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# A Compact Dual-Band, 9 Circle Receiving Array — Part 2

Part 1 of this article in the September/October 2011 *NCJ* described a high-performance, low-band receiving antenna design for the space-challenged radio amateur. It is an array of nine short, vertical elements — I use a height of 15 feet — within a 140 foot diameter circle. Eight elements are arranged around the circle's the perimeter, with a ninth element at the center. This design provides eight switchable directions of azimuth on 160 and 80 meters. Its receiving directivity factor (RDF) on 160 meters is 12.2 dB at 20° elevation, which is within about 1 dB of some of the best-performing vertical receiving arrays. This concluding installment will describe the combiner/controller circuit and design parameters, as well as implementation and construction details of key array components.

Figure 1 offers an overall system diagram, showing the vertical elements, feed-point amplifiers, phase combiner/controller, feed-line chokes, and feed-line connections.

### Accuracy Counts!

Successful realization of an optimally performing array depends upon a circuit that combines signals from the antenna elements with very accurate phase shifts and amplitude weightings. The circuit I'll describe here meets these requirements. I used an AIM 4170 impedance analyzer and a Ten-Tec TAPR vector network analyzer (VNA) to refine the design and to tweak component values in order to minimize errors; I used precision components in critical areas. With the actual feed lines, delay line sections and high-impedance preamplifiers connected to the combiner, amplitude errors from all antenna ports to the output of the combiner — as measured by the VNA — were less than ±0.2 dB, and with phase errors no greater than ±1.0°, which represent the limits of what I could reliably measure.

### Combiner/Controller Circuit

The circuit consists of (1) the combiner, which implements beam-forming by amplitude-weighting and time-delay phasing of the various signals from the vertical elements, and (2) the controller, which carries out the direction-switching function. Figure 2 depicts my prototype of the combiner/controller circuit. The combiner works with three inline elements at a time (designated ANT 1, ANT 2, and ANT 3 ). It has four ports: ANT 1, ANT 2, ANT 3, and the receiver port, RX. The circuit (see Figure 3) coherently combines signals from the three selected antenna inputs with the correct phase shifts and amplitude weightings. The desired amplitude ratios between elements 1, 2 and 3 are 1.05:2:1.05. To beam toward ANT 1, the relative phases of ANT 1, ANT 2, and ANT 3 should be: 0°, –200° and – 40°, respectively. ANT 1 and ANT 3 are selectively connected to specific elements on the circumference of the circle as the heading of the array is switched, but ANT 2 is *always* connected to the center element.

The combiner circuit provides a 75 Ω termination impedance at all ports, which allows the use of RG-6 coax delay lines DL1 and DL2 for phasing. A high-quality coaxial line must be used, with a characteristic impedance as close to 75 Ω as possible. I used Commscope RG-6, a flooded cable designed for direct burial. Its measured velocity factor is 0.84 on 160 meters. When using other types of RG-6, the electrical lengths of DL1 and DL2 must be measured with an antenna analyzer or VNA to ensure correct phasing. Do not trust published velocity factor data.

The lengths of the feed lines between the antenna elements and the combiner/controller ANT ports *must be exactly the same*. They can be any length that is sufficient to reach. I used 80 foot feed lines, because I installed the controller/combiner at the center of the array.

The antenna ports are isolated from each other electrically by means of "magic T" transformers T2 and T3. T3 combines the signals from ANT 1 and ANT 3, and it contributes 3 dB path loss. The impedance on the RX side of T3 is 37.5 Ω (75 Ω divided by 2). The 37.5 Ω resistive pi-attenuator, composed of R2, R3, and R4, attenuates

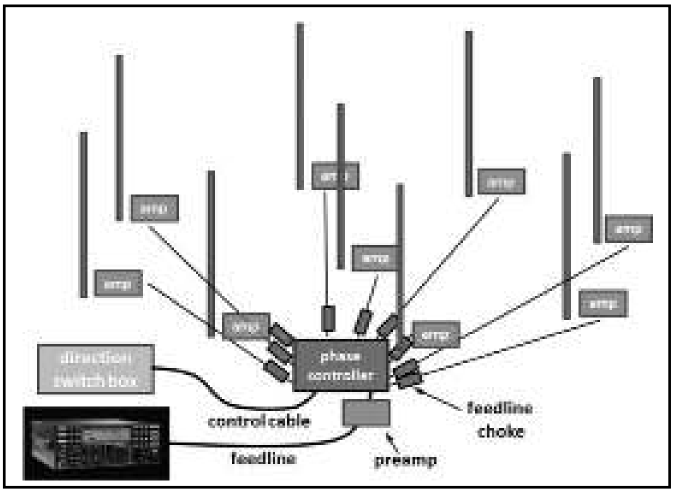


Figure 1 — Overall 9 circle system diagram

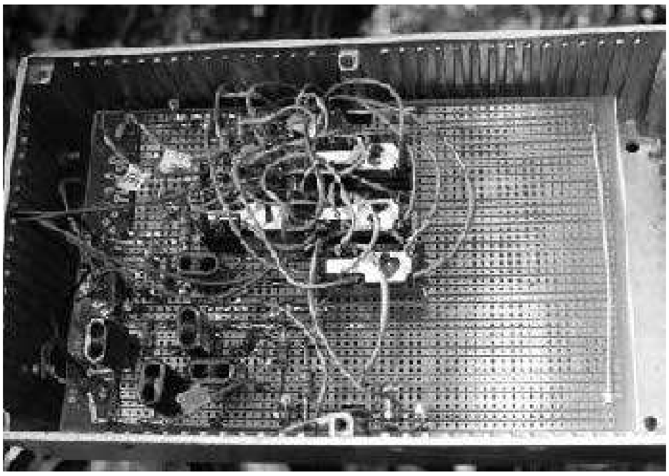
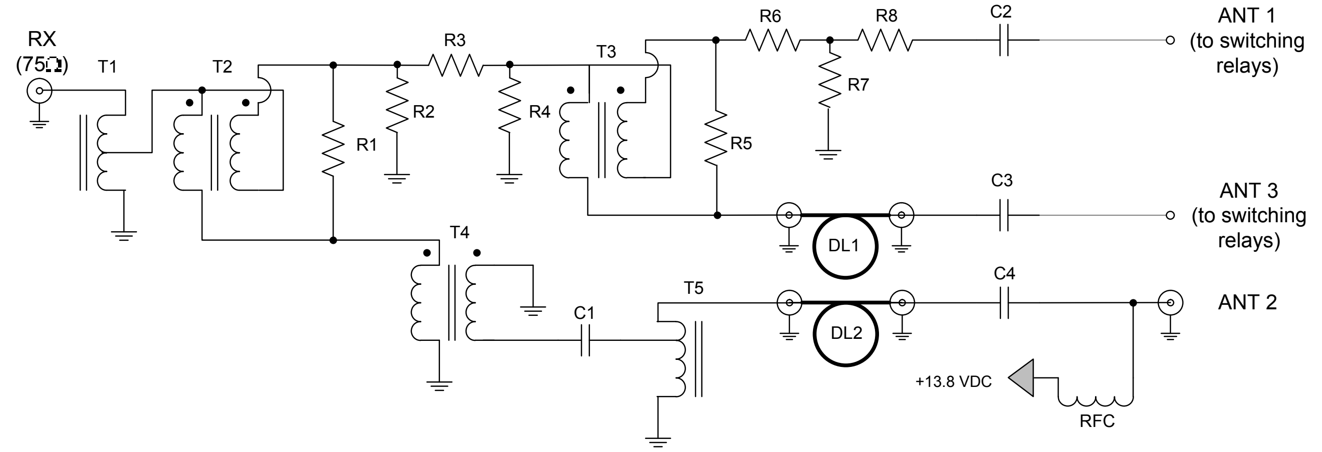


