40 Meter Phased Vertical Array at N6RO

Detailed Design Document

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A major event at N6RO is the California QSO Party where we run a multi-multi operation including simultaneous SSB and CW on some bands. This leads to some in-band interference problems and that is the main reason for this project. The primary antenna on 40 m is a 4/4 Yagi stack located toward the Western part of the property. A simple sloping dipole, oriented toward the East, was rigged off of a tower at the East end of the property (Fig. 1). While usable, the SSB station, operating on the stack, often suffered interference from the CW station on the sloper. The transceivers were all K3s, so signals are already about as clean as possible, and turning down the power was not in the cards, so instead we sought more antenna isolation. As a bonus, having another quality antenna on 40 m would provide a backup for the stack. And everyone knows you can never have too many antennas.

Three goals of this antenna design were to increase isolation through:

- Maximizing distance between antennas
- Polarization
- Pattern

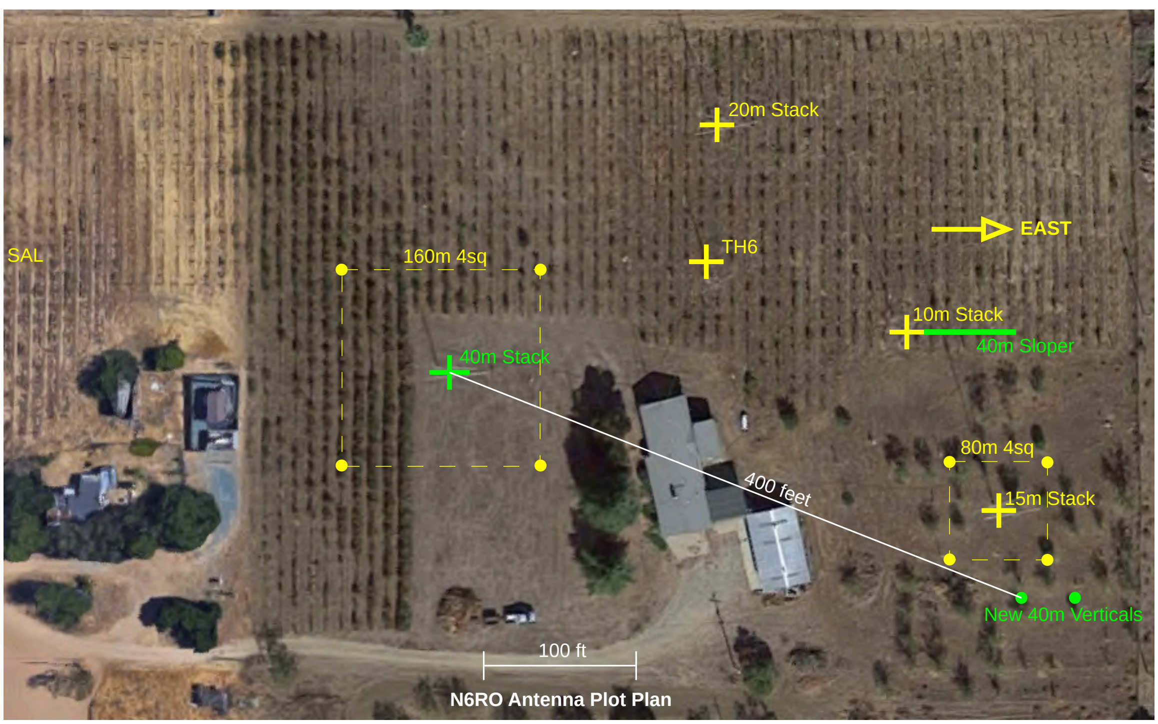


Figure 1. Plot plan, highlighting the 40 m antennas.

To keep cost and complexity low, we settled on a conventional phased array of two full-sized verticals with elevated radials. It was sited on a hilltop at the Southeast corner of the property, as far from the 40 m stack as possible. With quarter-wave separation and both elements driven with 90° phasing, a cardioid pattern is produced. When pointed East, the null is toward the stack while still providing good coverage North and South. Such an array meets all our basic requirements.

1. One Test Antenna

With the help of Lee, KI6OY, we visited the N6RO bone pile and picked out an element from an old KLM 40M-2 and put that up in the desired location with four elevated radials at 10 ft. My main concern after testing this short (23-foot) antenna was that the feedpoint impedance was very low, only about 18 ohms at resonance. This is problematic because, when placed in a phased array, the impedance will be even lower. That leads to extra ground losses, more loss in the phasing network, and narrower bandwidth. For those reasons, I switched to a full-sized element for the final design.

The test antenna did show that its isolation was superior to the sloper, so we knew we were on the right track.

