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Vertical Phased Arrays from Compromised Locations

INTRODUCTION

Although my primary interest in amateur radio has always been biased towards weak signal VHF working, the reduction in activity in the winter months has for many years led me towards CW DX working on 80 and 160m during this period. The initial impetus to improve my antennas for 80m came when I decided to go US county chasing, but only on 80m CW. Not too dissimilar from 'square chasing' on 144MHz but at least I could do it all on CW!

Available literature on the design and locating of phased vertical antennas for the LF bands has been well documented over the years, predominantly in publications from the USA (See Bibliography).

When erecting multiple element vertical phased arrays with directional switching using common phasing components, electrical symmetry of all elements is essential. If this criteria is not met, good front to back performance will not be achieved. The forward gain of multi element arrays is not very critical on phasing, but rear rejection is. These antennas really want to work, but great care needs to be taken to realise the full potential.

So what happens, if like most UK amateurs, we do not have a 5 hectare field that allows us to space the verticals perfectly and lay down a perfect 120 radial ground system?

I hope that this article goes some way to address some of these issues and show how the spacing, phasing, and general performance can be adjusted to suit individual situations. There are, of course, compromises that must be accepted but it is still possible to get a system working in a less than perfect situation.

My existing antenna for 80m is a 3-element in line phased array that is switched NW-SE and was arranged this way to provide a good forward lobe into the USA and long path ZL whilst providing rejection towards Europe. Fortunately, I have access to some woodland, and the antenna is constructed from wire elements suspended in tall oak trees. The spacing was dictated by, rather than selected by, the position of suitable oak trees. In my case this was 0.165λ at 3.5MHz.

The ground radial system consists of roughly 20-30 radials per vertical using insulated instrument wire laid directly onto the ground. The Easterly vertical has less wires to the East as the house is in the way. The measured self impedances of each vertical, are unfortunately, not identical.

So, this is my compromised phased vertical system for 80m. Later I will describe what I have done to match and phase this system to perform in both directions.

COMPLEX NUMBERS

No description of phased antennas can made without reference to complex numbers whether in rectangular or polar form. All that is required as a reader is a basic understanding. Not wishing to fill this article with pages of formulae and maths, I have provided all of the calculations as separate useable and viewable only files. These are available to those that want them at the location shown in the bibliography. The manipulation of these values has been done in Mathcad™. Please see the footnote regarding the use of Mathcad.

MUTUAL COUPLING

Mutual coupling is a factor that must be recognised and measured as it has a large influence on the correct design of phased arrays. If two resonant elements are placed in close proximity to one another, mutual coupling will exist. This has the direct effect of altering the drive point impedances of the array and must be taken into consideration when designing the feed system. Excellent in depth descriptions on this subject can be found written by Forrest Gehrke, K2BT and Roy Lewallen, W7EL. See the Bibliography [1, 2].

ANTENNA MEASUREMENTS

In order to correctly design a feed system, the feed point impedances and mutual impedances of the array need to be measured. There are numerous antenna analysers and VNA's available today at reasonable prices that will accurately measure the complex feed point impedance of antennas.

As an introduction, assume a 2-element array, first measure the impedance of each of element with the other one open circuit. This is defined as the element 'self impedance'. In an ideal world these should both be resonant (zero ohms reactance) and both have the same value of resistance; achieved by adding ground radials to one so that both have the same self impedance.

To measure the 'mutual coupling', measure one antenna with the other connected to the ground radial system. Now reverse the measurement with the other element grounded. They should of course be the same (reciprocal). Armed with these values, the 'drive point impedance' can be calculated for a given value of antenna current magnitude and phase. I have written a Mathcad™ file that can crunch these complex numbers. Alternatively, if you have the ARRL publication *Low-Band DXing* by ON4UN, it comes with some software that will do the same calculations but is DOS based.

INTRODUCTION: THE 2-ELEMENT ARRAY

By way of an introduction to the theory of phased verticals and a method used to correctly feed them, it is ideal to analyse the classic 2 element phased array as an example. It has electrically identical elements spaced at λ/4 and is fed with

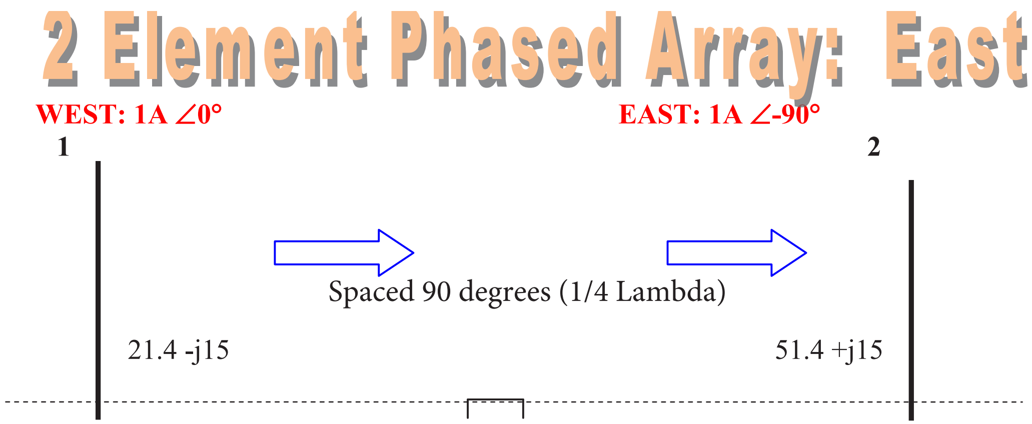

FIGURE 1: An array with antenna 2 current lagging antenna, 1 by 90 degrees.

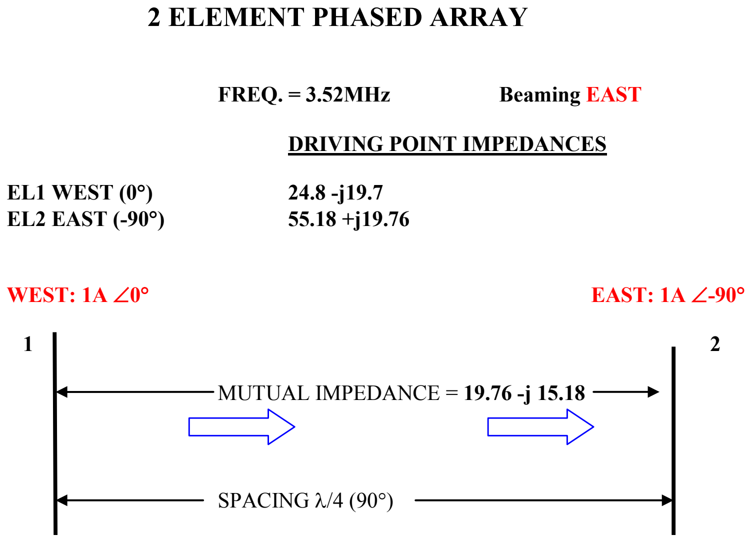

FIGURE 2: Values for 2 -element array spaced 90 degrees and fed 0 and -90 degrees.

identical currents of 1 amp, with one element phase shifted by 90°. **Figure 1** shows such an array with antenna 2 current lagging antenna, 1 by 90 degrees. Values for mutual and drive point impedances are hypothetical but realistic and are shown in **Figure 2**. Drive impedance results may seem a little surprising as they are very different from the measured self impedance of the individual antennas. This is mutual coupling at work.

