Notes on Designing Large Five-Band Quads

Would you like to design a large loop Yagi and achieve the design performance in reality? Here's how.

By L. B. Cebik, W4RNL

The design of large five-band quad arrays has a number of facets, each of which deserves attention by the would-be quad user. We can divide them into three general groups:

1. The use of antenna modeling software as the design vehicle: How do we set up the model for effective design work?
2. The performance of the quad as designed: How can we use the modeled performance as a guide to evaluating and improving designs?
3. The transition from model to physical antenna: What factors play a role in determining if and how the modeled array should be built?

Although it is not possible to provide definitive answers to all of these questions, we can run through a design exercise and extract as much guidance from it as possible. Although not exhaustive, the amount of guidance will be considerable.

For our project, let's consider the design of one or more large five-band HF quad arrays. By large, I mean an array with at least four elements per band.

Setting Up the Design Project

The availability of *NEC*-based antenna modeling programs has moved much of the design process from the antenna tower to the computer. However, the process of design may prove daunting unless we approach it in a somewhat systematic manner.

Constraints

Designing a large quad array involves some concessions to reality from the start. For example, multiband quad arrays typically employ planar groups of elements: that is, flat, four-arm nonconductive structures to support an element for each of the bands of concern. Consequently, the designer cannot, for each band, select the optimal spacing between elements for maximizing key performance parameters, such as gain, front-to-back ratio (F/B) and SWR bandwidth. Every performance outcome will be a compromise, with its foundation in the initial spacing decisions for the sets of support arms.

Equally limiting will be the fact that quad arrays typically use wire elements. At the outset, I shall specify #12 AWG copper wire as the material of choice for this exercise. However, that very choice will limit and direct the design effort. As I have shown elsewhere, the gain and the operating

1434 High Mesa Dr
Knoxville, TN 37938-4443
e-mail **cebik@cebik.com**

bandwidth (in terms of both F/B and the 2:1 SWR curves) are functions of the element diameter when specified as a fraction of a wavelength.[1] In the upper-HF region, #12 wire is a small fraction of a wavelength. Achieving full operating potential requires element diameters approaching about 0.5 inch at 10 meters and 1 inch at 20 meters.

However, the planar arrangement of elements does permit the quad designer to achieve—at least on some bands—a higher level of performance than would be provided by a monoband version of the array using similar dimensions.[2] The effects of element interactions on the large quad array will be among the phenomena we shall examine.

A Starting Point

Because many examples of large quad-array design already exist, we need not begin at random. One of the better designs available is the product of Danny Mees, ON7NQ.[3] It consists of three elements on 20, 17 and 15 meters, with a fourth element added for 12 and 10 meters. As a three-element quad on the lower three bands, the array uses a familiar set of element spacing. As shown in part of Fig 1, the reflector is 10 feet from the driver, with a director 8 feet forward of the driver. On 12 and 10 meters, Danny added new elements centered between the reflector and the driver. The new element becomes the driver for the upper two bands, with two directors in front of it. Table 1 supplies the modeled dimensions of the ON7NQ 3-4-element quad and the dimensions of the other large quads we shall explore. Fig 2 shows the general outline of the entire ON7NQ array.

Since one facet of quad design is reducing the number of variables involved, we will use the initial spacing selections of the ON7NQ array as a starting point. Then we shall add one or more elements to each band. In Fig 1B you can see that an additional director has been added, once more at the standard 8-foot spacing from the ON7NQ forward element, resulting in a 26-foot boom. Thus we have a 4-5-element array. Fig 3 shows an outline sketch of the full set of elements.

Fig 1C shows the layout using a wider spacing for the new director. This places the forward elements 12 feet from the ON7NQ forward elements, resulting in a 30-foot boom length. However, for reasons that will become clear as we proceed to analyze the design, it became necessary to add another partial element set equally spaced between the two forwardmost full element sets. The new support holds elements only for 15 and 10 meters. The end product is a 4-5-6-element quad array, shown in Fig 4.

Specifications for 4-5-Element Quad

The design process could proceed without a set of goals, but then you would never know when to stop. A set of clear specifications, based on reasonable expectations that emerge from experience, can direct the work of optimizing a design. This converts an endless task into a merely long but finite one. For the design project at

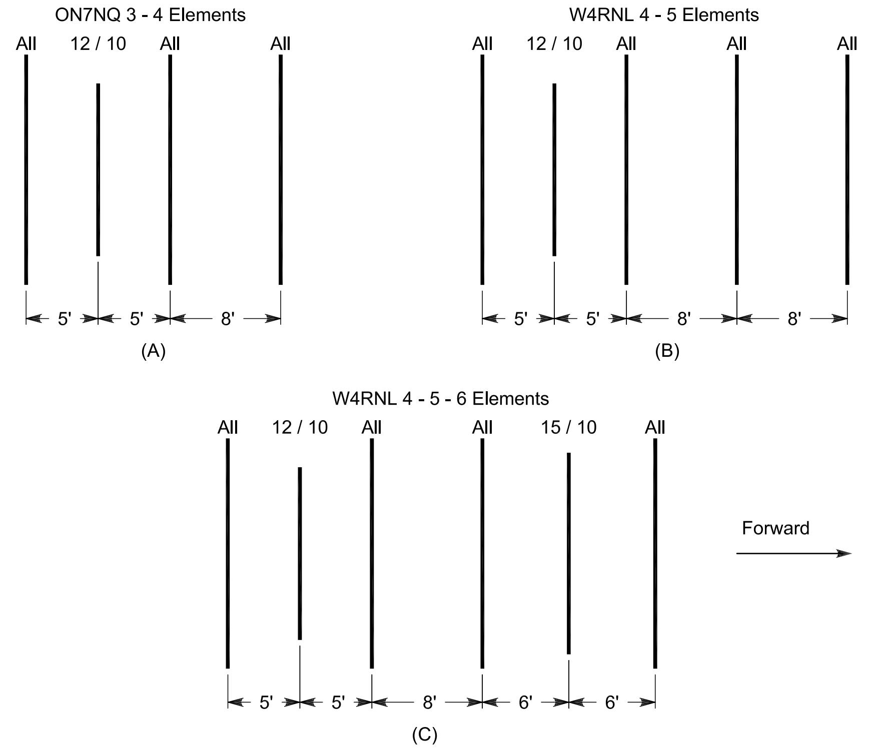

Fig 1—Element spacing for three large five-band quad designs.

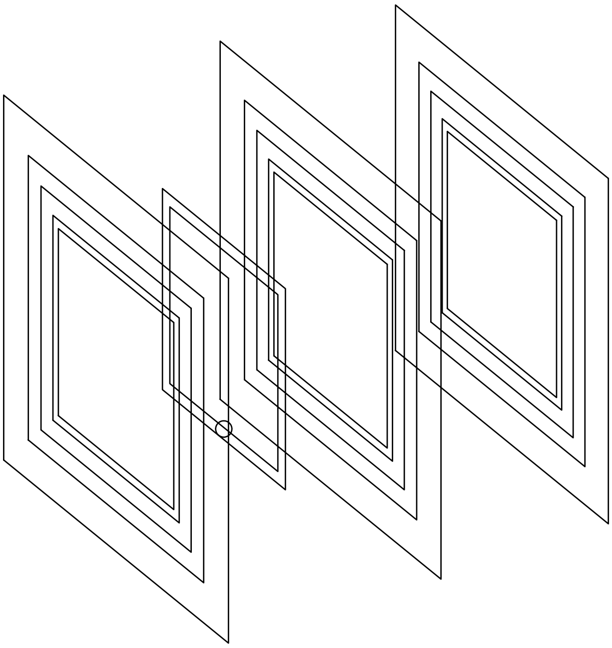

Fig 2—Outline sketch of the 3-4-element ON7NQ five-band quad.

[1] Notes appear on page 24.

