Getting the Most from Half-Wave Sloper Arrays

So you want to put up a really big 160-meter directional array? Here are some tips.

By Rudy Severns, N6LF

For those who have a single tall support, λ/4 or higher, the half-wave sloper family of antennas described by K1WA,[1] K8UR,[2] K3LR[3,4] and others can be a relatively simple way to make an antenna with modest gain, good F/B and an electrically steerable pattern on 80 or 160 meters. Previous articles have provided much information on this family of antennas. But having just come through a cycle of building several variations, I found that a lot more needed to be said. Fig 1A shows two different half-wave sloper array element shapes that I will refer to as the "K1WA" and the "K8UR," with the understanding that many other arrays use these shapes. Fig 1B shows some other possible element shapes.

This article presents a 160-meter variation of this family of antennas and, more importantly, a discussion of the details of how to get such a beast working really well. You could simply put up four precut dipoles, with 3/8-λ phasing lines *à la* K1WA and the array will work with reasonable F/B. However, with extensive modeling I discovered that fanatical attention to detail and tuning and adding a first-class ground system will greatly enhance performance.

In the summer of 2000, I put up a pair of 150-foot wooden poles placed east-west along a ridge. I called George, W2VJN, who had been using half-wave slopers for years and asked for his advice. That began a long series of conversations and experiments. George supplied many key insights while I was doing field testing and modeling work. I very quickly learned how difficult it is to actually obtain the performance predicted from modeling in a real 160-meter antenna. The configuration reported here is a bit different from earlier versions but is simpler to build and, more importantly, easier to get up and running at full performance.

Initial Experiments

You can use several slopers spaced uniformly around the support to produce a steerable pattern. These can be simple λ/2 slopers (K1WA) or diamond-shaped (K8UR), with the lower ends brought back to the base of the support. The slopers may be driven as a phased array (K8UR) or as a parasitic array (K1WA and K3LR). It is very common to drive and/or load the center of each element.

There is another possibility, however. You can use voltage feed at the lower ends of the elements. This approach, while certainly known, has not gotten much press. It has some advantages when K8UR-shaped elements are used.

My experiments began with a 2-element version of the K3LR antenna, where the length of the feed line from the center of an element to a switch box is adjusted to tune one element as a reflector while the other element is driven. The non-driven element is open-circuited at the switch box. This allowed me to switch the direction of the main lobe from east to west with a SPDT relay, selecting one or the other feed line. I quickly discovered how much the

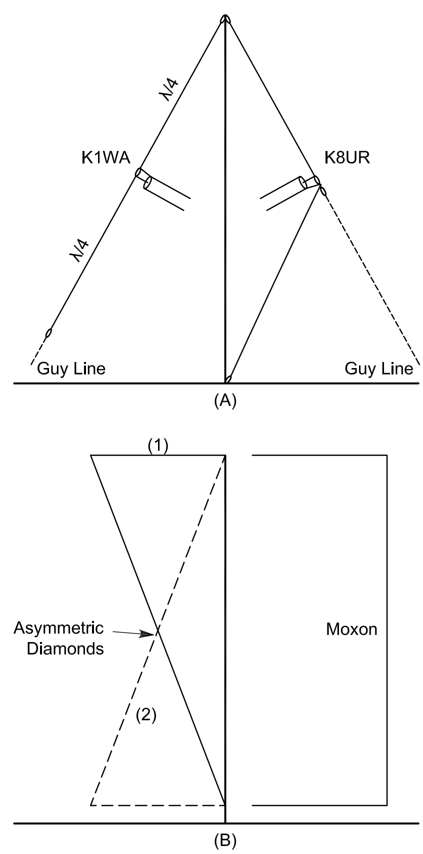

Fig 1—Half-wave sloper array element shapes.

[1]Notes to appear on page 80.

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shape of the actual array differs from the nice straight-line wires we use in modeling.

First, there is the sag in the 130-foot wire spans on each side of the feed point where the guy lines used to spread the array are attached (see Fig 1A). I found I had to move the guy-line anchor point much farther away from the support to get enough tension to control sag. This was made worse by the weight of the roughly 114 feet of RG-8X feed line going back to the support.

Testing showed that the F/B was not very high—a few decibels at most—and the feed-point impedances were substantially different from predicted, making for a poor match. Further checking with a clip-on RF ammeter showed lots of current on the feed lines.

I then modeled the antenna with the actual sags in the elements and feed line I use Nittany Scientific's *GNEC*, which implements the *NEC*-4 catenary wire (CW) and insulating sheath (IS) cards. Guess what? Lots of RF on the feed lines, lousy F/B and mediocre gain were indicated. I put common-mode chokes baluns at the feed points (more weight, more sag, more loss) and that helped, but only a bit. The extra weight also increased the tension in the wire and guy line to the point where wire stretch and subsequent detuning became a problem.

I also found that if I wanted to actually tune the elements so that they behaved as a parasitic array, I had to make measurements at ground level—at the end of about 200 feet of coax. I had to calibrate the coax and then transform the measurements by the transmission-line equation to get the actual feed-point impedance.

Then I had to lower the array and trim each end of the elements. This was doable but what a pain! It was clear from the modeling and measurements that the actual shape of the elements and whether or not insulated wire was used had a significant effect on the behavior of the array.

I groused about all this to George as we drove up to the Northwest DX convention last June (2001) and he said "Why not use voltage feed instead?" The light went on. I wanted a parasitic array in the K8UR configuration, but voltage-fed at the bottom of the driven element. The other elements would be open, acting as reflectors. This would have some advantages:

1. All the coax, baluns, relay boxes, etc, hanging up in the air are eliminated. That removes a lot of stress on the array and lowers the expense and the loss in the cable, even on 160 meters. The extent of cable loss was pointed out in the K3LR articles.
2. There is no longer any need for the elements to assume a symmetrical shape (equal lengths at top and bottom) to minimize coupling to the feed line hanging from the center point. They can have considerable deviation from symmetry, as shown in Fig 1B.
3. All the measurements, pruning, tuning and switching can be done at the base of the support, right at ground level. Very convenient!
4. With much less weight and windage the array is less susceptible to damage. This is particularly important if you live in an area where icing is a problem.
5. The loading on the support is much less. Not a big deal with a guyed tower, but important when using a tall wooden pole or other light support.

Of course, there are some disadvantages too:

1. The switching relay(s) must now be capable of handling high voltage (>5 kV), mandating vacuum relay(s).
2. A tuning unit is required at the base of the antenna.

The Array At N6LF

Fig 2 shows a side view of the array presently installed at N6LF. This has performed very well this winter (2001-2002). Note that the shape of the individual elements is not symmetrical—the triangle apex is well above the midpoint. In my installation I have another 150-foot pole 300-feet east and an anchor point at 100 feet in a tree 400 feet west of the main support. These allowed me to raise the apex (corner) of the element farther above ground, reducing ground losses somewhat.