All calculations for evaluating the mutual and drive point impedances are shown in a pdf file (DrivePoint_for 2 Ele Vertical.pdf/) to view, or the Mathcad file (DrivePoint_for 2 Ele Vertical.mcdx) if you want to change values to suit your own measurements. Please see footnotes regarding this application.

MUTUAL IMPEDANCE CALCULATION

One very important point regarding mutual impedance calculation concerns the sign of the calculated value. Mutual impedance calculations (Zm) requires the square root extraction of complex numbers giving two possible solutions, positive or negative. The correct sign is related to the spacing of the elements and is most simply decided by reading directly from a graph of spacing versus impedance (R±jx). This graph is clearly shown in the Mathcad files and complies with the following rules between 0 and 1 lambda.

Reactance should be negative for spacing between 0.15 and 0.7 lambda, otherwise positive.

Resistance should be positive for spacing from 0 to 0.44 ;lambda and negative from 0.44 to 0.97 lambda.

FEEDING THE WRONG WAY

The intuitive answer to feed this antenna that requires a 90° phase shift, would be to make one feeder λ/4 (90°) longer than the other to

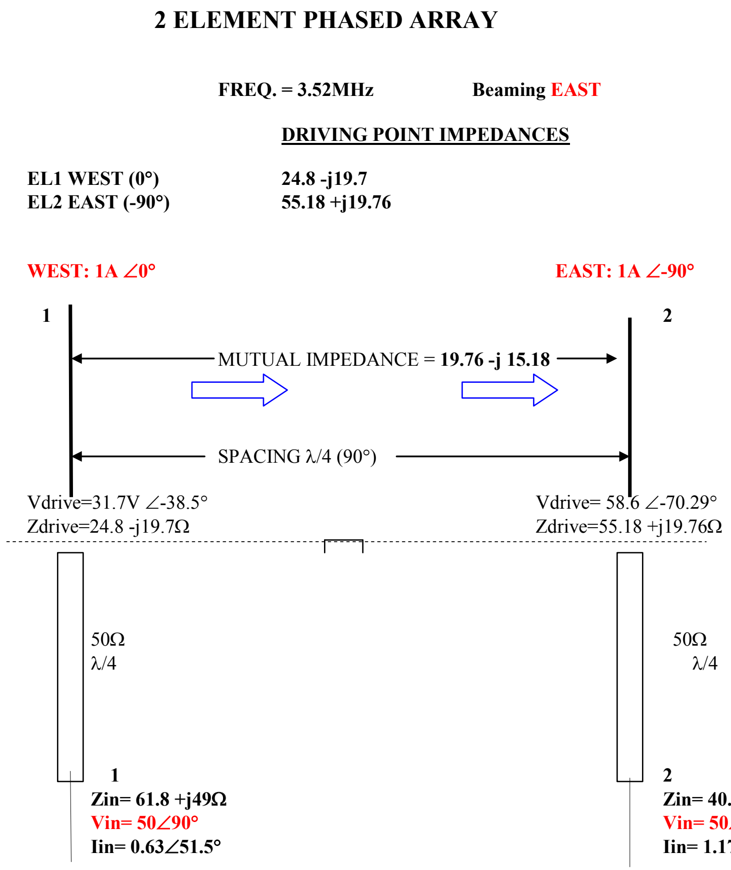

FIGURE 3: **The antenna layout with currents, voltages and impedances that have been calculated from results obtained earlier for driving point impedance and current.**

provide the required 90° phase shift. A common mistake that will not provide the expected shift. As the driving point impedance of each element will differ considerably from the characteristic impedance of the coaxial cable, standing waves will exist causing impedance, voltage, and current, to vary along the line. Unlike the case in a correctly terminated line.

We can only place the two coaxial feeder lines together if the voltage magnitude and phase are the same.

CORRECT FEEDING AND PHASING

Inspection of **Figure 3** shows the antenna layout with currents, voltages and impedances that have been calculated from results obtained earlier for driving point impedance and current. If each antenna is fed with coaxial cables having an electrical length of λ/4, we need to know the complex values for voltage and impedance that exist at the ends.

Using the Mathcad file Coax_Z_V_I_2ele.mcdx all of the voltages, currents and

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impedances along the coax lines are calculated and displayed. If you only wish to look at the workings it can be seen as a pdf file Coax_Z_V_I_2ele.pdf. Values shown in Figure 3 are taken from this. It is very interesting to note that the phase of current at each coax output, lags the voltage phase at the input by 90°. This occurs regardless of the terminating impedance and is one of the magical properties of λ/4 lines. See [2].

With the antenna drive currents shown in Figure 3, there will be 50 volts with a phase angle of 90 degrees (50V ∠90°) at the input to antenna 1 and 50 volts with a phase angle of 0 degrees (50V ∠0°) at the input to antenna 2 There is now 50V ∠90° at the input to antenna 1 and 50 volts with a phase angle of 0 degrees (50V ∠0°) at the input to antenna 2. We know from the earlier statement, that simply adding a λ/4 line will not provide the correct phasing as the complex voltages would not be the same. So, how long must the additional coaxial cable be to provide the correct voltage and 90° phase shift, to enables the feeders to be joined in parallel?

THE CORRECT PHASING LINE

Referring back to the Mathcad (or pdf) file Coax_Z_V_I_2ele we need to find a voltage match of 50V ∠90° for antenna 2 so that it can be connected in parallel with the feeder for antenna 1. Scanning down the calculated results for 'Voltage input to coaxial cable 2', it can be seen that at 158 degrees from the load, (antenna 2) the voltage is 51.16V ∠89.5°. This is a close enough match to allow the feeders to be joined together and shows that the additional length of coax to achieve this is **not** 90 degrees but 68 degrees, (158-90). **Figure 4** shows the feeder layout and values.

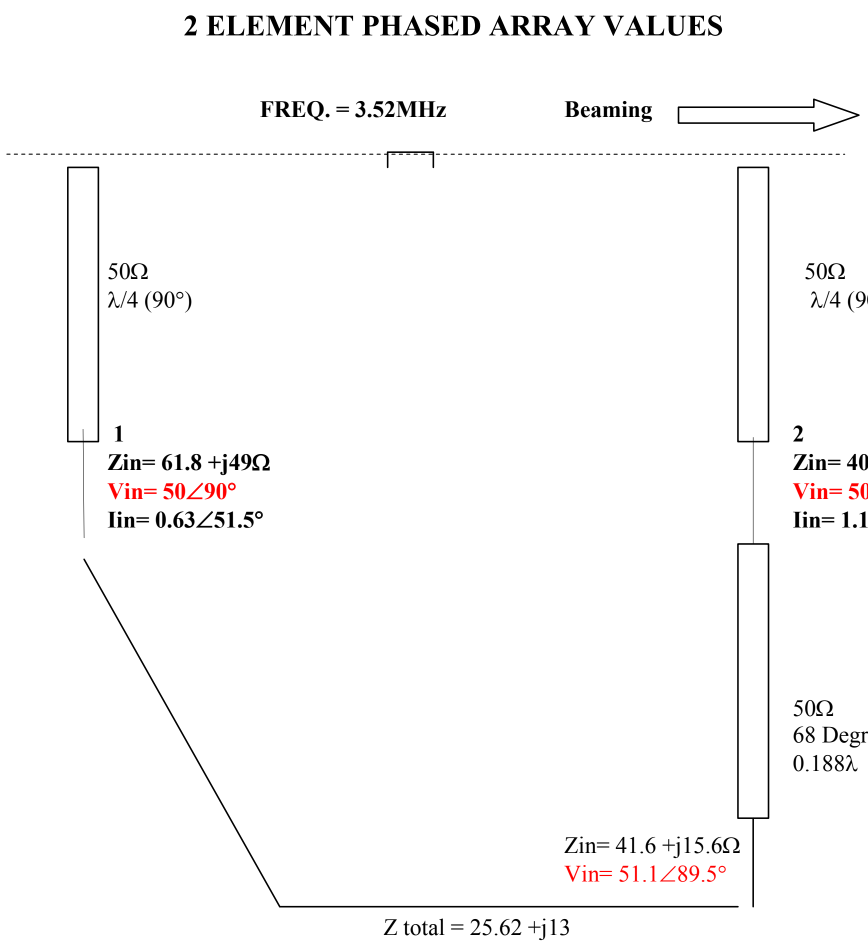

FIGURE 4: The feeder layout and values.