2. Simulation in EZNEC

This is an easy antenna to simulate (Fig. 2). My main objectives were to optimize elevated radials positions and to try various phase angles. I also simulated the entire phasing network, using the examples supplied with *Low-Band DXing[1]*. This was a great educational exercise.

Table 1 shows some of the results when varying phase. It turned out that, around 100°, a deep null appeared exactly at the angle where the 40 m stack would appear, so I decided that anything between 90° and 100° would be acceptable. Peak takeoff angle is 20° but there is plenty of high-angle radiation for short skip contacts during CQP.

Table 1. Array Gain Versus Phase

Phase	Gain, dBi	F/B, dB	Beamwidth, deg.
80	3.1	18	181
90	3.4	30	169
100	3.7	25	158
110	3.9	17	148

Since this antenna is located near the 80 m four-square, I also ran simulations including the nearest 80 m element. There will be significant coupling to that element, so 40-80 m band isolation requires attention. Also, the pattern will be distorted to some degree (mostly you lose the deepest null off the back). Of course, there are even more conductors out there: Guys, other radials, and a nearby tower. All of these affect pattern and antenna impedance.

The most useful simulation was radial positioning. I wanted at least three radials but four was even better. I found it important to avoid overlapping radials, or having their ends very close. Also, a fully symmetrical radial layout is required to establish a symmetrical pattern. Finally, I verified that the antenna is well-balanced so the common-mode chokes will dissipate little power.

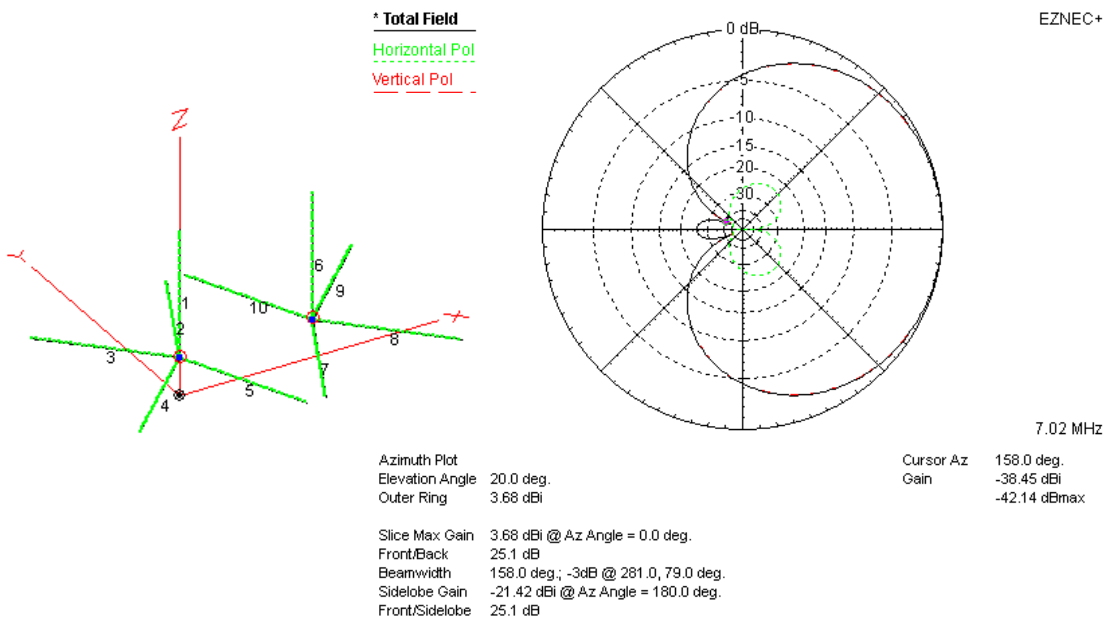
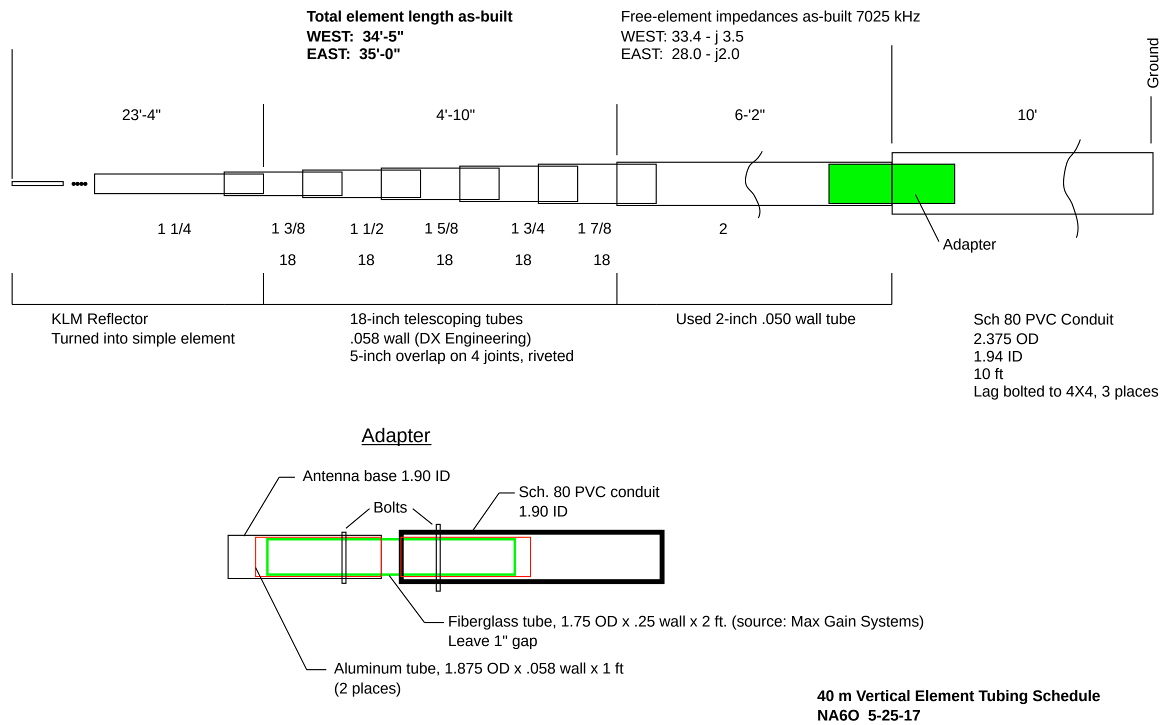


