

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
1434 High Mesa Drive
Knoxville, TN 37938-4443
cebik@cebik.com

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 feed line junction and yield a feed-point impedance that we can match to our most common feed lines.

The HB9CV

The original HB9CV design, shown at the top of **Figure 1**, attempted to permit the use of 300- Ω (or other parallel line available in the 1950s) with single tubular elements by the use of T or double gamma-match sections. A later version, shown in the lower part of the figure varied the feed line system for use with 75- Ω 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 one 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 generally 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 feed point is shown at the forward element of the illustrated versions of the HB9CV, various feed points between that point and the mid-point between elements are used.

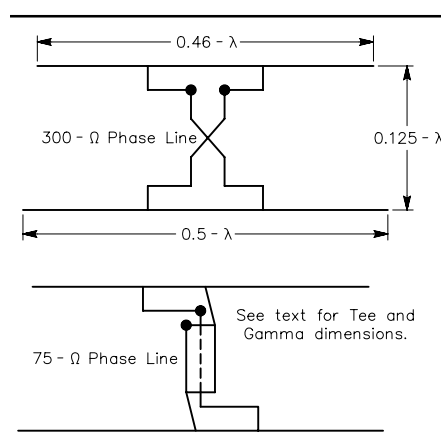


Figure 1—General outlines of two versions of the HB9CV array.

HB9CV specified certain dimensions for the antenna. The rear element should be 0.5λ long, and the forward element should be 0.46λ long, if the element is between 0.004 and 0.007λ in diameter. At 10 meters, 0.004λ is well over 1.5 inches, 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 T 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 sections 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 systems.

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 T and gamma versions of the HB9CV that use 1-inch diameter materials throughout. The forward element is 0.46λ long, while the rear element is 0.508λ long, with an element spacing of 0.125λ . The gamma sections are spaced 0.0096λ from the main element with lengths adjusted as follows: The Ts are 0.125λ long, while the one-sided gammas are 0.053λ 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

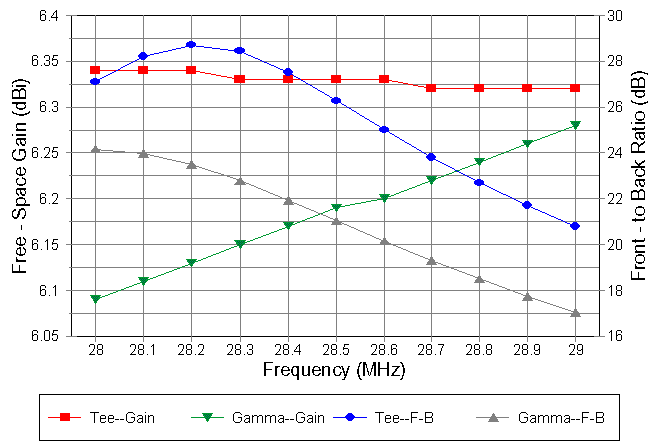


Figure 2—Gain and 180° front-to-back ratio of the sample HB9CV arrays from 28.0 to 29.0 MHz.

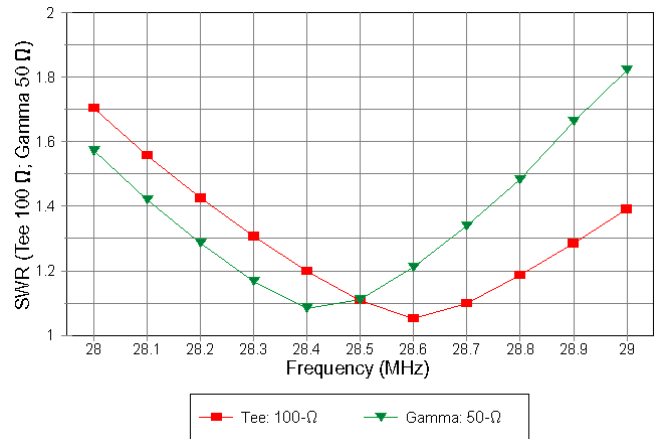


Figure 3—SWR curves of the sample HB9CV arrays from 28.0 to 29.0 MHz.

the original design chiefly in the spacing and length of the T 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 elements 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 them.