REVERSING AND MATCHING

The setup shown in Figure 4 depicts antenna 2 with the lagging phase and thus the direction of fire. To reverse this, all that needs to be done is to swap the 68 degree feeder across to antenna 1 feeder and apart from final matching is 'job done'. At the end of the file Coax_Z_V_I_2ele there is a simple calculation to provide the combined complex impedance of both antennas and also calculate values for a simple L-C match and a 50 ohm feed-point. The only input required is the impedance at the input to the additional 68 degree feeder. In the example 41.6 +j15.6.

Al Christman, K3LC (ex KB8I) describes this method in *Ham Radio* magazine, May 1985 using coaxial cables to provide the matching of a 2-element array. This requires the same drive point impedance information and the inspection of voltage amplitude and phase along each feeder until a suitable match is found. It is both simple to expedite and very effective.

This relative simplicity highlights the big advantage of making both antennas symmetrical, but at the same time, begs the question posed earlier in the introduction, what if we are unable to and are forced to make a compromise due to location.

A 3 ELEMENT IN LINE PHASED ARRAY

The general principles for a 2-element array have been described that works very well. If constructed for 20m the elements only require a spacing of around 5 metres. I used just such an arrangement for many years on 80m until I decided to try a 3-element in line phased array. As mentioned at the start, the elements were going to have to be wires, and they would need to be suspended in large oak trees.

A good look at my options forced me into wondering whether this was a good idea! The position of the house would restrict radials on the East antenna and the positioning of the oak trees restricted the element spacing to about 14 metres, 0.165λ. Direction was good.

The first stage was to look at what might be achieved using this spacing and what would be the most suitable phase for the drive current. The 3-element in line uses a binomial or 1-2-1 current distribution and is ideally suited to λ4 feed lines using current forcing. This method is described by Roy Lewallen, W7EL in the *ARRL Antenna Book*. It uses a feed line to the centre element that is λ/4 long and half the impedance of feeders to the outer elements forcing double the current to the centre element.

MODELING THE 3 ELEMENT ARRAY

In order to find the most suitable phasing for my compromised spacing of 0.165λ I modelled the antenna using EZNEC **[8]** over real ground. Each vertical element was resonant and λ/4 long. The end result was to use a current phase close to ±135 degrees referenced to the centre element,

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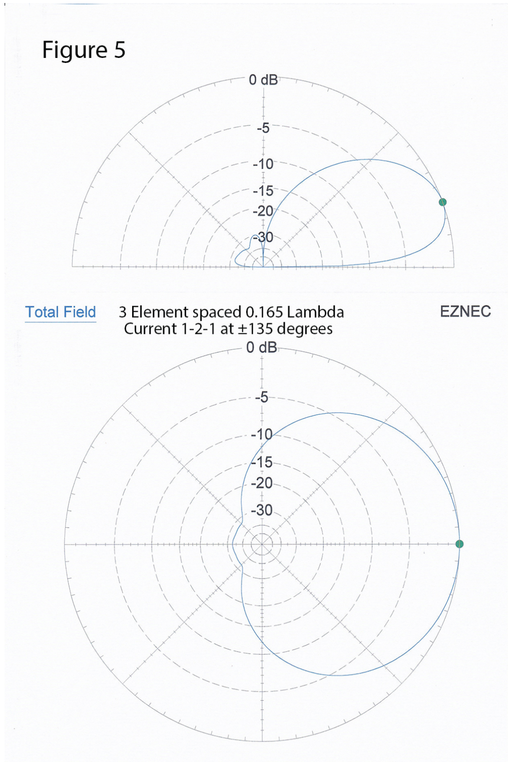

FIGURE 5: Azimuth and elevation plots using EZNEC.

with the current amplitude fixed at the required 1-2-1 ratio.

Designing for a good rear pattern is the most important and most difficult aspect of end-fire array design. Getting the perfect cardioid pattern with its deep rear notch is only possible under some circumstances but 30dB should be readily achievable with care in a compromised set-up. Forward gain, as mentioned earlier, is far more tolerant of amplitude and phase errors. This arrangement with the fixed oak tree spacing provides a good compromise in my set of circumstances. Azimuth and elevation plots using EZNEC with 1-2-1 current distribution and a phase angle of ±135 degrees referenced to the centre element are shown in **Figure 5**.

Element spacing does not have to be at a fixed 'text book' value but can be what is convenient if you do not have the luxury of choice. However, it does come with some caveats. As the element spacing is reduced the drive point impedance will decrease, element current will increase leading to higher loss, matching difficulty and reduced radiation efficiency. Where possible, it is advisable to try and keep the spacing above 0.125λ, 10.7 metres at 3.5MHz.

ELEMENT SYMMETRY

Wires for the 3-element array were 'launched' in the appropriate oak trees and as many radials as I could manage to install through the brambles and bushes were laid down. This amounted to between 20 and 30 for each vertical with a small gap in the East vertical as the house was in the way!

For those dubious regarding the effectiveness of verticals in trees, especially at LF, may I bring your attention to the piece in Forrest Gehrke's (K2BT) article **[1]** in part he states, "In commenting on vertical phased arrays, several writers have cautioned against placing arrays near trees. The apparent assumption is that trees represent resonant loss elements or somehow disturb the field so that the radiated pattern will be changed. I remain unconvinced". And so do I.

Every publication, without exception, regarding the use of phased verticals in the amateur world places element symmetry at the heart of every good design. The reasons for this are obvious, if the antenna is to be switched in more than one direction (using common phasing networks) the phasing would be wrong in directions other than for which it is designed.

Despite much effort, I was unable to reach this ideal goal of symmetry. The most recent measurements for self impedance for the 3 elements are shown in **Table 1**.

To the vertical phased array purist, these results would demand many more hours of work, planting more radials, cutting and trimming. Admittedly, these results are not as good as when I first installed the antennas but rabbits squirrels and other wildlife digging up my hard work has not helped over the past few of years. The elements are all resonant at around 3.6MHz and the values shown are for 3.515MHz which is why they all show a capacitive reactance.

TABLE 1: Measured values for self Impedance.

47.5–j7.2	Self Impedance of Antenna A [West No 1]
41.7–j25	Self Impedance of Antenna B [Centre No 2]
42.2–10.8	Self Impedance of Antenna C [East No 3]

TABLE 2: Measurement of antennas used to calculate mutual impedance.

40.4–j5.6	Impedance of Antenna 1: West, with 2: Centre, Grounded
49.9–j2.2	Impedance of Antenna 1: West, with 3: East, Grounded
36.1–j19.5	Impedance of Antenna 2: Centre, with 1: West, Grounded
32.8-j21.3	Impedance of Antenna 2: Centre, with 3: East, Grounded
45.1–j7.8	Impedance of Antenna 3: East, with 1: West, Grounded
34.2–j7.9	Impedance of Antenna 3: East, with 2: Centre, Grounded

These are the numbers that will be used to design the system at 3.515MHz. But what about the lack of symmetry?