The elevation pattern for this array is shown in Fig 3 at several points across the band. I maximized gain at 1.830 MHz, where the F/B is about 7 dB. Below that both the gain and F/B drop off but the gain is still quite useable. As you go up the band the gain falls slowly but the F/B improves. At 1.890 MHz the low-angle F/B is very good (about 24 decibel) but if you look at the full rear quadrant the F/R is only 12 dB, pretty much in line with the expectations from free-space modeling.

Because I almost always use a Beverage antenna for receiving I elected to go for maximum gain at 1.830 MHz. You could just as well go for high F/B and sacrifice a half dB or so of gain. I adjusted the tuner for minimum SWR at 1.830 MHz. This gave an SWR of 1.1:1 at 1.800 MHz and 2:1 at 1.970 MHz. It would have been quite possible to adjust for an SWR < 2:1 over the whole band but the gain starts dropping off above 1.900 MHz.

This antenna has been up since August 2001 and was used in the ARRL, Stew Perry and CQ CW 160-meter contests. It has performed very well indeed, despite the truly terrible conditions on 160 meters at this part of the sunspot cycle and due to my less-than-ideal location. During the

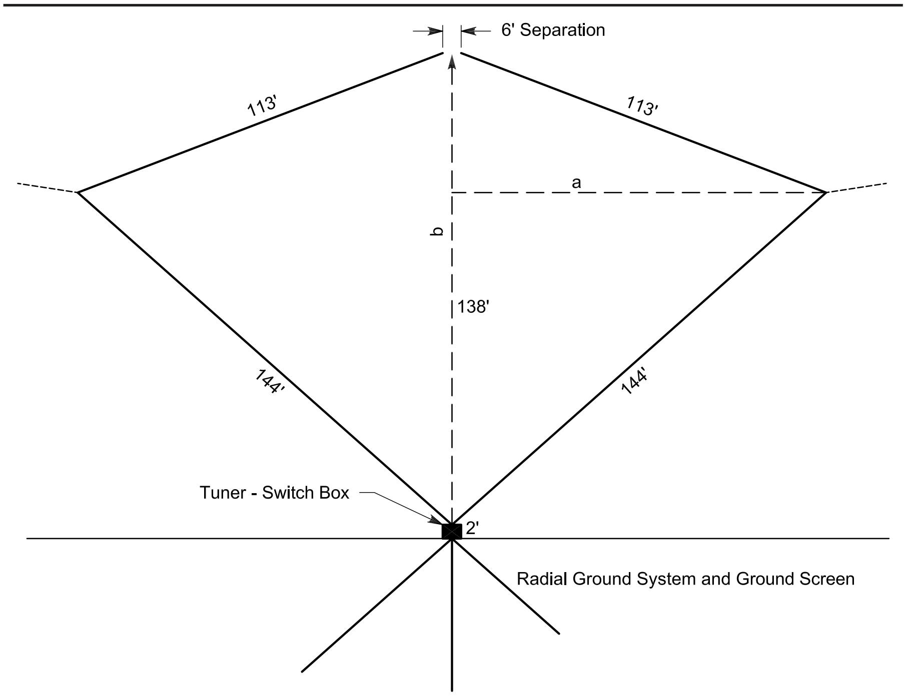

Fig 2—Present array at N6LF.

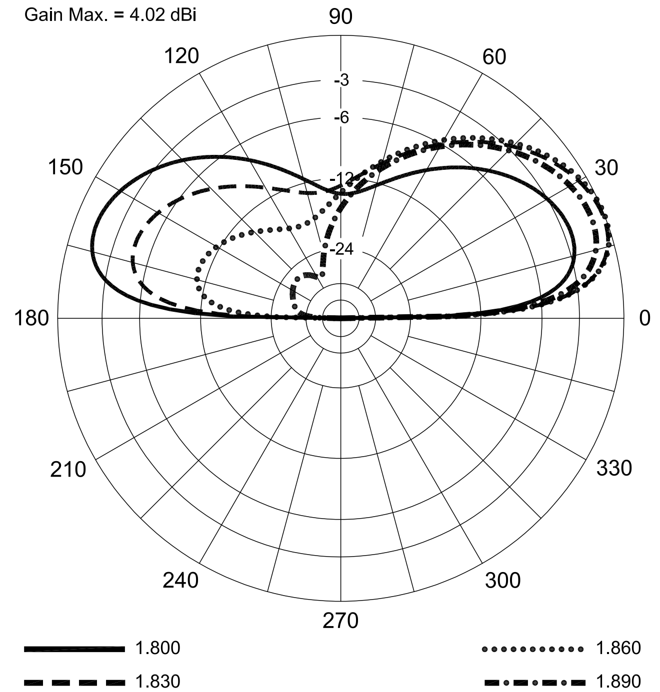

Fig 3—Elevation radiation patterns at 1.800, 1.830, 1.860 and 1.890 MHz for the N6LF two-element array.

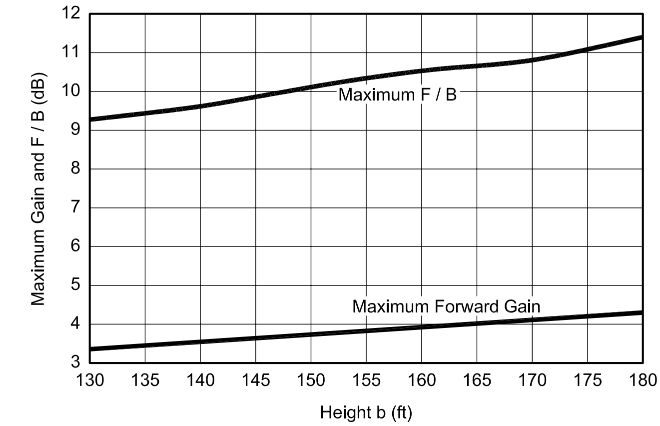

Fig 4—Typical maximum free-space gain and F/B for two-element diamond-shaped array.

ARRL 160-meter contest George was operating on the east coast from W3BGN's shack and he compared signals from the west-coast stations.

Of course, K6SE (who was using a balloon vertical over the Salton Sea salt flats) beat us all hands down. Compared to the other big stations, however, my signal was right in there, so the antenna is clearly starting to work well. And there is even more I can do to improve it. The following details how I achieved my level of performance and what could be done to improve it.

Comparison To Other Antennas

Even with the best design and construction, this antenna will not beat out an equally well-designed and installed four square. It will also be outperformed by the Spitfire antennas[7] that are similar to this antenna. The Spitfire uses the supporting tower as the driven element and the parasitic elements as reflectors and directors to form a 3-element, rather than a 2-element, vertical Yagi with a steerable pattern. However, when done well, the full-wave sloper family of antennas is not hopelessly outclassed—and they are far easier and less expensive to build compared to a four-square system if a suitable support is already in place.

In all of the modeling to follow, ground is assumed to have σ = 0.005 S/m (conductivity) and ε = 13 (relative dielectric constant). For the radiation patterns, the main axis of the array is in the (y, –y) direction (90° to 270°).

Element Length

In most two-element Yagi designs the length of the driven element is adjusted so that the feed-point impedance is resistive. The parasitic element length is adjusted to perform either as a director or a reflector. In low-frequency arrays, the size is usually much too large to allow the array to be physically rotated, and the driven and parasitic elements must be interchanged to switch the pattern. This can be accomplished in several ways. The most common is to add or subtract some length or loading and then interchange the element you wish to feed as the driven element.

