Some Notes on Two-Element Horizontal Phased Arrays
Part 4: Removing the Limits of a Single Phase Line by Element Matching

L. B. Cebik, W4RNL (SK)

The chief limitation of the ZL-Special form of a 2-element horizontal phased array has been mechanical: how to use single tubular elements with phase lines that are not susceptible to interaction with a metallic boom supporting the elements. Successful tubular-element ZL-Specials require low-impedance phase lines, while higher-impedance phase lines are more suited to folded-dipole elements.

Solutions to this problem have been available since R. Baumgartner, HB9CV, developed the array bearing his call in 1954. Interestingly, the HB9CV array has been exceptionally popular on the continent of Europe, but has met mostly silence in the English-speaking realm of amateur radio. Indeed, Rothammels *Antennenbuch* (now produced by DARC) devotes several sections to HB9CVs for various frequency ranges, and 1984 saw the production of a book devoted to the antenna (Fuchs-Collins, *HB9CV: Richtantenne mit allen Variationen* [Frech-Verlag, 1984]). This later book still insisted on favorably comparing the phased 2-element array to a 4-element Yagi.

Since the HB9CV's appearance, several other systems of overcoming the shortcomings of the ZL-Special have appeared. We shall sample only two of them: the recent N7CL phased array and a system of capacitively matching elements to the phase line. All three systems have a common thread. If the natural impedance of the rear element does not match well with a higher impedance phase line, we may alter the impedance of the element through the use of a matching system. The techniques that we shall examine vary chiefly in the means used to effect the match.

All of the variables that we examined in the case of the ZL-Special remain in effect. Element diameter and length, and the relative lengths of the two elements, determine the required relative current magnitudes and phase angles on the individual elements for a desired level of performance within the limits set in Part 1. However, instead of selecting the physical dimensions that will match the phase line we opt to use, we shall select dimensions that are appropriate for the application of a matching network to create the desired impedance on the rear element. We shall not ignore the forward element, since its dimensions must not only provide the desired rear element impedance when combined with that element, but as well, its impedance must allow the desired current division at the feedline junction and yield a feedpoint impedance that we can match to our most common feedlines.

The HB9CV

The original HB9CV design, shown at the top of **Fig. 4-1**, attempted to permit the use of 300-Ohm (or other parallel line available in the 1950s) with single tubular elements by the use of Tee or double gamma-match sections. A later version, shown in the lower part of the figure, varied the feedline system for use with 75-Ohm coaxial cable. By setting the gamma match in opposite directions on the two elements, the coax shield could connect to the element centers and to the boom. In fact, later versions of the HB9CV employed the boom as in of a pair of lines, with a small diameter line forming the partner. Since the smaller wire in a parallel line with different diameter wires general determines the line impedance, a single line could run from the rear element connection to the forward element connection and serve both as half the phase line and as the gamma section. Although the feedpoint is shown at the forward element of the illustrated versions of the HB9CV, various feedpoints between that point and the mid-point between elements are used.

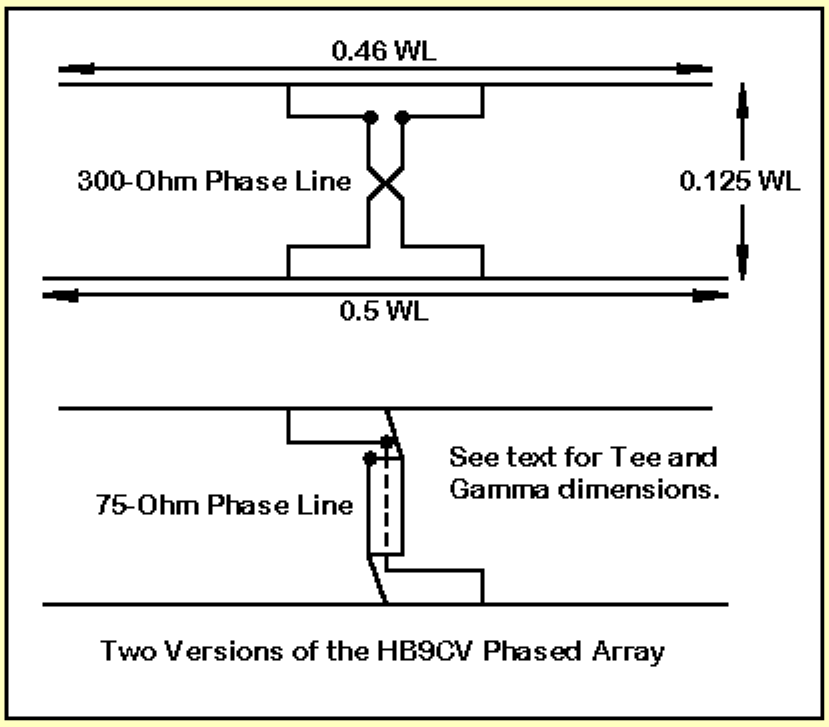

Fig. 4-1. General outlines of 2 versions of the HB9CV array.

HB9CV specified certain dimensions for the antenna. The rear element should be 0.5 wavelength long, and the forward element should be 0.46 wavelength long, if the element diameter is between 0.004 and 0.007 wavelength in diameter. At ten meters, 0.004 wavelength is well over 1.5", which is larger than most builders would use. Therefore, adjustments are natural to HB9CV design. As well, HB9CV also specified the lengths and spacing of the gamma sections for both the Tee and gamma versions. Once more, these dimensions will vary with the actual materials used in construction.

Although not fully appreciated by some antenna modelers, the HB9CV antenna is somewhat difficult to model physically. Since the gamma sections will have a different diameter than the elements, we encounter angular junctions of dissimilar diameter wires in NEC-2 and NEC-4 models, and this situation tends to yield inaccurate results. MININEC models do not suffer this problem, but require very high segmentation densities, since the wires of the antenna structure create so many sharp angles. As well, the gamma match section are closely spaced to the elements and may need a version of MININEC having a close-wire correction factor. I have created models of the HB9CV with unreasonably high gain reports (>8.1 dBi free-space gain) by violating some of the limitations of the modeling system.

However, the HB9CV antenna can be modeled in principle within NEC-2 or NEC-4 by using a constant diameter wire size for both the elements and the gamma sections, adequate segmentation, and a TL phase line. In these notes, I shall examine the modeled results of both Tee and gamma versions of the HB9CV that use 1" diameter materials throughout. The forward element is 0.46 wavelength long, while the rear element is 0.508 wavelength long, with an element spacing of 0.125 wavelength. The gamma sections are spaced 0.0096 wavelength from the main element with lengths adjusted as follows: The Tees are 0.125 wavelength long, while the one-sided gammas are 0.053 wavelength long. The results do not report directly on the performance of the original designs or any specific variation of them, but they do indicate a set of reasonable expectations for performance.

These modeled dimensions vary from the original design chiefly in the spacing and length of the Tee and gamma sections. The revised model spacing is to avoid potential NEC inaccuracies of closely spaced wires of different lengths. However, the sections are only crucial to performance in setting the impedance of the elements, as seen by the phase line, at a desired level. As long as the element obtain the required relative current magnitudes and phase angles for a desired performance level, one may use any gamma diameter and length that will produce it.