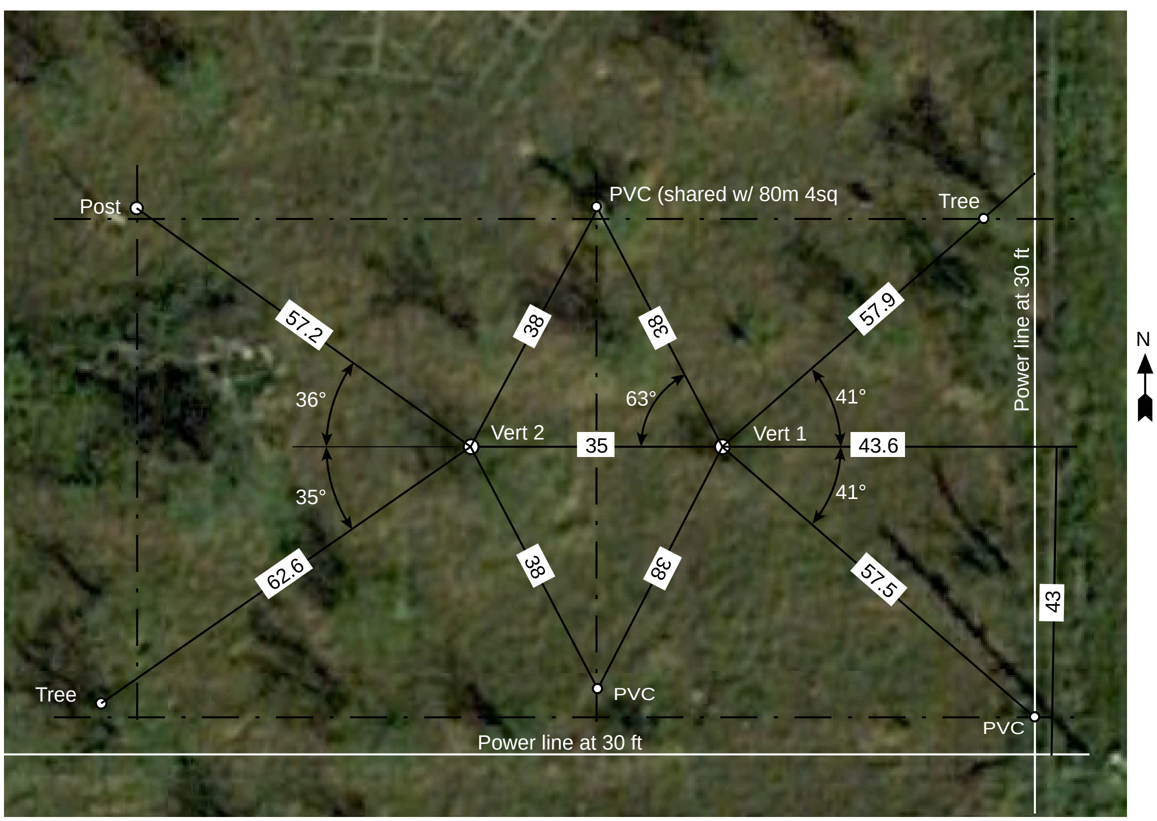
Figure 2. Simulation results for 100° phasing. A deep null occurs at 22 degrees off the back, right at the angle towards the 40 m stack.