There is another possibility that has not received much attention. If you take two equal-length parallel conductors, spaced on the order of 0.1 to 0.3 λ, one of which is driven and the other parasitic and do some free-space modeling, you will find that as you increase the length of the elements (keeping both the same length) that the parasitic element will first act as a director and then as a reflector as *both* are made longer. The advantage of this is that both elements are identical and there is no change in length or loading when you change direction. You simply change which element is driven.

This is particularly helpful when multiple elements are used and only one is driven at a time. For an end-fed element this makes it very easy to change directions. You simply use a system of relays to select which element is to be driven, leaving the other element open to act a reflector. A single tuning network at the base of the antenna is required, and it sees an impedance that does not change as the pattern direction is changed.

Of course the driven element in this case will not be resonant and will exhibit some reactance. With a simple parallel L-C tuner at the base, that is not a problem. Typically, the reactance will be equivalent to 5 to 10 pF, which can easily be accommodated by adjusting the tuning capacitor in the tuner.

Modeling two elements in free space gives a general idea of how this works for K8UR-shaped elements. The gain and F/B will depend on the overall height of the diamond (dimension "b" in Fig 2) and the width (dimension "a" in Fig 2). Fig 4 graphs typical free-space gain and F/B for elements varying in height from 130 to 180 feet at 1.830 MHz, using #12 bare copper wire. Notice these are the maximum values found by fixing the height and adjusting the width in the model.

As in any Yagi, maximum gain and maximum F/B do not occur for the same dimensions. In general, at the maximum F/B point the gain will be down by about 0.5 dB. There are no surprises here—the taller the array, the more gain and F/B you can obtain. However, even at $\lambda/4$ (≈ 130 feet), there is usable gain and F/B, even though this is half the length ($\lambda/2$) of normal Yagi elements.

Notice also from Fig 2 that I set the separation distance between the top ends at 6 feet. This is not a magic number, but the distance between the ends of the elements does affect the behavior. Spacings of order of 1 to 3 feet each side away from the support structure seem to work fine, although others should work also. Chose a spacing during the design phase and be careful to stick with it when erecting the array.

Element Shape

Besides the obvious mechanical difference between the K1WA and K8UR elements, there are important radiation-pattern differences too. If you start with a single half-wave sloper, with the top at 150 feet, the radiation pattern in Fig 5 will have a combination of vertical and horizontal radiation. That's no real surprise, since you have a slanting dipole.

When you combine this into a two-element array, however, some funny things start to happen, as shown in Fig 6A for in-phase and Fig 6B for 180° out-of-phase excitation. The pattern doesn't look anything like the broadside-endfire you expect in a 2-element vertical array. The problem is that the vertical and horizontal fields add up differently and the array does not behave quite as you might expect. While 160-meter operators generally favor vertical polarization for transmitting, for receiving the combination of vertical and horizontal polarizations may help. I hasten to say that this is speculation on my part.

For a four-element half-wave sloper array, where three of the elements are reflectors, the radiation pattern is shown in Fig 7. The total pattern is quite reasonable but is made up of vertical and horizontal components that individually have very different patterns. Again, it is not clear if there are any advantages or disadvantages to this mixed polarization.

The K8UR-element shape has a very different pattern. Fig 8 shows the

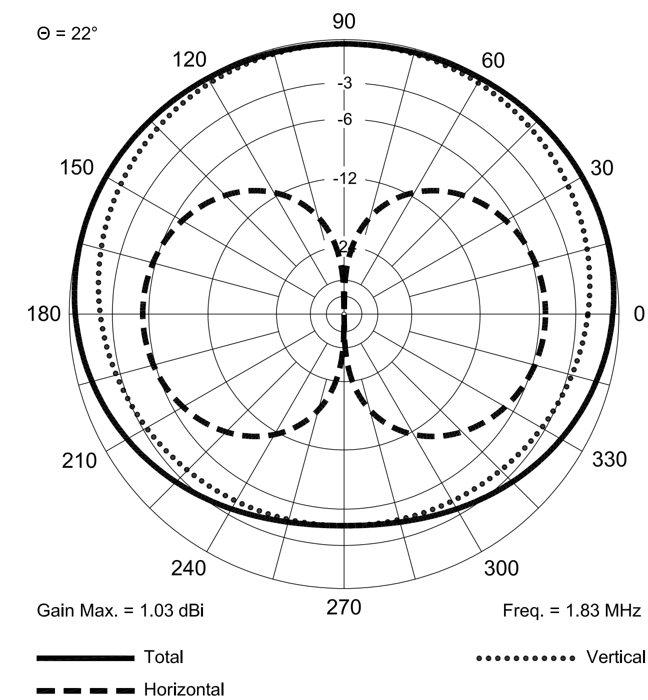

Fig 5—Vertical, horizontal and total pattern at 22° elevation for a single half-wave sloper with the upper end at 150 feet.

