quads and attempted to optimize various operating characteristics. For the design sequence we shall explore in this chapter, the required driver-to-director spacing is nearly double that of the reflector-to-driver spacing. **Fig. 6-1** illustrates the relationships among the elements.




It is certainly possible to emphasize one parameter over another and achieve a different design from the one used in this exercise. In the next chapter, we shall examine a higher-gain model. However, the compromise of gain and operating bandwidth in the version under study here yields a very workable 3-element quad design with boom lengths of about 0.4 wavelengths.

The procedures for developing the design algorithms are the same as for the 2-element quads. I optimized designs in the 10 meter band using wires between 0.0000316 wavelength and 0.01 wavelength. I then subjected the resulting curves to regression analysis to produce a series of equations that can be placed into a modeling program with model-by-equation facilities or into a utility program for simple calculation of dimensions and basic operating data. As I have noted in connection with simpler quad designs, regression equations do not have theoretic significance in and of themselves, but they do yield outputs that model as resonant quad arrays for any wire size within the set limits and for any HF or VHF frequency. As with the 2-element equations, the gain figures tend to be higher than the baseline at lower HF frequencies and lower than the baseline at VHF frequencies, since everything has been calibrated at 10 meters for copper wire elements.

The following GW Basic utility program requires only the entry of the wire size and the design frequency to set the calculations in motion. Refer to Chapter 1 for a correlation between wire diameter and various wire gauges.

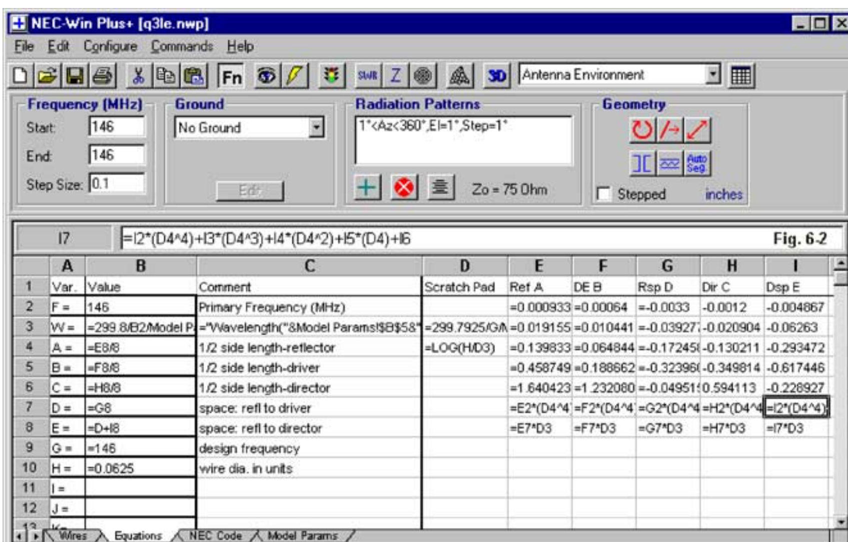
Besides the usual dimensional outputs, the program will also display the wire diameter as a function of a wavelength. The performance data includes the approximate gain at the design frequency, the feedpoint impedance, the 2:1 SWR bandwidth as a percentage of the design frequency, the >20 dB front-to-back bandwidth as a percentage of the design frequency, and the rate of change of gain over a span of 1% of the design frequency. Remember that the line with the “LOG” entry is, for GW Basic, a natural log and requires a correction factor to create a common log. If you translate the program to another medium, you can drop the conversion factor if the medium recognizes common logs.

```
10 CLS:PRINT "Program to calculate the dimensions of a resonant
   square 3-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"
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=.00064:BD=.01044148148#:CD=.06484444444#:DD=.1886626455#:
   ED=1.232080635#
200 DE=(AD*(D1^4))+(BD*(D1^3))+(CD*(D1^2))+(DD*D1)+ED
210 AR=.0009333333333#:BR=.01915555556#:CR=.13983333333#:
   DR=.4587492063#:ER=1.64042381#
220 RE=(AR*(D1^4))+(BR*(D1^3))+(CR*(D1^2))+(DR*D1)+ER
230 AI=-.0012#:BI=-.0209037037#:CI=-.13021111111#:DI=-
   .3498137566#:EI=.5941126984#
240 IR=(AI*(D1^4))+(BI*(D1^3))+(CI*(D1^2))+(DI*D1)+EI
250 AS=-.0033#:BS=-.03927777778#:CS=-.1724583333#:DS=-
   .3239603175#:ES=-.04951547619#
260 SP=(AS*(D1^4))+(BS*(D1^3))+(CS*(D1^2))+(DS*D1)+ES
```

```
270 AP=-.004866666667#:BP=-.06262962963#:CP=-.29347222222#: DP=-
   .6174457672#:EP=-.2289269841#
280 IP=(AP*(D1^4))+(BP*(D1^3))+(CP*(D1^2))+(DP*D1)+EP
290 AZ=-2.227066667#:BZ=-26.75247407#:CZ=-115.9142556#: DZ=-
217.8183323#:EZ=-79.59203175#
300 ZR=(AZ*(D1^4))+(BZ*(D1^3))+(CZ*(D1^2))+(DZ*D1)+EZ
310 AG=-.07#:BG=-.7877777778#:CG=-3.350833333#:DG=-6.143888889#:
   EG=5.104166667#
320 GN=(AG*(D1^4))+(BG*(D1^3))+(CG*(D1^2))+(DG*D1)+EG
330 AW=-.05847333333#:BW=-.5028392593#:CW=-.4586494444#:
   DW=6.080227037#:EW=17.61091389#
340 SW=(AW*(D1^4))+(BW*(D1^3))+(CW*(D1^2))+(DW*D1)+EW
350 AF=.11695666667#:BF=1.717985556#:CF=9.6510925#:DF=
   25.23848992#: EF=27.78167988#
360 FB=(AF*(D1^4))+(BF*(D1^3))+(CF*(D1^2))+(DF*D1)+EF
370 AN=-.04666666667#:BN=-.5414814815#:CN=-2.302777778#: DN=-
   4.364074074#:EN=-3.092777778#
380 DG=(AN*(D1^4))+(BN*(D1^3))+(CN*(D1^2))+(DN*D1)+EN
390 WL=299.7925/F:PRINT "Wavelength in Meters =";WL;"    ";
400 WF=983.5592/F:PRINT "Wavelength in Feet =";WF
410 PRINT "Quad Dimensions in Wavelengths, Feet, and Meters:"
420 PRINT "Driver Side =";(DE/4);" WL or";(DE/4)*WF;"Feet or";(DE/
   4)*WL;"Meters"
430 PRINT "Driver Circumference =";DE;" WL or";DE*WF;"Feet
   or";DE*WL;"Meters"
440 PRINT "Reflector Side =";(RE/4);" WL or";(RE/4)*WF;"Feet
   or";(RE/4)*WL;"Meters"
450 PRINT "Reflector Circumference =";RE;" WL or";RE*WF;"Feet
   or";RE*WL;"Meters"
460 PRINT "Reflector-Driver Space =";SP;" WL or";SP*WF;"Feet
   or";SP*WL;"Meters"
470 PRINT "Director Side =";(IR/4);" WL or";(IR/4)*WF;"Feet
   or";(IR/4)*WL;"Meters"
480 PRINT "Director Circumference =";IR;" WL or";IR*WF;"Feet
   or";IR*WL;"Meters"
490 PRINT "Director-Driver Space =";IP;" WL or";IP*WF;"Feet
   or";IP*WL;"Meters"
500 PRINT "Approx. Feedpoint Impedance =";ZR;"Ohms   ";
510 PRINT "Free-Space Gain =";GN;"dBi"
520 PRINT "Approximate 2:1 VSWR Bandwidth =";SW;"% of Design
   Frequency"
```

```
530 PRINT "Approximate >20 dB F-B Ratio Bandwidth =";FB;"% of
    Design Frequency"
540 PRINT "Approximate Rate of Gain Change =";DG;"dB per 1% of
    Design Frequency"
550 INPUT "Another Value = 1, Stop = 2: ";P
560 IF P=1 THEN 10 ELSE 570
570 END
```

The dimensional portion of the program can also be placed in a model within a program having model-by-equation facilities. **Fig. 6-2** shows the equations screen for a NEC-Win Plus model of the program, set for a design and test frequency of 146 MHz and a wire diameter of 0.0625". In this spreadsheet arrangement, LOG already means a common logarithm and so the correction factor required by GW Basic is omitted.




Only the design frequency and the wire size need be entered for each design revision. No regression-derived equations for the supplemental data on operating bandwidth is included, although a modeler might easily place those equations into the spreadsheet. The added data in the GW Basic program can be directly derived for any particular design simply by executing the NEC core run of the program. Use the design frequency or a frequency sweep to derive the desired curves.

### Wire Size and 3-Element Quad Performance

The effects of wire size on gain are as vivid for a 3-element quad as for a 2-element quad, as shown in **Fig. 6-3**. In this figure, wire size is listed in wavelengths, using values that translate into a linear progression of the logarithms of the wire sizes. There is well over a dB difference in the gain of arrays using the thinnest wire size and arrays using the fattest wire size. Moreover, the increase in gain over the corresponding 2-element quad also increases with wire size. The thinnest wire size 3-element quad shows a 1.3 dB improvement in gain over a 2-element quad using the same wire, whereas the fattest wire 3-element quad shows a gain improvement of nearly 2 dB over its corresponding 2-element array.

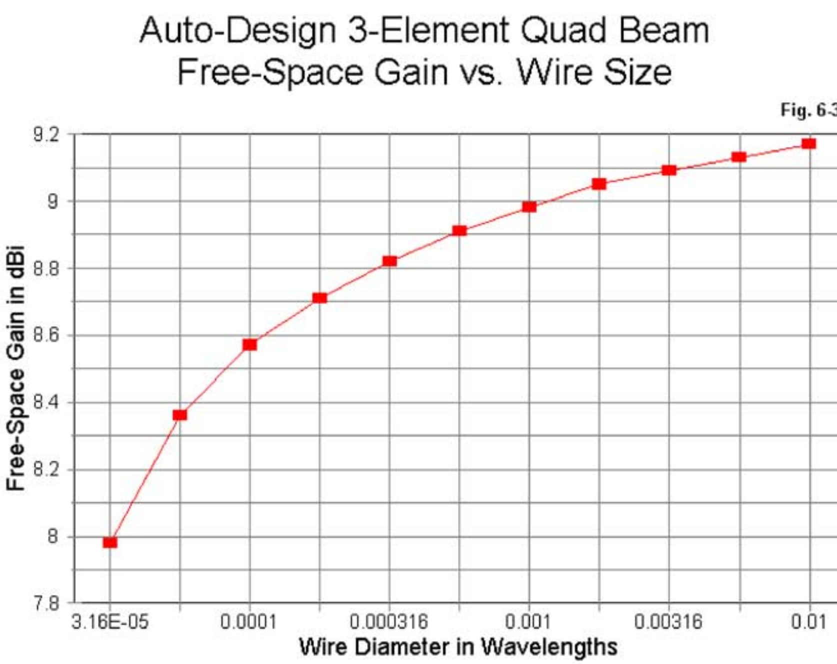
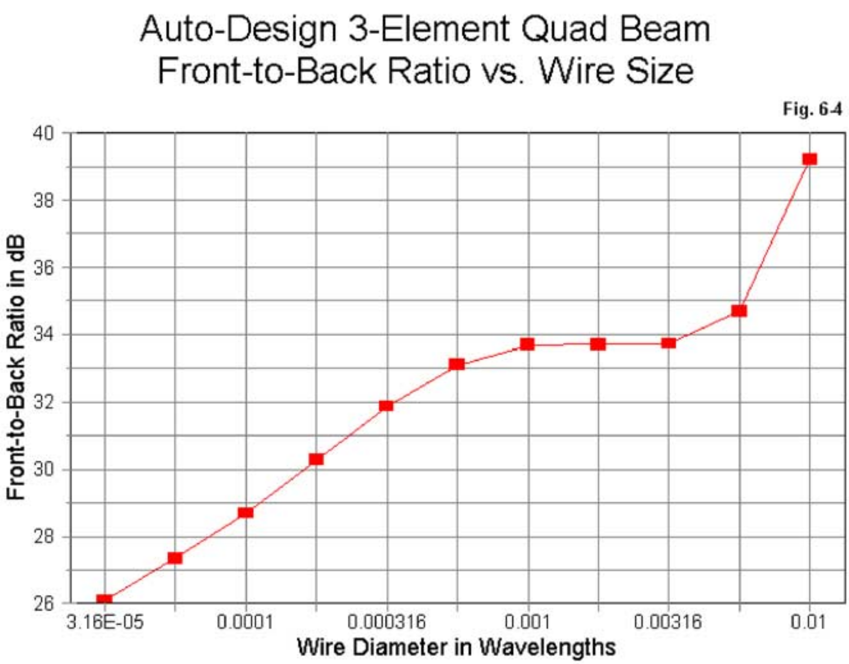


**Fig. 6-4** shows the change of maximum front-to-back ratio with increasing wire size. Theoretically, the curve should be smooth and almost linear across the scale. Since the checkpoint models were hand optimized, allowing the maximum front-to-back ratio to occur as little as 10-15 kHz from the design frequency yields the flat portion of the curve. However, in practice, this slightly less than optimal design curve makes no practical difference, since constructing a quad so that its front-to-back ratio maximum is precisely at the design frequency is more hope than reality. Nevertheless, the increase of both gain and front-to-back ratio with wire diameter demonstrates the importance that wire size has in effecting maximum mutual coupling between quad elements. Thin wire quads of the sort we generally construct at HF with #14 or #12 wire simply are not capable of achieving all of the performance that a quad can provide.




The feedpoint impedances as a function of wire size appear in **Fig. 6-5**. Here, the curve is very real and not a function of optimizing variance. With the thinnest wire, the gain peak and the front-to-back ratio peak are very close together, yielding less than a peak feedpoint impedance value. As the wire size increases, the gain peak occurs well below the design frequency so that the front-to-back maximum value dominates the production of the feedpoint impedance. As a general rule, attempting to construct a 3-element quad with wire sizes less than 0.0001 (1E-4) wavelengths is unwise if one has any hope of obtaining any operating bandwidth from the array. Conversely, those services which operate on specific frequencies are not limited by bandwidth constraints for antenna design. Indeed, in many instances, the narrower the bandwidth of the array, the better the performance in terms of immunity from coupling to nearby arrays that are relatively close in frequency.

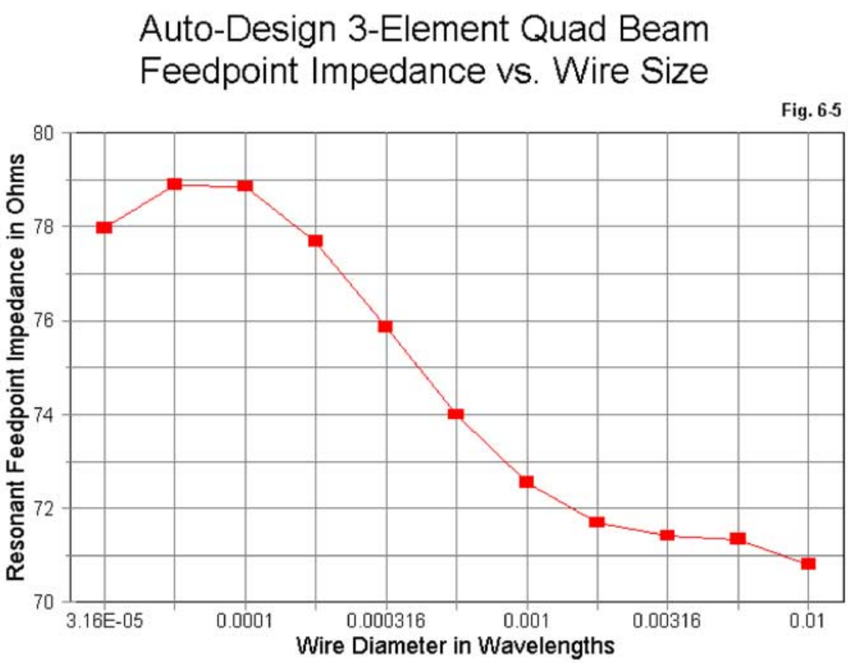
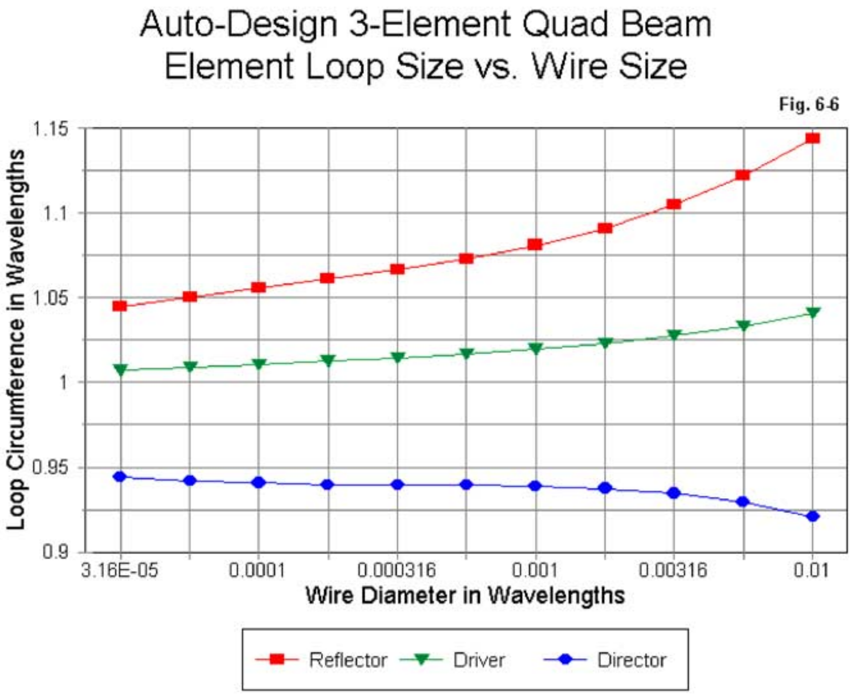


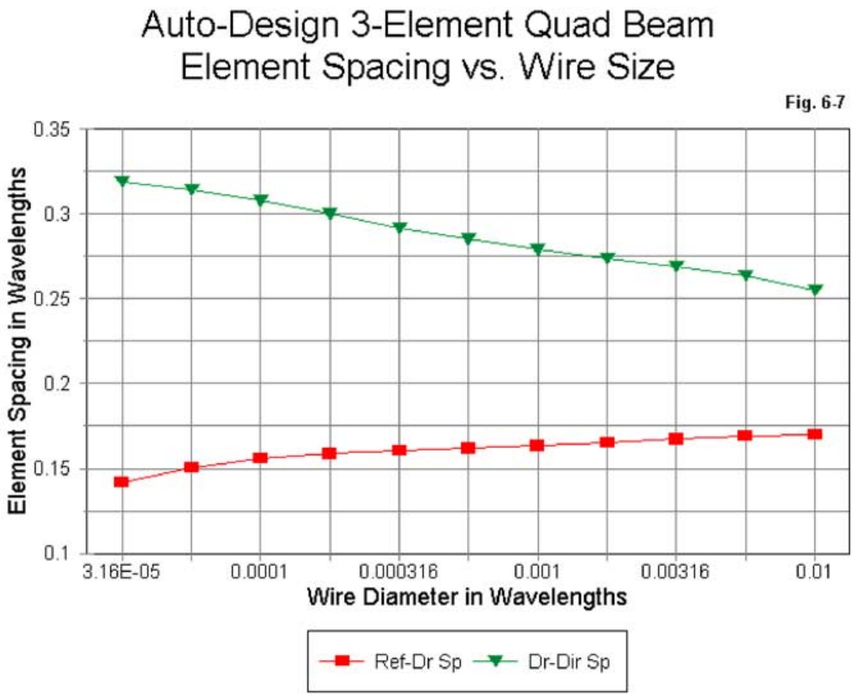

**Fig. 6-6** shows the circumference of each of the 3 elements in wavelengths. As with the 2-element quads, the reflector size increases more rapidly than the

driver size.  However, the required reflector circumference is shorter in the 3-element quad than in the 2-element quad for any given wire size.




Interestingly, the director circumference does not follow the pattern for the other two elements.  As the wire size increases, the required director size decreases.  If we were to normalize the driver circumference so that it graphs as a straight line across the page, the director line would move down at almost the same rate as the reflector line moves up.

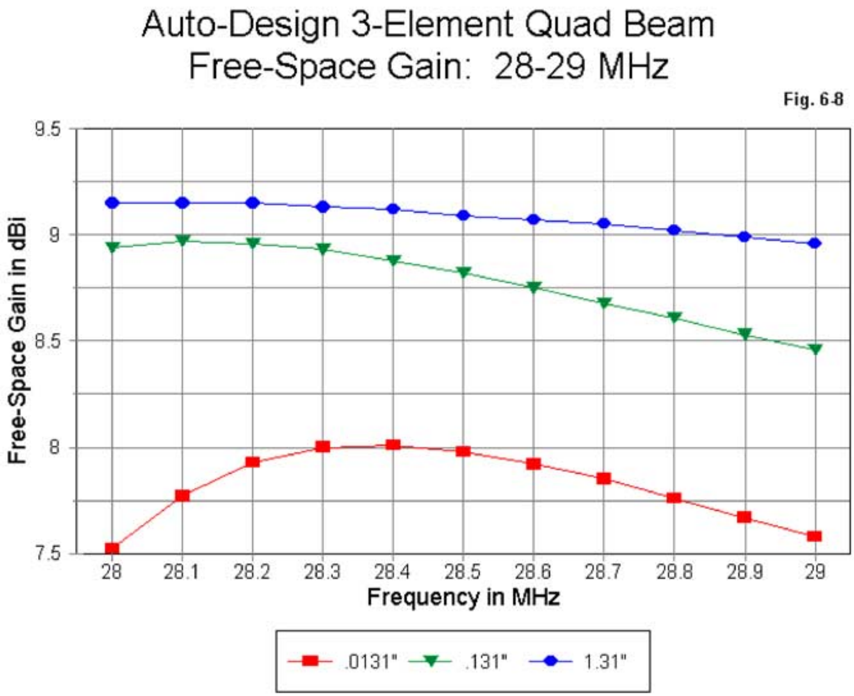
The spacing graphic, in **Fig. 6-7**, gives some precision to the earlier remark that the driver-to-director spacing is about twice the reflector to driver spacing.  In fact, the spacing from the driver to the reflector increases with wire diameter—between about 0.14 and 0.17 wavelength for the span of wire sizes included in the exercise. In contrast, the required director-to-driver spacing decreases with increases in wire size—from about 0.32 wavelength for the smallest wire to about 0.25 wavelength for the fattest wire.




In the antenna modeling version of the GW Basic program, note that the wire spacing equation for the director in the left-most column of the spreadsheet adds the driver-to-director spacing to the reflector-to-driver spacing. This move simply indicates that on wire geometry page, the reflector has been set at zero on the boom with the remaining elements counting in a positive direction for their positions.

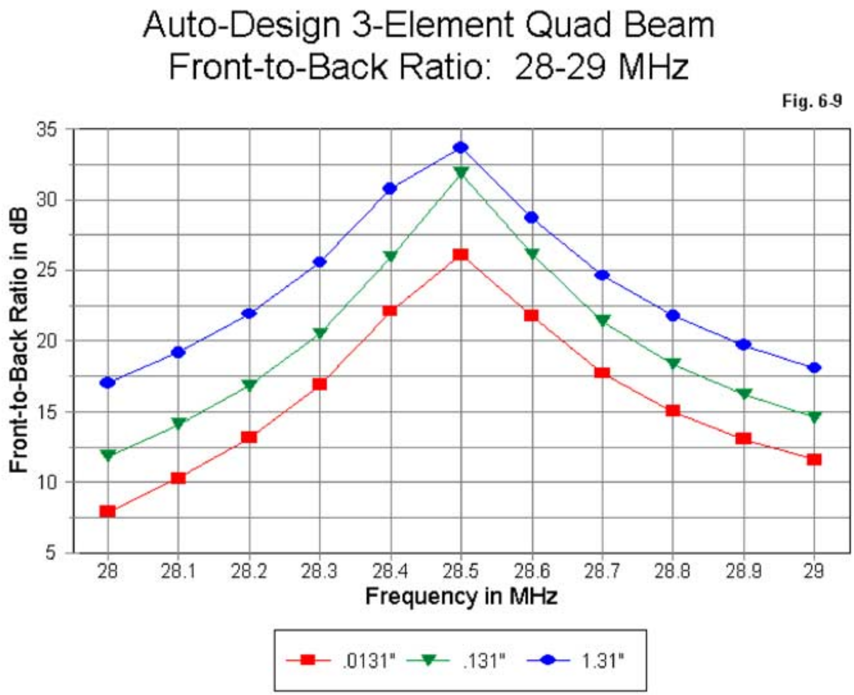
### Sample Frequency Sweeps

The full story of what happens as we change wire sizes becomes much more evident if we perform some frequency sweeps. So I designed quads using three wire sizes: 0.0131" (near to #28 AWG), 0.131" (near to #8 AWG), and 1.31". The design frequency was 28.5 MHz, and the wire sizes correspond to 0.0000316, 0.000316, and 0.00316 wavelength diameters. The frequency sweep used 0.1 MHz intervals from 28 to 29 MHz.



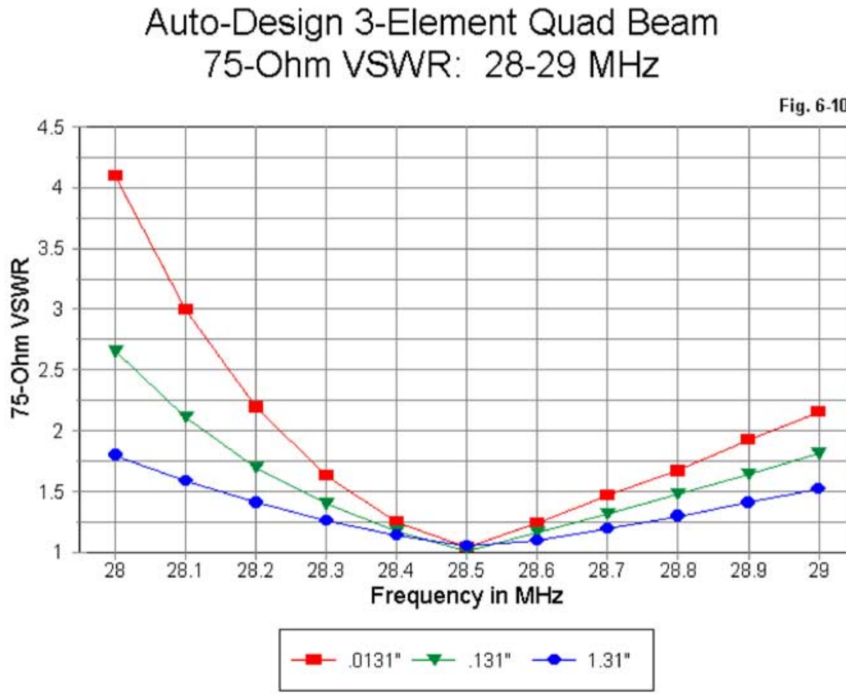

In **Fig. 6-8**, we have the gain curves across the first MHz of 10 meters for the 3 quads. The lowest curve for the thinnest wire shows the gain peak within 0.1 MHz of the design frequency, with a rapid drop in gain at the low end of the band. For the middle-size wire, the gain peak is evident at 28.1 MHz, while for the fattest wire, gain is peak but flat for the first 0.2 MHz of the passband.

Equally evident to the gain advantage of the fattest wire is the very slow rate of gain decrease compared to the thinner wires. The thinner wires show a full half dB variance in gain across the passband, while the range of gain is only 0.2 dB for the fattest wire.




The front-to-back curves in **Fig. 6-9** show several things. First, the slight displacement of the curve for the fattest wire downward in frequency by about 15 kHz corresponds to the flattened portion of the front-to-back curve in **Fig. 6-4**. Apart from that slight offset, the three curves are remarkable congruent with each other. The rates of decrease from the peak are similar for all three curves and are parallel both above and below the design frequency. Finally, note the steeper rate of decrease below design frequency than above design frequency. These curves are fully consistent with those for 2-element quads.

If we select some arbitrary dividing value, such as a 20 dB front-to-back ratio, it is clear that even the fattest wire version of the 3-element quad does not cover all of the 1 MHz passband of the exercise. In this regard, the 3-element quads designed here have slightly narrower front-to-back ratio operating bandwidths than corresponding 2-element models.




A similar narrowing of the operating bandwidth applies to the 2:1 SWR dividing line commonly used to denote acceptable performance, as shown in **Fig. 6-10**. Only the fattest wire model covers the entire passband. By judiciously lowering the resonant frequency of the middle-size wire model, it can be set to show under 2:1 SWR just about all the way across the passband. This fact results from the more rapid rise in SWR below design frequency than above it. Since the entire set of resonant feedpoint impedance is between 70 and 80 Ohms for all wire sizes at the design frequency, all SWR values in the curves are referenced to 75 Ohms.

## Some Sample 3-Element Quad Arrays

To provide a sample of the program's output, here are some dimensions and performance data for a few 3-element quads.

1. 20 meters, #14 wire, design frequency: 14.175 MHz

| | |
|---|---|
| Wire Diameter: | 0.0641" or 7.70E-5 wl |
| Reflector Circumference: | 73.09' |
| Driver Circumference: | 70.06' |
| Director Circumference: | 65.31' |
| Refl-Driver Spacing: | 10.69' |
| Driver-Dir Spacing: | 21.58' |
| Total Boom Length: | 32.27' |
| Feedpoint Impedance: | 79.5 Ohms |
| Free-Space Gain: | 8.47 dBi |
| SWR Bandwidth: | 3.10% or 0.439 MHz |
| >20 dB F-B Bandwidth: | 1.18% or 0.167 MHz |
| Rate of Gain Change: | 0.22 dB/1% of design frequency |

Although the quad array modeled here has an acceptable SWR across all of 20 meters, the front-to-back ratio becomes a limiting factor. On a crowded band such as 20 meters, front-to-back ratio is very often an important antenna design consideration. For most installations, therefore, the antenna would likely be designed for either the CW/digital end of the band or for the phone end of the band.

2. 10 meters, #12 wire, design frequency: 28.5 MHz

| | |
|---|---|
| Wire Diameter: | 0.0808" or 1.95E-4 wl |
| Reflector Circumference: | 36.64' |
| Driver Circumference: | 34.95' |
| Director Circumference: | 32.43' |
| Refl-Driver Spacing: | 5.49' |
| Driver-Dir Spacing: | 10.30' |
| Total Boom Length: | 15.79' |
| Feedpoint Impedance: | 77.2 Ohms |
| Free-Space Gain: | 8.74 dBi |
| SWR Bandwidth: | 3.34% or 0.952 MHz |
| >20 dB F-B Bandwidth: | 1.41% or 0.402 MHz |
| Rate of Gain Change: | 0.21 dB/1% of design frequency |

Let's compare this array with another for the same frequency.

3. 10 meters, 0.5" wire, design frequency: 28.5 MHz

| | |
|---|---|
| Wire Diameter: | 0.5" or 1.21E-3 wl |
| Reflector Circumference: | 37.42' |
| Driver Circumference: | 35.22' |
| Director Circumference: | 32.39' |
| Refl-Driver Spacing: | 5.66' |
| Driver-Dir Spacing: | 9.57' |
| Total Boom Length: | 15.23' |
| Feedpoint Impedance: | 72.3 Ohms |
| Free-Space Gain: | 9.00 dBi |
| SWR Bandwidth: | 4.42% or 1.20 MHz |
| >20 dB F-B Bandwidth: | 2.11% or 0.601 MHz |
| Rate of Gain Change: | 0.10 dB/1% of design frequency |

The 0.5" wire quad shows all of the dimensional characteristics in comparison to the #12 AWG version that we have seen in the curves. As well, 0.5" performance is slightly up, while the feedpoint impedance is slightly down relative to the #12 wire model. Most significantly, the SWR and front-to-back operating bandwidths for the fat-wire model are 30% or more greater than those of the thin-wire array. Of course, it is impractical to consider construction of a quad array for 10 meters that has half-inch diameter elements. However, we shall return to this problem before we close the book on this exercise.

4. 6 meters, 0.25" wire, design frequency: 51 MHz

| | |
|---|---|
| Wire Diameter: | 0.25" or 1.08E-3 wl |
| Reflector Circumference: | 20.87' |
| Driver Circumference: | 19.67' |
| Director Circumference: | 18.10' |
| Refl-Driver Spacing: | 3.16' |
| Driver-Dir Spacing: | 5.37' |
| Total Boom Length: | 8.53' |
| Feedpoint Impedance: | 72.4 Ohms |
| Free-Space Gain: | 8.99 dBi |
| SWR Bandwidth: | 4.14% or 2.11 MHz |
| >20 dB F-B Bandwidth: | 2.05% or 1.05 MHz |
| Rate of Gain Change: | 0.11 dB/1% of design frequency |

The 6-meter version of the 3-element quad is similar in characteristics to the 0.5" 10-meter array, since the wire diameters are similar relative to a wavelength. However, even a wire size of about 0.001 wavelength is insufficient to provide a full front-to-back operating bandwidth for the wide 6-meter band. Elements closer to 1" in diameter would be necessary for this task.

5. 2 meters, 0.1" wire, design frequency: 146 MHz

| | |
|---|---|
| Wire Diameter: | 0.1" or 1.24E-3 wl |
| Reflector Circumference: | 7.31' |
| Driver Circumference: | 6.88' |
| Director Circumference: | 6.32' |
| Refl-Driver Spacing: | 1.11' |
| Driver-Dir Spacing: | 1.87' |
| Total Boom Length: | 2.98' |
| Feedpoint Impedance: | 72.2 Ohms |
| Free-Space Gain: | 9.00 dBi |
| SWR Bandwidth: | 4.24% or 6.19 MHz |
| >20 dB F-B Bandwidth: | 2.19% or 3.20 MHz |
| Rate of Gain Change: | 0.10 dB/1% of design frequency |

The same 4-MHz bandwidth, when moved from 6 to 2 meters, presents less of a problem for a 3-element quad composed of 0.001 wavelength wire. The >20 dB operating bandwidth now covers about 80% of the band. The use of 0.25" wire would easily permit the achievement of all benchmarks across the entire 2-meter band.

Hopefully, these examples will provide some guidance in developing a sense of the requisite wire size to achieve not only a desired gain level, but as well a desired operating bandwidth for 3-element quad arrays of the present design.

## Simulating Large-Diameter Elements

In a past 2-element quad exercise, we looked at the use of spaced #14 AWG wires to simulate fatter single wires. In that effort, we used 2 #14 AWG copper wires spaced 5" apart and joined at the corners. We explored two different configurations and found no significant difference between them. The resulting 2-element quad easily replicated the performance of a 0.5" diameter quad, with a bit to spare. The consequences of substituting 2 thinner wires for one fatter one were a slight enlargement of the reflector and a slight decrease in the driver circumference.

I repeated the exercise for the 3-element 0.5" wire array noted among the examples. Since the number of variables increases with every new element, I restricted my efforts to planar loops, illustrated in **Fig. 6-11**. Note the structure of the planar loops, including the necessary corner wires. Optimizing the model required some further adjustments in director circumference and spacing, since the 2-element array showed the dual-wire version to act like a wire slightly fatter than a half-inch in diameter.

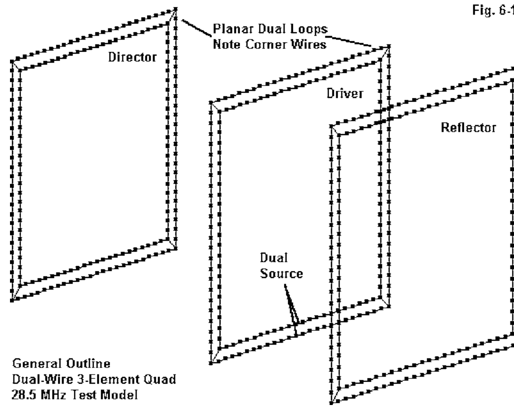


Fig. 6-11

**Table 6-1** provides a comparison of the dimensions (in inches) between the two models. Note that the dimensions for the dual-wire model represent positions halfway between the two wires, so that the actual wire positions are +/- 2.5" relative to the coordinates that would emerge from the listed dimensions.

**Table 6-1. Dimensions of Single and Dual Wire Quads**

| Dimension | 0.5" Single Wire | | 2x#14 AWG Wires | |
|---|---|---|---|---|
| Reflector Circumference: | 449.0" | 1.084 wl | 449.3" | 1.085 wl |
| Driver Circumference: | 422.7" | 1.021 wl | 421.4" | 1.018 wl |
| Director Circumference: | 388.6" | 0.939 wl | 385.3" | 0.930 wl |
| Refl-Driver Spacing: | 67.9" | 0.164 wl | 67.9" | 0.164 wl |
| Driver-Dir Spacing: | 114.8" | 0.277 wl | 111.0" | 0.268 wl |
| Total Boom Length: | 182.7" | 0.441 wl | 178.9" | 0.432 wl |

Although the differences are small, they are significant in arriving at the final operating characteristics of the array. While the dual-wire reflector is slightly larger than the single-wire elements, the dual-wire driver and director are both slightly smaller. As well, the dual-wire director is closer to the driver, resulting in a shorter overall boom length for the array.

Performance for the 3-element dual-wire array parallels that of its 2-element cousin. The model shows slightly less gain at the design frequency, but whether this minuscule gain loss is real or an artifact of the closely spaced wires in the model remains uncertain.

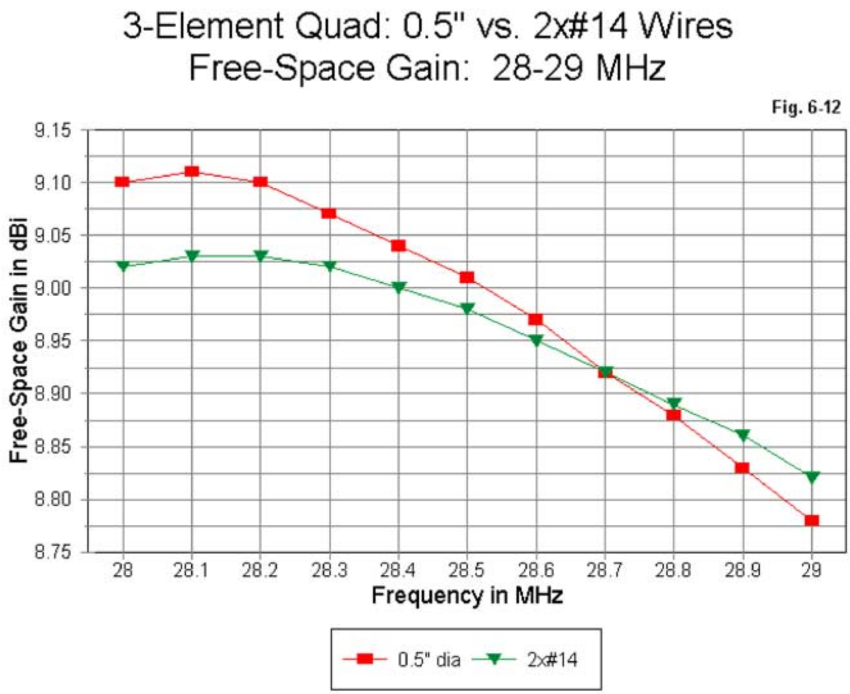
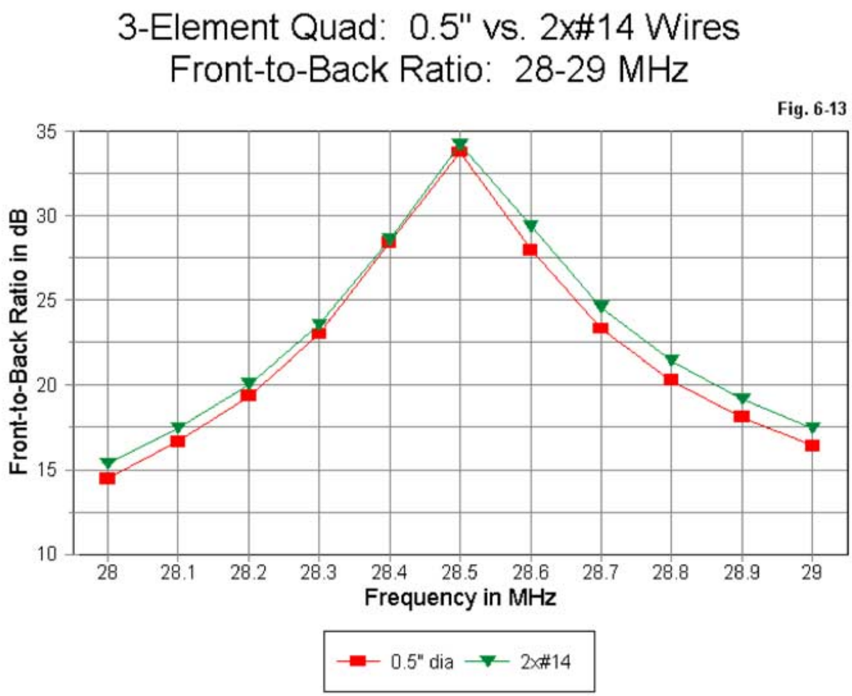



**Fig. 6-12** shows the gain curves for both versions of the array from 28 to 29 MHz. Immediately apparent is the fact that the dual-wire gain decreases more slowly than the single wire gain. Shallower gain curves are generally characteristic of fatter wires with higher overall gain—a fact which contributes to the uncertainty over the slight gain deficit in the dual wire model at the design frequency. However, the gain differences between versions of the antenna would make no operational difference at all.

A second piece of evidence that the 5" spacing of the dual wire model acts similarly to a wire somewhat fatter than the 0.5" model appears in **Fig. 6-13**. The front-to-back curve of the dual-wire version is slightly wider than that of the 0.5" single-wire model. Again, the differences make no operational difference, but their existence is numerically significant in the process of equating dual-wire arrangements with corresponding diameters of single wires.




The slightly broader operating bandwidth of the dual-wire quad over its single fat-wire counterpart is consistent with the results obtained in Chapter 5 for the 2-element quad comparison. The consistency strongly indicates that the technique of replicating fatter wires with multiple strands of thinner wires is not an isolated phenomenon, but is, rather, generally applicable.

