Twin-C Antennas

A simple antenna that uses coupled bent dipoles provides some surprising benefits.

By Brian Cake, KF2YN

In my eyes, there are two basic antenna structures that are remarkable: the half-wave dipole and the long Yagi antenna. The half-wave dipole is simplicity personified: almost one-dimensional, slim, with wide bandwidth and it forms the basic building block for umpteen varieties of more complex antennas.

The long Yagi antenna is close to one-dimensional and it is also beautifully simple—if you don't need to design one! The problem with both the half-wave dipole and the long Yagi is that *they are way too long.* For some years now I have been intrigued by the problems associated with improving short antennas; and, in particular, getting high gain from a short-boom Yagi-like antenna. It seemed to me that I ought to be able to squeeze more gain out of a given boom length by moving from what is virtually a two-dimensional structure to a three-dimensional structure. Stacking is the traditional method of doing this, but it involves mechanically assembling two or more Yagis and feeding power to each of them. Besides, there was no challenge here: It had all been done before. I went looking for a new way to achieve the same result. The search led to both reduced boom-length beams and to a new physically small dipole element with very interesting properties. The following article is the first of two parts that will present some results of my study. I hope you will find at least something of interest. I must cover quite a bit of ground here, so the depth of coverage of individual antennas may not be ideal; I hope that the principles will be clear.

Unless otherwise stated, the data I provide are derived from computer simulation using *EZNEC pro* 3.0 as the modeling program.[1] Don't worry. I have built and range-tested a large number of antennas based on this simulation software, and the accuracy of the simulations is incredibly good.

Short Dipole Problems

When the length of a dipole is reduced, some well-known problems arise:

- The feed-point impedance drops dramatically, even if end loading is used. Some form of matching

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[1]Notes appear on page 18.

circuit is necessary in order to allow the antenna to be driven by a transmitter and feeder system that is designed to drive 50 ohms.
- The self-resonant feature is lost, and the antenna must be brought to resonance somehow. This normally involves the use of inductors, with their associated losses.
- The bandwidth is reduced.
- To radiate the same power from a short antenna, the antenna currents and voltages increase dramatically as the length is reduced.

In the following, I'll describe new methods of reducing the length of a dipole, while avoiding or minimizing some of the above effects.[2] The resulting basic antenna element has a square perimeter with side lengths of around λ/6, or about one-third the length of a half-wave dipole. It is self-resonant, with a feed point resistance at resonance of 50 Ω. The feed-point resistance may be changed over a greater than 2:1 range by changing the aspect ratio of the element while still maintaining self-resonance. The efficiency is virtually 100% when copper or aluminum elements of sensible diameter are used. The SWR bandwidth is about 3.5% of the center frequency, as compared to about 10% for a full size dipole. Elements may be connected in parallel to provide multiband coverage without band switching. Ground-plane antennas using the element reduce the size still further. The element may be used in directional antennas. In one particular case that will be described in the second part, it can provide high directivity (high gain) on two harmonically related frequencies, such as 2 m and 70 cm, while providing an excellent, broadband match to a single feeder on both bands. For these Yagi-like antennas, the gain of the antenna on the higher of the two bands is substantially greater, for a given boom length, than that of a high performance conventional Yagi.

I have called the basic element the "Twin C" simply because its outline resembles two stylized "C" shapes back-to-back. A more appropriate name might be "open folded dipole," as we shall see, but this is already in use for a special version of a folded dipole.[3] I use the name "Box Kite" to describe the dual-band Yagi that uses a version of the basic element. (The structure reminds me of happy days

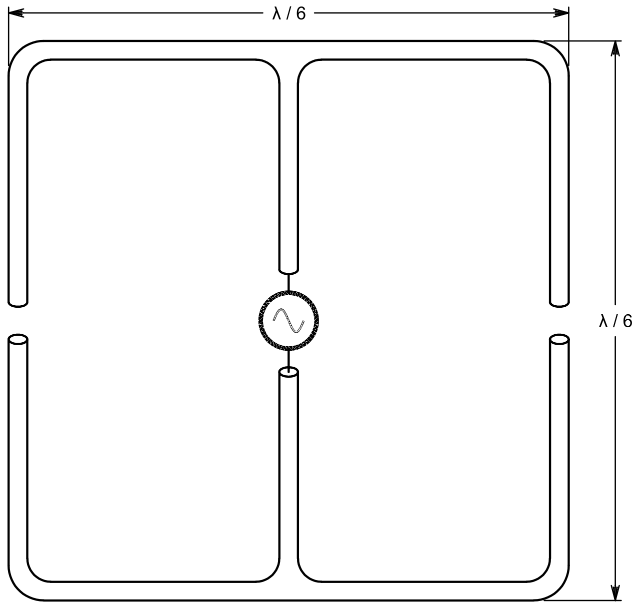


Fig 2—A wide bandwidth bent half-wave dipole.

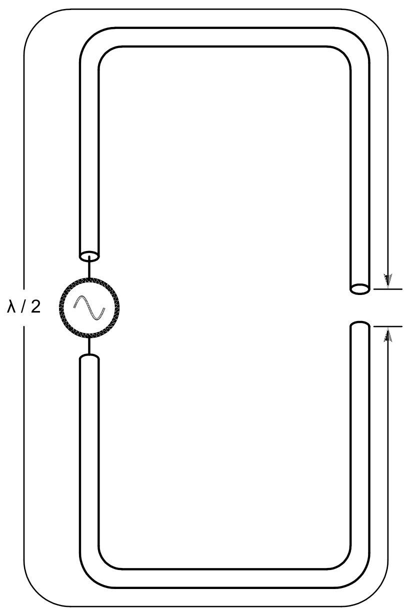


Fig 1—A bent half-wave dipole.

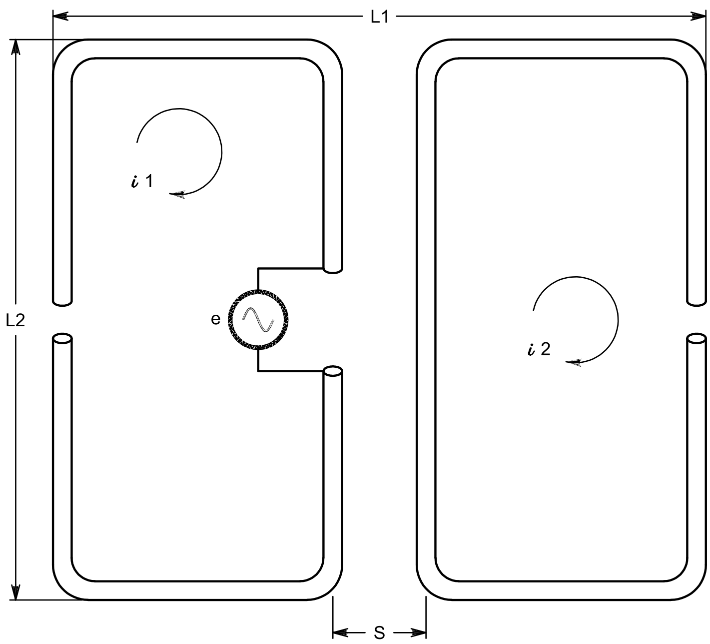


Fig 3—A Twin C dipole.

flying kites an awfully long time ago, with the structure of the antenna resembling in some way the support rods for box-kite fabric!)