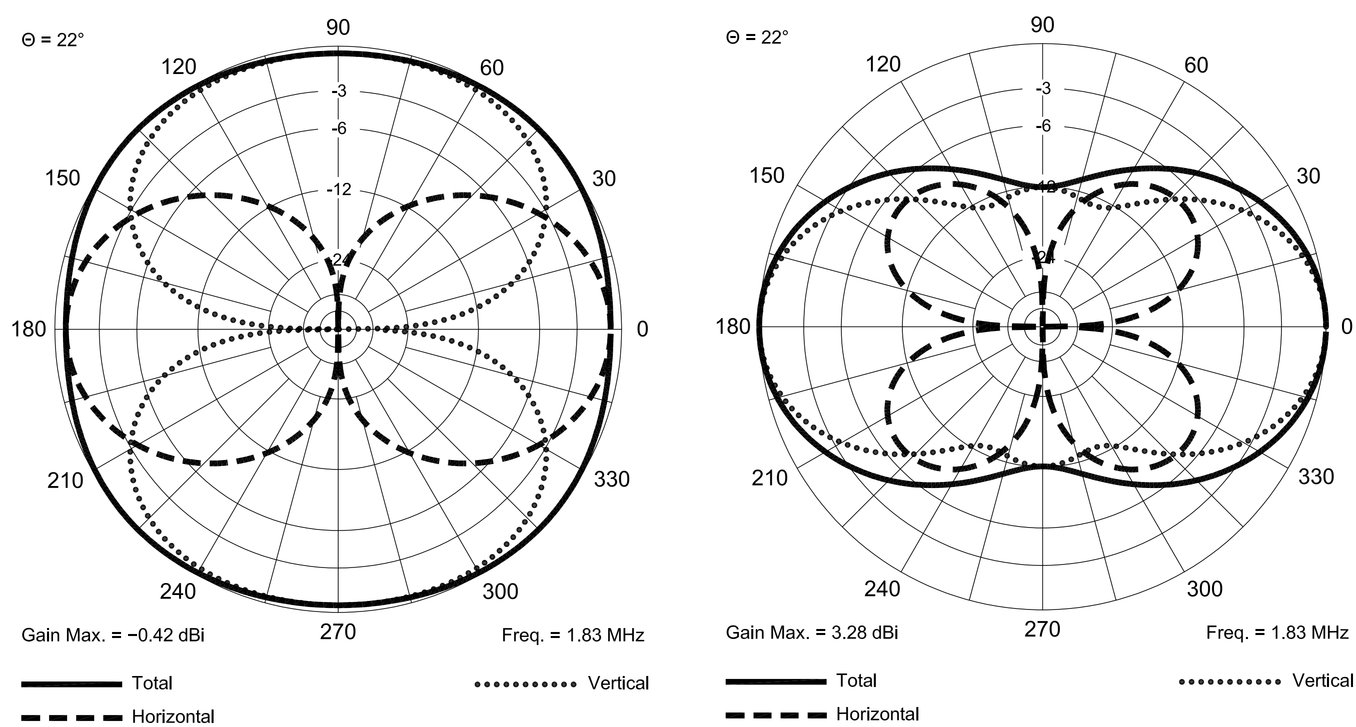

Fig 6—Vertical, horizontal and total pattern at 22° elevation for two half-wave slopers. At A, driven in-phase and at B, 180° out of phase, with the upper ends at 150 feet.

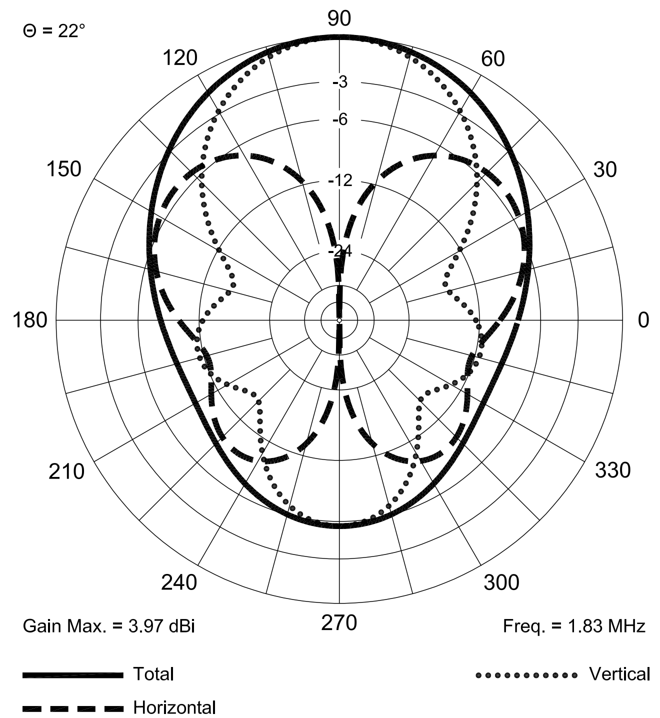

Fig 7—Vertical, horizontal and total pattern at 22° elevation for a four-element K1WA array, one driven element and three reflectors.

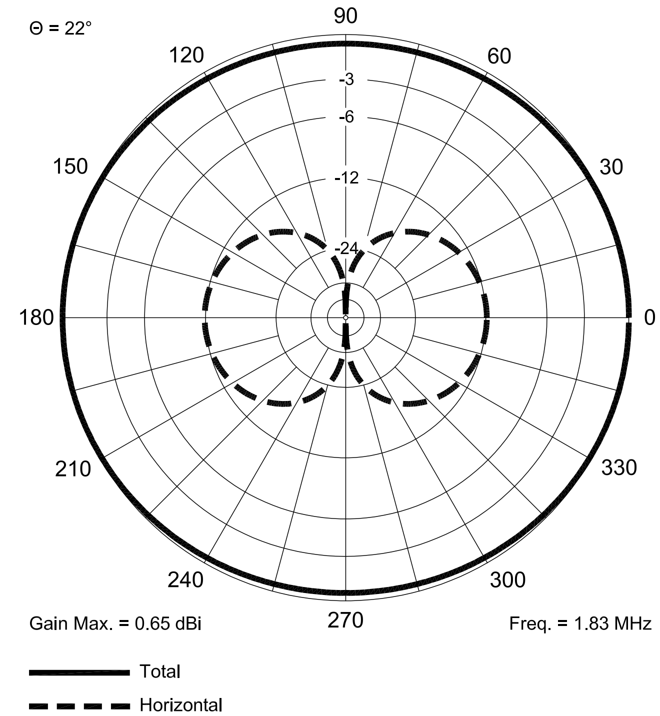

Fig 8—Vertical, horizontal and total pattern at 22° for a single K8UR-shaped element.

patterns for a single K8UR element. The horizontal component is much lower, –12 dB or more, and contributes little to the total pattern. This is one of the reasons that this shape is usually preferred if you are building a vertically polarized array.

In the K1WA and K8UR antenna models, I fed the elements at the center and I made every effort to keep things symmetrical to minimize coupling to the feed line. However, when fed from the end there is no necessity to make the element shape symmetrical. Fig 1B shows two asymmetric shapes (1 and 2). The advantage of shape 2 is that the anchor point for the guy line is much closer to the support. The overall space required for the antenna is greatly reduced. The downside of shape 2 is that it places a high E-field close to ground for a considerable distance. This increases ground losses *if an extensive ground system is not used under the antenna*.

Lifting the apex up, as shown in shape 1, reduces the ground loss significantly but requires a high anchor point for the guy lines. In the installation at N6LF these two points were available and the initial design did not use an extensive ground system. Later I realized just how much could be gained by adding a ground system. With a good ground system the additional loss due to shape 2 can be almost eliminated and the guy-line anchor points moved in much closer to the main support.

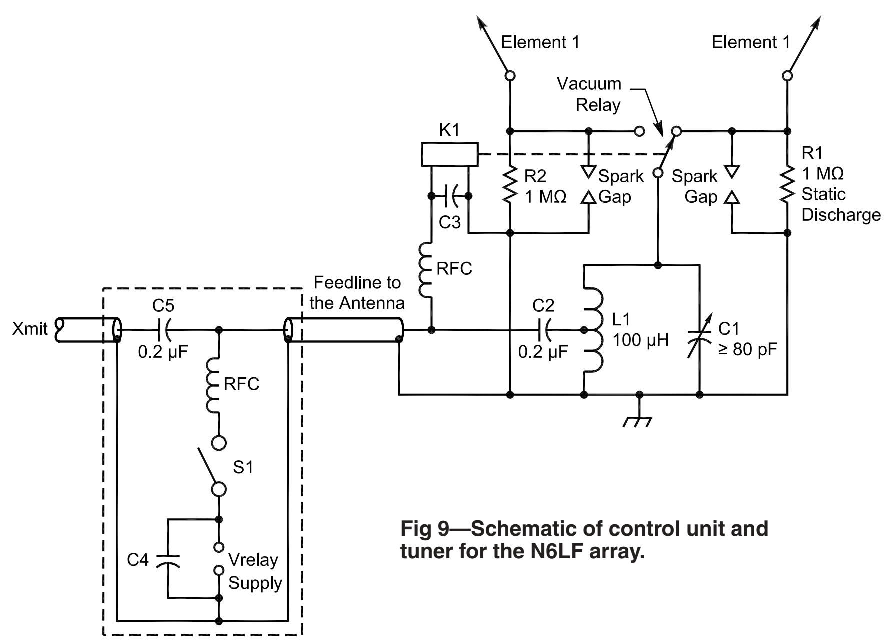

Fig 9—Schematic of control unit and tuner for the N6LF array.