Comparing the feedpoint impedances between the two version of the array does not permit an easy chart. The dual-wire model uses a dual feed system of driver wires fed essentially in parallel. Hence, the composite feedpoint impedance required hand calculation. (The short transmission line technique of modeling the dual-wire 3-element quad was not used in this case. It remains applicable, should anyone care to replicate these results.) However, a table (**Table 6-2)** of values may be equally useful in exploring the feedpoint situation. Resistances (R) and reactances (X) are in Ohms.

**Table 6-2. Feedpoint Performance for 1- and 2-Wire Quads**

| Frequency | 0.5" Single Wire | | | 2x#14 AWG Wires | |
|---|---|---|---|---|---|
| MHz | R | X | 75-Ohm SWR | R | X |
| 28.0 | 53.10 | -43.78 | 2.13 | 53.76 | -38.55 |
| 28.1 | 56.78 | -34.52 | 1.80 | 57.97 | -30.44 |
| 28.2 | 60.57 | -25.56 | 1.54 | 60.25 | -22.55 |
| 28.3 | 64.44 | -16.90 | 1.33 | 63.57 | -14.86 |
| 28.4 | 68.33 | - 8.51 | 1.16 | 66.89 | - 7.34 |
| 28.5 | 72.19 | - 0.38 | 1.04 | 70.18 | - 1.01 |
| 28.6 | 75.99 | 7.54 | 1.11 | 73.43 | 7.20 |
| 28.7 | 79.70 | 15.28 | 1.23 | 76.62 | 14.32 |
| 28.8 | 83.31 | 22.89 | 1.36 | 79.73 | 21.36 |
| 28.9 | 86.79 | 30.41 | 1.49 | 82.76 | 28.36 |
| 29.0 | 90.16 | 37.88 | 1.63 | 85.73 | 35.37 |

Both antennas would easily cover the first MHz of 10 meters with a VSWR under 2:1, although the 0.5" model might require a slight adjustment of the driver to bring its resonant point lower in the band. (Such adjustments to the driver, if modest, have no significant effects on the other operating characteristics of the array.)

Besides looking at raw feedpoint impedance values, it is often useful to examine the swing of both resistance and reactance across the passband in question. The dual-wire array changes resistance nearly 14% less than the single-wire model, while the dual-wire reactance changes nearly 10% less. Both numbers are clear indications that the dual-wire system with its 5" spacing represents a single wire that is larger than the 0.5" diameter used for comparison.

The bottom line on the exercise is that a set of dual-wire loops for a quad array can effectively improve 3-element quad performance relative to the customary single #14 AWG quad structure. Even if one discounts the gain advantage of the dual-wire array as operationally marginal, the improvement to both the SWR and front-to-back operating bandwidths is undeniably significant to all except those operators who use only small portions of the wider amateur bands.

The process of converting one of the automated designs to a dual-wire version does require hand-optimization at present. Moreover, as we discovered in Chapter 5, the process is not without limitations. Scaling the 10-meter quad design to 20 meters would yield in the single wire version an element diameter of 1.0". The corresponding scaling of the 2-wire version would require 10" of spacing between wires, and the wires would need to be roughly equivalent to #8 AWG (0.1282"). The designer would have several options. He might use aluminum wire to save weight. Or, he might experiment with a 3-wire #14 AWG substitute for the 20-meter elements. Finally, he might settle for a lesser bandwidth by equating a 2-wire #14 element at 20 meters with a smaller diameter single element. The lesser bandwidth would not affect the SWR bandwidth so much as the front-to-back bandwidth.

Despite these limitations, the automated designs that emerge from the utility program shown in this chapter provide some useful starting points for developing realistic 3-element monoband quad arrays that live up to their theoretical potential. This wide-band design focuses on one potential improvement in quad array performance. In every exercise of the type used here, there is a chance that a slightly different (or perhaps even a radically different) sequence of baseline models would yield even better wide-bandwidth performance at equal or higher gains for a 3-element quad. To this point, there has been insufficient exploration of the fundamental quad element performance factors to blithely guarantee these results as the very best obtainable. I can only note that these results are the best I have been able to obtain so far.

Perhaps the most sound principle used in obtaining the baseline data from which the automated program was obtained is this: for every quad design, there is a sequence of designs that will vary as a function of the element diameter and the original design will have a place in the sequence. How the sequence progresses is a function of which operating characteristics one emphasizes. In this case, maximum operating bandwidth, as defined in terms of front-to-back ratio, became the primary criterion, and a maximum 180-degree front-to-back ratio was used as a marker of this characteristic. Gain and feedpoint impedance became secondary criteria that were optimized to the degree possible without departing significantly from the primary criterion.

Obviously, one might well use a different set of criteria to obtain a baseline data set for a sequence of quad array designs based on element diameter changes. While this chapter has focused on operating bandwidth, the next chapter's high-gain design focuses on another potential for quad arrays.

# Chapter 7
# Automating the Design of 3-Element Monoband Quad Beams: A High-Gain Model

In the first part of this small study on automating the design of 3-element quad beams, we explored a wide-band version of the array—at least, as wide-band a version as we could obtain while still developing reasonably good gain. The results yielded a quite feasible set of potential designs. As with any quad design, the fatter the element used, the better the performance.

Dan Handelsman, N2DT, reviewed an early draft of the initial program and design. He pointed out an alternative design that achieved significantly higher gain, had good front-to-back figures, and had a relatively low feedpoint impedance suitable for a direct 50-Ohm match. The sacrifice in operating bandwidth—as defined by the >20 dB front-to-back ratio rather than the 2:1 VSWR ratio—was still far less than with some other high gain designs.

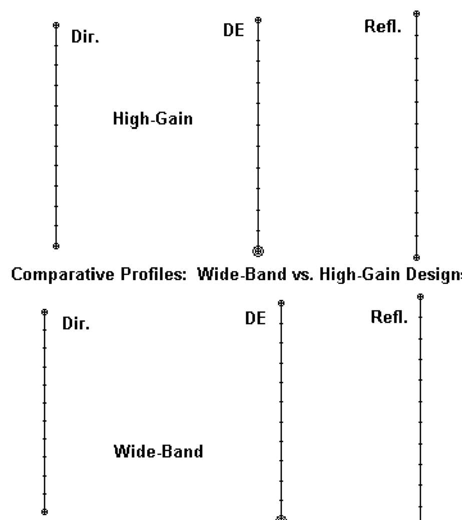
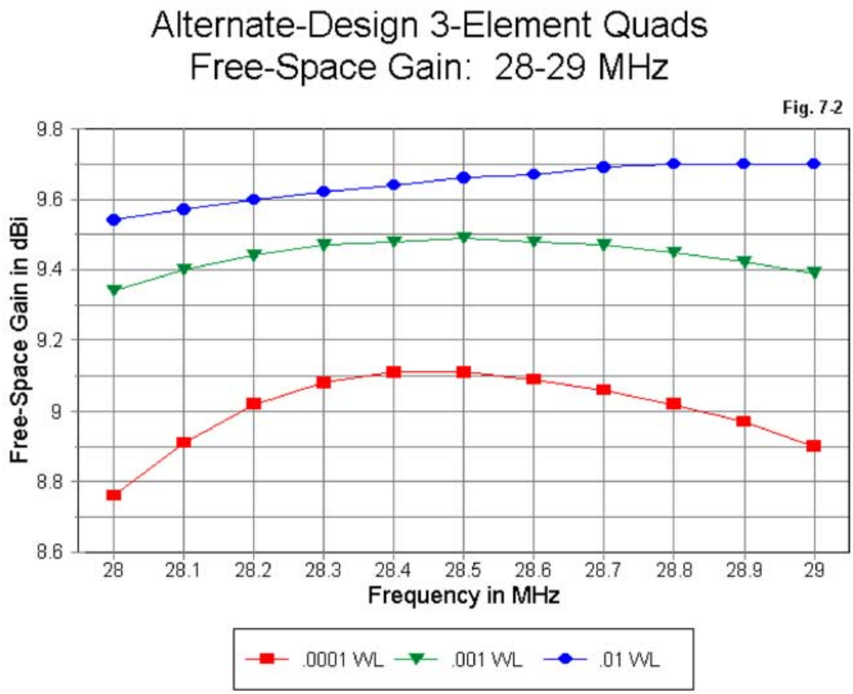


Fig. 7-1

The high-gain 3-element quad has a quite different profile than the wide-band model, as revealed in **Fig. 7-1**. Although the overall boom-length is similar—about 0.4 wavelength—the high-gain design spaces the driver considerably farther from the reflector and closer to the director. Ordinarily, in Yagi design, increasing the driver-reflector spacing increases the feedpoint impedance. However, in the case of these quad designs, the feedpoint impedance decreases from the wide-band design values.




The high-gain design has a number of other interesting properties. For example, the gain curve is roughly centered in the passband. **Fig. 7-2** shows the gain curves for the design using three wires sizes: 0.0001 wavelength, 0.001 wavelength, and 0.01 wavelength. For the 2 thinner wire sizes, the gain peaks on the design frequency. The fattest wire size shows a peak just above the design frequency (28.5 MHz in this case), as well as a much smaller increase in gain relative to the next smaller wire size. There appears to be a limit in this design to the gain increase with increasing wire size, possibly connected with a maximum degree of inter-element coupling.

As well, the front-to-back ratio peaks are not variable from one wire size to the next. Instead, the front-to-back ratio remains constant within +/-0.5 dB of 30 dB throughout the series of optimized models.

## Automated Design

Nonetheless, the high-gain design is amenable to automated design predicated on the entry of the design frequency and the wire size. The performance varies with the common logarithm of the wire size as measured in fractions of a wavelength. By applying regression analysis to optimized models at various wire sizes, it is possible to develop algorithms that produce working designs for any HF or VHF frequency within close tolerances.

The following GW Basic utility program encapsulates the design data. As always, LOG in GW Basic means a natural logarithm and requires a correction factor to yield a common log. If the program is entered in another medium that treats LOG as a common logarithm, the conversion factor can be omitted.

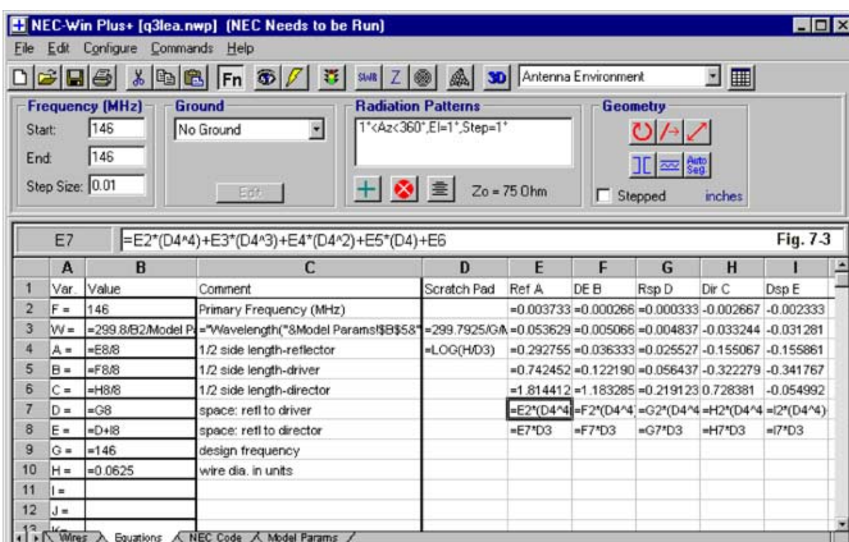
The program deletes one piece of data useful to the wide-band design: the rate of change of gain per 1% of frequency change. Since the gain peaks at the design frequency rather than outside the passband of the antenna for an amateur band, the rate-of-change figure loses its meaningfulness.

```
10 CLS:PRINT "Program to calculate the dimensions of a resonant
   square 3-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 "Alternate Design",,,"L. B. Cebik, W4RNL"
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=.000266666667#:BD=.00506666667#:CD=.03633333333#:
   DD=.1221904762#:ED=1.183285714#
200 DE=(AD*(D1^4))+(BD*(D1^3))+(CD*(D1^2))+(DD*D1)+ED
210 AR=.0037333333333#:BR=.05362962963#:CR=.29275555556#:
   DR=.7424529101#:ER=1.814412698#
220 RE=(AR*(D1^4))+(BR*(D1^3))+(CR*(D1^2))+(DR*D1)+ER
230 AI=-.00266666667#:BI=-.033244444444#:CI=-.1550666667#:DI=-
   .3222793651#:EI=.7283809524#
240 IR=(AI*(D1^4))+(BI*(D1^3))+(CI*(D1^2))+(DI*D1)+EI
250 AS=.00033333333#:BS=.004837037037#:CS=.02552777778#:
   DS=.05643756614#:ES=.2191230159#
260 SP=(AS*(D1^4))+(BS*(D1^3))+(CS*(D1^2))+(DS*D1)+ES
270 AP=-.002333333333#:BP=-.03128148148#:CP=-.15586111111#: DP=-
   .3417669312#:EP=-.05499206349#
280 IP=(AP*(D1^4))+(BP*(D1^3))+(CP*(D1^2))+(DP*D1)+EP
290 AZ=4.4029#:BZ=53.43954444#:CZ=239.2408583#:DZ=462.3614437#:
   EZ=373.3035655#
300 ZR=(AZ*(D1^4))+(BZ*(D1^3))+(CZ*(D1^2))+(DZ*D1)+EZ
310 AG=-.15#:BG=-1.768518519#:CG=-7.763055556#:DG=-14.78592593#:
   EG=-.609722222#
320 GN=(AG*(D1^4))+(BG*(D1^3))+(CG*(D1^2))+(DG*D1)+EG
330 AW=.16666666667#:BW=2.265925926#:CW=11.706111111#:
   DW=27.93058201#:EW=28.88753968#
340 SW=(AW*(D1^4))+(BW*(D1^3))+(CW*(D1^2))+(DW*D1)+EW
350 AF=.11933333333#:BF=1.671777778#:CF=8.9885#:DF=22.45931746#:
   EF=23.68797619#
360 FB=(AF*(D1^4))+(BF*(D1^3))+(CF*(D1^2))+(DF*D1)+EF
370 WL=299.7925/F:PRINT "Wavelength in Meters =";WL;"    ";
380 WF=983.5592/F:PRINT "Wavelength in Feet =";WF
390 PRINT "Quad Dimensions in Wavelengths, Feet, and Meters:"
400 PRINT "Driver Side =";(DE/4);" WL or";(DE/4)*WF;"Feet or";(DE/
   4)*WL;"Meters"
410 PRINT "Driver Circumference =";DE;" WL or";DE*WF;"Feet
   or";DE*WL;"Meters"
420 PRINT "Reflector Side =";(RE/4);" WL or";(RE/4)*WF;"Feet
   or";(RE/4)*WL;"Meters"
```

```
430 PRINT "Reflector Circumference =";RE;" WL or";RE*WF;"Feet
   or";RE*WL;"Meters"
440 PRINT "Reflector-Driver Space =";SP;" WL or";SP*WF;"Feet
   or";SP*WL;"Meters"
450 PRINT "Director Side =";(IR/4);" WL or";(IR/4)*WF;"Feet
   or";(IR/4)*WL;"Meters"
460 PRINT "Director Circumference =";IR;" WL or";IR*WF;"Feet
   or";IR*WL;"Meters"
470 PRINT "Director-Driver Space =";IP;" WL or";IP*WF;"Feet
   or";IP*WL;"Meters"
480 PRINT "Approx. Feedpoint Impedance =";ZR;"Ohms   ";
490 PRINT "Free-Space Gain =";GN;"dBi"
500 PRINT "Approximate 2:1 VSWR Bandwidth =";SW;"% of Design
   Frequency"
510 PRINT "Approximate >20 dB F-B Ratio Bandwidth =";FB;"% of
   Design Frequency"
520 INPUT "Another Value = 1, Stop = 2: ";P
530 IF P=1 THEN 10 ELSE 540
540 END
```

My preference for setting up utilities in GW Basic rests on the transparency of the programming language. The program structure and the equations used to pro-

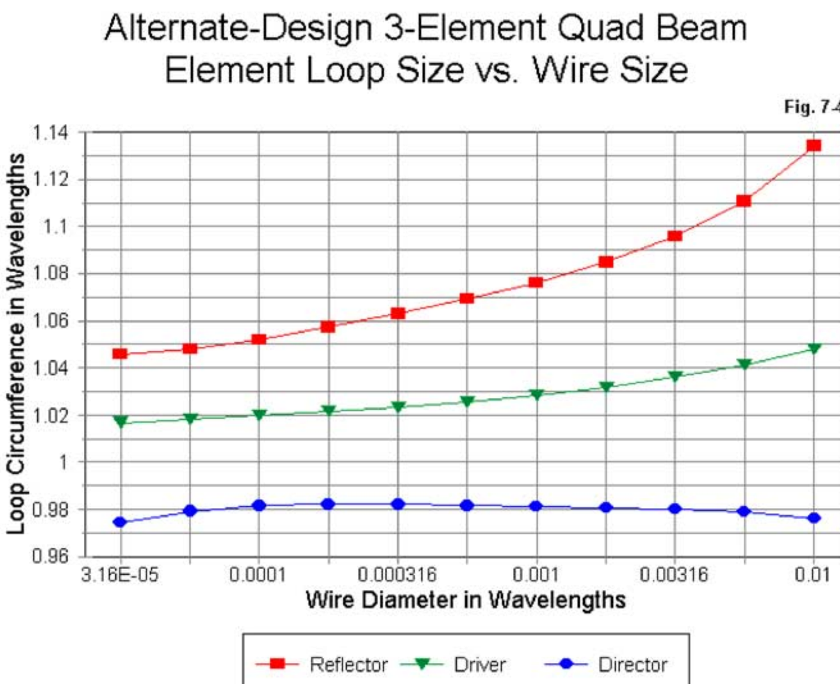


duce the output values are completely accessible for easy transport to any desired medium. Most spreadsheets use straightforward embellishments of Basic.

For example, the spreadsheet in the modeling program NEC-Win Plus allows one to enter the equations and produce a model directly. In fact, the only difference between the equations page shown in **Fig. 7-3** and the one shown in the last chapter are the values of the constants for the regression equations.

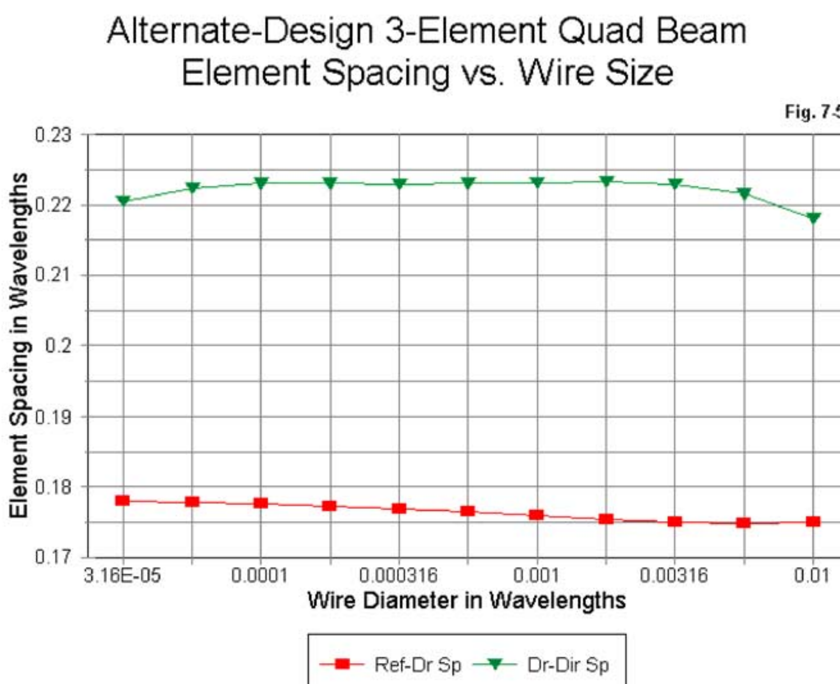
### Some Graphic Results

The program outputs can be graphically presented to show the general trends of the high-gain design dimensions. **Fig. 7-4** shows the loop circumference dimensions as a function of a wavelength for wires sizes that are also functions of a wavelength. The reflector and driver curves are familiar to those who have looked at the wide-band design. Although the exact values differ, the growing loop size as



wire diameter increases is a familiar feature. The director loop circumference, however, is another matter. It changes very little across the span of wire diameters, with down-turns at both ends of the scale. In fact, as the wire size decreases to the thinnest region, the wide-band and the high-gain design begin to resemble each other, since the gain peak comes closer to the design frequency for each version.

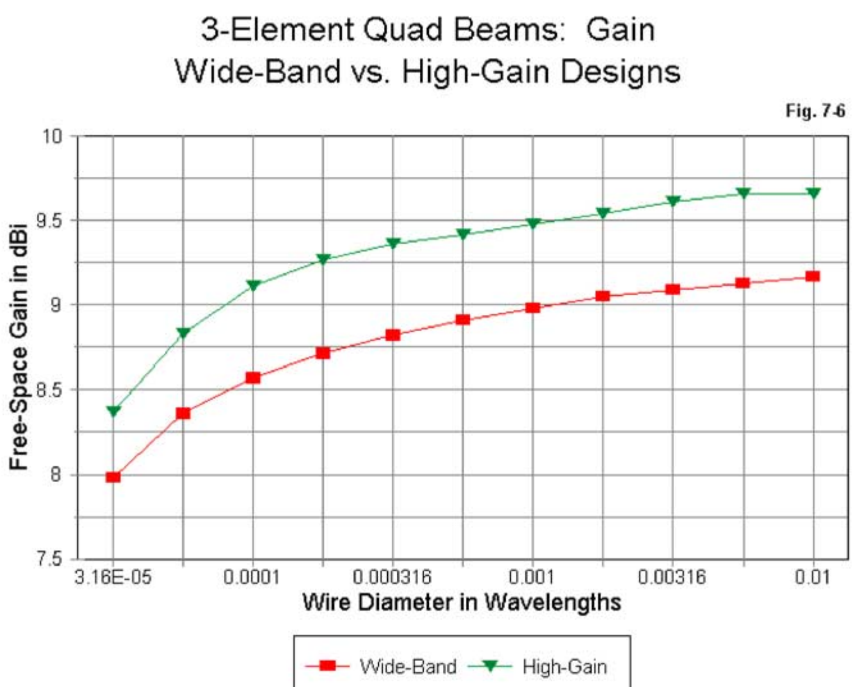
The element spacing required for optimized high-gain design follows rules that differ from those applicable to the wide-band design. The reflector-to-driver spacing decreases with increasing wire size—exactly the opposite of the case with the wide-band design. In contrast, the driver-to-director spacing shows a curve similar to the director loop circumference graph, with down-turns at both ends of the wire-size scale. Likewise, the range of variation is very small with the high-gain design. In contrast, the wide-band model showed a significant reduction of required spacing between the driver and director as the wire size increased. The high-gain model curves appear in **Fig. 7-5**.



## Some Performance Comparisons

Dimensions are not the only parameters that lend themselves to graphical comparisons. As well, we can look at some of the performance predictions for both the wide-band and the high-gain versions of the antenna. Most significant among these parameters are gain, the 2:1 SWR bandwidth, and the >20 dB front-to-back bandwidth.

**Fig. 7-6** shows the comparative gains for the two designs. Once we move above the thinnest wires, the high-gain version of the antenna shows an average gain advantage of about 0.5 dB over the wide-band version. The gain advantage does not come at the expense of significant changes in pattern shape. In fact, the free-space azimuth patterns of the two designs are quite similar, as shown in **Fig. 7-7**. For any chosen height above ground, the patterns would resemble these and remain similar to each other.



The free space azimuth patterns are predicated on 0.5" diameter copper elements with a design frequency of 28.5 MHz. As we noted in preceding chapters, elements of this diameter on 10 meters can be simulated effectively with #14 AWG wires spaced about 5" apart. Because of the rear side lobes of the two patterns are so similar, the differential in front-to-back ratios will not be operationally significant. How significant the gain differential will be must be a user measure based on an assessment of all of the critical parameters.

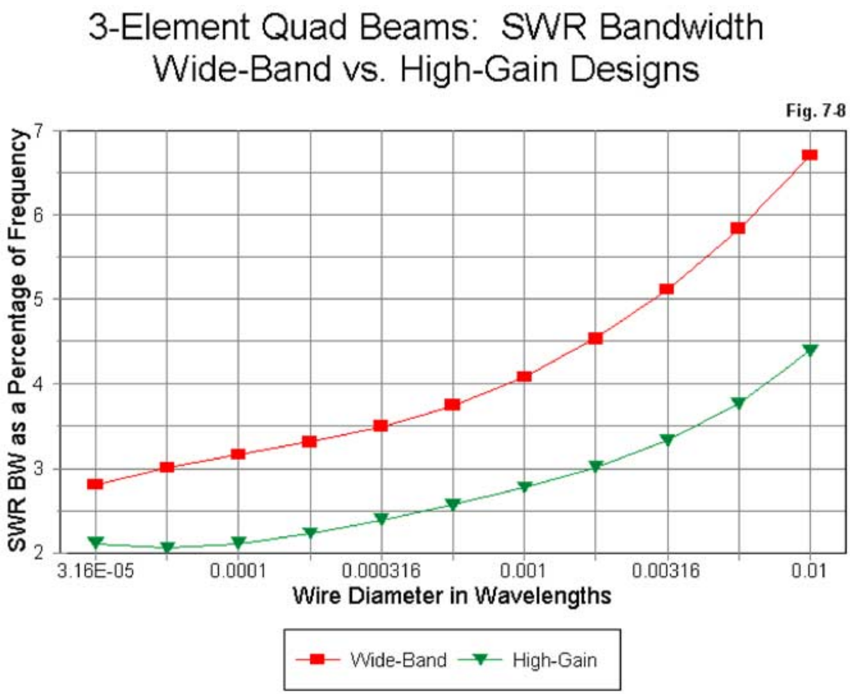
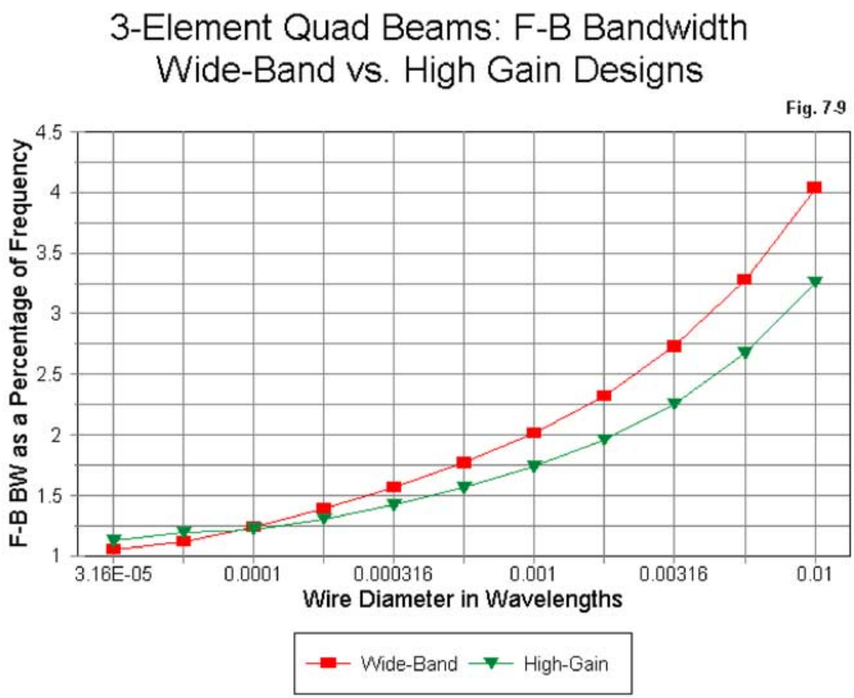
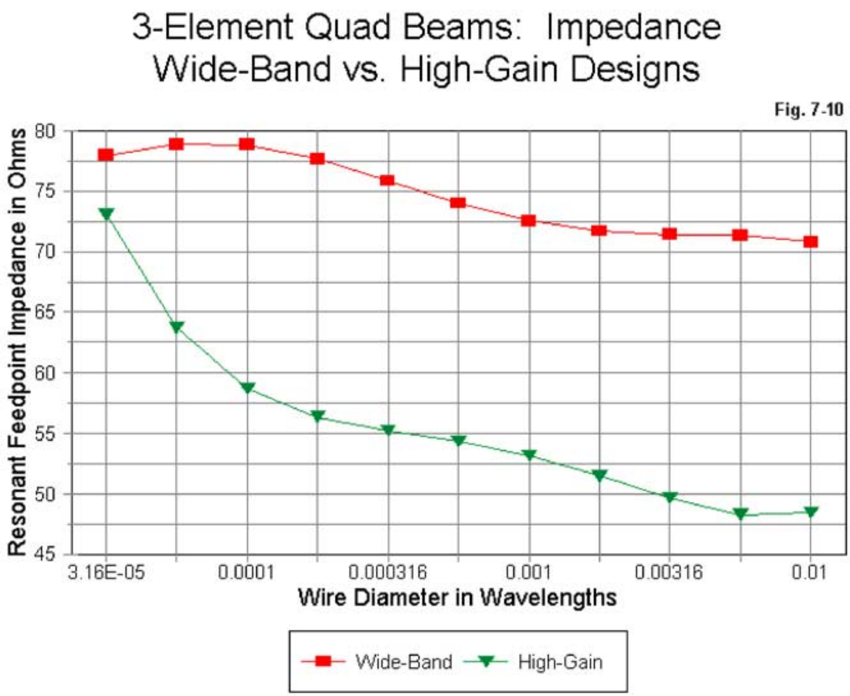



**Fig. 7-8** shows the comparative values of 2:1 SWR bandwidths, where the bandwidths are taken as a percentage of the operating frequency. The graph shows an advantage of better than 1.5:1 for the wide-band version of the antenna. However, whether that degree of increase in SWR bandwidth is necessary depends upon the bandwidth required for the operating goals of the individual installation. With respect to the SWR bandwidth, any wire size that is 0.0003 wavelength will cover any

of the wider HF ham bands (excluding 80 meters). For equivalent coverage with the high-gain version, a wire size equal or greater than about 0.004 wavelength is necessary. Consult the tables in Chapter 1 for the bandwidth of each of the amateur bands, as well as the wires gauge vs. diameter data. I shall merely repeat the suggestion in that chapter that the reader place paper clips on these much-used data table pages.




More critical to many operations than the SWR bandwidth is the >20 dB operating bandwidth. **Fig. 7-9** shows the differences for the two designs. Once one passes the 0.001 wavelength wire size, the average advantage for the wide-band design is about 20-23%. Full coverage of the first MHz of 10 meters would require a wire size of about 2.5" for the wide-band design, while the high-gain will not quite cover this passband with a diameter (or its equivalent in multiple wires) of over 4". Nonetheless, half-inch wire (or tubing) may suffice for nearly full band coverage of 2-meters using the high-gain design. Moreover, not every 3-element quad application needs to cover the entirety of any of the wider HF ham bands.




One significant difference in the designs is related to the feedpoint impedance, as shown in **Fig. 7-10**. The wide-band design resonant feedpoint impedance varies by under 10 Ohms across the entire span of wire sizes. However, the high-gain design shows an increasing feedpoint impedance as wire size decreases, from a low of about 48 Ohms with 0.01 wavelength wire to a high of nearly 73 Ohms for the thinnest wire. As the wire reaches the thinnest values in the progression, the curve is ever more steep. As noted earlier, with the thinnest wire size, the 3-element quad performance values become quite similar for the two designs. The thicker the wire of the high-gain design, the easier it becomes to directly match a 50-Ohm feedline.

### Some Practical Design Examples

To get a better sense of how the two designs differ, let's compare some models that alternately use the wide-band and the high-gain designs.

1. 20 meters, #14 wire, design frequency: 14.175 MHz

| | Wide-Band | High-Gain |
|---|---|---|
| Wire Diameter: | 0.0641" or 7.70E-5 wl | |
| Reflector Circumference: | 73.09' | 72.86' |
| Driver Circumference: | 70.06' | 70.71' |
| Director Circumference: | 65.31' | 68.04' |
| Refl-Driver Spacing: | 10.69' | 12.33' |
| Driver-Dir Spacing: | 21.58' | 15.46' |
| Total Boom Length: | 32.27' | 27.79' |
| Feedpoint Impedance: | 79.5 Ohms | 60.6 Ohms |
| Free-Space Gain: | 8.47 dBi | 9.00 dBi |
| SWR Bandwidth: | 3.10% or 0.439 MHz | 2.07% or 0.293 MHz |
| >20 dB F-B Bandwidth: | 1.18% or 0.167 MHz | 1.12% or 0.159 MHz |
| Rate of Gain Change: | 0.22 dB/1% of dsn. fq. | ———- |

2. 10 meters, #12 wire, design frequency: 28.5 MHz

| | Wide-Band | High-Gain |
|---|---|---|
| Wire Diameter: | 0.0808" or 1.95E-4 wl | |
| Reflector Circumference: | 36.64' | 36.52' |
| Driver Circumference: | 34.95' | 35.26' |
| Director Circumference: | 32.43' | 33.89' |
| Refl-Driver Spacing: | 5.49' | 6.12' |
| Driver-Dir Spacing: | 10.30' | 7.70' |
| Total Boom Length: | 15.79' | 13.82' |
| Feedpoint Impedance: | 77.2 Ohms | 56.1 Ohms |
| Free-Space Gain: | 8.74 dBi | 9.29 dBi |
| SWR Bandwidth: | 3.34% or 0.952 MHz | 2.26% or 0.644 MHz |
| >20 dB F-B Bandwidth: | 1.41% or 0.402 MHz | 1.32% or 0.376 MHz |
| Rate of Gain Change: | 0.21 dB/1% of dsn. fq. | ———- |

3. 10 meters, 0.5" wire, design frequency: 28.5 MHz

| Wire Diameter: | 0.5" or 1.21E-3 wl | |
|---|---|---|
| | Wide-Band | High-Gain |
| Reflector Circumference: | 37.42' | 37.23' |
| Driver Circumference: | 35.22' | 35.53' |
| Director Circumference: | 32.39' | 33.86' |
| Refl-Driver Spacing: | 5.66' | 6.07' |
| Driver-Dir Spacing: | 9.57' | 7.70' |
| Total Boom Length: | 15.23' | 13.77' |
| Feedpoint Impedance: | 72.3 Ohms | 52.7 Ohms |
| Free-Space Gain: | 9.00 dBi | 9.50 dBi |
| SWR Bandwidth: | 4.42% or 1.20 MHz | 2.84% or 0.809 MHz |
| >20 dB F-B Bandwidth: | 2.11% or 0.601 MHz | 1.80% or 0.513 MHz |
| Rate of Gain Change: | 0.10 dB/1% of dsn. fq. | ———- |

4. 6 meters, 0.25" wire, design frequency: 51 MHz

| Wire Diameter: | 0.25" or 1.08E-3 wl | |
|---|---|---|
| | Wide-Band | High-Gain |
| Reflector Circumference: | 20.87' | 20.78' |
| Driver Circumference: | 19.67' | 19.84' |
| Director Circumference: | 18.10' | 18.92' |
| Refl-Driver Spacing: | 3.16' | 3.39' |
| Driver-Dir Spacing: | 5.37' | 4.30' |
| Total Boom Length: | 8.53' | 7.69' |
| Feedpoint Impedance: | 72.4 Ohms | 53.0 Ohms |
| Free-Space Gain: | 8.99 dBi | 9.49 dBi |
| SWR Bandwidth: | 4.14% or 2.11 MHz | 2.80% or 1.43 MHz |
| >20 dB F-B Bandwidth: | 2.05% or 1.05 MHz | 1.76% or 0.90 MHz |
| Rate of Gain Change: | 0.11 dB/1% of dsn. fq. | ———- |

5. 2 meters, 0.1" wire, design frequency: 146 MHz

| Wire Diameter: | 0.1" or 1.24E-3 wl | |
|---|---|---|
| | Wide-Band | High-Gain |
| Reflector Circumference: | 7.31' | 7.27' |
| Driver Circumference: | 6.88' | 6.94' |
| Director Circumference: | 6.32' | 6.61' |
| Refl-Driver Spacing: | 1.11' | 1.18' |

| | | |
|---|---|---|
| Driver-Dir Spacing: | 1.87' | 1.50' |
| Total Boom Length: | 2.98' | 2.68' |
| Feedpoint Impedance: | 72.2 Ohms | 52.5 Ohms |
| Free-Space Gain: | 9.00 dBi | 9.50 dBi |
| SWR Bandwidth: | 4.24% or 6.19 MHz | 2.85% or 4.16 MHz |
| >20 dB F-B Bandwidth: | 2.19% or 3.20 MHz | 1.81% or 2.64 MHz |
| Rate of Gain Change: | 0.10 dB/1% of dsn. fq. | ———- |

If you have read Chapter 5, you will recognize the sample 3-element quads, since I used the same frequencies and wire sizes for the high-gain models in the right-hand column. In each case the dimensional differences are significant. However, for most folks, the gain and the operating bandwidth comparisons will be more interesting. In each case, the high-gain design shows its higher gain. Likewise, the wide-band design shows the wider SWR and front-to-back bandwidths.

## Conclusion

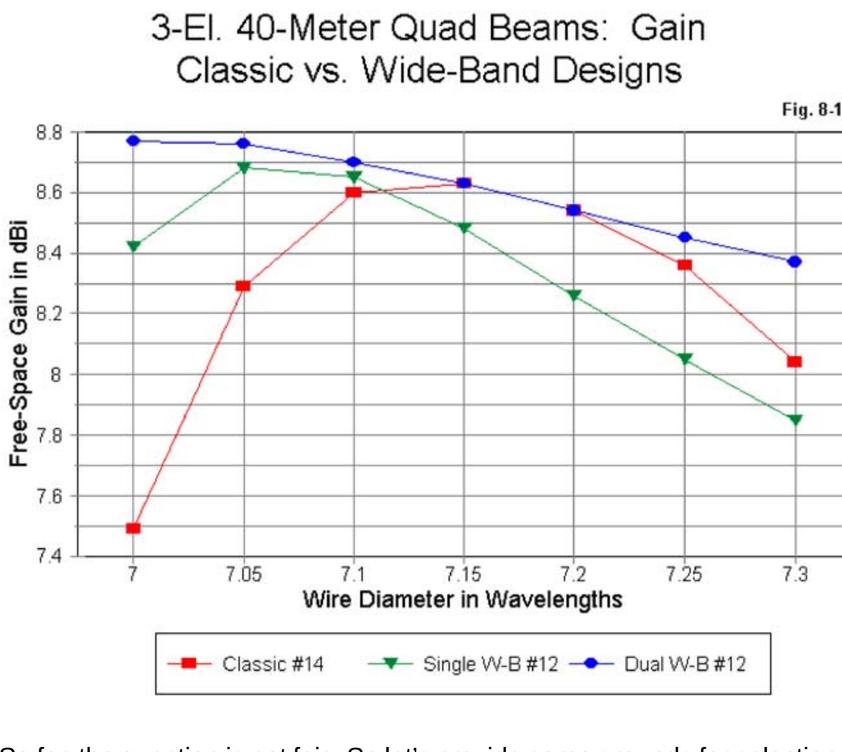
We have surveyed and automated the design of two significantly different 3-element quad beams. Even so, we have not exhausted the possibilities for the antenna type. One may design for even higher gain values, although the operating bandwidth and the feedpoint impedance will continue to decrease. Similarly, one may design for even wider operating bandwidths, but at a cost to array gain. If one pursues this latter course, eventually, the array gain will decrease to the level of a Yagi with a similar bandwidth and element diameter. In that case, the advantages of moving to a quad design would disappear, and the added complexities of quad construction might no longer warrant the effort. The precise point at which the transition occurs must be determined by the end-user.

Nonetheless, these exercises are useful in many ways. Besides the obvious benefit of yielding relatively optimized designs for any HF/VHF frequency and wire size, the programs provide an easy means of designing quads for comparative purposes. The evaluation of antennas at a practical level is very often a matter of comparing available designs. Yagi comparators are easy to find. Up to now, an adequate sampling of comparable quad designs has been hard to find. These utility programs considerably ease the process of uncovering 3-element quad designs and their capabilities.

One final caution: the designs are monoband quads throughout. One cannot simply plug them into a multi-band array and expect each quad to perform as specified here. In multi-band quad arrays, virtually all elements are significantly active, adding to or subtracting from the performance of the focal set of elements for any band. Therefore, creating an effective multi-band quad array requires considerably more adjustment than a mere field tweak on the monoband designs.

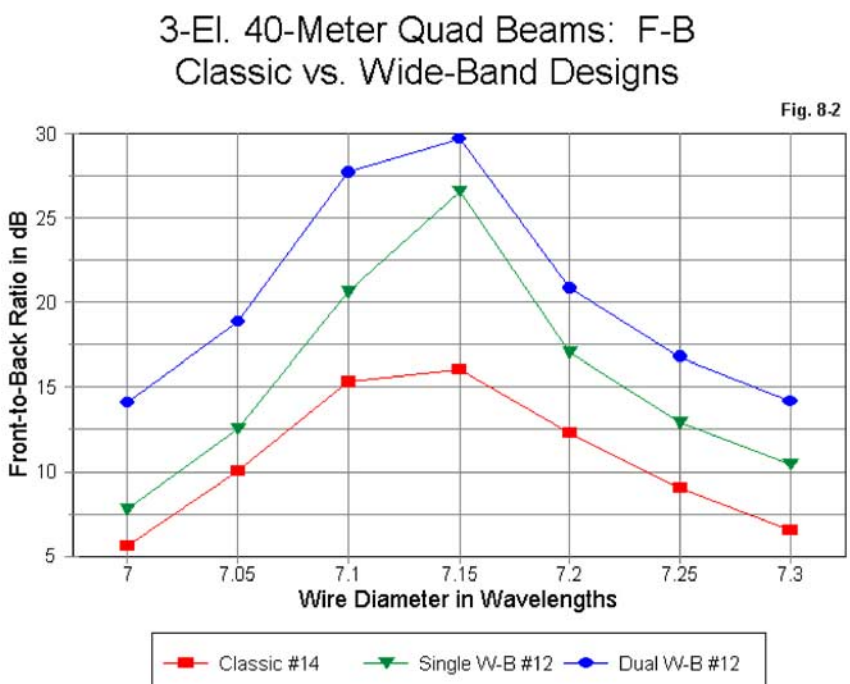
# Chapter 8
# 40-Meter Wide-Band 3-Element Quad Designs

Let's begin with a pop quiz. Suppose first that you wanted a directional 3-element quad array to cover as much of 40 meters as possible. Suppose further that space for the array is not problem. Finally, suppose that you had a choice among the following three designs: the "Classic #14," "the Single W-B #12," and the "Dual W-B #12." Which would you choose?