Twin-C Theory

The evolution of the Twin C antenna from a full size half-wave dipole is illustrated in Figs 1 through 3. A half-wave dipole is slightly shorter than λ/2 and has a feed-point resistance of around 73 Ω at resonance, with a 2:1 SWR bandwidth of about 10% of the resonant frequency for common length-to-diameter ratios. First, we take the λ/2 dipole and bend it as shown in Fig 1, so that the side length of the resulting antenna is about λ/6 and the width about λ/12, and there is a small gap between the open ends. As may be expected, the resonant frequency is shifted somewhat by the reshaping; but by adjusting the lengths of the open ends, the antenna will again resonate at the original frequency. Since the effective length of the antenna is reduced, the feed-point resistance is reduced, for the dimensions shown, to around 13 Ω, and the SWR bandwidth is reduced to about 2.5% of the resonant frequency, or one-quarter of the bandwidth of a full size half-wave dipole. The SWR bandwidth can be improved somewhat by arranging the antenna element as shown in Fig 2, where a second pair of "wings" is connected to the center section. This does not significantly change the feed-point resistance, but the SWR bandwidth is raised to about 3.5% of the resonant frequency or one-third that of a dipole.

The Twin C antenna is similar in shape to Fig 2, but consists of two identical subelements bent into back-to-back "C" shapes, with a close parallel section, as shown in Fig 3. The center of one of the subelements, or halves, is driven by the source, preferably via a 1:1 balun, because the antenna is balanced. The total length of wire in each half is close to λ/2 at the operating frequency, and the dimensions L1 and L2 in Fig 3 are approximately λ/6. The spacing, *S*, between the parallel sections should be less than about λ/20. The close parallel sections magnetically couple the driven and undriven halves, so currents flow in both halves. The magnitude and phase of these two currents is determined by the coupling between the two halves and by the operating frequency.

The lumped equivalent circuit is shown in Fig 4. This shows two identical halves coupled by mutual inductance. With the dimensions shown, in coupled tuned circuit parlance, the two halves are overcoupled. The resistances, *R*, represent the radiation and loss resistances of the two halves. An analysis of Fig 4 shows that, as is usual with overcoupled tuned circuits, there are two resonant frequencies: one below and one above the natural resonant frequency of each half. We'll call these two frequencies *F1* and *F2*, respectively.

At *F1*, *i1* and *i2* are approximately equal in amplitude and are in antiphase, so they flow in the same direction through the close parallel sections. At *F2*, the currents are in phase and flow in opposite directions through the close parallel sections. The operating frequency is *F1*. It can be shown that the effect of the two almost identical currents flowing in the same direction in the two halves increases the feed impedance by a factor of four. Also, the radiation pattern is virtually identical to that of a single wire of the same length, occupying the mean position of the two wires. This is similar to the manner in which the feed-point resistance of a conventional folded dipole is increased. Thus, although the radiation resistance of an element as shown in Fig 2 is approximately 13 Ω, the feed-point resistance for the Twin C antenna is four times this, or close to 50 Ω, at *F1*. At *F2*, the currents flowing in opposite directions in the two halves cause a reduction in the feed-point resistance. This is a problem only if elements are connected in parallel in order to provide multiband operation, as we shall see later.

The 2:1 SWR bandwidth for the Twin C described above is similar to that of the element shown in Fig.2. That is, approximately 3.4% for normal conductor diameter-to-wavelength ratios, as compared to about 10% for a conventional half-wave dipole. It is important that the amplitudes of the currents in the two halves are approximately half those needed to radiate the same power in a single wire. Because of this, the power loss caused by any resistive loss in a Twin C is smaller by a factor of two than that for a conventional single-wire dipole. This means that inductive loading of somewhat shorter subelements is possible without seriously degrading the efficiency.

Reverse Twin Cs and Double Dipoles

It is well-known that a pair of tuned circuits can be coupled in many different ways, the above being just one example. A pair of Twin C halves may be capacitively coupled by simply re-

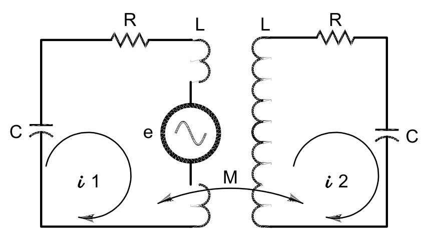


Fig 4—A lumped-element equivalent circuit of the Twin C dipole.

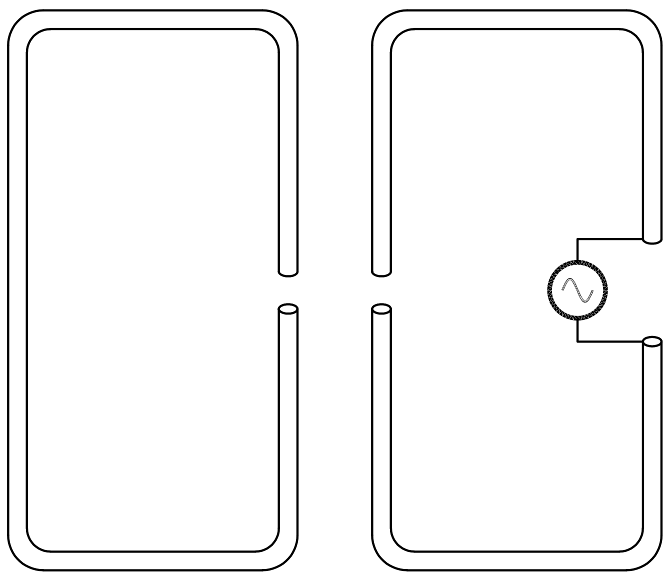


Fig 5—A reverse Twin C dipole.

versing each half so that the Cs are “front-to-front” as illustrated in Fig 5. Now the coupling is predominantly capacitive because the high impedance ends of each half are close to each other, and the low impedance sections are well separated. It can be shown from coupled-circuit theory that, with two identical tuned circuits capacitively coupled, there are again two resonances: one above and one below the natural resonant frequency of each half. Yet now the currents in the center of each C are in the same direction and equal in magnitude at the upper of the two resonant frequencies, as opposed to the lower frequency for the Twin C. The feed point resistance is multiplied just as before. The Reverse Twin C, as I call it, has the disadvantage that it does not behave as a simple vertical dipole when vertically mounted because the high current sections are well separated, and there is considerable directionality in the H-plane pattern. However, for some applications this might be useful.

Short dipoles that use inductive loading at their centers to bring them to resonance can also be coupled capacitively, simply by mounting two such dipoles very close together, as shown in Fig 6. I call this arrangement a Double Dipole. Feed-point resistance multiplication occurs just as for the Twin Cs, and power loss in the loading inductors is reduced because of reduced current. The pairs of dipoles can be paralleled with pairs for other bands, provided that capacitive coupling between pairs for different bands is not too high. It is very important that the mutual inductance between the two loading coils should be small, otherwise inductive and capacitive coupling fight each other and full impedance multiplication will not be possible.

The Double Dipole antenna is not as rosy as it may seem, however. The operating frequency is *F2*, which is higher than the self-resonant frequency of the two dipoles. This means that the loading inductance, and therefore its loss resistance, is larger than for a single dipole, so the gain in efficiency is not as high as we might first expect.