If two high supports are available, then you can use the Moxon rectangle (shape 3 in Fig 1B). This yields somewhat better gain and F/B but does require two supports.

Tuner Design

Fig 9 is a schematic of the tuner. The heart of the tuner is a simple parallel-resonant L-C circuit, with a tap on the inductor for matching to the feed line. *GNEC* predicted a feed-point impedance of 5318 – *j* 1776 Ω and the actual array impedance was within 5% of this. Notice that this is the series-equivalent impedance shown in the sidebar, “Design of the Tuner”).

To design the matching network,

the series-equivalent is transformed to the parallel-equivalent circuit. The parallel equivalent impedance is about 6 kΩ in parallel with 5 pF. The next step is to chose a loaded Q. Typically this would be in the range of 5 to 10, so I chose Q = 5 to minimize the size of the tuning capacitor (C1), which must be rated for > 5 kV peak at 1.5 kW operation. A lower loaded Q also reduces the circulating current and increases the match bandwidth somewhat.

The downside of a low loaded Q is that the inductor is larger, as are its losses. However, as shown in the sidebar, for unloaded coil Q > 200 the loss is less than 0.1 dB. The coil I used was 6 inches in diameter by 5 inches long, with 29 turns of #12 wire. It had a measured unloaded Q higher than 400 on an HP 4342A Q-meter. The coil loss is thus quite small.

I use 7/8-inch CATV cable for the long runs to the shack. To match the 75-Ω feed line, the tap was 4.5 turns from the bottom of the coil. George reminded me that this would be a good place to use a shielded loop made of coax with a series-tuning capacitor. This would give better harmonic suppression and provide dc decoupling and some improvement in lightning protection. It also would provide more isolation from BC station pickup, which can be a real problem in an antenna this large. In my case I went with the simpler direct tap and it has worked well but when I improve (translation: rebuild because I can't stop fooling with it) the antenna next summer I will probably incorporate a shielded coupling loop.

C_1 is a vacuum variable, but it could just as well be an air variable with widely spaced plates. The capacitance required is only of the order of 80 pF and not all of that needs to be variable. You could for example use a fixed 50-pF capacitor in parallel with a 30-pF air variable, which would be relatively small physically. Keep in mind that these network values are for a particular design. Other designs may have somewhat different impedances and the component values must be selected accordingly.

Relay K1 switches between the east and west elements in the array to switch the pattern. I used a surplus RB1H Jennings SPDT vacuum relay rated for 12 kV. The relay coil called for 26.5 V but I found that it would start to pull in at 16 V and worked just fine with 20 V or more to activate it. For the dc power source I used a wall transformer power supply rated for 18 V, but which actually puts out 22 V. The relay is activated through the feed line using dc-blocking capacitors (C2 and C5) and RF chokes. The control unit is located in the shack and I simply flip switch S1 to change directions.

If you want to use three or four elements, then more relays will be needed. Fig 10 shows an arrangement of two relays for three elements. It is possible to use ac combined with dc and some diodes to control as many as three relays from the shack through the coax, as is done in the Ameritron RCS-4 remote coaxial switches. Of course, a separate control cable can be used also. In my case the distance from the shack to the array is > 700 feet, so I opted for feed-line control.

Capacitors C2 and C5 are for dc blocking. They must carry the full RF current, about 5.5 A at 1.5 kW when the load is matched to 50 Ω. I chose to use multiple NPO disk ceramic capacitors in parallel because they were readily available and inexpensive. NPO capacitors are larger for a given capacitance than other ceramic capacitors, but they have lower losses. You may be tempted to use 0.1 μF capacitors instead of a number of 0.01 or 0.02 μF capacitors in parallel, but be careful. The self-resonant frequencies for the larger disk ceramics can approach 1 MHz and you don't want the capacitor to be operated at or above its self-resonant frequency. In addition, a number of smaller capacitors in parallel will have much more surface area and cool much better, enhancing the current-carrying capability, which is primarily limited by temperature rise. Arrange the parallel capacitors with space between them so each one can cool itself.

There are a few other parts in the box that deserve some attention. The 1-MΩ resistors connected from the end of each element to ground are there for static discharge. The long wires in the array can develop high static potentials under some conditions. That potential on the free-floating reflector element can cause the relay to arc when transmitting. I happened to have on hand a bunch of 2-W, 100-kΩ carbon-composition resistors, so I simply built up R1 and R2 using 10 of these in series.

The 20-W overall power rating was not really necessary, but using several resistors in series increased the voltage rating. Thus I did not have to worry about arcing the resistors while transmitting, when there is a high potential at the ends of both the driven and parasitic elements. The loss introduced by these resistors is small. I also placed a spark-gap to ground across the drain resistors for lightning protection. A lightning strike anywhere within a quarter mile of this large antenna will induce very high voltages and full-up lightning protection is absolutely necessary.

The layout of the tuner is shown in Fig 11. I chose a plastic container for the enclosure because they are readily available in a wide variety of sizes and are economical. The use of a plastic enclosure also keeps the coil's unloaded Q high by keeping conducting surfaces away from it. A large metal box would also work and might have some advantages. One disadvantage of the plastic box is that ultraviolet from the sun will degrade it. In Oregon that is not a big problem but I do keep it covered with a shade cloth.

For ground within the box I used a 2-inch copper strap, which is brought out the bottom of the box to real ground. It is very important to have a good RF *and* lightning ground at this point. I use a 24-inch diameter by 8-foot culvert pipe surrounding the base of the support pole acting as a socket so that the pole can be removed with a crane for repair and alterations. This provides an excellent ground. If

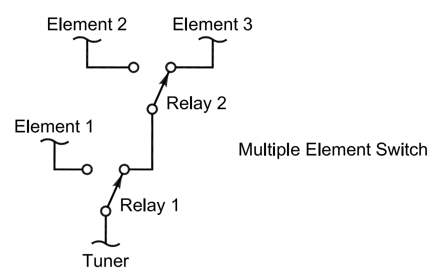

Fig 10—Relay connections for a three-element array.

Fig 11—Photograph of the tuner.

you use a tower, there should be a series of ground rods at the base for lightning grounding in any case and these can be used as a starting point for your RF ground system.

Tuning and Adjustment

One of the advantages of parasitic arrays is that the phasing of the element currents is automatically taken care of by tuning the element lengths properly. You can thus avoid the multiple matching networks and feed lines used in a phased array, where every element current and amplitude must be adjusted.

Unfortunately, the tuning in a parasitic array is strongly effected by the size and shape of the elements, which vary with tension and wire size. Sometime I wonder whether the phase of the moon manages to get into the act!