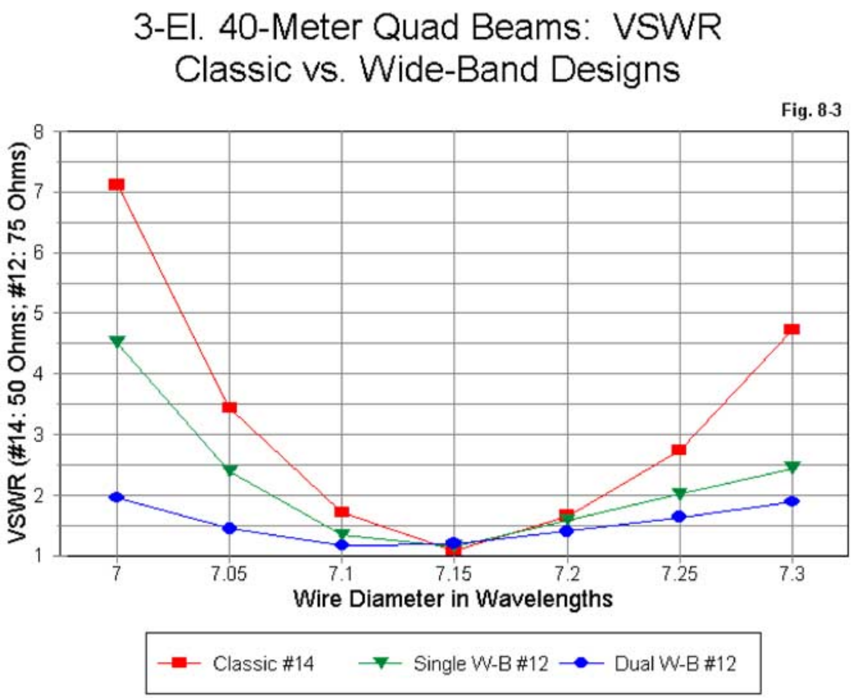



So far, the question is not fair. So let's provide some grounds for selection with a few performance graphs. **Fig. 8-1** shows the gain curves for the three choices. The classic #14 peaks at about 7.15 MHz, but falls off rapidly on either side of the design frequency, especially the low frequency side. Still, this is a normal curve for a quad beam in almost every performance category. The single W-B #12 has its gain peak at about 7.05 MHz, although the design frequency is higher. It is not clear from the graph whether the dual W-B #12 has a gain peak at 7.0 MHz or somewhat lower in frequency. From the graph, the antenna with the most consistent gain from one end of the band to the other is clear.

The front-to-back ratio curves in **Fig. 8-2** are equally clear. The peak front-to-back ratio in all cases occurs between 7.1 and 7.15 MHz. However, the classic #14 does not reach 20 dB (with the possible exception of a few kHz at its peak). The single W-B #12 does considerably better, but still manages >20 dB front-to-back ratio for only about 85 kHz. The dual W-B #12 has the widest >20 dB front-to-back ratio bandwidth and never drops below 14 dB across the 40-meter band.



The classic #14 array is--near the design frequency--a 50-Ohm antenna, and the SWR curve in **Fig. 8-3** is referenced to that value. Unfortunately, the <2:1 SWR region is only about 130 kHz wide. The single W-B #12 version of the antenna covers about 200 kHz with under 2:1 SWR--this time referenced to the array's near-75-Ohm feedpoint impedance. Only the dual W-B #12 model manages under 2:1 SWR (referenced to 75 Ohms) across the entire band.




For someone interested in the entire 40-meter band, there is a clear winner in this selection process: the dual W-B #12 model. But, before we look at what this model is, let's review the lesser arrays in the group.

## The Classic #14 3-Element Quad Design

For at least a quarter century, we have been given a set of formulas for constructing 3-element quads:

| | | |
|---|---|---|
| Reflector loop circumference in feet | = | 1030/frequency in MHz |
| Driver loop circumference in feet | = | 1005/frequency in MHz |
| Director loop circumference in feet | = | 975/frequency in MHz |

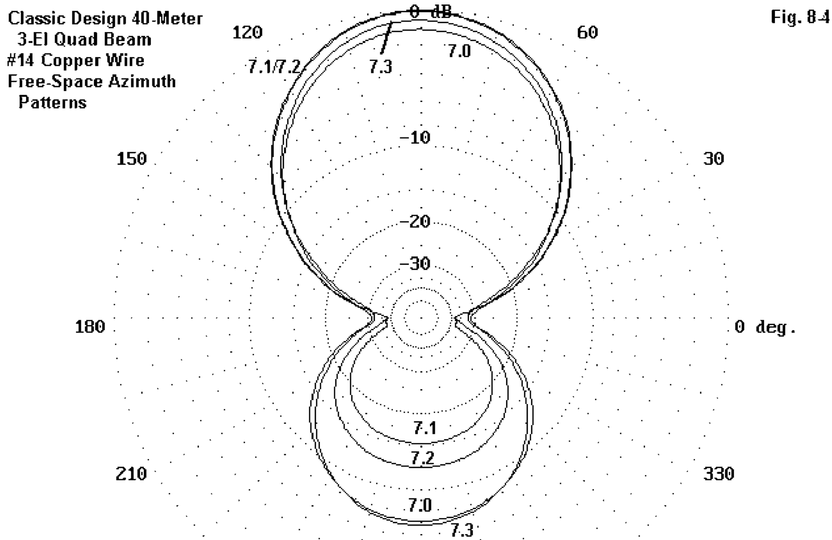
Many hams have believed that an independently fed quad loop answers to the driver formula, but it does not--not even close. Likewise, other hams have believed that we can make a 2-element quad using just the driver and reflector formulas. Any such array is less than optimal. Few folks have noticed that the spacing is left vacant, subject to our own construction limitations.

In fact, the formulas apply to fairly short 3-element quads using quite thin wire. The formulas are not perfect and require some optimization to bring the gain, front-to-back ratio, and SWR "best" numbers into reasonably close alignment. The following design in #14 AWG copper wire provides good figures at the design frequency (close to 7.15 MHz):

| | | |
|---|---|---|
| Reflector loop length: | 1719.4" | 143.29' |
| Driver loop length: | 1683.8" | 140.31' |
| Director loop length: | 1634.9" | 136.24' |
| Reflector-Driver space: | 219.5" | 18.30' |
| Driver-Director space: | 284.4" | 23.70' |
| Total boom length: | 503.9" | 42.00' |

Although this array is capable of about 8.6 dBi free-space gain at the design frequency, it has a very narrow operating bandwidth in every performance category. The gain drops to about 7.5 dB (1.1 dB off peak) at the low end of the band. The front-to-back ratio is below 10 dB for much of the band. The 2:1 SWR bandwidth covers less than half of the 40-meter band.

The selected azimuth patterns that scan 40-meters in 100 kHz intervals tell much of the classic #14's story in graphical detail in **Fig. 8-4**. Beyond the center 100 kHz of the band, the pattern of the array is more bi-directional than directional.




The use of the classical formulas on 40 meters provides somewhat of an overstatement of the inadequacies of these old numbers. A beam of this design might make a useful array for either the CW or the SSB end of 40 meters, but certainly not both. (This conclusion, of course, references the US 40-meter band. The array might be adequate to European interests in the band.)

For those who model and might wish to adjust the design to one or the other end of the 40-meter band, the following model description may be useful:

```
3-element 40-meter classic quad                        Frequency = 7  MHz.

Wire Loss: Copper -- Resistivity = 1.74E-08 ohm-m, Rel. Perm. = 1

              --------------- WIRES ---------------
Wire Conn. --- End 1 (x,y,z : ft)  Conn. --- End 2 (x,y,z : ft)  Dia(in) Segs
1     W4E2 -17.911,  0.000,-17.911  W2E1  17.911,  0.000,-17.911    # 14   11
2     W1E2  17.911,  0.000,-17.911  W3E1  17.911,  0.000, 17.911    # 14   11
3     W2E2  17.911,  0.000, 17.911  W4E1 -17.911,  0.000, 17.911    # 14   11
4     W3E2 -17.911,  0.000, 17.911  W1E1 -17.911,  0.000,-17.911    # 14   11
5     W8E2 -17.539, 18.296,-17.539  W6E1  17.539, 18.296,-17.539    # 14   11
6     W5E2  17.539, 18.296,-17.539  W7E1  17.539, 18.296, 17.539    # 14   11
7     W6E2  17.539, 18.296, 17.539  W8E1 -17.539, 18.296, 17.539    # 14   11
8     W7E2 -17.539, 18.296, 17.539  W5E1 -17.539, 18.296,-17.539    # 14   11
```

```
9    W12E2 -17.030, 41.998,-17.030 W10E1  17.030, 41.998,-17.030    # 14   11
10    W9E2  17.030, 41.998,-17.030 W11E1  17.030, 41.998, 17.030    # 14   11
11   W10E2  17.030, 41.998, 17.030 W12E1 -17.030, 41.998, 17.030    # 14   11
12   W11E2 -17.030, 41.998, 17.030  W9E1 -17.030, 41.998,-17.030    # 14   11

              -------------- SOURCES --------------
Source    Wire      Wire #/Pct From End 1    Ampl.(V, A)  Phase(Deg.)  Type
          Seg.     Actual      (Specified)
1           6     5 / 50.00   (  5 / 50.00)      0.707       0.000       V

Ground type is Free Space
```

## The Single-Wire Wide-Band #12 3-Element Quad Design

How might we improve the classic design? First, we should go to a larger diameter wire. However, #12 AWG copper wire is about the largest value that most hams will use for quad construction. That fact will initially limit the improvements we can make. #12 AWG is only about 1.26 times larger in diameter than #14 AWG. If we can recall the data from earlier chapters, we will instantly recognize that major improvements in performance—especially operating bandwidth—tend to come when we increase element diameters be at least a factor of 10, if not more. Increasing a #14 element by this amount would yield a diameter of about 5/8". Hence, the move from #14 to #12 would be marginal, indeed.

**Fig. 8-5** illustrates a second design move we can make: enlarge the spacing to something nearer to optimal. The figure shows the profiles of the classic and the improved designs, revealing that it will take another 20+ feet of boom to get significant improvements in operating bandwidth on 40 meters.

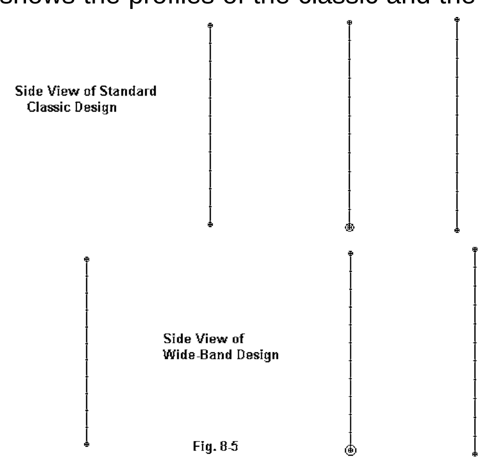


Fig. 8-5

I used the wide-band version of the automated design program that I presented in Chapter 6 to obtain the widest-band 40-meter beam I could develop with #12 wire. As shown in the figure, the boom length is very much longer than the classic design, even though the elements have a similar set of circumferences. Although the element dimensions are similar from one perspective, it is their differences that produces a workable design for the refigured quad. The dimensions that resulted from the design work are these:

| | | |
|---|---|---|
| Reflector loop length: | 1736.8" | 144.73' |
| Driver loop length: | 1669.2" | 139.10' |
| Director loop length: | 1560.3" | 130.02' |
| Reflector-Driver space: | 246.8" | 20.56' |
| Driver-Director space: | 522.6" | 43.55' |
| Total boom length: | 769.4" | 64.11' |

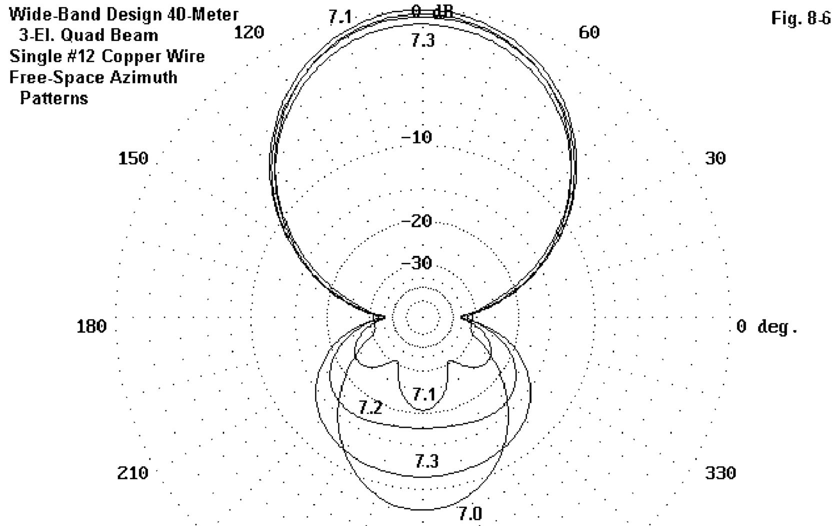
Wide-band design requires a driver-to-director spacing that is greater than the entire boom length of the classic design. Wide-band operation of a 3-element quad beam simply needs considerably greater boom-length than we have thought about using in the past.

Even with the longer boom length, the wire diameter we have chosen continues to limit performance. #12 wire is a very thin conductor at 40 meters--about 5E-5 wavelengths. Consequently, optimizing loop dimensions and element spacing will not provide full 40-meter coverage.

Gain is not the problem, since it holds to a free-space value of about 8.4 dBi or better across the band. The front-to-back ratio, although significantly improved compared to the classic #14 model, remains less than stellar. It actually falls below 10 dB at the low end of the band and exceeds 20 dB for less than 100 kHz. The 75-Ohm 2:1 SWR passband is only about 180 kHz wide--about 50 kHz wider than for the classic #14 design. Although the single-wire #12 wide-band design provides considerable improvements in gain and front-to-back ratio relative to the classic #14 model, it falls short of covering the band by a wide margin. Just getting full SWR coverage would require a wire about 3-4" in diameter.

**Fig. 8-6** shows our situation graphically through spot azimuth patterns across the band. The single-wire array will simply not do the job we specified at the beginning of this exercise.

Those who wish to try some adjustments to the array under discussion may benefit from the following model description:




```
3-element 40-meter single-wire wide-band quad          Frequency = 7  MHz.

Wire Loss: Copper -- Resistivity = 1.74E-08 ohm-m, Rel. Perm. = 1

              --------------- WIRES ---------------
Wire Conn. --- End 1 (x,y,z : ft)  Conn. --- End 2 (x,y,z : ft)  Dia(in) Segs
1     W4E2 -18.091,  0.000,-18.091  W2E1  18.091,  0.000,-18.091    # 12   11
2     W1E2  18.091,  0.000,-18.091  W3E1  18.091,  0.000, 18.091    # 12   11
3     W2E2  18.091,  0.000, 18.091  W4E1 -18.091,  0.000, 18.091    # 12   11
4     W3E2 -18.091,  0.000, 18.091  W1E1 -18.091,  0.000,-18.091    # 12   11
5     W8E2 -17.388, 20.563,-17.388  W6E1  17.388, 20.563,-17.388    # 12   11
6     W5E2  17.388, 20.563,-17.388  W7E1  17.388, 20.563, 17.388    # 12   11
7     W6E2  17.388, 20.563, 17.388  W8E1 -17.388, 20.563, 17.388    # 12   11
8     W7E2 -17.388, 20.563, 17.388  W5E1 -17.388, 20.563,-17.388    # 12   11
9    W12E2 -16.253, 64.113,-16.253 W10E1  16.253, 64.113,-16.253    # 12   11
10    W9E2  16.253, 64.113,-16.253 W11E1  16.253, 64.113, 16.253    # 12   11
11   W10E2  16.253, 64.113, 16.253 W12E1 -16.253, 64.113, 16.253    # 12   11
12   W11E2 -16.253, 64.113, 16.253  W9E1 -16.253, 64.113,-16.253    # 12   11

              -------------- SOURCES --------------
Source    Wire      Wire #/Pct From End 1    Ampl.(V, A)  Phase(Deg.)  Type
          Seg.     Actual      (Specified)
1           6     5 / 50.00   (  5 / 50.00)      0.707       0.000       V

Ground type is Free Space
```

## The Dual-Wire Wide-Band #12 3-Element Quad Design

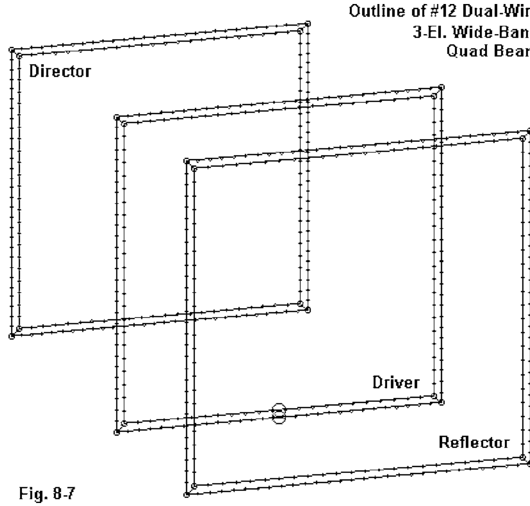


Fig. 8-7

A 40-meter quad beam by any accounting is a sizable structure. The spreaders should easily be able to support 2 #12 AWG wires. Indeed, except for an additional potential for snow and ice loading, the structure may benefit in strength and rigidity from the use of multiple wires. Therefore, we may simulate a fat wire by using double-wire elements in a planar arrangement. **Fig. 8-7** shows the general outline for such a beam. Note the connections between each element loop at every corner. The model and the anticipated construction of such an array make use of the standard “planar” design features. What will mark this beam as different from those we have previously discussed is the wire size, the wire spacing, and the frequency of operation. Even though the 7-MHz range may seem like a low frequency for quads, they have been used down to the 160-meter band and might even make a good AM broadcast antenna for stations that transmit only after sunset, hoping for skip reception. A 1.5 MHz fixed-direction quad suspended amidst a system of towers is certainly feasible.

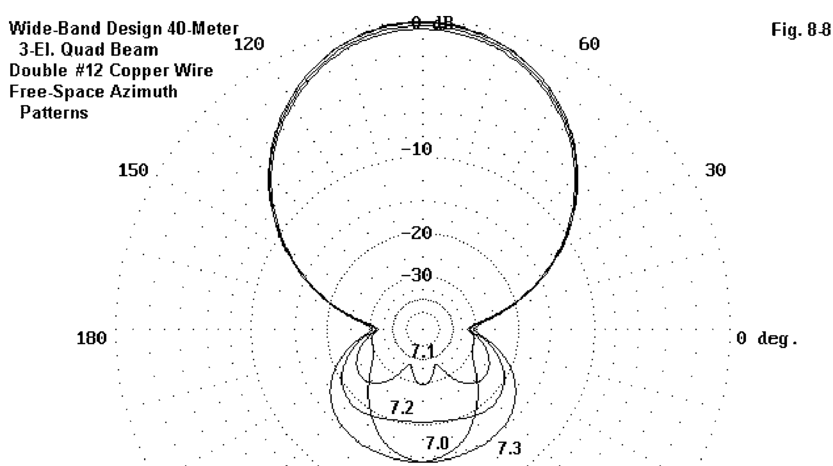
It proved possible to cover all of the first MHz of 10 meters with a very good front-to-back ratio using a single 0.5" diameter wire or 2 #14 wires spaced 5" apart. A 40-meter quad with comparable coverage would need wires spaced more than 20 inches apart. As a more modest design project, I aimed simply to achieve an SWR of under 2:1 across the band. This goal required the use of 10" #12 wire spacing.

The optimized dimensions for the dual-wire model yields an array that is close to 4' shorter than the single-wire version. The following dimensions list the circumferences of both the inner and outer loops for each element:

| | | | |
|---|---|---|---|
| Reflector loop length: | Outer | 1823.3" | 151.94' |
| | Inner | 1743.3" | 145.27' |
| Driver loop length: | Outer | 1725.9" | 143.83' |
| | Inner | 1645.9" | 137.16' |
| Director loop length: | Outer | 1569.4" | 130.79' |
| | Inner | 1489.4" | 124.12' |
| Reflector-Driver space: | | 287.7" | 23.97' |
| Driver-Director space: | | 435.6" | 36.30' |
| Total boom length: | | 723.3" | 60.27' |

For our trouble, we obtain a smooth gain curve across the band with under 0.3 dB variation. In addition, the front-to-back ratio is above 14 dB across the band and above 20 dB for over half the band. Finally, the 75-Ohm SWR is less than 2:1 across the entire band. Although still less than perfect, the 10" spacing of the dual-wire elements provides very significant improvements in performance over either of the other models.

**Fig. 8-8** provides a graphic sense of the improvements. All of the pattern elements are more tightly grouped than in the comparable azimuth pattern sweeps for the other designs. For those who wish to examine the model structure, the following listing may be useful.



**3-element 40-meter dual-wire wide-band quad          Frequency = 7 MHz.**

**Wire Loss: Copper -- Resistivity = 1.74E-08 ohm-m, Rel. Perm. = 1**

**--------------- WIRES ---------------**

| Wire | Conn. | --- End 1 (x,y,z : ft) | Conn. | --- End 2 (x,y,z : ft) | Dia(in) | Segs |
|---|---|---|---|---|---|---|
| 1 | W4E2 | -17.978, 0.000,-17.978 | W2E1 | 17.978, 0.000,-17.978 | # 12 | 29 |
| 2 | W10E1 | 17.978, 0.000,-17.978 | W3E1 | 17.978, 0.000, 17.978 | # 12 | 29 |
| 3 | W9E1 | 17.978, 0.000, 17.978 | W4E1 | -17.978, 0.000, 17.978 | # 12 | 29 |
| 4 | W12E1 | -17.978, 0.000, 17.978 | W11E1 | -17.978, 0.000,-17.978 | # 12 | 29 |
| 5 | W8E2 | -17.145, 0.000,-17.145 | W6E1 | 17.145, 0.000,-17.145 | # 12 | 23 |
| 6 | W10E2 | 17.145, 0.000,-17.145 | W7E1 | 17.145, 0.000, 17.145 | # 12 | 23 |
| 7 | W9E2 | 17.145, 0.000, 17.145 | W8E1 | -17.145, 0.000, 17.145 | # 12 | 23 |
| 8 | W12E2 | -17.145, 0.000, 17.145 | W11E2 | -17.145, 0.000,-17.145 | # 12 | 23 |
| 9 | W2E2 | 17.978, 0.000, 17.978 | W6E2 | 17.145, 0.000, 17.145 | # 12 | 1 |
| 10 | W1E2 | 17.978, 0.000,-17.978 | W5E2 | 17.145, 0.000,-17.145 | # 12 | 1 |
| 11 | W1E1 | -17.978, 0.000,-17.978 | W5E1 | -17.145, 0.000,-17.145 | # 12 | 1 |
| 12 | W3E2 | -17.978, 0.000, 17.978 | W7E2 | -17.145, 0.000, 17.145 | # 12 | 1 |
| 13 | W16E2 | -18.992,-23.973,-18.992 | W14E1 | 18.992,-23.973,-18.992 | # 12 | 29 |
| 14 | W22E1 | 18.992,-23.973,-18.992 | W15E1 | 18.992,-23.973, 18.992 | # 12 | 29 |
| 15 | W21E1 | 18.992,-23.973, 18.992 | W16E1 | -18.992,-23.973, 18.992 | # 12 | 29 |
| 16 | W24E1 | -18.992,-23.973, 18.992 | W23E1 | -18.992,-23.973,-18.992 | # 12 | 29 |
| 17 | W20E2 | -18.159,-23.973,-18.159 | W18E1 | 18.159,-23.973,-18.159 | # 12 | 23 |
| 18 | W22E2 | 18.159,-23.973,-18.159 | W19E1 | 18.159,-23.973, 18.159 | # 12 | 23 |
| 19 | W21E2 | 18.159,-23.973, 18.159 | W20E1 | -18.159,-23.973, 18.159 | # 12 | 23 |
| 20 | W24E2 | -18.159,-23.973, 18.159 | W23E2 | -18.159,-23.973,-18.159 | # 12 | 23 |
| 21 | W14E2 | 18.992,-23.973, 18.992 | W18E2 | 18.159,-23.973, 18.159 | # 12 | 1 |
| 22 | W13E2 | 18.992,-23.973,-18.992 | W17E2 | 18.159,-23.973,-18.159 | # 12 | 1 |
| 23 | W13E1 | -18.992,-23.973,-18.992 | W17E1 | -18.159,-23.973,-18.159 | # 12 | 1 |
| 24 | W15E2 | -18.992,-23.973, 18.992 | W19E2 | -18.159,-23.973, 18.159 | # 12 | 1 |
| 25 | W28E2 | -16.348, 36.302,-16.348 | W26E1 | 16.348, 36.302,-16.348 | # 12 | 29 |
| 26 | W34E1 | 16.348, 36.302,-16.348 | W27E1 | 16.348, 36.302, 16.348 | # 12 | 29 |
| 27 | W33E1 | 16.348, 36.302, 16.348 | W28E1 | -16.348, 36.302, 16.348 | # 12 | 29 |
| 28 | W36E1 | -16.348, 36.302, 16.348 | W35E1 | -16.348, 36.302,-16.348 | # 12 | 29 |
| 29 | W32E2 | -15.515, 36.302,-15.515 | W30E1 | 15.515, 36.302,-15.515 | # 12 | 23 |
| 30 | W34E2 | 15.515, 36.302,-15.515 | W31E1 | 15.515, 36.302, 15.515 | # 12 | 23 |
| 31 | W33E2 | 15.515, 36.302, 15.515 | W32E1 | -15.515, 36.302, 15.515 | # 12 | 23 |
| 32 | W36E2 | -15.515, 36.302, 15.515 | W35E2 | -15.515, 36.302,-15.515 | # 12 | 23 |
| 33 | W26E2 | 16.348, 36.302, 16.348 | W30E2 | 15.515, 36.302, 15.515 | # 12 | 1 |
| 34 | W25E2 | 16.348, 36.302,-16.348 | W29E2 | 15.515, 36.302,-15.515 | # 12 | 1 |
| 35 | W25E1 | -16.348, 36.302,-16.348 | W29E1 | -15.515, 36.302,-15.515 | # 12 | 1 |
| 36 | W27E2 | -16.348, 36.302, 16.348 | W31E2 | -15.515, 36.302, 15.515 | # 12 | 1 |

**-------------- SOURCES --------------**

| Source | Wire Seg. | Wire #/Pct From End 1 Actual | (Specified) | Ampl.(V, A) | Phase(Deg.) | Type |
|---|---|---|---|---|---|---|
| 1 | 15 | 1 / 50.00 | ( 1 / 50.00) | 0.707 | 0.000 | V |
| 2 | 12 | 5 / 50.00 | ( 5 / 50.00) | 0.707 | 0.000 | V |

**Ground type is Free Space**

Note in the model the use of two sources which are essentially in parallel. You may use the standard parallel impedance equations to calculate the composite feedpoint impedance. In practice, of course, a builder would bring the two loop wires together at the feedpoint for a single feedline connection. For modeling purposes, creating a short (1") transmission line using the TL facility would also provide quite accurate impedance figures. A line of about 150 Ohms would suffice. Since the line is mathematical only, its physical length need not match reality, and the very short segment of transmission line between elements minimizes errors due to impedance transformation down the line.

The dual-wire planar loop design is not the answer to all limitations of 3-element quad bandwidth, but it goes a long way toward overcoming them. For such a large initial array, the two-wire loop is fairly straightforward, if not simple, to implement. The cost will be something over 400' in extra wire.

### A Note on Designing 3-Element Quads with Modeling Software

I habitually use a mixture of two NEC programs for quad design--NEC-Win Plus and EZNEC. Although many of the graphics that appear here are from models cross-checked on EZNEC/4, the basic design work was done with NEC-Win Plus using the model-by-equation facility.

**Fig. 8-9** provides a simple illustration of the first step in the design process--chosen because a quad design with a single-wire structure makes a more compact and easily read graphic. (The same illustration using the dual wire model would have required 36 lines in the “wires page” section along with additional equations to set the dimensions of the second loop on each element relative to the first loop or to a center-line.) By setting the “half-side” dimensions of the quad in terms of a fraction of a wavelength, the task of hand-optimizing a design is considerably eased. In this case, the director spacing is actually the spacing from the reflector to the director, and finding the distance from the driver to the director is a simple case of subtraction. Alternatively, one might set the driver at zero and use a negative value for the reflector spacing and a positive value for the director. Finding the total boom length then becomes a simple case of addition.

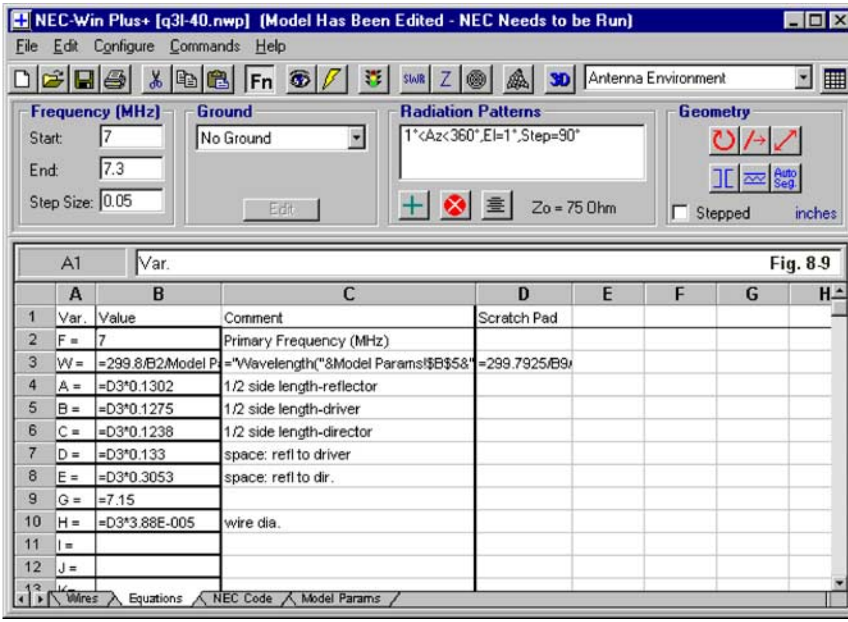
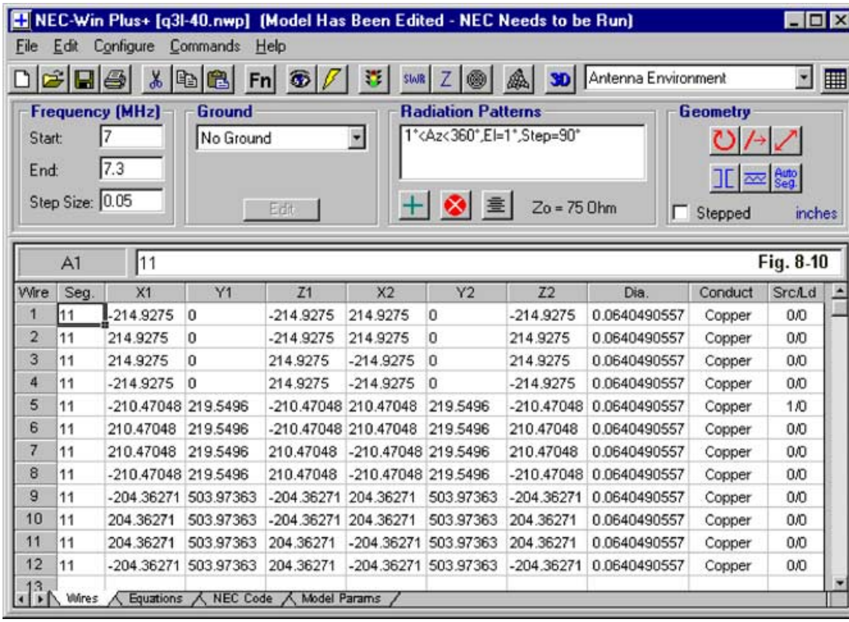



**Fig. 8-10** shows the resultant dimensions using the equations in **Fig. 8-9**. Underlying this page is a set-up that specifies variables for each of the points in the antenna geometry—along with + and - signs as applicable to this free-space model. See **Fig. 8-11**. Such models allow easy manipulation of dimensions for trial-and-error optimizing of a design. When there is only one number to change to vary a full element (which has 8 corner points in a 2-wire arrangement), the impact of errors is less discouraging. Nonetheless, in all hand-optimizing efforts, two subsidiary activities are essential to making progress.

First, it is crucial to keep a side pad that records each set of values tried. Nothing brings frustration more than the discovery that one has been covering the same ground over and over again. Second, it is equally critical to the process to record trends that occur with each small increment of change. These trend notes can become complex, since there are variable “breaking” points. As one adjusts the spacing or the loop circumference of one or more elements, the point at which a progressive gain increase turns into a decrease with changes to any single dimensions will change.

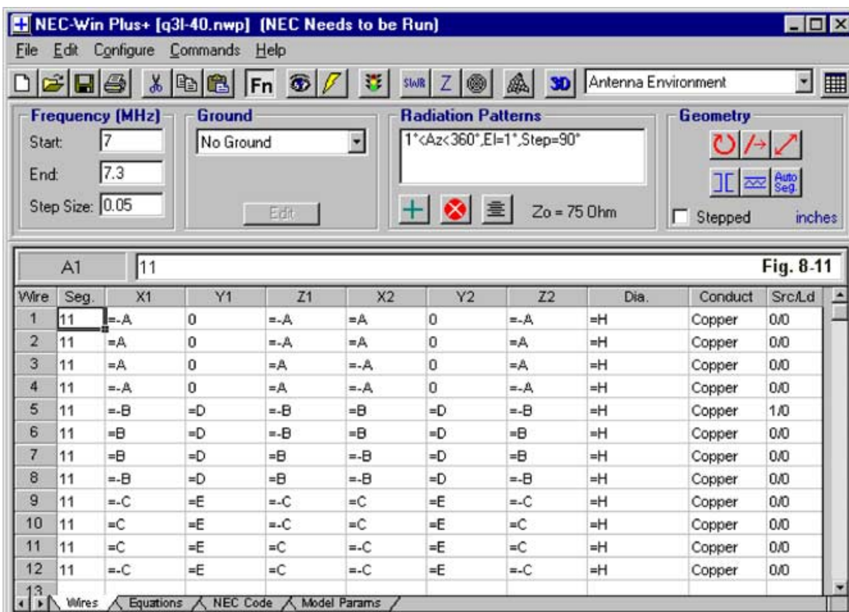
Watching and recording trends will be useful in determining the best composite (or compromise) set of dimensions.




The earlier note in this chapter on the rough equivalency of a 3-4" wire to the 10" double #12 wire arrangement can be verified by using the 3-element wide-band automated design program. A 3" wire is the minimum diameter single copper wire that will yield a 75-Ohm <2:1 SWR curve for a 40-meter array. The model below is one example of such a design. Note that when run on NEC-4, the properties will show a slight displacement (under 50 kHz) in frequency. The curve was developed in NEC-2.

```
3-Element Wide-Band 40-M design:  3" elements        Frequency = 7.15  MHz.

Wire Loss: Copper -- Resistivity = 1.74E-08 ohm-m, Rel. Perm. = 1

                --------------- WIRES ---------------
Wire Conn. --- End 1 (x,y,z : in)  Conn. --- End 2 (x,y,z : in)  Dia(in) Segs
1     W4E2 -226.06,  0.000,-226.06  W2E1 226.061,  0.000,-226.06 3.00E+00  11
2     W1E2 226.061,  0.000,-226.06  W3E1 226.061,  0.000,226.061 3.00E+00  11
3     W2E2 226.061,  0.000,226.061  W4E1 -226.06,  0.000,226.061 3.00E+00  11
4     W3E2 -226.06,  0.000,226.061  W1E1 -226.06,  0.000,-226.06 3.00E+00  11
```

```
5     W8E2 -211.88,273.902,-211.88  W6E1 211.876,273.902,-211.88 3.00E+00  11
6     W5E2 211.876,273.902,-211.88  W7E1 211.876,273.902,211.876 3.00E+00  11
7     W6E2 211.876,273.902,211.876  W8E1 -211.88,273.902,211.876 3.00E+00  11
8     W7E2 -211.88,273.902,211.876  W5E1 -211.88,273.902,-211.88 3.00E+00  11
9    W12E2 -194.11,727.268,-194.11 W10E1 194.109,727.268,-194.11 3.00E+00  11
10    W9E2 194.109,727.268,-194.11 W11E1 194.109,727.268,194.109 3.00E+00  11
11   W10E2 194.109,727.268,194.109 W12E1 -194.11,727.268,194.109 3.00E+00  11
12   W11E2 -194.11,727.268,194.109  W9E1 -194.11,727.268,-194.11 3.00E+00  11

              -------------- SOURCES --------------
Source     Wire      Wire #/Pct From End 1    Ampl.(V, A)  Phase(Deg.)  Type
           Seg.     Actual     (Specified)
1            6      5 / 50.00   (  5 / 50.00)      0.707        0.000       V

Ground type is Free Space
```




| Wire | Seg. | X1 | Y1 | Z1 | X2 | Y2 | Z2 | Dia. | Conduct | Src/Ld |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 11 | =-A | 0 | =-A | =A | 0 | =-A | =H | Copper | 0/0 |
| 2 | 11 | =A | 0 | =-A | =A | 0 | =A | =H | Copper | 0/0 |
| 3 | 11 | =A | 0 | =A | =-A | 0 | =A | =H | Copper | 0/0 |
| 4 | 11 | =-A | 0 | =A | =-A | 0 | =-A | =H | Copper | 0/0 |
| 5 | 11 | =-B | =D | =-B | =B | =D | =-B | =H | Copper | 1/0 |
| 6 | 11 | =B | =D | =-B | =B | =D | =B | =H | Copper | 0/0 |
| 7 | 11 | =B | =D | =B | =-B | =D | =B | =H | Copper | 0/0 |
| 8 | 11 | =-B | =D | =B | =-B | =D | =-B | =H | Copper | 0/0 |
| 9 | 11 | =-C | =E | =-C | =C | =E | =-C | =H | Copper | 0/0 |
| 10 | 11 | =C | =E | =-C | =C | =E | =C | =H | Copper | 0/0 |
| 11 | 11 | =C | =E | =C | =-C | =E | =C | =H | Copper | 0/0 |
| 12 | 11 | =-C | =E | =C | =-C | =E | =-C | =H | Copper | 0/0 |
| 13 | | | | | | | | | | |

To obtain a >20 dB front-to-back curve for the entirety of the US 40-meter band requires a much greater single-wire diameter:  about 20". The following model provides such a curve on NEC-2, with the usual slight frequency displacement in NEC-4.

```
3-Element Wide-Band 40-M design:  3" elements        Frequency = 7.15  MHz.

Wire Loss: Copper -- Resistivity = 1.74E-08 ohm-m, Rel. Perm. = 1

              --------------- WIRES ---------------
Wire Conn. --- End 1 (x,y,z : in)  Conn. --- End 2 (x,y,z : in)  Dia(in) Segs
1     W4E2 -238.14,  0.000,-238.14  W2E1 238.145,  0.000,-238.14 2.00E+01  11
2     W1E2 238.145,  0.000,-238.14  W3E1 238.145,  0.000,238.145 2.00E+01  11
3     W2E2 238.145,  0.000,238.145  W4E1 -238.14,  0.000,238.145 2.00E+01  11
4     W3E2 -238.14,  0.000,238.145  W1E1 -238.14,  0.000,-238.14 2.00E+01  11
5     W8E2 -215.68,280.836,-215.68  W6E1 215.680,280.836,-215.68 2.00E+01  11
6     W5E2 215.680,280.836,-215.68  W7E1 215.680,280.836,215.680 2.00E+01  11
7     W6E2 215.680,280.836,215.680  W8E1 -215.68,280.836,215.680 2.00E+01  11
8     W7E2 -215.68,280.836,215.680  W5E1 -215.68,280.836,-215.68 2.00E+01  11
9    W12E2 -189.54,696.975,-189.54 W10E1 189.536,696.975,-189.54 2.00E+01  11
10    W9E2 189.536,696.975,-189.54 W11E1 189.536,696.975,189.536 2.00E+01  11
11   W10E2 189.536,696.975,189.536 W12E1 -189.54,696.975,189.536 2.00E+01  11
12   W11E2 -189.54,696.975,189.536  W9E1 -189.54,696.975,-189.54 2.00E+01  11

              -------------- SOURCES --------------
Source    Wire      Wire #/Pct From End 1    Ampl.(V, A)  Phase(Deg.)  Type
          Seg.     Actual      (Specified)
1           6     5 / 50.00   (  5 / 50.00)      0.707       0.000       V

Ground type is Free Space
```

Developing a multi-wire equivalent for a 20" diameter wire is likely not feasible with only two wires. Even if the SWR and front-to-back curves can be replicated, the full gain (9.2 dB at design center frequency) will not be available without several wires per loop--perhaps 4 wires on 10" centers (as a speculative guess). The 20" wire in the model presses the limits of wire diameter (0.01 wavelength) for which the design program has been calibrated. Nevertheless, for one who seeks the maximum gain and operating bandwidth from a 3-element quad on 40 meters, experimentation with multi-wire elements is certainly worthwhile.

Let me add one final note relating to the various automated design programs and models that we have presented. I have been asked on occasion why I use an independent value for the wavelength (cell D3 in most of the NEC-Win Plus equations spreadsheets) in most of my equations. The frequency-vs.-wavelength constant (299.7925) is surely more precise than one could possibly need in any final result. That is, seven significant digits is more than one can possibly replicate in construction.