3. Antenna Fabrication and Installation

We added about 13 ft of aluminum tubing to each old KLM element to get to full-size. Some of that came from the bone pile and the rest was nice new DX Engineering telescoping tubing. Each base was elevated on 10 ft of 2-inch schedule 80 PVC conduit and bolted to a 4x4 set in concrete. John, WB6ETY, helped me erect the antennas and tune the radials to resonance around 7045 kHz (Fig. 3). We were very careful on the site survey to make sure everything was as symmetrical as possible.



Tubing assembly for each vertical. Tip was extended at final tuning.



Verticals: East: 35'-0" West: 35'-5" on 10 ft PVC poles
Radials: 4 x 36'-8" #14 elevated 10 ft, on each antenna

N6RO 40 m Phased Vertical Pair
Plot Plan As-Built
NA6O 6-5-17

Figure 3. WB6ETY bolts the East element into place.

4. Measurements on Installed Verticals

Both were resonant around 7045 kHz when installed. Data taken 6-9-17 and used to calculate phasing components. Data in red taken 6-26-17 during final installation and adjustment. Both resonances had shifted.

Element	Vertical Length	Radial Length
East	35’-0”	36’-8”
West	35’-5”	36’-8”

Impedances at 7025 kHz
Measured with Rig Expert AA-54, corrected for cable extension.
Z11 East, with West floating: 28.0 - j 0.5 ohms (28.5 - j 7)
Z22 West, with East floating: 33.9 - j 5.6 ohms (39 - j1.8)

Z12 East, with West grounded: 31.3 + j 2.4 ohms
Z21 West, with East grounded: 37.2 + j 2.8 ohms

Calculated mutual impedance
(using W1MK spreadsheet from *Low-Band DXing* (w1mk-on4un-oh1tv-arrays.xls))
Z12 (East lagging 100°) 2.04 - j 11.25 ohms
Z21 (West lagging 100°) 0.73 - j 18.0 ohms

Calculated drive point impedance with -100° phasing, radiating Eastward
(using ArrayFeed1 tool from ARRL Antenna Handbook)
East antenna 38.72 + j 4.46 ohms
West antenna 22.47 - j 5.66 ohms
System input impedance: 23.8 + j 20.15 ohms

Calculated drive point impedance with -100° phasing, radiating Westward
(using ArrayFeed1 tool from ARRL Antenna Handbook)
East antenna 16.01 - j 3.19 ohms
West antenna 45.64 + j 4.35 ohms
System input impedance: 21.66 + j 20.2 ohms

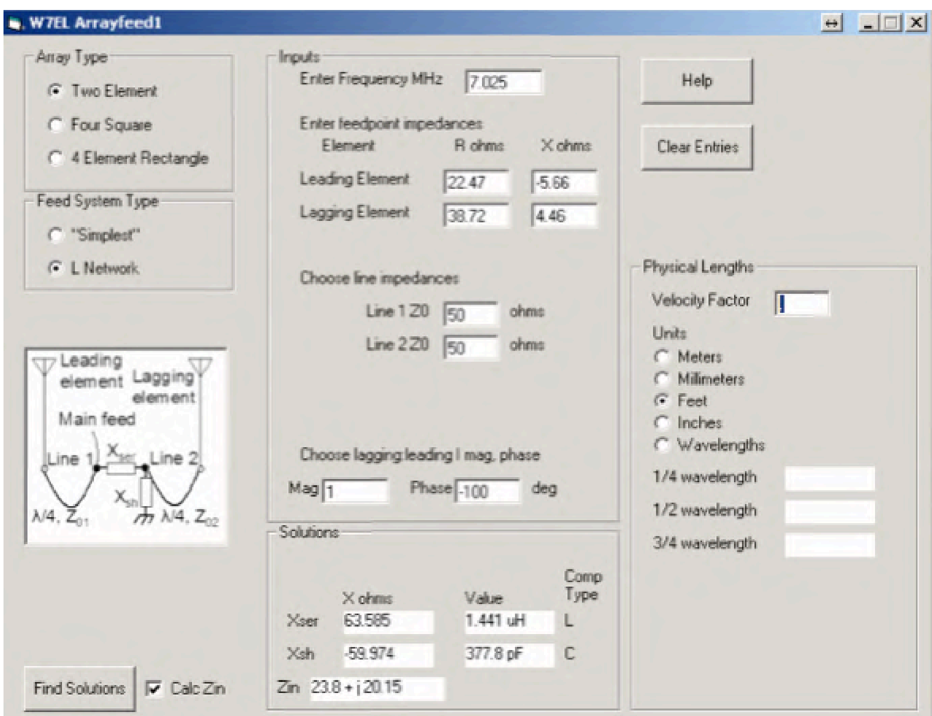
Calculated system input impedance with 0° phasing (Omni)
(using ArrayFeed1 tool from ARRL Antenna Handbook)
32.25 + j 13.49 ohms