Figure 2 shows the modeled free-space gain and front-to-back performance of the T and gamma models. The T uses a 300-Ω phase line, while the gamma uses a 75-Ω 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 T-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 Ω 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-Ω 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-Ω range for a direct 50-Ω coax feed.

The cost of the T-version's relatively even performance across the first MHz of 10 meters is the feed-point impedance. As shown in **Figure 3**, the HB9CV has an SWR curve with a reference impedance value of about 100 Ω. A 2:1 matching network or device is required for standard coax feed. In contrast, the gamma version shows a well-behaved 50-Ω SWR curve. **Figure 4** samples the

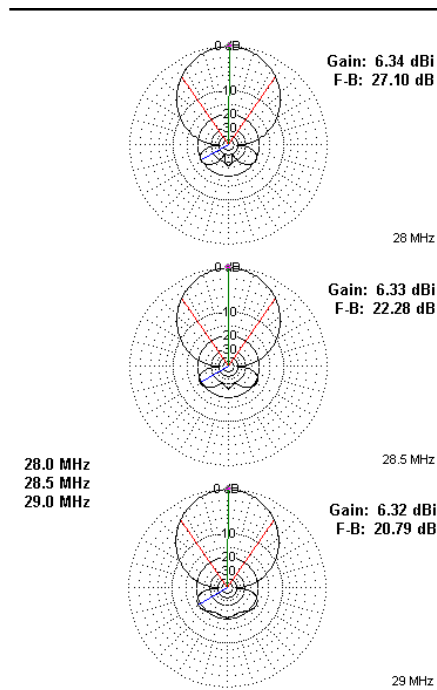


Figure 4—Free-space azimuth patterns of the T-version of the HB9CV array at 28.0, 28.5 and 29.0 MHz.

free-space azimuth patterns of the T-version of the HB9CV at 28.0, 28.5 and 29.0 MHz to indicate the evolution of the pattern across the operating passband.

In the 1950s, the $1/8\lambda$ 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 $1/8\lambda$ spacing. It represents a reasonable balance between operating bandwidth and gain. Beyond the $1/8\lambda$ mark, gain tends to decrease ever more rapidly for elements near the $1/2\lambda$ or self-resonant length. Below a spacing of $1/8\lambda$, the operating bandwidth decreases ever more rapidly.

However, for the proper phasing of an array to produce good performance—relative to having only two 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 λ. The gamma and T matching system needed 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 feed-point 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.

Figure 5 shows the schematic outline of the N7CL phased array. It consists of two elements, a phase line and two stubs. For the phase line, N7CL selected a 100- Ω 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- Ω phase lines. The key to effecting a match between the rear element and the phase line is to change the element impedance from its natural value to something very close to 100 Ω . 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 feed points. 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 feed line-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-inch aluminum elements, I selected a forward element length of 0.4446λ and a rear element of 0.4772λ . The element spacing is 0.1112λ . With

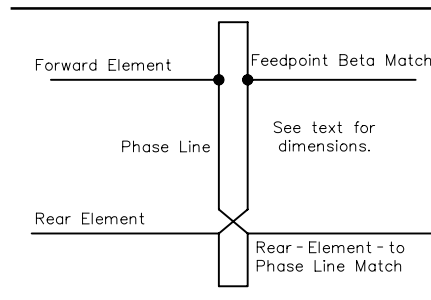


Figure 5—General outlines of the N7CL phased array.

this combination and a rear element relative current magnitude of 0.8762 at -38.53° , 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 $20.9 - j32.7 \Omega$. The rear element impedance is $16.4 - j39.7 \Omega$. I selected a 100- Ω phase line. To raise the impedance of the rear element to about 100 Ω , I added a shorted stub, the shunt component of a beta or L-network. The required value from network calculations was about $j44 \Omega$. 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- Ω stub with an electrical length of 0.1116λ .