When letting software perform a string of calculations, I tend to prefer to use the most precise value for physical and mathematical constants that I can find. This includes such values as PI (3.1415927), the speed of electromagnetic radiation in free space (299.7925 m/s), and the ratio of natural to common logarithms (2.3025851) or its inverse (0.4342945). I then save rounding to the desired number of significant digits for the final step of calculations performed by software programs. Others may wish to use only the least number of significant digits in the weakest input value in all numeric entries. However, I have found that, because various programs perform their rounding operations at different places—usually invisibly to the user—retaining a high calculation precision in the course of multi-step calculations produces better correlations with the results of other programs that arrive at the same quantities by other steps.

Whatever procedure one finds most comfortable, the process of developing a wide-band 40-meter 3-element quad takes more than a few formulas whose limitations have been lost in the mists of summary, custom, and usage. Even the best of the designs here can be improved by judicious further modeling using either wider spacing of dual wires or larger multi-wire loops. There are many modeling challenges ahead before the quad beam has exhausted its potential.

# Chapter 9
# 4-Element Monoband Quad Design

The most common designs of 4-element quads suffers 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 using elements at 20 meters that average about 1" in diameter, free-space gains average 8.6 dBi are more typical in the HF bands.

Outline of a 4-Element Monoband Quad Array

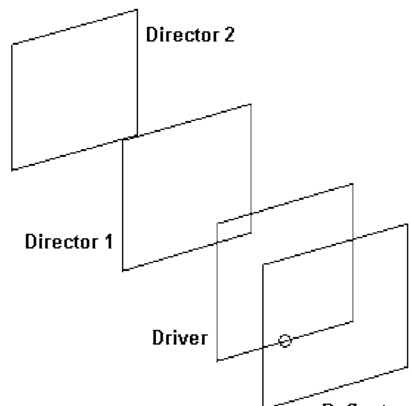



Fig. 9-1

The average monoband 4-element quad has the appearance of **Fig. 9-1**. 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 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.

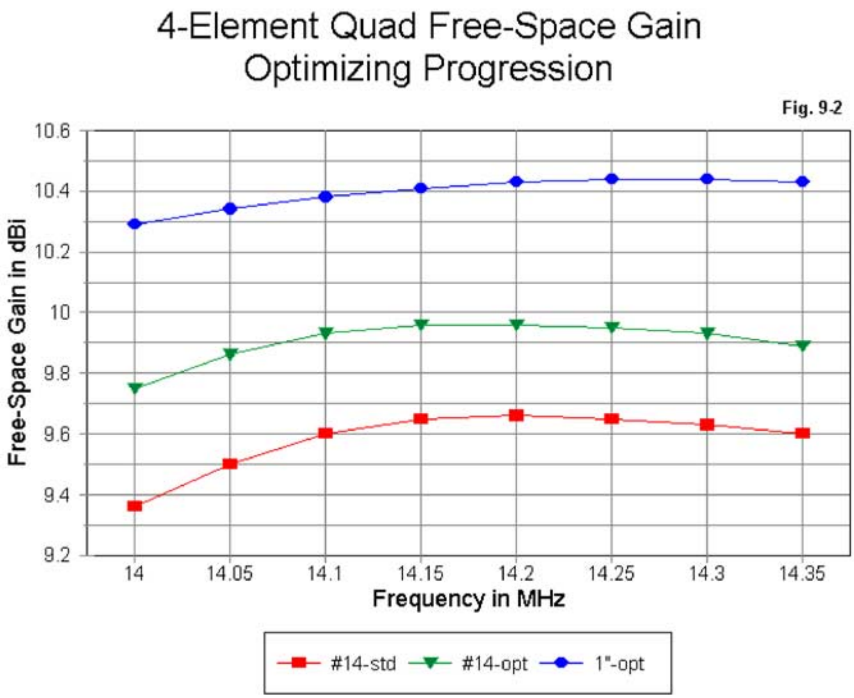
As we have seen from designing quads with fewer elements, almost every category of performance benefits from enlarging the effective diameter of the elements. Consider the following design using 1" diameter elements. The 1" diameter elements can be synthesized from properly spaced pairs of wires in accord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

Design Data for an “Optimized” 4-Element Quad

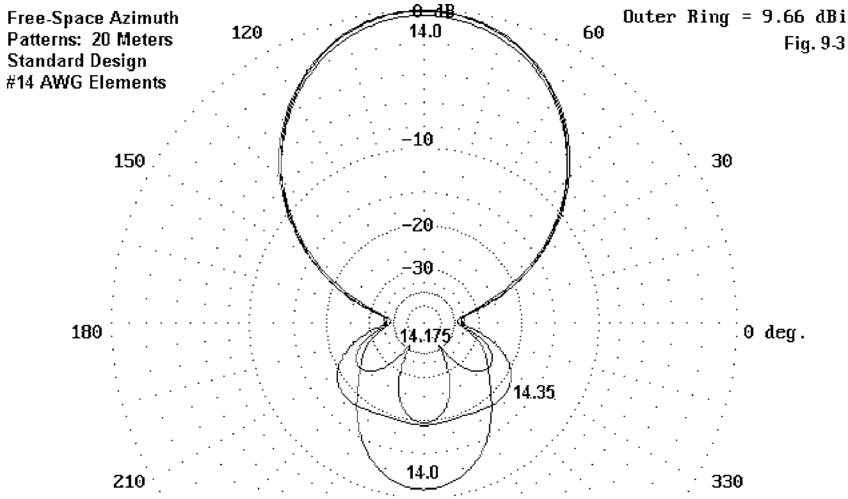
| | |
|---|---|
| Element Diameter: | 1.0" |
| Reflector Circumference: | 74.84' |
| Driver Circumference: | 71.04' |
| Director 1 Circumference: | 67.04' |
| Director 2 Circumference: | 64.68' |
| Refl-Driver Spacing: | 11.37' |
| Driver-Dir 1 Spacing: | 22.07' |
| Dir 1-Dir 2 Spacing: | 25.13' |
| 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.

A graphical comparison of the 3 designs can perhaps portray the performance better than words. **Fig. 9-2** 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. Although in preceding chapters, we have stressed the effects of element diameter on the operating bandwidth in terms of front-to-back and SWR performance, there is in all cases a variation of the gain-bandwidth performance with element diameter as well. In many cases, the effect is not very significant, but in some instances, the effect may be worth noting.




Often, a series of strategically taken azimuth plots can show the strengths and weakness of designs even better than graphed curves. **Fig. 9-3** 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 result is intentional or accidental. The "formulas" for this model 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. Since the formula-driven design provides no guidance other than the equations, the matter must rest in the "unknown" basket.



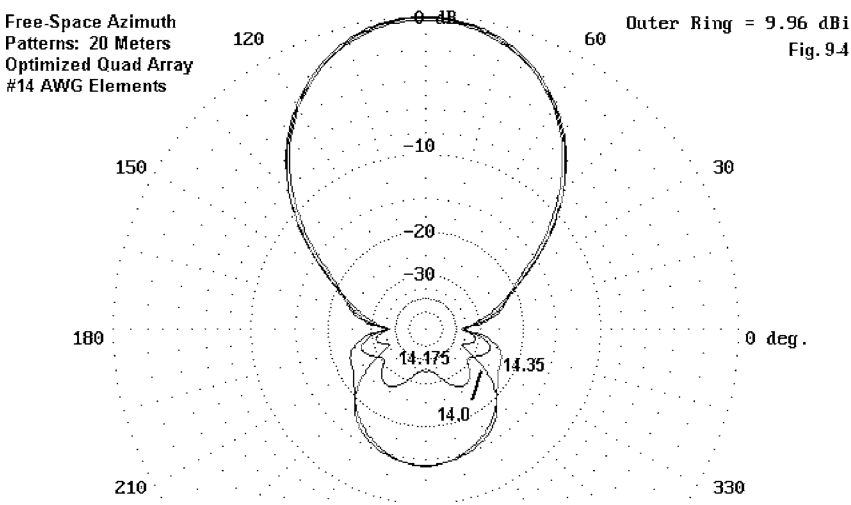
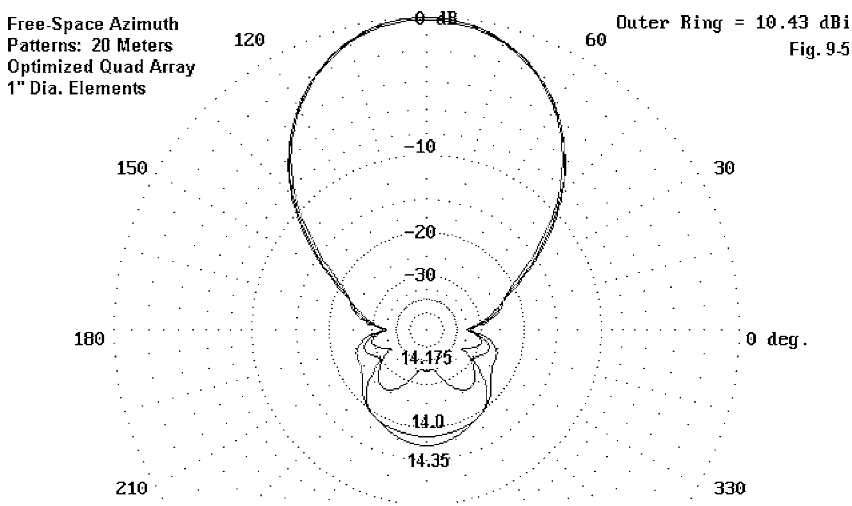




**Fig. 9-4** provides the comparable set of patterns for the #14 optimized long-boom array. In this design exercise, the design frequency of 14.15 MHz provides well-balanced band-edge performance, although the rear lobes become significant

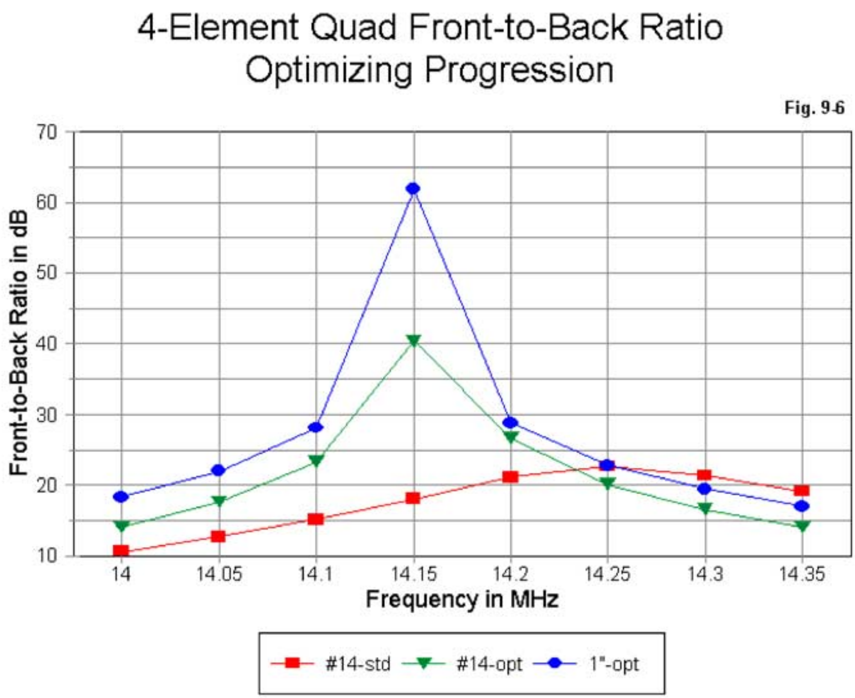
at both 14.0 and 14.35 MHz. A user would have to think long and hard about whether the front-to-back performance of this array would be truly satisfactory for the types of operation selected for a given installation.

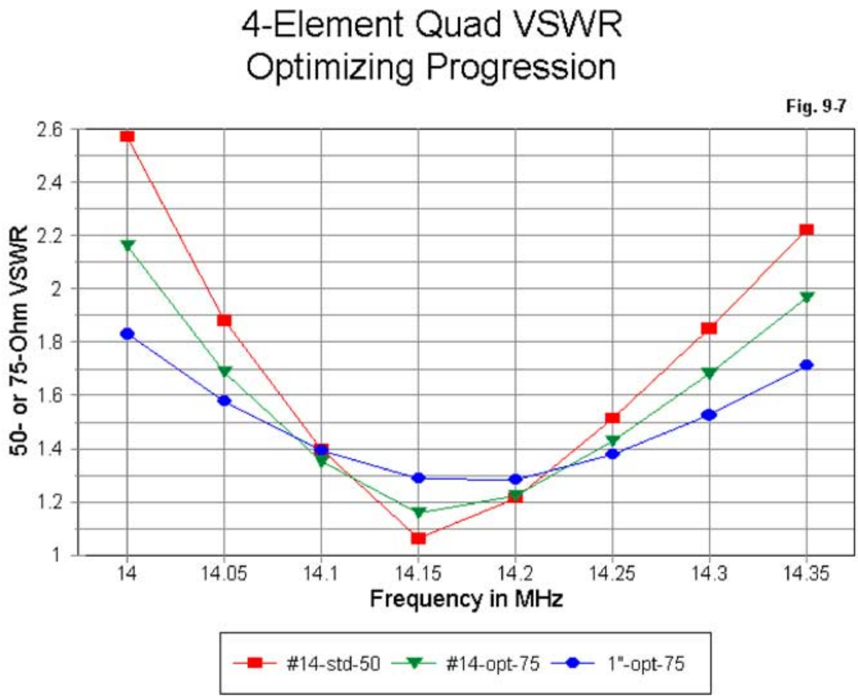
The rear lobes of **Fig. 9-5** show that the 1" diameter model belongs to the same design sequence as the optimized #14 model. However, the band-edge rearward performance is considerably improved over the thin-wire model. The rear lobe aligned 180-degrees from the forward lobe at 14.175 MHz shows how steep the front-to-back curve is, since the peak occurs at 14.15 MHz.




In fact, **Fig. 9-6** reveals the 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.

In **Fig. 9-7**, we have the SWR curves, although we must remember which represent a 50-Ohm value and which 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 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.



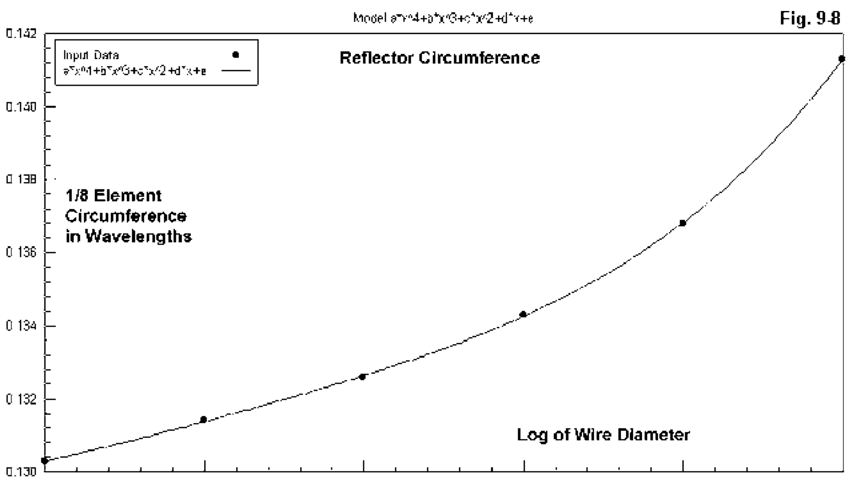



**Automating 4-Element Quad Design**

Both optimized design 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 changed in increments that resulted in a sequence of the common logarithms of the wire size in wavelengths of 0.5. This interval ensure a regression analysis that could be carried out to the 4th order.

**Fig. 9-8** shows the reflector circumference (more correctly, the value of 1/8 of the reflector circumference) curve developed vie 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 required for the 3-element quads shown in preceding episodes. The spacing required 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 span 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 <2:1 SWR standard (50 Ohms), but the front-to-back ratio hold 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, the program does give proper 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 (although 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.

```
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"
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"
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 <2:1 SWR bandwidth as a percentage of the design frequency, and the >20 dB front-to-back ratio bandwidth also as a percentage of the design frequency. Since the latter two curves are not symmetrical on either side of the design frequency, careful selection of the design frequency is important.

As with the other GW Basic programs in this volume, 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 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.

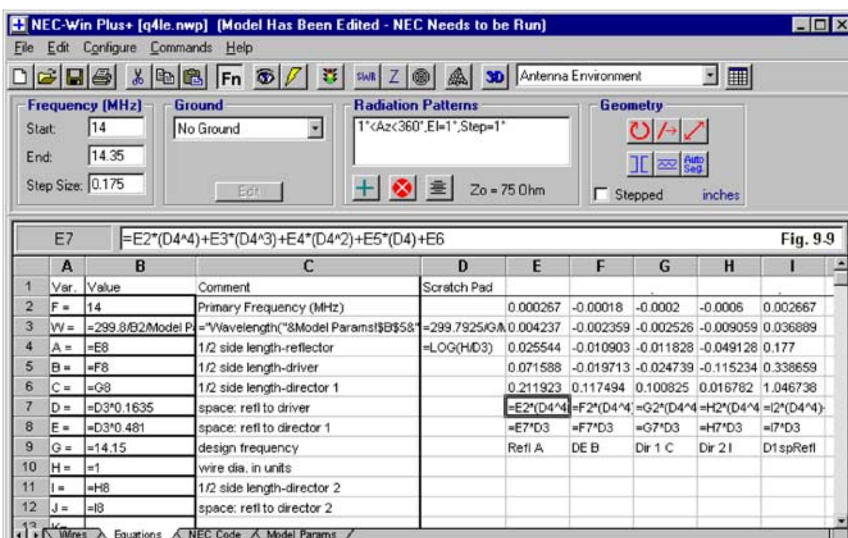
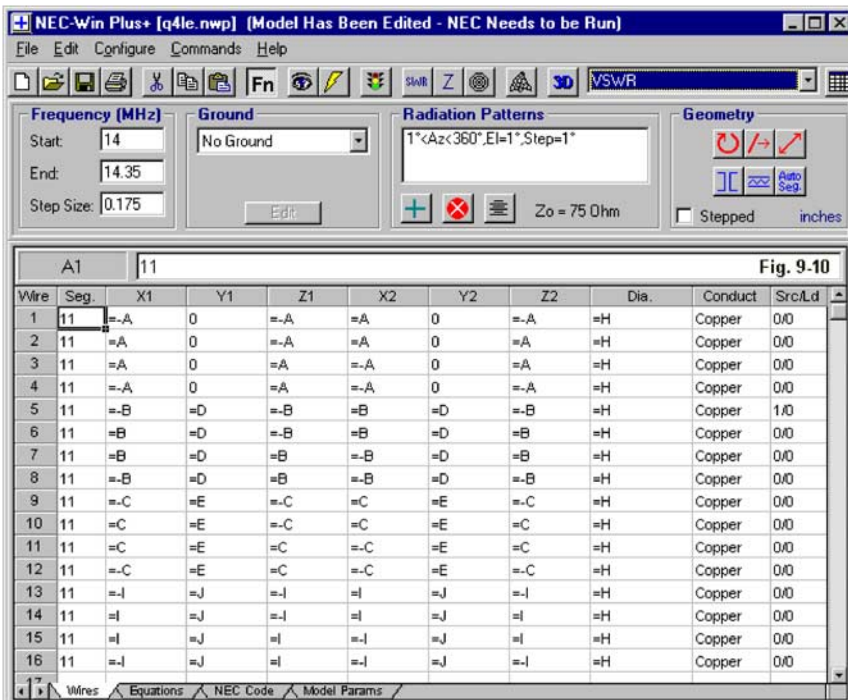


**Fig. 9-9** shows the equations page for the 4-element automated design. The two "fixed" element spacing figures can be spotted in the left-most column, since they do not make reference to the spreadsheet cells right of the comments column.

The forward director variables occur after the design input and element diameter variables (which the user varies to change a design). This placement results from using and expanding a previous 3-element model to arrive at the 4-element version. The sample page uses 1" elements with a design frequency of 14.15 MHz to equalize band edge performance to the degree possible.




| Wire | Seg. | X1 | Y1 | Z1 | X2 | Y2 | Z2 | Dia. | Conduct | Src/Ld |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 11 | =-A | 0 | =-A | =A | 0 | =-A | =H | Copper | 0/0 |
| 2 | 11 | =A | 0 | =-A | =A | 0 | =A | =H | Copper | 0/0 |
| 3 | 11 | =A | 0 | =A | =-A | 0 | =A | =H | Copper | 0/0 |
| 4 | 11 | =-A | 0 | =A | =-A | 0 | =-A | =H | Copper | 0/0 |
| 5 | 11 | =-B | =D | =-B | =B | =D | =-B | =H | Copper | 1/0 |
| 6 | 11 | =B | =D | =-B | =B | =D | =B | =H | Copper | 0/0 |
| 7 | 11 | =B | =D | =B | =-B | =D | =B | =H | Copper | 0/0 |
| 8 | 11 | =-B | =D | =B | =-B | =D | =-B | =H | Copper | 0/0 |
| 9 | 11 | =-C | =E | =-C | =C | =E | =-C | =H | Copper | 0/0 |
| 10 | 11 | =C | =E | =-C | =C | =E | =C | =H | Copper | 0/0 |
| 11 | 11 | =C | =E | =C | =-C | =E | =C | =H | Copper | 0/0 |
| 12 | 11 | =-C | =E | =C | =-C | =E | =-C | =H | Copper | 0/0 |
| 13 | 11 | =-I | =J | =-I | =I | =J | =-I | =H | Copper | 0/0 |
| 14 | 11 | =I | =J | =-I | =I | =J | =I | =H | Copper | 0/0 |
| 15 | 11 | =I | =J | =I | =-I | =J | =I | =H | Copper | 0/0 |
| 16 | 11 | =-I | =J | =I | =-I | =J | =-I | =H | Copper | 0/0 |

**Fig. 9-10**

**Fig. 9-10** shows the set-up page for the quad. As with all of the multi-element quad arrays, the standard material is copper. The performance data for aluminum would not significantly differ from copper. Nor would the requisite design frequency to equalize band edge performance.

The set-up wires page does show that as one adds only a single element to an array, two more variables appear to make the process of optimization more complex and less certain. Consequently, to treat this program and model as more tentative than the preceding versions for 2- and 3-element arrays is very much in order.

### Some Foreshadowings

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 quad 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.

# Chapter 10
# Some Notes on Long-Boom Quads

In the course of examining existing designs for long-boom, high-gain monoband quad beams, I have been struck but the "hit or miss" nature of the designs. Although popular since the 1960s, quad design appears to have missed out on anything systematic. The absence of systematic design principles does not apply to the basic nature of loops, which are well covered in books by Haviland and Orr. However, the addition of parasitic elements to achieve gain, front-to-back, and operating bandwidth seems almost devoid of adequate study and full treatment.

As a step in the direction of such investigations, these notes offer some thoughts on modeling studies into parasitic quad beams. More precisely, they offer three (of many possible) approaches to the design of long boom quad beams. What the designs reveal may be useful to others in further work.

The baseline for each of the approaches was to produce a quad beam model that yielded 11 dBi free-space gain and about 20 dB or more of 180-degree front-to-back ratio across the operating bandwidth. The operating bandwidth itself would eventually become a consideration, but was not among initial concerns. All antennas were designed and modeled for 20 meters, with a 14.175 MHz design frequency.

I selected the gain level based on the popular notion that a quad loop can achieve about 1.8 to 1.9 dB more gain than an equivalent dipole. This notion has given rise to the presumption that a quad beam has about the same gain advantage over a Yagi with the same number of elements and a similar boom length. However, the presumption does not work out in reality, largely because quad beams are constructed using thin wire elements in contrast to the fatter tubing used by typical Yagis. Because the thin wire results in lower levels of inter-element coupling, the quad's gain advantage is seriously reduced and is often completely negated in large arrays. Some of the gain advantage can be restored by the use of fatter elements, which in models can be single fat wire elements or multi-wire simulated fat elements. The restoration of gain through the use of dual-wire elements, despite the higher material losses of the dual thin wires, tends to demonstrate the relative dominance of inter-element coupling over wire loss in establishing the gain of a large array. For this reason, the models we shall discuss use a variety of wire sizes, ranging from 1/10 to 1/2 inch.

The selection of the 20-dB front-to-back criterion rests on the ability of monoband Yagis to achieve this figure routinely across the designed operating passband. Equivalent performance should be possible from a quad if it is to justify itself as a competitor for the Yagi. (This considerations is apart from operational reports that quads have an advantage at band openings and closings. Models cannot simulate the propagation conditions that would either confirm of disconfirm such reports.)

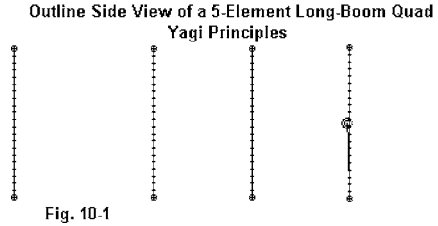
The approaches taken to designing this collection of long-boom quads are varied. The first design is a direct adaptation of parasitic element placement taken from Yagi design. The second is a wide-band variation of Yagi design sometimes called optimized wide-band arrays (OWA). The third approach uses wide-spaced principles in which elements use approximately the same spacing throughout the design.

### 1. The Standard Yagi Approach

The first approach to quad designs uses standard Yagi spacing as a basis for quad design, with element size and spacing optimized after initial placement. I used the approach to design a 3-element quad with excellent performance over its passband. However, several peculiarities--relative to a comparison Yagi--appeared in the results. First, the element spacing was somewhat larger than for the Yagi, despite elements of the same diameter. Second, the operating bandwidth for both the front-to-back ratio and the SWR were considerably narrower than for the Yagi. Third, instead of the traditional 50 to 100 Ohm quad feedpoint impedance, the 3-element quad showed a feedpoint impedance close to 25 Ohms. All of these conditions and limitations also showed up on a longer version of the antenna.

For a Yagi model, I took a 3-element 20-meter design developed by K6STI and added 2 directors. It is equivalent to a 48' boom length Yagi that would provide about 10.1 dBi free space gain across 20 meters with good front-to-back figures. I then built a quad based on the Yagi. After optimizing the 0.1" diameter elements and spacing them to achieve 11 dBi free-space gain and a good front-to-back ratio, the boom length rose to 50.36'. **Fig. 10-1** presents a side view of the antenna to show the relative element spacing.

**Fig. 10-2** provides a free-space azimuth pattern for the antenna at the design frequency. Despite its excellent pattern, the antenna turned out to have a narrow operating bandwidth: a little over 110 kHz on 20 meters. If we accept this restriction, then the antenna has much to recommend it, including the achievement of 11 dBi free-space gain with only 5 elements. (Wide-band designs will require 6 elements for the same gain.) **Table 10-1** provides dimensions for the antenna (in feet).



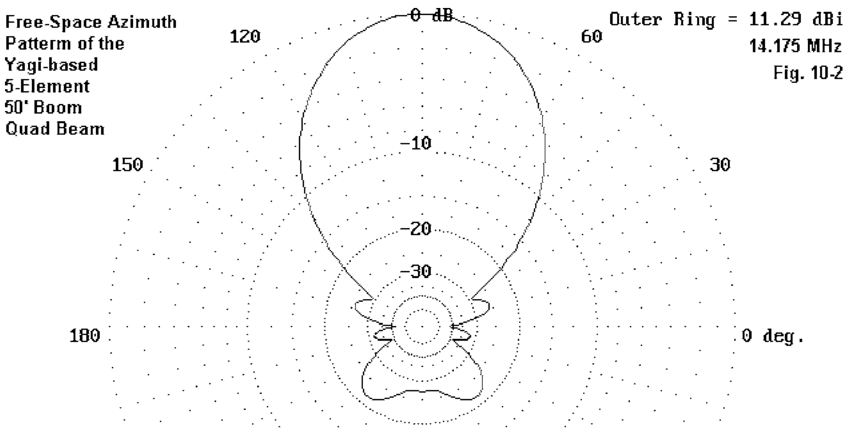




**Table 10-1. 5-Element Yagi-Based Quad Dimensions**

| Element | Length/Side (feet) | Circumference (feet) | Distance from Reflector (feet) |
|---|---|---|---|
| Reflector | 18.11 | 72.45 | ----- |
| Driver | 17.77 | 71.06 | 11.25 |
| Director 1 | 17.38 | 69.54 | 22.62 |
| Director 2 | 17.38 | 69.54 | 34.00 |
| Director 3 | 17.38 | 69.54 | 50.36 |

**Fig. 10-3** presents the free-space gain of the 5-element quad over its working bandwidth. The rate of gain change--nearly 0.25 dB over 110 kHz--is quite high, and that performance is one mark of a narrow-band antenna design. Nonetheless, the gain figures exceed the 11 dBi target everywhere in the passband.

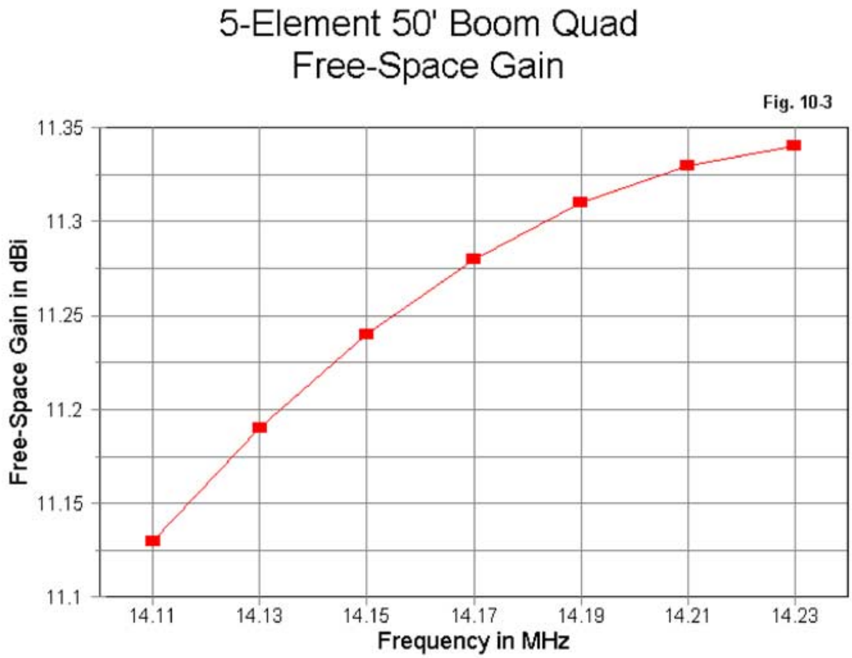
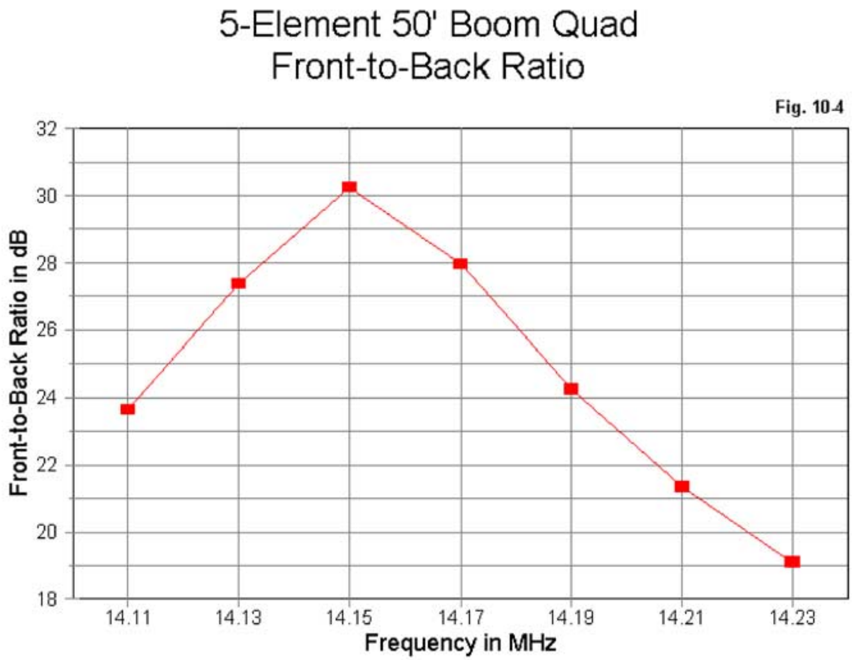


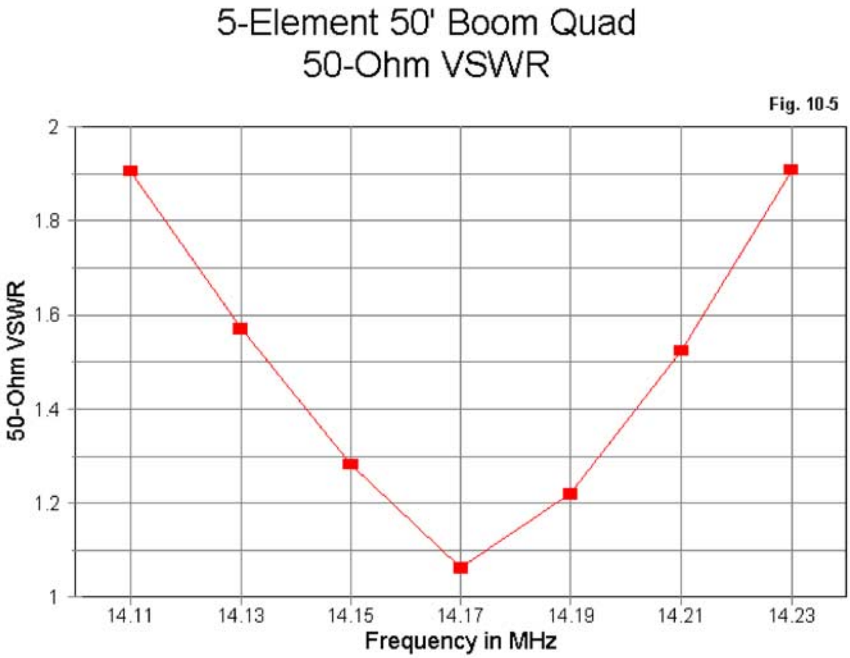

**Fig. 10-4** shows the front-to-back ratio over the same bandwidth. The peak is over 30 dB, but the rate of decrease from the peak is fairly rapid. With slightly more optimizing effort, the peak front-to-back ratio might be better centered in the passband. The result of centering the front-to-back peak would be better than 20 dB across the passband.

The VSWR curve (**Fig. 10-5**) is the 50-Ohm SWR resulting from matching the feedpoint of the model. The resonant 25-Ohm feed impedance was transformed via a 1/4-wavelength section of 37.5-Ohm coax (presumptively made from parallel sections of 75-Ohm cable). The limits of the graph show values just above 1.9:1 at each end. However, the SWR curve continues to steepen at both ends of the passband so that only about another 10-15 kHz are available before the SWR reaches 2:1.




The 5-element quad design would be inappropriate for use on 20 meters except for certain operators who use only small portions of the band. However, scaled to 17 or 12 meters, the antenna would provide the same performance and cover the entire 100 kHz band. Indeed, if this design has a home at all, it would be on the WARC bands.

Of all the quad designs that we shall consider, the 5-element Yagi-based design is the most compact. However, most quad builders shy away from antennas with odd numbers of elements. Performance is not so much the worry as is mounting the antenna. With an odd number of elements, the center-most element comes quite close to the tower unless one uses a long mast above the tower-top. One can overcome the problem to some degree by weighting the mast to one side or the other. Still, balancing weight loads and wind loads makes this move uncertain for all but those with considerable mechanical engineering experience.




The following table is the EZNEC model description for anyone who wishes to experiment further with the design.

```
5 el quad 20 m                                Frequency = 14.175  MHz.

Wire Loss: Copper -- Resistivity = 1.74E-08 ohm-m, Rel. Perm. = 1

              --------------- WIRES ---------------

Wire Conn. --- End 1 (x,y,z : ft)  Conn. --- End 2 (x,y,z : ft)  Dia(in) Segs

1     W4E2  -9.056,  0.000, -9.056  W2E1   9.056,  0.000, -9.056 1.03E-01  21
2     W1E2   9.056,  0.000, -9.056  W3E1   9.056,  0.000,  9.056 1.03E-01  21
3     W2E2   9.056,  0.000,  9.056  W4E1  -9.056,  0.000,  9.056 1.03E-01  21
4     W3E2  -9.056,  0.000,  9.056  W1E1  -9.056,  0.000, -9.056 1.03E-01  21
5     W8E2  -8.883, 11.248, -8.883  W6E1   8.883, 11.248, -8.883 1.03E-01  21
6     W5E2   8.883, 11.248, -8.883  W7E1   8.883, 11.248,  8.883 1.03E-01  21
```

```
7     W6E2   8.883, 11.248,  8.883  W8E1  -8.883, 11.248,  8.883 1.03E-01  21
8     W7E2  -8.883, 11.248,  8.883  W5E1  -8.883, 11.248, -8.883 1.03E-01  21
9    W12E2  -8.692, 22.623, -8.692 W10E1   8.692, 22.623, -8.692 1.03E-01  21
10    W9E2   8.692, 22.623, -8.692 W11E1   8.692, 22.623,  8.692 1.03E-01  21
11   W10E2   8.692, 22.623,  8.692 W12E1  -8.692, 22.623,  8.692 1.03E-01  21
12   W11E2  -8.692, 22.623,  8.692  W9E1  -8.692, 22.623, -8.692 1.03E-01  21
13   W16E2  -8.692, 33.999, -8.692 W14E1   8.692, 33.999, -8.692 1.03E-01  21
14   W13E2   8.692, 33.999, -8.692 W15E1   8.692, 33.999,  8.692 1.03E-01  21
15   W14E2   8.692, 33.999,  8.692 W16E1  -8.692, 33.999,  8.692 1.03E-01  21
16   W15E2  -8.692, 33.999,  8.692 W13E1  -8.692, 33.999, -8.692 1.03E-01  21
17   W20E2  -8.692, 50.360, -8.692 W18E1   8.692, 50.360, -8.692 1.03E-01  21
18   W17E2   8.692, 50.360, -8.692 W19E1   8.692, 50.360,  8.692 1.03E-01  21
19   W18E2   8.692, 50.360,  8.692 W20E1  -8.692, 50.360,  8.692 1.03E-01  21
20   W19E2  -8.692, 50.360,  8.692 W17E1  -8.692, 50.360, -8.692 1.03E-01  21
21          -0.128, 11.503,  0.000         0.128, 11.503,  0.000 1.03E-01  1

              -------------- SOURCES --------------

Source    Wire      Wire #/Pct From End 1    Ampl.(V, A)  Phase(Deg.)  Type
          Seg.     Actual      (Specified)

1           1    21 / 50.00   ( 21 / 50.00)      1.000       0.000       V

No loads specified
                -------- TRANSMISSION LINES ---------

Line  Wire #/% From End 1   Wire #/% From End 1    Length       Z0   Vel Rev/
      Actual  (Specified)   Actual  (Specified)                Ohms Fact Norm