Figure 2 — Prototype combiner/controller circuit board



T1: 6 turns center-tapped
T2, T3: 7 bifilar turns
T4: 5 bifilar turns
T5: 7 turns, tap at 5 turns above ground
R1: 75 Ω
R2, R4: 240 Ω
R3: 12 Ω
R5: 150 Ω
R6, R8: 1.0 Ω
R7: 3300 Ω
C1: 0.022 μF
C2, C3, C4: 0.22 μF
RFC: 470 μH
DL1: 40 deg delay line (50' 2" Commscope RG-6)
DL2: 20 deg delay line (25' 1" Commscope RG-6)

Notes:

- All transformer cores Fair-Rite 2873000202, use #26 enamel wire
- All resistors 1/4W, 5% or 2%
- All capacitors 50V or higher
- RX port must see a 75 Ω RX load for proper termination
- ANT2 port connects to center element through 75' feedline
- DL2 can be eliminated by increasing length of feedline from ANT2 by 25'1"
- Hi-Z preamps (75 ohm output) at antenna feedpoints
- Voltage amplitude ratios: 1.05:2.0:1.05 in ANT1:ANT2:ANT3

**Figure 3 — Combiner schematic. The transformers use Fair-Rite binocular cores. See ON4UN's *Low Band DXing* (5th ed), Fig 7-93 for winding details.**

the combined signal in the ANT 1 + ANT 3 paths to establish the desired amplitude ratios between elements.

ANT 2 requires –200° phasing, which is realized by the cascade of the 180° phase-reversal transformer T4 and the 20° delay line DL2. Figure 3 shows DL2 explicitly as a delay line, but the phasing of the center element (ANT 2) is never switched in this design. Therefore, the lenghth of the feed line from the combiner/controller to ANT 2 can be longer than the feed lines to the other elements by exactly the length of DL2. In that case DL2 does not need to be added as a separate delay line. T5 is a 2:1 impedance step-down transformer in the ANT 2 path, which provides a 37.5 Ω output on the RX side for matching the 37.5 Ω impedance on the RX side of combiner T3.

T2 combines the ANT 2 signal from the RX side of T4 and the ANT 1 + ANT 3 signal from the RX side of the R2-R3-R4 attenuator. The impedance on the RX side of T2 is 18.75 Ω (37.5 Ω divided by 2), which is stepped up to 75 Ω on the RX port by the 1:4 step-up transformer T1.

The 40° delay-line DL1 (50 feet, 2 inches of Commscope RG-6) has about 0.2 dB of loss on 160 meters. This loss is equalized by the resistive T attenuator R6-R7-R8, so the ANT 1 and ANT 3 signals on the two input ports to T3 have the same amplitudes after losses.

The phase-reversal transformer T4 has a few degrees of excess phase shift, because its output looks slightly inductive (non-ideal transformer behavior). The capacitive reactance of C1 cancels this excess phase to yield an exact 180° phase shift out of T4 on 160 meters.

### Testing the Combiner

Testing of the combiner should be carried out before it's installed in the field. The first test is to confirm that the termination impedance on all four combiner ports is 75 Ω. Significant deviations (more than a few ohms) from this value indicate wiring or component errors. This test requires three 75 Ω resistors and an accurate antenna/impedance analyzer.

Connect a 75 Ω resistor to each of the three antenna ports and the analyzer to the RX port. Do *not* connect the 13.8 V dc source for this test. The RX port impedance, as measured by the analyzer, should be very close to 75 Ω resistive, with little or no reactance on both 160 and 80 meters.