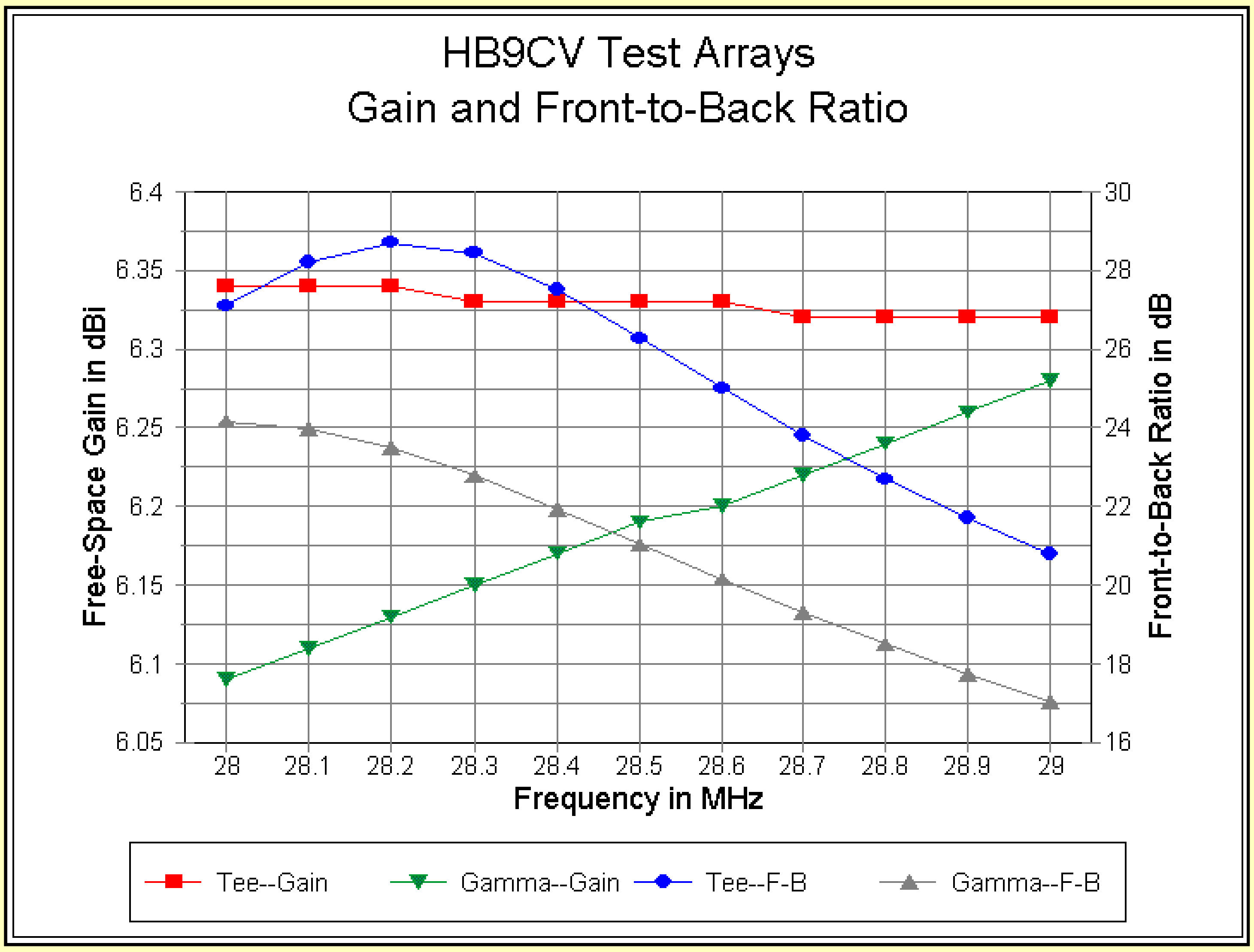

Fig. 4-2. Gain and 180-degree front-to-back ratio of the sample HB9CV arrays from 28.0 to 29.0 MHz.

Fig. 4-2 shows the modeled free-space gain and front-to-back performance of the Tee and gamma models. The Tee uses a 300-Ohm phase line, while the gamma uses a 75-Ohms line. As with all of the models in this series, these models do not necessarily indicate the peak performance of which an array is capable. They only serve to illustrate the principles of the array designs. Hence, the relatively low gain figures for the gamma-HB9CV might well increase with further optimization.

More interesting than the precise numbers for the reported gain is the difference in the gain curves for the two types of HB9CVs. The gamma version shows the nearly linear increase in gain with frequency to which we have grown accustomed from our ZL-Special efforts. However, the balanced Tee-HB9CV shows an almost perfectly flat gain across the first MHz of 10 meters. Independent element versions of the modeled design show the rear element, with its matching section, to have an impedance of about 250 Ohms with almost no reactance, a good match for the phase line. The single-sided gamma version does not show the same closeness of match with its 75-Ohms line. Indeed, measurements on an HB9CV 2-meter antenna that uses a single-wire for the phase line and gamma sections indicates a line in the 200-Ohm range for a direct 50-Ohm coax feed.

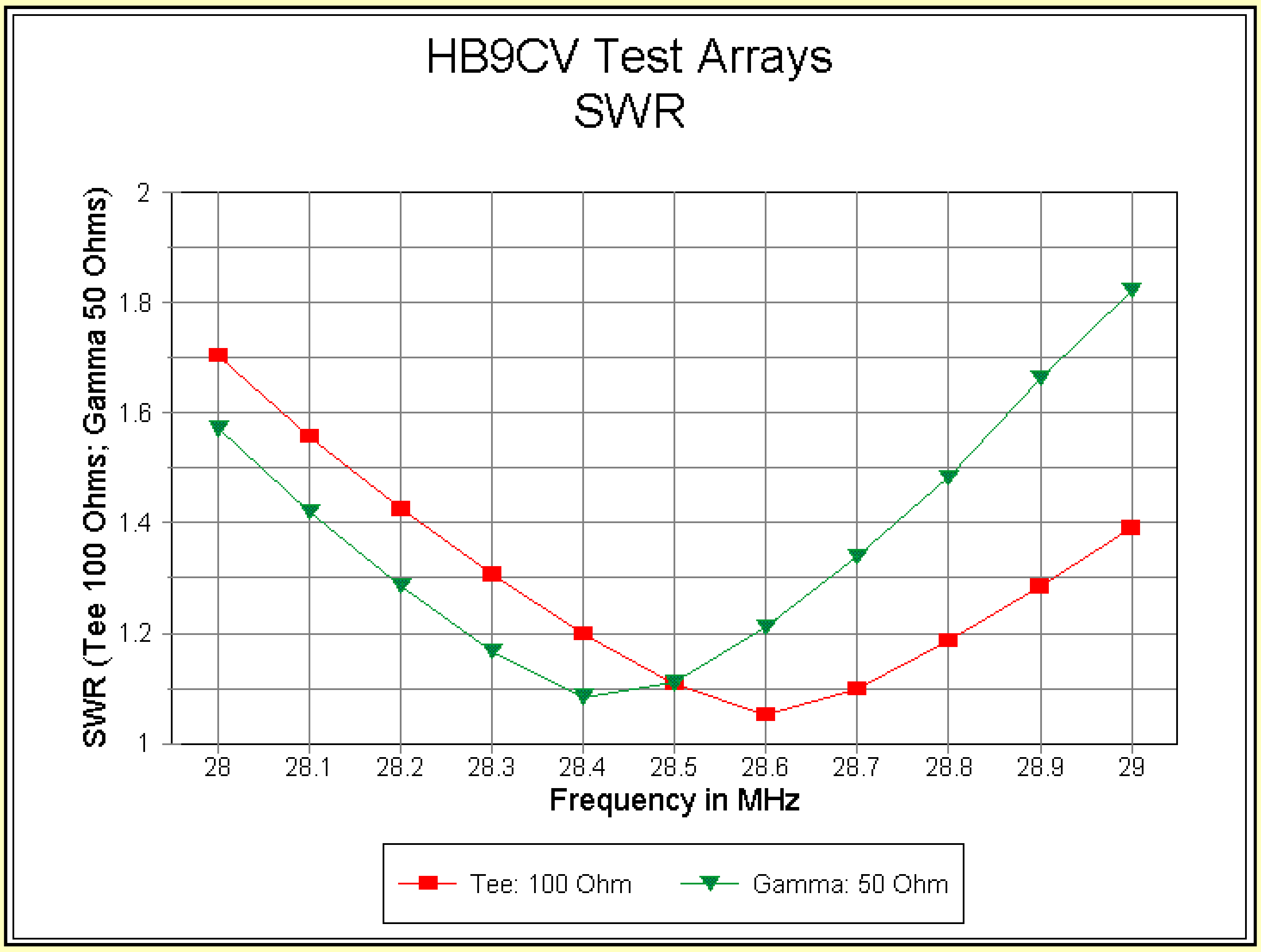

Fig. 4-3. SWR curves of the sample HB9CV arrays from 28.0 to 29.0 MHz.