Table 1—Three-Large 5-Band Quad Array Dimensions

ON7NQ, 3-4-Element 5-Band Quad Dimensions (Inches)

Antenna Part	*Side Length*	*Loop Circumference*
20 Refl	217.0	868.0
20 Driver	213.7	854.8
20 Dir 1	205.0	820.0
17 Refl	168.5	674.0
17 Driver	166.3	665.2
17 Dir 1	159.8	639.2
15 Refl	144.8	579.2
15 Driver	142.0	568.0
15 Dir 1	138.0	552.0
12 Refl	122.4	489.6
12 Driver	119.9	479.6
12 Dir 1	118.2	472.8
12 Dir 2	118.7	474.8
10 Refl	110.68	442.7
10 Driver	105.8	423.2
10 Dir 1	104.6	418.4
10 Dir 2	103.99	416.0

W4RNL, 4-5-Element 5-Band Quad Dimensions (Inches)

Antenna Part	*Side Length*	*Loop Circumference*
20 Refl	217.0	868.0
20 Driver	213.0	852.0
20 Dir 1	195.0	780.0
20 Dir 2	196.0	784.0
17 Refl	168.5	674.0
17 Driver	165.6	662.4
17 Dir 1	159.8	639.2
17 Dir 2	159.8	639.2
15 Refl	145.4	581.6
15 Driver	141.4	565.6
15 Dir 1	139.5	558.0
15 Dir 2	139.3	557.2
12 Refl	122.4	489.6
12 Driver	120.6	482.4
12 Dir 1	118.2	472.8
12 Dir 2	119.8	479.2
12 Dir 3	118.6	474.4
10 Refl	110.0	440.0
10 Driver	105.8	423.2
10 Dir 1	104.4	417.6
10 Dir 2	105.0	420.0
10 Dir 3	104.0	416.0

W4RNL, 4-5-6-Element 5-Band Quad Dimensions(Inches)

Antenna Part	*Side Length*	*Loop Circumference*
20 Refl	217.0	868.0
20 Driver	213.0	852.0
20 Dir 1	201.2	804.8
20 Dir 2	194.8	779.2
17 Refl	168.5	674.0
17 Driver	165.6	662.4
17 Dir 1	160.2	640.8
17 Dir 2	159.6	638.4
15 Refl	145.8	583.2
15 Driver	141.4	565.6
15 Dir 1	139.0	556.0
15 Dir 2	138.8	555.2
15 Dir 3	138.4	553.6
12 Refl	121.8	487.2
12 Driver	120.2	480.8
12 Dir 1	119.4	477.6
12 Dir 2	120.2	480.8
12 Dir 3	117.4	469.6
10 Refl	110.6	442.4
10 Driver	105.7	422.8
10 Dir 1	104.4	417.6
10 Dir 2	104.8	419.2
10 Dir 3	104.8	419.2
10 Dir 4	104.2	416.8

See text and Fig 1 for element spacing data.

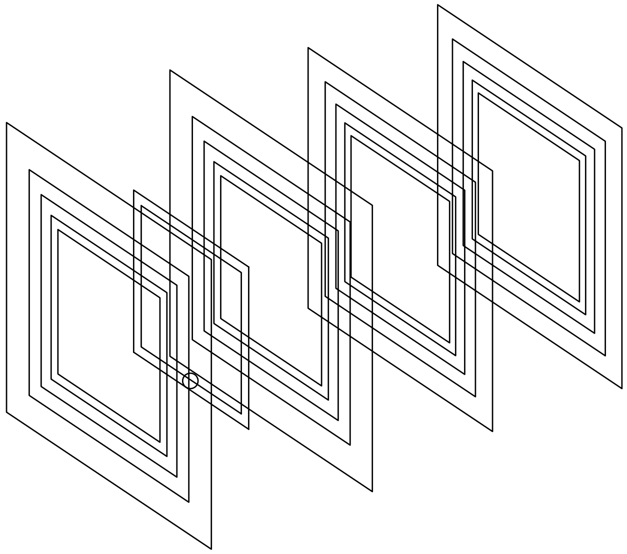

Fig 3—Outline sketch of the 4-5-element W4RNL five-band quad.

hand, the following specifications were set for the 4-5-element quad.

Gain: The average free-space gain of the 4-5-element quad should be about 0.7 dB higher than the ON7NQ array on each band. This goal is likely to be achieved on all but 20 meters, where the boom length is short for four elements. The length is adequate for a monoband optimized Yagi, but the fixed spacing of the quad array limits improvements. First, a monoband quad generally requires greater spacing than a monoband Yagi to achieve its full gain potential for any given element diameter. Second, on 20 meters the elements do not have other elements outward from which to potentially derive a modicum of performance enhancement. Third, the individual element spacing may not be optimal. When the spacing was increased to the 30-foot boom length for the 4-5-6-element array, the gain specification was raised by about 0.2 dB as the design goal.

Front-to-Back Ratio: It is almost impossible to obtain a 20-dB front-to-back ratio from a wire quad across any HF band (except for the narrow WARC bands). Consequently, the 20-dB standard, long applied to monoband Yagi designs, had to be set aside. More realistic is a goal of achieving a 15 dB front-to-back ratio across the bands. Even this reduced standard cannot be achieved on every band with every configuration. Part of the analysis will deal with why some bands fall short of this goal for some array configurations.

The front-to-back specification is given in terms of the 180° front-to-back ratio. Due to element interactions and the fixed spacing of the elements, a full front-to-rear evaluation will only sometimes match the 180° front-to-back ratio. A front-to-rear evaluation examines the entirety of the radiation pattern to the rear of the beam. Large multiband quad array rear patterns can range from good to exceptionally "messy."

Feed-Point Impedance: Since the ON7NQ array was designed for direct feed with a 50-Ω coaxial cable, the larger arrays also use this feed-point impedance as a specification. The usual 2:1 SWR standard will be applied to determine if the feedpoint impedance falls within the range limits.

Bandwidth Coverage: Although the ON7NQ array was optimized for the CW end of each of the HF bands covered, the goal for the larger arrays was to allow operation over each band. This was not always possible. The 20-meter band is especially resistant to full coverage within the other performance specifications. The 10-meter band was also limited to coverage of the first 800 kHz (from 28.0 to 28.8 MHz), since broader coverage required a severe reduction in performance levels.

Design Strategy

The discussion of a starting point and a set of specifications involve basic "whats," but they do not tell us anything of the "how" of design. Design work with antenna-modeling software requires a strategy if the work is to proceed effectively, even efficiently. Modeling a five-band quad with more than three elements results in a large model.

Moreover, each element that will be modified in the design process involves—assuming a free-space model—the alteration of 16 coordinate values for each and every change. For the task at hand, modeling software that permits the use of variables as coordinates can simplify the work of alteration to a single operation. Consequently, the design work was performed using *NEC-Win Plus*, which permits 24 variable assignments—just enough for the entire project without resorting to workarounds.

Another strategic issue is the segmentation of the element loops. Ideally, a good *NEC* model attempts to align segment junctions to achieve maximum accuracy. Since each wire is to some degree active on all bands, the 20-meter elements should have about twice the number of segments as the 10-meter elements, so that each segment is about the same length at the highest frequency to be used. Since five segments per side is about the minimum level of segmentation to assure accurate results with a closed-loop structure, the overall segmentation becomes a matter of number juggling.

If we place seven segments on each side of a 10-meter element, and if we increase the number by two for each lower band in order, we arrive at 15 segments per side on the 20-meter elements. Fig 5 sketches the elements and the suggested level of segmentation for one set of elements for five bands. This segmentation scheme comes close to meeting the desired 2:1 ratio of segments between 20 and 10 meters and yields a practical alignment of segment junctions from one band to the next.

The resulting arrays are large in both the number of wires and the number of segments. A fully segmented ON7NQ array requires 68 wires and 724 segments, already more sizable than the limits of some widely used software. The 4-5-element array needs 88 wires and 944 segments, while the final 4-5-6-element quad

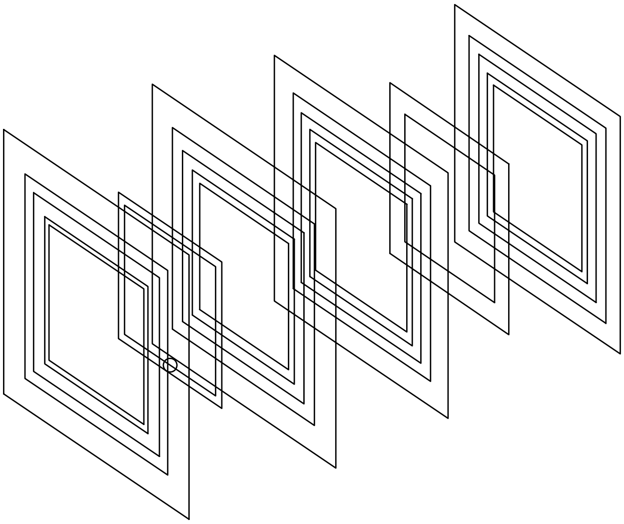

Fig 4—Outline sketch of the 4-5-6- element W4RNL five-band quad.