As an example, let’s consider a Double Dipole for the 15-m band: two 10′ long 1″ diameter dipoles, each center loaded with 5-µH inductors ($Q \approx 100$) mounted in free space with a spacing of 10″ between them. This gives an efficiency of about 75%, a minimum SWR of 1:1 and a 2:1 SWR bandwidth of 500 kHz. No matching circuit is necessary when fed with 50 Ω cable: The feed point needs only a good 1:1 balun, the simplest of these being a few turns

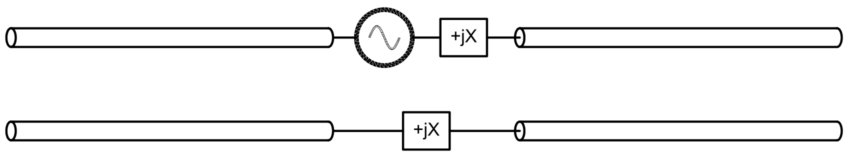


Fig 6—A “Double Dipole.”

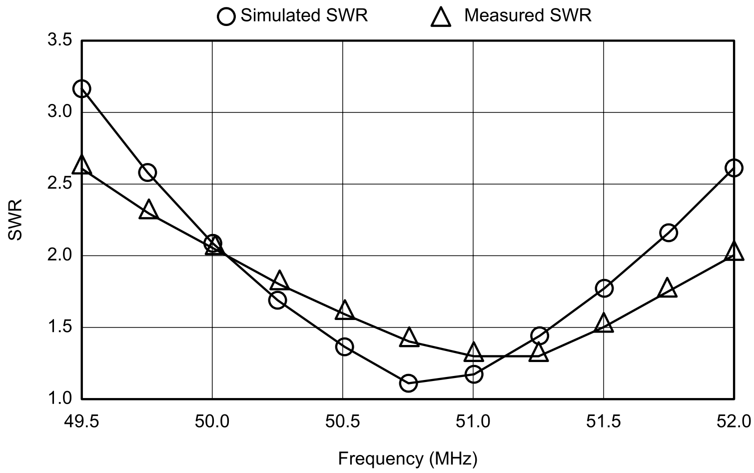


Fig 7—Simulated and measured SWR curves for a prototype 6 m Twin C.

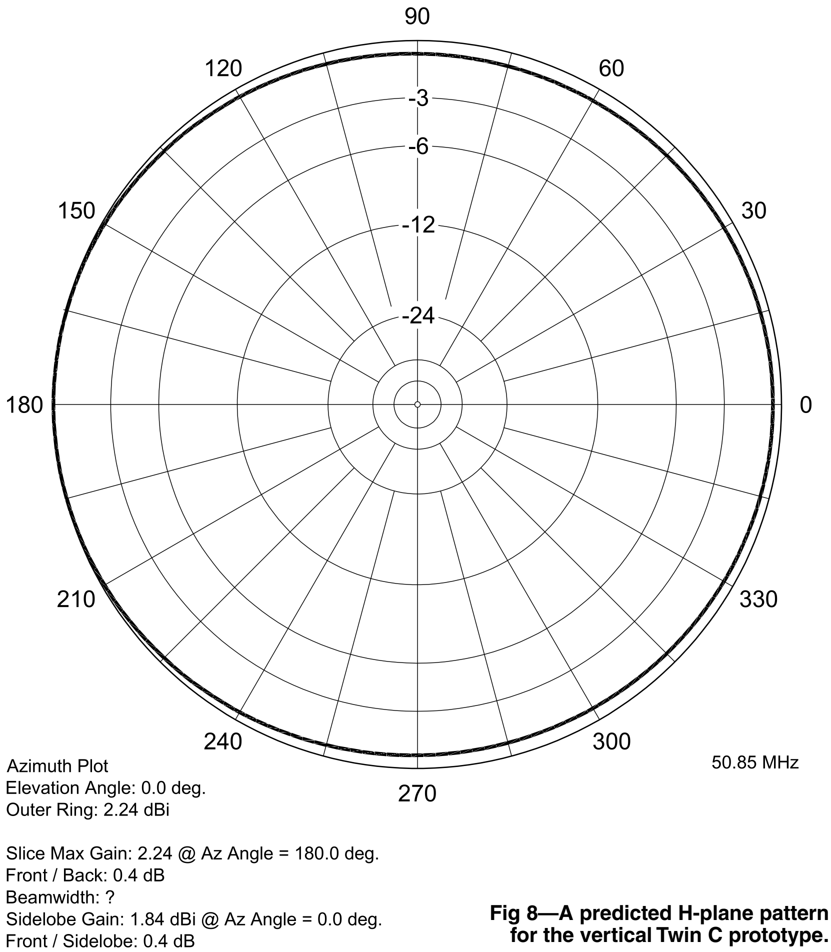


Fig 8—A predicted H-plane pattern for the vertical Twin C prototype.

of the feed cable around a suitable ferrite toroid. The single-dipole equivalent with the same length and diameter uses a 4-µH inductor with a *Q* of 100; it has a feed-point resistance of 15 Ω, an SWR bandwidth in a 15-Ω system of 350 kHz, and an efficiency of 66%. Any loss in the matching circuit will of course further reduce efficiency. Ground-plane versions of these antennas are of course practical, although efficiencies are likely to be lower.

Practical Twin Cs

As an example of Twin C antenna design, let's use the prototype that I built for 6 m. In Fig 3, *L1* is 36 inches, *L2* is 40 inches and *S* is 2 inches. The antenna was fabricated from 1/2-inch copper pipe and fed via a current balun consisting of a few toroids slid over the feed cable. The closely coupled parallel sections were secured to opposite sides of a plastic construction level. The SWR plots from both computer model and measurements of a prototype (mounted about 25 feet above ground on my deck) agree reasonably closely: The simulated and measured results are shown in Fig 7. Notice that I have found on several occasions that the presence of wood in the near field area of VHF or UHF antennas affects the SWR somewhat. The simulation results assume a free-space environment. The measured 2:1 SWR bandwidth is about 2 MHz, or about 4% of the center frequency. A full-size half-wave dipole for 6 m is almost 10 feet long, whereas the Twin C equivalent is around 3 feet on a side. There is a difference in directivity, or gain. A full-size dipole has a directivity of 2.14 dBi, whereas the Twin C in theory behaves as a short Hertzian dipole with a directivity of about 1.8 dBi.

However, when used as a vertical, the pattern is not perfectly omnidirectional because of the currents flowing in the outer vertical wires. The simulated H-plane pattern for the vertical prototype Twin C is shown in Fig 8.

More than two identical subelements may be coupled together in similar manner to the Twin C. With three subelements, the feed impedance is increased by roughly three squared, or nine times, and so forth.

The Twin C shown in Fig 3 has both subelements in the same plane. In fact, one of the halves may be rotated around the vertical axis of the antenna with little effect on performance, except for a slight reduction in SWR bandwidth and center frequency, until the angle between the halves is roughly 30°. For angles less than 30°, the capacitive coupling between the halves increases and the feed point resistance drops rapidly.