If this array was to be used in a single direction, the phasing could be arranged such that it provides the required performance as shown in the plots of Figure 5. However, if the direction of fire was reversed the phasing would be wrong due to the lack of antenna and drive symmetry. Although more complex, my answer was to provide two phasing networks, one for firing East and another for firing West. It does require additional components and more crunching of complex numbers, but is done relatively easily with the Mathcad files provided.

DRIVE IMPEDANCE: CRUNCHING THE NUMBERS

The measurements taken to enable mutual impedance to be calculated are shown in **Table 2**.

You will observe that two measurements have been made for each pair, ie West (1) with Centre grounded and Centre with West (1) grounded. These values should, of course, be identical, but there are small measurement differences and I prefer to take both and use the average of the two measurements in the calculation for driving point impedance.

Calculations for finding the element drive point impedances, voltages and current from measured antenna data can be found in the Mathcad file East_DrivePoint3EL_135deg.mcdx and may be changed to suit personal measurements. There is also a viewable only file East_DrivePoint3EL_135deg.pdf. This configuration represents the array beaming towards antenna 3 (East), the element with lagging current phase.

The layout of the array with the associated drive voltages and impedances calculated from the file are shown in **Figure 6**. Transformation of voltage and current at the coaxial phasing lines input are considered next.

COAXIAL PHASING LINES

With λ/4 coaxial current forcing feeders in

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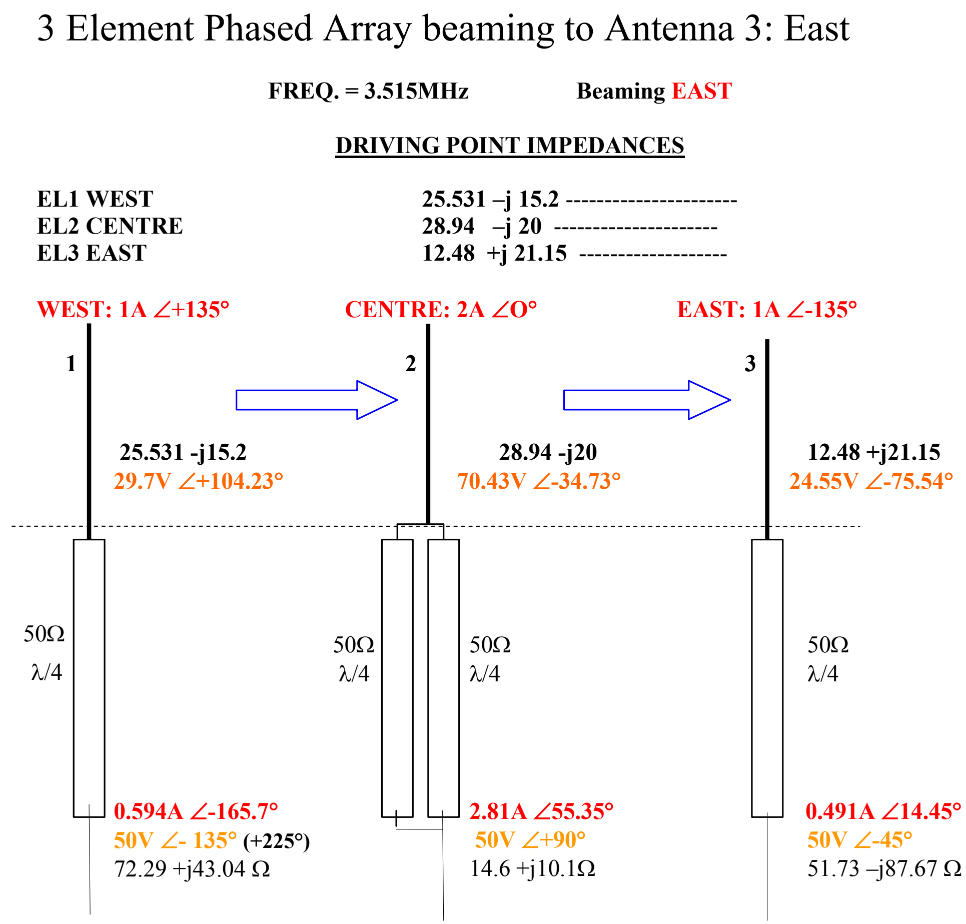

FIGURE 6: The layout of the array with the associated drive voltages and impedances.

TABLE 3: Input required to calculate V and Z along coaxial feeders.

Antenna 1 (W) beaming towards antenna 3 (E)	
Zo := 50 + j 0	ENTER: Coax characteristic Impedance
Zant := 25.531 – j 15.2	ENTER: Ant. Load (drive point Impedance)
Fr := 3.515	ENTER: Frequency in MHz
Ld := 90	ENTER: Cable Length in Degrees
Ima := 1∠135°	ENTER: Magnitude & Phase of Antenna Current
Repeat for Centre and antenna 3.	

place, the transformed values of impedance and voltage must be defined. This calculation must be repeated for each antenna feeder in the array and for both directions of fire. The file used to make these calculations is COAXZ_V_I_3ele.mcdx or the viewable only file COAXZ_V_I_3ele.pdf. In order to define the values at the feed-line inputs just enter the values already generated for drive point and feeder characteristic impedance plus the antenna current, see **Table 3** for antenna 1 (West) beaming to antenna 3 (East) and highlighted in yellow. Leave the format exactly as it is given and only change the values and sign.

The resultant complex values for voltage impedance and current, firing towards antenna 3 are shown in Figure 6.

Under normal circumstances, and with a system that possesses perfect symmetry, these results for the phasing lines would be complete. However, as a consequence of the compromises being made, this array is being treated as a separate design for each direction and so we need to calculate all values when the antenna is switched towards antenna 1, the reverse direction. The reason for this is down to the differing drive point impedance presented by the lack of symmetry. This will be done after completing the phasing networks required for the system described and shown in Figure 6.

PHASE SHIFTERS - LINE STRETCHERS

Looking at Figure 6, it can be seen that the voltage phases at the phasing line inputs are all different. In the explanation for the 2-element array it was shown that these voltages must be made the same amplitude and phase before the feeders can be connected together. The centre antenna coaxial feed point voltage of 50V ∠90° is used as the reference, and the outer antenna feeds will be phase matched to this, so only two are needed. When this criteria is satisfied, the feeders can be connected in parallel, matched, and connected to a single feed-line.

Line stretchers or constant impedance phase shift networks are an effective way to do this and calculation for these networks are more conveniently made into a purely resistive termination.

All calculations for these networks and the shunt components required to cancel the reactive part of the load impedance are done in Mathcad file: Line_stretch_Pi_T.mcdx or the read only file Line_stretch_Pi-T.pdf. As shown, the calculation is for antenna 3 beaming towards antenna 3 (East). The only user input data required, is phase in, phase out, frequency and load impedance. A choice of Tee or Pi network will then be presented along with the appropriate values and the component type to cancel the load reactance at the input to the coaxial phasing line. Additionally, values are calculated for a simple L network to match the combined array impedance to 50 ohms.

Figure 7 shows the computed data with phase shift network values for the complete 3-element array when it is beaming towards antenna 3, in this instance towards the East. This would complete the design if no directional switching were required. This may well be all that is required in some circumstances, and as detailed earlier, it could be switched with the existing networks, but would result in poor phasing due to the lack of antenna symmetry.