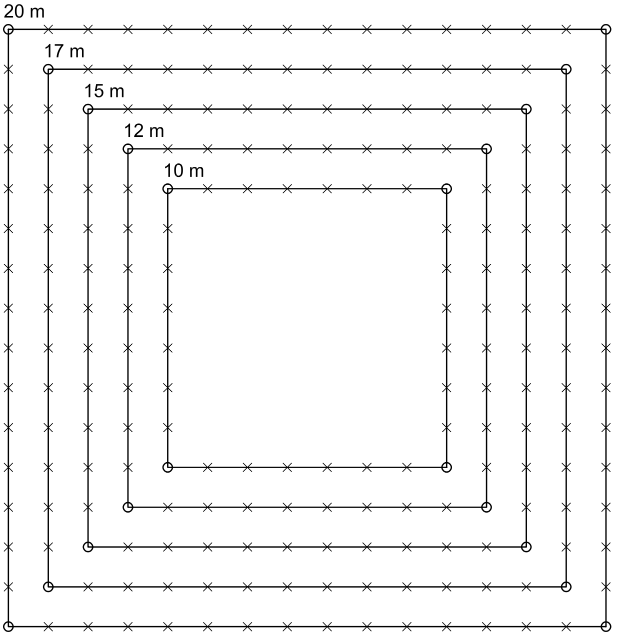

Fig 5—Recommended "full" segmentation of a five-band set of quad elements. Notice how the segments align among the elements.

calls for 96 wires and 1016 segments. Since the time required for each run of the model goes up by the power of the number of wires and the number of segments, core runs for the largest array can approach the limit of most people's patience!

The solution is to use a lower level of segmentation, but only after verifying its adequacy, if not its accuracy. Therefore, I ran a set of comparative curves on the ON7NQ array using full segmentation and a lower level: five segments per side for the upper three bands, and seven segments per side for the lowest two bands. The resulting models produced operating bandwidth data such that in only two instances was a final small adjustment required using the fully segmented model. However, the actual gain and front-to-back figures were sufficiently off that only the performance trends were used to optimize the model. The final tables reflect the performance for the fully segmented models.

Table 1 thus reflects the dimensions for the fully segmented arrays. Without the preparation outlined above, the few hours of work needed to produce these figures might well have lengthened into the work of many weeks.

Design Evaluation

In the course of the design exercise, a number of interesting properties of large quad arrays emerged. Some of the patterns making up the properties might not have been so easily discovered without the efficiency of computer-aided design, although an automated design procedure might have obscured some of them. Let's analyze the designs band-by-band. We shall use a mixture of tabular and graphic data to examine each band.

20 Meters

All of the large arrays show a steady increase in gain with each step upward in frequency band. Of all the bands, 20 meters shows the least improvement as we enlarge the array. Table 2 provides the data for the band edges and in the middle of the band. Fig 6 sweeps the band to provide a complete picture of the free-space gain.

At the low end of the band, the 4-5 array shows a significant increase over the 3-4 version. The gain increase tapers off as we move up the band so that the average gain margin between versions 3-4 and 4-5 is the same as between version 4-5 and 4-5-6. However, the gain of ON7NQ's version 3-4 had been optimized at the expense of full-band coverage. Both 4-5 and 4-5-6 provide full coverage of 20 meters, even if at lesser levels at the high end of the band.

The front-to-back ratio curves for all three quad versions appear in Fig 7. The curves are roughly congruent, but the increasing boom length of the array as we move from one version to the next yields a higher peak value at about 14.1 MHz. Although both larger arrays have a higher ratio than the original ON7NQ array at the low end of the band, all three pass the upper end of the band with similar values. Likewise, as shown in Fig 8, the two larger arrays have similar SWR curves that barely fit within the band at less than 2:1 SWR relative to 50 Ω. In this feature, they are superior to the original ON7NQ array, since its SWR curve cannot be moved sufficiently to cover the entire band without a significant reduction in peak gain.

Adding a second director to the initial ON7NQ thus allows an improvement of gain of modest amounts. The added director permits coverage of the entire 20-meter band by judicious selection of director loop sizes, which differ as we change the boom length. Without major changes in individual element spacing, further performance improvement is unlikely, since the first director has two functions. In combination with the driver and the reflector, it sets the feed-point impedance. In combination with the second director, the first director sets the operating

Table 2—20-Meter Performance of Three Quad Designs

Frequency (MHz)	*Gain (dBi)*	*Front/Back (dB)*	*Impedance (R ± jX)*	*50-Ω SWR*
ON7NQ 3-4-Element, 5-Band Quad				
14.0	8.42	11.83	37.6 –*j*18.5	1.66
14.175	8.29	15.06	44.3 + *j*4.4	1.17
14.35	8.06	9.76	34.8 + *j*36.5	2.50
W4RNL 4-5-Element, 5-Band Quad				
14.0	8.81	15.02	33.6 –*j*20.5	1.88
14.175	8.58	16.76	51.9 + *j*10.0	1.22
14.35	8.14	9.96	57.8 + *j*33.8	1.89
Average gain over 3-4: 0.25 dB				
W4RNL 4-5-6-Element, 5-Band Quad				
14.0	9.04	15.37	31.7 –*j*18.4	1.89
14.175	8.82	17.82	54.9 + *j*12.8	1.29
14.35	8.41	10.36	56.6 + *j*35.3	1.94
Average gain over 4-5: 0.25 dB. Average gain over 3-4: 0.50 dB				

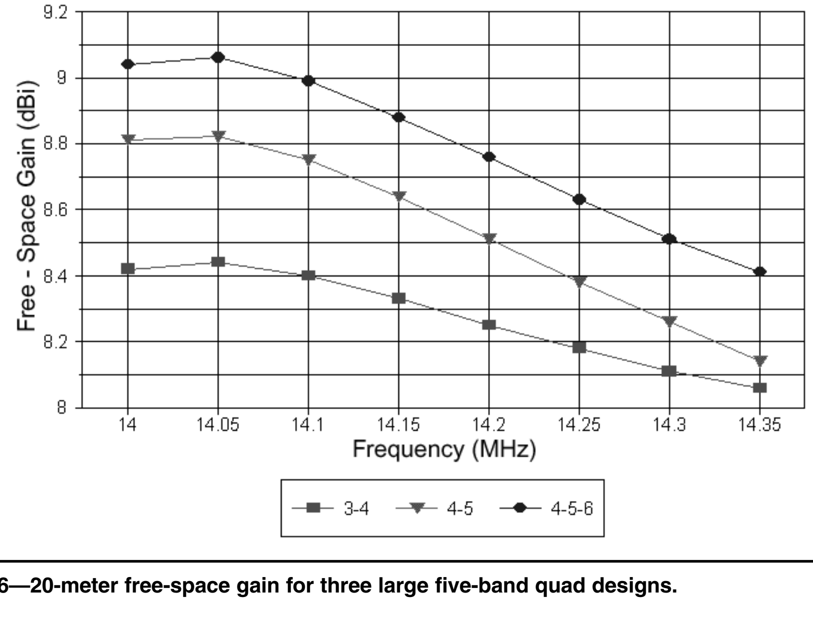

Fig 6—20-meter free-space gain for three large five-band quad designs.

bandwidth for the major parameters. Hence, the two four-element 20-meter designs use very different director sizes, although the driver and reflector remain constant. All in all, both larger 20-meter sections have boom lengths that remain well under 0.4 λ, which is short for a four-element parasitic array.

17 Meters

Because 17 meters is such a narrow band (100 kHz), the data in Table 3 will suffice to permit an evaluation of the performance of the arrays on this band. Three factors allow the 17-meter portions of the larger arrays to achieve significant gain over the initial three-element quad. First, the boom length increases as a fraction of a wavelength so that the two new sections bracket a half wavelength of boom length. Second, the extra element is well suited to setting the element mutual coupling for a higher gain level. Third, the 17-meter band is narrow, permitting the operating performance to be well focused.

Nevertheless, the 30-foot-boom version requires different lengths than the 26-foot version for the two directors to achieve the final 0.2-dB gain increment. However, the added length also permits the designer to obtain feed-point impedances closer to 50 Ω, even though both four-element designs have comparable F/B values.

Despite the factors that allow the 17-meter section to achieve gain in excess of the specifications for the larger arrays, the gain differential between the 17-meter and 20-meter sections calls for brief comment. The longer boom length (in terms of a fraction of a wavelength) and the narrow band requirements on 17 meters contribute to the gain excess over that at 20 meters. The 17-meter elements in their planar supports are surrounded on both sides by elements for other bands. Changes in the 20-meter and 15-meter elements do affect the performance curves of 17 meters—much more of an effect than changes to the 17-meter elements have upon the 20-meter performance curves. In general, being surrounded by elements for other bands tends to improve gain, but this also tends to slightly reduce the F/B and SWR bandwidth.

15 Meters

As shown in Table 4 and in Fig 9, 15 meters is marked by remarkable gain stability for all three quad versions. The gain improvement for the 4-5 array over the 3-4 array is more than 1 dB, with another $^{1}/_{3}$ dB added by the increased boom length of the 4-5-6 quad. However, these values, which are in excess of expectations for the 4-5-6-element design, required the addition of a new director six feet between the first and second directors for 20 and 17 meters. Table 4 shows the best gain values obtained with the longer boom, with and without the added director. Obviously, the longer boom—about $^{5}/_{8}$ λ—was insufficient to provide stable gain across the band without an intervening director.