5. Calculating Component Values

Everything I needed to know was included in *Low-Band DXing* and the *ARRL Antenna Handbook[2]*. A fundamental decision is what type of phasing network to use. The most flexible topology is based on quarter-wave current-forcing transmission lines to each antenna with an L network to generate the phase shift.

The real magic in these phased array designs is coming up with the actual drive point impedances, which are the impedances when both elements are driven with the desired phase relationship. You can't directly measure this, but you can obtain it from an EZNEC simulation, or through calculations. Required data for the calculations includes the free-element impedances (with the other element disconnected), and the coupled impedances (with the other element grounded to its radial system). After antenna installation, I used my antenna analyzer, a RigExpert AA-54, to make these measurements of complex impedance for each of the completed antennas at the design operating frequency.

I used three handy calculators to come up with the required component values. First is a spreadsheet that comes with *Low-Band DXing*, which computes the drive point impedance from the measured data. Second, I used an application from the *Antenna Handbook* called *ArrayFeed1*. It computes values for the L network that generates the 100° phase shift, and also the system input impedance. Third, I use *TLW* to come up with L networks to match the input impedance (in each mode) to 50 ohms.



***ArrayFeed1*, with actual values entered.**

6. Phasing Box Design and Assembly

Some relays are need to switch between East, West, and Omni modes. I made one compromise to simplify the switching: I used the same phase shift network for both East and West modes. This won't be perfect because the two antennas are not truly identical. But simulation showed that this is close enough. In Omni mode, the two elements are simply driven in parallel.

Inductors are all relatively small and were wound from #10 solid copper wire. For capacitors, I took the advice of VA6AM and bought Russian surplus transmitting doorknob caps on Ebay (search for K15Y). These are a *great* deal compared to anything else I could find. Voltage ratings start at about 3.5 kV, and many are rated in kVAR. Temperature coefficients are N470 or N1500, which is ok for a network like this with low sensitivity factors. Shipping from the Ukraine took about 10 days.

Figure 6 shows the system wiring diagram. Common-mode chokes are very important for this system. Without chokes at each antenna feedpoint, common-mode current would couple directly to the other element with unpredictable results. The feedline and control cable from the shack are also choked for the usual reasons.

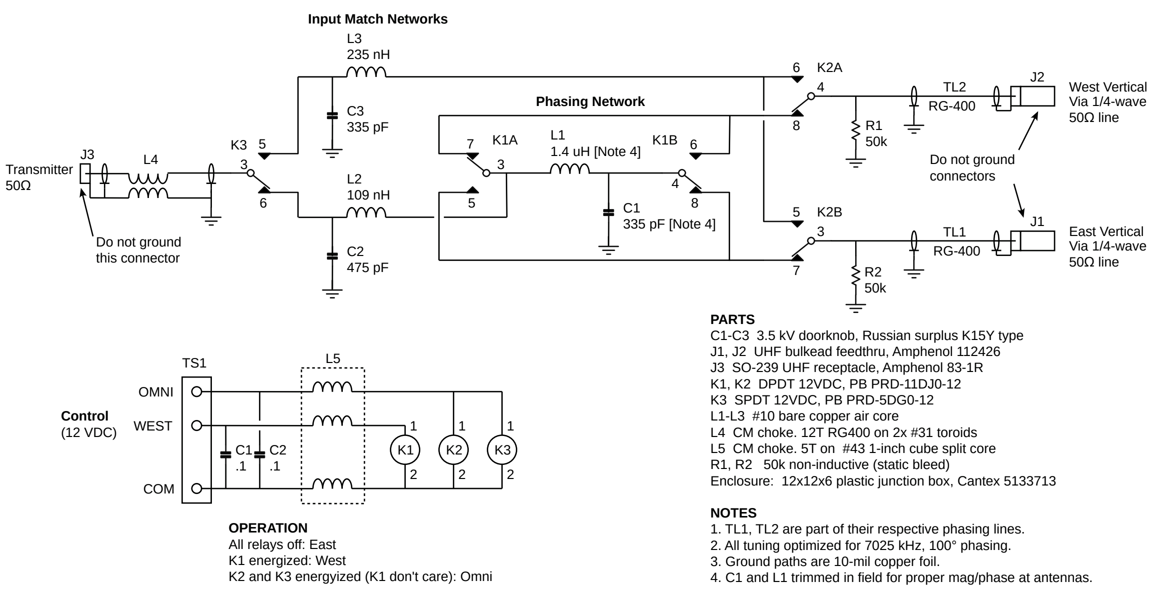


Figure 4. Phasing box schematic.