When you use insulated wire for the elements, the insulation material itself has a considerable effect. For a typical 20-meter array made with aluminum tubing, dimensions derived from modeling are usually very close and any adjustments needed are merely for matching. For a large 160-meter wire array with an arbitrary element shape that is not the case. The elements *must* be carefully tuned in the field for full performance.

What I elected to do was to design the array in *GNEC* with the element shapes as close to reality as possible, including insulation, sag, etc. When I optimized the array, I modeled one element alone and determined its self-resonant frequency. In the field I then erected one element at a time and adjusted it to be resonant at the same frequency as the model. I used solid #12 THHN insulated wire because it was much more economical than bare #12 (for some strange reason) and available in 2500-foot reels at a retail outlet near me.

Besides cost, I prefer to avoid the surface oxidation normal in bare wire. As I showed in my *QEX* article,[5] insulation in reasonable condition introduces very little loss, while an oxidized surface introduces significant loss, at least in low-impedance arrays. However, the insulation significantly changes the resonant frequency of an element and it increases the weight, requiring more tension to maintain the shape.

For the first pass I erected an element with the shape shown in Fig 2. The upper dimension for this first try was 113 feet and the lower section 153 feet. With bare wire, the resonant frequency was 1.838 MHz and with insulated wire the resonant frequency dropped to 1.789 MHz. That's a shift of almost 3%—no big deal in a dipole but bad news for a Yagi element. I experimented with other wires and insulations that had even larger frequency shifts.

So I went back to *GNEC* and modeled the resonant frequency with bare wire and with two different types of insulation. The insulation on THHN wire is listed as having a dielectric constant in the range of 3 to 4, so I used a value of 4. Back in the field I erected elements using bare wire and the two different insulations. The correlation between the *GNEC* insulating sheath (IS card) calculation and the actual measurements in the field was very good. It was better than 0.1%, so long as I kept sufficient tension on the element. I did repeated measurements as a check.

For tensioning I used a filled 2.5-gallon water jug, approximately 25 lbs, on the halyard for hoisting the upper end of the element. Higher tension had very little effect on element resonant frequency. However, reducing the tension below about 15 lbs allowed the sag to visibly increase and the resonant frequency dropped by nearly 60 kHz. These two effects combined were more than sufficient to seriously mistune the element.

By trimming the length of the lower section to resonate the individual elements (one at a time, with the other element not present) and maintaining a constant tension, I was able to get the array to work very well. Testing of F/B in the ARRL, Stew Perry and CQ 160-meter contests when numerous stations were available showed that the antenna had a F/B of 8 to 10 dB. This was just about where it should have been and the performance was all I could ask for.

One problem I encountered was how to measure the resonant frequency of an end-fed element. For a single element, the feed-point impedance is approximately 6 kΩ at resonance. This is out of the range of most amateur impedance bridges. You could use a more professional bridge, such as a General Radio 916 or 1606A, but again the impedance is outside of the normal range and some range-extending tricks have to be used.

I tried using a dip meter, with very poor results. The frequency calibration is very poor in most dip meters and there is considerable frequency pulling at resonance. Even using a frequency counter to track the dip meter was not totally satisfactory because of the effect of the meter itself and the fact that hand capacitance altered the resonant frequency. The resonant frequency of the elements is very sensitive to small amounts (a few pF) of capacitive loading at the ends—right where you are trying to make the measurement.

Another problem with the dip meter and with other ham test gear can come from broadcast-band (BC) signals. In my case there is a 1-kW BC station a few miles away. At the station frequency I get induced voltages of a volt or more at the open end of an element under test, and almost 100 mV on the transmission line back in the shack. I used an MFJ-249 SWR analyzer and the AEA complex-impedance analyzer to check the match at the tap point. Both instruments go bonkers in the presence of a large BC signal.

I could make the measurement with these instruments if I placed a BC high-pass filter between the instrument and the tap, but that doesn't help with the resonant frequency measurement. I found the use of a Bird directional wattmeter to be more satisfactory for SWR adjustment and used a Boonton 250A RX meter for the resonance check. It may be possible to adapt a noise bridge with a tuned detector to make direct measurements on the antenna but I did not try that.

Indeed, I am very fortunate to have my old Boonton 250A RX meter. This is a vacuum-tube instrument that seems to shrug off the BC signal. The RX meter measures parallel impedance up to 100 kΩ and proved ideal for these measurements. I picked up mine for $35 at a corporate surplus sale many years ago and recently bought another for $46 on eBay. For low-band antenna enthusiasts this is a very nice instrument to have. Keep an eye out at flea markets and on eBay.

The frequency calibration is not adequate in the 250A but I fixed that with an inexpensive external frequency counter to monitor the internal generator frequency. I also calibrated the RX meter using 1% film resistors to further improve the accuracy. These are inexpensive and readily available.

There are other impedance-measuring instruments on the used market that appear regularly on eBay and at flea markets. A more modern instrument that is fairly common is the HP 4815A vector impedance meter. These also go up to 100 kΩ but suffer from much greater sensitivity to BC interference than the Boonton 250A. While the HP 4815A is relatively inexpensive on the used market, you have to be very careful to get one with a functioning probe. The probes are easily damaged and prohibitively expensive to have repaired.

In making the actual measurements, I was very careful to keep the layout as close as possible to the final one. I positioned the Boonton 250A in the same location the tuning unit would occupy. I then brought a 2-inch ground strap up to the same point it would be in the tuner and connected the strap to the "low" terminal of the 250A. I brought the end of the element down to where the tuner would be with a 12-inch pigtail from the insulator at the lower end of the element.

I zeroed the meter and then connected the pigtail to the "high" terminal of the 250A. Yes, all of this fussing around is necessary to get accurate measurements! An important check is to see if placing your hands on the test gear has any effect on the readings. There should be none. If there is, then you have to work on your layout, most likely the grounding. You should also try to keep away from the bottom of the element. Holding a hand near the element will shift the resonant frequency.

In the end the array has worked very well, but at the low end of the band the F/B appears to be higher than

Design of the Tuner

The tuner is a simple parallel-tuned L-C network, with a tap on the inductor to match to the feed line, as shown in Fig 6 in the main article. The task at hand it to determine the values for L1 and C1.

An equivalent circuit for the tuner and the antenna is given in **Fig A1A**. The antenna is represented by R_a and X_a in series and the tuner by the parallel combination of L1, C1 and R_1, where R_1 represents the loss in the L-C network, almost entirely due to the finite unloaded Q of L1.

The values for R_a and X_a are determined using modeling and confirmed by measurements on the completed array:

R_a = 5318 Ω and X_a = –1776 W (capacitive reactance)

The next step is to convert the series-equivalent circuit for the antenna to a parallel equivalent, as shown in **Figure A1B** using the following expressions:

$$Q_a = \frac{|X_a|}{R_a} = \frac{|-1776|}{5318} = 0.334$$

$$Q_a^2 = 0.334^2 = 0.112$$

Parallel equivalents of R_a and X_a are:

$$R_p = R_a \times \left[1 + Q_a^2\right] = 5318 \times \left[1 + 0.112\right] = 5914\,\Omega$$

$$X_P = X_a \times \left[1 + \frac{1}{Q_a^2}\right] = -1776 \times \left[1 + \frac{1}{0.112}\right] = 17633\,\Omega$$

X_P is the impedance at 1.830 MHz for a shunt capacitance of 4.9 pF.