The front-to-back curves for 15 meters, shown in Fig 10, are equally interesting. The initial 3-4 array, with a single director for 15 meters, shows the typical "spike" in the maximum front-to-back value. Both longer boom models provide much smoother performance across the entire band. The smoother performance is also reflected in the feed-point impedance values. The 3-4 array can be adjusted for less than 2:1 SWR across the band, but it cannot approach the leveled values for the longer-boom arrays.

Part of the reason for the impedance and SWR situation is revealed in Fig 11, the 50-Ω SWR curves for the three arrays. The 3-4 array shows the typical curve of a three-element beam, with a single SWR minimum. Both the 4-5 and the 4-5-6-element arrays display two SWR minimums at different points within the band. The double-dip

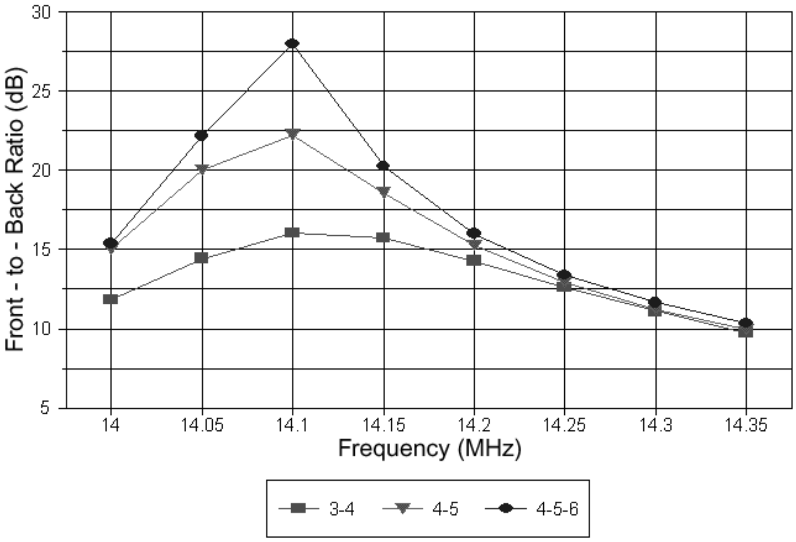

Fig 7—20-meter front-to-back ratios for three large five-band quad designs.

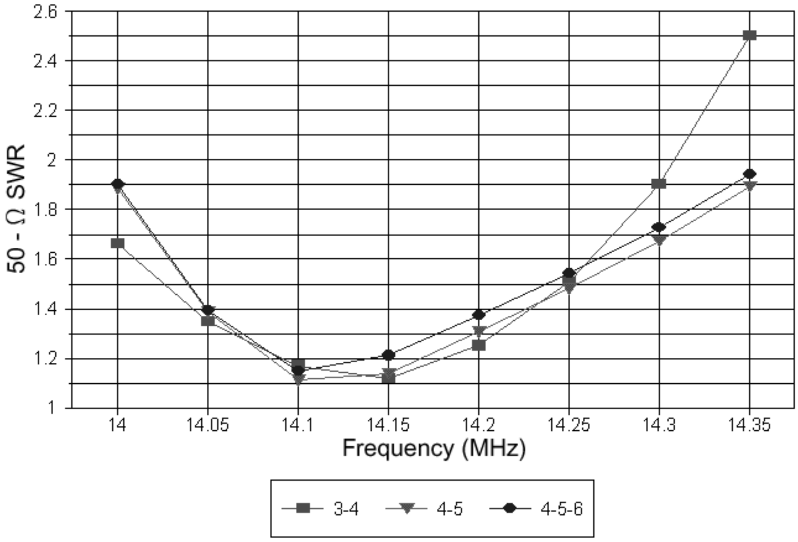

Fig 8—20-meter 50-Ω SWR curves for three large five-band quad designs.

curve is a mark of "wide-band" tuning of a parasitic array, as the term is defined in the series of Yagis designed by NW3Z and WA3FET.[4] The 15-meter array spaces the reflector and the first director at nearly optimal distances from the driver to set the feedpoint impedance for wide-band 50-Ω operation. The reflector is about 0.216λ behind the driver, while the first director is about 0.173λ ahead. An additional director or directors then provide gain, as shown in Table 1. The additional director in the 30-foot model permits the designer to achieve smoother wide-band performance in all categories at a boom length that is beyond the capabilities of a single director.

Both larger quads call for a smooth decrease in the sizes of the directors, although some wide-band applications with five elements may require that the second director length be equal to or slightly larger than the first director. This phenomenon is an indication that the forward two directors are the principal determinants of the bandwidth for the gain and F/B curves.

12 Meters

For all three arrays, 12 meters is the lowest band to use a driver spaced five feet from the reflector, with the element at the 10-foot mark becoming a director. Table 5 provides the operating figures for this five-element section. The 4-5 (26 foot) array provides over 1 dB gain improvement over the 3-4 (18 foot) array on 12 meters, with similar F/B and SWR curves.

When increasing the boom length to 30 feet, the forward director moves from 0.2 to 0.3 λ ahead of the second director. The larger spacing is near the limit of the ability of the forward two directors to control both gain and front-to-back ratio, even on a narrow (100 kHz) band such as 12 meters.

Indeed, without a further director, one can improve either the gain or the smoothness of F/B—but not both. As shown in Table 5, the design approach used for the 4-5-6 array was to raise the lowest level of F/B by about 2 dB—a value just verging on operational detectability.

The gain of the longer-boom array increases insignificantly over that of the 26-foot model. However, since the overall gain increase was in excess of 1 dB relative to the initial 3-4-element array, this design decision seems appropriate. For the same reason, I didn't add a new director to the support arms used for the added 15-meter director. The absence of an added director for 12 meters illustrates once more the different requirements for narrow and wide amateur HF bands.

10 Meters

Of all the HF bands, 10 meters is the widest. From the outset, it was apparent that a thin-wire quad array could not cover even the full first megahertz of 10 meters adequately. An 800-kHz operating bandwidth is a much more feasible goal, and it is achieved by all three arrays, as shown in Table 6.

On average, the 4-5-element quad shows better than 0.8 dB more gain than the 3-4 array. The 30-foot boom model adds more than 0.4 dB more gain (using a fourth director), for a 1.25-dB total improvement over the original 18-foot quad design. However, these figures—as averages—may be deceptively simple in view of the wide operating bandwidth on 10 meters.

Despite the best efforts to achieve a smooth gain performance, 10 meters exhibits the highest differential between minimum and maximum gain for all three of the arrays. The differential runs between 0.9 dB and 1.1 dB,

Table 3—17-Meter Performance

Frequency (MHz)	*Gain (dBi)*	*Front/Back (dB)*	*Impedance (R ± jX)*	*50-Ω SWR*
ON7NQ 3-4-Element, 5-Band Quad				
18.068	8.47	21.80	42.7 –*j*5.1	1.21
18.118	8.42	25.52	43.5 –*j*0.3	1.15
18.168	8.36	20.90	43.2 + *j*4.6	1.19
W4RNL 4-5-Element, 5-Band Quad				
18.068	9.24	22.03	36.0 –*j*1.7	1.39
18.118	9.18	21.26	39.3 + *j*5.7	1.31
18.168	9.10	17.39	42.3 + *j*12.5	1.37
Average gain over 3-4: 0.75 dB.				
W4RNL 4-5-6-Element, 5-Band Quad				
18.068	9.45	18.43	42.7 + *j*0.7	1.17
18.118	9.39	21.33	47.9 + *j*6.5	1.15
18.168	9.31	20.50	42.4 + *j*10.8	1.24
Average gain over 4-5: 0.21 dB. Average gain over 3-4: 0.96 dB				

Table 4—15-Meter Performance of Three Quads

Frequency (MHz)	*Gain (dBi)*	*Front/Back (dB)*	*Impedance (R ± jX)*	*50-Ω SWR*
ON7NQ 3-4-Element, 5-Band Quad				
21.0	8.43	15.28	49.7 –*j*20.1	1.49
21.225	8.52	20.98	46.4 –*j*0.0	1.08
21.45	8.47	10.24	36.2 + *j*30.7	2.16
W4RNL 4-5-Element, 5-Band Quad				
21.0	9.49	15.33	41.4 –*j*15.6	1.47
21.225	9.47	17.04	57.0 + *j*7.5	1.21
21.45	9.55	19.16	31.3 + *j*9.9	1.70
Average gain over 3-4: 1.03 dB.				
W4RNL 4-5-6-Element, 5-Band Quad (before adding fifth element)				
21.0	9.36	11.43	46.4 –*j*19.8	1.51
21.225	9.65	22.65	58.1 –*j*8.8	1.25
21.45	9.95	15.68	28.2 + *j*8.7	1.85
W4RNL 4-5-6-element, 5-Band Quad (after adding fifth element)				
21.0	9.78	15.70	46.9 –*j*7.6	1.19
21.225	9.74	20.57	63.4 + *j*1.0	1.27
21.45	10.00	15.03	35.0 + *j*11.9	1.57
Average gain over 4-5: 0.34 dB. Average gain over 3-4: 1.37 dB.				

depending on the version of the array. The 4-5-6-element array would have shown an unacceptably high differential—more than 1.5 dB—had the final design not included a new director on the same support arms as the added 15-meter director. Fig 12 shows the gain curves for all three final designs. Even with the new director, the 4-5-6 version displays a more rapid gain fall-off at the upper end of the band than the other two quads.