I then created a phase line with the specifications of 100 Ω and a velocity factor of 0.78 to simulate RG-8X or similar cable. The physical length is 0.1314λ 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 0.1684λ , the length necessary to transform the current magnitude and phase

for the desired conditions on each element. With the rear stub and the 100- Ω phase line added to the model, we obtain the desired performance indicated from the initial model with independently fed elements. However, the feed-point impedance at the junction of the forward element and the phase line is $21.33 - j22.45 \Omega$.

The capacitive reactance and low resistance at the feed point are ripe for a second beta match, this time a 50- Ω shorted stub with an electrical length of about 0.126λ . The result is a feed-point impedance of $43.8 - j7.0 \Omega$ at the design frequency.

Figure 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.

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 **Figure 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 0.11λ —also works to narrow the operating passband of the array. **Figure 8** shows sample free-space azimuth patterns at both the band edges and mid-band.

The N7CL phasing system is currently in use in 30-meter and 40-meter arrays under the Cal-Av label. I am grateful to

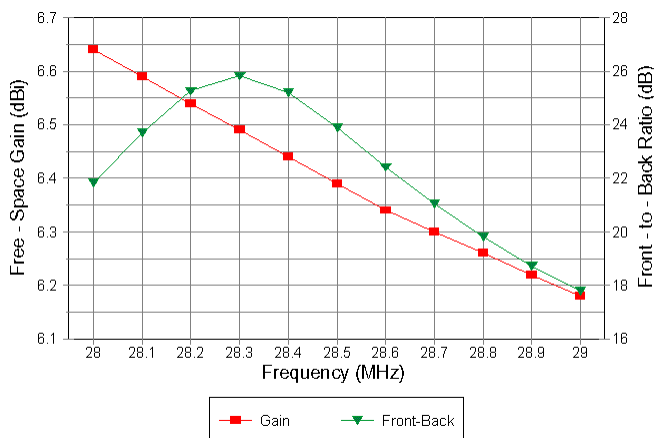


Figure 6—Gain and 180° front-to-back ratio of the sample HB9CV arrays from 28.0 to 29.0 MHz.

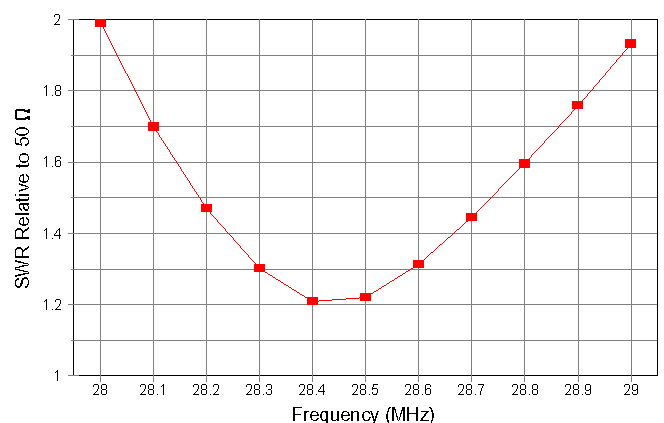


Figure 7—SWR curve of the N7CL phased array from 28.0 to 29.0 MHz.