THE EFFECT OF PHASING ERRORS

It is interesting to look at the difference in pattern for this "compromised" arrangement if

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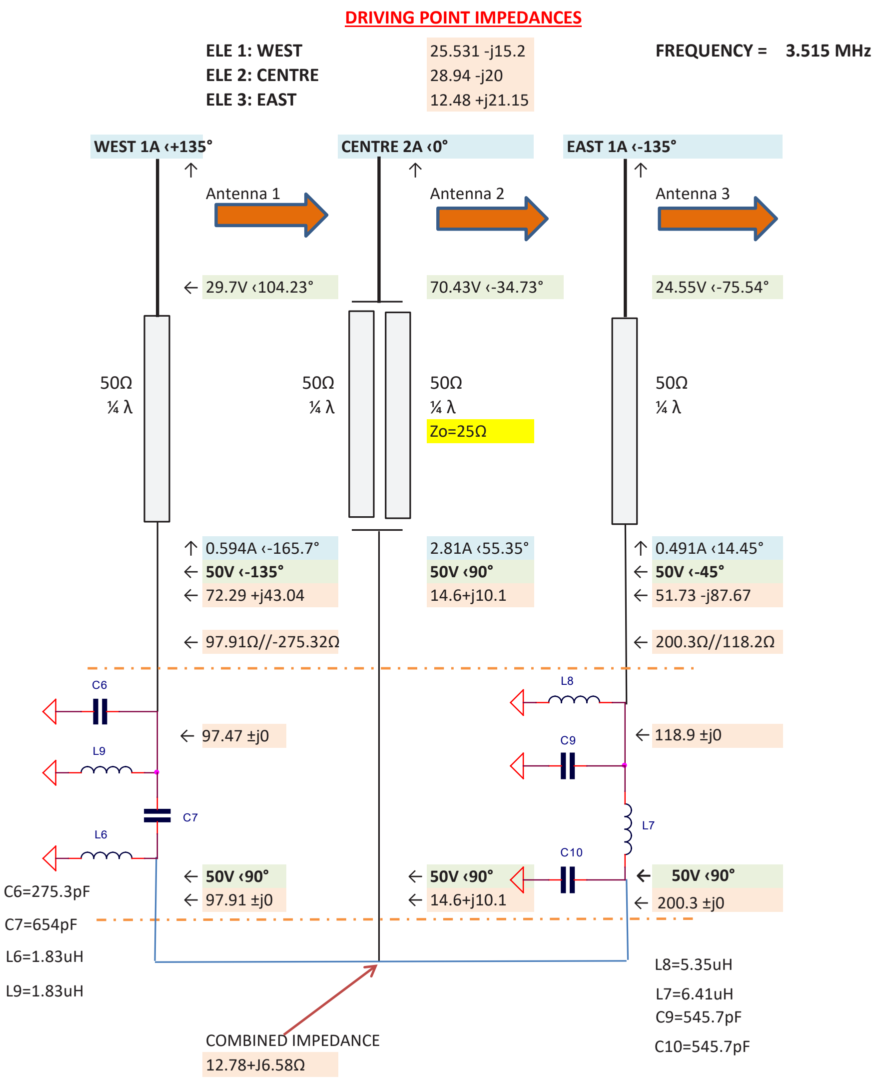

FIGURE 7: The computed data with phase shift network values for the complete 3-element array when it is beaming towards antenna 3.

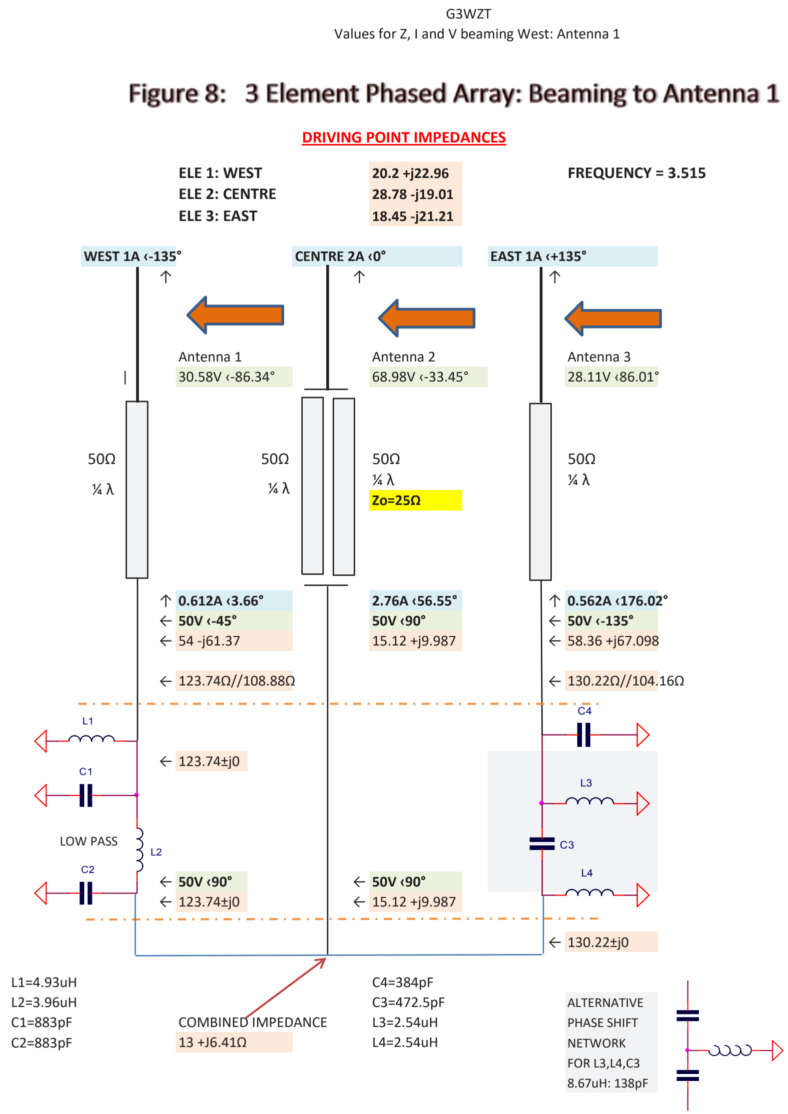

FIGURE 8: The final design beaming towards antenna 1 (West) shows the complete set of values for Z, V and I, along with phasing component values derived from the measured values in Tables 1 and 2.

the array is switched in the opposite direction using the same phasing networks designed for firing towards antenna 3. The centre (reference) element current will always be correct, 2A ∠0° as it is fed directly, with no phasing components. Simulation shows that when firing towards antenna 1 with the existing phasing networks, the current is 0.7A ∠-124° in Antenna 1, and 0.97A ∠149° in Antenna 3.