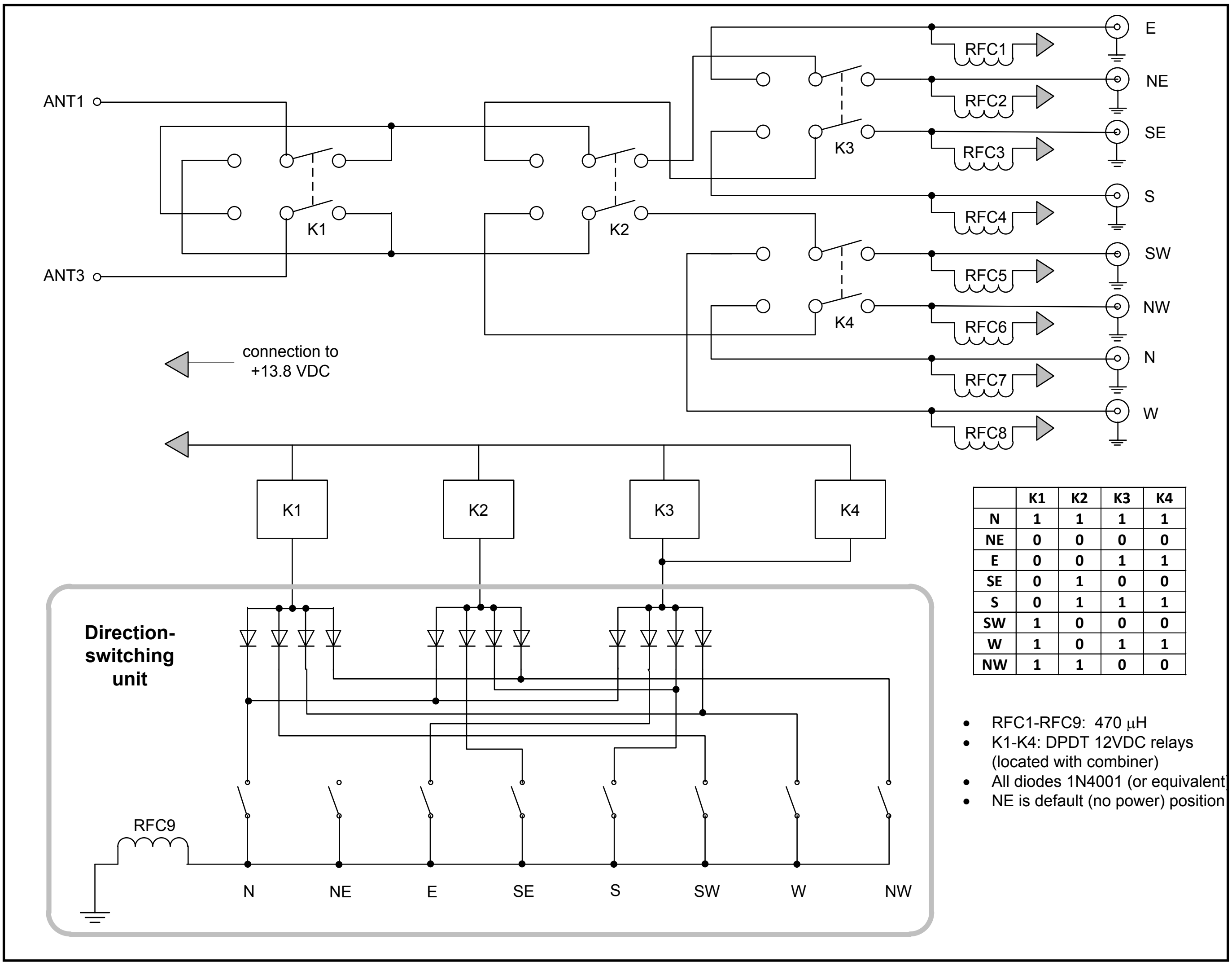
Repeat the same test with the analyzer connected to ANT 1 and a 75 Ω resistor on the RX port. The analyzer should read very close to 75 Ω. Repeat for the ANT 2 and ANT 3 ports.

### Controller Circuit

Switching for eight directions requires four DPDT relays, which are colocated with the combiner circuit. Figure 4 depicts the controller circuit; the circuit in the box represents the direction-switching control unit in the shack. Diode logic encodes eight possible switch contact closures to relay control signals on three conductors of a control cable between the combiner and the shack. The RF chokes RFC1-RFC8 feed 13.8 V dc to power the preamplifiers at each vertical through their respective feed lines. Figure 5 shows the as-built direction-switching unit in my shack.

### Antenna Feed-Point Amplifier

The array employs "active" vertical elements, with a high-impedance-input amplifier at the feed point of each vertical. I used commercial amplifiers from Hi-Z Antennas[1] (all notes appear on page 13) in the first prototype of the 9 circle array. Excellent results were obtained with the Hi-Z amplifiers, but for those who like to roll their own, here's a homebrew alternative.



| | K1 | K2 | K3 | K4 |
|---|---|---|---|---|
| N | 1 | 1 | 1 | 1 |
| NE | 0 | 0 | 0 | 0 |
| E | 0 | 0 | 1 | 1 |
| SE | 0 | 1 | 0 | 0 |
| S | 0 | 1 | 1 | 1 |
| SW | 1 | 0 | 0 | 0 |
| W | 1 | 0 | 1 | 1 |
| NW | 1 | 1 | 0 | 0 |

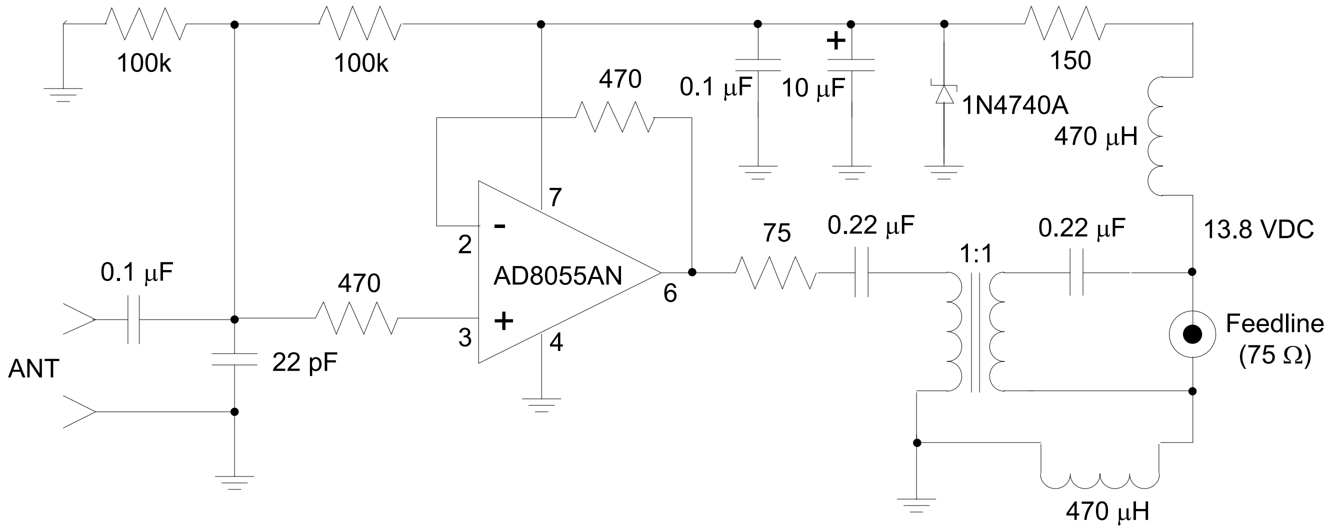
- RFC1-RFC9: 470 μH
- K1-K4: DPDT 12VDC relays (located with combiner)
- All diodes 1N4001 (or equivalent
- NE is default (no power) position

**Figure 4 — Controller schematic. The diodes in the direction-switching unit implement the truth table at the lower right above, where "1" represents relay activation.**

The homebrew amplifier employs an Analog Devices AD8055 operational amplifier[2] in the circuit shown in Figure 6. This op amp has a 300 MHz gain-bandwidth product. This may seem like overkill for use on 160 and 80 meters but is necessary to ensure high-accuracy gain and phase matching as well as high linearity in the frequency range of interest. Do not substitute other op amp parts here. The circuit shown is designed specifically around the AD8055 for stability and low noise. The amplifier is powered by a single-ended dc voltage (13.8 V nominal) that is put on the coax feed line by the controller circuit in Figure 4.