1      5/50.0  (  5/50.0)   21/50.0  ( 21/50.0)   11.619 ft    37.5  0.67  N

Ground type is Free Space
```

## 2. The OWA-Yagi Approach

The second and third design approaches attempt to see what might be required to achieve a quad beam with full 20-meter coverage. Ideally, this coverage would include the following criteria:

1. Less than 2:1 SWR across the band;
2. Greater than 11 dBi free-space gain across the band;
3. Greater than 20 dB 180-degree front-to-back ratio across the band.

In the end, I settled for some reasonable compromises. Still, the resulting designs have some aspects that make them less fit for direct construction.

The second approach also uses Yagi parasitic element principles, but of a special type. In Yagi design, the originator, NW3Z, refers to them as optimized wide-band arrays. He has developed 20 meter Yagis for 48' booms with about 10.1 dBi average gain and greater than 20 dB front-to-back ratio across 20 meters. These initial specifications sound very much like those of other 5-element Yagis on similar booms. However, the NW3Z design adds one more element, a director. By judicious spacing of the reflector and the added director from the driven element, the Yagi achieves a direct match top to a 50-Ohm feedline with low SWR (under 1.3:1) across the entire band.

Adapting the OWA principle to quad design proves to be feasible, although not without certain costs. First, the spacing of the reflector and the first director differ substantially from the Yagi version. As well, the entire array must by longer (61.2') than its Yagi counterpart to achieve the design goal of 11 dBi free-space gain.

Outline Side View of a 6-Element Long-Boom Quad
OWA Principles

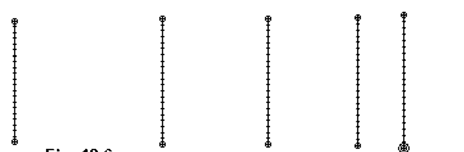


Fig. 10-6

**Fig. 10-6** shows the side view of the final design to provide a perspective on the required element spacing. Note especially the reflector and first director positions. **Fig. 10-7** is a free-space azimuth pattern for the design at its design frequency, 14.175 MHz.

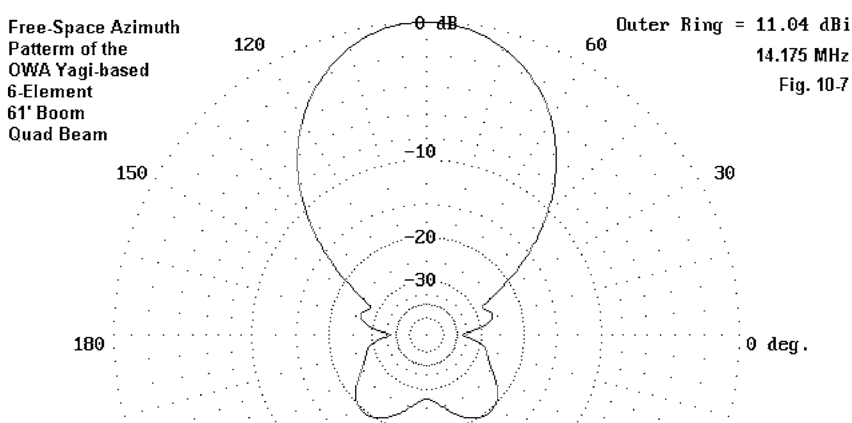
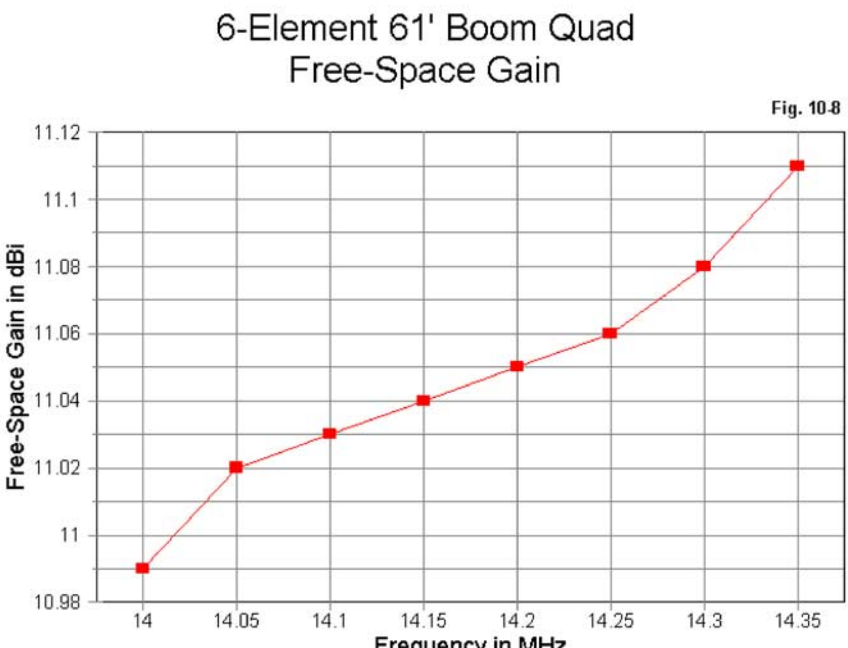



Fig. 10-7

An added cost to achieve the design goals was the use of 0.5" diameter elements in all of the elements. Hence, the design is unlikely to be directly implemented, although alternative element construction is possible. **Table 10-2** provides the array dimensions for 20 meters. Once more, all dimensions are in feet.

**Table 10-2. 6-Element OWA Quad Dimensions**

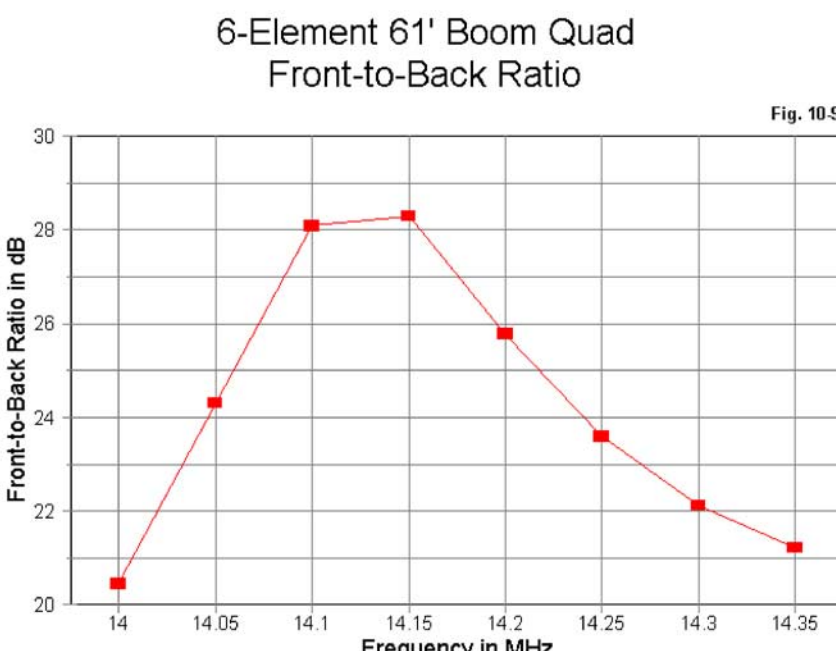
| Element | Length/Side (feet) | Circumference (feet) | Distance from Reflector (feet) |
|---|---|---|---|
| Reflector | 18.54 | 74.16 | ----- |
| Driver | 18.52 | 74.08 | 9.06 |
| Director 1 | 17.06 | 68.24 | 15.32 |
| Director 2 | 16.84 | 67.36 | 27.39 |
| Director 3 | 16.82 | 67.28 | 41.38 |
| Director 4 | 16.30 | 65.20 | 61.20 |



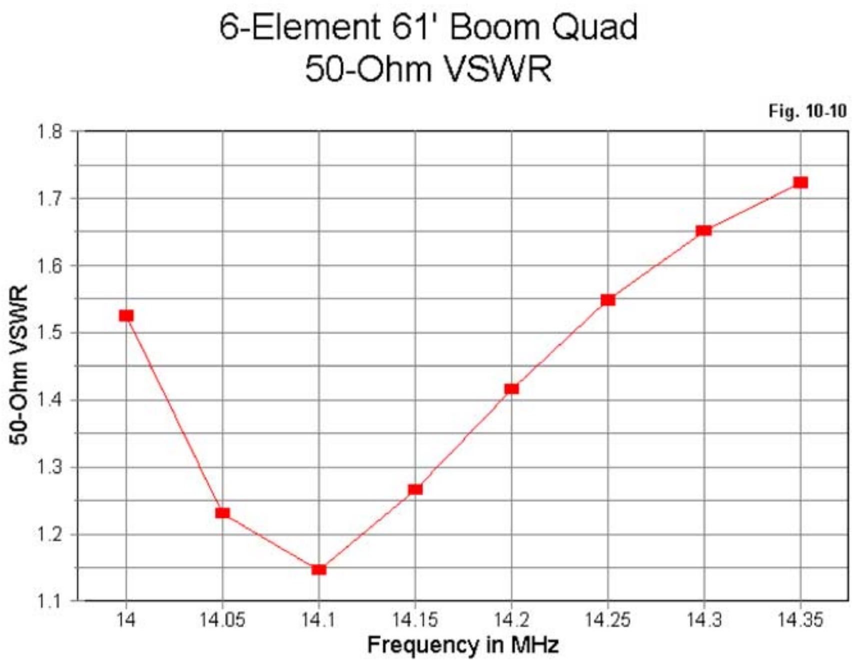
If you compare the element dimensions with those for the 5-element narrow-band quad, you will discover some interesting differences other than spacing. First, the OWA reflector and driver have dimensions that are quite close to each other, with both being somewhat longer than the corresponding elements in the 5-element array. Second, the directors tend to be shorter than those in the smaller beam.

For the performance curves, we shall use the entire 20 meter band from 14.0 to 14.35 MHz. The gain of the OWA 6-element quad is quite stable, as shown in **Fig. 10-8**. It ranges from 10.99 to 11.11 across the band. This is about 1/3 the variation of the smaller array despite the 3-fold increase in operating bandwidth. The shape of the gain curve, however, suggests that the gain stability limits of the array are not very much wider than the 20 meter band itself. Note the increasing rates of change near the band edges.

The front-to-back ratio across 20 meters appears in **Fig. 10-9**. Of all the array approaches tested in this exercise, the OWA design is the only one to achieve greater



than 20 dB front-to-back ratio for the full passband. Part of the reason for this result stems from the use of very large diameter elements. Single-wire elements of the usual #12/#14 AWG material will not yield the front-to-back operating bandwidth. However, large-diameter single-wire elements may be simulated within limits by 2- and 3-wire elements, as described in Chapter 5.




The OWA 6-element quad provides a direct 50-Ohm match with no matching network components, as shown in **Fig. 10-10**. Interestingly, the shape of the pattern resembles that for the corresponding OWA 6-element Yagi, but with higher band-edge values. Despite the ability of the design to cover 20 meters fully, the quad shows itself to be inherently more narrow-banded than counterpart Yagis.

The OWA quad is quite possibly a usable design for a high performance, full band coverage array, with one exception. The 0.5" diameter elements are not feasible using standard quad construction techniques that employ relatively lightweight fiberglass or similar element support arms. Significant reductions in the effective element diameter reduce inter-element coupling and result in gain and operating bandwidth reductions. The solution is to redesign the array for dual-wire elements using #14 or #12 wire. However, the substitutions will require extensive re-optimization of element lengths to restore the performance curves. Because the closely-spaced loops would require between 2 and 3 times the number of segments per element, with an increase in the number of modeling wires, the slow process was not endured for this exercise. Nonetheless, more extensive work on 2-element quads, described in past articles, strongly suggests that the substitution is quite achievable.

For anyone who wishes to work further with this type of design, the following table is the EZNEC model description.

**6 el 20 meter owa quad** **Frequency = 14.175 MHz.**

**Wire Loss: Copper -- Resistivity = 1.74E-08 ohm-m, Rel. Perm. = 1**

**--------------- WIRES ---------------**

| Wire | Conn. | --- End 1 (x,y,z : ft) | Conn. | --- End 2 (x,y,z : ft) | Dia(in) | Segs |
|---|---|---|---|---|---|---|
| 1 | W4E2 | -9.270, 0.000, -9.270 | W2E1 | 9.270, 0.000, -9.270 | 5.00E-01 | 21 |
| 2 | W1E2 | 9.270, 0.000, -9.270 | W3E1 | 9.270, 0.000, 9.270 | 5.00E-01 | 21 |
| 3 | W2E2 | 9.270, 0.000, 9.270 | W4E1 | -9.260, 0.000, 9.270 | 5.00E-01 | 21 |
| 4 | W3E2 | -9.260, 0.000, 9.270 | W1E1 | -9.270, 0.000, -9.270 | 5.00E-01 | 21 |
| 5 | W8E2 | -8.950, 9.056, -8.950 | W6E1 | 8.950, 9.056, -8.950 | 5.00E-01 | 21 |
| 6 | W5E2 | 8.950, 9.056, -8.950 | W7E1 | 8.950, 9.056, 8.950 | 5.00E-01 | 21 |
| 7 | W6E2 | 8.950, 9.056, 8.950 | W8E1 | -8.950, 9.056, 8.950 | 5.00E-01 | 21 |
| 8 | W7E2 | -8.950, 9.056, 8.950 | W5E1 | -8.950, 9.056, -8.950 | 5.00E-01 | 21 |
| 9 | W12E2 | -8.530, 15.320, -8.530 | W10E1 | 8.530, 15.320, -8.530 | 5.00E-01 | 21 |
| 10 | W9E2 | 8.530, 15.320, -8.530 | W11E1 | 8.530, 15.320, 8.530 | 5.00E-01 | 21 |
| 11 | W10E2 | 8.530, 15.320, 8.530 | W12E1 | -8.530, 15.320, 8.530 | 5.00E-01 | 21 |
| 12 | W11E2 | -8.530, 15.320, 8.530 | W9E1 | -8.530, 15.320, -8.530 | 5.00E-01 | 21 |
| 13 | W16E2 | -8.420, 27.388, -8.420 | W14E1 | 8.420, 27.388, -8.420 | 5.00E-01 | 21 |
| 14 | W13E2 | 8.420, 27.388, -8.420 | W15E1 | 8.420, 27.388, 8.420 | 5.00E-01 | 21 |
| 15 | W14E2 | 8.420, 27.388, 8.420 | W16E1 | -8.420, 27.388, 8.420 | 5.00E-01 | 21 |
| 16 | W15E2 | -8.420, 27.388, 8.420 | W13E1 | -8.420, 27.388, -8.420 | 5.00E-01 | 21 |
| 17 | W20E2 | -8.410, 41.383, -8.410 | W18E1 | 8.410, 41.383, -8.410 | 5.00E-01 | 21 |
| 18 | W17E2 | 8.410, 41.383, -8.410 | W19E1 | 8.410, 41.383, 8.410 | 5.00E-01 | 21 |
| 19 | W18E2 | 8.410, 41.383, 8.410 | W20E1 | -8.410, 41.383, 8.410 | 5.00E-01 | 21 |
| 20 | W19E2 | -8.410, 41.383, 8.410 | W17E1 | -8.410, 41.383, -8.410 | 5.00E-01 | 21 |
| 21 | W24E2 | -8.150, 61.200, -8.150 | W22E1 | 8.150, 61.200, -8.150 | 5.00E-01 | 21 |
| 22 | W21E2 | 8.150, 61.200, -8.150 | W23E1 | 8.150, 61.200, 8.150 | 5.00E-01 | 21 |
| 23 | W22E2 | 8.150, 61.200, 8.150 | W24E1 | -8.150, 61.200, 8.150 | 5.00E-01 | 21 |
| 24 | W23E2 | -8.150, 61.200, 8.150 | W21E1 | -8.150, 61.200, -8.150 | 5.00E-01 | 21 |

```
              -------------- SOURCES --------------

Source    Wire      Wire #/Pct From End 1    Ampl.(V, A)  Phase(Deg.)  Type
          Seg.     Actual      (Specified)

1          11     5 / 50.00   (  5 / 50.00)      1.000       0.000       V

No loads specified
No transmission lines specified
Ground type is Free Space
```

### 3. The Wide-Spaced Approach

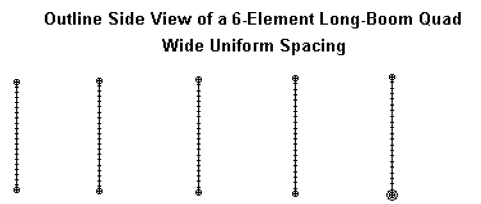


Fig. 10-11

A third approach to long-boom quad design employs relatively wide but uniform spacing between elements. Beginning with a driver-reflector spacing that approaches the optimum for a 2-element maximum front-to-back ratio design, the directors are then added at similar spacings from each other. The director element lengths show a consistent decrease in length as one moves forward from the driver. **Fig. 10-11** shows the side view to give some perspective on the overall design of a 6-element array capable of 11 dBi free-space gain.

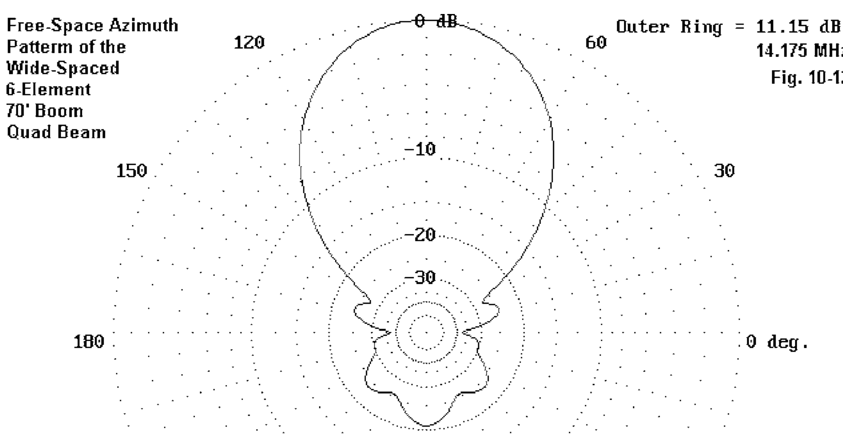


Fig. 10-12

The design-frequency free-space azimuth pattern appears in **Fig. 10-12**. The pattern is as well-behaved at the center of the passband as either of the other designs. No large unwanted side lobes appear in either the forward or the rear quadrants. Perfectionists, however, may still wish to remove the vestigial forward side lobes.

As a design exercise, I optimized the 6-element wide-spaced array using #8 AWG wire (0.1285" diameter). In part, I wanted to see what differences might result for the operating bandwidth, especially with respect to the front-to-back ratio. **Table 10-3** provides the physical dimensions of the model. As usual, all dimensions are in feet.

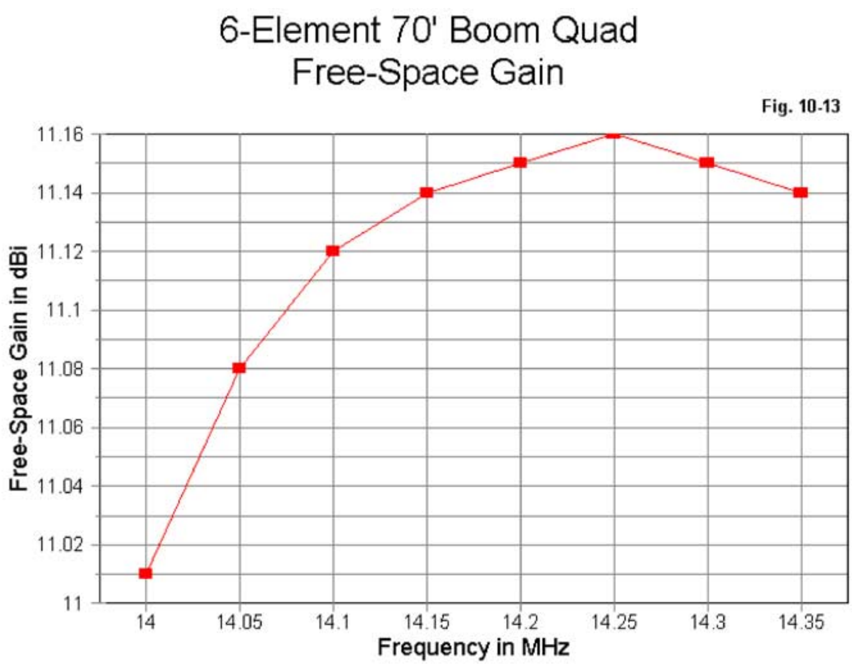



**Table 10-3. 6-Element Uniform Wide-Spaced Quad Dimensions**

| Element | Length/Side (feet) | Circumference (feet) | Distance from Reflector (feet) |
|---|---|---|---|
| Reflector | 18.43 | 73.72 | ----- |

| | | | |
|---|---|---|---|
| Driver | 17.70 | 70.80 | 13.95 |
| Director 1 | 17.23 | 68.92 | 28.29 |
| Director 2 | 16.83 | 67.32 | 42.78 |
| Director 3 | 16.57 | 66.27 | 57.60 |
| Director 4 | 16.13 | 64.51 | 69.82 |

Immediately apparent is the greater length of the array compared to the OWA version of a wide-band quad: 70' vs. 61'. More subtle are the required variations from uniformity in the element spacing. Although the average spacing is nearly 0.2 wavelength, the director spacings cannot be set by simple adherence to the average. Performance deteriorates rapidly using mere rules of thumb as guidance.

**Fig. 10-13** shows the gain curve across 20 meters for the wide-spaced array. Like the OWA array, the curve shows good stability, with a net variance of only 0.15 dB across the band. Note especially that a wide-spaced design is capable of placing the peak gain of the antenna well within the boundaries of the operating passband.

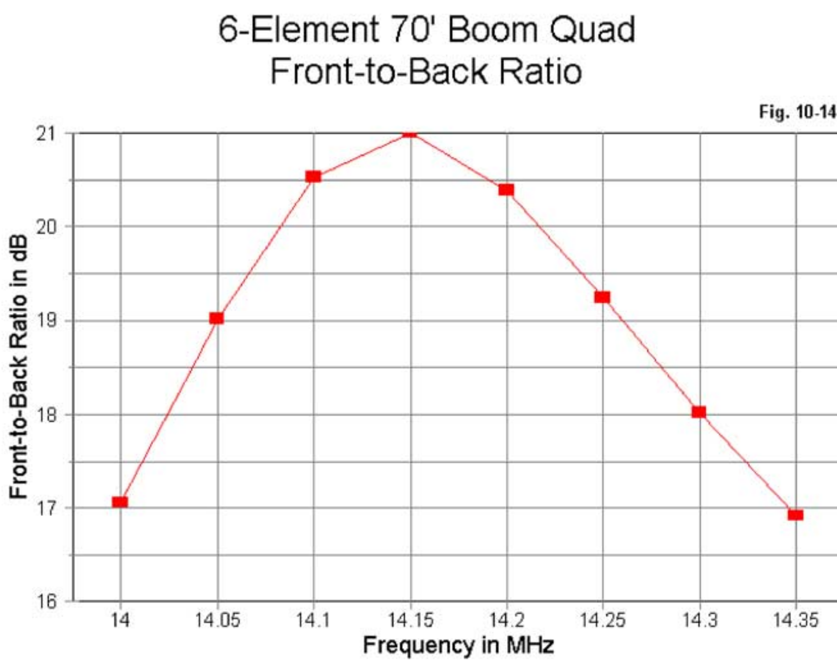
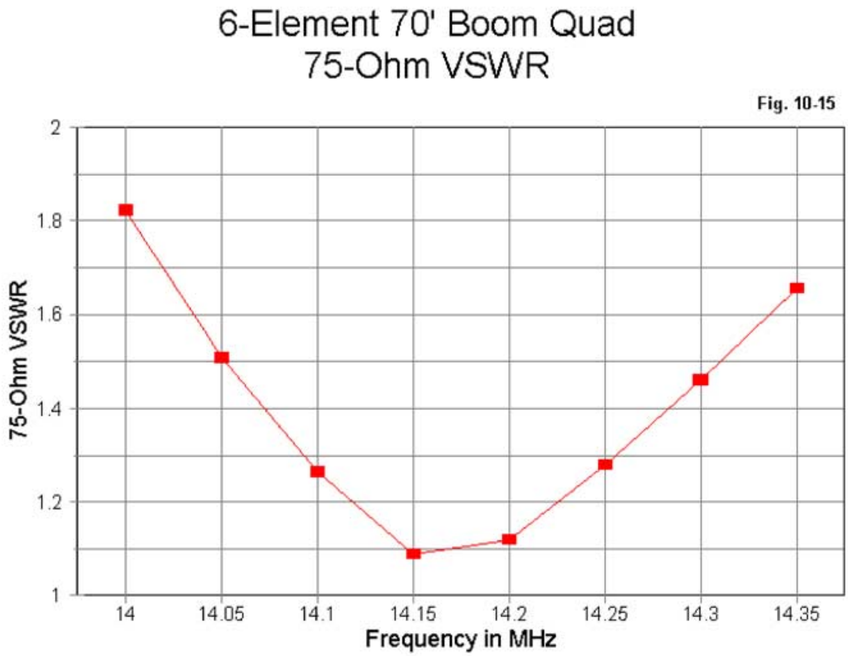


**Fig. 10-14**, the front-to-back curve across 20 meters, shows the effect of using small diameter wire for the elements. The band-edge front-to-back ratio is about 17 dB, and the peak value is 21 dB. To the present, I have found no way to increase the front-to-back performance within the constraints of the overall length and the wire size. However, the use of large-diameter elements or dual-wire substitutes shows promise of improving this aspect of performance considerably.




The SWR curve for the wide-spaced 6-element array appears in **Fig. 10-15**. Unlike the other curves, this one is a 75-Ohm VSWR curve, the inherent feedpoint impedance of the antenna. Matching the antenna to a 50-Ohm feedline requires the use of a simple transmission-line transformer. The band-edge reactance is well under +/-j40 Ohms for mid-band resonance of the driver.

The wide-spaced 6-element array has considerable potential for further development through the use of larger diameter elements or substitutes. Nevertheless, the key limiting factor in this direction is the boom length. Comparable Yagi designs with the same boom length would likely use 7 elements and provide equal gain, but superior front-to-back performance.

Those who might wish to further optimize the design can refer to the following EZNEC model description.

```
6-element wide-spaced 20m quad                      Frequency = 14.175  MHz.

Wire Loss: Aluminum -- Resistivity = 4E-08 ohm-m, Rel. Perm. = 1

              --------------- WIRES ---------------

Wire Conn. --- End 1 (x,y,z : ft)  Conn. --- End 2 (x,y,z : ft)  Dia(in) Segs

1     W4E2  -9.216,  0.000, -9.216  W2E1   9.216,  0.000, -9.216    #  8   21
2     W1E2   9.216,  0.000, -9.216  W3E1   9.216,  0.000,  9.216    #  8   21
3     W2E2   9.216,  0.000,  9.216  W4E1  -9.216,  0.000,  9.216    #  8   21
4     W3E2  -9.216,  0.000,  9.216  W1E1  -9.216,  0.000, -9.216    #  8   21
5     W8E2  -8.850, 13.945, -8.850  W6E1   8.850, 13.945, -8.850    #  8   21
6     W5E2   8.850, 13.945, -8.850  W7E1   8.850, 13.945,  8.850    #  8   21
7     W6E2   8.850, 13.945,  8.850  W8E1  -8.850, 13.945,  8.850    #  8   21
8     W7E2  -8.850, 13.945,  8.850  W5E1  -8.850, 13.945, -8.850    #  8   21
9    W12E2  -8.615, 28.289, -8.615 W10E1   8.615, 28.289, -8.615    #  8   21
10    W9E2   8.615, 28.289, -8.615 W11E1   8.615, 28.289,  8.615    #  8   21
11   W10E2   8.615, 28.289,  8.615 W12E1  -8.615, 28.289,  8.615    #  8   21
12   W11E2  -8.615, 28.289,  8.615  W9E1  -8.615, 28.289, -8.615    #  8   21
13   W16E2  -8.415, 42.775, -8.415 W14E1   8.415, 42.775, -8.415    #  8   21
14   W13E2   8.415, 42.775, -8.415 W15E1   8.415, 42.775,  8.415    #  8   21
15   W14E2   8.415, 42.775,  8.415 W16E1  -8.415, 42.775,  8.415    #  8   21
16   W15E2  -8.415, 42.775,  8.415 W13E1  -8.415, 42.775, -8.415    #  8   21
17   W20E2  -8.284, 57.600, -8.284 W18E1   8.284, 57.600, -8.284    #  8   21
18   W17E2   8.284, 57.600, -8.284 W19E1   8.284, 57.600,  8.284    #  8   21
19   W18E2   8.284, 57.600,  8.284 W20E1  -8.284, 57.600,  8.284    #  8   21
20   W19E2  -8.284, 57.600,  8.284 W17E1  -8.284, 57.600, -8.284    #  8   21
21   W24E2  -8.064, 69.822, -8.064 W22E1   8.064, 69.822, -8.064    #  8   21
22   W21E2   8.064, 69.822, -8.064 W23E1   8.064, 69.822,  8.064    #  8   21
23   W22E2   8.064, 69.822,  8.064 W24E1  -8.064, 69.822,  8.064    #  8   21
24   W23E2  -8.064, 69.822,  8.064 W21E1  -8.064, 69.822, -8.064    #  8   21

              -------------- SOURCES --------------
Source    Wire      Wire #/Pct From End 1    Ampl.(V, A)  Phase(Deg.)  Type
          Seg.     Actual      (Specified)

1          11     5 / 50.00   (  5 / 50.00)      1.000       0.000       V

No loads specified
No transmission lines specified
Ground type is Free Space
```

## A Few Tentative Conclusions

Long-boom, high-performance, wide-bandwidth monoband quad design is not easily obtained. Although only three design approaches have been employed in this exercise, they indicate several trends in large quads:

1. A wide operating bandwidth is improbable for quad lengths similar to corresponding Yagi lengths, if superior performance is expected. Wide-band quads with superior performance will likely require greater boom lengths.

2. A key limiting factor in quad design is the use of small-diameter elements. Large-diameter elements, or suitable substitute dual-wire elements having similar inter-element coupling potential, are necessary for achieving high gain, high front-to-back ratios, and 2:1 SWR curves across the wider amateur bands.

3. Of the designs so far surveyed, perhaps the OWA version holds the most potential for the wider amateur bands (20, 15, and 10 meters). The 5-element array should be adequate for 30, 17, and 12 meters, assuming that one can compensate for the mechanical difficulty presented by the use of an odd number of elements.

Of course, this exercise is limited by exploring only three design approaches to the development of quads meeting the original design criteria. Hopefully, it will serve as a stepping stone in a more thorough exploration of all relevant design approaches. What seems clear is that the design of high-performance quads can no longer be left to haphazard approaches. Expecting wide operating bandwidths and high performance requires a full appreciation of parasitic element principles. Equally key to the process is an understanding of how quad elements resemble their corresponding Yagi elements and how quad elements differ in the process of inter-element coupling. None of the designs we have investigated can yet be said to have come close to the full potential of long-boom quads. At best, they are merely “pretty good.”

# Chapter 11
# A Place for Narrow-Band Quad Designs

One of the chief goals of this investigation has been to determine the conditions necessary for the widest possible operating bandwidth for monoband quad arrays. For this reason, we passed over the 5-element 20-meter quad based on Yagi principles. Its operating bandwidth did not come close to either the OWA of uniform wide spaced models using 6 elements.

However, there are important places in amateur radio operations for narrower band quads. Lest you think that I have wholly neglected such applications, you might review Volume 1 of this study. More to the point, let's examine a couple of designs for the non-harmonic amateur bands, otherwise known as the "WARC" bands. In particular, we shall explore adaptations of the array we neglected so that it becomes a very fitting quad beam for 17 and for 12 meters.

## A 5-Element Quad for 17 Meters

The outline of a 5-element quad for 17 meters appears in **Fig. 11-1**. There is no detectable difference between this sketch and the outline of the first 20-meter quad in chapter 10. The chief adjustments are the scaling of the element lengths, spacings, and wire diameter for the 18 MHz band, which is only 100 kHz wide (18.068 - 18.168 MHz). The wire size has been set to #12 AWG (0.0808"), since this is a standard wire and the wider bandwidth offered by fatter elements is not needed.

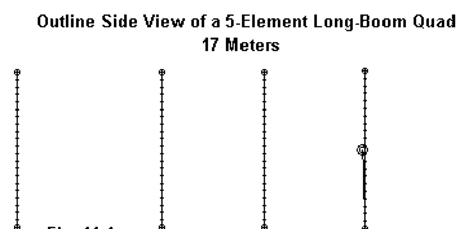


Fig. 11-1

The following EZNEC model description provides all of the design data. The boom length is 39.4'. Hence, the array would fit a 40' boom, including hardware for the support arms.

```
5 el quad 17 m                                      Frequency = 18.118  MHz.

Wire Loss: Copper -- Resistivity = 1.74E-08 ohm-m, Rel. Perm. = 1

              --------------- WIRES ---------------

Wire Conn. --- End 1 (x,y,z : ft)  Conn. --- End 2 (x,y,z : ft)  Dia(in) Segs

1     W4E2  -7.085,  0.000, -7.085  W2E1   7.085,  0.000, -7.085    # 12   21
2     W1E2   7.085,  0.000, -7.085  W3E1   7.085,  0.000,  7.085    # 12   21
3     W2E2   7.085,  0.000,  7.085  W4E1  -7.085,  0.000,  7.085    # 12   21
4     W3E2  -7.085,  0.000,  7.085  W1E1  -7.085,  0.000, -7.085    # 12   21
5     W8E2  -6.950,  8.800, -6.950  W6E1   6.950,  8.800, -6.950    # 12   21
6     W5E2   6.950,  8.800, -6.950  W7E1   6.950,  8.800,  6.950    # 12   21
7     W6E2   6.950,  8.800,  6.950  W8E1  -6.950,  8.800,  6.950    # 12   21
8     W7E2  -6.950,  8.800,  6.950  W5E1  -6.950,  8.800, -6.950    # 12   21
9    W12E2  -6.800, 17.700, -6.800 W10E1   6.800, 17.700, -6.800    # 12   21
10    W9E2   6.800, 17.700, -6.800 W11E1   6.800, 17.700,  6.800    # 12   21
11   W10E2   6.800, 17.700,  6.800 W12E1  -6.800, 17.700,  6.800    # 12   21
12   W11E2  -6.800, 17.700,  6.800  W9E1  -6.800, 17.700, -6.800    # 12   21
13   W16E2  -6.800, 26.600, -6.800 W14E1   6.800, 26.600, -6.800    # 12   21
14   W13E2   6.800, 26.600, -6.800 W15E1   6.800, 26.600,  6.800    # 12   21
15   W14E2   6.800, 26.600,  6.800 W16E1  -6.800, 26.600,  6.800    # 12   21
16   W15E2  -6.800, 26.600,  6.800 W13E1  -6.800, 26.600, -6.800    # 12   21
17   W20E2  -6.800, 39.400, -6.800 W18E1   6.800, 39.400, -6.800    # 12   21
18   W17E2   6.800, 39.400, -6.800 W19E1   6.800, 39.400,  6.800    # 12   21
19   W18E2   6.800, 39.400,  6.800 W20E1  -6.800, 39.400,  6.800    # 12   21
20   W19E2  -6.800, 39.400,  6.800 W17E1  -6.800, 39.400, -6.800    # 12   21
21          -0.100,  9.000,  0.000          0.100,  9.000,  0.000    # 12   1

              -------------- SOURCES --------------

Source    Wire      Wire #/Pct From End 1    Ampl.(V, A)  Phase(Deg.)  Type
          Seg.     Actual      (Specified)

1           1    21 / 50.00   ( 21 / 50.00)      1.000       0.000       V
No loads specified

                -------- TRANSMISSION LINES ---------

Line  Wire #/% From End 1   Wire #/% From End 1    Length       Z0   Vel Rev/
      Actual  (Specified)   Actual  (Specified)                Ohms Fact Norm

1      5/50.0  (  5/50.0)   21/50.0  ( 21/50.0)    9.090 ft    37.5  0.67  N

Ground type is Free Space
```

Included in the design is a quarter-wavelength matching section, since the native feedpoint impedance is close to 25 Ohms. For this reason, the model also has an extra wire (W21) that acts as the termination of the transmission line section and as the model source.

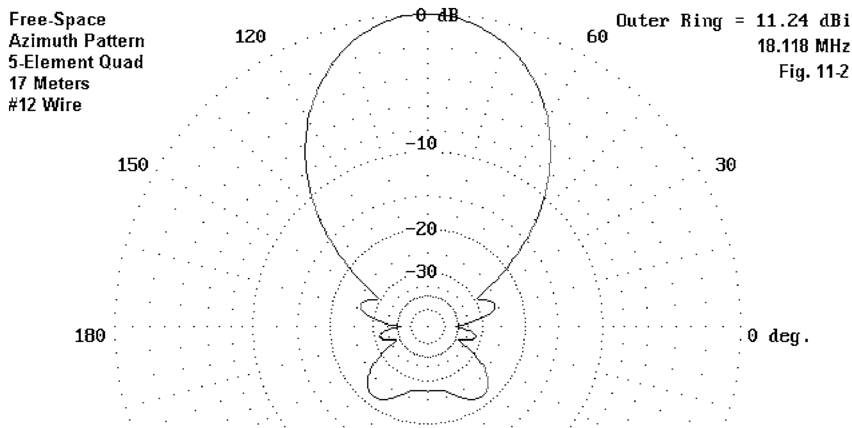



**Fig. 11-2** presents the free-space azimuth pattern for this array. Since large graphs of performance are unnecessary for such a narrow band as 17 meters, **Table 11-1** will summarize operating performance.

**Table 11-1. Performance of the 17-Meter 5-Element Quad**

| Frequency MHz | Gain dBi | F-B Ratio dB | Feedpoint Z R +/- jX Ohms | 50-Ohm VSWR |
|---|---|---|---|---|
| 18.068 | 11.16 | 28.85 | 44.5 + j 17.5 | 1.47 |
| 18.118 | 11.24 | 27.02 | 52.3 - j 1.5 | 1.05 |
| 18.168 | 11.28 | 20.79 | 42.7 - j 20.6 | 1.60 |

The worst-case front-to-back ratio is greater than 20 dB across the band. The gain varies by only 0.12 dB, while the SWR values at the band edges leave a good margin for inevitable construction variations that might displace the curve a bit.

## A 6-Element Quad for 12 Meters

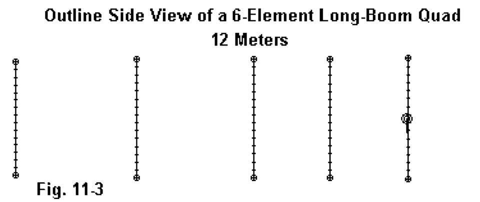


Fig. 11-3

If we readjust the design for 12 meters, retaining the #12 AWG elements, the resultant boom length is short enough to support another element without exceeding the 17-meter boom length. Therefore, I re-optimized the design as a 6-element array within the 39.4' length used by the 17-meter model. **Fig. 11-3** presents the outline of the resulting array.

The 12-meter array has a native feedpoint impedance similar to that of the 17-meter beam. Therefore, as shown in the model description that follows, a quarter-wavelength matching section is apt to this design as well.

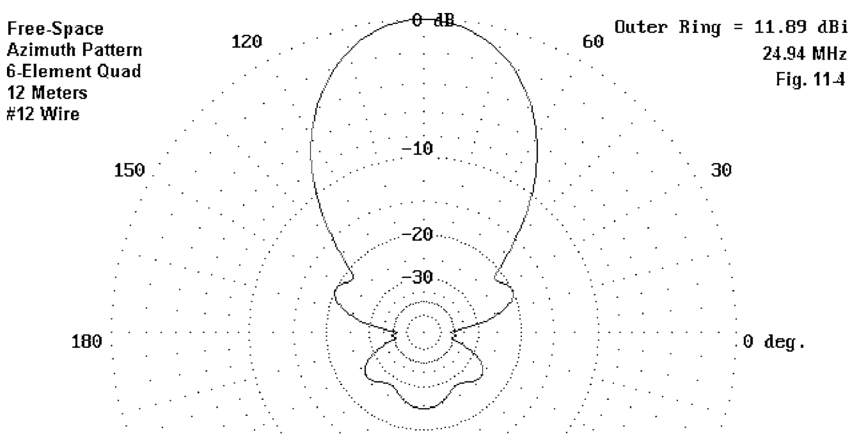
**6 el quad 12 m** **Frequency = 24.94 MHz.**

**Wire Loss: Copper -- Resistivity = 1.74E-08 ohm-m, Rel. Perm. = 1**

**--------------- WIRES ---------------**

| Wire | Conn. | --- End 1 (x,y,z : ft) | Conn. | --- End 2 (x,y,z : ft) | Dia(in) | Segs |
|---|---|---|---|---|---|---|
| 1 | W4E2 | -5.150, 0.000, -5.150 | W2E1 | 5.150, 0.000, -5.150 | # 12 | 15 |
| 2 | W1E2 | 5.150, 0.000, -5.150 | W3E1 | 5.150, 0.000, 5.150 | # 12 | 15 |
| 3 | W2E2 | 5.150, 0.000, 5.150 | W4E1 | -5.150, 0.000, 5.150 | # 12 | 15 |
| 4 | W3E2 | -5.150, 0.000, 5.150 | W1E1 | -5.150, 0.000, -5.150 | # 12 | 15 |
| 5 | W8E2 | -5.050, 6.400, -5.050 | W6E1 | 5.050, 6.400, -5.050 | # 12 | 15 |
| 6 | W5E2 | 5.050, 6.400, -5.050 | W7E1 | 5.050, 6.400, 5.050 | # 12 | 15 |
| 7 | W6E2 | 5.050, 6.400, 5.050 | W8E1 | -5.050, 6.400, 5.050 | # 12 | 15 |
| 8 | W7E2 | -5.050, 6.400, 5.050 | W5E1 | -5.050, 6.400, -5.050 | # 12 | 15 |
| 9 | W12E2 | -4.950, 13.000, -4.950 | W10E1 | 4.950, 13.000, -4.950 | # 12 | 15 |
| 10 | W9E2 | 4.950, 13.000, -4.950 | W11E1 | 4.950, 13.000, 4.950 | # 12 | 15 |
| 11 | W10E2 | 4.950, 13.000, 4.950 | W12E1 | -4.950, 13.000, 4.950 | # 12 | 15 |
| 12 | W11E2 | -4.950, 13.000, 4.950 | W9E1 | -4.950, 13.000, -4.950 | # 12 | 15 |
| 13 | W16E2 | -4.950, 19.350, -4.950 | W14E1 | 4.950, 19.350, -4.950 | # 12 | 15 |
| 14 | W13E2 | 4.950, 19.350, -4.950 | W15E1 | 4.950, 19.350, 4.950 | # 12 | 15 |
| 15 | W14E2 | 4.950, 19.350, 4.950 | W16E1 | -4.950, 19.350, 4.950 | # 12 | 15 |
| 16 | W15E2 | -4.950, 19.350, 4.950 | W13E1 | -4.950, 19.350, -4.950 | # 12 | 15 |
| 17 | W20E2 | -5.000, 29.200, -5.000 | W18E1 | 5.000, 29.200, -5.000 | # 12 | 15 |
| 18 | W17E2 | 5.000, 29.200, -5.000 | W19E1 | 5.000, 29.200, 5.000 | # 12 | 15 |
| 19 | W18E2 | 5.000, 29.200, 5.000 | W20E1 | -5.000, 29.200, 5.000 | # 12 | 15 |
| 20 | W19E2 | -5.000, 29.200, 5.000 | W17E1 | -5.000, 29.200, -5.000 | # 12 | 15 |
| 21 | W24E2 | -4.750, 39.400, -4.750 | W22E1 | 4.750, 39.400, -4.750 | # 12 | 15 |
| 22 | W21E2 | 4.750, 39.400, -4.750 | W23E1 | 4.750, 39.400, 4.750 | # 12 | 15 |

```
23   W22E2   4.750, 39.400,  4.750 W24E1  -4.750, 39.400,  4.750    # 12   15
24   W23E2  -4.750, 39.400,  4.750 W21E1  -4.750, 39.400, -4.750    # 12   15
25          -0.073,  6.538,  0.000         0.073,  6.538,  0.000    # 12   1

              -------------- SOURCES --------------

Source    Wire      Wire #/Pct From End 1    Ampl.(V, A)  Phase(Deg.)  Type
          Seg.     Actual      (Specified)

1           1    25 / 50.00   ( 25 / 50.00)      1.000       0.000       V
No loads specified

                -------- TRANSMISSION LINES ---------

Line  Wire #/% From End 1   Wire #/% From End 1    Length       Z0   Vel Rev/
      Actual  (Specified)   Actual  (Specified)               Ohms Fact Norm