The required values, by design, are 1A ∠-135° for antenna 1 and 1A ∠135° for antenna 3. Simulating these values using EZNEC gives the

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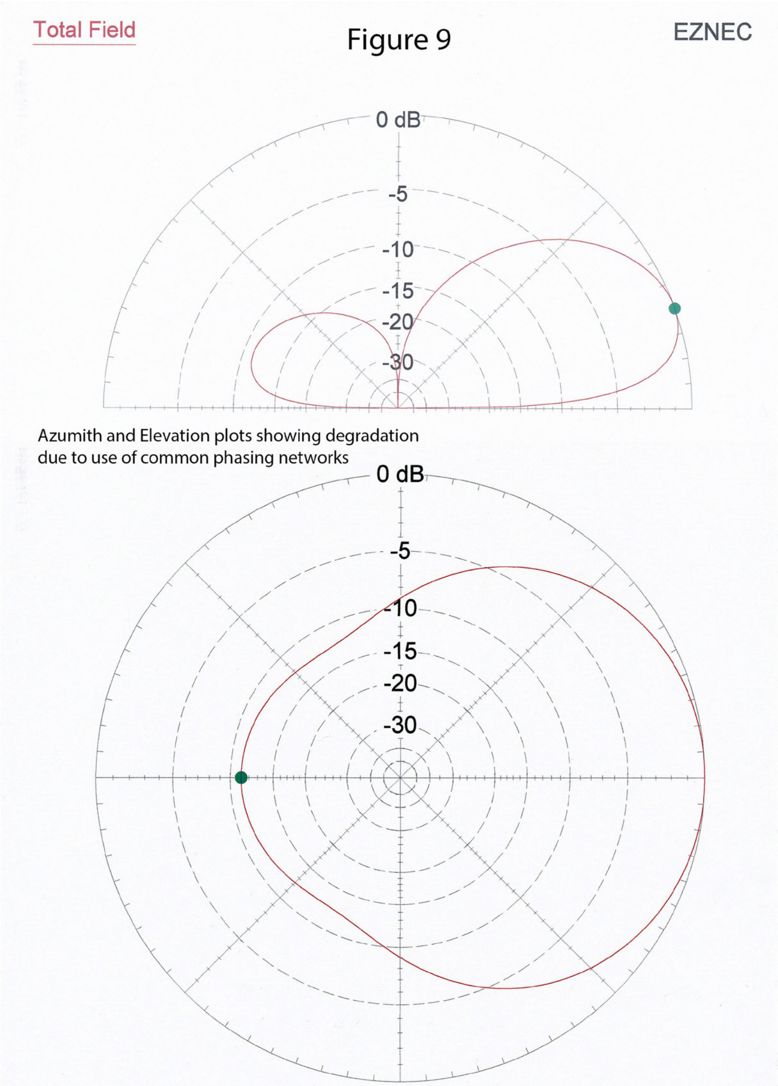


FIGURE 9: EZNEC gives this pattern when the similation is run.

pattern shown in Figure 9. It can be seen, the degradation in front to back performance is now unacceptable. It highlights exactly why every article written on phased arrays emphasises the need for symmetry of individual antennas within the array when using common phasing components.

Phasing errors will occur as the frequency is changed, even in a perfectly designed system. The λ/4 verticals alone are unlikely to cover the complete 80m band without additional matching components. This combined with the bandwidth limiting effect of phasing networks and coaxial phasing lines will give a gradual change in front to back performance. I would suggest somewhere around 5% bandwidth is to be expected. Forward gain will change very little over a much wider bandwidth but the VSWR will then start to bite. As this is a DX antenna there will be little requirement to design for the middle of the 80m band and so will be designed for 3.5 or 3.8MHz depending on the operators preference. It certainly will not cover both the 80m CW and SSB DX sectors and is in common with most antennas.

SWITCHING DIRECTION

In order to switch direction and maintain a good polar pattern, the design process just carried out beaming towards antenna 3 must be repeated for the opposite direction. This is the price that must be paid for a non symmetrical and compromised array. It is only two additional networks for the outer antennas and some additional switching and number crunching. Although it is quite straightforward to use the same file used earlier to obtain the drive point impedances and voltages, I have arranged one specifically for beaming towards antenna 1 (West in the example). This is West_DrivePoint_135deg.mcdx or the read only file West_DrivePoint_135deg.pdf. Calculations for phase shift networks are made using the same file as before.

The final design beaming towards antenna 1 (West) shows the complete set of values for Z, V and I, along with phasing component values derived from the measured values in Tables 1 and 2 are shown in Figure 8.

COMPLETED SYSTEM

For completeness, a circuit diagram is given in **Figure 10**. It shows the required switching and the phase shift networks that have been calculated in the design procedures described previously. These values will of course change with each individual

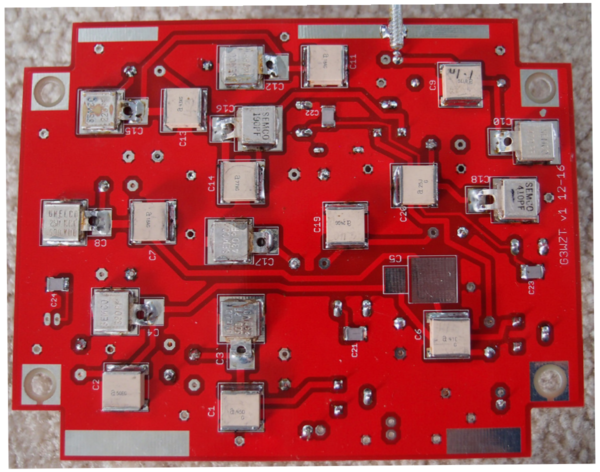
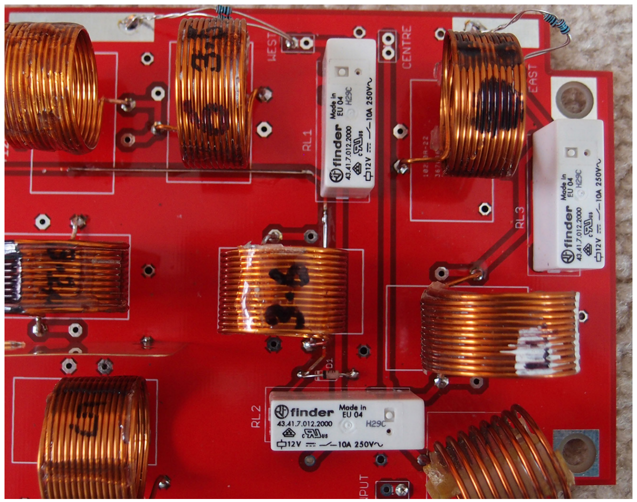


PHOTO 1:



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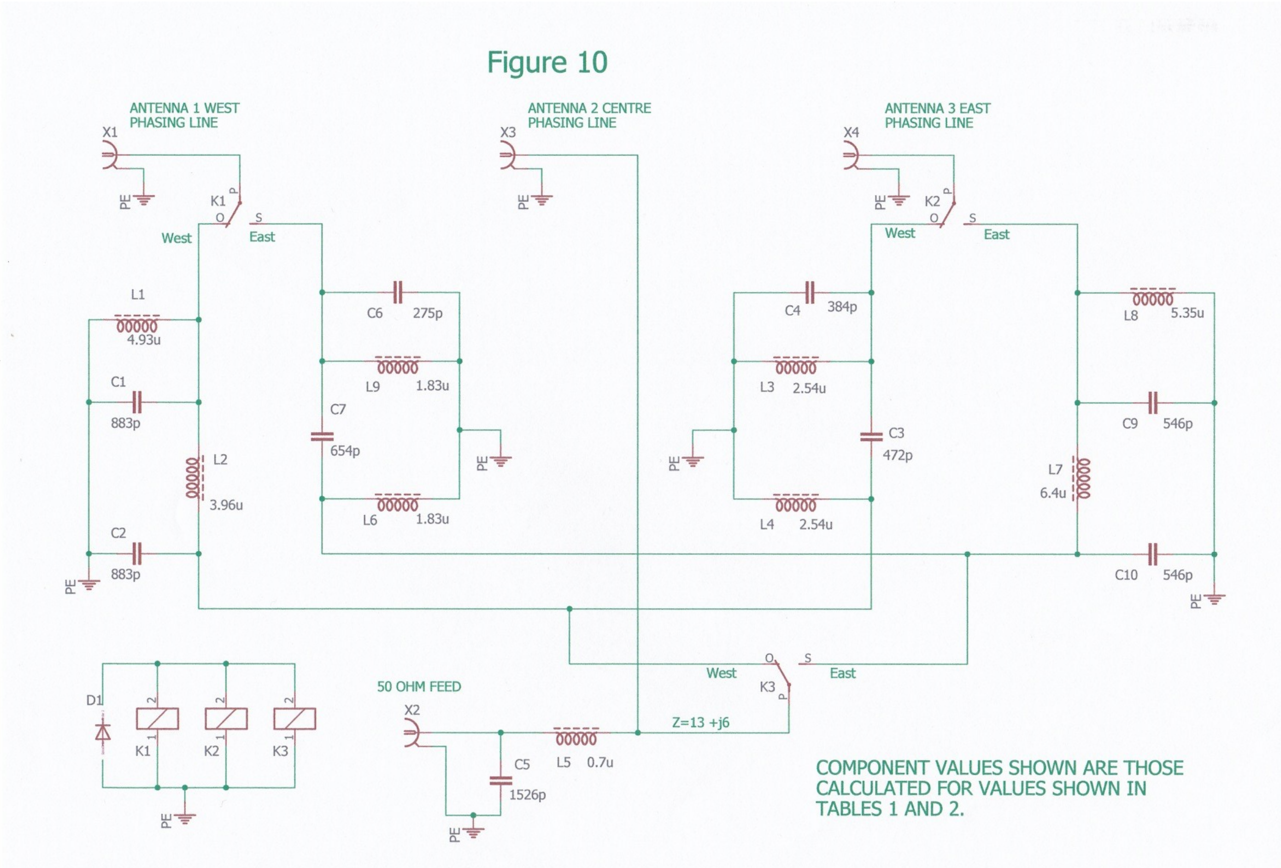

FIGURE 10: The circuit diagram shows the required switching and the phase shift networks that have been calculated in the design procedures.

design. Coaxial phasing lines are not shown as they form part of the feed network and are common, whatever the direction. I have used 50 ohm coax but 75 ohm could be used if convenient providing the centre feed has half the characteristic impedance of the outer ones. **Photos 1** and **2** show a practical implementation of the circuit from Figure 10 using hand wound inductors and a mixture of ATC ceramic and Semco mica RF capacitors.

UNEQUAL ANTENNA SPACING

So what can be done, if for some reason, spacing between the verticals cannot be made equal? This is another situation where a 'compromise' may have to be made. The array is still the 3-element in-line phased array and needs to be switched. Let's assume that the design is still for the CW end of the 80m band and the supports, natural or otherwise, are spaced at 0, 12 and 29 metres (0.14λ and 0.2λ). Design procedure is the same as before using current forcing method proposed by W7EL and a 1-2-1 current distribution.

The most effective way I have found is to simulate using EZNEC and try feeding the array with different current phases. In the case above, assuming the centre is the reference element at 2A ∠0°, 1A ∠125° and 1A ∠-105° for the outer elements provides an acceptable pattern with good rejection. The result for this feed arrangement is shown in **Figure 11**. Forward gain reduction is virtually unchanged from the original design and performance off the rear at low elevation angles is very good. At high angles (around 60°) rejection is poorer but high angle rejection can be improved by changing the outer element feeds to 1A ∠125° and 1A ∠-115°, see **Figure 12**. The trade of is slightly less low angle rejection, which may not be too much of a problem.

For most of us it's all about compromise, and making the very best of what is available. Switching to the opposite direction is simply a case of reversing the current phase of the outer elements as before, and crunching the numbers using the files provided.

COMPONENT RATING

Component RF ratings need some careful consideration if high power is used. For example, assuming a 50 ohm feed impedance, the capacitor in the matching network (C5) must be capable of 5 amps RMS with 400 watts into the array (V/XC). Items within the phasing networks are under less current stress as the power is distributed 3 ways.

The voltages calculated for each of the phasing lines shown in Figures 7 and 8 provide the voltages present, with the design value of 1 Amp into antennas 1 and 3. The value of 50V (∠90°) shown in Figure 8 will be 72V RMS at 400W RF input given the combined input impedance of 13 ohms. In this case, C2 (Figure 8) must be rated at 72V RMS (plus a safety margin) and have a current rating of 1.4 amps RMS. (XC2=51 ohms, VC2 = 72V) All based on an operating frequency of 3.52MHz.

GROUND RADIAL SYSTEM

The subject of grounds, radials and earth losses could easily fill a complete edition of *RadCom* and I have no intention of doing that! There are many well documented articles written by those with a far deeper knowledge than I have on the subject, most of which is derived from hours of practical work and careful measurement.

Poor ground systems in the near field reduce the efficiency of the system and the higher the losses due to ground resistance, the lower is the efficiency. Valuable RF power ends up heating the ground. It is important to make every effort to get as symmetrical a ground system down as space will allow. The omission of radials in one direction will degrade and distort the azimuth polar pattern. Put down as much as you can and read the excellent 7-part article written by Rudy Severns, N6LF published in *2009 QEX6* and look at his website **[7]**.

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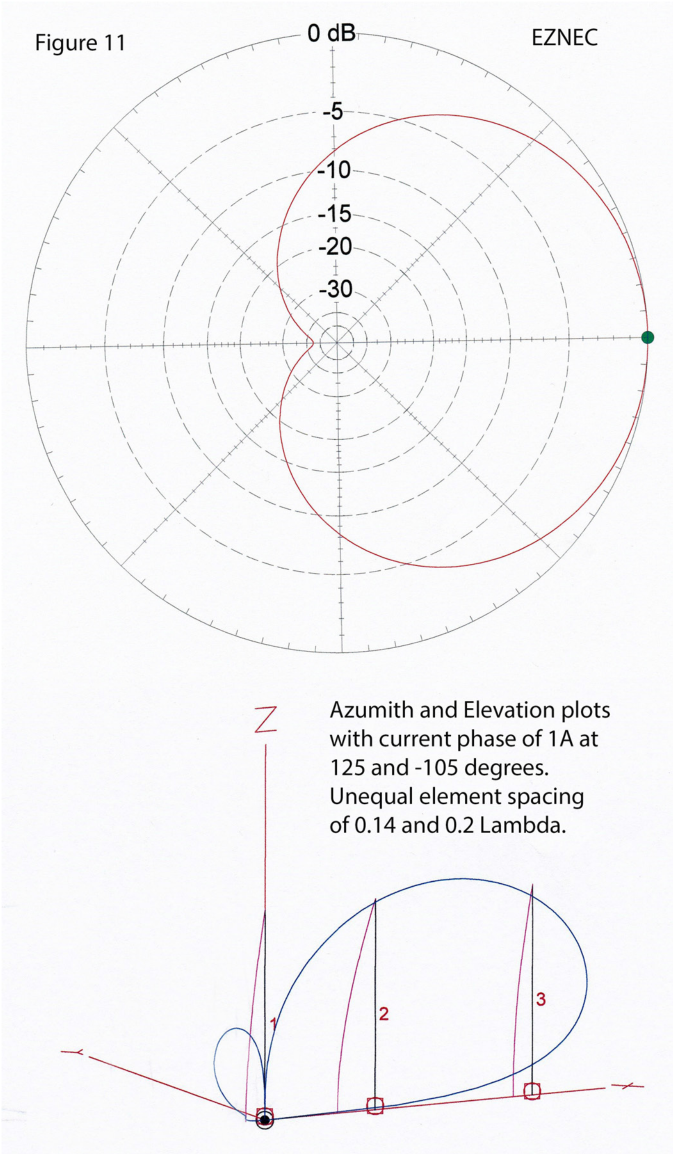