The Twin C SWR is very tolerant of changes in the dimensions *L1* and *L2*. Fig 9 shows how the SWR for the 50-MHz prototype varies with dimensions in a 50 Ω system. As the length *L2* increases (*L1* must be decreased to maintain resonance), so does the feed-point resistance, and vice versa. However, changing the spacing between the two halves changes the coupling coefficient, and thus changes the resonant frequency. Shifts in resonant frequency of a few percent can be achieved simply by changing *S*, but this does of course mean that construction should be such that *S* is well defined in order to ensure frequency stability. In the prototype 6-m antenna, a change in spacing of 1 inch, from *S* = 2″ to *S* = 3″, shifted the resonant frequency by 700 kHz, and changed the resonant SWR from 1.14 to 1.2. A change in *S* of 4 inches, from *S* = 2″ to *S* = 6″, shifted the resonant frequency by 1.8 MHz, and changed the resonant SWR from 1.14 to 1.32. From a practical standpoint, frequency adjustment could be provided either by physically moving the two halves closer together; or, perhaps simpler, by providing a small loop, in one or both of the parallel sections, that can be adjusted to change the coupling coefficient.

Dimensions for Twin C dipoles for the 20-, 15- and 10-m bands are shown in Table 1. These are for Twin Cs mounted vertically, as in Fig 3, so that the center of the antenna is located 8 feet above ground with average conductivity. The antennas are made of 0.0625″ copper wire, but this dimension is not at all critical. In all cases, the gap in the ends of the Cs is 4″, and the dimensions referred to are those shown in Fig 3.

Notice that these dimensions are considerably shorter and "fatter" than those for the Twin C in free space, simply because the presence of the ground increases the feed-point resistance. The dimension *L2* is reduced in each case to bring the feed-point resistance back to 50 Ω, and *L1* is increased to maintain resonance at the design center frequency. These dimensions should be treated as good starting points: Be prepared to trim the dimensions to accommodate your local conditions.

Basic Twin C dipoles can also be connected in parallel, just as full size dipoles, to provide multiband operation. One might ask whether a folded-up folded dipole could be used. The well-known problem with folded dipoles is that the feed-point impedance drops to a very low level at the second harmonic. This has to do with the behavior of the short-circuited transmission line that is inherent in the structure. This effect means that folded *folded* dipoles (intentional double adjective) cannot be connected in parallel and operated at a frequency that is near their second harmonic of the dipole cut for the lowest frequency. For example, operation on 20 m and 10 m is not possible: The low impedance of the 20-m dipole on 10 m effectively shorts out the 10-m dipole. This is not the case with parallel-connected Twin C dipoles. There is a frequency for each dipole at which the feed

Table 1—Dimensions for Vertical Twin-C Antennas

Band	*L1*	*L2*	*S*	*SWR Bandwidth*
20 m	212″	96″	6″	400 kHz
15 m	126″	76″	6″	550 kHz
10 m	82″	64″	6″	800 kHz

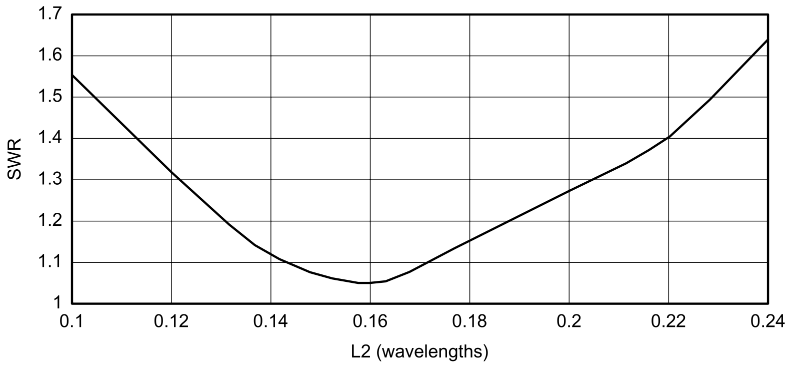


Fig 9—SWR plot for the prototype 6 m Twin C as a function of dimension *L2* (see Fig 4).

point impedance is very low; but this can be shifted up or down simply by changing the coupling coefficient between the two halves, as noted above. As with parallel full-size dipoles, there is interaction between the individual elements, and generally the SWR bandwidth is reduced significantly on the higher frequency bands. For a three-band (10-, 15- and 20-m) Twin C antenna, mounted with the center 8 feet above ground with average conductivity, the modeled 2:1 SWR bandwidths are >400 kHz on 20 m, 250 kHz on 15 m and 300 kHz on 10 m. This antenna has maximum dimensions of 14 feet wide by 9 feet high. The Twin Cs are spaced apart eight inches, giving a total antenna thickness of 16 inches. They can, of course, be spaced by more than this if you have the room, or they can be interleaved radially, like a paddle wheel.

The outer wings of the Twin C do not have to conform to the shape shown in Fig 3. They may be "dressed out" from the close parallel sections in quite a number of ways, as long as the capacitive coupling between the halves is kept reasonably low. Capacitive coupling can significantly change the total coupling between the two halves.

Before moving on to beams using Twin C elements, let's look briefly at some Twin C ground planes. A design for 2 m is shown in Fig 10. This antenna has a height of a fraction under 9 inches, and a width of 10 inches. It is essentially omnidirectional, and has an SWR of less than 2:1 from 141-148 MHz. Its 1.5:1 SWR bandwidth is 4 MHz.

I mentioned the use of more than two Cs earlier on. As an example, Fig 11 shows a double Twin C ground plane for 2 m, that uses four subelements. The antenna is 3.5 inches tall and has a diameter of 26 inches. SWR bandwidth is 4 MHz. For 1/8″ elements of aluminum or copper, the efficiency is well over 90%. A three subelement version of this for 10 meters is 22 inches tall with a diameter of about 7 feet. This antenna has bent outer wings, and is shown in Fig 12. SWR bandwidth is 800 kHz when using 1/2″ elements and 700 kHz when using 1/16″ elements. For the Twin C ground planes, it is important that the total ground current is the sum of the currents in the individual subelements, so the ground plane must be made of low-resistance conductors or efficiency will suffer.

Twin C Beams

So much for the basic Twin C dipole—for the moment. We will revisit the basic element and look at its behavior on the third harmonic later. The Twin C dipole may be used as a short driven element in a Yagi-like antenna. Initially one might think that only one subelement is necessary for the parasitic elements. However, the use of a full Twin C element substantially improves the SWR and gain bandwidths. Fig 13 shows a three-element beam for 6 m; Fig 14 shows the pattern at 50.2 MHz, and Fig 15 shows the SWR plot, both the latter being derived from computer simulation in free space. The elements are constructed from 1/2″ aluminum, and the pattern shown incorporates the conductor loss resistance. For a full-size three-element beam (in this example based on the NBS dimensions), the gain is 9.5 dBi. It can be seen from Fig 14 that the gain for the Twin C is 8.1 dBi, a perfectly tolerable reduction from full size given the significant reduction in