The cost of the Tee-version's relatively even performance across the first MHz of 10 meters is the feedpoint impedance. As shown in **Fig. 4-3**, the HB9CV has an SWR curve referenced to 100 Ohms. A 2:1 matching network or device is required for standard coax feed. In contrast, the gamma version shows a well-behaved 50-Ohm SWR curve. **Fig. 4-4** samples the free-space azimuth patterns of the Tee-version of the HB9CV at 28.0, 28.5, and 29.0 MHz to indicate the evolution of the pattern across the operating passband.

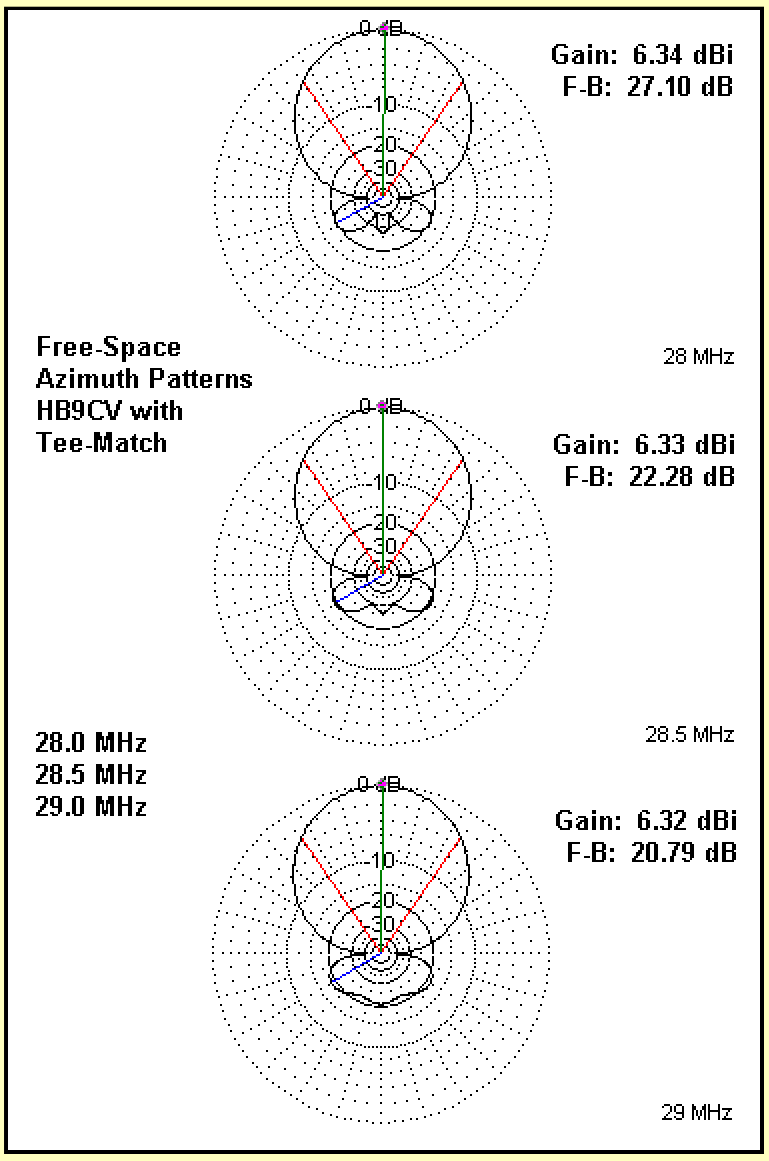

Fig. 4-4. Free-space azimuth patterns of the Tee-version of the HB9CV array at 28.0, 28.5, and 29.0 MHz.

In the 1950s, the 1/8 wavelength spacing of elements and the use of element lengths similar to those of 2-element Yagis held a mystique among phased array designers. From our work with both ideal phased arrays in Part 1 and optimized Yagis in Part 2, we now understand the appeal of the 1/8 wavelength spacing. It represents a reasonable balance between operating bandwidth and gain. Beyond the 1/8 wavelength mark, gain tends to decrease ever more rapidly for elements near the 1/2 wavelength or self-resonant length. Below a spacing of 1/8 wavelength, the operating bandwidth decreases ever more rapidly.

However, for the proper phasing of an array to produce good performance--relative to having only 2 elements--there is no magic spacing. So long as we achieve the correct confluence of all of the variables in a phased 2-element horizontal array, we may use any spacing between 0.05 and 0.2 wavelength. The gamma and Tee matching system to bring the rear element into reasonable alignment with the impedance of a chosen phase line and the forward element to an impedance that yields the proper current division and feedpoint impedance might well be adaptable to other element lengths and spacings. However, the success builders have had with the original HB9CV designs has tended to suppress both experimentation and calculation that would yield new variants.

The N7CL Beta-Matching System

In the search for less complex mechanical designs of 2-element horizontal phased arrays, Eric Gustafson, N7CL, has developed within the past few years a different approach to the same end. N7CL wanted to do away with virtually all of the visible superstructure of the HB9CV while achieving similar performance capabilities. To this end, he turned to the shorted-stub form of the beta or hairpin stub, although he used coaxial cable sections for his stubs.

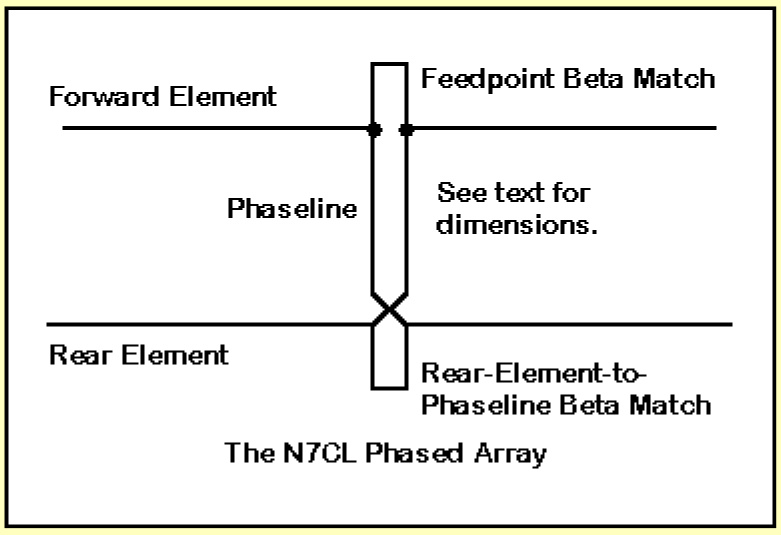

Fig. 4-5. General outlines of the N7CL phased array.

Fig. 4-5 shows the schematic outline of the N7CL phased array. It consists of 2 elements, a phase line, and two stubs. For the Phase line, N7CL selected a 100-Ohm line created from side-by-side (series) sections of standard coaxial cable. The shielding provided by the cable braids permit the line to ride inside the metal mast supporting the elements with no ill effects.

However, single tubular elements do not match well to 100-Ohms phase lines. The key to effecting a match is to change the element impedance from its natural value to something very close to 100 Ohms. A beta match will do the job, but under the condition that the element impedance exhibits a sufficient capacitive reactance to form the series reactance to go with the shunt or parallel inductive reactance of the stub in classic L-network terms.

We cannot simply apply a beta match to any element and expect good results. We must begin with an acceptable 2-element design using separate feedpoints. Since the rear element must show a capacitive reactance, it must be shorter than a self-resonant half-wavelength, if we are to believe the indications of the tables in Part 1. We shall want a net reactance on the feedline-phase line junction that is also capacitive, which indicates a forward element that is shorter still.