Builders are strongly encouraged to read the datasheet for the AD8055 to understand its operation. RF construction techniques, which include extremely short leads in the signal path and use of a ground plane for a low-impedance ground path, are mandatory with this device. A prototype feed-point amplifier circuit board that I constructed and

**Figure 5 — 9 circle direction-selection box in the shack.**



Notes:

- Transformer core Fair-Rite 2873000202, 5 turn primary, 5 turn secondary, use #26 enamel wire
- All resistors 1/4W, 5%
- All capacitors 50V or higher, 10%

**Figure 6 — Antenna feed-point amplifier circuit diagram**

tested is seen in Figure 7. This circuit was constructed on prototyping "perf board" that has a solid copper ground plane on its top side, and it has worked very well in my 9 circle system. The amplifier's intrinsic noise is low enough that overall system noise is dominated by ambient atmospheric noise, even during quiet daytime conditions on 160 and 80 meters.

## Standalone 3 Element Inline Array Option

Some users may want to deploy just the single 3 element inline array I described in Part 1, perhaps because of space restrictions or because they would like to have the receiving performance of a single long Beverage in a much more compact form factor. The good news is that it is a very simple matter to implement a single inline array by simplifying the direction-switching circuitry. Let's say the user wants an array that is switchable between the northeast and southwest. The combiner circuit (see Figure 3) should be built exactly as already described, and the ANT 2 port connects directly to the feed line from the center element. The simplified direction-switching circuitry for the other two elements is shown in Figure 8 and replaces the circuit of Figure 4. A single-control-line conductor switches relay K1.

## Post-Combiner Preamplification

The system's gain is very low on 160 meters, even with the amplifiers at the antenna feed points, so additional preamplification is recommended on the receiver side of the combiner circuit to make up for throughput losses in the combiner circuit as well as post-combiner feed-line loss. The antenna port of the preamplifier must present 75 Ω impedance to the RX port of the combiner in order to terminate the combiner circuit properly. If the input dif-

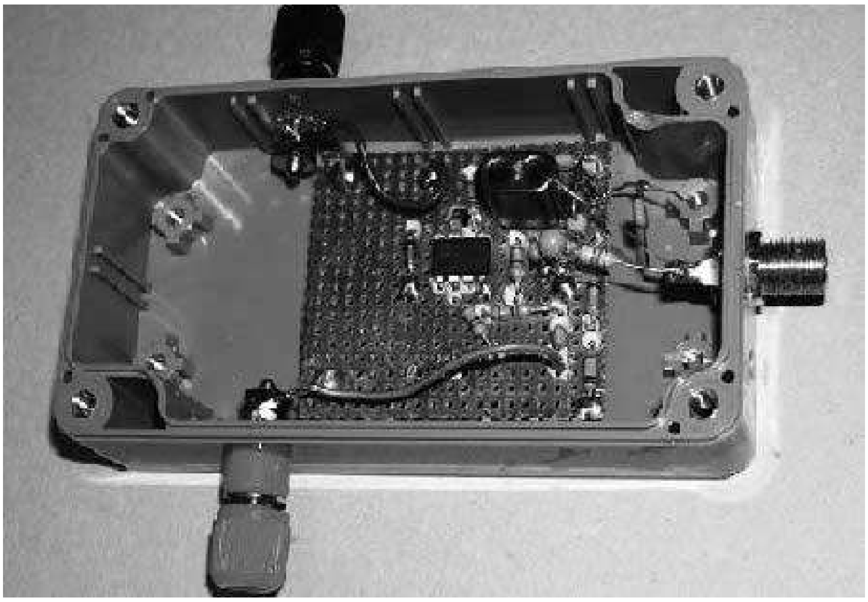


**Figure 7 — Prototype feed-point amplifier circuit board**

fers significantly from 75 Ω, the delay lines will not function optimally, and degraded array performance can be expected. If the preamplifier antenna port impedance is 50 Ω, it can be stepped up to 75 Ω by means of the broadband transformer shown in Figure 9, wound on a Fair-Rite 2873000202 binocular ferrite core. To avoid transfer of common-mode signals across the transformer, signal grounds on the primary and secondary sides should kept separate.

Note that the input impedance of receive preamplifiers typically varies with the impedance that terminates their output ports. Therefore it is also important that the output side of the preamplifier be terminated in the proper impedance. The termination specifications are device-specific.

In general, the system noise figure is optimized by installing the preamplifier as close to the combiner/controller as possible. If the feed line to the receiver is short enough (ie, has negligible loss), the preamplifier could be installed at the receiver, rather than at the combiner/controller box, for convenience.

My system uses the Hi-Z Antennas 75 Ω preamplifier, which is designed specifically for use with 75 Ω feed lines.[3] It provides a gain of about 18 dB with high dynamic range. To ensure that a 75 Ω termination impedance is presented to the RX port of the combiner circuit, I used the approach in Figure 10. In the shack, the 50 Ω–to-75 Ω transformer in Figure 9 is inserted at the receiver end of the feed line. In addition, a 6 dB 50 Ω attenuation pad (see Figure 11) is inserted between the 50 Ω side of the transformer and the receiver. The pad stabilizes the impedance looking into the receiver's antenna port at close to 50 Ω, because most receivers, including my Elecraft K3, do not present a true 50 Ω load at their antenna ports. If the preamplifier gain is large, the insertion loss of the pad will have negligible impact on the overall system noise figure.