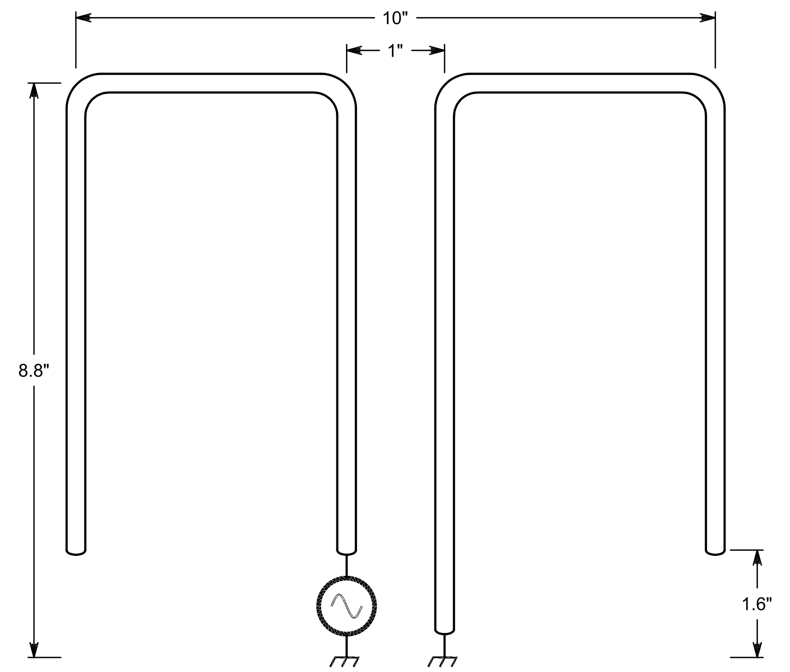


Fig 10—Twin C ground plane for 2 m. Element diameter is 1/8″.

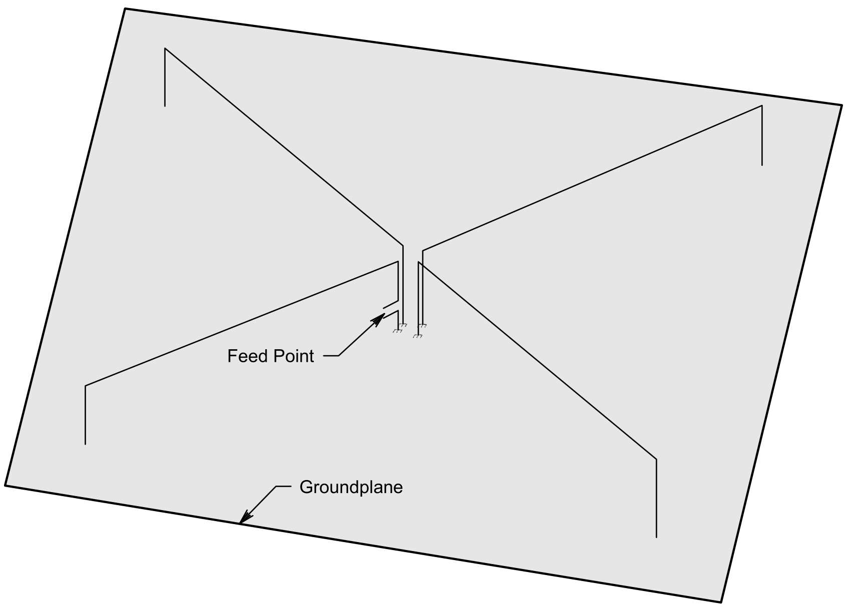


Fig 11—Double Twin C for 2 m.

size. Gain bandwidth (to 1dB down) and SWR bandwidth are 2.8 MHz and 1.2 MHz respectively, compared to 1.5 MHz and 700 kHz for the full-sized beam.

This particular implementation of the Twin C beam is with all elements coplanar. This means that for a horizontally polarized beam, the vertical dimension is just the thickness of the elements. This arrangement gives greater gain than if the orientation of each element is vertical, because of the directivity of the basic element as described earlier. It is also easier to construct, but be warned that you must make sure that the spacing between the close parallel sections of the subelements is well defined, and can't blow around in the breeze! As mentioned earlier with respect to the Twin C dipole, the beam can be tuned by adjusting the spacing of the subelements. The 6-m, three-element Twin C beam is 55″ wide by 95″ long; whereas the full size beam is 115″ wide by 95″ long, so the "wingspan" of the Twin C beam is less than half that of the full size beam and is comparable with that of a quad antenna. This reduction in the maximum dimension of course applies to Twin C beams designed for any band. A 10-m version of the three-element Twin C has dimensions of about 15′ long by about 8′ wide. The 2:1 SWR bandwidth is about 600 kHz, and the gain bandwidth (to the –1dB points) is 1.5 MHz.

A Twin C beam has a constructional bonus, in that the element diameter can be smaller than that of a full-size beam because the bent-back element ends can be supported on insulators mounted on the boom. This means that the element diameter needs to be sufficient to support just one quarter of the span of a full size element, rather than half the span. I rather suspect this might be important in beams for the lower HF bands. In my next article we will further explore beams made from Twin C elements: Box Kites.

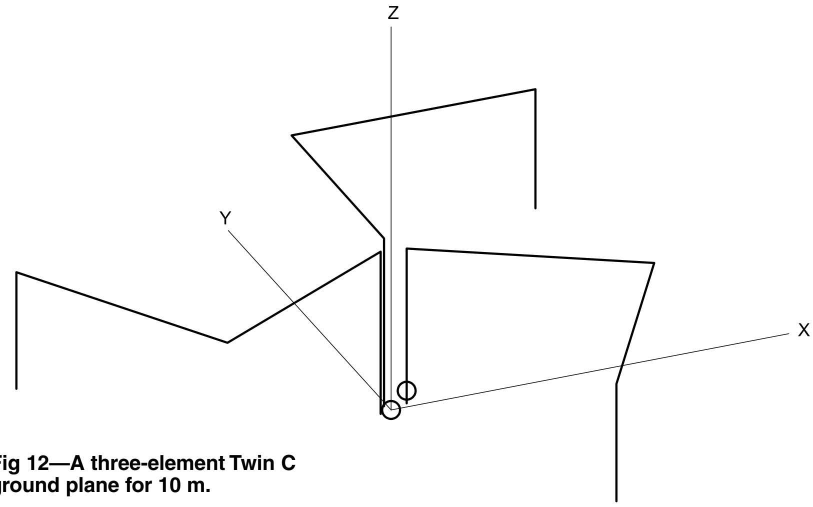


Fig 12—A three-element Twin C ground plane for 10 m.