For this 10-meter design example, using 0.5" aluminum elements, I selected a forward element length of 0.4446 wavelength and a rear element of 0.0.4772 wavelength. The element spacing is 0.1112 wavelength. With this combination and a rear element relative current magnitude of 0.8762 at -38.53 degrees, we obtain a performance potential of 6.39 dBi free-space gain and 23.88 dB front-to-back ratio. One might further vary these values for higher performance, but for the design example, I declared them satisfactory.

The forward element impedance is 20.9 - j 32.7 Ohms. The rear element impedance is 16.4 - j 39.7 Ohms. I selected a 100-Ohm phase line. To raise the impedance of the rear element to about 100 Ohms, I added a shorted stub, the shunt component of a beta or L-network. The required value from network calculations was about j 44 Ohms. Since the length of a shorted stub will vary with both the desired reactance and the characteristic impedance of the line used, I arbitrarily created a 50-Ohms stub with an electrical length of 0.1116 wavelength.

I then created a phase line with the specifications of 100 Ohms and a velocity factor of 0.78 to simulate RG-8X or similar cable. The physical length is 0.1314 wavelength to ensure that there is enough cable to reach from the center of the boom tube to the elements at each end. The line has an electrical length of 0.1684 wavelength, the length necessary to transform the current magnitude and phase for the desire conditions on each element. With the rear stub and the 100-Ohms phase line added to the model, we obtain the desired performance indicated from the initial model with independently fed elements. However, the feedpoint impedance at the junction of the forward element and the phase line is 21.33 - j 22.45 Ohms.

The capacitive reactance and low resistance at the feedpoint are ripe for a second beta match, this time a 50-Ohm shorted stub with an electrical length of about 0.126 Ohms. The result is a feedpoint impedance of 43.8 - j 7.0 Ohms at the design frequency.

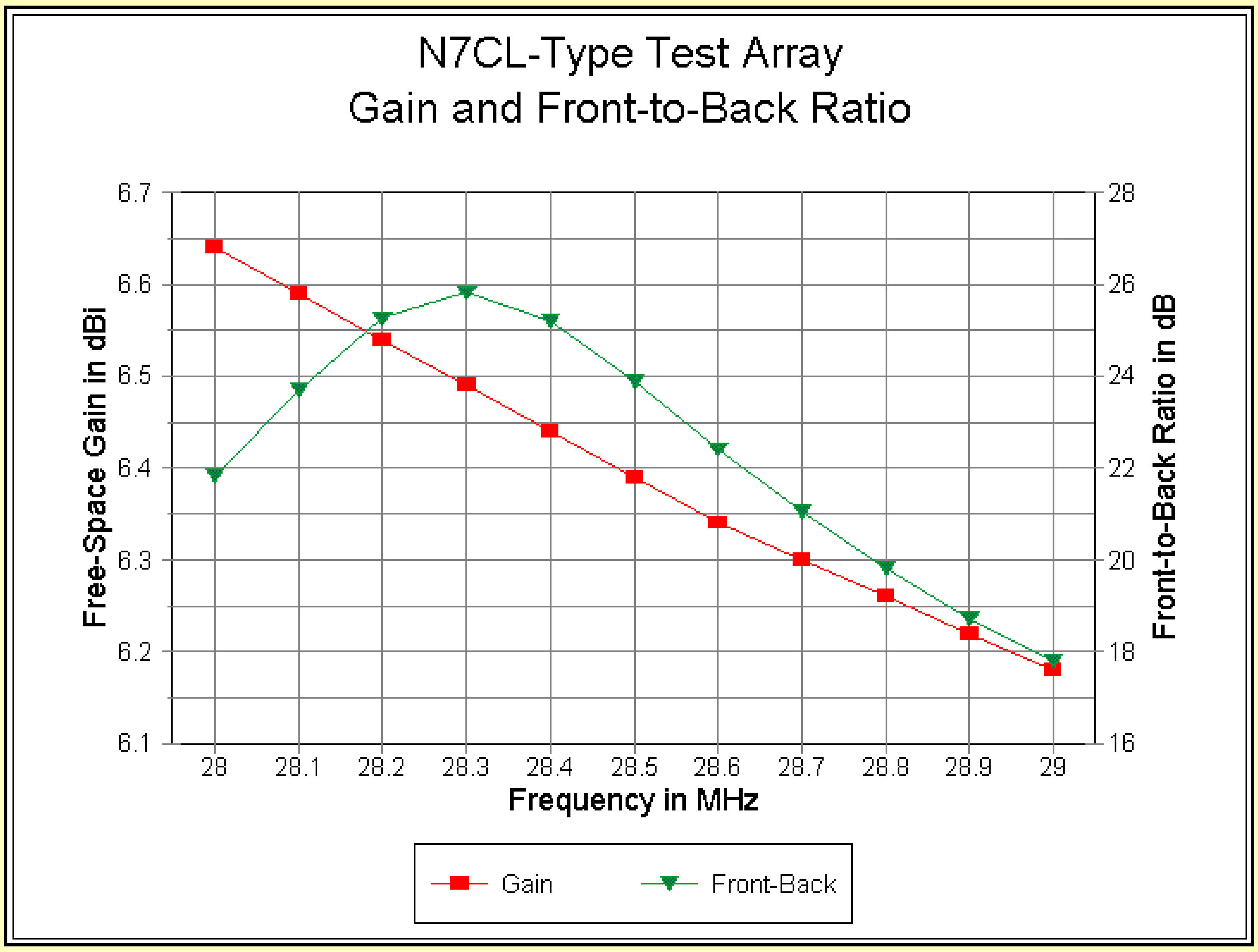

Fig. 4-6. Gain and 180-degree front-to-back ratio of the N7CL phased array from 28.0 to 29.0 MHz.

Fig. 4-6 shows the free-space gain and front-to-back curves for this sample design across the first MHz of 10 meters. Because the rear-element beta match reverses the impedance progression with changing frequency relative to an element with no matching system, the gain curve shows a reverse direction relative to other phased arrays with which we have worked. The front-to-back curve peaks at about 28.3 MHz. Both progressions of values can be altered with further design refinements.