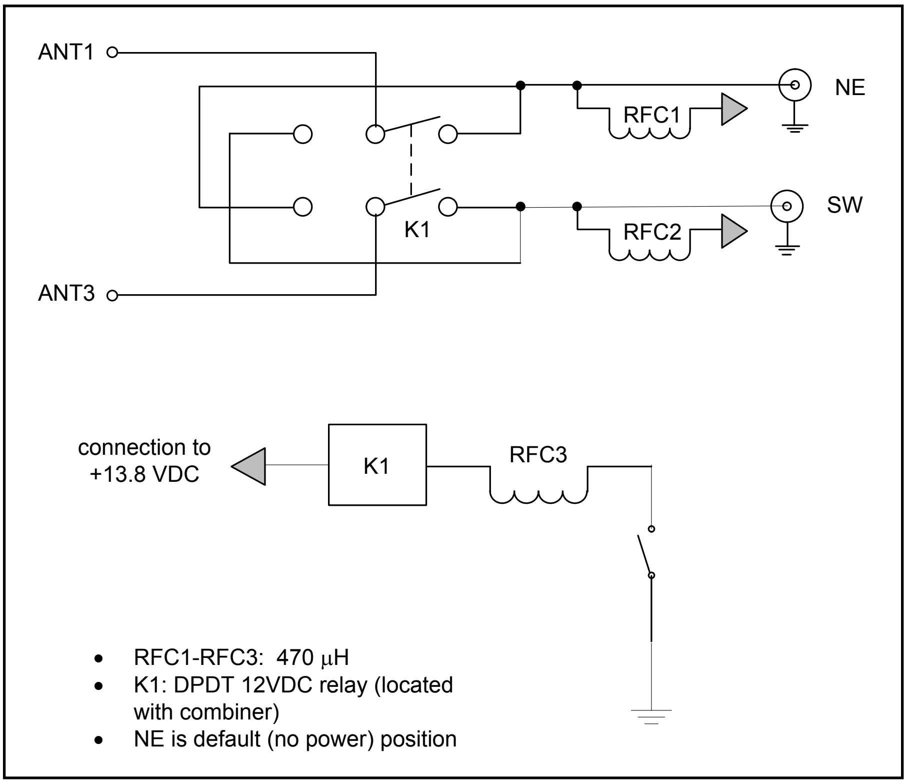


**Figure 8 — Direction-switching circuitry for single 3 element inline array**

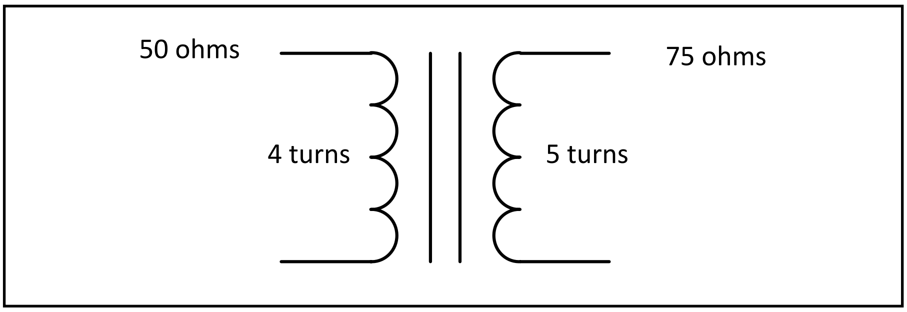


**Figure 9 — 50-to-75 Ω transformer (Fair-Rite no 2873000202 core)**

### Antenna Construction

All verticals must be constructed as identically as possible. The height is not critical, but they should all exactly the same. As noted, my system uses 15 feet with excellent results on 160 and 80 meters. Increased height does not improve RDF or any other aspect of the beam pattern, but it does yield somewhat greater signal output. For a system used only on 160 meters, heights up to 25 feet or so will work very well. Builders should adhere very closely to the spacing specifications between inline elements (70 feet element-to-element). Deviations from this spacing translate directly into phasing errors. The array is more tolerant to element placement offsets that are perpendicular to the axis of the array, and errors up to three or four feet here have negligible effect.

Construction (tubing diameters, lengths) should be exactly the same for all vertical elements. All wiring from the vertical feedpoint preamplifiers to the vertical elements and to the ground rod connections should be kept as short as possible (no more than a few inches). All verticals should use exactly the same wiring lengths in the same physical arrangement. Ideally each vertical should have the same surroundings. Figure 12 shows one of my 15 foot verticals well camouflaged in the woods.

I use a single four foot ground rod as the grounding system under each vertical. Do not use radials. Wires of significant length in the vicinity of electrically short vertical elements will induce beam-pattern distortion. It does not take much in the way of stray coupling to disrupt a nice pattern with this array.

The verticals should be installed on level ground with little or no elevation change around the circle. Clear away any foliage within five feet or so of each vertical, and trim away any tree branches that may come into contact with them. As Figure 12 shows, I installed my verticals in a heavily wooded area, spray-painting them black to turn them into "stealth" verticals. At my location the presence of the trees seems to have very little effect on array performance, so it is probably safe to conclude that nearby trees are not a concern, as long as there is at least a small amount of separation from the verticals. Do not install the verticals near large metal objects (towers, other antennas, etc), however. Apply detuning techniques to any nearby resonant transmitting antennas.