The F/B curves in Fig 13 show something about where to place the peak F/B value for optimal performance—if there is design room to vary it without adversely affecting other properties. The 3-4-element array centers the curve. The 4-5-element version moves the maximum 180° F/B to the upper end of the band. The result is less performance at the lower end of the band. However, the 180° F/B is not the sole determinant of placement. The general shape of the rearward lobes and the strength of rearward side lobes can also play a role in the design decision. Placing the maximum F/B ratio at the high end of the band in the 4-5 array provided the best F/B performance across the band.

The addition of another director to make the 10-meter section a six-element array was prompted by the F/B performance as much as by the gain curve of the array. Table 6 shows the high in-band, peak F/B without the new director. The consequence is relatively poor F/B performance except for a small portion of the band. With the added director, the F/B performance curve spreads the higher levels of performance over a greater portion of the band, although the band edges fall below the target levels in the specifications.

The added 10-meter director also resolves another problem. Without the director, the elevated SWR between the two wide-band minimums rises too high and exceeds the 2:1 level by a considerable amount at 28.6 MHz. As shown in Fig 14, all three final versions of the arrays achieve the double-minimum wide-band curve, although in different patterns. The 4-5-6-element 30-foot array achieves the flattest curve of all, but all three curves remain below the 2:1 SWR level for the entire operating bandwidth. In both the 4-5 and 4-5-6 arrays, the first director plays its most significant role in setting the feedpoint impedance of the array and hence turns out to be smaller than the second director.

Overall Evaluation: The 4-5-element and the 4-5-6-element 5-band quads achieve most of the operating goals set forth in the original specifications for array gain. Each array exhibits increased gain as we change bands upward in frequency. Only 12 meters fails to provide at least 0.2 dB more gain for the 4-5-6 array over the 4-5 version. Only 20 meters fails to meet the goal of the 4-5 quad in providing at least 0.7 dB more gain than the array used as the starting point.

The F/B goals—with cautions that we shall further discuss—are generally met, except at the upper end of 20 meters and the passband edges of 10 meters. Both the 4-5-element and the 4-5-6- element quads cover all of the assigned passbands with less than a 2:1 SWR relative to a 50-Ω standard. However, in several cases the limit is pressed on one or the other end of the band, and on both ends of the 20-meter band.

Within these restrictions, then, the design is reasonably successful in achieving a design for a larger five-band quad array. Indeed, more important than this evaluation are the design principles and limitations discovered along the design road. The notes on these matters give us further insight into how multielement, multi-band quads operate.

Moreover, it is critical to understand that the designs emerged from some initial constraints of wire size and fixed element spacing. Revising the element spacing among sets of elements might

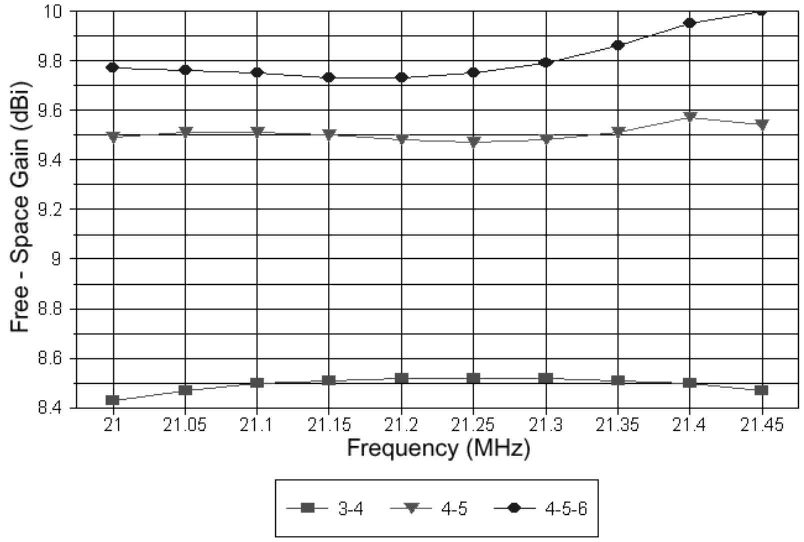

Fig 9—15-meter free-space gain for three large five-band quad designs.

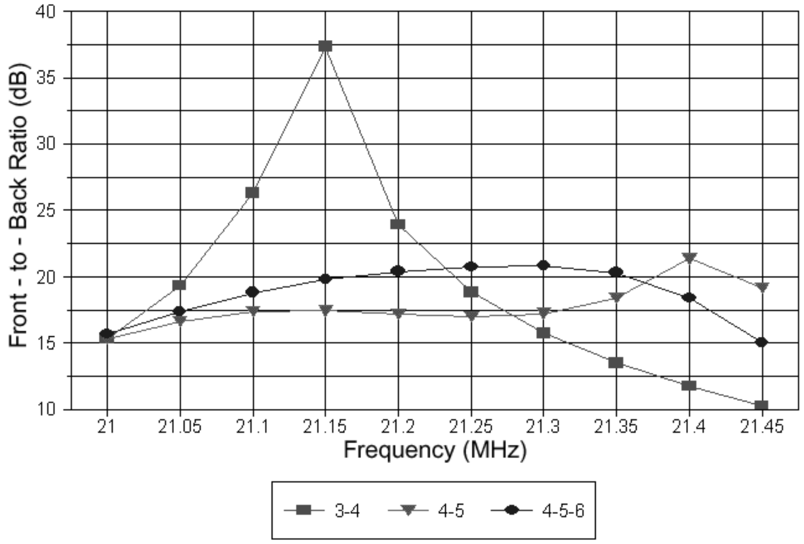

Fig 10—15-meter front-to-back ratios for three large five-band quad designs.

yield differences in F/B curves and SWR curves. Consequently, the designs are now suited to the application of both incremental and genetic optimizing routines. The incremental routines may provide further tweaking of the element sizes in the direction of perfected performance curves. Genetic algorithms might well uncover unsuspected potentials for the array designs.

Even if we accept the declaration of relative success in designing 4-5-element and 4-5-6-element quad arrays, the design process is far from over. First, there are some further general cautions about multiband quads that deserve to be addressed. Second, although the use of antenna modeling software shows good efficiency in developing a design, if the design cannot be translated into an effective physical antenna with adequate performance, the exercise is somewhat futile!

Limitations, Cautions and Correlation Techniques

The numbers that emerge from an antenna-modeling program used to design a large quad array can be deceptive, unless we use extreme caution in reading them and in using them to construct a physical version of the array. In this final part of the exercise, I want to explore at least some of the limitations and cautions that attach to the design model and its transferal into wire and fiberglass.

Patterns

The basic design work has been done with free-space models. Hence, all gain figures require readjustment relative to a proposed height for the array above a specific ground quality. Ordinarily, the F/B or rearward lobes and the SWR curve will hold if the array is more than λ/4 above ground. Quads are less sensitive to ground influences on the feed-point impedance and other operating characteristics than are arrays with open-ended linear elements. The exact gain of the strongest lobe and the elevation angle of that lobe will, of course, be functions of antenna height, as measured in wavelengths above ground.

With the exception of quite low mounting heights, azimuth patterns over real ground will closely resemble at the elevation angle of maximum radiation the free-space patterns from the design model. However, we might need to adjust our expectations for such patterns due to the high levels of interaction among the elements of a multiband quad. Not all bands produce the clean patterns we have come to expect from monoband Yagis.

Fig 15, for example, might represent both the 20-meter and 17-meter bands for the 4-5-6-element array. In both cases, we have well-behaved patterns, with single forward lobes and no forward side lobes. We also have radiation to the rear that follows fairly standard progressions: showing three small rearward lobes, a single broad lobe or something in-between the two. However, even the pattern for 18.168 MHz reveals a good reason for the quad designer to look at each pattern over several frequencies. The rearward pattern at the upper end of 17 meters shows a worst-case front-to-rear ratio of about 17.5 dB, despite a 180° F/B of better than 20 dB.