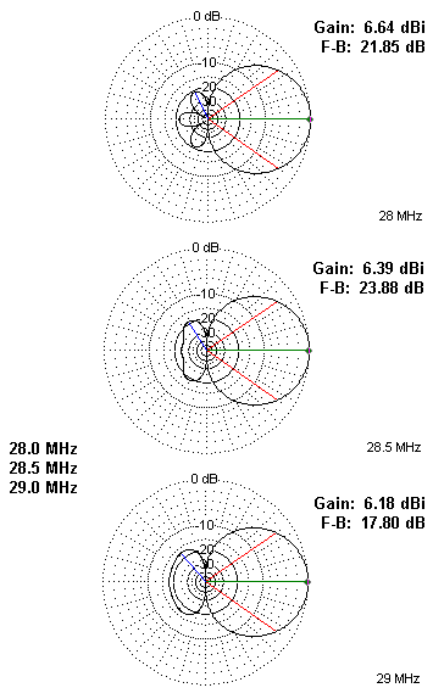


Figure 8—Free-space azimuth patterns of the N7CL phased array at 28.0, 28.5 and 29.0 MHz.

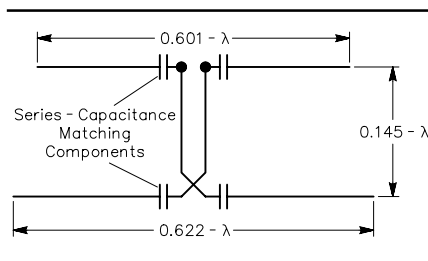


Figure 9—General outlines of the capacitive-element-matching phased array.

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” at www.cebik.com/hb.html.) As we increase the length of a dipole, the impedance increases. If we lengthen the dipole sufficiently, the impedance approaches 100 Ω resistive, but with a considerable inductive reactive component. We may compensate for this reactance by inserting capacitors at the element feed point in series with the element.

When we deal with two 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 **Figure 9**. The forward element is 0.602 λ long, while the rear element is 0.622 λ long. The elements are 1-inch diameter aluminum. Because the gain of a dipole tends to increase modestly with increases in length, I used a relatively wide spacing of 0.145 λ to achieve satisfactory performance. The longer elements offset the gain reduction caused by the wider element spacing, but yielded a wider operating bandwidth.

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 elements separately fed, the rear element impedance is 82.9 – j11.4 Ω, while the forward element is 102.6 + j35.7 Ω. We may now add a 100-Ω phase line using the same 0.78 velocity factor twin 50-Ω coax construction used in the preceding example. The physical length for the design example is 0.145 λ, although in practice, some extra line may be useful for making connections. A 0.150-λ line will not significantly change performance due to the initial good match between the line and the rear element. The feed-point junction requires no additional matching network, because the forward-element capacitors were adjusted to provide a low 50-Ω SWR.

Figure 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-Ω line with a 150-Ω line, as might be obtained by employing 75-Ω coax lengths as shielded twinlead. However, the system is relatively optimized for the 100-Ω line. The 150-Ω line shows superior band-edge front-to-back performance, although the 100-Ω 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.

In **Figure 11**, we find the SWR curves for both the 100-Ω and the 150-Ω line versions. Both are satisfactory. However, we might classify the 100-Ω line version as somewhat “tamer.” **Figure 12** provides the standard 28.0, 28.5 and 29.0 MHz free-space azimuth patterns for

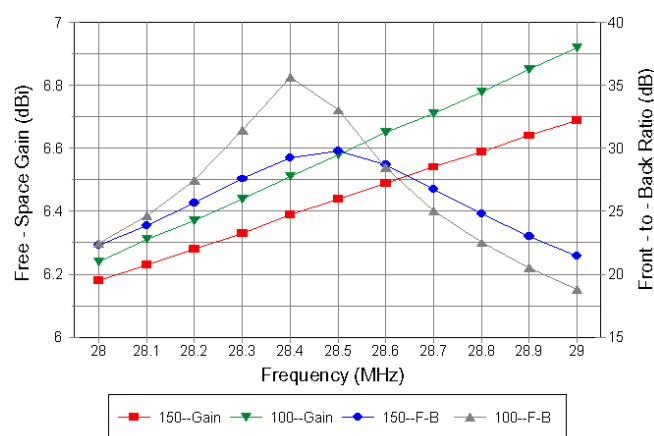


Figure 10—Gain and 180° front-to-back ratio of the capacitive-element-matching phased array from 28.0 to 29.0 MHz.