Despite its being located very close to

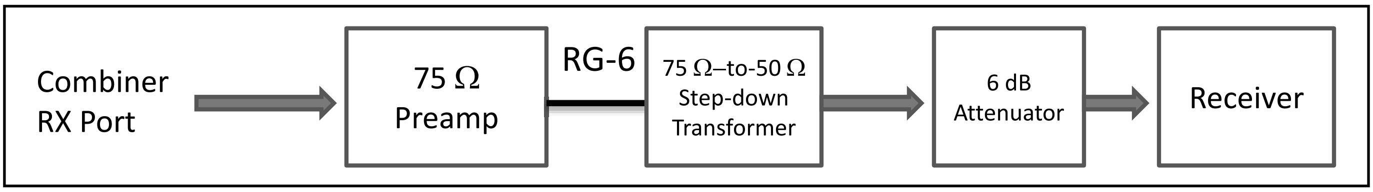


Figure 10 — Signal path from combiner to receiver

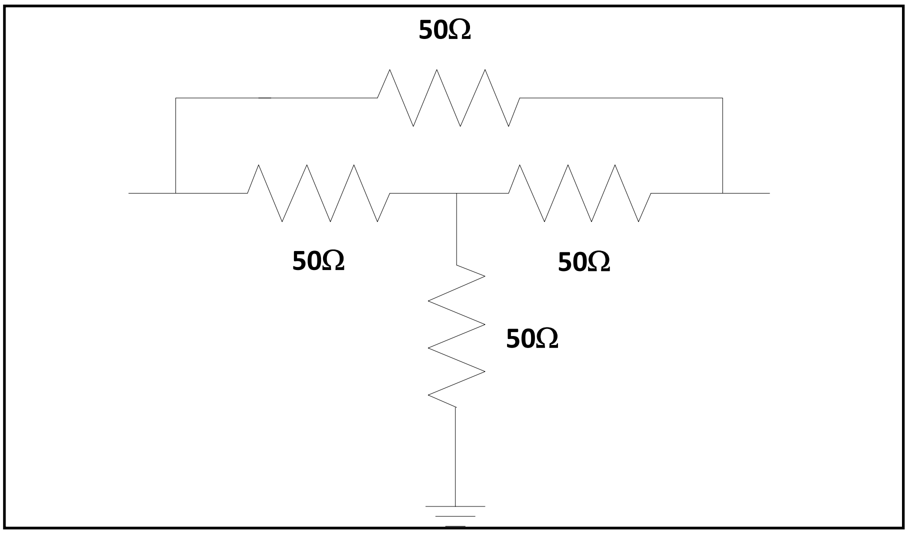


Figure 11 — 6 dB 50 Ω attenuator circuit

ground level, the system is potentially susceptible to damage from electrical surges caused by nearby lightning strikes that are conducted through control cable and/or ground connections. Consider disconnecting the system during thunderstorm season.

### Feed-Line Chokes

During initial testing of the array, it became apparent that the observed beam pattern seemed to fall significantly short of *EZNEC* predictions. After some head scratching, I discovered why, and I confirmed my suspicions through additional *EZNEC* modeling. My initial installation neglected to suppress signal pickup on the outsides of the coax feed-line shields. All feed-line shields were electrically tied to a common ground point on the chassis of the combiner/controller box in the array's center. This connection of feed-line shields created an extended ground screen inside the array circle, with strong parasitic coupling to the vertical elements themselves. The result was severe beam-pattern distortion.

I performed an *EZNEC* calculation, modeling the feed lines as wires on the ground, with a common connection point in the middle of the circle but with *no* connection to the verticals. The result (see Figure 13) was serious distortion in the form of a very large high-angle component in the elevation plane. The nice azimuth pattern I'd modeled earlier turned into the mess seen in Figure 14. No wonder the performance didn't seem to live up to expectations!

The solution to this feed line-induced distortion problem is to add feed-line chokes on every feed line at its point of entry to the combiner/controller box (assuming the box is located in the array's center). This breaks the electrical path for current flow on feed-line shields. *EZNEC* confirms that this measure is sufficient to almost completely eliminate the pattern distortions.

Figure 15 depicts the feed-line choke I used. It consists of eight turns of RG-179 miniature 75 Ω coaxial line wound through two cylindrical 31 material ferrite cores (Fair-Rite part no 2631102002) in the binocular arrangement shown. Needless to say, when constructing multiple chokes for each antenna feed line, the lengths of RG-179 should be exactly the same. Each choke has its own plastic enclosure, and the box inserts in line with the coax feed line.[4] This choke produces several thousand ohms of common-mode choking impedance on 160 and 80 meters, according to the AIM 4170 analyzer. The feed line running the short distance from the center element to the combiner/controller box does *not* need a choke, because (in my system, at least) the feed line is simply coiled on the ground. Consequently it has negligible signal pickup.

Also install a choke on the control cable, which carries power and switching signals from the shack to the combiner, at the point where the cable connects to the combiner/controller box. This choke consists of winding three turns of the cable through five snap-on ferrite cores of 31 material (Fair-Rite part no 0431176451), as seen in Figure 16. The coil diameter is five inches.

With these measures in place, the observed beam pattern cleaned up dramatically, just as *EZNEC* predicted.

### Interactions with Nearby Metal Structures

As noted, interaction with nearby metal objects is a potential concern with this array. I conducted an extensive *EZNEC* investigation of potential degradation that could occur in practice in a number of different scenarios. The results emphasize the need to install the array in an open area, where the possibility of such interactions is minimized. All calculations were performed at 1.83 MHz, but similar considerations apply on 80 meters.

A common scenario is a grounded quarter-wave vertical transmitting antenna in close proximity (see Figure 17), where the vertical is 100 feet in front of three inline elements in the direction of the main lobe of the array. Similar effects can be expected if the transmit antenna is an inverted L, or another vertically polarized antenna. The *EZNEC* model includes 32 radials on the ground, each 100 feet long, around the transmit vertical, as shown.

The azimuth pattern calculated by *EZNEC* (see Figure 18) exhibits severe distortion. Similar degradations occur if the transmit vertical is located to the side of the inline array at approximately the same separation. When the transmitting vertical is even closer, the problem is more severe.

Fortunately, the simple remedy involves breaking the ground connection at the base of the quarter-wave vertical when it is not being used for transmitting. An SPST relay at the feed point of the vertical, keyed by the transmitter, will do the job, assuming a serial feed system for the vertical. If a multi-element transmitting vertical array is used, then the base connections at all of the verticals must be broken on receive. I found it necessary to employ this tech-

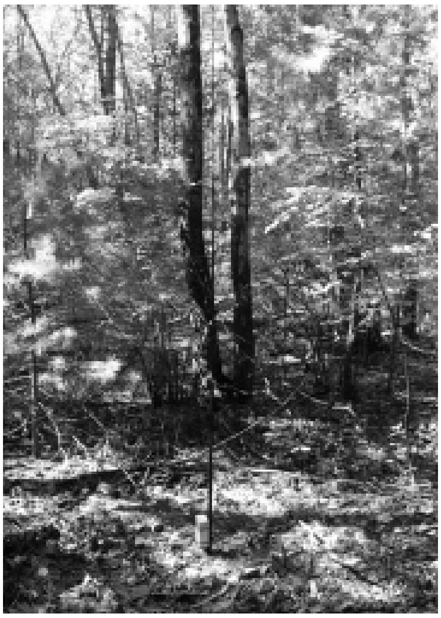


Figure 12 — Can you spot the "stealth" 15-foot vertical?