Above 17 meters, the patterns—both forward and rearward—can grow considerably less well behaved. In the progression from the middle of 15 meters to the upper end in Fig 16, we find the development of forward side lobes. Although they remain diminutive at 15 meters, on higher bands, the side lobes can grow to proportions that affect the overall forward beamwidth of the array between –3 dB power points. In addition, the large rearward radiation pattern, with a worst-case ratio to the forward lobe of 15 dB may have operational consequences. This is because the response to the rear would no longer be in a pair of narrow directions, but instead would cover most of the rear quadrants. In your preconstruction evaluation of a large quad design, you

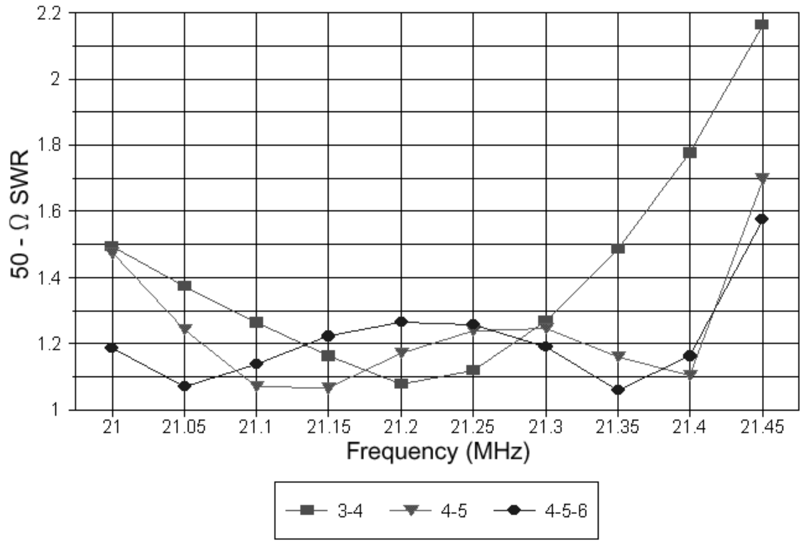

Fig 11—15-meter 50-Ω SWR curves for three large five-band quad designs.

Table 5—12-Meter Performance of Three Quads

Frequency (MHz)	*Gain (dBi)*	*Front/Back (dB)*	*Impedance (R ± jX)*	*50-Ω SWR*
ON7NQ 3-4-Element, 5-Band Quad				
24.89	9.26	22.72	35.1 –*j*2.1	1.43
24.94	9.22	18.92	41.1 + *j*2.3	1.27
24.99	9.18	16.70	47.6 + *j*4.8	1.12
W4RNL 4-5-Element, 5-Band Quad				
24.89	10.27	21.77	38.6 + *j*5.2	1.33
24.94	10.29	19.80	40.2 + *j*9.1	1.34
24.99	10.25	16.77	41.9 + *j*14.3	1.43
Average gain over 3-4: 1.04 dB.				
W4RNL 4-5-6-Element, 5-Band Quad				
24.89	10.34	18.78	25.9 + *j*3.5	1.94
24.94	10.37	20.98	37.0 + *j*7.9	1.42
24.99	10.25	21.69	49.1 –*j*2.5	1.06
Average gain over 4-5: 0.06 dB. Average gain over 3-4: 1.10 dB				

should decide whether or not the patterns (as well as the performance numbers) are satisfactory for your intended operation.

Efficiency

The *NEC* core at the heart of most antenna-modeling software packages provides a power budget that lists a value for efficiency. The efficiency of an antenna is simply the power radiated (without regard to where it goes) to the power supplied to the antenna, expressed as a percentage. The calculation does not include anything not modeled; for example, matching sections or networks, feed-line losses, and so on. However, it does include material losses within the antenna elements as a result of their resistivity, and it also includes resistive losses associated with any traps or reactive loads. This latter category of losses does not apply to our quad arrays, but wire losses do apply, since we are using #12 AWG copper wire. The wire size is as important as the material, since skin effect is partially a function of element surface area. In fact, with large element surface areas, such as with the use of aluminum tubing, material losses can be very small. For example, I have models of six-element Yagis in my collection with efficiencies approaching 99%.

Thinner wire (as a fraction of a wavelength) and higher frequencies increase losses and lower the efficiency of an antenna. These general rules would reveal themselves if we developed a sequence of simple monoband Yagis by which to test them. However, the large quads we have been exploring display complex interactions among the elements. In doing so, they reveal another dimension to antenna efficiency that is not as well appreciated as element diameter and frequency.

Table 7 lists the calculated mid-band efficiencies of each of the quads reviewed. Notice that the highest efficiency is considerably lower than that for a "fat-element" Yagi. Although we can detect a pattern in the general direction of changes in efficiency, there are some surprises. Especially noticeable is the very low efficiency figure for 12 meters for the largest array.

If we return to Table 5, we discover that the 12-meter portion of the largest array provided less than 0.1 dB gain advantage over the next shorter quad, with most other characteristics being roughly equal between the two. What limits gain is the inability of the elements on fixed spacings to achieve the most effective interelement coupling to yield a higher gain. If the larger array had resulted in significantly larger rear lobes, the efficiency might actually have been higher. Had it resulted in higher forward gain—or even a wide beamwidth—we might also see a higher efficiency value. However, we often neglect a third possibility: the current distribution in all elements is such that the sum of radiation in all directions does not increase, but instead, the current levels are higher in regions of the antenna where losses exceed contributions to radiation. The result is lower efficiency without a change in wire size, wire lengths or frequency.

For the 12-meter case, we might raise efficiency somewhat by adding a fourth director (as was done on 10 meters), even though it would add to wire losses. We might optimize further the relative spacing of the 12- and 10-meter drivers from the reflector.

Efficiency is (or can be) an indicator of possible design improvement. However, it does not affect the reported gain of the array, since that gain already takes into account the radiation efficiency of the total antenna model. Indeed, attaching the wrong significance to efficiency can result in a misuse of the data. For example, achieving 99% efficiency in a directional array, where the added radiation is to the rear or sides, would not amount to a design improvement.

Element Precision

An array with highly interactive parasitic elements requires consider-

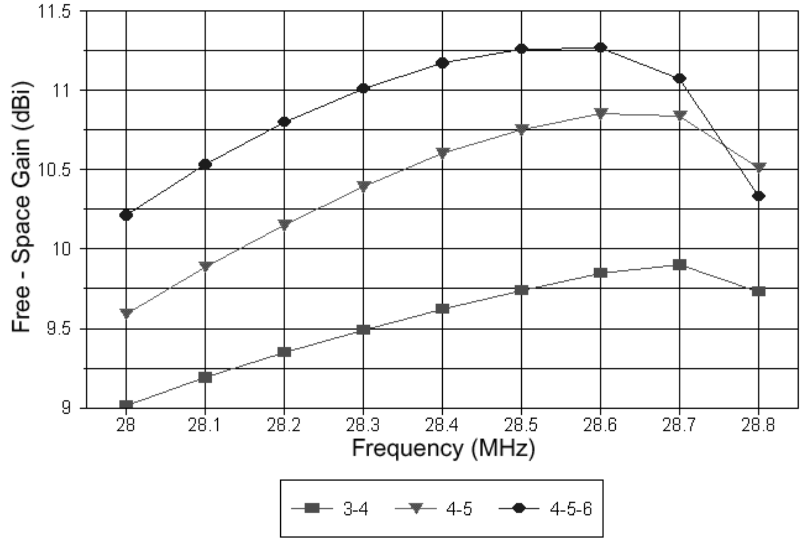

Fig 12—10-meter free-space gain for three large five-band quad designs.

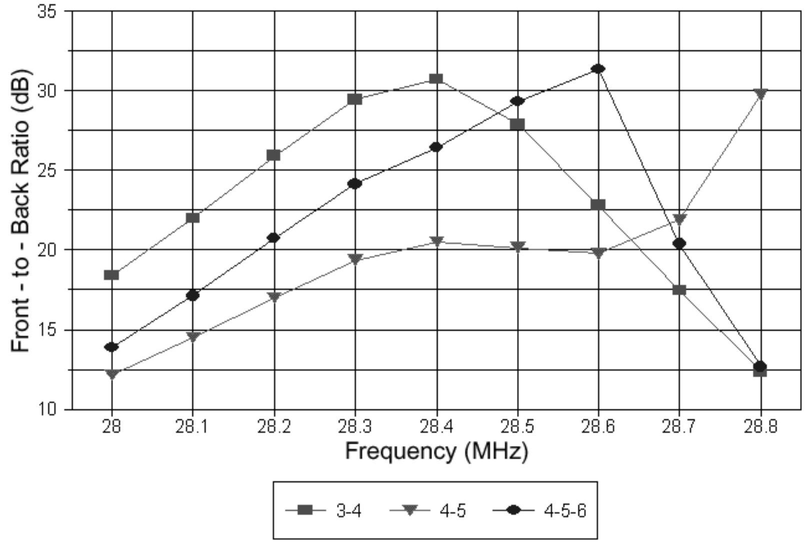

Fig 13—10-meter front-to-back ratios for three large five-band quad designs.

able precision in construction to achieve the design results. One aspect of construction precision is understanding which elements can be adjusted and which should be precisely built and then left alone. The following guidelines may be useful, although their application may vary from one design to another.