1      5/50.0  (  5/50.0)   25/50.0  ( 25/50.0)    6.600 ft    37.5  0.67  N

Ground type is Free Space
```




As shown by **Fig. 11-4**, the extra element improves performance by about 0.6 dB. Like the 17-meter array, the 12-meter quad worst-case front-to-back ratio exceeds 20 dB across the band, and the total gain change is under 0.05 dB. **Table 11-2** provides full band data on performance.

**Table 11-2. Performance of the 12-Meter 6-Element Quad**

| Frequency MHz | Gain dBi | F-B Ratio dB | Feedpoint Z R +/- jX Ohms | 50-Ohm VSWR |
|---|---|---|---|---|
| 24.89 | 11.86 | 20.23 | 45.4 + j 11.8 | 1.30 |
| 24.94 | 11.89 | 24.23 | 49.3 + j 0.0 | 1.01 |
| 24.99 | 11.88 | 29.92 | 46.4 - j 13.2 | 1.33 |

As a percentage of the center frequency, the 12-meter band is narrower than the 17-meter band. Hence, the SWR curve is shallower on the upper band, despite the additional element.

## A Composite 5/6-element Quad Array for 17 and 12 Meters

The gain of the 6-element array can be slightly improved with an increase in spacing (and consequential resizing) of the most forward director. However, selection of the 39.4' boom length was not accidental. Both arrays can be combined on a single boom, using the same support arms for the reflectors and for the most forward directors of each array. **Fig. 11-5** outlines the resulting composite array. We shall address construction challenges before closing the book on this design.

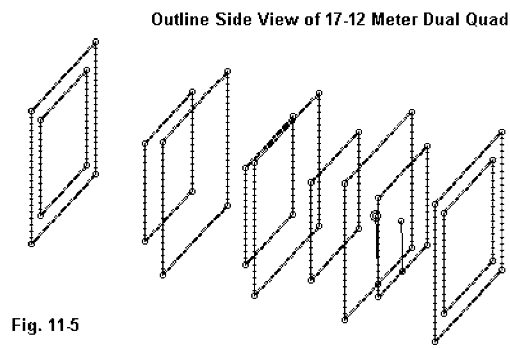


Fig. 11-5

The element lengths require only very slight adjustments to bring each array within the 17 and 12 meter band limits. The composite array has essentially the same performance as the independent quads that are combined. The following model description will help us locate the necessary changes.

**5/6 el quad 17/12 m Frequency = 18.118 MHz.**

**Wire Loss: Copper -- Resistivity = 1.74E-08 ohm-m, Rel. Perm. = 1**

**--------------- WIRES ---------------**

| Wire | Conn. | --- End 1 (x,y,z : ft) | Conn. | --- End 2 (x,y,z : ft) | Dia(in) | Segs |
|---|---|---|---|---|---|---|
| 1 | W4E2 | -5.150, 0.000, -5.150 | W2E1 | 5.150, 0.000, -5.150 | # 12 | 15 |
| 2 | W1E2 | 5.150, 0.000, -5.150 | W3E1 | 5.150, 0.000, 5.150 | # 12 | 15 |
| 3 | W2E2 | 5.150, 0.000, 5.150 | W4E1 | -5.150, 0.000, 5.150 | # 12 | 15 |
| 4 | W3E2 | -5.150, 0.000, 5.150 | W1E1 | -5.150, 0.000, -5.150 | # 12 | 15 |
| 5 | W8E2 | -5.050, 6.400, -5.050 | W6E1 | 5.050, 6.400, -5.050 | # 12 | 15 |
| 6 | W5E2 | 5.050, 6.400, -5.050 | W7E1 | 5.050, 6.400, 5.050 | # 12 | 15 |
| 7 | W6E2 | 5.050, 6.400, 5.050 | W8E1 | -5.050, 6.400, 5.050 | # 12 | 15 |
| 8 | W7E2 | -5.050, 6.400, 5.050 | W5E1 | -5.050, 6.400, -5.050 | # 12 | 15 |
| 9 | W12E2 | -4.950, 13.000, -4.950 | W10E1 | 4.950, 13.000, -4.950 | # 12 | 15 |
| 10 | W9E2 | 4.950, 13.000, -4.950 | W11E1 | 4.950, 13.000, 4.950 | # 12 | 15 |
| 11 | W10E2 | 4.950, 13.000, 4.950 | W12E1 | -4.950, 13.000, 4.950 | # 12 | 15 |
| 12 | W11E2 | -4.950, 13.000, 4.950 | W9E1 | -4.950, 13.000, -4.950 | # 12 | 15 |
| 13 | W16E2 | -4.950, 19.350, -4.950 | W14E1 | 4.950, 19.350, -4.950 | # 12 | 15 |
| 14 | W13E2 | 4.950, 19.350, -4.950 | W15E1 | 4.950, 19.350, 4.950 | # 12 | 15 |
| 15 | W14E2 | 4.950, 19.350, 4.950 | W16E1 | -4.950, 19.350, 4.950 | # 12 | 15 |
| 16 | W15E2 | -4.950, 19.350, 4.950 | W13E1 | -4.950, 19.350, -4.950 | # 12 | 15 |
| 17 | W20E2 | -5.000, 29.200, -5.000 | W18E1 | 5.000, 29.200, -5.000 | # 12 | 15 |
| 18 | W17E2 | 5.000, 29.200, -5.000 | W19E1 | 5.000, 29.200, 5.000 | # 12 | 15 |
| 19 | W18E2 | 5.000, 29.200, 5.000 | W20E1 | -5.000, 29.200, 5.000 | # 12 | 15 |
| 20 | W19E2 | -5.000, 29.200, 5.000 | W17E1 | -5.000, 29.200, -5.000 | # 12 | 15 |
| 21 | W24E2 | -4.850, 39.400, -4.850 | W22E1 | 4.850, 39.400, -4.850 | # 12 | 15 |
| 22 | W21E2 | 4.850, 39.400, -4.850 | W23E1 | 4.850, 39.400, 4.850 | # 12 | 15 |
| 23 | W22E2 | 4.850, 39.400, 4.850 | W24E1 | -4.850, 39.400, 4.850 | # 12 | 15 |
| 24 | W23E2 | -4.850, 39.400, 4.850 | W21E1 | -4.850, 39.400, -4.850 | # 12 | 15 |
| 25 | | -0.073, 6.538, 0.000 | | 0.073, 6.538, 0.000 | # 12 | 1 |
| 26 | W29E2 | -7.050, 0.000, -7.050 | W27E1 | 7.050, 0.000, -7.050 | # 12 | 21 |
| 27 | W26E2 | 7.050, 0.000, -7.050 | W28E1 | 7.050, 0.000, 7.050 | # 12 | 21 |
| 28 | W27E2 | 7.050, 0.000, 7.050 | W29E1 | -7.050, 0.000, 7.050 | # 12 | 21 |
| 29 | W28E2 | -7.050, 0.000, 7.050 | W26E1 | -7.050, 0.000, -7.050 | # 12 | 21 |
| 30 | W33E2 | -6.940, 8.800, -6.940 | W31E1 | 6.940, 8.800, -6.940 | # 12 | 21 |
| 31 | W30E2 | 6.940, 8.800, -6.940 | W32E1 | 6.940, 8.800, 6.940 | # 12 | 21 |
| 32 | W31E2 | 6.940, 8.800, 6.940 | W33E1 | -6.940, 8.800, 6.940 | # 12 | 21 |
| 33 | W32E2 | -6.940, 8.800, 6.940 | W30E1 | -6.940, 8.800, -6.940 | # 12 | 21 |
| 34 | W37E2 | -6.800, 17.700, -6.800 | W35E1 | 6.800, 17.700, -6.800 | # 12 | 21 |
| 35 | W34E2 | 6.800, 17.700, -6.800 | W36E1 | 6.800, 17.700, 6.800 | # 12 | 21 |
| 36 | W35E2 | 6.800, 17.700, 6.800 | W37E1 | -6.800, 17.700, 6.800 | # 12 | 21 |
| 37 | W36E2 | -6.800, 17.700, 6.800 | W34E1 | -6.800, 17.700, -6.800 | # 12 | 21 |
| 38 | W41E2 | -6.800, 26.600, -6.800 | W39E1 | 6.800, 26.600, -6.800 | # 12 | 21 |
| 39 | W38E2 | 6.800, 26.600, -6.800 | W40E1 | 6.800, 26.600, 6.800 | # 12 | 21 |
| 40 | W39E2 | 6.800, 26.600, 6.800 | W41E1 | -6.800, 26.600, 6.800 | # 12 | 21 |
| 41 | W40E2 | -6.800, 26.600, 6.800 | W38E1 | -6.800, 26.600, -6.800 | # 12 | 21 |
| 42 | W45E2 | -6.750, 39.400, -6.750 | W43E1 | 6.750, 39.400, -6.750 | # 12 | 21 |

```
43   W42E2   6.750, 39.400, -6.750 W44E1   6.750, 39.400,  6.750    # 12   21
44   W43E2   6.750, 39.400,  6.750 W45E1  -6.750, 39.400,  6.750    # 12   21
45   W44E2  -6.750, 39.400,  6.750 W42E1  -6.750, 39.400, -6.750    # 12   21
46          -0.100,  9.000,  0.000         0.100,  9.000,  0.000    # 12   1

              -------------- SOURCES --------------

Source    Wire      Wire #/Pct From End 1    Ampl.(V, A)  Phase(Deg.)  Type
          Seg.     Actual      (Specified)

1           1    46 / 50.00   ( 46 / 50.00)      1.000       0.000       V
No loads specified

                -------- TRANSMISSION LINES ---------

Line  Wire #/% From End 1   Wire #/% From End 1    Length       Z0   Vel Rev/
      Actual  (Specified)   Actual  (Specified)                Ohms Fact Norm

1     30/50.0  ( 30/50.0)   46/50.0  ( 46/50.0)    9.090 ft    37.5  0.67  N
2      5/50.0  (  5/50.0)   25/50.0  ( 25/50.0)    6.600 ft    37.5  0.67  N

Ground type is Free Space
```

The forward-most directors on each array have been altered to compensate for interactions within the same support arm system. At the rear end of the array, adjustments were made to the 17-meter reflector and driver, but the corresponding elements on the 12-meter array required no changes. Intermediate directors are unchanged. The performance figures for the combined array (using separate feedlines) appear in **Table 11-3**.

**Table 11-3. Performance of the 17/12-Meter 5/6-Element Quad**

| Frequency MHz | Gain dBi | F-B Ratio dB | Feedpoint Z R +/- jX Ohms | 50-Ohm VSWR |
|---|---|---|---|---|
| 17-Meters | | | | |
| 18.068 | 11.07 | 26.72 | 44.0 + j 17.9 | 1.49 |
| 18.118 | 11.14 | 28.08 | 50.6 + j 0.7 | 1.02 |
| 18.168 | 11.17 | 20.96 | 43.3 - j 16.3 | 1.46 |
| 12-meters | | | | |
| 24.89 | 11.79 | 20.42 | 44.7 + j 10.4 | 1.28 |
| 24.94 | 11.83 | 24.37 | 48.0 + j 0.4 | 1.04 |
| 24.99 | 11.84 | 32.06 | 46.8 - j 11.2 | 1.27 |

The 17-meter gain decreases by an average of 0.1 dB, while the 12-meter gain average decrease by a mere 0.06 dB. The front-to-back curves retain a worst-case value above 20 dB across both bands. The 50-Ohm SWR curves—with matching sections in place—are shallower than those for independent models.

The present array is certainly usable with good results on the upper 2 WARC bands, with appropriate construction cautions. First, finding the center of mass in this array will require extensive analysis or experimental techniques. Second, some elements will come quite near to the mast. Hence, it will likely require a mast that extends at least 7.5' above a tower and its guy wires to ensure that there is minimal electrical interaction and no physical interference as the array rotates.

The 2-band design specifically retained the original independent quad design values, even though this requires separate support arm structures for the intermediate elements. The goal of the exercise was to see whether the designs—optimized as independent arrays—could be brought together without significant change in performance. Decreasing the number of support systems would result in considerable weight savings, but at the cost of settling for compromise performance on at least one of the two bands. One of the premises of this volume—and the reason for working with monoband arrays almost exclusively—has been to look seriously at the performance potentials of quads without contending with the compromises inherent in multi-band designs. The present 17/12 meter design is the one concession to multi-band quad operation and is included because it requires no compromises in performance.

### Adding a 30-Meter Quad?

One goal of many operators is to combine as many antennas on a single boom as possible in order to save the expense and complexity of having separate tower supports and related equipment necessary to feed and rotate an array. Since the WARC bands are not contest fre-

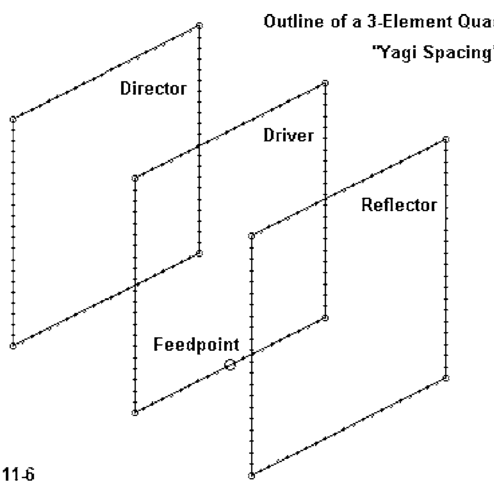



Fig. 11-6

quencies, but instead are good “DX” bands, combining the array just discussed with a 30-meter quad seems natural.

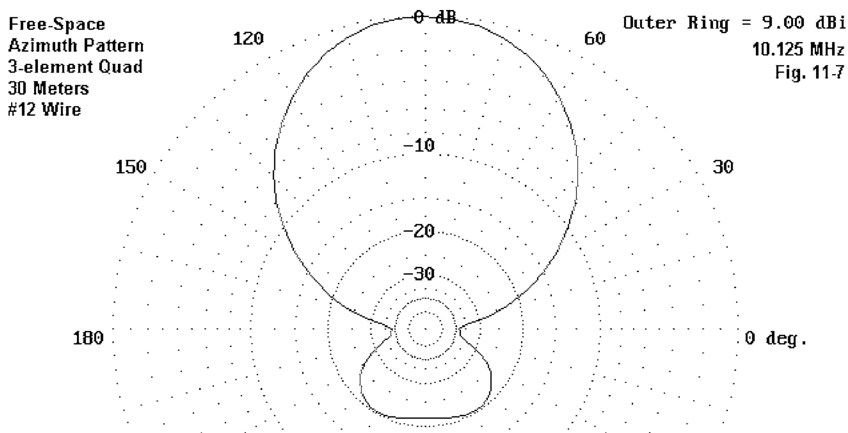
One possibility for such an array might be the 3-element “Yagi-spaced” 20-meter quad discussed in Volume 1, readjusted for 30 meters. For consistency, the readjustment will use #12 AWG copper wire. Since the 30-meter band is only 50 kHz wide, the thinner element size will create no bandwidth problems.

**Fig. 11-6** shows the outline of the array. It is 31.5' long, about 8' shorter than the composite array for 17 and 12 meters. A builder has several choices. He can align one of the elements with an element in the composite array and save the weight of at least one support system. Or he might wish to juggle the dimensions through further modeling to arrive at element spacings that coincides with 3 of the existing support structures. This latter exercise will require considerable effort, but the weight savings will be significant. The model description—when compared to the composite model for 17 and 12 meters—will indicate something of the size of the task.

```
3 el quad--Yagi Spacing--30 m           Frequency = 10.125  MHz.

Wire Loss: Copper -- Resistivity = 1.74E-08 ohm-m, Rel. Perm. = 1

              --------------- WIRES ---------------

Wire Conn. --- End 1 (x,y,z : ft)  Conn. --- End 2 (x,y,z : ft)  Dia(in) Segs

1     W4E2 -12.680,  0.000,-12.680  W2E1  12.680,  0.000,-12.680    # 12   21
2     W1E2  12.680,  0.000,-12.680  W3E1  12.680,  0.000, 12.680    # 12   21
3     W2E2  12.680,  0.000, 12.680  W4E1 -12.680,  0.000, 12.680    # 12   21
4     W3E2 -12.680,  0.000, 12.680  W1E1 -12.680,  0.000,-12.680    # 12   21
5     W8E2 -12.430, 15.394,-12.430  W6E1  12.430, 15.394,-12.430    # 12   21
6     W5E2  12.430, 15.394,-12.430  W7E1  12.430, 15.394, 12.430    # 12   21
7     W6E2  12.430, 15.394, 12.430  W8E1 -12.430, 15.394, 12.430    # 12   21
8     W7E2 -12.430, 15.394, 12.430  W5E1 -12.430, 15.394,-12.430    # 12   21
9    W12E2 -12.036, 31.488,-12.036 W10E1  12.036, 31.488,-12.036    # 12   21
10    W9E2  12.036, 31.488,-12.036 W11E1  12.036, 31.488, 12.036    # 12   21
11   W10E2  12.036, 31.488, 12.036 W12E1 -12.036, 31.488, 12.036    # 12   21
12   W11E2 -12.036, 31.488, 12.036  W9E1 -12.036, 31.488,-12.036    # 12   21

              -------------- SOURCES --------------

Source     Wire      Wire #/Pct From End 1    Ampl.(V, A)  Phase(Deg.)  Type
           Seg.     Actual      (Specified)