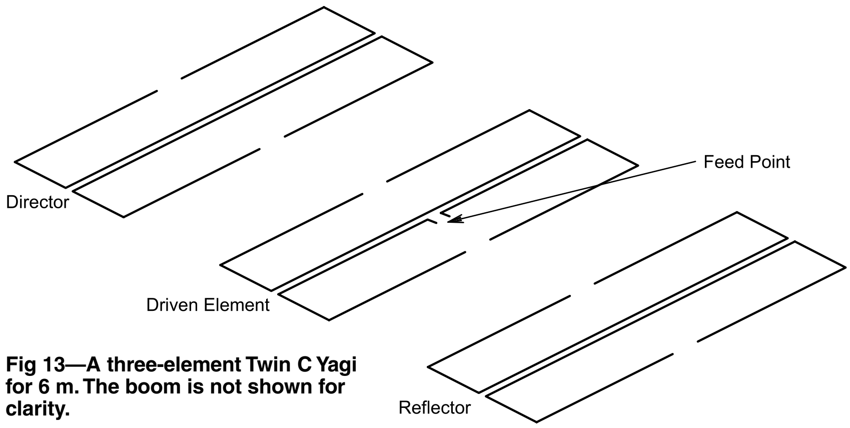


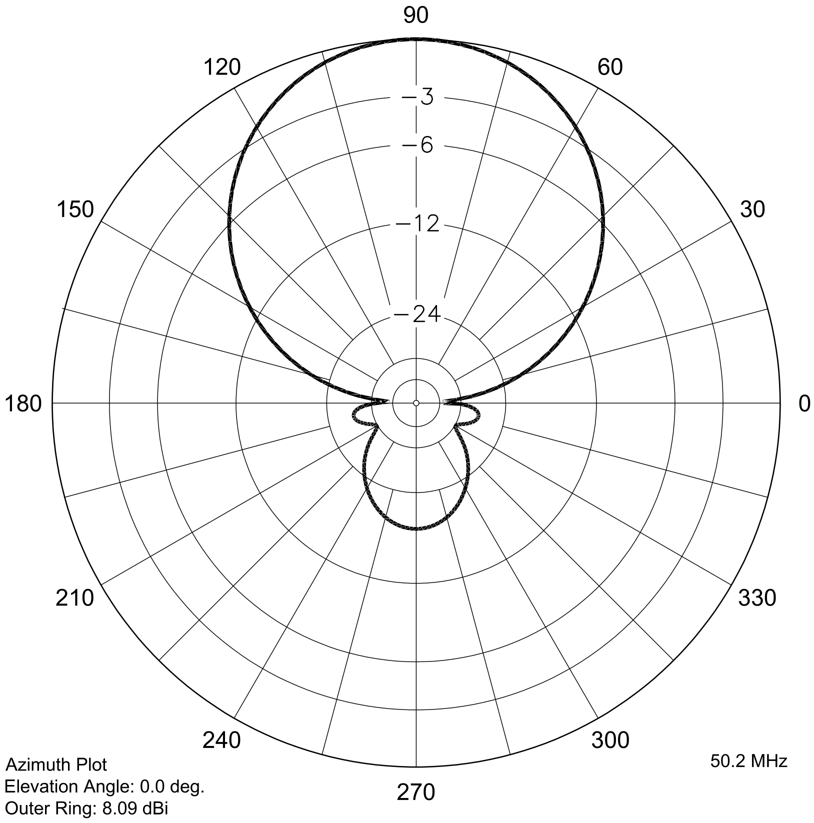
Fig 13—A three-element Twin C Yagi for 6 m. The boom is not shown for clarity.

Notes

[1]*EZNEC pro* 3.0 is available from Roy Lewallen, W7EL, at **www.eznec.com**.

[2]The new methods described are patent pending.

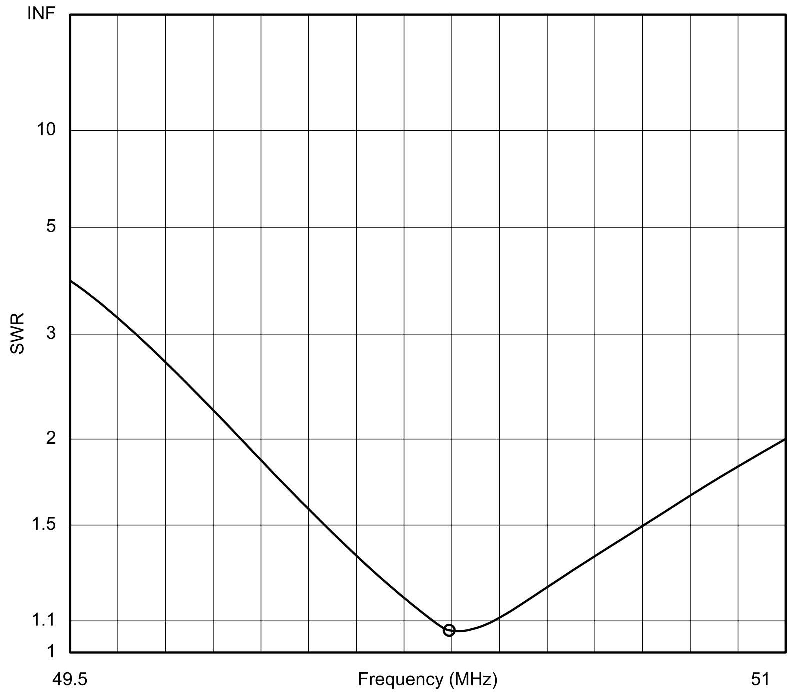
[3]R. Johnson, *Antenna Engineering Handbook*, third edition, (New York: McGraw-Hill, 1987).



Azimuth Plot
Elevation Angle: 0.0 deg.
Outer Ring: 8.09 dBi

Slice Max Gain: 8.09 @ Az Angle = 90.0 deg.
Front / Back: 18.23 dB
Beamwidth: 68.4 deg., −3 dBi @ 55.8, 124.2 deg.
Sidelobe Gain: −10.14 dBi @ Az Angle = 270.0 deg.
Front / Sidelobe: 18.23 dB

Fig 14—E-plane pattern for 3 element Twin C 6 m Yagi.



Freq 50.3 MHz
SWR 1.055
Z 47.56 + j 0.9487 ohms
Refl Coeff 0.02686 at 158.22 deg.
Source # 1
Z0 50 ohms

Fig 15—SWR plot for three-element Twin C 6 m Yagi.

Boxkite Yagis

Arrays of Twin C elements provide gain at the fundamental frequency and its third harmonic.

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The elements used in the "Boxkite" Yagi are based on a derivative of the basic Twin C element. The derivation is probably easier to illustrate and understand if we back into it from a different direction. Fig 1 shows one version of a classic "Lazy H," which consists of four half-wave dipoles end fed in phase. The arrows show the current direction on each dipole; the currents are a maximum at the dipole centers. If we consider the top two dipoles, they are end fed in series via a λ/4 balanced transmission line that transforms the high impedance of the dipoles down to a low impedance at the feed point. The lower two dipoles are fed the same way, and the upper and lower halves are fed in parallel by the source. The horizontal and vertical stacking distances are both λ/2, and the element produces a bidirectional horizontally polarized field with a gain of close to 8 dBi.

If we now put a source in series with one of the feed lines and put a phase reversal in the transmission line to preserve the correct phases, we arrive at Fig 2. Notice from Fig 1 that the total length of wire in each half of the element is 3λ/2 and that the total length of the transmission-line segment is λ/2. This means that at one-third of the design frequency the transmission-line section is λ/6 long and the total length of wire in each

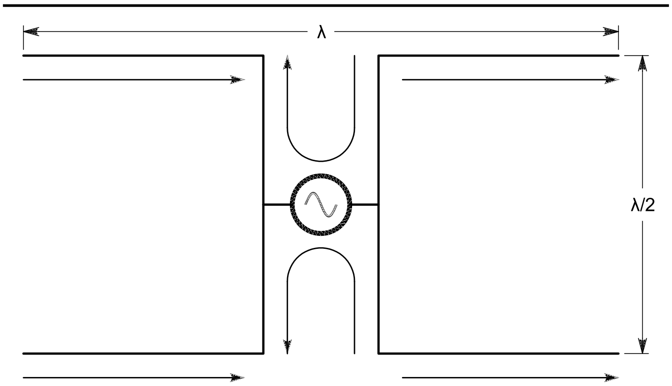

Fig 1—Lazy H antenna.