Reflector-driver-first director: For arrays with two or more directors on a band, fine tuning of the reflector-driver-first-director combination tends to set the source impedance across the band in question. Once set, you should not perform further adjustments on this set of elements—with one exception. The driver loop can be adjusted to tune out reactance at the feed point. However, reductions in driver size will normally also reduce the resistive component of the feed-point impedance, and increases in size will raise the feed-point's resistive component. In constructing a given large array, adjustments here should be done last.

First director: Where there are two or more directors, the size of the first director may be sufficiently critical that, once set you should not alter it. On some bands, less than a 1-inch change in the first director can create large changes in the performance within the passband, involving any of the key operating parameters: gain, F/B or SWR curve. In general, the further forward along the boom you make element changes, the less critical they are.

The two forward-most directors: As Table 1 reveals by comparing dimensions among arrays, you can go far toward controlling the characteristics on a band by changing the forward directors. For wide-band service, the most-forward director becomes shorter to enhance high-end performance and the next director to the rear becomes larger to enhance low-end performance. Both moves tend to raise the feed-point resistive component a bit, which is why hasty adjustments to the driven element should be avoided.

Obviously, where there are too few elements to adhere to these guidelines, you will need to employ other measures. For example, a band with four elements may require a slight enlargement of the reflector to enhance low-end performance. However, this move may require re-adjustment of the driver and first director to restore or obtain desired feed-point impedance and the SWR curve across the whole band. A three-element band becomes a real ballet of interactions among the elements, such that the reflector is normally used to control both radiation resistance and low-end performance, while the director controls high-end performance, with the driver sized to create the best possible situation for the antenna feed. Since large multiband quad arrays normally begin with fixed spacing, there are many instances where meeting all design specifications may not be possible.

Table 6—10-Meter Performance of Three Quads

Frequency (MHz)	*Gain (dBi)*	*Front/Back (dB)*	*Impedance (R ± jX)*	*50-Ω SWR*
ON7NQ 3-4-Element, 5-Band Quad				
28.0	9.01	18.40	43.8 –*j*31.6	1.96
28.2	9.35	25.89	45.3 –*j*11.0	1.29
28.4	9.62	30.72	51.3 + *j*6.8	1.15
28.6	9.85	22.80	58.7 + *j*9.6	1.27
28.8	9.73	12.38	31.1 + *j*8.1	1.68
W4RNL 4-5-Element, 5-Band Quad				
28.0	9.59	12.15	40.7 –*j*27.4	1.88
28.2	10.15	17.00	49.3 –*j*12.7	1.29
28.4	10.60	20.50	47.1 –*j*2.8	1.09
28.6	10.85	19.76	42.6 + *j*18.0	1.52
28.8	10.51	29.74	64.9 + *j*12.1	1.40
Average gain over 3-4: 0.83 dB				
W4RNL 4-5-6-Element, 5-Band Quad (before adding sixth element)				
28.0	9.54	18.64	41.3 –*j*19.4	1.59
28.2	10.22	43.18	40.0 –*j*1.3	1.25
28.4	10.72	20.43	39.2 + *j*23.6	1.78
28.6	11.04	16.89	59.1 + *j*55.3	2.70
28.8	10.67	11.37	56.4 –*j*19.1	1.46
W4RNL 4-5-6-Element, 5-Band Quad (after adding sixth element)				
28.0	10.21	13.85	58.9 –*j*31.2	1.80
28.2	10.80	20.75	51.9 –*j*21.9	1.54
28.4	11.17	26.41	47.1 + *j*0.6	1.06
28.6	11.27	31.30	62.3 + *j*16.0	1.43
28.8	10.33	12.67	34.0 + *j*1.7	1.47
Average gain over 4-5: 0.42 dB. Average gain over 3-4: 1.25 dB				

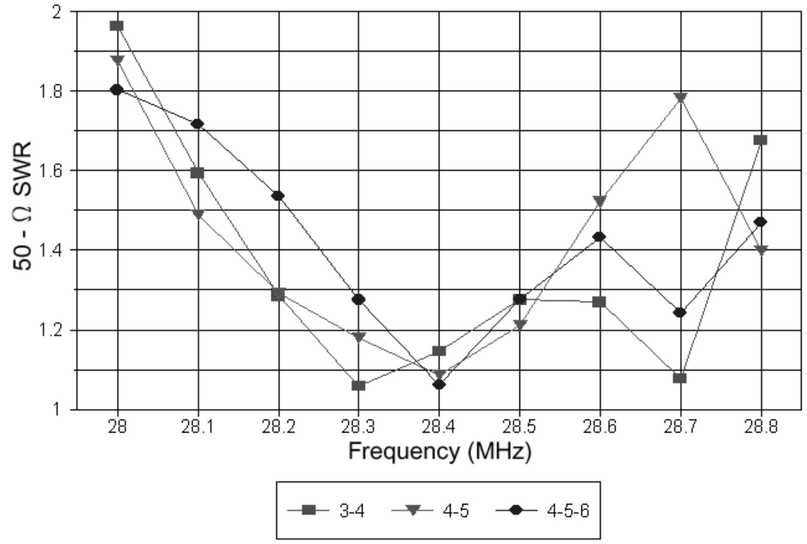

Fig 14—10-meter 50-Ω SWR curves for three large five-band quad designs.

Computer Models and Reality

Because many dimensions within a large multiband quad array require precise measurement of the loop circumference to within less than one inch, constructing such an array is not a casual endeavor. Indeed, it may lie beyond the realm of simple backyard build-and-play techniques. However, with some care, trials and testing, constructing a modeled design is still feasible. The key lies in understanding both the model and the realities of a proposed construction technique.

Fig 17 sketches loosely some of the ways builders attach quad-loop corners to the support arms. In two of these, we see metal rings wrapped around the nonconductive support arm. In some cases, the element wire may be wrapped at the corner to reduce abrasion. Whether or not directly connected, we can end up with a small one-turn coil in close proximity to the quad-loop corner. The current at a quad loop corner is significant, in fact higher than the current magnitude on a linear element the same distance from center. The closed loop may function as a load on the quad loop, and it

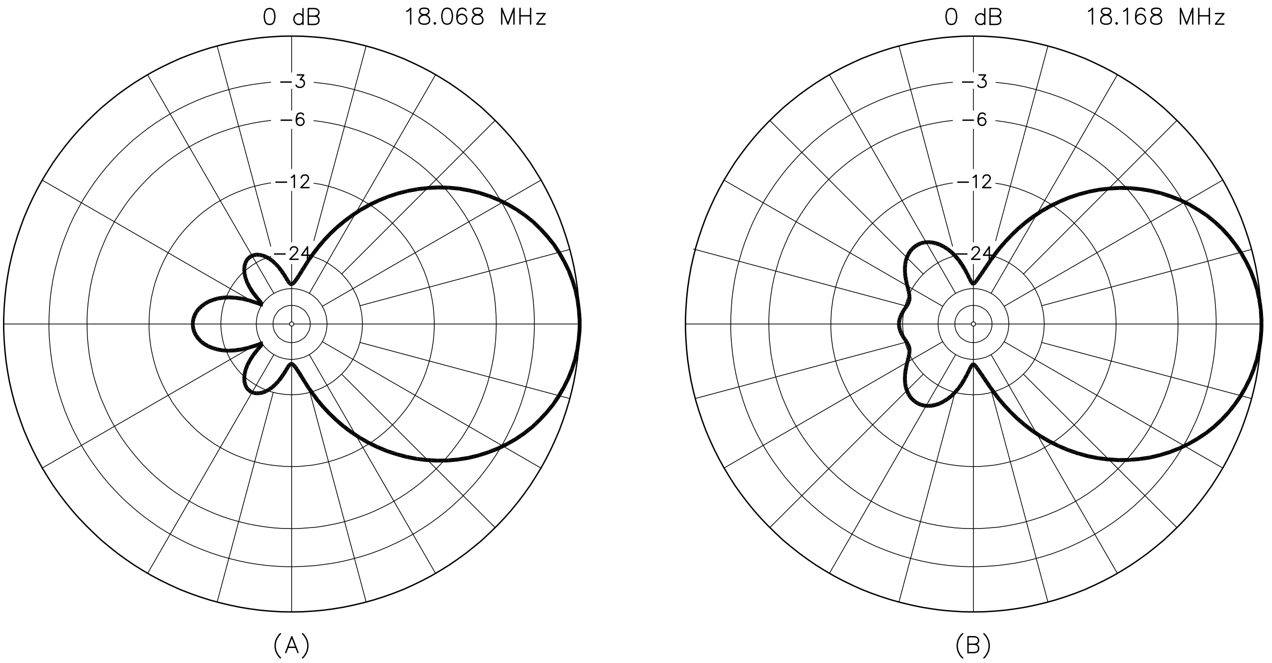

Fig 15—Sample well-behaved free-space azimuth patterns from 17 meters.