1           11     5 / 50.00   (  5 / 50.00)      1.000        0.000       V
```

```
No loads specified
No transmission lines specified
Ground type is Free Space
```

Unlike the narrow-band Yagi-spaced quads that we have so far discussed, this design does not require a quarter-wavelength matching section. The element diameter is 0.0808" (#12 AWG), which grows smaller as a fraction of a wavelength when we decrease the operating frequency. At 30 meters, the copper wire size provides a direct match for a 50-Ohm coaxial cable.




As shown in **Fig. 11-7**, the 3-element quad acquits itself well in terms of gain and a well controlled set of rear lobes, even if it cannot match the performance of the arrays for higher frequencies. The worst-case rear quadrant lobes are more than 19.5 dB down from the forward lobe across the band. **Table 11-4** presents the performance figures of greatest relevance.

**Table 11-4. Performance of the 30-Meter 3-Element Quad**

| Frequency MHz | Gain dBi | F-B Ratio dB | Feedpoint Z R +/- jX Ohms | 50-Ohm VSWR |
|---|---|---|---|---|
| 10.10 | 8.98 | 19.88 | 43.2 - j 9.2 | 1.28 |
| 10.125 | 9.00 | 21.44 | 44.0 - j 0.9 | 1.14 |
| 10.15 | 9.00 | 20.92 | 44.5 + j 7.4 | 1.22 |

Construction of a 3-band composite using a number of support structures and some individual band arrays with an odd number of elements presents a considerable challenge. In order for the 30-meter center element to clear the tower-and-guy structure, the mast above the tower will like need to be long and massive—but perhaps not as long as some that bear stacked Yagis systems. The exact placement of the 30-meter elements along the boom will likely call for some minor adjustments in the length of the 17-meter or the 12-meter elements that the 30-meter element effectively surrounds.

In short, the results of this design exercise are not necessarily to be recommended for construction. Instead, the designs are an effort to show what is possible if one removes mechanical compromises from the design equation set. For narrow band applications, individual high performance quads can be combined in principle, so long as each is given the support that it needs to live up to its potential. However, it remains one of the facts of antenna life that mass and gravity may always force upon us compromises in performance. With this exercise as a reference—or with better exercises as a more precise reference—we shall at least now have some understanding of the degree of compromise that we accept when simplifying the mechanical design of a multi-band quad array.

The design exercise also establishes that there is indeed a place for narrow-band quad designs in the amateur bands—the narrow bands. They also have a place wherever the builder decides as part of an overall operating plan (not to be confused with mere acceptance as an act of resignation) that only part of one or more wider ham bands is desired for primary use. For total coverage of the wider HF bands, wide-band designs can be devised, at least for monoband arrays.

## Work to Be Done

In the collection of notes on long-boom designs, whether for wide-band or narrow-band applications in this chapter and in Chapter 10, I have made no attempt to develop an automated design process of quads of 5 or more elements. The reasons are many. First, as an initial foray into understanding long-boom quads, exploring the approaches to design has seemed to be a large enough task. Although the selected approaches are illuminating, they are hardly exhaustive of all the possible angles from which one may approach such design work within the criteria set out at the beginning.

Second, the development of an automated design process requires the development of a reliable sequence of models that vary regularly with changes in wire diameter. Identifying a workable sequence becomes more complex and uncertain as the number of elements increases. Even the 4-element program presented in Chapter 9 bears the label “tentative” and claims only to be the best uncovered so far. At the present moment, I am far from uncovering a usable sequence for 5 or more elements.

Once uncovered, a sequence must be run through a range of element diameters such that each baseline model meets certain standards, according to the goals of the effort. The 4-element program proved feasible only because certain element spacings proved to be close to constant over the range of element diameters used. Hence, the number of variables involved in the optimizing portion of the work was manageable. Whether similar results would accrue to the development of baseline models for 5-element arrays is not wholly clear—and is likely only in the case of the uniformly spaced model.

Nevertheless, new optimizer routines and programs are emerging as I write. Consequently, the probability of developing a 5- or 6-element program in the future will likely increase with time. Indeed, it may prove feasible to tweak the quads explored here even further and to explore other design potentials as well. Not only is our understanding of how quads work improving, but as well, new tools are arriving to speed the process of increasing that understanding further. They likely will open up some not-yet-dreamt-of possibilities and directions for new quad array designs.

These notes, then, are not in any way an end to the analysis and design of quad arrays, both grand and modest. Instead, they are the barest beginning, a few steps on a very long, challenging, and fascinating road ahead.

# Chapter 12
# Some Notes on Size and Height

In the very first chapter to the first volume of these notes, I stated--and showed with some elevation patterns--that there is no significant difference in the elevation angle of maximum radiation (take-off angle) for Yagis and quads at the same effective height.  The statement had a limited context:  that of eliminating one of the coarser myths about quad performance.  It remains true

However, there are some differences between Yagi and quad elevation patterns that might make a difference to some quad builders and users.  These differences are potentially significant within a limited range of installations.  They will apply to quad designs with fewer elements and installed at lower heights--a natural amateur operation combination.  The exact degree of significance that these differences will have will depend upon the goals and limitations of the individual user, so we must be careful not to make too much of them.  Nevertheless, the differences are interesting and worth a brief examination.

## 3-Element Yagis and Quads

The best way to begin is to set a baseline.  Let's examine the elevation patterns of three 3-element Yagis having different boom lengths.  We shall set each Yagi at a height of 5/8 wavelength so that the results can be extrapolated to any of the upper HF bands.  The height is not arbitrary, and that means a short digression into the reason why 5/8 wavelength is a good test height.

Virtually any horizontally polarized antenna shows less than a smooth curve of gain as we increase its height from about 1/2 wavelength up to nearly 1.5 wavelength.  If we choose a simple dipole, we shall find not only variations in the rate of gain increase as we raise height (where gain is taken at the take-off angle), but as well, we shall find some height regions where the gain actually decreases relative to a slightly lower height.  The region around 7/8 wavelength is a prime example, relative to a height of 5/8 wavelength.  Another minor decrease occurs at 1 3/8 wavelength, but it is negligible.  As the antenna rises above about 1.25 wavelength up, the ripples in the curve of gain-increase with height largely wash out and become invisible.

**Table 12-1** provides a systematic glimpse at the phenomenon for a simple wire dipole.

**Table 12-1. Dipole Gain and TO Changes with Height**

| Height WL | Gain dBi | T-O Angle degrees | Height WL | Gain dBi | T-O Angle degrees |
|---|---|---|---|---|---|
| 0.375 | 6.06 - | 38 | 1.125 | 7.88 + | 12 |
| 0.5 | 7.21 | 28 | 1.25 | 7.61 | 11 |
| 0.625 | 7.73 + | 22 | 1.375 | 7.47 - | 10 |
| 0.75 | 7.28 | 19 | 1.5 | 7.75 | 9 |
| 0.875 | 7.13 - | 16 | 1.625 | 7.95 + | 9 |
| 1.0 | 7.61 | 14 | 1.75 | 7.76 | 8 |

In the table, we note not only the regions in which gain is lower than surrounding heights, but as well the heights at which the gain reaches a peak value. The peaks recur at 1/2 wavelength intervals, as do the valleys. If you care to look back at a study in *Communication Quarterly* ("The Effects of Antenna Height on Other Antenna Properties: A Computer Study,") for Fall, 1992, pages 57-79, you will find a rudimentary but detailed survey of many antenna types.

When we create directive arrays, the detection of actual peaks and valleys in the gain curve with increasing height becomes marginal. However, we can detect changes in the rate of gain increase with increasing antenna height. This fact has two consequences of note here. First, when we create a baseline of data for various horizontally polarized antennas, we must use a consistent antenna height. For our purposes, selecting a height that results in maximum gain (or very close to it) seems reasonable.

Second, many quad builders and users have limited space and resources. Unlike some fully committed DX and contest operators, who place many towers over a large parcel of ground, the average builder uses a shorter tower of lighter construction. Optimizing the height--at least for a monoband antenna--seems a reasonable course of action.

With this background, we can return to our collection of 3-element Yagis. Let's place them at the 5/8-wavelength mark. We shall use good ground with a conductivity of 0.005 S/m and a dielectric constant of 13 for all of our antennas, but with horizontally polarized antennas, changes in ground quality do not make very large differences in performance.

We shall be interested in several facets of Yagi characteristics and performance. The boom length of a well-designed Yagi largely determines the maximum gain obtainable. The height of the Yagi above ground will have a bearing on the vertical beamwidth, as defined by the half-power or -3dB points above and below the take-off angle. As well, when we raise a horizontal antenna above the ground, we find not only a primary lobe--usually at the lowest elevation angle--but as well, secondary lobes. At a height of 5/8 wavelength, the second lobe is just beginning to form. We shall be interested in its strength relative to the main lobe of the elevation pattern.

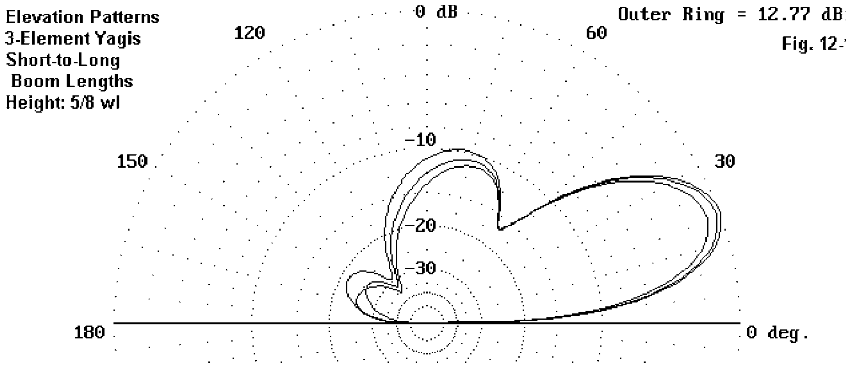
**Table 12-2** provides most of this data for 3 Yagis that might be classified as having short, medium, and long boom lengths.

**Table 12-2. Elevation Date for 3 3-Element Yagi Designs**

| Boom Length | Gain | T-O Angle | V. Beam | -3 dB Points | | F-S Lobe |
|---|---|---|---|---|---|---|
| in WL | dBi | degrees | degrees | Lower | Upper | Ratio dB |
| 0.217 | 11.98 | 21 | 24.3 | 10.2 | 34.5 | 8.98 |
| 0.286 | 12.53 | 21 | 24.1 | 10.1 | 34.2 | 10.37 |
| 0.325 | 12.77 | 21 | 23.9 | 10.1 | 34.0 | 11.15 |

Perhaps the most interesting aspect of the data in the table is how little it differs from one entry to the next. Gain, of course, increases with the increasing boom length. The gain increase translates into a very slightly narrower vertical beamwidth for longer boom lengths.

With respect to the formation of the secondary lobe, there is only a little over 2 dB difference in the forward-to-secondary lobe ratio. The range of actual gains for this lobe is even smaller, once the differences of maximum forward gain are taken into account. Moreover, as shown in the composite elevation patterns for the three beams in **Fig. 12-1**, the shapes of the patterns in the region from secondary lobe to the vertical (zenith) are very similar.




The Yagi, of course, is composed of linear elements laid out in a flat plane. That construction determines to a large degree the resulting elevation patterns--whatever the height. There is very little one can do to a Yagi to change the lobe formation.

Quads are another matter. Inherently, they consist of elements laid out in 3 dimensions, with two dipoles per element spaced about 1/4 wavelength apart. The basic geometry of the quad does not entirely overcome the fact that it remains a horizontally polarized antenna. Hence, we can expect relatively normal lobe formation according to the height of the antenna. However, especially at lower heights, we can expect some differences.

**Table 12-3** presents modeling data on three different 3-element quad designs having different boom lengths and design goals. The shortest quad is designed for high-gain, narrow-bandwidth operation. The middle-length quad attempts to maximize gain over a wider operating bandwidth, while the longest quad strives solely for the maximum operating bandwidth. For this comparison, all use copper wire. The booms are set at 5/8 wavelength up, which will give the quad about a degree lower TO angle than the Yagis.

**Table 12-3. Elevation Date for 3 3-Element Quad Designs**

| Boom Length in WL | Gain dBi | T-O Angle degrees | V. Beam degrees | -3 dB Points Lower | Upper | F-S Lobe Ratio dB |
|---|---|---|---|---|---|---|
| 0.324 | 13.34 | 20 | 22.5 | 9.5 | 32.0 | 17.22 |
| 0.401 | 13.42 | 20 | 22.7 | 9.6 | 32.3 | 16.23 |
| 0.462 | 12.99 | 20 | 22.9 | 9.7 | 32.6 | 14.39 |

The most notable entries occur in the last column that lists the relative strength of the secondary lobe with respect to the main forward lobe. The quads as a group show less secondary lobe development for the same height--in this lower range of operating heights--than the Yagis. As shown in **Fig. 12-2**, there are other differences as well.

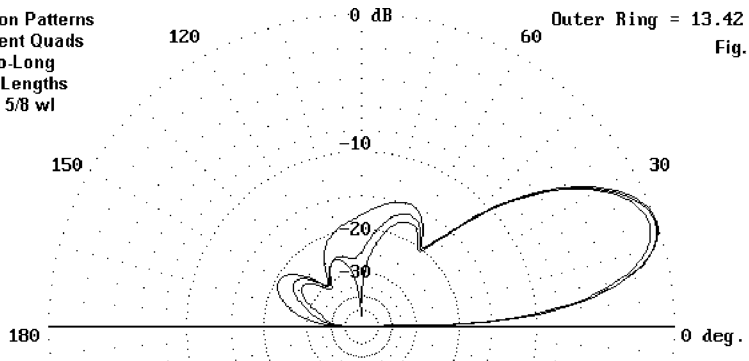


Fig. 12-2

The response of the secondary higher-angle lobe is 5 dB or more weaker than with the Yagis, with the wide-band design showing the largest secondary lobe. Some quad designs can actually show a major null in the vertical direction. Of the three designs shown here, the short-boom, narrow-band design shows a very deep vertical null.

The key result of our first steps into looking at quad elevation patterns is this: quads show a variability of elevation pattern development among designs that is very much larger than the variability among Yagi designs. Second, at lower antenna heights, the development of secondary elevation lobes at higher angles can be reduced by design choices. (I am indebted to Carroll Allen, AA2NN, who first called this phenomenon to my attention.)

### 3-Element vs. 5-Element Quads from 1/2 to 7/8 Wavelength Up

If a 3-element quad shows this much variation in high-angle lobe structure, perhaps larger quads do as well. Let's compare a 3-element design with a related 5-element design and see what happens as we run them both through some lower height options. The designs, outlined in **Fig. 12-3**, represent a 3-element design with Yagi-spacing, originally discussed in Volume 1. The 5-element design was discussed in the two preceding chapters of this volume. For this exercise, however, we shall continue our generic references to boom length in terms of wavelengths--with antenna heights also recorded as a fraction of a wavelength. Note that the smaller quad has a little less than half the boom length of the larger one.

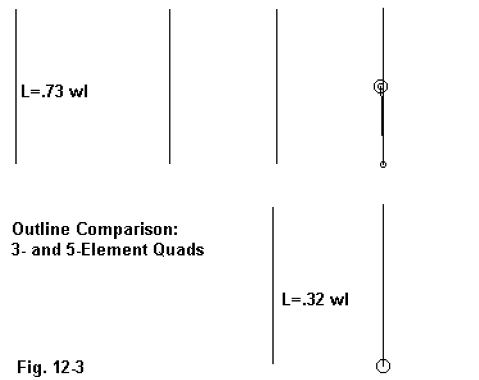


Fig. 12-3

For the exercise, let's place each quad at heights of 1/2, 5/8, 3/4, and 7/8 wavelength. We shall expect the gain to rise as we elevate each antenna. However, we shall also be interested in the emergence of the higher-angle secondary lobe, along with the decreasing vertical beamwidth of the lowest or major lobe in the pattern. **Table 12-4** provides the data.

**Table 12-4. Elevation Data for 3- and 5-Element Quads at Low Heights**

3-Element Quad

| Height WL | Gain dBi | F-S Lobe Ratio dB | V. Beam degrees | -3 dB Points Lower | -3 dB Points Upper |
|---|---|---|---|---|---|
| 0.5 | 12.58 | N/A* | 27.2 | 10.9 | 38.1 |
| 0.625 | 13.34 | 17.22 | 22.5 | 9.5 | 32.0 |
| 0.75 | 13.81 | 10.72 | 18.9 | 8.3 | 27.2 |
| 0.875 | 14.06 | 7.52 | 16.3 | 7.3 | 23.6 |

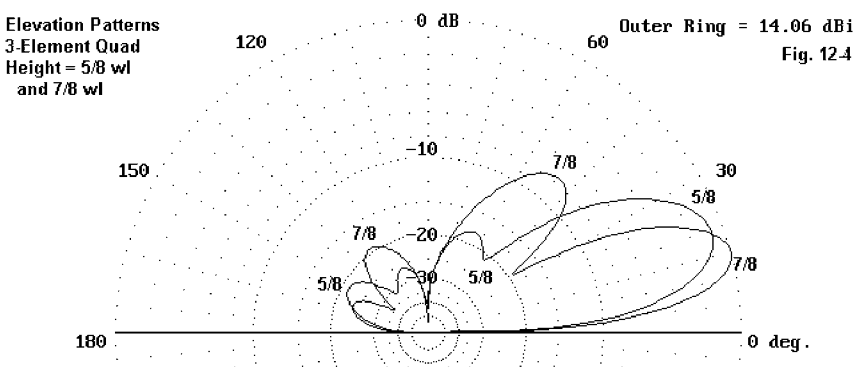
5-Element Quad

| Height WL | Gain dBi | F-S Lobe Ratio dB | V. Beam degrees | -3 dB Points Lower | -3 dB Points Upper | Gain over 3-Element |
|---|---|---|---|---|---|---|
| 0.5 | 14.02 | N/A* | 24.0 | 9.9 | 33.9 | 1.44 dB |

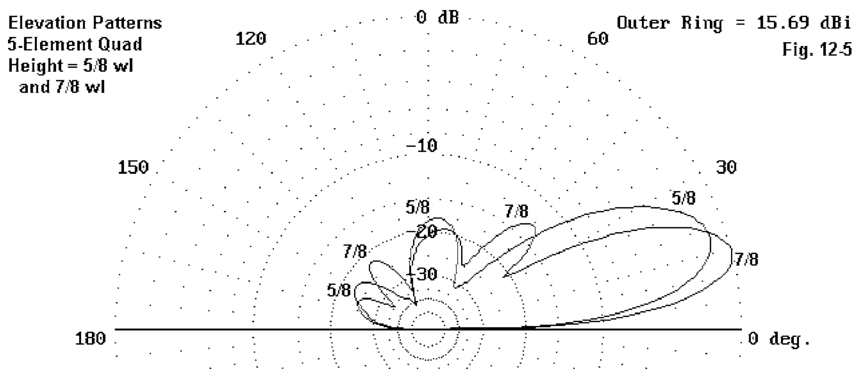
| | | | | | | |
|---|---|---|---|---|---|---|
| 0.625 | 14.73 | 16.76 | 20.8 | 8.8 | 29.6 | 1.39 |
| 0.75 | 15.24 | 15.54 | 18.1 | 7.8 | 25.9 | 1.43 |
| 0.875 | 15.69 | 12.90 | 15.8 | 7.0 | 22.8 | 1.63 |

The tables reveal a number of interesting facets of quad behavior, if we know how to interpret the data. Let's first look at the gain advantage of the 5-element quad over the 3-element design. The highest gain advantages occur at heights we previously noted as having reduced gain in dipoles--and vice versa. These data indicate a general fact about directive parasitic arrays: the higher the gain, the smoother the gain increase curve with increased height. The smaller quad, while having enough gain to provide continuous increases as we raise the height, nevertheless varies in the rate of gain change in step with the dipole. The higher gain 5-element design does not vary as much and hence shows higher gains over the 3-element quad at the heights where the basic dipole is poorest.

The second notable data feature is the decreasing vertical beamwidth with increasing gain and height. The differential in vertical beamwidth for any given height between the two designs is a function of the relative gain of the two antennas. The decreases in vertical beamwidth for each design as we increase height is a function of the emergence and growth of the secondary lobe. At the highest level in the tables, the 3-element quad has a secondary lobe that has a gain of 6.54 dBi at an elevation angle of 49 degrees. **Fig. 12-4** shows the elevation patterns of the antenna at 5/8 and 7/8 wavelength up. At the lower height, the secondary lobe is scarcely noteworthy. However, at the upper height, the secondary lobe is a prominent feature of the elevation pattern.



The 5-element pattern for the same heights is shown in **Fig. 12-5**. The secondary lobe at 7/8 wavelength up is only 2.79 dBi at 45 degrees elevation. However, notice that in the case of the 5-element quad, a third lobe pointing straight up is beginning to emerge. It has about the same size and shape as secondary lobe when the antenna is at 5/8 wavelength up. In contrast, the 3-element quad shows a deep null near the zenith angle at both heights.




The general, but not necessarily universal, conclusion that these pattern illustrate is that as the gain of the quad increases as a result of increasing the boom length and number of elements, the resulting array patterns more and more resemble those of comparably sized Yagis. The secondary lobes may be smaller than those of most Yagi designs, but they are present nevertheless. The quad's ability to suppress high-angle lobes is most evident in smaller designs.

A third consideration arises if we compare the tabulated and pictured data with some notes earlier in this chapter. We noted that, as a rule, hams who set up towers with lower maximum heights generally use lighter structures. If we combine this tendency with the data that we have been exploring, then we might suggest that the 5/8 wavelength height using the smaller quad design may be among the best compromise installations when viewed as a whole. The smaller design has a 1.5 dB gain deficit, but reduces mechanical concerns relative to boom lengths over twice as long that one needs to overcome the deficit. The nearly single forward lobe pattern has a beamwidth that covers most of the domestic and DX angles.

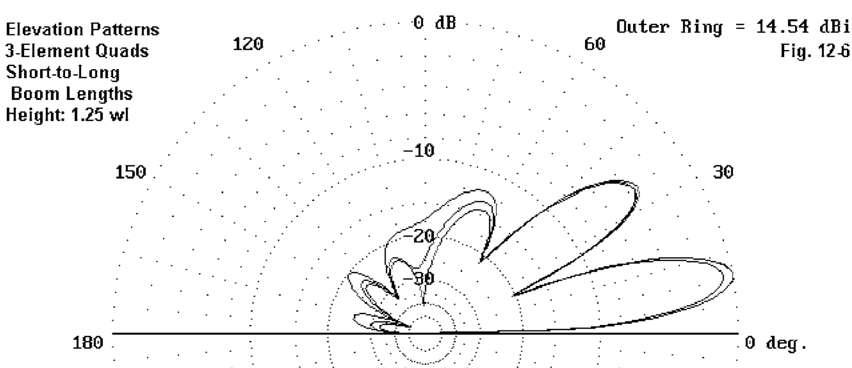
I shall not recommend the summary evaluation just noted as a universal solution. Rather, let's think of it as an example of one important aspect of antenna planning: combining the performance of the antenna with the feasible support structure and a set of operating goals to reach the best composite judgment of how much antenna to build and how high to place it. Of course, one would add in azimuth data in terms of pattern shape and front-to-back ratio to fill the installation design matrix (not to mention land and monetary resource limitations). The data suggest that in some circumstances, there may be such a thing as mounting a given antenna too high.

To illustrate the point, let's return to the original 3 3-element quads whose 5/8 wavelength height data was shown in **Table 12-3** and **Fig. 12-2**. Now, let's raise the antenna height to 1.25 wavelengths in order to see what changes occur in the patterns and the data. First, **Table 12-5**.

**Table 12-5. Elevation Date for 3 3-Element Quad Designs**

| Boom Length in WL | Gain dBi | T-O Angle degrees | V. Beam degrees | -3 dB Points Lower | -3 dB Points Upper | F-S Lobe Ratio dB |
|---|---|---|---|---|---|---|
| 0.324 | 14.53 | 11 | 11.4 | 5.4 | 16.8 | 3.59 |
| 0.401 | 14.54 | 11 | 11.4 | 5.4 | 16.8 | 3.34 |
| 0.462 | 14.00 | 11 | 11.5 | 5.4 | 16.8 | 3.03 |

As **Fig. 12-6** shows, at the higher position, the three beams lose much of what distinguished them at lower heights. From the perspective of elevation patterns, the region near the zenith angle becomes almost incidental to the strengths and other



properties of the main and second major lobes. In all cases, the second lobe occurs at 35-degrees elevation with a strength ranging from 10.94 to 11.20 dBi. It is now only about 3.0 to 3.5 dB weaker than the lowest main lobe. Moreover, there is in all three cases a major null between the lower and upper major lobes.

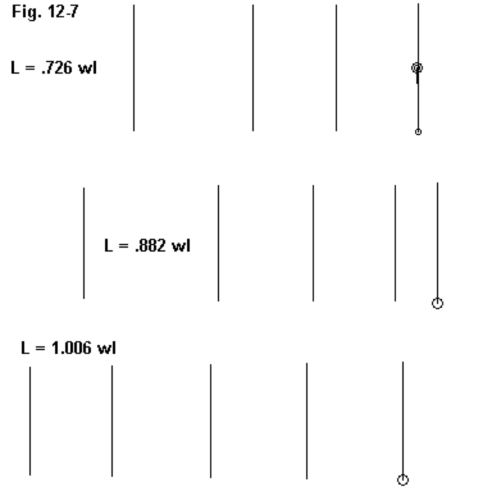
The chief advantage of the increased height lies in the lower limit of the -3dB points. The antenna can take advantage of extremely low angle signals. However, in doing so, it may be also limit its ability to handle domestic communications, relative to the pattern with the antennas at 5/8 wavelength up. In short, there is no general case to be made for one height relative to the other. Each height becomes preferable by reference to a clear set of operating goals.

### A Final Note on 5-Element and Larger Quads

We have so far seen that zenith-angle differences in 3-element designs are largely significant for mounting heights below 1 wavelength. We have also noted that a sample 5-element quad design showed a smoother set of curves as its mounting height was changed from 1/2 to 7/8 wavelength. The remaining question is whether we might find some of the same differences in zenith-angle behavior among 5-element and larger quads when mounted at low heights.

To answer this question, we shall take a final look at the spread of spot designs examined in Chapter 10. As shown in **Fig. 12-7**, this group included a narrow bandwidth design using 5 elements, an OWA quad using 6 elements, and a uniformly wide-spaced quad also using 6 elements. Although we may order the quads by boom length, the spread from 0.726 to 1.006 wavelength can hardly be said to have a short-boom quad among the group. Nonetheless, there are enough design differences at the root of the collection of quads to reveal significant differences of zenith-angle performance, if they exist.

Fig. 12-7




Relative Sizes of 5-Element Quads

**Table 12-6** provides the basic data that we have been tracking throughout this exploration of elevation patterns of quad arrays. Throughout, we must remember that we are dealing only with design-frequency data. Operating bandwidth data must also play a role in the final overall analysis. We are merely focusing on one region of the overall evaluation of antenna designs.

**Table 12-6. Elevation Date for 3 5-Element Quad Designs**

| Boom Length in WL | Gain dBi | T-O Angle degrees | V. Beam degrees | -3 dB Points Lower | -3 dB Points Upper | F-S Lobe Ratio dB |
|---|---|---|---|---|---|---|
| 0.726 | 14.81 | 18 | 20.7 | 8.8 | 29.5 | 16.67 |
| 0.882 | 14.79 | 19 | 21.2 | 9.0 | 30.2 | 16.71 |
| 1.006 | 14.86 | 19 | 21.0 | 8.9 | 29.9 | 15.81 |

If the table suggests that with respect to elevation concerns, the three designs are too similar to separate, the elevation patterns in **Fig. 12-8** confirm the judgment. As quad boom lengths and numbers of elements increase, the elevation patterns at any antenna height lose their distinctive features. There may be mechanical, bandwidth, and other properties by which to differentiate the designs, but the elevation patterns give no hint of which antenna may be better for a job.

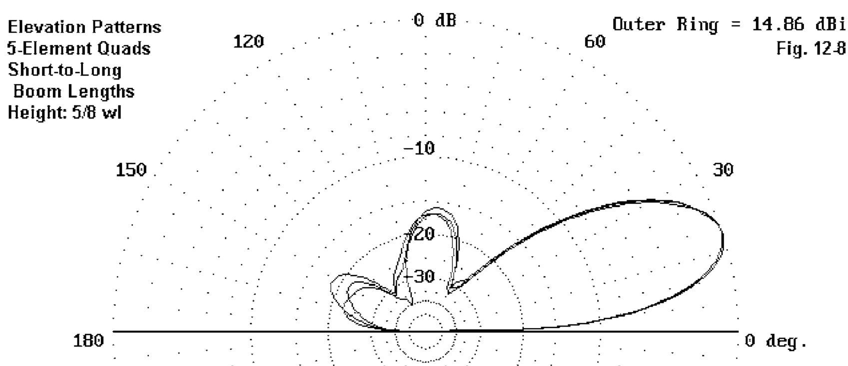


Fig. 12-8

Had we examined only the 5-element quads, we might believe that elevation patterns have little important data to offer us in making design decisions. Fortunately, the 3-element designs rebut that belief and suggest that a thorough exploration of elevation behavior has much to offer. Besides, I could not conclude this study without a few elevation patterns to offset the seeming obsession with azimuth patterns in all of the preceding chapters.

# Chapter 13
# Some Notes on VHF Quad Design

In this chapter, I shall look at the question of VHF quad design, at least through 4-element arrays. The chapter will serve two purposes. First, it will provide a focus on issues that are, while not unique to VHF quads, of perhaps more concern to building quads above the HF range. Second, these notes will serve as a summary of some of the major elements underlying the overall study.

In fact, I might as well begin with a summary.

1. Quad antennas, whether single loops or arrays, are narrow-band arrays by nature--contrary to the long standing myth about them. Because quads often offer a very wide SWR curve in some configurations, the entire set of antennas has received the unwarranted categorization as “low-Q” devices. Unfortunately, this has misled many builders into believing that the quad is a non-critical antenna so that careful construction is not really necessary.

In effect, compared to properly design Yagis, the quad array with the same number of elements is a narrow-band antenna. Its front-to-back performance falls off more than 2.5 times as fast as the SWR curve deteriorates. Although some users claim they only care about the gain, the design challenge for me is to discover what it takes to obtain superior performance in all major categories across a given band.

2. The physical specifications for a quad array are critically dependent upon the diameter of the elements that compose them. I have shown along the way just how much the quad is dependent in raw performance (such as gain) upon element diameter as much as it is dependent upon the loop circumference for each of the elements and upon the element spacing. The element-diameter factor is elusive in trial-and-error design exercises, but can become clear when optimizing basic quad designs becomes a systematic enterprise. In fact, we have shown that monoband 2-, 3-, and 4-element quad design is amenable to computerized calculations requiring only the element diameter and the design frequency as inputs.

3. For optimal performance, the parasitic coupling of quad elements requires considerably more spacing than equivalent coupling of linear elements in Yagi design. Indeed, beyond a certain point, the boom length of an optimized quad with reasonably wide-band performance characteristics may be the limiting factor in comparisons with Yagis of similar performance capabilities. At this point, I might estimate the break-even point to be somewhere between 4 and 5 elements. However, this estimate is very tentative, as the work is nowhere near complete.

4. The theoretical gain of a quad over a Yagi with a similar number of elements cannot be attained if the quad elements are significantly smaller in diameter than the Yagi elements. HF quads suffer most in the regard, since the #12 to #16 AWG wire we generally use is often less than 0.1 the diameter of typical Yagi elements for the same frequencies. However, VHF quads suffer similarly when they use thin wire, while the Yagis with which they compete employ aluminum rod or tubing. In many cases, the wire quad will lose up to half of the theoretic advantage over a single linear element solely in terms of wire losses. If we wish a quad to achieve its full theoretical potential relative to Yagis, we shall have to use "Yagi-size" elements.

5. A limiting factor for most quad designs with superior gain and front-to-back ratio at their design frequency is a very rapid rate of change of reactance across a chosen passband. Low rates of reactance change tend to accompany low performance quad arrays.

We shall see significant confirming evidence of these general propositions as we look at VHF quad design. For the purposes of keeping everything coherent, all of the quads examined in this chapter have a design frequency of 146 MHz. In terms of properties, I have set the 2-meter band in the U.S. (144-148 MHz) as the design bandwidth for both the SWR bandwidth curve and the front-to-back bandwidth curve. Front-to-back figures will be given as the 180-degree front-to-back value, although we shall examine the rear quadrant performance in more detail as we proceed.

## 2-Element Quad Beam Design

To fully appreciate a 2-element quad beam, it may be useful to make a few comparisons to comparable 2-element Yagi behavior. In a 2-element driver-reflector configuration, a Yagi exhibits maximum front-to-back ratio in the region of about

0.1 to 0.12 wavelengths spacing, with element lengths optimized. The peak front-to-back ratio is low--about 12 dB--and the curve is shallow as we increase the spacing.

The behavior of the Yagi represents a limit for parasitic operation of two 1/2-wavelength linear elements. It is possible to derive much higher front-to-back ratios for any pair of such elements by any one of many methods of phase-feeding both center-points. In fact, for any spacing and set of near-1/2-wavelength element lengths, we can find a set of relative current magnitudes and phases for the two elements to achieve at least 50 dB of 180-degree front-to-back ratio. However, parasitically, the mutual coupling between elements is not sufficient to achieve more than the approximate 12 dB figure at the optimal spacing.

A quad loop may--for this exercise--be thought of as two dipoles bent so that the ends meet each other. In this configuration, the current distribution along each of the two dipoles is different from that of a linear dipole. The current at the square loop corners--which approximates the distance from the center to the mid-points of a linear element--is about 14% higher with double the phase shift of the current on the corresponding points of a linear element. The net result is a high level of mutual coupling between elements. Since the optimal distance for achieving maximum front-to-back ratio is a function of coupling, we should expect that the element spacing for a quad would have to be greater than for a driver-reflector Yagi. It is: in the neighborhood of 0.17 wavelengths.

For both the Yagi and the quad, the exact spacing required for maximum front-to-back ratio is a function of two other variables: the element lengths and the element diameter. As the element diameter increases, the quad loop lengths (for maximum front-to-back ratio combined with driver resonance) increase and the required spacing between elements increases. It is possible to derive a series of antenna models using NEC--which is highly accurate in this kind of exercise--that track the array dimensions for any element diameter ("wire size") from 3.16E-5 up to 1E-2 wavelengths. Subjecting the results to regression analysis results in a series of equations suitable for automated design of a 2-element quad beam having maximum front-to-back ratios of more than 50 dB. Such a program, in GW Basic format for structural transparency, appears in Chapter 4 of this study. One need only enter the element diameter and the design frequency to derive 2-element quad dimensions and some basic performance data.

At VHF, few will be tempted to build a quad using wire in the 3.16E-5 range--somewhere in the #80 AWG range. However, the program is calibrated for 3 to 300 MHz, and quads in the 1300 kHz range have been developed from the automated process. There are a few cautions to observe. The program lists a design frequency gain that is correct for about 30 MHz. Since skin effect and its resultant losses do not change linearly with the change in element diameter, the actual gain of an array will be higher than predicted for frequencies significantly lower than 30 MHz and be lower than predicted for frequencies higher than the median. As well, changing antenna materials will result in small deviations from the predictions, especially for very thin element quads. The result of material changes will be minimal with elements larger than 1E-3 wavelengths in diameter.

**Table 13-1** lists the wires sizes that we shall sample in this study, arranged in an overall 8:1 total ratio in 2:1 increments. The smallest size is just barely thinner than #14 AWG (0.0641"). The largest size (0.5") represents a practical limit to modeling accuracy for the exercise, as the diameter approaches 1E-2 wavelengths at 146 MHz. The common logs for the wire diameters (in wavelengths) are also listed, since the properties of antennas tend to vary more directly with the common log of wire size than with the size itself.

**Table 13-1: Wire Sizes Used in This Study**

| Wire Size in Inches | Wire Size in Wavelengths | Common Log of Wire Size |
|---|---|---|
| 0.0625 | 0.0007731 | -3.1118 |
| 0.125 | 0.0015462 | -2.8107 |
| 0.25 | 0.0030925 | -2.5097 |
| 0.5 | 0.0061849 | -2.2087 |

My concern to develop the automated program for maximum front-to-back 2-element quads stems from the fact that the maximum front-to-back configuration also yields the widest operating bandwidth for this array type, where bandwidth includes both 2:1 SWR and >20 dB front-to-back ratio. **Table 13-2** lists the resultant quad designs based on this analysis. Unless otherwise specified, all antennas are designed for a center frequency of 146 MHz. Also, all models use aluminum wire and hence will show slightly less gain than predicted by the GW Basic program, which is calibrated for copper wire. Models are calibrated for resonance in NEC-2. NEC-4 will show a very slight (operationally insignificant) frequency shift for resonance.

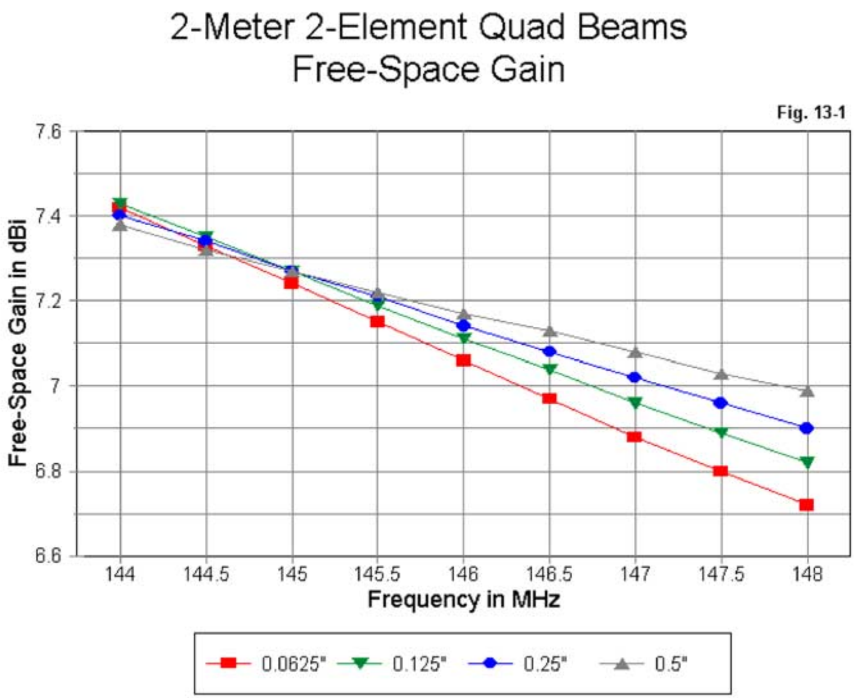
### Table 13-2: Calculated Data for 2-Element Quads Modeled

| | | | |
|---|---|---|---|
| 1. | | 2. | |
| Wire Diameter: | 0.0625" | Wire Diameter: | 0.125" |
| Reflector Circumference: | 88.480" | Reflector Circumference: | 89.672" |
| Driver Circumference: | 82.304" | Driver Circumference: | 82.584" |
| Refl-Driver Spacing: | 13.140" | Refl-Driver Spacing: | 13.324" |
| Feedpoint Impedance: | 141.1 Ω | Feedpoint Impedance: | 142.3 Ω |
| Free-Space Gain: | 7.06 dBi | Free-Space Gain: | 7.11 dBi |
| < 2:1 SWR Bandwidth: | 18.17 MHz | < 2:1 SWR Bandwidth: | 20.78 MHz |