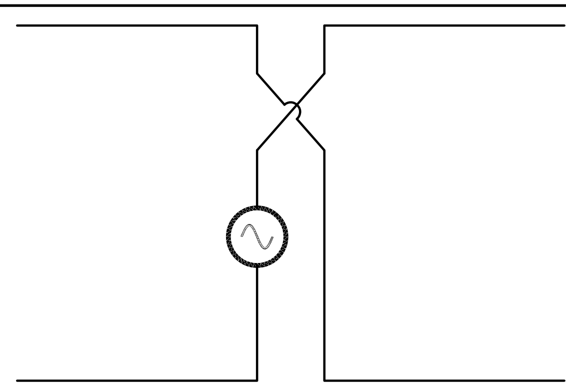

Fig 2—Boxkite element arrangement.

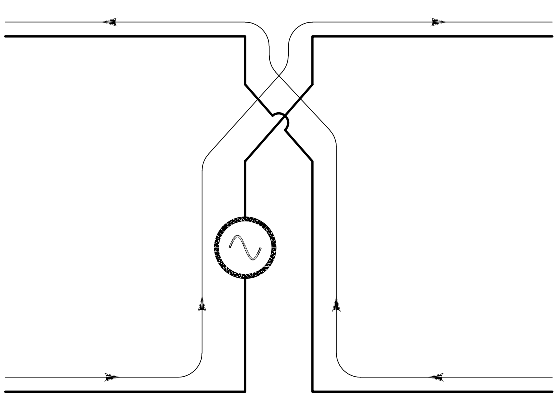

Fig 3—Boxkite element currents at *F1*.

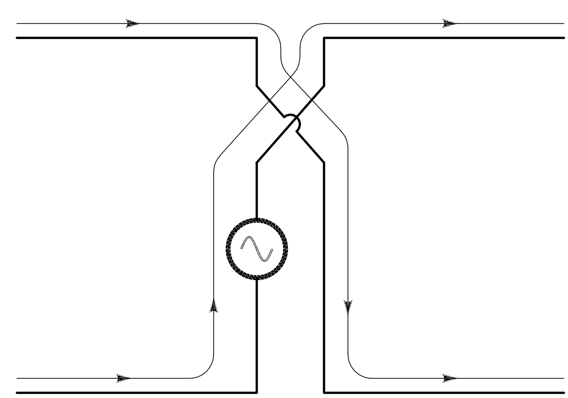

Fig 4—Boxkite element currents at *F2*.

half is λ/2. Does that sound familiar? At this frequency, the element behaves exactly like a Twin C, although the transmission-line section has been transposed and the wings straightened out. So, we end up with an element that behaves as a vertical Twin C at the lower, or fundamental, frequency and as four stacked horizontal dipoles at the third harmonic. The connection of the source in series with one leg of the transmission line raises the resonant resistance at the third harmonic to four times that of the equivalent Lazy H and permits operation of the element at the fundamental. The current flow in the Boxkite element is shown in Figs 3-5. Fig 3 shows operation at the fundamental frequency, *F1*. The currents in the horizontal sections are in antiphase, and those in the vertical transmission-line segments are in phase, so the element behaves as a vertical radiator. Fig 4 shows the current phases at *F2*. The currents in the transmission lines are now in antiphase, but the horizontal-section currents are now all in phase, so the element produces a horizontally polarized field. Fig 5 shows the current phases at the third harmonic, which we will call *F3*. Here again, the vertical fields cancel and the element produces a horizontally polarized field.

We will only concern ourselves here with operation at *F1* and *F3*, although operation at *F2* is intriguing since the models show that optimizing at *F1* and *F3* also produces excellent characteristics at *F2*, both in terms of pattern, gain and SWR. I have spent no time trying to analyze or utilize this phenomenon. It is possible that a Boxkite antenna operating at *F1* and *F2* could be very useful, since the two frequencies need not be harmonically related. The difference in frequency between *F1* and *F2* is controlled by the coupling coefficient, which we can vary over a wide range. Investigation of this must wait until I have finished other urgent projects!

There is an important point to remember about how operation on *F1* and *F3* is possible, since *F1* and *F3* can be exactly harmonically related. We know that a λ/2 dipole resonant at *F1* will exhibit third harmonic resonance at a slightly lower frequency than *F3* because the element diameter at *F3* is a larger fraction of a wavelength than at *F1*. Conversely, this means that, if the element length is reduced so that resonance is achieved at *F3*, then the element will resonate at a higher frequency than *F1*.

You will recall that the natural resonant frequency of the subelements in a Twin C needs to be somewhat

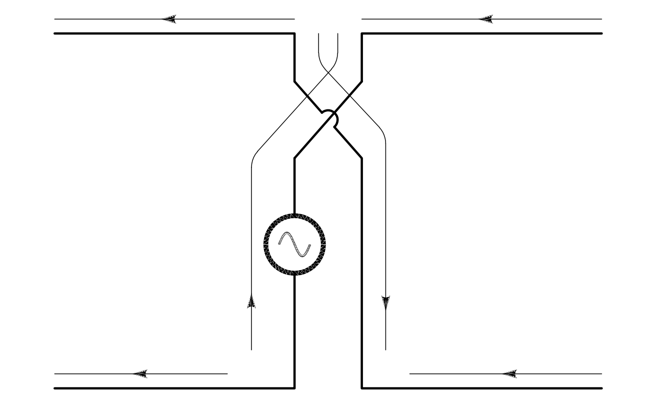

Fig 5—Boxkite element currents at *F3*.

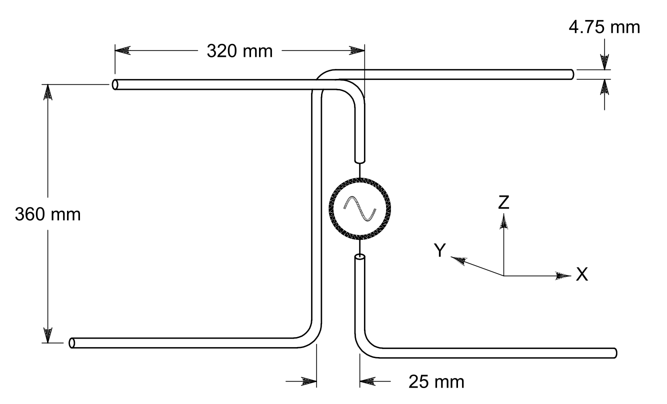

Fig 6—Physical Boxkite driven element for 2 m and 70 cm.