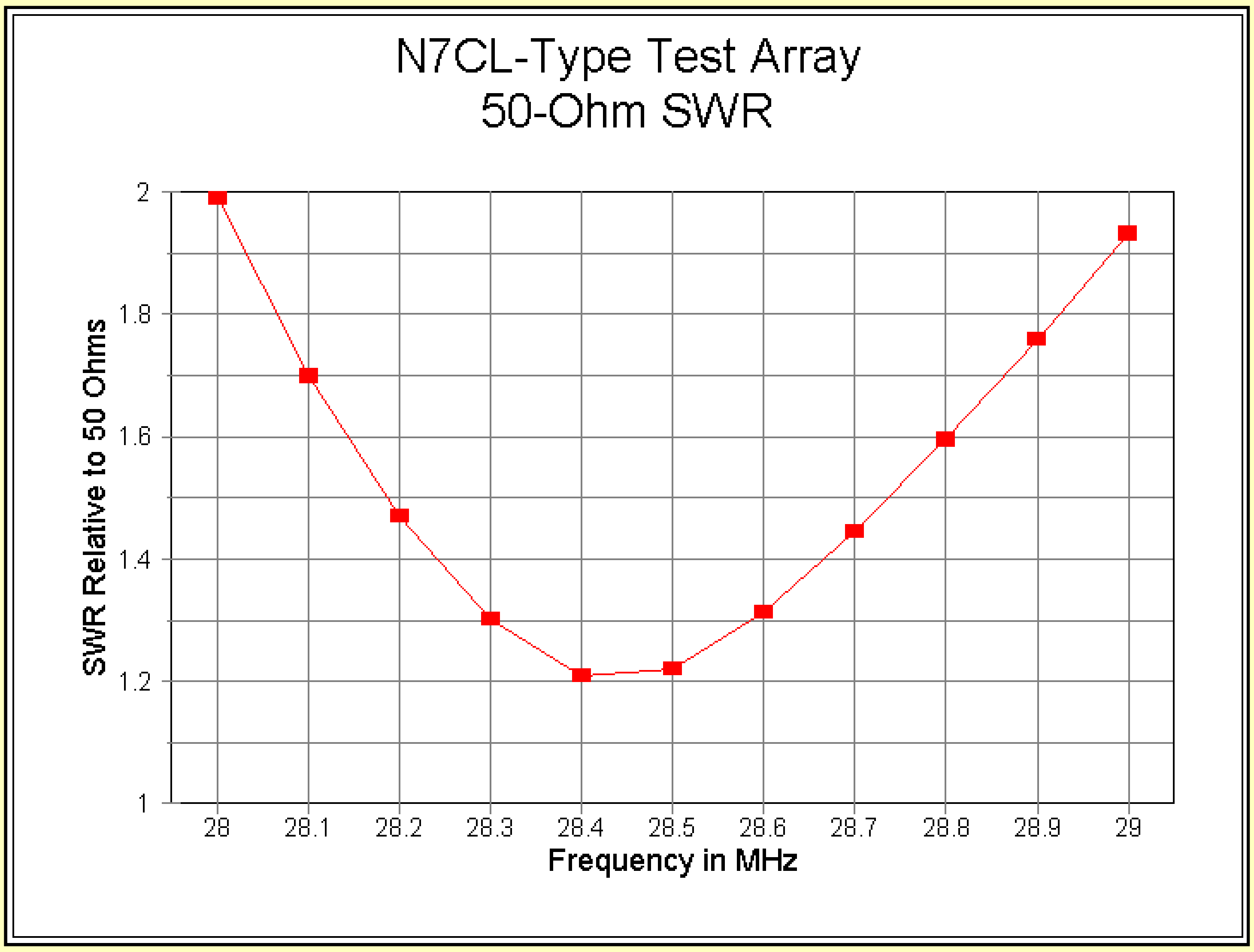

Fig. 4-7. SWR curve of the N7CL phased array from 28.0 to 29.0 MHz.

In the design example, the elements were not sufficiently optimized to yield both an SWR under 2:1 across the passband and a minimum value close to 1:1, as shown in **Fig. 4-7**. The feat may be more difficult than might appear at first sight, since any adjustment to the length of the forward element to move the SWR curve will also affect the natural--and hence, the transformed--impedance of the rear element. Moreover, the element spacing--just over 0.11 wavelength--also works to narrow the operating passband of the array. **Fig. 4-8** shows sample free-space azimuth patterns at both the band edges and mid-band.

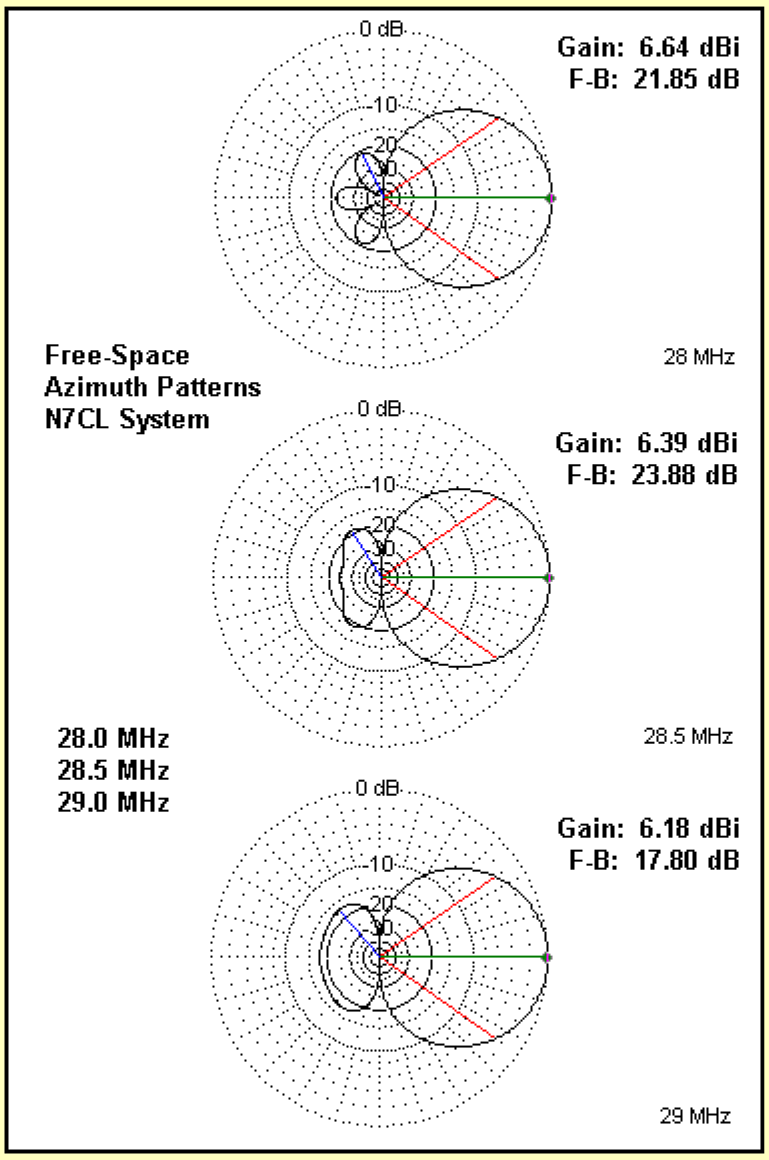

Fig. 4-8. Free-space azimuth patterns of the N7CL phased array at 28.0, 28.5, and 29.0 MHz.

The N7CL phasing system is currently in use in 30-meter and 40- meter arrays under the Cal-Av label. I am grateful to Eric for permission to describe his patented matching system, although he is in no way responsible for the slant given to the explanation or for my simple design example. As I have noted, design examples do not necessarily equal production designs in performance.

Capacitive Element Loading

A few years ago (1998-99), I took a different tack in trying to overcome the problem of designing a phased array that could use a higher impedance or twin-coax phasing line. (See "The HB9CV Phased Array and Gain Comparisons".) As we increase the length of a dipole, the impedance increases. If we lengthen the dipole sufficiently, the impedance approaches 100 Ohms resistive, but with a considerable inductive reactive component. We may compensate for this reactance by inserting capacitors at the element feedpoint in series with the element.

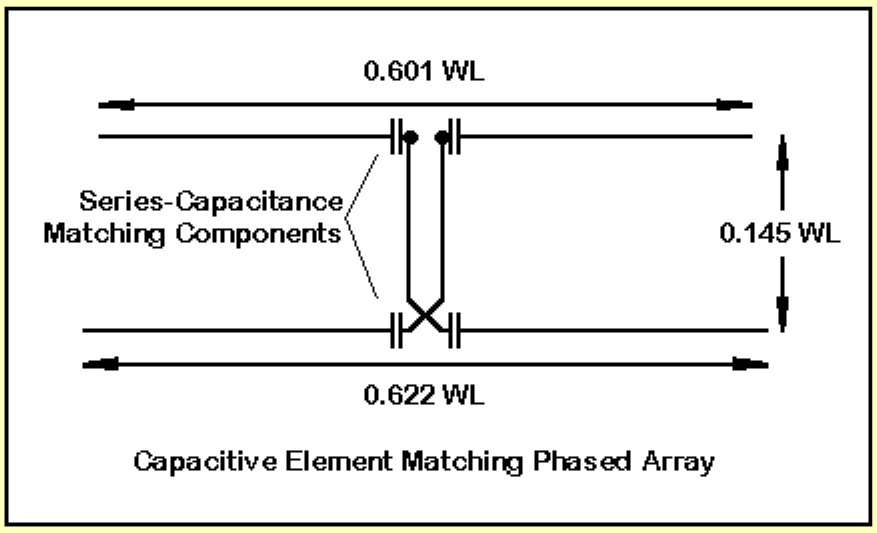

Fig. 4-9. General outlines of the capacitive-element-matching phased array.