Selection of L1 and C1

The next step is to choose a loaded Q_L for the tuned circuit when the antenna is connected. A Q_L in the range of 2 to 10 would be typical. Smaller Q_L means a smaller capacitor and a larger inductor, along with somewhat wider matching bandwidth. The problem is that a larger inductor will have greater loss. I chose Q_L = 5, which works out very well, with minimal coil loss. For:

$$Q_L = 5$$

$$X_L = 2\pi f L_1$$

$$Q_L = \frac{R_p}{X_L} \text{ meaning } L_1 = \frac{R_p}{2\pi f Q_L} = \frac{5914}{2 \times 3.14 \times 1.83 \times 5} = 103\,\mu\text{H}$$

$$C_0 = \frac{1}{4\pi^2 f^2 L_1} = \frac{1}{4 \times 3.14^2 \times 1.83^2 \times 103 \times 10^{-6}} = 73.4\,\text{pF}$$

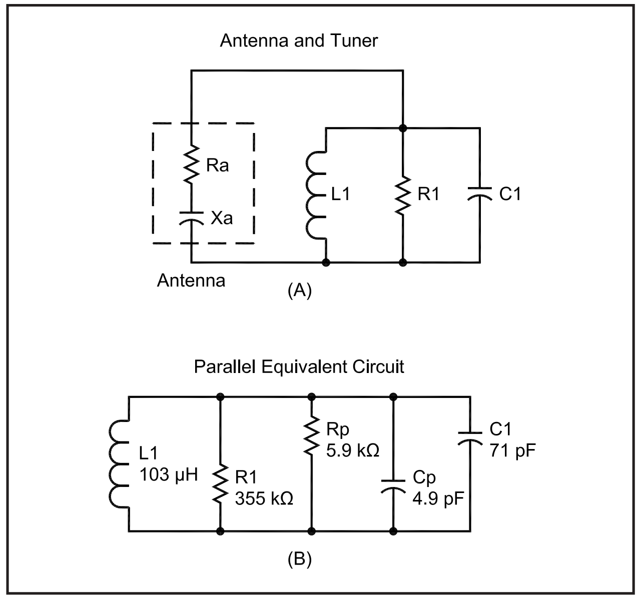

Fig A1—Equivalent circuits for the antenna and tuner.

C_0 is the capacitance needed to resonate at 1.830 MHz with L_1.

$$C1 = C_0 - C_p = 73.4 - 4.9 = 68.5\,\text{pF}$$

Loss Due to L1

R1 represents the loss in L1 and depends on the unloaded Q_1 of L1:

$$Q_1 = \frac{R1}{X_L} \text{ which means that } R1 = X_L\, Q_1$$

$$X_L = \frac{R_p}{Q_L} = \frac{5914}{5} = 1183\,\Omega$$

$$\text{For } Q_1 = 300$$

$$R1 = 1183 \times 300 = 355\,\text{k}\Omega$$

$$\text{Loss Ratio} = \frac{R_p}{R1} = \frac{5914}{355000} = 0.0167$$

$$\text{Loss Ratio} = 10 \times \log\left(1 - 0.0167\right) = -0.07\,\text{dB}$$

This is pretty small, and you can ignore the coil loss as long as Q_1 > 200. Coil Qs of 400 or more are not very difficult to obtain with a little care in construction.

predicted. I suspect that the final array is tuned a bit low in frequency due to stray capacitance loading at the bottom of the array, probably caused by the tuner and the final layout. Of course in an 80-meter array this effect could be exploited by switching in a small amount of capacitance to shift down from 3.790 to 3.510 MHz.

Ground System

One of the underlying assumptions for this family of antennas has been that since they use full-size half-wave dipoles, fed at the center, no ground system is required. It is true that the antennas will work reasonably well without the extensive ground system typical of a $\lambda/4$ vertical. However, the lower ends of the elements have a very high potential to ground. Using *GNEC* to plot the near-field electric (E) and magnetic (H) field intensities shows that the E field intensities are >800 V/m for 1.5 kW at ground level beneath the ends of the elements. This translates into high ground losses in the near field.

The K3LR articles mention the use of four elevated radials to improve performance somewhat, but that is about all that has been said on the subject. I began by modeling the fields under the array to get a feeling for ground losses and then modeled the array with 60 buried radials of progressively longer length out to 0.3 λ. The result was a steady increase in peak gain due to lower ground loss. The gain increase amounted to 0.6 to 1.5 dB, depending to some extent on the modeling approach. Even at the low end of this range, this is a very worthwhile improvement.

In the present N6LF array there is a ground screen made from 2-inch mesh chicken wire with a radius of 50 feet. From there, I go out another 150 feet with #12 insulated radials lying on the surface of the ground. Because I use only two elements at present, the field intensities are not uniform in all directions around the array, being higher under the elements and lower off to the sides. I therefore have placed more copper and ground screen in the high-field regions. With three or four elements the field intensities are much more uniform as you go around the array and standard symmetrical radial systems would be more appropriate. The ground system is not yet complete but already it appears to make a difference. Certainly the modeling says it should.

Wire Issues

Conductor loss, using #12 solid copper wire, is about 0.5 dB, which is reasonable but it could be reduced. Using a larger-diameter copper wire would help but also increases the weight of the element. Aluminum wire, although it has a lower conductivity than copper, can provide less resistance for the same weight. For example, a #7 aluminum wire will weigh about the same as a #12 copper wire, but will have a loss about 40% lower (taking into account skin effect, where resistance varies with the square root of conductivity). Of course, it will have more windage and the loss improvement is only a fraction of a decibel, so going to large aluminum wire may be a bit too picky.

Whether you decide to use copper or aluminum wire, stretching of the wire is a concern because it detunes the array. I tried a simple experiment: I took a 100-foot piece of copper wire, anchored one end and yanked really hard on the other end. It stretched a bit, about 6 inches (≈ 1/2%). Conventional wisdom says that stretching the wire this way will increase its resistance by work-hardening the copper and also by reducing the diameter. I measured the wire resistance very carefully before and after stretching, using a Kelvin bridge good to a fraction of a milliohm. The dc resistance increase was right in line with the increase in length, ≈ 1/2%.

Work hardening and diameter reduction effects were too small to detect. For this reason I pre-stretched my elements and then trimmed them to length because it was more important to have the element correctly tuned than worry about a very small loss effect. This winter I had a lot of strong winds push the array around but no icing, which is very rare in any case. So far the pre-stretched elements have been stable. If you live in an area where icing is a problem, then you probably need to use either Copperweld or Alumoweld wire, both of which are much stronger but real pains to work with.