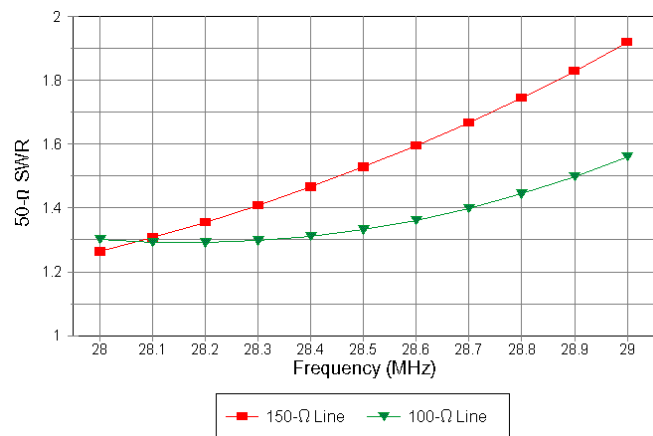


Figure 11—SWR curve of the capacitive-element-matching phased array from 28.0 to 29.0 MHz.

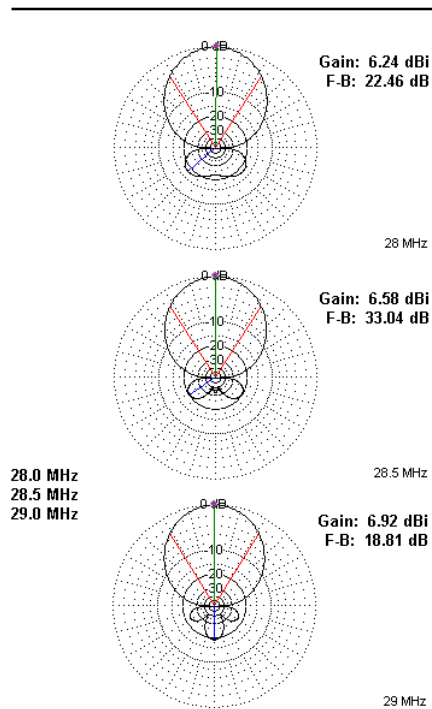


Figure 12—Free-space azimuth patterns of the capacitively-element-matching phased array at 28.0, 28.5 and 29.0 MHz.

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 feed point impedance to standard coaxial cable feed lines.

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.

Table 1

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

1. Reflector-Driver Yagi

Dimensions:

Reflector Length (λ)	Driver Length (λ)	Element Spacing (λ)	Element Diameter (λ)
0.5028	0.4620	0.1250	0.001207 (0.5 inch)

Performance:

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

2. Driver-Director Yagi

Dimensions:

Driver Length (λ)	Director Length (λ)	Element Spacing (λ)	Element Diameter (λ)
0.4972	0.4670	0.0750	0.001207 (0.5 inch)

Performance:

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

3. ZL-Special

Dimensions:

Rear Element Length (λ)	Forward Element Length (λ)	Element Spacing (λ)	Element Diameter (λ)	Phase Line Length (λ) ¹	Z_0 (Ω)	VF
0.5060	0.4650	0.1250	0.001207 (0.5 inch)	0.1300	35	0.66

Performance:

Gain (dBi)	TO Angle (degrees)	Second Lobe Gain (dBi)	Angle (degrees)	Main-to-Second Lobe Δ (dB)	Front-to-Back Ratio (dB)
11.68	14	9.51	47	-2.17	31.62

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

Dimensions:

Rear Element Length (λ)	Forward Element Length (λ)	Element Spacing (λ)	Element Diameter (λ)	Phase Line Length (λ) ²	Z_0 (Ω)	VF
0.4972	0.4670	0.0750	0.001207 (0.5 inch)	0.1314	100	0.78

Performance:

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

¹ZL-Special uses a feed-point impedance matching section.