| >20 dB F-B Bandwidth: | 3.45 MHz | >20 dB F-B Bandwidth: | 4.19 MHz |
| 3. | | 4. | |
| Wire Diameter: | 0.25" | Wire Diameter: | 0.5" |
| Reflector Circumference: | 91.304" | Reflector Circumference: | 93.608" |
| Driver Circumference: | 83.064" | Driver Circumference: | 83.936" |
| Refl-Driver Spacing: | 13.493" | Refl-Driver Spacing: | 13.718" |
| Feedpoint Impedance: | 145.0 Ω | Feedpoint Impedance: | 150.4 Ω |
| Free-Space Gain: | 7.14 dBi | Free-Space Gain: | 7.17 dBi |
| < 2:1 SWR Bandwidth: | 24.63 MHz | < 2:1 SWR Bandwidth: | 31.11 MHz |
| >20 dB F-B Bandwidth: | 5.29 MHz | >20 dB F-B Bandwidth: | 6.87 MHz |

The dimensional growth of the array with increasing element diameter is clear in the table. The feedpoint impedances are resonant at the design frequency within +/-1 Ohm reactance. We can summarize a number of the other features of the table better in a selection of graphs that capture frequency sweeps of each design across the 2-meter band. For example, **Fig. 13-1** records not only the free-space gain of the array at the design frequency, but as well the rate of change of gain across the band. As one might expect, the fatter the element, the lower the rate of gain change, thus ensuring more equal gain at both band edges. While commenting on element diameter, we should add that, contrary to experience with linear elements, closed loops tend to grow larger with increasing diameter elements and to have higher feedpoint impedances.

**Fig. 13-2** extracts the 180-degree front-to-back data, which reflect also the >20 dB bandwidth entry in the **Table 13-2**. Note that the front-to-back bandwidth--when held to this standard--does not exceed 4 MHz until the element diameter reaches

0.125", and with a mid-band design frequency, does not exceed 20 dB at the low end of the band until we use a 0.25" diameter element. We shall shortly explore why it is best to design quad arrays for a position about 1/3rd up from the bottom of the desired operating passband.




The SWR curves (relative to the resonant impedance of each array) for these 2-element optimized arrays, as shown in **Fig. 13-3**, present little concern to the builder. They are the reason so many builders classify the quad as a "low-Q" antenna, although the front-to-back curves--even for these fat-element arrays--show the inaccuracy of that claim.

The use of 180-degree front-to-back values was necessary to achieve maximum operating bandwidth for the antenna. However, these values should not be mistaken for the overall performance in the rear quadrants of a 2-element quad.

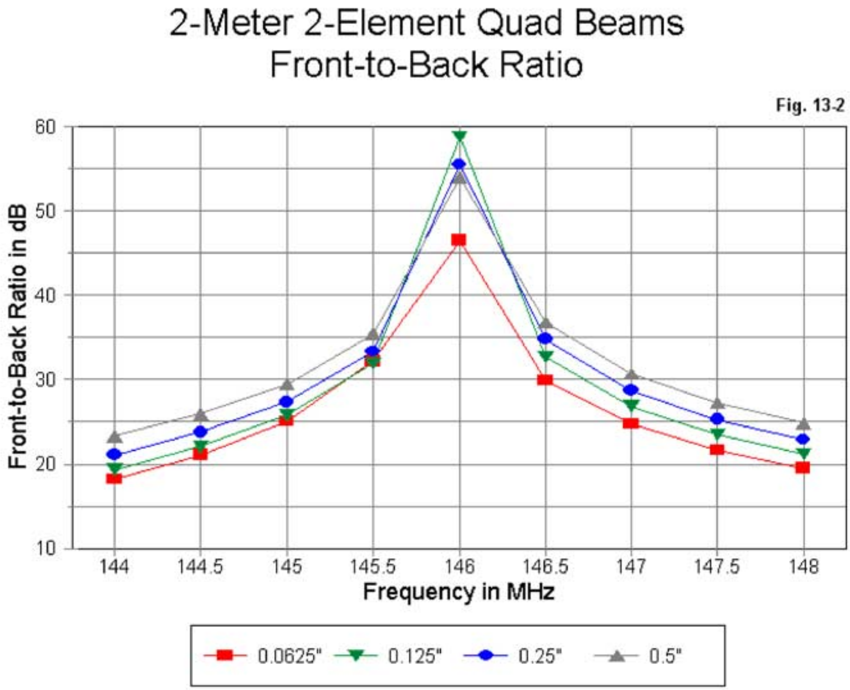
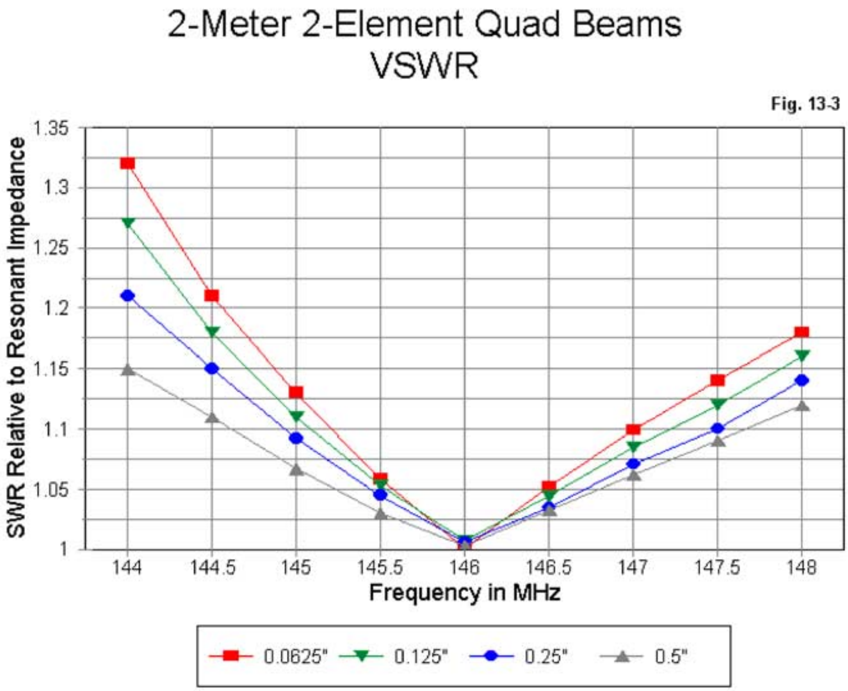
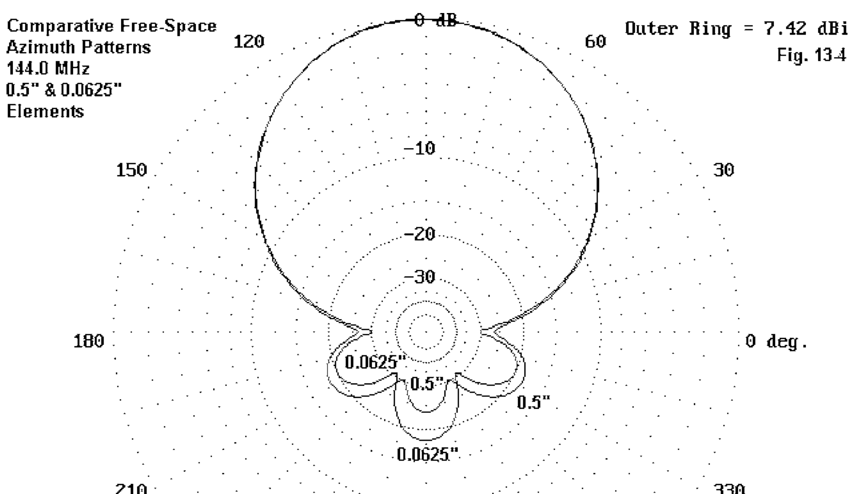


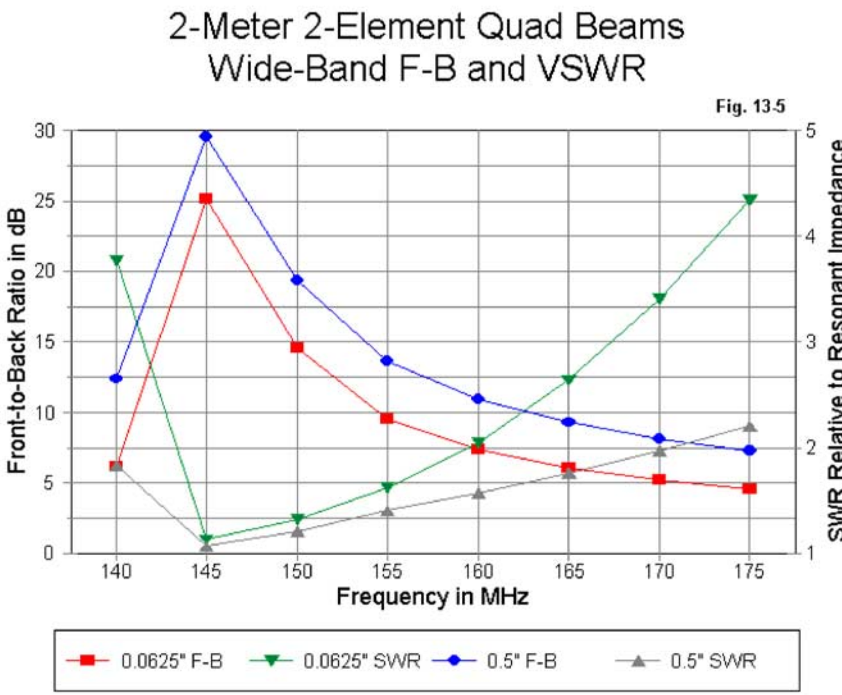

**Fig. 13-4** shows free-space azimuth patterns for the low end of the band for the thinnest and thickest elements used in this study. Note that in each case, the worst-case front-to-back ratio just approaches 18 dB--which tends to hold for all models used across the band. What does not appear as rearward gain in one direction tends to show up as gain in another direction within the rear quadrants. Thus, there is an overall limit to rear quadrant performance for any 2-element single-feed quad array.

While we are comparing the thinnest and thickest elements in our collection of models, let's look more closely at the wider-band performance of the array--especially at the front-to-back ratio and at the SWR curves. **Fig. 13-5** presents the data for each parameter from 140 through 175 MHz, with each array having a design frequency of 146 MHz. Note that the front-to-back curves fall off much more rapidly below design frequency than above it, although the two curves parallel each other


2-Meter 2-Element Quad Beams
VSWR
Fig. 13-3
SWR Relative to Resonant Impedance
1.35
1.3
1.25
1.2
1.15
1.1
1.05
1
144
144.5
145
145.5
146
146.5
147
147.5
148
Frequency in MHz
0.0625"
0.125"
0.25"
0.5"


Comparative Free-Space
Azimuth Patterns
144.0 MHz
0.5" & 0.0625"
Elements
Outer Ring = 7.42 dBi
Fig. 13-4
0 dB
-10
-20
-30
120
60
150
30
180
0 deg.
210
330
0.0625"
0.5"
0.5"
0.0625"

closely. With respect to SWR, we would correctly anticipate a steeper curve for the thinner element model. However, for both the 0.625" and 0.5" model, the curves are both more shallow above design frequency than below. The lesson of these curves is simple: for a given desired operational passband, design the quad array for a frequency about 1/3rd the way up from the lower end of that passband in order to achieve roughly equal values of SWR and front-to-back ratio at both ends of the passband. The loss of gain from using this procedure will be rather slight.




The actual resonant frequency of the driver is, for small changes in loop diameters, relatively independent of changes in front-to-back ratio--which is largely controlled by the spacing and loop diameter of the reflector. Hence, for special purposes, one may place the resonant frequency of the driver almost anywhere within a passband without moving the frequency of maximum front-to-back ratio significantly. In short, the 2-element quad array can be customized within reason to the builder's desires.

Although 2-element quads for 2-meters are "small potatoes" by most VHF array standards, it is necessary to understand the properties of these basic antennas in order to better understand the properties of larger quads. (Indeed, one must understand the linear dipole to understand the quad loop and the quad loop to understand the 2-element quad.) Therefore, let's add a director to the 2-element quad and see what happens.

## 3-Element Quad Beam Design

The addition of a director to a quad array introduces a plethora of new variables into beam design. Not only must we account for the spacing between individual elements, we must also account for the relative spacing between driver-director and driver-reflector. Consequently, the number of design variables increases exponentially as we add elements to the array. Little wonder that many builders seek out a simple standard by which to build these antennas.

In my own efforts to optimize 3-element quad arrays, I selected two criteria initially: gain and operating bandwidth. Initially, I gave precedence to operating bandwidth, using the >20 dB front-to-back standard. Later, I turned to gain as the paramount criterion, with reasonably-wide bandwidth as the secondary standard. The results proved interesting. For the wire sizes we have selected as most relevant to 2-meter arrays, the arrays ranged between 32" and 36" long. This value is nearly 30% longer than most 3-element 2-meter quads, but the results turn out to be very consistent in each category for operating properties. **Table 13-3** lists the resultant arrays for both wide-band and for high-gain applications.

**Table 13-3: Calculated Data for 3-Element Quads Modeled**

| 1. Wire Diameter: | 0.0625" | |
|---|---|---|
| | Wide-Band | High-Gain |
| Reflector Circumference: | 87.088" | 86.736" |
| Driver Circumference: | 82.320" | 83.040" |
| Director Circumference: | 75.92" | 79.336" |
| Refl-Driver Spacing: | 13.155" | 14.244" |

| | | |
|---|---|---|
| Driver-Dir Spacing: | 22.759" | 18.033" |
| Total Boom Length: | 35.914" | 32.277" |
| Feedpoint Impedance: | 74.3 Ohms | 54.5 Ohms |
| Free-Space Gain: | 8.87 dBi | 9.36 dBi |
| <2:1 SWR Bandwidth: | 5.72 MHz | 3.91 MHz |
| >20 dB F-B Bandwidth: | 2.77 MHz | 2.41 MHz |

2. Wire Diameter: 0.125"

| | Wide-Band | High-Gain |
|---|---|---|
| Reflector Circumference: | 88.008" | 87.512" |
| Driver Circumference: | 82.632" | 83.352" |
| Director Circumference: | 75.824" | 79.296 |
| Refl-Driver Spacing: | 13.323" | 14.193" |
| Driver-Dir Spacing: | 22.234" | 18.050" |
| Total Boom Length: | 35.557" | 32.243" |
| Feedpoint Impedance: | 72.4 Ohms | 52.1 Ohms |
| Free-Space Gain: | 8.99 dBi | 9.48 dBi |
| <2:1 SWR Bandwidth: | 6.44 MHz | 4.31 MHz |
| >20 dB F-B Bandwidth: | 3.27 MHz | 2.77 MHz |

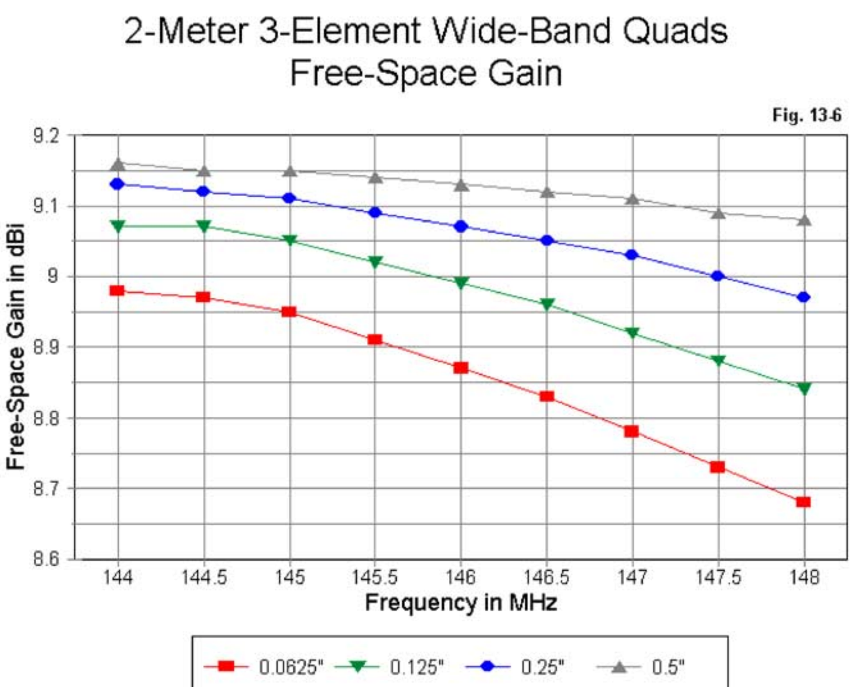
3. Wire Diameter: 0.25"

| | Wide-Band | High-Gain |
|---|---|---|
| Reflector Circumference: | 89.256" | 88.552" |
| Driver Circumference: | 83.056" | 83.752" |
| Director Circumference: | 75.568" | 79.240" |
| Refl-Driver Spacing: | 13.521" | 14.150" |
| Driver-Dir Spacing: | 21.760" | 18.024" |
| Total Boom Length: | 35.281" | 32.174" |
| Feedpoint Impedance: | 71.7 Ohms | 50.2 Ohms |
| Free-Space Gain: | 9.07 dBi | 9.57 dBi |
| <2:1 SWR Bandwidth: | 7.43 MHz | 4.84 MHz |
| >20 dB F-B Bandwidth: | 3.96 MHz | 3.28 MHz |

4. Wire Diameter: 0.5"

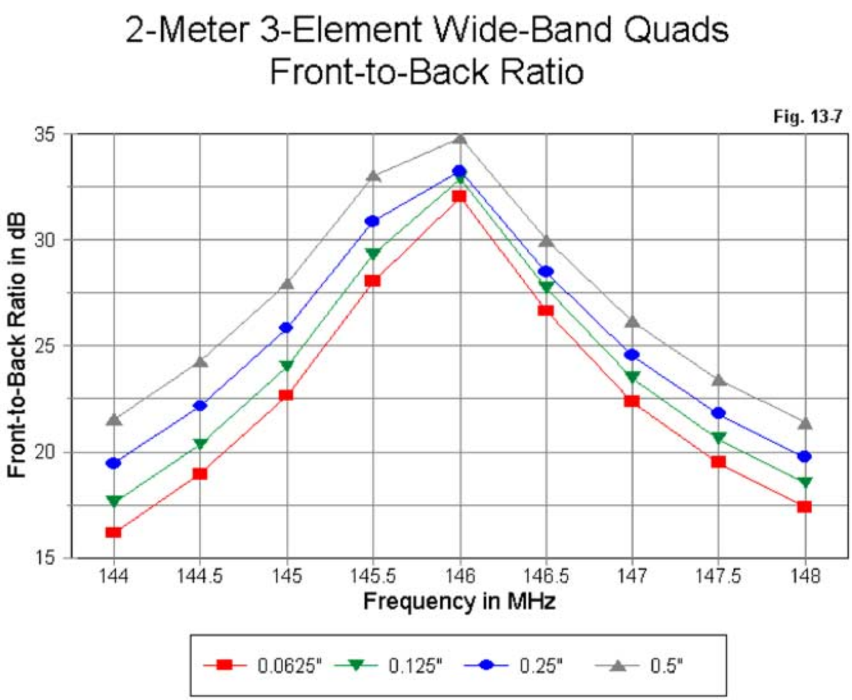
| | Wide-Band | High-Gain |
|---|---|---|
| Reflector Circumference: | 90.960" | 90.032" |
| Driver Circumference: | 83.624" | 84.272" |
| Director Circumference: | 75.040" | 79.104" |
| Refl-Driver Spacing: | 13.693" | 14.133" |
| Driver-Dir Spacing: | 21.194" | 17.869" |
| Total Boom Length: | 34.887" | 32.002" |
| Feedpoint Impedance: | 71.5 Ohms | 49.0 Ohms |
| Free-Space Gain: | 9.13 dBi | 9.63 dBi |
| <2:1 SWR Bandwidth: | 8.72 MHz | 5.63 MHz |
| >20 dB F-B Bandwidth: | 4.95 MHz | 4.03 MHz |

Let's begin with the wide-band arrays. **Fig. 13-6** shows the frequency sweep of gain across the 2-meter band for each array in the left column of **Table 3**. For wide-



band operation, the peak gain occurs below the lower limit of the operating passband. Hence, gain decreases across the band. However, the decrease is significantly lessened as we increase the element diameter, with the 0.5" element model showing just over a 0.05 dB change. When maximum operating bandwidth is the primary consideration in 3-element design, increasing the element diameter draws the point of maximum gain closer to being within the operating passband so that the gain curve is at its shallowest.

The 180-degree front-to-back curve in **Fig. 13-7** reveals that the operative design technique--as used with the 2-element quad--was to place maximum front-to-back at or very near to the design frequency. However, the addition of the 3rd element limits the maximum value of front-to-back ratio as well as the bandwidth over which the value exceeds 20 dB. Although any of the curves might well be usable for many purposes, in terms of the design standards of this exercise, only the 0.5" element version of the antenna achieves 20 dB across the entire band.



As with the 2-element quads, the SWR bandwidth of the arrays is considerably wider than the front-to-back bandwidth, as shown in **Fig. 13-8**. The more rapid rise in SWR below the design frequency is evident for all versions of the array. However, all of the curves would be acceptable. In fact, referring to **Table 13-3**, any of these antennas would be matchable directly to a 75-Ohm main feedline.

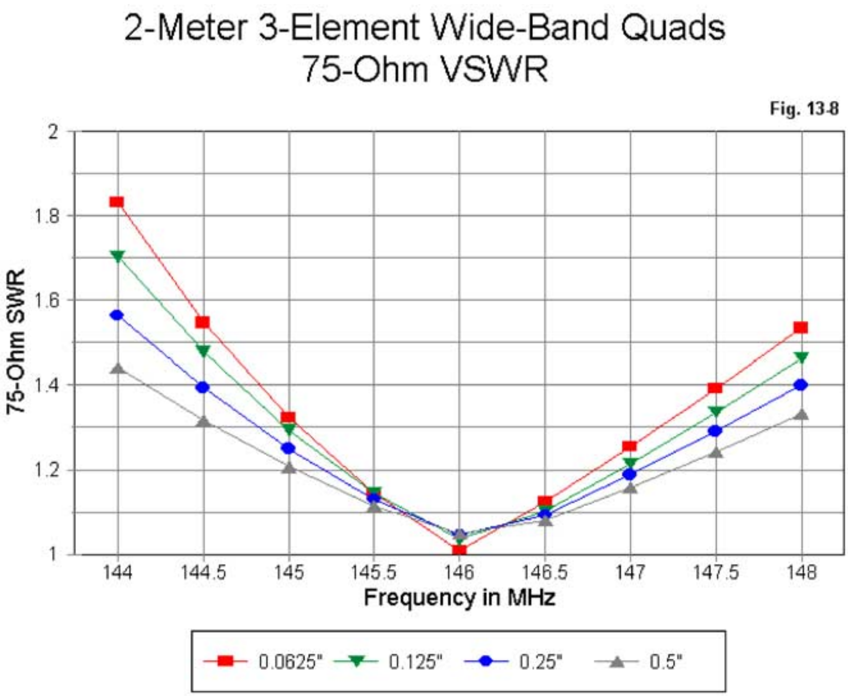
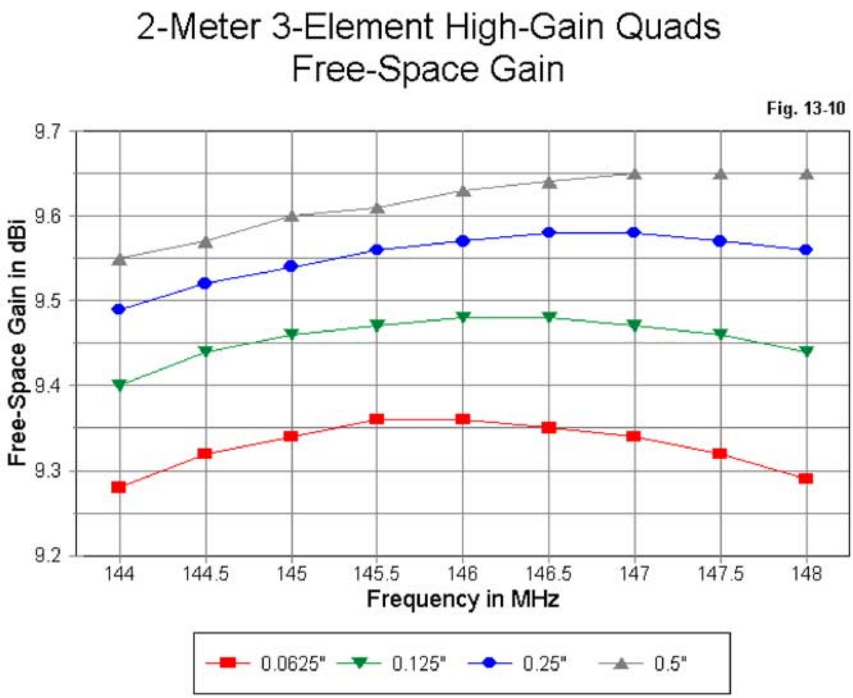
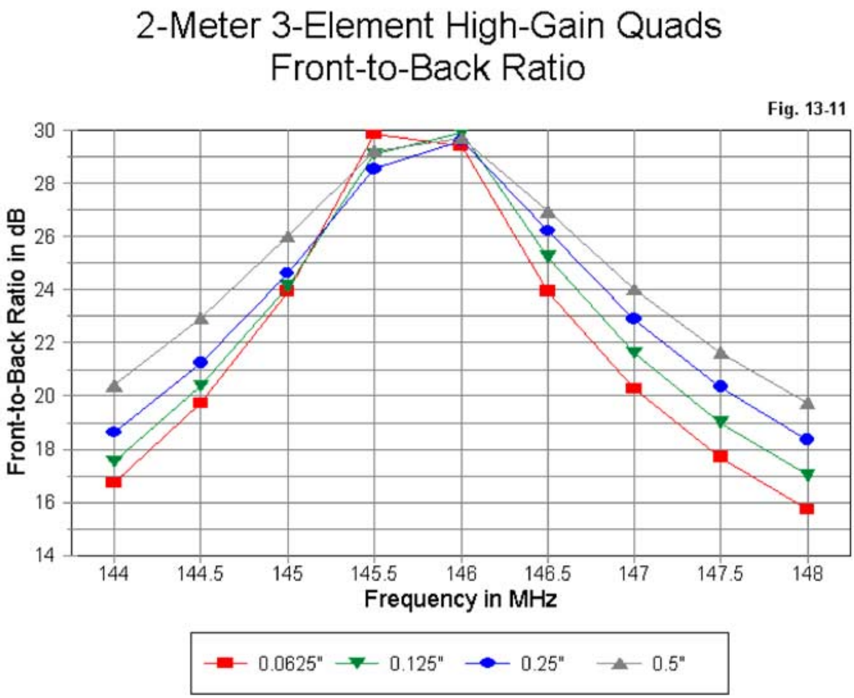



**Fig. 13-9** provides--among the models given in **Table 13-3**--a worst-case look at the patterns of the 0.0625" element diameter model for the entire 2-meter band. In practical terms, the gain is reasonably stable, even if not as good as that of the 0.5" model. As well, the rear quadrants--although not up to the 20 dB standard at the band edges--remain quite well controlled and predictable. The nearly 9 dBi free-space gain is rarely achieved in common short-boom 4-element Yagis.

If we turn to the high-gain versions of the antenna, we should expect more gain and a narrower operating bandwidth. In fact, the design of these arrays turned out to be something of a surprise for the designer. As shown in **Fig. 13-10**, the peak gain appears within the operating passband, although it gradually shifts toward the high end of the band with the fattest-element version of the array. For the 0.5" diameter model, the gain is about a half dB higher than for the wide-band version, with excellent gain stability across the band.



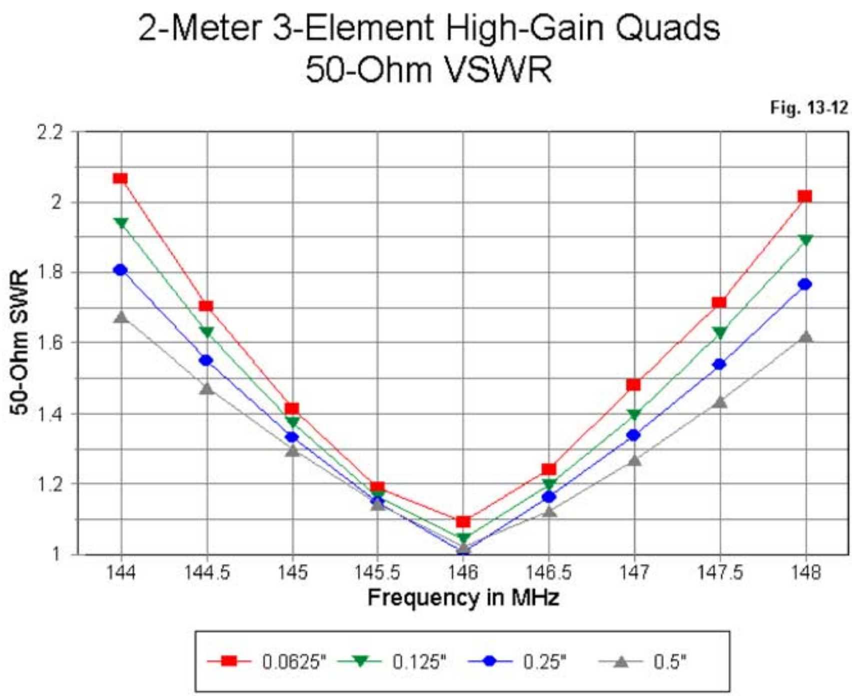

In terms of front-to-back ratio, graphed in **Fig. 13-11**, the peak front-to-back ratio approaches that of the wide-band array and almost achieves the 20-dB standard with 0.5" diameter elements. Since peak gain was the primary criterion, the exact placement of the front-to-back peak was left a bit more variable, but it occurs in all cases between 145.5 and 146.0 MHz.




The limiting factor in the high-gain arrays is the SWR curve. The second surprise of the design exercise was that fact that these arrays all yielded impedance values close to 50 Ohms. The 0.0625" element model fails to achieve a 2:1 50-Ohm SWR curve for the entire 2-meter band. However, the larger-diameter models fit safely within the limits, although with higher band-edge SWR values than for the wide-band models.

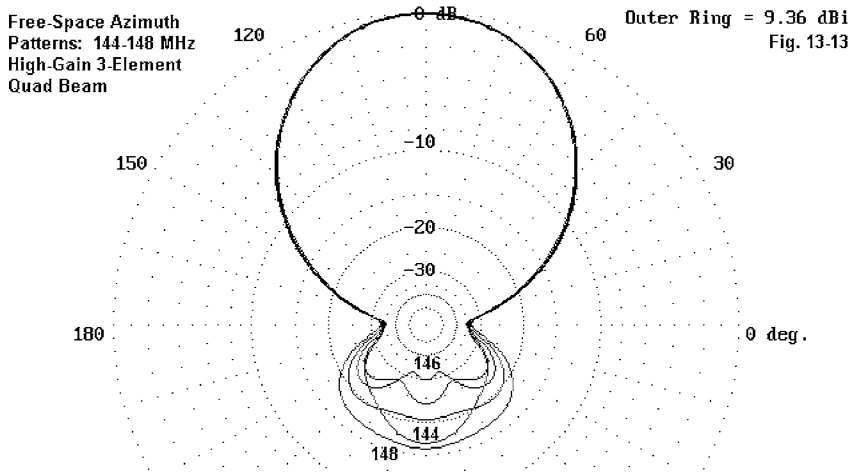
**Fig. 13-12** provides a set of free-space azimuth patterns across the band for the 0.0625" model--allowing a comparison with the wide-band version of the array shown in **Fig. 13-9**. Whether these patterns are suitable for particular applications is a user judgment.

The maximum design-frequency gain of the high-gain models is about 9.6 dBi (free-space), which approaches the gain of a standard 5-element Yagi (about 10 dBi). The wide-band version achieves about 9.1 dBi for the same 0.5" element diameter, with a proportionally wider operating bandwidth. The most interesting aspect of this seemingly small set of differentials is that they require very different dimensional profiles to maximize each set of design goals. An inspection of the numbers in **Table 13-3** will tell the difference in profiles, and a comparative drawing appears in Chapter 7.




Nonetheless, each type of array follows a natural progression similar to that of the 2-element arrays. It is possible to optimize a series of each type of array using wire sizes ranging from 3.16E-5 through 1E-2 wavelengths and then to subject the results to regression analysis. The regression equations can than be programmed into any setting for calculations of array dimensions and properties that hold good for 3 to 300 MHz. The same limitations regarding skin effect and array gain that applied to 2-element quads also apply to these arrays. Chapter 6 provides a GW

Basic listing for the wide-band array design, while Chapter 7 supplies a similar listing for the high-gain version.




As with the 2-element arrays, the designs are resonated within +/-1 Ohm reactance at the design frequency. However, the driven element can be adjusted to place resonance as much as a MHz away from the design frequency with minimal effect on the other antenna properties. Alterations to the director and reflector loop sizes have greater consequences for performance. Thus, to move the center point for the peak front-to-back ratio or SWR curve lower in the band, it is recommended that one choose a slightly lower design frequency.

## 4-Element Quad Array Design

The foray into 4-element quad array design is fraught with further complications. The additional director multiplies the number of variables. However, we may be able to indicate some useful directions for design effort--and possibly some limitations that may be inherent in long quads.

A useful place to begin would be with a sample or two of existing design. I have selected two widely disseminated design, although they appear in disguise. Models of each of them required that I frequency scale the design in order to produce any usable results. Hence, one is redesigned 1.5 MHz below its original design frequency, while the other is 2 MHz below its original design frequency. **Table 13-4** summarizes the design and performance data for the two designs.

**Table 13-4: Design Data for Two 4-Element Quad Arrays**

| | Version A: | Version B: |
|---|---|---|
| Element Diameter: | #14 AWG | #18 AWG |
| Reflector Circumference: | 87.696" | 85.264" |
| Driver Circumference: | 83.448" | 83.136" |
| Director 1 Circumference: | 80.960" | 80.712" |
| Director 2 Circumference: | 78.554" | 78.272" |
| Refl-Driver Spacing: | 15.152" | 16.320" |
| Driver-Dir 1 Spacing: | 12.460" | 13.187" |
| Dir 1-Dir 2 Spacing: | 12.452" | 11.192" |
| Total Boom Length: | 40.064" | 40.699" |
| Feedpoint Impedance: | 42.4 Ohms | 42.4 Ohms |
| Free-Space Gain: | 10.18 dBi | 10.05 dBi |

Performance Data: 144-148 MHz

Version A:

| Frequency MHz | Free-Space Gain dBi | Front-to-Ratio dB | Feed Impedance R +/- jX Ohms | 50-Ohm SWR |
|---|---|---|---|---|
| 144 | 9.68 | 7.99 | 31.6 - j 32.9 | 2.50 |
| 145 | 9.99 | 10.25 | 34.9 - j 12.8 | 1.60 |
| 146 | 10.18 | 12.81 | 39.0 + j 6.4 | 1.33 |
| 147 | 10.27 | 15.61 | 43.5 + j 24.3 | 1.71 |
| 148 | 10.30 | 18.43 | 47.7 + j 40.4 | 2.24 |

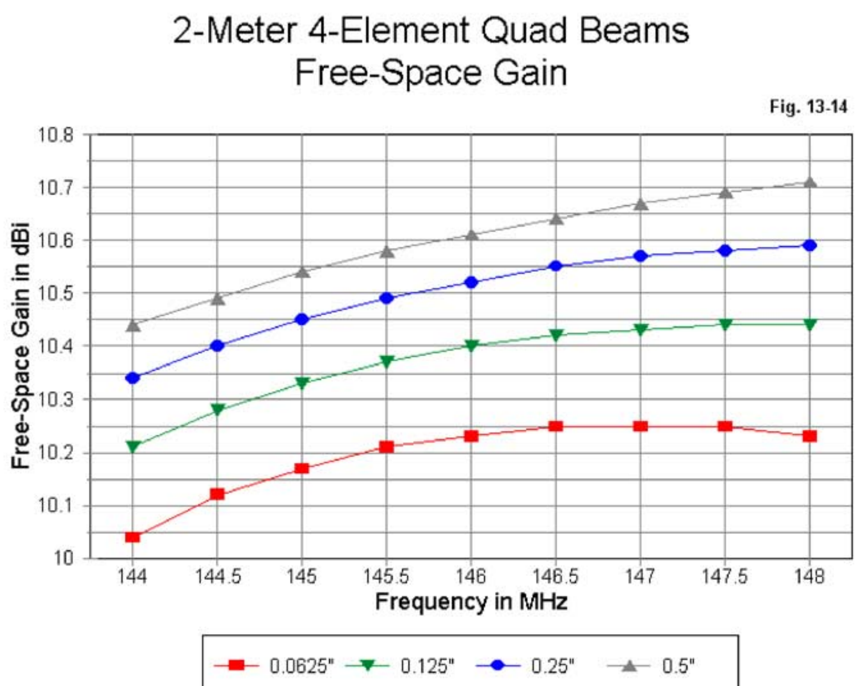
Version B:

| Frequency MHz | Free-Space Gain dBi | Front-to-Ratio dB | Feed Impedance R +/- jX Ohms | 50-Ohm SWR |
|---|---|---|---|---|
| 144 | 9.55 | 7.89 | 35.6 - j 39.0 | 2.50 |
| 145 | 9.86 | 10.04 | 38.6 - j 17.3 | 1.60 |
| 146 | 10.05 | 12.42 | 42.4 + j 3.7 | 1.20 |
| 147 | 10.14 | 14.85 | 46.7 + j 23.7 | 1.63 |
| 148 | 10.17 | 16.86 | 50.8 + j 42.4 | 2.27 |

The similarity of the final designs is a function of their design premises: to use thin wire and a short boom. There should be little wonder that the performance is similar for each array, since there is so little difference in the design, despite their independent sources.

The two designs have boom lengths about 6" longer than the average 3-element quad, and their design frequency gain level is only about 0.4 dB higher than the best of the high-gain series of 3-element quads. The point of maximum front-to-back ratio is well above the passband of the array (that is, above 148 MHz). Finally, the neither antenna manages to provide less than 2:1 SWR across 2-meters.

However, it is possible to design 4-element quads with better than 10 dB free-space gain across the entirety of 2-meters. **Table 13-5** provides the specifications



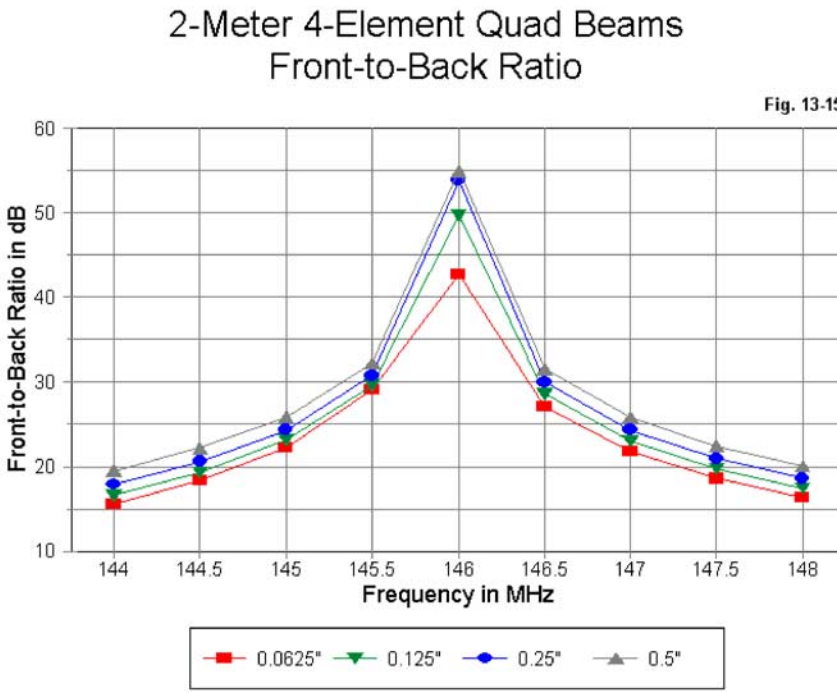
for 4 such quads with our standard range of element diameters. As shown in **Fig. 13-14**, even the thinnest element provides good gain across the band, although the 0.5" diameter version supplies an additional 0.4 or more dB gain.

**Table 13-5: Design Data for a Wide-Band 4-Element Quad**

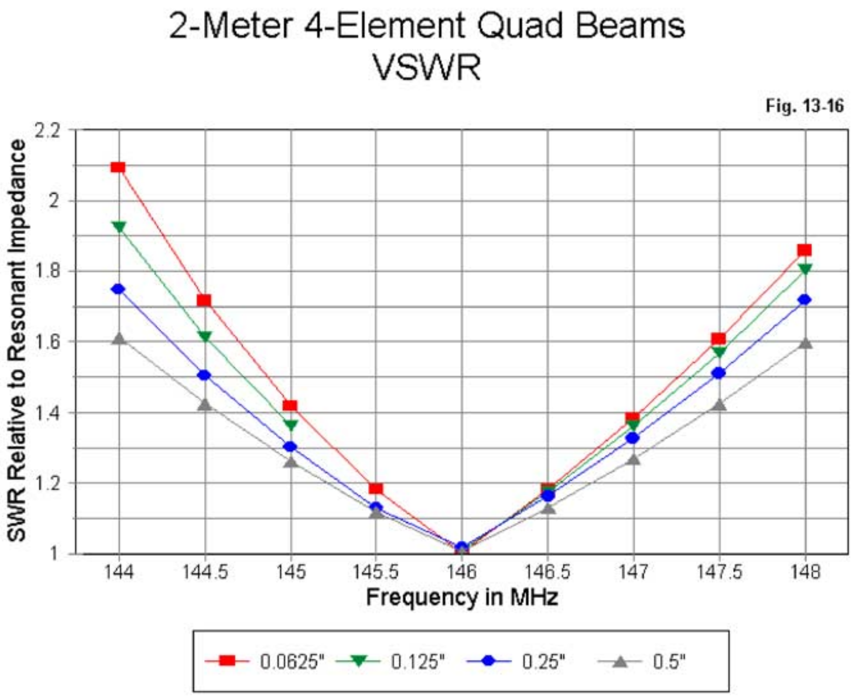
| 1. | | 2. | |
|---|---|---|---|
| Wire Diameter: | 0.0625" | Wire Diameter: | 0.125" |
| Reflector Circumference: | 86.658" | Reflector Circumference: | 87.360" |
| Driver Circumference: | 82.448" | Driver Circumference: | 82.728" |
| Refl-Driver Spacing: | 13.218" | Refl-Driver Spacing: | 13.218" |
| Dir 1 Circumference: | 78.024" | Dir 1 Circumference: | 77.952" |
| Refl-Dir 1 Spacing: | 38.885" | Refl-Dir 1 Spacing: | 38.885" |
| Dir 2 Circumference: | 75.264" | Dir 2 Circumference: | 75.192" |
| Refl-Dir-2 Spacing: | 68.338" | Refl-Dir-2 Spacing: | 67.947" |
| Feedpoint Impedance: | 60.6 Ω | Feedpoint Impedance: | 58.5 Ω |
| Free-Space Gain: | 10.23 dBi | Free-Space Gain: | 10.40 dBi |
| < 2:1 SWR Bandwidth: | 2.82 MHz | < 2:1 SWR Bandwidth: | 3.08 MHz |
| >20 dB F-B Bandwidth: | 1.74 MHz | >20 dB F-B Bandwidth: | 1.99 MHz |

| 3. | | 4. | |
|---|---|---|---|
| Wire Diameter: | 0.25" | Wire Diameter: | 0.5" |
| Reflector Circumference: | 88.448" | Reflector Circumference: | 89.976" |
| Driver Circumference: | 83.072" | Driver Circumference: | 83.424" |
| Refl-Driver Spacing: | 13.218" | Refl-Driver Spacing: | 13.218" |
| Dir 1 Circumference: | 77.782" | Dir 1 Circumference: | 77.760" |
| Refl-Dir 1 Spacing: | 38.885" | Refl-Dir 1 Spacing: | 38.885" |
| Dir 2 Circumference: | 74.992" | Dir 2 Circumference: | 74.352" |
| Refl-Dir-2 Spacing: | 67.446" | Refl-Dir-2 Spacing: | 66.953" |
| Feedpoint Impedance: | 57.3 Ω | Feedpoint Impedance: | 55.0 Ω |
| Free-Space Gain: | 10.52 dBi | Free-Space Gain: | 10.61 dBi |
| < 2:1 SWR Bandwidth: | 3.46 MHz | < 2:1 SWR Bandwidth: | 4.02 MHz |
| >20 dB F-B Bandwidth: | 2.32 MHz | >20 dB F-B Bandwidth: | 2.75 MHz |

These wide-band 4-element quads are only relatively wide--that is, for the class of 4-element quads. In **Fig. 13-15**, we can see that only the 0.5" version of this design provides better than 20 dB 180-degree front-to-back ratio for the entirety of 2 meters, although the thinnest element version provides better than 15 dB front-to-back ratio across the band. The SWR curves in **Fig. 13-16** reveal that 3 of the 4 arrays meet the 2:1 SWR standard. Since (as shown in **Table 13-5**) the resonant impedances are all close to 50 Ohms, these curves will reflect performance with a standard 50-Ohm cable as well.




Very often gain and 180-degree front-to-back ratios come at the expense of general pattern shape. However, the designs we are presently discussing have well controlled patterns. The free-space azimuth patterns for the 0.5" diameter element version of the array appear in **Fig. 13-17** to verify this claim. The forward lobe is especially consistent from one end of the band to the other, while the rear lobes remain quite well controlled.




The arrays that we have sampled emerged from a small GW Basic program, which is listed in Chapter 9. The optimized samples that provided the basis for the regression analysis are extensions of the 2- and 3-element wide-band quads that we earlier discussed.

The collection of quad designs with which we have been working reveals some interesting trends. **Fig. 13-18** graphs the design-frequency gains of all four programmed quad designs for each of the sample 2-meter element diameters. Although the relative gain figures for 2-, 3-, and 4-element quads are interesting, the relative slope of the curves is the key attention-getter. Note that the more elements we add to the quad design, the more dependent the quad becomes on the element diameter. Making multi-element quads of thin wire at VHF and up is one way to lose a significant part of any design's potential.

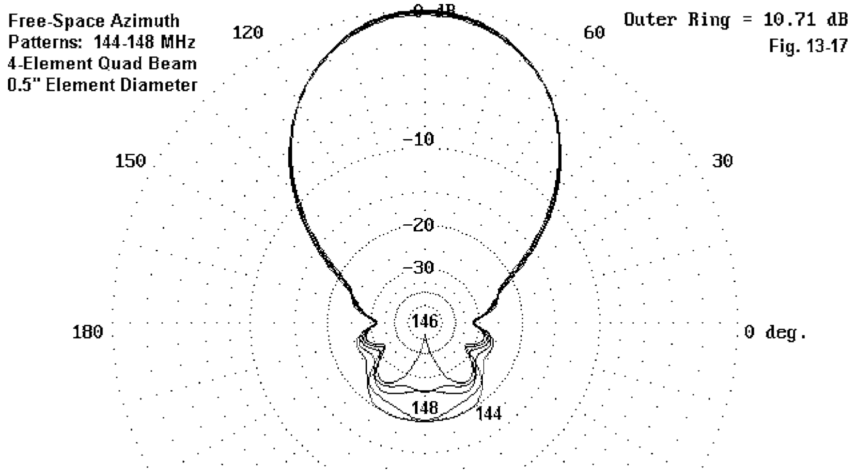



Fig. 13-17

## Element Size vs. Quad Gain
## Free-Space Gain at Design Frequency

Fig. 13-18

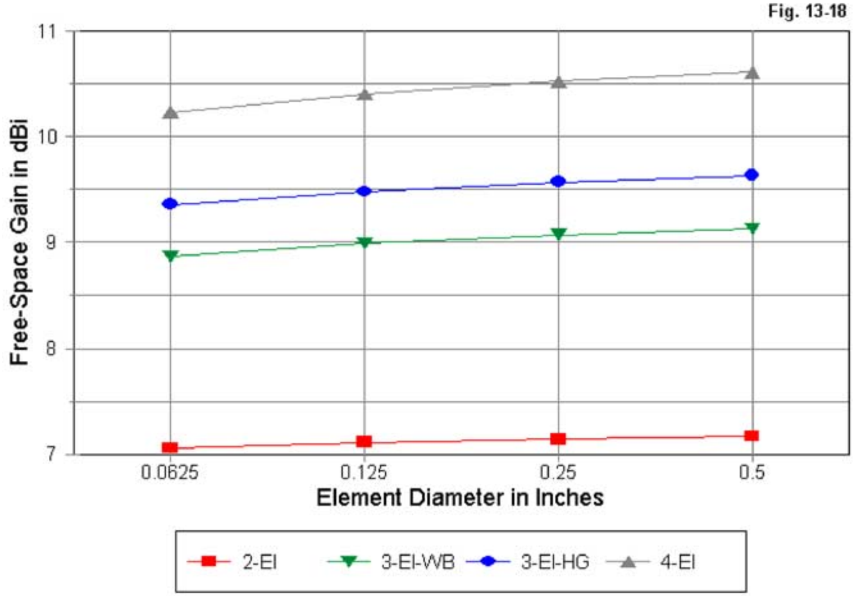
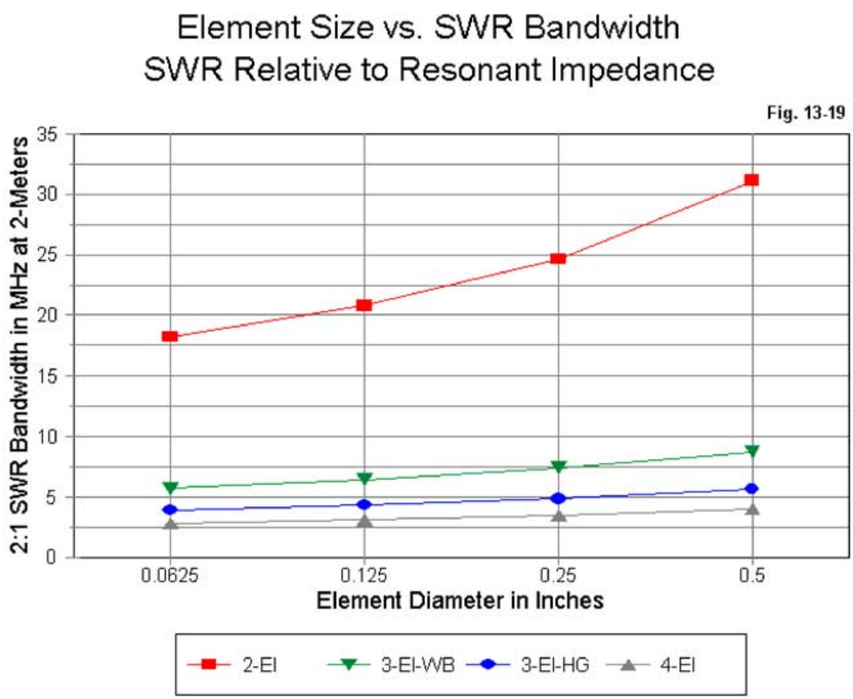


**Fig. 13-19** reveals another fact of life about quads: the greater the number of elements, the narrower the SWR bandwidth of the array. Above a certain number of elements (I do not yet know the exact number), the only way to achieve a wide SWR bandwidth may be to stagger parasitic elements. However, in every case of stagger-tuned elements, the gain falls below maximum. Hence, the multi-element quad may be self-limiting relative to competing designs wherever operating bandwidth is a significant consideration.




If we permit a narrower operating bandwidth, then we can derive considerably more gain from a 4-element quad. For significantly higher gain from a 4-element quad, we must turn to a design with fat elements and wide spacing. **Table 13-6** lists the structural parameters of one such design.

**Table 13-6: 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" |
| Feedpoint Impedance: | 43.1 Ohms |
| Free-Space Gain: | 10.98 dBi |

Three items should be immediately apparent from **Table 13-6**. First, the design uses large-diameter elements: 1/2" in this case. Second, the boom is quite long--about 2" shy of 6'. Third, the design frequency gain is nearly a full dB higher than for the short-boom models with which we began our foray into 4-element quads. The question remaining is whether we have made sufficient improvements to justify the added mechanical requirements of a quad over a Yagi.

To partially answer this question, I shall present the design data for 3 OWA Yagis for 2 meters: a 6-element design using 3/16" elements, a 7-element design using 0.1" elements, and another 7-element design using 1/4" elements. Comparative physical and performance data may prove instructive--at least provisionally.

As shown in **Table 13-7**, the boom lengths of the Yagis bracket our improved 4-element quad array. The 70" quad boom lies roughly evenly between the 54" 6-element Yagi boom and the 84" 7-element Yagi booms. As well, the 4-element quad gain also lies between the Yagi numbers. However, before we make judgments using date from just the design frequency, let’s survey the entirety of the 2-meter band for all 4 antenna designs.

**Table 13-7: Design Data for 3 OWA Yagis**

| Antenna | 6 0.1875" El | 7 0.1" El | 7 0.25" El |
|---|---|---|---|
| Reflector Length | 40.520" | 41.180" | 41.200" |
| Driver Length | 39.962" | 39.634" | 39.400" |
| Director 1 Length | 37.376" | 37.338" | 36.800" |

| | | | |
|---|---|---|---|
| Director 2 Length | 36.310" | 36.660" | 36.100" |
| Director 3 Length | 36.310" | 36.730" | 36.100" |
| Director 4 Length | 34.960" | 36.542" | 35.900" |
| Director 5 Length | ---- | 34.856" | 34.200" |
| Refl-Driver Spacing: | 10.130" | 8.570" | 8.942" |
| Driver-Dir 1 Spacing: | 4.192" | 4.923" | 4.658" |
| Dir 1-Dir 2 Spacing: | 10.974" | 12.016" | 12.030" |
| Dir 2-Dir 3 Spacing: | 11.356" | 15.484" | 15.253" |
| Dir 3-Dir 4 Spacing: | 16.936" | 20.848" | 20.538" |
| Dir 4-Dir 5 Spacing: | ---- | 22.488" | 22.079" |
| Total Boom Length: | 54.218" | 84.329" | 83.500" |
| Feedpoint Impedance: | 50.0 Ohms | 45.7 Ohms | 44.3 Ohms |
| Free-Space Gain: | 10.23 dBi | 11.47 dBi | 11.55 dBi |

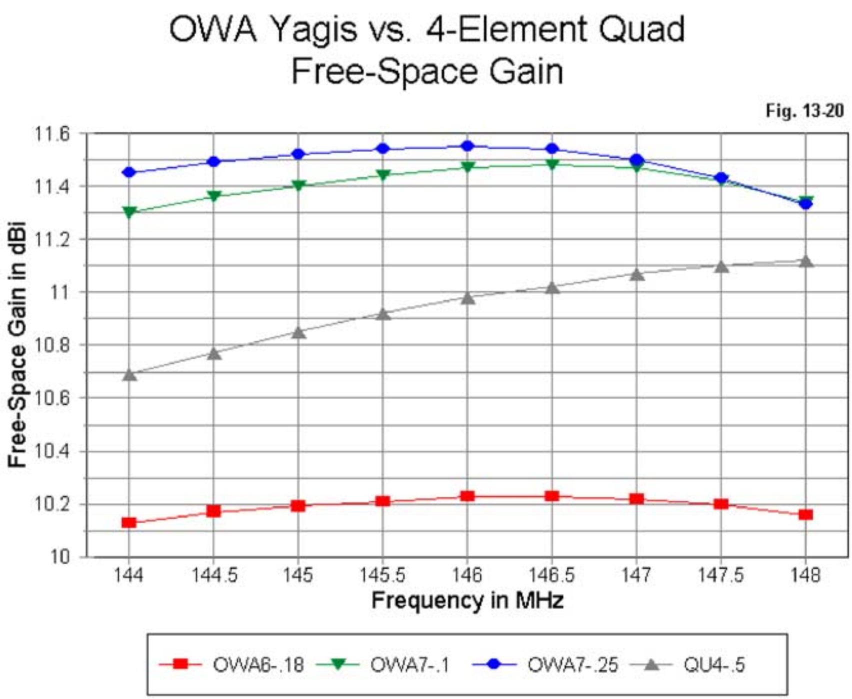
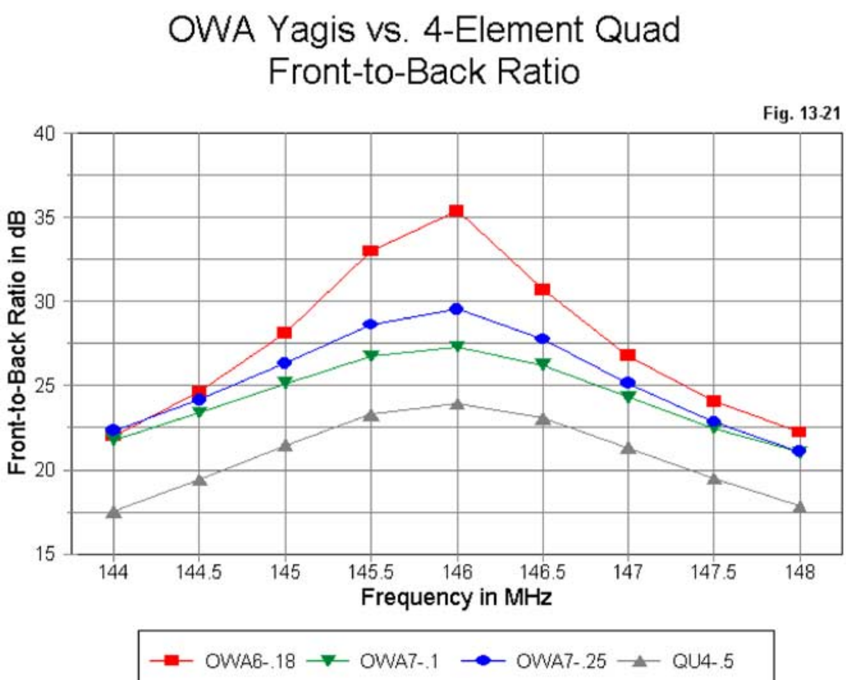


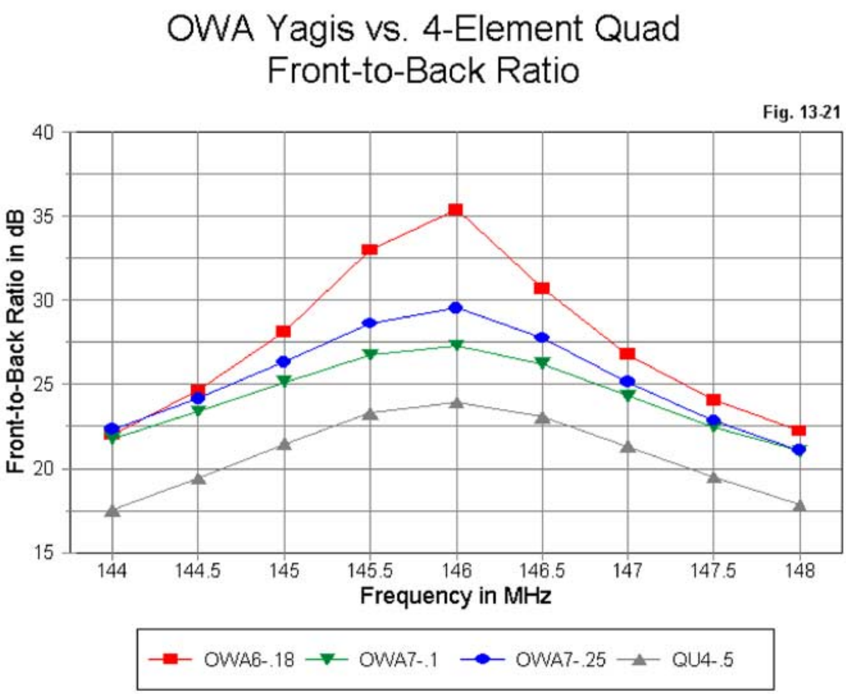
**Fig. 13-20** shows the free-space gain figures for the 4 antennas--3 Yagis and a quad. Apparent is the greater stability of the Yagi gain, as the quad changes gain by over 0.4 dB across the band. By way of contrast, the Yagis show a maximum gain change of about 0.2 dB. How significant this factor is to a given operation will be a user judgment.

Of perhaps more interest is the fact that the relative average gains of the arrays shown in the graph is almost wholly proportional to the boom lengths of the arrays. The quad boom length is almost precisely the median between the 6- and 7-element OWA Yagis, and its average gain also closely fits that same position. Hence, the gain advantage of the quad relative to boom length--when optimized for a considerable bandwidth--begins to disappear as we reach 4-elements. There are spot designs that can achieve the same gain on a shorter boom--and a few such designs may show a good operating bandwidth for certain element diameters. However, the

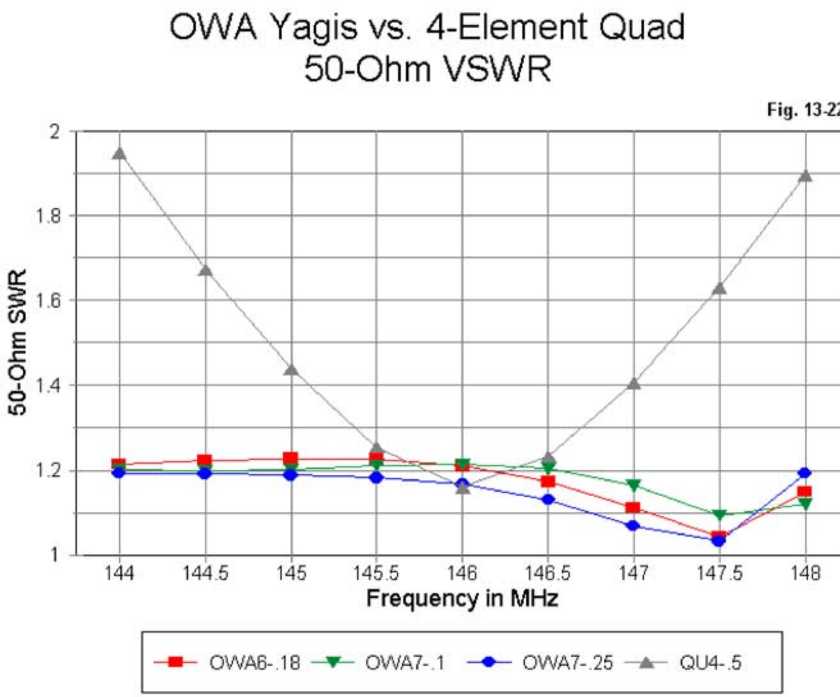


ones I have so far examined tend to narrow in operating bandwidth with decreasing element diameter at a faster rate than the high-gain 4-element example used here.

The 180-degree front-to-back figures appear in **Fig. 13-21**. Although the 6-element OWA Yagi shows the highest peak front-to-back ratio, the band-edge values for all three Yagis are very similar to each other and are above 20 dB. In contrast, the 4-element quad achieves a 20 dB front-to-back ratio for only about 3/4 of the passband. Once more, the relatively narrow-band operating characteristic of the quad emerges. To obtain a wider front-to-back bandwidth, using the 20 dB standard, one would have to turn either to the lower-gain wide-band designs or to a serendipitous spot design.



All of the antennas achieve 50-Ohm SWR values of under 2:1 across 2 meters, as shown in **Fig. 13-22**. All three OWAs have values of under 1.25:1 across the band, with the 7-element 0.25" element version achieving under 1.2:1 across 2 meters. All three Yagis can be tweaked for this level of performance, although the 1.25:1 maximum of the three designs is likely to prove acceptable under most circumstances. The quad comes nowhere near the Yagi performance, although it does stay within the <2:1 SWR standard. Whether the OWA curves are significantly preferable to the quad curve may rest on a user judgment of the significance of line losses within the total antenna-feedline system. For a given installation, a complete analysis of line losses across the band would be a wise procedure to use before reaching a conclusion.




It is interesting also to investigate pattern shape for various antennas that one might consider using. **Fig. 13-23** compares the free-space azimuth patterns for the quad with those for the 0.25" element 7-element OWA Yagi. The Yagi displays better control of rear quadrant radiation across the band. However, the long Yagi also shows some “neck bulges,” that is, emergent secondary lobes. Similar lobes are just appearing within the quad pattern, but are far less prominent. To an antenna designer who is not under the press of commercial deadlines, the existence of all such pattern bulges is a sign that further development work is in order. Such emergent lobes are not always eliminable, but the purist tries anyway. This last note is a way of saying that the work is still in progress and far from complete.

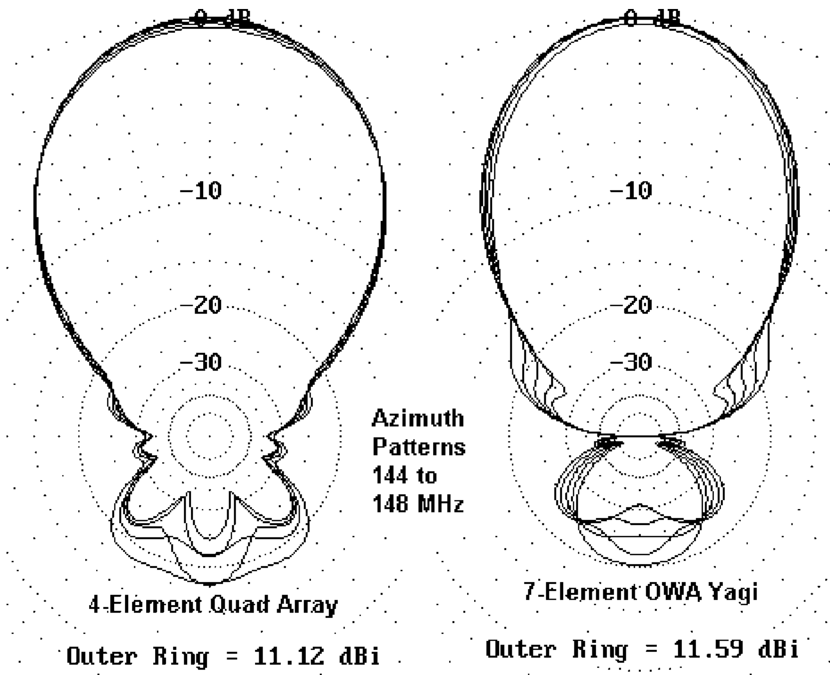



Fig. 13-23

## Some Very Tentative Conclusions

The conclusions to be drawn from this investigation may be obvious, but are perhaps worth noting anyway.

1. For quad design at VHF, using large-diameter elements can be beneficial in achieving close to the full theoretical gain of a quad over a Yagi with a similar number of elements. Thin-wire elements narrow the operating bandwidth and reduce gain by significant amounts.

2. Traditional short-boom monoband quad designs fail to realize full quad gain and bandwidth by overlooking the naturally higher mutual coupling of quad elements--a factor that dictates longer boom lengths for optimal performance (relative to arrays with linear elements).

3. Quads up through 3 elements are certainly capable of performance that is superior to that of Yagis with the same number of elements and relevantly similar boom lengths. However, above 3 elements, the need for added boom length to achieve optimum inter-element coupling may set a limit on the utility of quads wherever operating bandwidth is an equal concern with gain.

4. Quads--even short-boom quads--may still excel for narrow-band applications. However, achieving full performance from a narrow-band quad requires the use of sizable element diameters. Otherwise, the simplicity of VHF Yagi construction may prevail, especially with the availability and simplicity of OWA designs.

5. When it comes down to simple and cheap utility antennas with some gain and directivity, the Yagi-quad decision becomes more a matter of what materials are available and depends less upon the purist considerations that have gone into these notes. Coat hangers, scrap wire, wood, and PVC have yielded generations of utility antennas of either the Yagi or the quad type.

6. The work is far from done.

# Chapter 14
# Quad Horizons

What I think this volume might have accomplished has been summed up in the preceding chapter. What remains to be done I shall list here, at least as I see it today.

First, there are a number of spot designs that seem to violate the progressions uncovered in the work so far. They manage to achieve high gain and reasonably broad-banded operation on shorter than expected boom lengths, for a given number of elements. Finding a progression of such designs with consistent rates of reactance change has so far been elusive. However, elusiveness does not mean impossible-to-find, but only that I have not found the desired progressions. Whether such progressions exist may rest on the translation of these findings into more theoretically sound fundamental relationships governing quad loop interaction. Indeed, there may be some "periodic" functions associated with quad loop interaction.

The nature of this investigation has been systematic, but not theoretically based--other than the degree to which the modeling programs themselves are theoretically based. At most, I have uncovered some progressions of quad operation that suggest fundamental properties, but the discoveries do not establish the suggested principles to the exclusion of all others. Much remains to be done with respect to quad theory.

Second, there are a number of directions that I have not taken in this study. The potentials of parasitic arrays composed of asymmetrical and symmetrical rectangles of two or more loops each is work that others are exploring. Such loops show great promise of providing wide operating bandwidths on shorter booms with fewer elements--but, of course, at the expense of a far more complex structure within each element of the array.

In addition, there are a number of hybrid parasitic arrays, general known as "quagis." These arrays may use only a quad loop reflector or a quad loop driver, or both, with several linear dipole directors. When these hybrids first appeared, they showed great promise, generally outperforming Yagis of the period. However, those Yagis were generally of the era before computer optimization. How much a quagi design might add to the present generation of Yagi designs remains to be determined. Of course, we might also let the quad loop elements be multi-loop elements, either asymmetrical or symmetrical. Whether there is a design that combines the best of both worlds remains on the horizon.

Finally, but not exhaustively, much remains to be done in the region of multiband quads. Volume 1 of this effort established that the concentric rings of quad elements not only interact, but do so in good designs so as to enhance operation on at least some bands. The enhancement may show up as gain or as operating bandwidth. However, to have shown that these effects exist is a long way from understanding how they occur and an even longer way from being able to control them so as to optimize multi-band quads to desired levels of performance.

With respect to long-boom quad arrays, we showed that it is possible to interlace designs effectively. But, this effect only established that the interlacing could be done without detracting from the performance of the arrays when treated individually. This result still leaves open the question of how concentric elements mutually enhance operation, as we saw in the KC6T planar quad array. To what degree and limit we may expand the principle to quads with more than 2 elements is still uncertain.

To the degree, then, that this study has solved any problems in quad design, only the easiest questions have met with some success. Many more theoretical and functional challenges still remain. Hopefully, this study, besides providing some practical analysis and design guidance, will inspire others to look into the fascinating world of quad loops and arrays. The more investigators and investigations, the greater the chance that we shall eventually understand how to put this class of antennas to its optimal set of uses.

## Other Publications

We hope you've enjoyed Volume 2 of the **Cubical Quad Notes ~ *Rethinking the Quad Beam!*** If you missed the companion Volume 1, ***A Review of Existing Designs***, you'll find it and many other very fine books and publicartions by the author L.B. Cebik, W4RNL in the ***antenneX Online Magazine BookShelf*** at the web site shown below.

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***antenneX Online Magazine***
**http://www.antennex.com/**
**POB 72022**
**Corpus Christi, Texas 78472 USA**



ISBN: 1-877992-10-0