FIGURE 11:

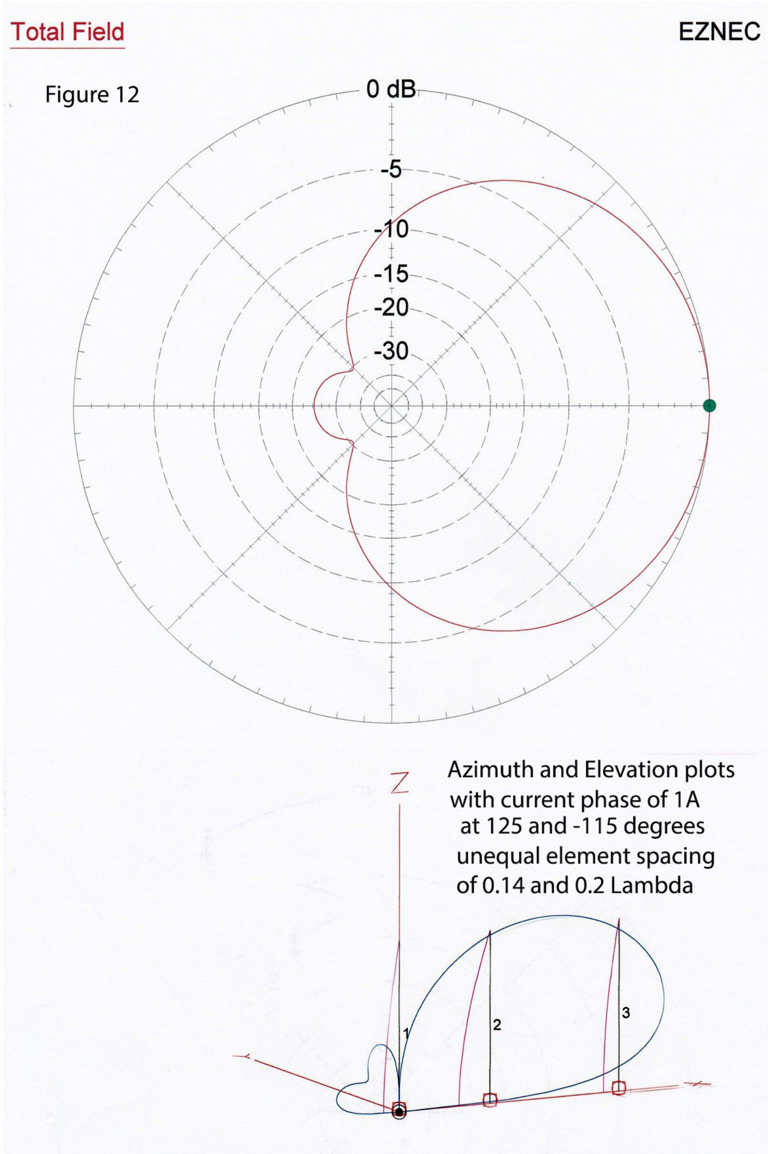

FIGURE 12

CONCLUSIONS

I have consciously written this article without filling the pages with masses of formulae and calculations. An instant turn-off for many readers, but essential when designing such an antenna and the required phasing components. All of this information is available in the files provided with this article, simply as a read only pdf file, or to calculate should you wish using PTC Mathcad Prime. There is also a mass of information referenced in the Bibliography.

The primary purpose was to construct a 3-element vertical, in line phased array and achieve acceptable azimuth performance in both switched directions with a compromised layout. In order to accomplish this it must be treated as two individual arrays. One beaming East and the other to the West, or whatever direction is required. With the arrangement described here it is only the outer pair that require line stretcher-phasing networks as the centre element is the reference element and fed directly with the 25 ohm 'current forcing' feeder.

It might seem like a lot of extra work, but realistically, when the first direction is completed sufficient knowledge will have been gained to make the second iteration much more straightforward. I appreciate that the software I have used may not suit everyone but it is what I used at the start and have continued to do so. A dedicated piece of SW on a platform available to all would perhaps be more convenient but is not something I want to take on!

My particular interest was in 80m and, owing to accessibility and size, was why compromises had to be sought. No three tower vertical array here with unlimited space available for ground radials, just insulated wires catapulted over suitable oak trees and designed to suit. For 40m operators, the space requirements are halved, along with the height, and would be easier to achieve with limited space. However I appreciate that in the UK many would find that too large, but the design process is the same for any frequency.

This arrangement has worked well for me, and the performance seems to offset the effort required to put it together. The original idea to 'chase' US counties on 80m CW and the ability to do it, has been improved greatly with this 'compromised' vertical array. 922 US counties worked on 80 CW only with just 2150 to go! It also works very well to ZL and the Pacific on long path.

The secret is to put down as many radials as possible, accept compromise if there is no alternative, make meaningful measurements and then do the design.

BIBLIOGRAPHY

There are very many fine articles written on the subject of vertical phased arrays. Listed here is a selection of what I consider as some of the best.

1: Vertical Phased Arrays: Forrest Gehrke K2BT: *Ham Radio*, May-July, October, December 1983, May 1984

2: *ARRL Antenna Book* 21st Edition, Chapter 8.10, Phased Array Techniques written by Roy Lewallen, W7EL.

3: ARRL *Low-Band DXing* 4th Edition, ON4UN. Chapter 11, Phased Arrays. With information from other respected experts on the subject. W0UN, W1MK, K9DX.

4: Feeding Phased Arrays, an alternative method. Al Christman, KB8I (K3LC). *Ham Radio* May 1985.

5: Phased Driven Arrays for the Low Bands. Al Christman, KB8I (K3LC). *Ham Radio* May 1992.

6: *ARRL QEX* March/April 2009: Experimental Determination of Ground System Performance for HF Verticals: Rudy Severns, N6LF.

7: Seaside antenna workshop. Rudy Severns, N6LF. http://antennasbyn6lf.com

8: EZNEC Antenna analysis software by Roy Lewallen, W7EL.

All files in the RadCom Plus section of the RSGB website www.rsgb.org.uk

Mathcad

I have used Mathcad files for all of the complex calculations needed to properly design vertical phased arrays based upon real practical measurements. The project was started some years ago and much of the work was done on early versions of the program. These older files were converted to the later version of PTC Mathcad Prime 3.1. For those familiar with Mathcad it might appear that some of the calculations could be done more simply. This is accepted as I have not completely re-worked all of the files. However the end results are the same.

As stated earlier, owners of the ARRL book, *Low Band DXing* by ON4UN will find software Low Band Dxing software included that also does these calculations. In my 2nd edition copy this software was in DOS and this is still the case in the 4th edition and may not run in Windows later than XP. I wanted to fully understand the processes involved, and for this reason chose to take the route that I did.

PTC Mathcad is a powerful maths tool to help with complex repetitive calculations, it can be downloaded for free after registration from www.ptc.com/engineering-math-software/mathcad/free-download with the following limitations as stated on the PTC website.

When you download PTC Mathcad Express and choose the 30-day full functionality option, you'll get access to the full version of PTC Mathcad Prime 3.1 for 30 days. At the end of 30 days, you'll then automatically have lifetime access to PTC Mathcad Express, a lighter version of PTC Mathcad 3.1.