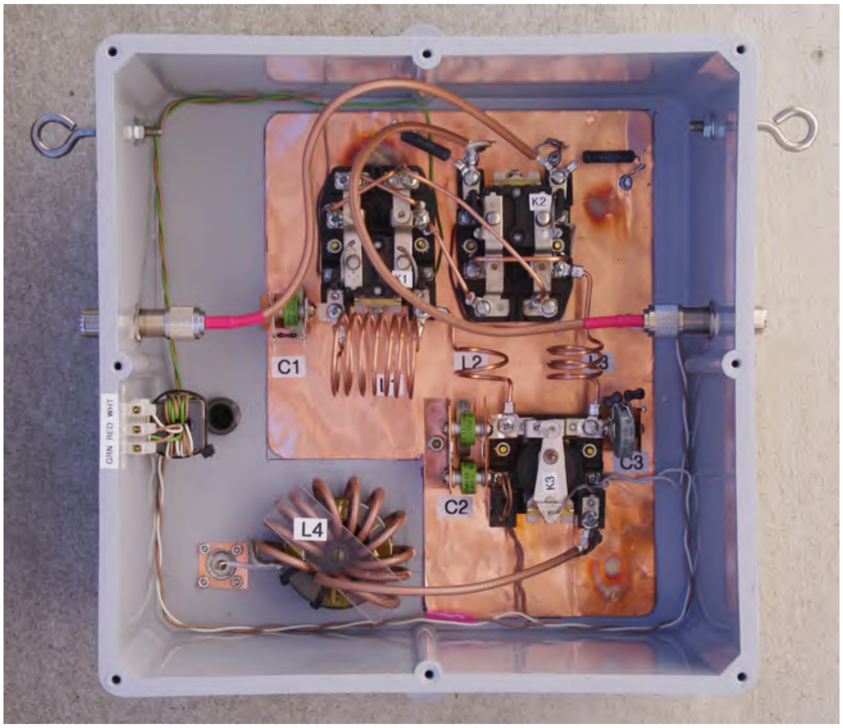


Figure 5. Phasing box internals. The ground plane is 10 mil copper.

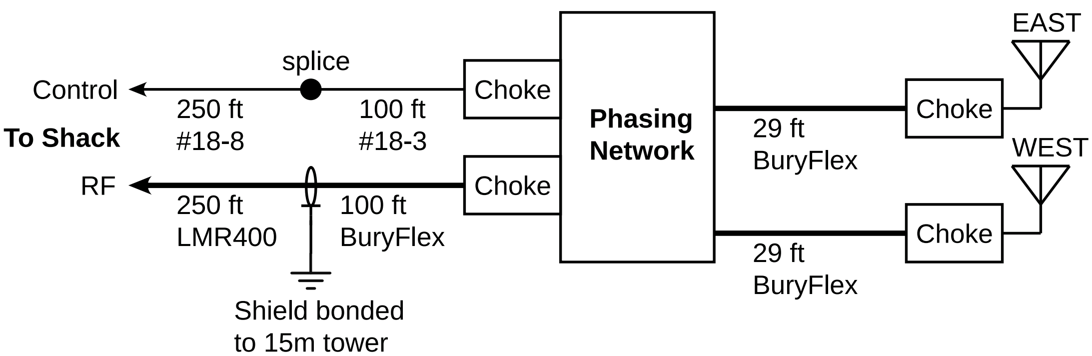


Figure 6. System wiring. Everything is well-choked.

7. LTSpice Phasing System Simulation

An LTSpice model (Fig. 7) was constructed to confirm the calculated network values and to provide estimated sensitivity factors for empirical tuning in the field. It uses calculated values as built into the phasing box. Below is a typical simulation. Currents through the loads are compared to verify magnitude and phase. Plotting the ratio of Vin/I1 provides the system input impedance.