When we deal with 2 elements, the problem becomes only slightly more complex due to the interaction of the elements. The result will be elements considerably longer than a self-resonant dipole. The final design result was the array pictured in **Fig. 4-9**. The forward element is 0.602 wavelength long, while the rear element is 0.622 wavelength long. Because the gain of a dipole tends to increases modestly with increases in length, I used a relatively wide spacing of 0.145 wavelength to achieve satisfactory performance. The elements are 1" diameter aluminum.

We need not bring each element to zero reactance in order to have a satisfactory array. The rear element uses a total capacitance of 25.4 pF (two 50-pF capacitors in series on each side of the feed junction). The forward element uses 15 pF (two 30-pF capacitors). When modeled as independent element separately fed, the rear element impedance is 82.9 - j 11.4 Ohms, while the forward element is 102.6 + j 35.7 Ohms. We may now add a 100-Ohms phase line using the same 0.78 velocity factor twin 50-Ohms coax construction used in the preceding example. The physical length for the design example is 0.145 wavelength, although in practice, some extra line may be useful for making connections. A 0.150-wavelength line will not significantly change performance due to the initial good match between the line and the rear element. The feedpoint junction requires no additional matching network, because the forward-element capacitors were adjusted to provide a low 50-Ohms SWR.

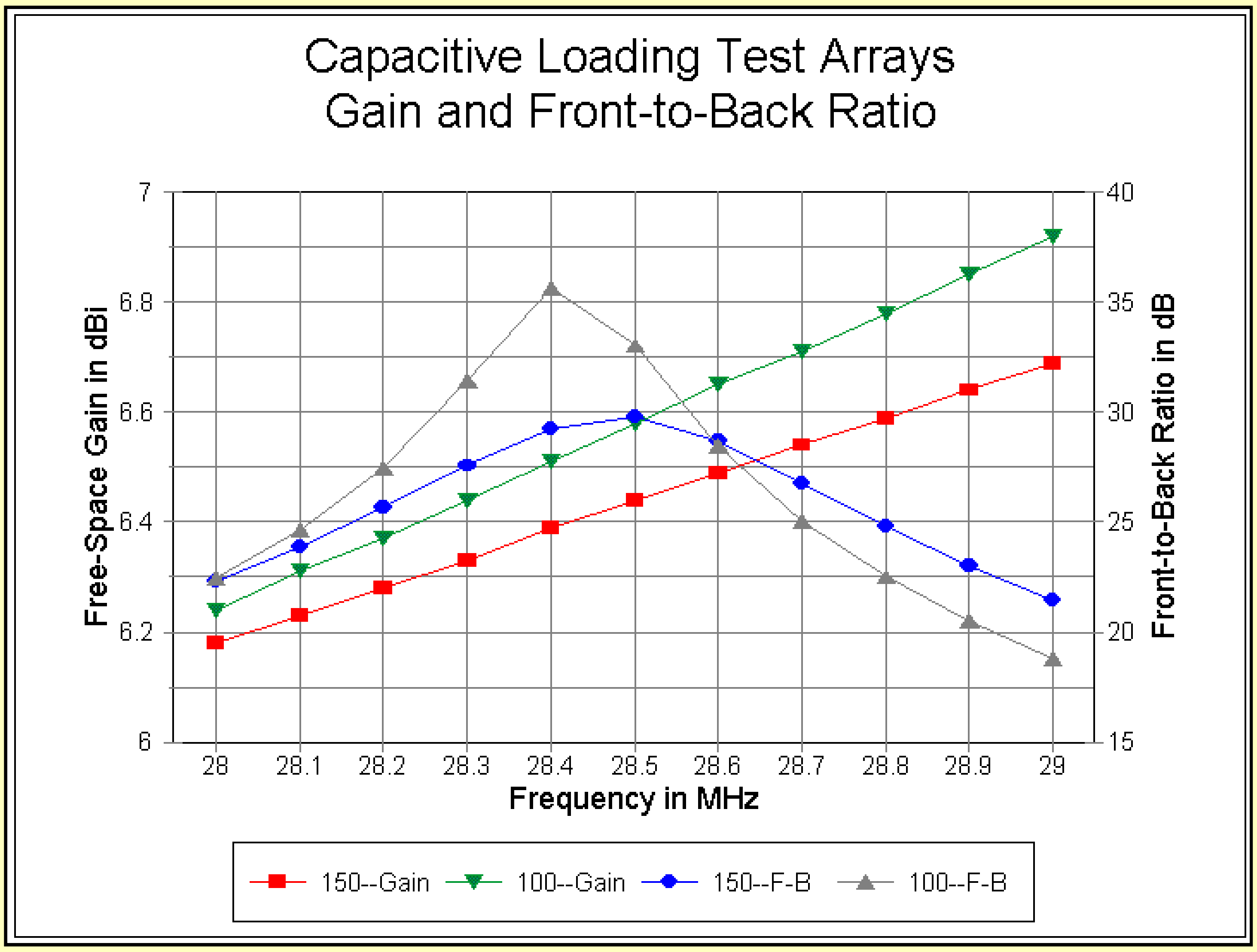

Fig. 4-10. Gain and 180-degree front-to-back ratio of the capacitive-element- matching phased array from 28.0 to 29.0 MHz.

Fig. 4-10 shows the free-space gain and front-to-back ratio potential performance across the 28.0 to 29.0 MHz spread. The system is not at all finicky, as revealed by the values obtained simply by replacing the 100-Ohm line with a 150-Ohm, as might be obtained by employing 75-Ohm coax lengths as shielded twinlead. However, the system is relatively optimized for the 100-Ohm line. The 150-Ohm line shows superior band-edge front-to-back performance, although the 100-Ohm line version shows a higher peak value. Since the matching capacitors only compensate for the element inductive reactance and do not transform the impedance, the gain curve shows its normal upward trend with frequency.