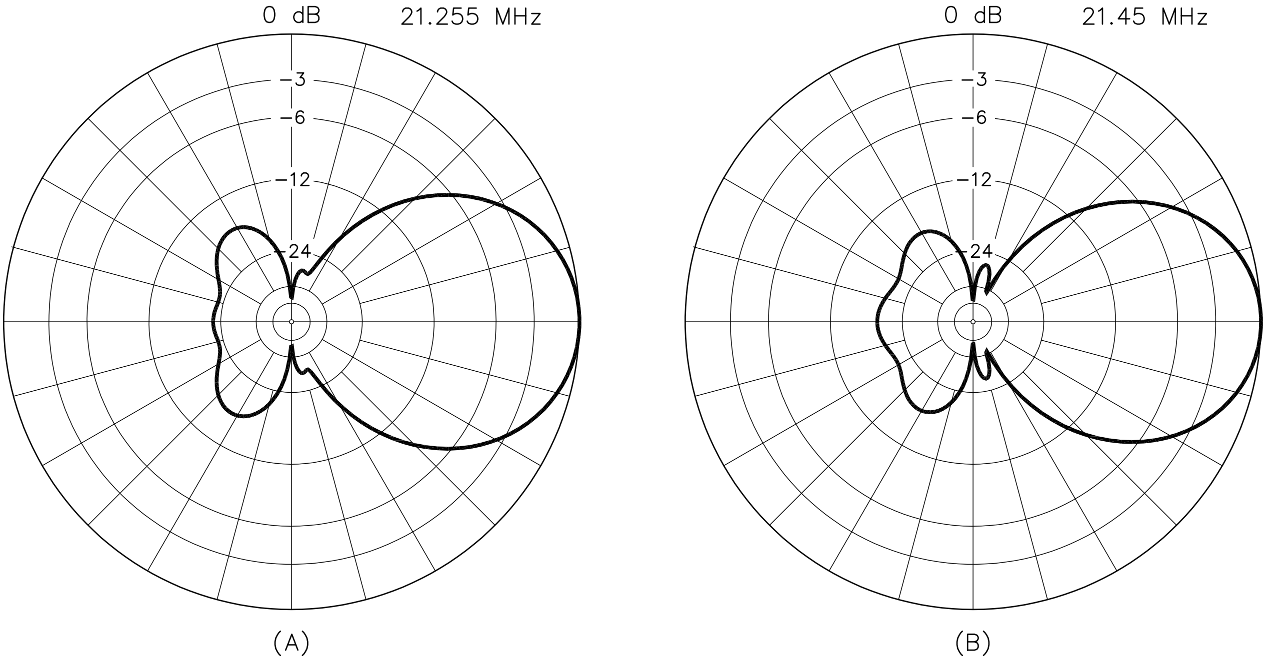

Fig 16—Sample less well-behaved free-space azimuth patterns from 15 meters.

does not take much of a load to detune the element relative to the original model of the loop.

Similarly, when quad arms are composed of combinations of aluminum and nonconductive material, the aluminum may be close enough to the loop corner to create a slight detuning. This is also equivalent to adding a very small load to the wire loop. Of the four methods for wire attachment to a support arm, the nonconductive cable-tie system comes closest to matching the computer model.

Some users employ an anti-abrasion sleeve over the element wire, making in effect a short piece of insulated wire. The insulation causes a velocity factor, making the physical and electrical length of that portion of the wire unequal. Corner sleeves may turn out to be harmless relative to the complex operation of a large multiband array, but they should not be presumed to be harmless.

There is a tedious, but straightforward, way you can determine the degree to which construction practices affect the operation of a quad relative to the "clean" bare-wire computer model on which it is based. First, model only the driven element assembly or assemblies. Determine as precisely as feasible the resonant frequency for each driver. Second, build as precisely as possible the driver assemblies using your preferred method of construction and elevate them to a good height. Now determine the actual resonant frequency for each driver. Either you'll be lucky, and resonant frequencies will match those of the model, or a pattern of offset will become evident. If you find offsets but no pattern, this will likely be good reason to review your initial driver construction.

Relative to the measured resonant frequencies, add identical reactive loads to each of the four corners of each driver so that the model resonates at the same frequency as the driver assembly tested. For each band, adding the same loads to each of the four corners of quad loops on that band will be an accurate representation of the effects your construction techniques have on the entire set of elements. Now, with the added loads, readjust the dimensions of the model to restore the performance curves of the original model. The resulting dimensions should result in correct operation of the array on all frequencies.

I can only state that they "should result in correct operation," but the effectiveness of this technique will rest upon the precision with which you construct your array during both the test and final construction phases of the operation. Even small amounts of loading or detuning on some elements may throw the array off the desired performance curve on some bands.

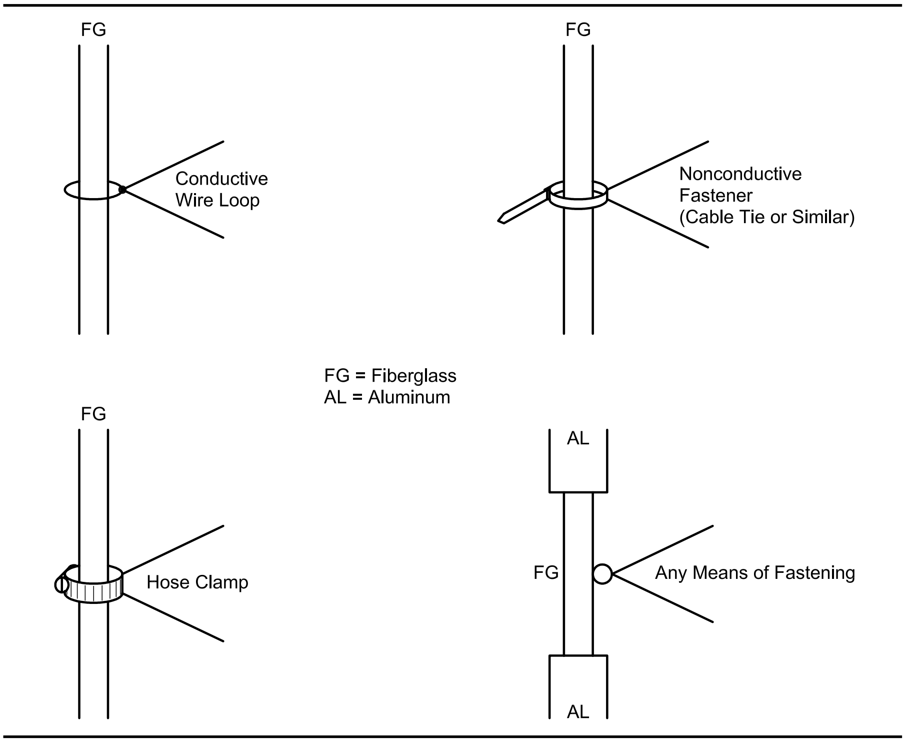

Fig 17—Sample element-to support mounting techniques.

Table 7—Radiation Efficiencies of Three Large Quad Arrays

Band	*Frequency*	***Antenna Efficiency (%)***		
(m)	*(MHz)*	*3-4-Element*	*4-5-Element*	*4-5-6-Element*
20	14.175	93.6	94.6	94.4
17	18.118	93.9	92.7	93.3
15	21.225	94.1	92.7	93.7
12	24.94	90.1	87.7	80.4
10	28.4	93.6	91.9	90.7

Note: Efficiency is the ratio of power radiated to the power supplied to the antenna and does not include matching or line losses.

Variations of the technique suggested here for correlating modeled quads and physical quads are adaptable to many other types of antennas. More important is the general thesis that models—usually using bare wire and with no modeled detuning effects—require correlation to the physical construction methods employed by the builder if the models are to be adequate guides to antenna design. Any success in building a large multielement, multiband quad of the order discussed in these notes will depend upon this step as much as any other in the design process.

The design of a large multiband quad array intended for eventual construction can be enhanced by the proper use of antenna modeling software. However, as we have seen, the task is not a mere modeling exercise. It must be preceded by careful consideration of constraints, specifications and modeling strategies to ensure reasonable results. Moreover, the task is not complete unless the final design model is carefully evaluated and then correlated to the proposed construction methods. These notes have had as their goal to make the process orderly, but by no means brief.

Notes

[1] *Quad Notes*, Vol 2 (Corpus Christi: AntenneX, 2001), throughout.

[2] *Quad Notes*, Vol 1 (Corpus Christi: AntenneX, 2000), Chapter 5.

[3] *Quad Notes*, Vol 1 (Corpus Christi: AntenneX, 2000), pp 206-216. See also Danny Mees, ON7NQ, "Improving the Cubex Three-Element, Five-Band Quad," *The ARRL Antenna Compendium*, Vol 6, pp 119-20.

[4] For a description of the set of "optimized wide-band antennas" or OWA Yagis, explore the following Web site: **nw3z.contesting.com**. □□