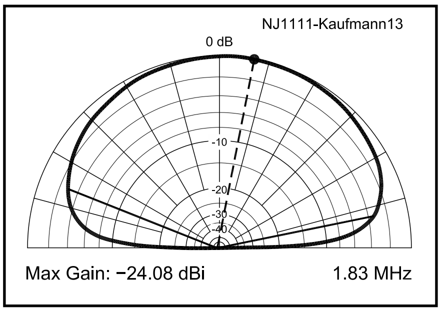


Figure 13 — Elevation pattern distortion without feed-line chokes

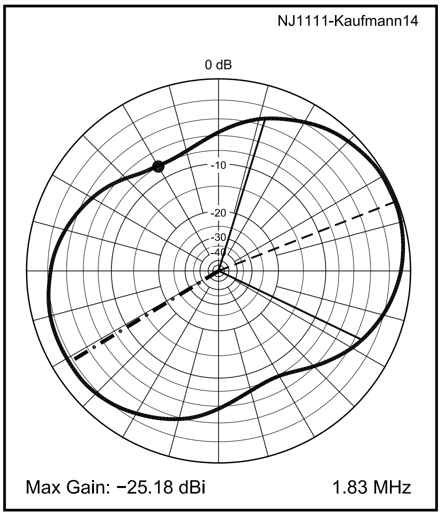


Figure 14 — Azimuth pattern distortion without feed-line chokes

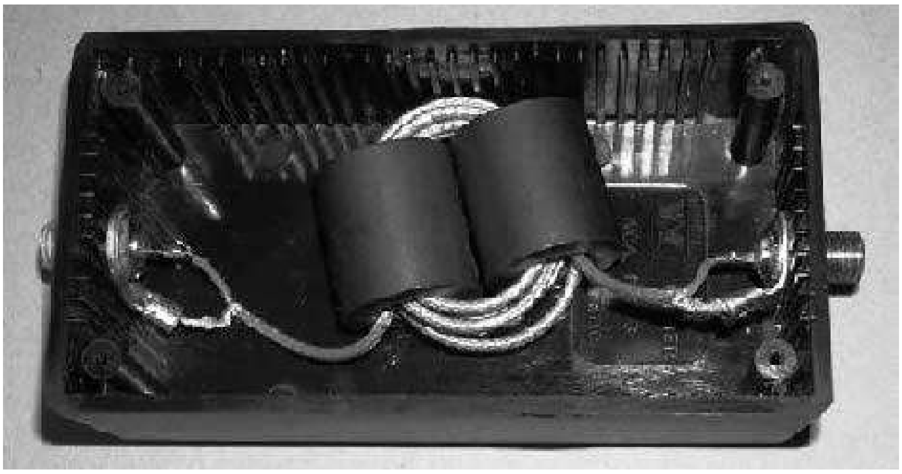


Figure 15 — Feed-line choke

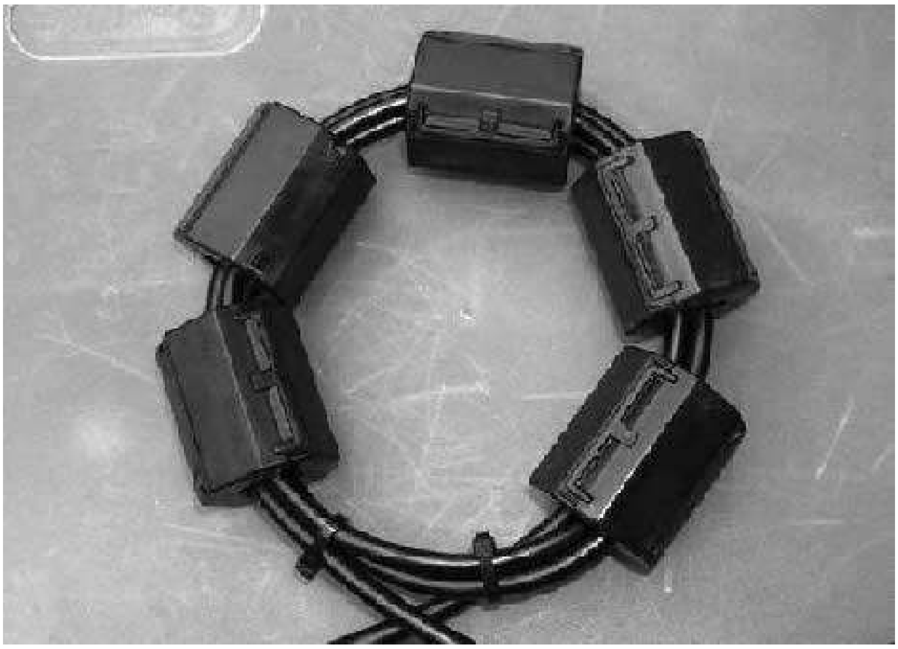


Figure 16 — Control-cable choke

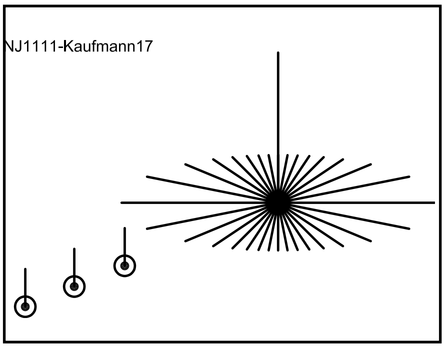


Figure 17 — 160 meter quarter-wave vertical 100 feet in front of inline array

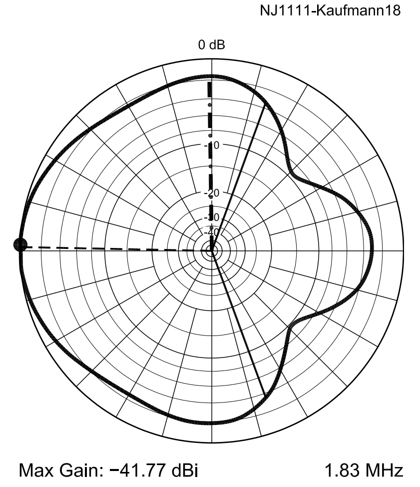


Figure 18 — Azimuth pattern with grounded quarter-wave vertical 100 feet in front of array