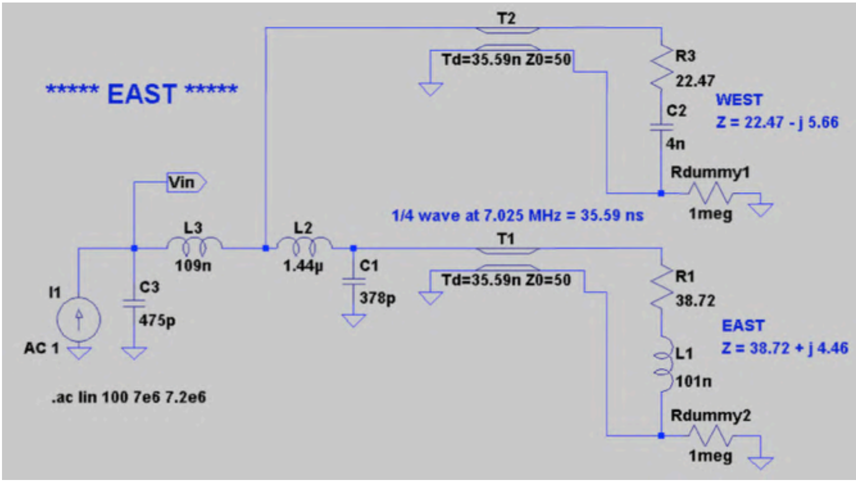


Figure 7. LTSpice model for the complete phased array.

EAST

L	C	phase	ampl ratio
1.44	378	100.0	1
1.44	400	103.4	1.01
1.44	350	95.6	.989
1.44	300	87.4	.985

C changes phase about 7.8 deg / 50 pF, 0.155 deg/pF
C changes amplitude 2% / 50 pF
Given tempco -1200 ppm/degC over 50 degC = 6%, phase change is 3.5 deg

L	C	phase	ampl ratio
1.44	378	100.0	1
1.5	378	102.3	1.05
1.4	378	98.4	.967

L changes phase about 3.8 deg / 100 nH
L changes amplitude 8.6% / 100 nH

With ideal settings, check phasing at 7.2 MHz:
104.5 deg, 1.04:1, input match 52.9 ohms -2.9 deg.

Input L Match

L	C	Ohms	phase
109n	475p	50	0
120n	475p	51	0
100n	475p	49.1	0.1

L changes magnitude about 1 ohm / 10 nH

L	C	Ohms	phase
109n	475p	50	0
109n	500p	49.9	-3.0
109n	450p	49.9	3.2
109n	400p	49.3	9.5

C changes phase about 6 deg / 50 pF

WEST
Switch to West direction. No network changes (as built).
Phasing: -98.4 deg, ratio .85 (East bigger)
input Z = 60.5 at -7.6 deg, = 60 - j8.0, SWR = 1.26

If phasing net gets proper values then phase and ratio are perfect (not implementing this).

OMNI
Input match perfect with required L network. Only a few deg variation over entire band.
Phase and amplitude perfect match.

8. Final Installation and Tuning

Everything was connected on-site and prepared for empirical tuning to optimize phase and amplitude matching in the Easterly direction. I noted that the impedance of the verticals had changed in the weeks since initial measurements were taken. So clearly some final tuning was going to be required.

For any phased array, the best tuning method is to measure RF current at the base of each element and compare the magnitude and phase. The method is described in ON4UN's book. I built and calibrated a matched pair of current transformers, and also a match pair of connecting coaxial lines. Chokes were placed on the coax to prevent any unexpected interaction with the antennas. Magnitude and phase were measured with my DG8SAQ VNWA network analyzer, used in transmission mode. Its output drives the array at the transmitter input to the network, while its input is connected to one or the other of the current transformers via a small RF switch. By toggling back and forth, you quickly get a relative reading of magnitude and phase with high precision.

Figure 8. At the antenna feedpoint, you can see the mighty K9YC-approved choke on the phasing line. Inset: A temporary current transformer is connected via a (choked) test cable.

Figure 9. The tiny VNWA is on the left. I used the old cardboard box trick to see my laptop in the sun.

Initially the measurement were noisy due to dirty relay contacts. Another problem was that the wind was blowing fairly hard and the verticals are quite flexible, so the readings moved around by 5 degrees or more at times.

Adjustments were made by temporarily adding and removing small capacitors and by manually stretching or compressing the inductors. Final capacitors were bolted or soldered in place. The only adjustments needed were to the main 100-degree phasing network and a little bit on the matching network for the Omni mode. In the end, C1 was reduced by 12% from the calculated value and L1 was changed by a small but unmeasured amount. Final Easterly phase at 7025 kHz was 97° (vs. 100 desired) and the magnitude match was within 0.3 dB. Before tuning, the phase was 86° and the magnitude match was about the same, so if I had not gone through this process the array still would have worked well.

Switching to Westerly, phase was 101° and the magnitude difference was 1.0 dB. This is quite good considering that I chose not to use a separate phasing network in this direction. In Omni mode, phase was zero as expected and magnitude difference was 0.5 dB.

The match was fine in all modes for the CW portion of the band, which was our objective. In retrospect, I could have tuned the verticals higher and achieved a better match for the entire band.