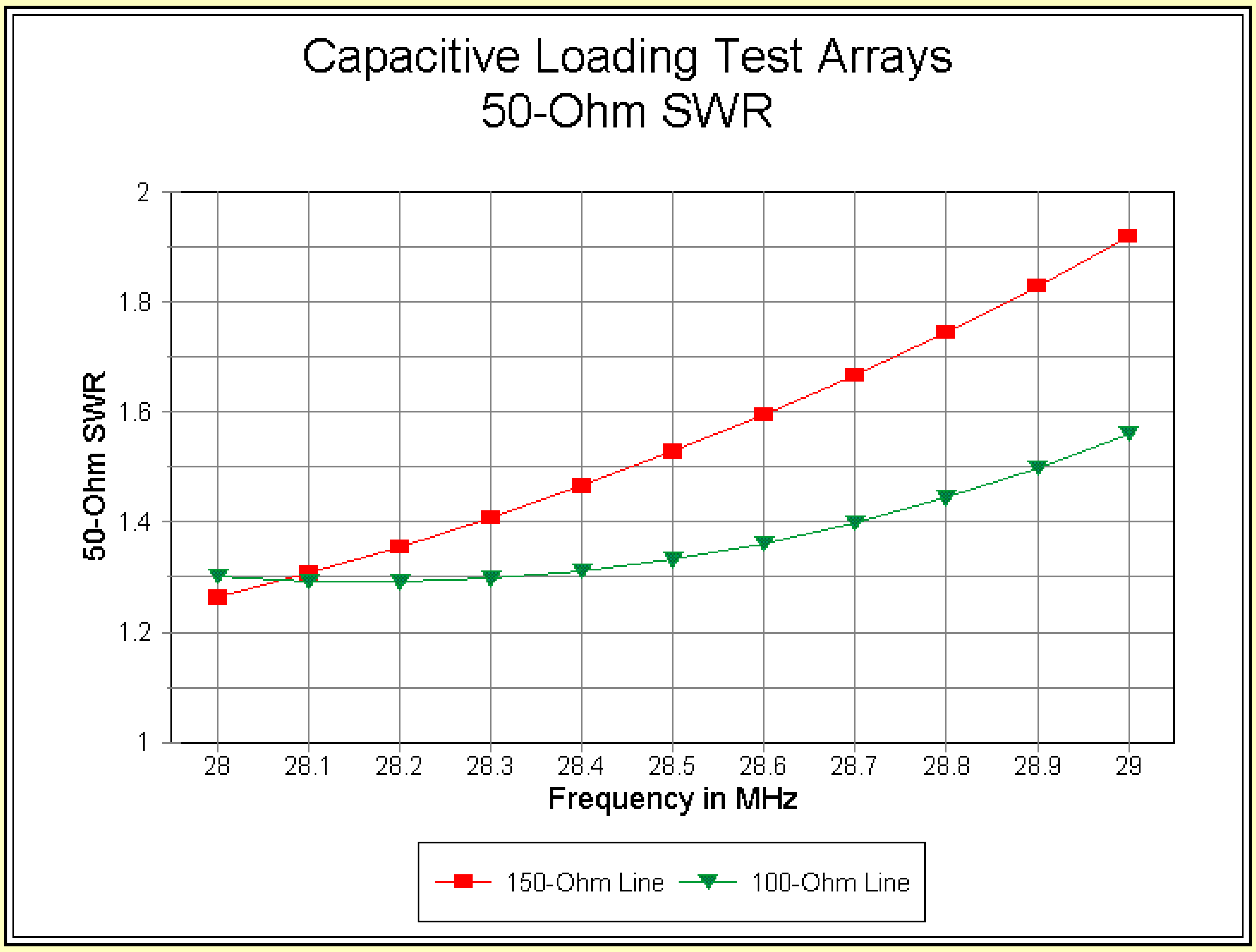

Fig. 4-11. SWR curve of the capacitive-element-matching phased array from 28.0 to 29.0 MHz.

In **Fig. 4-11**, we find the SWR curves for both the 100-Ohm and the 150-Ohm line versions. Both are satisfactory. However, we might classify the 100-Ohm line version as somewhat "tamer." **Fig. 4-12** provides the standard 28.0, 28.5, and 29.0 MHz free-space azimuth patterns for performance reference. The array with capacitively loaded elements is an experiment and not a finished product. The elements are long by most array standards--about 20% longer than those of a standard array. However, the reward for heavier elements is a somewhat simplified structure for matching the rear element impedance to the phase line and the array feedpoint impedance to standard coaxial cable feedlines.

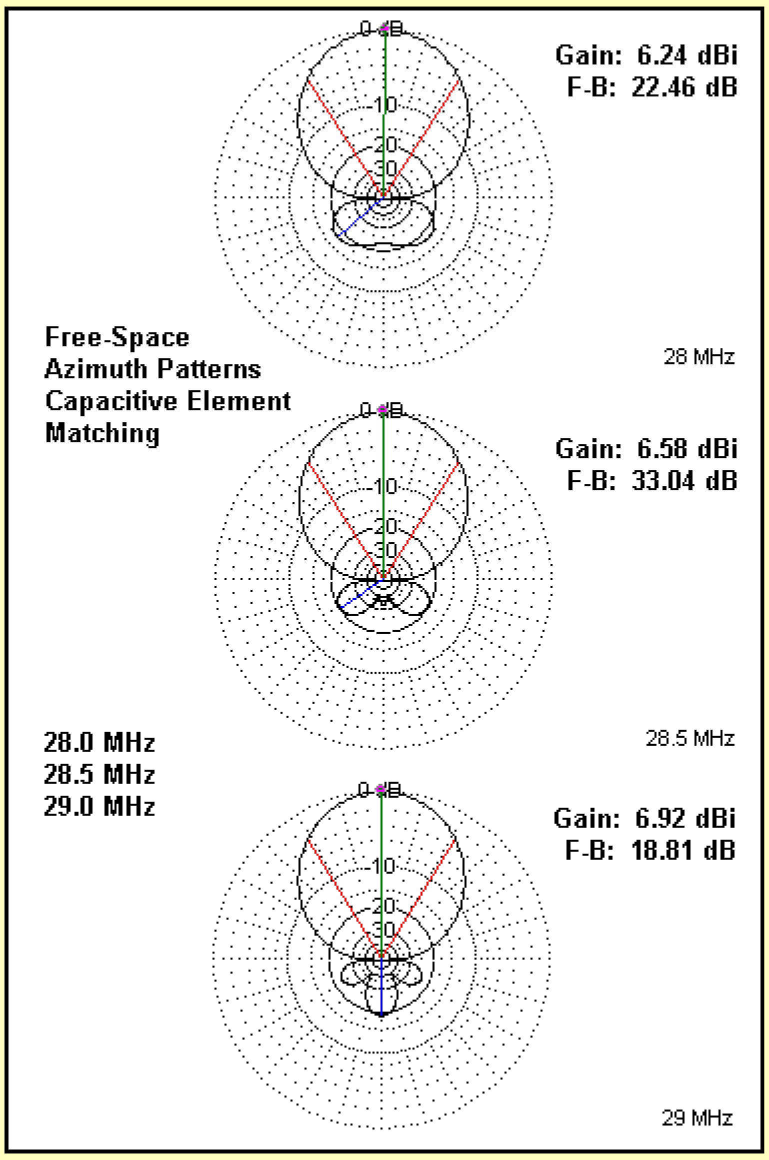

Fig.4-12. Free-space azimuth patterns of the capacitive-element-matching phased array at 28.0, 28.5, and 29.0 MHz.

Conclusions

The three systems we have explored in this part of the series illustrate ways in which we may achieve 2-element phased arrays using normal beam constructions with a metallic boom supporting the elements. In each case, the designer has matched the element impedances to a desired phase line, using a varied assortment of techniques. Once more, our goal has not been to produce paradigm production designs, but only design examples sufficient to illustrate the principles involved. If we have gained some appreciation of the techniques of matching the rear element to the phase line and changing everything else to align the other variables involved in a 2-element horizontal phased array, then we have gotten out of them everything intended.

Indeed, some may wish to emphasize the performance differences among the examples, but this would be a mistake. Many designs can undergo further optimization. What should strike us is the basic similarity in performance among the ZL-Special and the matched-element designs. One cannot be absolute on the basis of a sampling, but it is likely that the performance range among the models explored so far represents the main arena for 2-element horizontal phased array performance.

Free-space makes an ideal environment for comparing the potential performance of antennas of essentially the same type. However, over the years, some folks have questioned whether or not there might be a difference between the performance of phased horizontal arrays and of parasitic arrays over ground. The only free-space evidence a potential difference in performance would be a significant dissimilarity between the elevation or H-plane patterns of Yagis and phased arrays. None exists.