Another problem that caught me by surprise was the simple act of accurately measuring the length of a long piece of wire. I began by pulling the wire off the reel simultaneously with a long tape measure, both held in my hand. Every time I tried it I got a different final length—by a foot or more. The problem is that the wire slips with reference to the tape. So next I tried anchoring the end of the tape and stretching it out on the ground beforehand and then pulling the wire out and tensioning both the wire and the tape.

This was much more accurate and repeatable, but it also was a lot of trouble and requires a clear space of nearly 300 feet. George showed me his solution: a wire-length meter[6] like you see in hardware stores. It measures wire length to an inch in 300 feet without having to go out in the cold and wet. (It has been known to rain occasionally in Oregon.) It does the job quickly and easily and I was particularly glad I bought my own when I started to cut the numerous radials for the ground system. You have to build a simple 2×4 frame to hold the meter and a reel of wire but that's not difficult. If you want to do it right you can also buy an adjustable reel for the wire you cut off. That makes handling the long lengths much easier, especially when cutting numerous long radials.

Safety Issue

While end feeding the elements has many advantages, it presents a safety hazard because the fed ends are so close to ground level, where someone might be able to touch them. The voltages on the lower ends of the wires are very high while transmitting at high power. Some form of guard fence or safety screen is advisable if there is any likelihood of people or animals coming in contact with the wires.

Modeling Comments

Throughout this discussion I have emphasized the need for careful modeling. In my case I have no tower in the middle of things but most installations are likely to have one with HF Yagis attached. I began modeling a tower by obtaining an antenna file from Al Christman, K3LC (ex-KB8I), for a Rohn 55 tower, which models essentially every strut in the tower. The normal thing to do is to calculate the self-resonant frequency of the tower and then model it using a single wire with a diameter that results in the same resonant frequency. You can then use the simpler model in the overall antenna model. I found that I could find such an equivalent wire but the variation in feed-point impedance around resonance was not the same as for the tower. I got a better match in impedance characteristics by adjusting both the diameter *and* the height.

Using this equivalent model I then modeled George's antenna system. I found that his tower did not interact very much with his array. However, that represents a sample of one. It is perfectly possible that another tower, with a different collection of HF Yagis on it, might interact strongly and greatly modify the behavior. This has to be dealt with on a case-by-case basis for each installation.

The W2VJN Antenna

W2VJN has built a number of K1WA arrays over the years. When George was living in New Jersey, he had used a K1WA configuration on 80 meters with very good results. He began with a one-element sloper, then added another element and finally went to four elements. After moving out to the wilderness in Oregon he erected a 150-foot Rohn 55 tower with an array of HF Yagis on it. About 2½ years ago he put two elements on 160 meters and then a year later added two more elements. The array drives one element at a time, with the remaining three acting as reflectors.

The original K1WA array used λ/2 elements, with the length of the coax cable going to the switch box tuned to make the element a reflector when not driven. The result is that the match at the drive element is not all that good for a 50-Ω line—SWR is typically on the order of 1.8:1 or so. George has a variation that improves the match. The elements are cut for 1.850 MHz (by calculation, $L=492/f_{MHz}$). With three elements open and acting as reflectors, the apparent resonant frequency measured at the switch box is 1.770 MHz. This means that at 1.830 MHz there is an inductive reactance at the feed point in the switch box. This is tuned out with a 1200 pF capacitor, resulting in a much better match, close to 1:1 at 1.830 MHz.

George's array can be switched in four different directions and he uses it for receiving as well as transmitting. He has found that selecting the right direction can make a considerable difference in some cases. He has found his antenna to be very effective on receive despite (or perhaps because of) the mix of vertical and horizontal polarization.

Future Improvements at N6LF

While the present array works very well, there is more that I can do. One idea is to add directors. At N6LF I have three tall poles in a row that would allow me to hang director elements for increased gain. I have already done this accidentally. After finishing with the 160-meter array I put up an 80-meter dipole on the east side of the 160-meter array, suspended between the poles that support the 160-meter array, as shown in Fig 12.

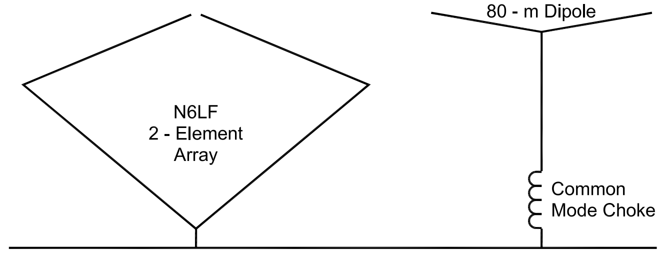

Fig 12—Combination of the N6LF array and an 80-meter dipole for modeling.

I checked to see if the 80-meter dipole had any effect on the 160-meter array by modeling the combination. It certainly did have an effect! With the 80-meter feed line grounded, the 80-meter dipole acted like a reflector and killed my gain to the east. Adding a coax common-mode choke balun turned the dipole into a director and this increased the gain to the east. The dipole is not a very reliable director, however, because as the wind blew it moved up and down, changing its characteristics. One minute it might be a director but a reflector at another. For now I drop the 80-meter dipole for contests or if I think there is the possibility of an opening to Europe. Next summer I plan to make other arrangements for the 80-meter antenna so that it does not interact with the 160-meter array.

And of course a three-element Yagi would have more gain and better F/B than a two-element Yagi. Next summer I will expand the array to three elements. I had originally planned to suspend the directors between the other available poles but after looking at the Spitfire antenna[7] I changed my mind. Since I already have an extensive ground system in place, it makes more sense for me to simply hoist a wire up along the supporting pole and use it as a driven element, and then use the other two elements as director/reflectors. I could even suspend a second director between the supports and go to a four-element (or even five-element) Yagi on 160-meters. Of course, the beamwidth will narrow and I would have to go to at least four-direction switching for the pattern to have reasonable coverage.

Although I use only two elements that allow me to switch the pattern from east to west, the present array has been very useful. Going to three elements (one driven and two reflectors) would be worthwhile. The gain is changed very little by having two reflectors but there is some improvement in F/B. The real improvement would be the ability to slew the pattern in three different directions rather than two. It is possible to have two driven elements and have one as a reflector. This in combination with one driven and two reflectors would give six headings for the pattern. I am not convinced that this would be worth the trouble, however.

Acknowledgements

Much of the progress I made in this project was the result of endless discussions with George Cutsogeorge, W2VJN. He was a tremendous help. I would also like to thank Dean Straw, N6BV, for putting me onto the antenna file for the Rohn tower and to Al Christman, K3LC, for sending it to me. This was very helpful in evaluating the effect of the tower on George's array and sloper arrays in general.

I have referenced only a few of the multitude of articles on sloper antennas. George told me to go to Google. com and enter "sloper arrays". I got over 500 references, about two thirds of which were for sloper antennas! No doubt everything said here has already been said many times but perhaps this forum will reach a wider audience.

John Devoldere's *Low-Band DXing*[8] is another great reference source. At the last moment in preparing this article John, EI7BA, made me aware of a particularly good article by Tony Preedy, G3LNP.[9] It deals with bent verticals less than λ/2wavelength long and arrays made from them, which are very much like the arrays in this article. This is also a "must read" article.

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