9. Testing in the Shack

Remote control switching worked fine and the match was excellent as expected; you can hardly miss when the load has a good match, and there is 350 ft. of transmission line in the field.

But here is the most interesting measurement of all. Remember that our primary goal was high isolation between the Yagi stack and this new antenna. How do you measure that? With the VNA of course. I haven't seen this reported as a standard procedure, but it sure is better than looking at an S meter. The technique is simple. Using the VNA in transmission (S21) mode, drive one antenna while measuring from another. Now you have a truly accurate full-system measurement of loss (isolation) at all frequencies.

With the Yagi stack pointed in the nominal Easterly direction one would use during CQP and the vertical array in the East mode, isolation was a pleasing 55 dB (Fig. 10). In West mode it was 41 dB, and in Omni mode it was 45 dB. Thus we have at least10 dB of pattern-related isolation from the verticals, in addition to polarization isolation. In comparison, the old sloper showed only 35 dB of isolation (a few dB of that is from the 300 ft of RG58 that feeds it!). The net improvement with the new antenna is therefore 20 dB.

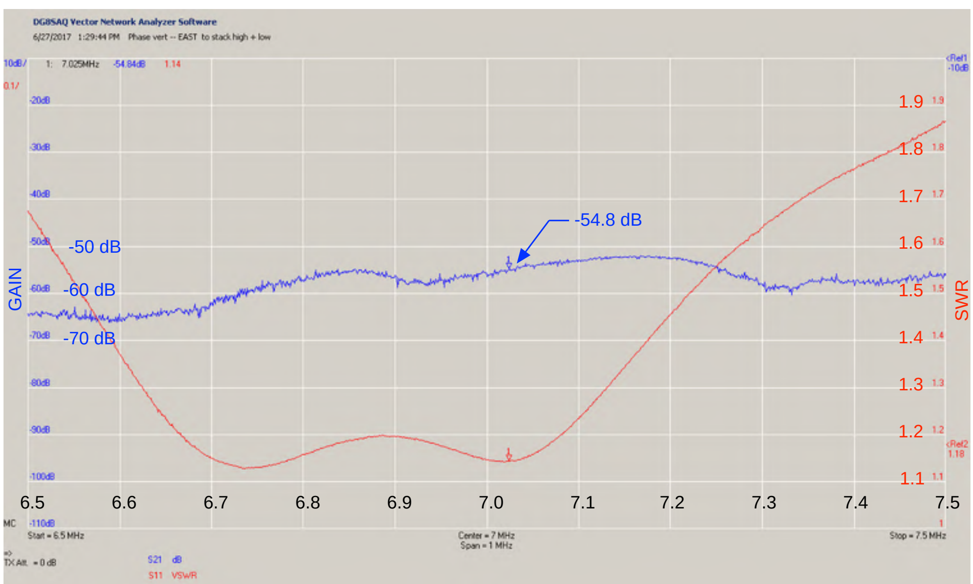


Figure 10. Isolation (gain) from the vertical array to the stack. Both antennas are pointed East. Measured in the shack.

Next, I turned to isolation with respect to the 80 m four-square. Again using the VNA to measure isolation, I found that it was 38 dB at 3.5 MHz and 34 dB at 7.0 MHz. Simulation in EZNEC predicted only 27 dB at 3.5 MHz, so I am glad it is better than that.

What does all this isolation data really mean?

For 40 m operation using the Yagi stack and vertical array, if we deliver 1 kW to one antenna, 2.5 mW (+4 dBm) will appear on the other. That would be S9+80 dB but will not damage the receiver. In comparison, using the sloper would result in 316 mW at the receiver, which worries me. No wonder there were problems in past operations.

On 80 m, quite a bit of power is exchanged between the four-square and the vertical array—nearing a Watt for the fundamentals. This demands bandpass filters to protect the receivers in both directions. We already have multiple levels of filtering at N6RO so this is taken care of. Coupling of 80 m harmonics can also be a problem. Again, our use of stubs plus high-power bandpass filters should be sufficient.

In on-the-air testing, East-West directionality is plainly audible. N6RO reports that, for domestic contacts, the vertical array is down about an S unit. Not bad for a couple of aluminum sticks! K3EST reported that it was not nearly as good toward Japan, however. Pickup of our notorious PG&E line noise is worse on the verticals, likely because they are situated with medium-voltage power lines on two sides, only 45 feet away. The *real* test will be the next CQP.

10. References

1. John Devoldere, ON4UN, **Low-Band Dxing**, 5th Ed., Chap. 11, *Phased Arrays*.
2. **ARRL Antenna Handbook**, 22nd Ed., Chap. 6, *Multielement Arrays*.