Comparative Performance Figures of Sample 2-Element Arrays
All Arrays 1 Wavelength Above Good Ground at 28.5 MHz

1. Reflector-Driver Yagi

Dimensions:

Reflector Length wl	Driver Length wl	Element Spacing wl	Element Diameter wl
0.5028	0.4620	0.1250	0.001207 (0.5")

Performance:

Gain dBi	TO Angle degrees	Second Lobe Gain dBi	Angle degrees	Main-Second Lobe Ratio dB	Front-Back Ratio dB
11.61	14	9.35	46	-2.26	12.52

2. Driver-Director Yagi

Dimensions:

Driver Length wl	Director Length wl	Element Spacing wl	Element Diameter wl
0.4972	0.4670	0.0750	0.001207 (0.5")

Performance:

Gain dBi	TO Angle degrees	Second Lobe Gain dBi	Angle degrees	Main-Second Lobe Ratio dB	Front-Back Ratio dB
11.83	14	9.49	46	-2.34	19.58

3. ZL-Special

Dimensions:

Rear El. Length wl	Forward El. Length wl	Element Spacing wl	Element Diameter wl	Phaseline--Note 1 Length	Zo	VF
0.5060	0.4650	0.1250	0.001207 (0.5")	0.1300	35	0.66

Performance:

Gain	TO Angle	Second Lobe	Angle	Main-Second	Front-Back

dBi	degrees	Gain dBi	degrees	Lobe Ratio dB	Ratio dB
11.68	14	9.51	47	-2.17	31.62

2. N7CL Phased-Array with Rear-Element-Matching

Dimensions:

Rear El. Length wl	Forward El. Length wl	Element Spacing wl	Element Diameter wl	Phaseline--Note 2 Length	Zo	VF
0.4972	0.4670	0.0750	0.001207 (0.5")	0.1314	100	0.78

Performance:

Gain dBi	TO Angle degrees	Second Lobe Gain dBi	Angle degrees	Main-Second Lobe Ratio dB	Front-Back Ratio dB
11.74	14	9.49	46	-2.25	31.44

Note 1: ZL-Special uses a feedpoint impedance matching section.
Note 2: N7CL array uses shorted stubs for rear-element matching and for feedpoint matching.

Table 1. Comparative performance figures of sample 2-element arrays with all arrays 1 wavelength above good ground at 28.5 MHz.

However, we may use a more direct demonstration by modeling sample parasitic and phased arrays over real ground. **Table 1** lists the critical performance parameters of two Yagis, a reflector-driver array with an element spacing of 0.125 wavelength and a driver-director array with a 0.075-wavelength element spacing. These arrays come from part 2 of the series. The sample phased arrays are the 35-Ohms phase line model from Part 3 and the N7CL array from our work in this section. All arrays are 1 wavelength above ground. At 1 wavelength, a parasitic array elevation pattern shows both a lower main lobe at about 14 degrees elevation along with a secondary lobe above. The differential in the secondary lobe is a good indicator of performance similarity or difference.

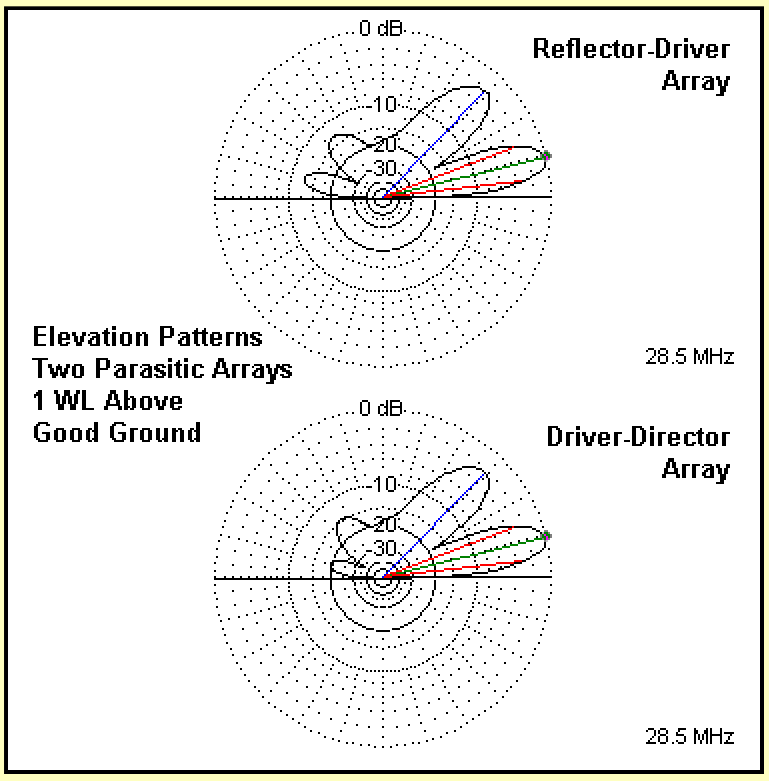

Fig. 4-13. Elevation patterns of two types of parasitic arrays 1 wavelength above good ground.

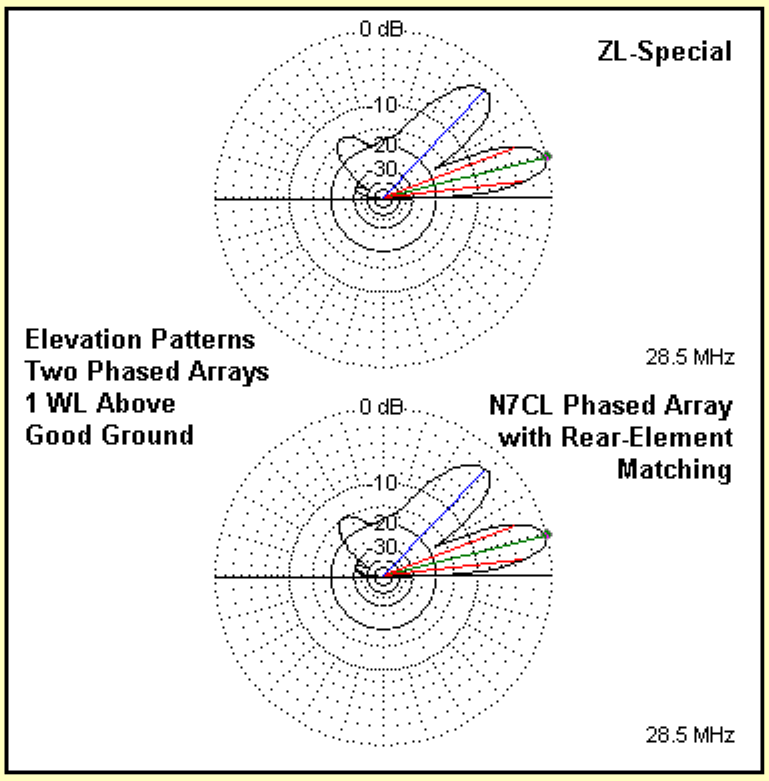

Fig. 4-14. Elevation patterns of two types of phased arrays 1 wavelength above good ground.

As the figures in the table show--backed up by the elevation patterns in **Fig. 4-13** and **Fig. 4-13**--the differentials are too small to support a claim of performance differential. The differentials that do exist lie in the realm of gain and front-to-back ratio. The 2-element horizontal phased array is capable of slightly higher gain than a 2-element Yagi of similar operating bandwidth. The gain advantage runs between 0.2 to 0.7 dB. However, with a reasonable front-to-back ratio, the gain of a 2-element horizontal phased array never reaches the level of a well-designed 2-element quad or a short-boom 3 element Yagi.

If the gain advantage of the horizontal phased array is marginal relative to parasitic arrays of similar operating bandwidth, the front-to-back advantage is significant and operationally noticeable. A reflector-driver Yagi with coverage of the first MHz of 10 meters will have a peak front-to-back ratio of about 12 dB. A similarly sized phased array with equal or greater gain is capable--when optimally designed--of nearly 20 dB across the full passband, with peak values in the 30 dB region. Whether one wishes the additional quietness from the rear of the phased array or wants to be able to hear what may be happening in directional to which the beam is not aimed depends on the type and style of operation. In short, the desirability of one type of array over another is a user judgment.

These comparative notes relate only to full-size models of both parasitic and phased arrays. Shortened, loaded elements yield lesser gain in virtually all circumstances, although loaded reflectors may increase the front-to-back ratio of a reflector-driver Yagi. A shorter-element phased array may be capable of the full gain that its elements permit with inherently good front-to-back ratio as well. In the end, the variables involved in antenna selection--where 2 elements form the common baseline among candidates--may outnumber the variables involved in properly phasing 2-element horizontal arrays.

Return to Series Index

Go to Main Index