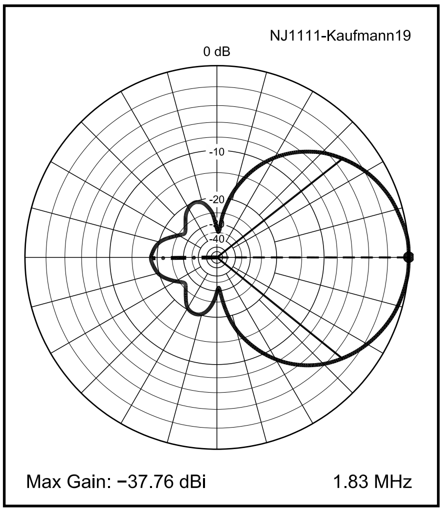


**Figure 19 — Azimuth pattern with open connection at quarter-wave vertical feed point**

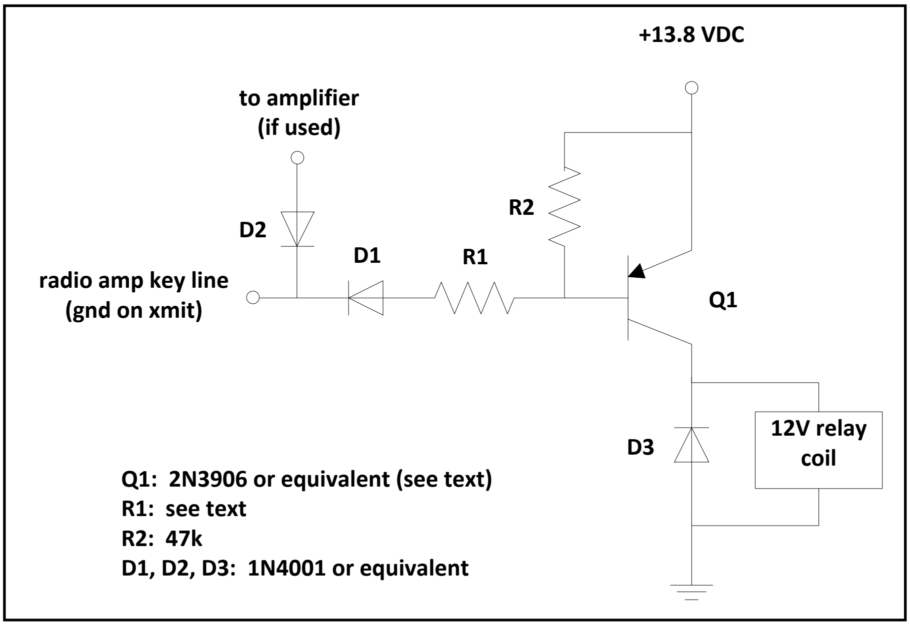


**Figure 20 — Relay keying circuit**

nique, because of the proximity of the 9 circle array to my 160 meter transmitting vertical. Breaking the transmitting antenna's connection to ground results in very noticeable improvement in array pattern (see Figure 19). If the vertical is shunt fed, then tower-detuning techniques, such as those W8JI describes on his Web site (**www.w8ji.com/detuning_towers.htm**) should be employed, with the relay used to close the connection to the detuning circuit when receiving. This measure may not fully mitigate the pattern distortion, however, if the transmitting vertical is much closer than 100 feet from the array.

I used the transistor driver circuit in Figure 20 to energize the relay when transmitting. The transistor is keyed for the radio's amplifier keying line. Grounding that line turns on the transistor and closes the relay. The circuit allows simultaneous activation of the amplifier and the relay. A generic PNP switching transistor can be used, but be sure its maximum current rating is sufficient for the current drawn by the type(s) of relay(s) used. The value of R1 will depend on the amount of current supplied to the relay(s). Start with a value of around 4.7 kΩ and, if necessary, trim R1 until the voltage between the transistor's collector and emitter drops to a few tenths of a volt when the amplifier keying line is grounded. Since I operate full-break-in CW, I employed a Gigavac GH-1 vacuum relay to follow fast keying.

Even non-resonant structures, such as towers that are not a multiple of a quarter wavelength tall, Beverages, feed lines on the ground or electric power lines are capable of interacting with the array. If possible these also should be kept at least 100 feet away. More separation is better. When these interactions are kept reasonably small, the RDF of the array suffers virtually no degradation, and the only impact is on the sidelobe and backlobe levels. RDF becomes impaired only when beam pattern distortions start to affect the forward lobe significantly.

### Real-World Results

My initial concern was whether the array would work as *EZNEC* predicted, given the relatively high sensitivity of the array to signal amplitude and phase errors — unavoidable to some degree in a real installation. My fears were unfounded. Careful adherence to strict design and construction practices resulted in a system that appears to work on 160 and 80 meters nearly as *EZNEC* predicted.

Observed front-to-back and front-to-side ratios are excellent and, as best as can be determined from on-the-air observations, seem to conform to the *EZNEC* beam-pattern calculations.[5] Signals can be made to disappear by switching directions. *EZNEC* predicted a F/B ratio of slightly greater than 20 dB on 160 meters at an elevation of 20°. In practice the ratio depends on the actual angle of arrival. At certain arrival angles, sharp notches are present, which results in F/B ratios that can greatly exceed 20 dB. This has been observed under certain conditions on some medium-range signals, such as from my Eastern Massachusetts location to VE1 or to W3. High-angle signals from stations at close range typically exhibit reduced F/B and F/S ratios, but this is because the forward-lobe response falls off sharply at higher angles in relation to the back and side lobes.

The array is working so well that I decommissioned the 500 foot Beverages I'd used for years. I hope that maintaining the 9 circle array will prove much less of a headache than did the Beverage antennas, whose wires frequently broke under falling branches and trees.

### Acknowledgments

The basic op amp circuit in Figure 6 for the antenna feed-point amplifiers was suggested by N1AL. I also gratefully acknowledge technical discussions with K7TJR, who generously provided a number of design tips and suggestions. Comments from multiple reviewers, especially W2RU and W4ZV, helped to improve this manuscript.

After writing this article, I learned that K4IQJ, working independently, came up with an almost identical design for an inline array of three K9AY loops, which I would like to acknowledge. Details are at **www.kkn.net/dayton2011/K4IQJ_Dayton_Update.pdf**.

### NOTES

[1] See **www.hizantennas.com/hiz_amplifiers.htm**.

[2] See **www.analog.com/static/imported-files/data_sheets/AD8055_8056.pdf**. The "AN" version of the AD8055 specified in the Figure 14 circuit, has an 8 pin dual-inline package. Other AD8055 package options are available.

[3] See **www.hizantennas.com/preamp.htm**.

[4] All feed-line chokes could be installed in a single, common enclosure at the combiner/controller box. If this is done, the feed-line coax shields must ***not*** electrically interconnect (eg, on a common metal chassis ground plane). For this reason, any common choke enclosure should be of non-conductive material, such as plastic. Maintain physical separation of at least a few inches between chokes to prevent unwanted stray coupling from reducing the electrical isolation between feed lines.

[5] The Elecraft P3 Panadapter, which is calibrated to display signal strengths in dBm, was used extensively to measure signal levels as the array was switched.