²N7CL array uses shorted stubs for rear-element matching and for feed point matching.

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 of a potential difference in performance would be a significant dissimilarity between the elevation or H-plane patterns of Yagis and phased arrays. None exists.

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 0.125λ and a driver-director array with a 0.075λ element spacing. These arrays come from **Part 2** of the series. The sample phased arrays are the $35\text{-}\Omega$ phase line model from **Part 3** and the N7CL array from our work in this section. All arrays are 1λ above ground. At 1λ , a parasitic array elevation pattern shows both a lower main lobe at about 14° elevation along with a secondary lobe above. The differential in the secondary lobe is a good indicator of performance similarity or difference.

As the figures in the table show—backed up by the elevation patterns in **Figure 13** and **Figure 14**—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 the direction 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 cir-

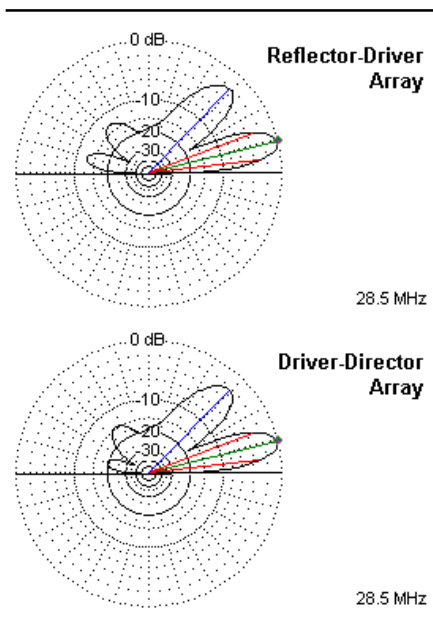


Figure 13—Elevation patterns of two types of parasitic arrays one wavelength above good ground.

cumstances, 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,

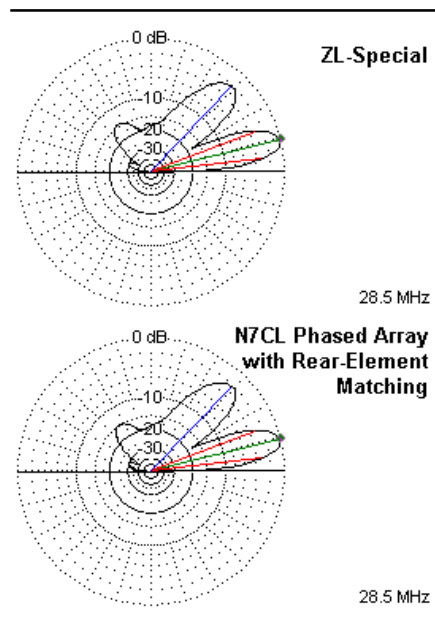


Figure 14—Elevation patterns of two types of phased arrays one wavelength above good ground.

the variables involved in antenna selection—where two elements form the common baseline among candidates—may outnumber the variables involved in properly phasing 2-element horizontal arrays. ■

Cabrillo Format

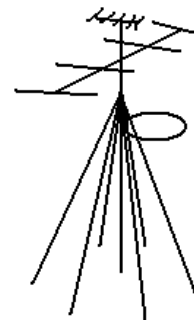
- Meets ARRL Standards
- ✉E-Mail your log
- ✉Meet Cabrillo Specs
- ✉Print, Save to file, etc.
- ✉Fast and easy to use

Davco Technology

E-mail — kd7gim@msn.com

Contest Logger

Contest Logger is FAST, USER Friendly Software that meets ARRL specification for CABRILLO FORMATTING. YOU specify which ARRL contest You are interested in, and I Will format the software To those specs, or Any other spec.



FAST, FRIENDLY
COURTEOUS,
CUSTOM
SERVICE.