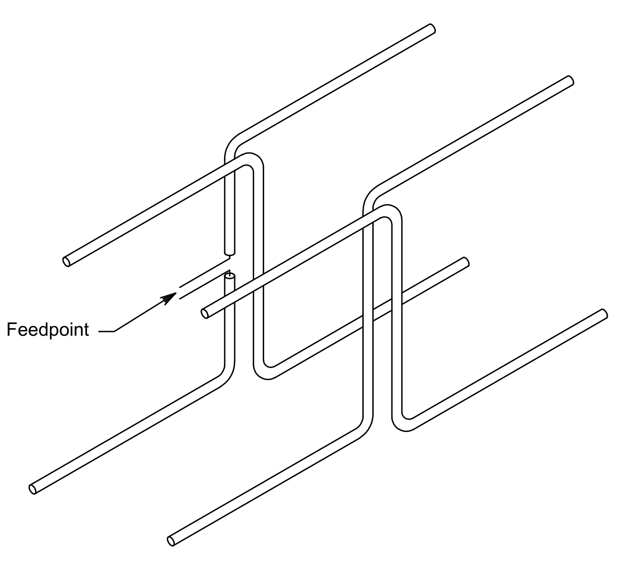

Fig 7—Prototype two-element Boxkite for 2 m/70 cm.

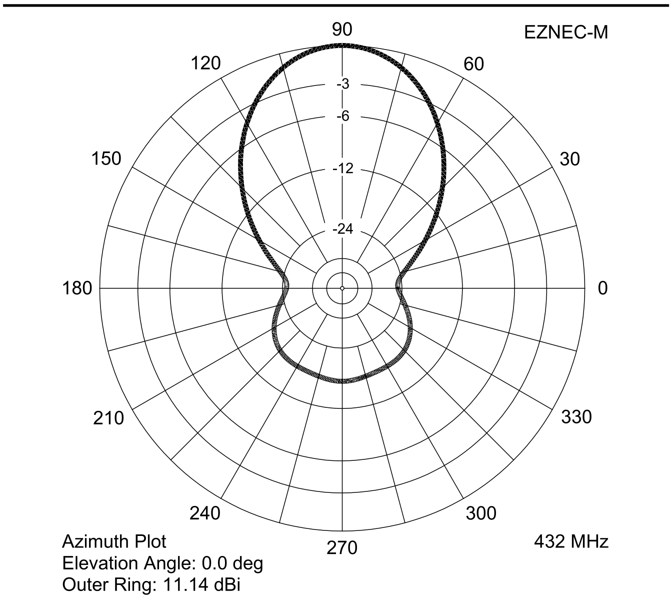

Fig 8—E-plane pattern for two-element prototype Boxkite at 432 MHz.

higher than the operating frequency, because the effects of coupling reduce the coupled resonant frequency somewhat. This effect allows the Boxkite element to resonate precisely at the fundamental and third harmonic. It is remarkable that the element-diameter effect allows this to happen and that the coupling coefficient is correct for spacing of the parallel sections that allows the correct impedance transformation ratio at *F3*.

I found that it is not only possible to adjust the element dimensions for operation on two harmonically related frequencies (for example 2 m and 70 cm), but also to equalize the feedpoint resistance at each frequency. The prototype Boxkite driven element dimensions for 2 m/70 cm are shown in Fig 6. It is fabricated from 3/16-inch-diameter aluminum rod. Its feedpoint resistance at both 144 MHz and 432 MHz is 125 Ω, and it has 2:1 SWR bandwidths of 12.5 MHz and 55 MHz, respectively, which makes it very useful for use as the driven element of a Yagi-like beam. Notice that the close parallel wires are not arranged as in the "lazy H," but are spaced as shown

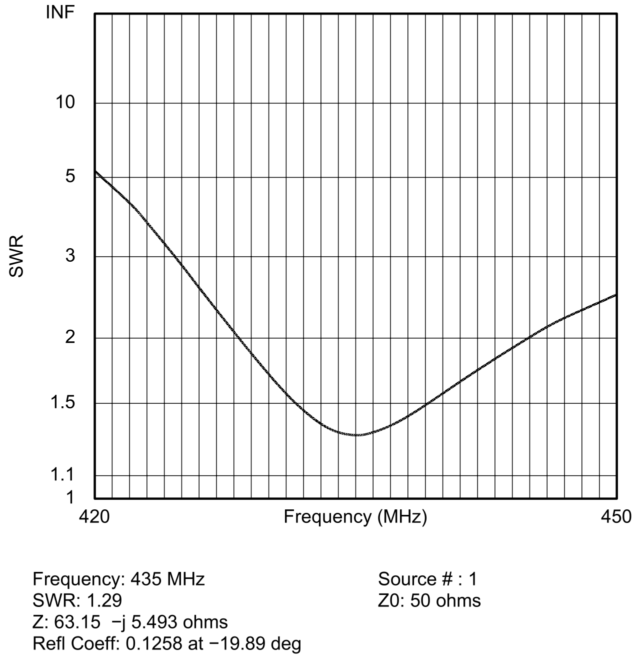

Fig 9—Two-element prototype Boxkite SWR on 70 cm.

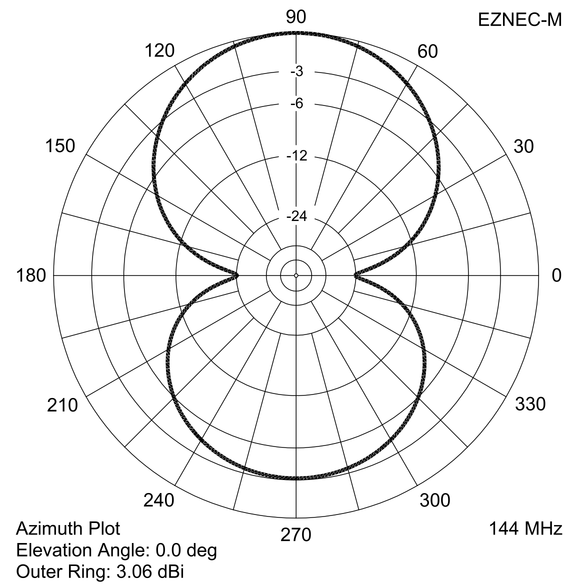

Fig 10—E-plane pattern for two-element prototype Boxkite at 144 MHz.

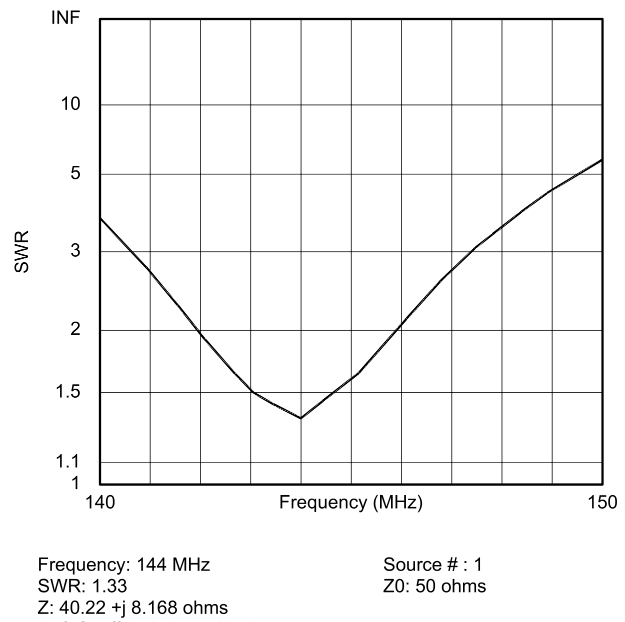

Fig 11—Two-element prototype Boxkite SWR on 2 meters.

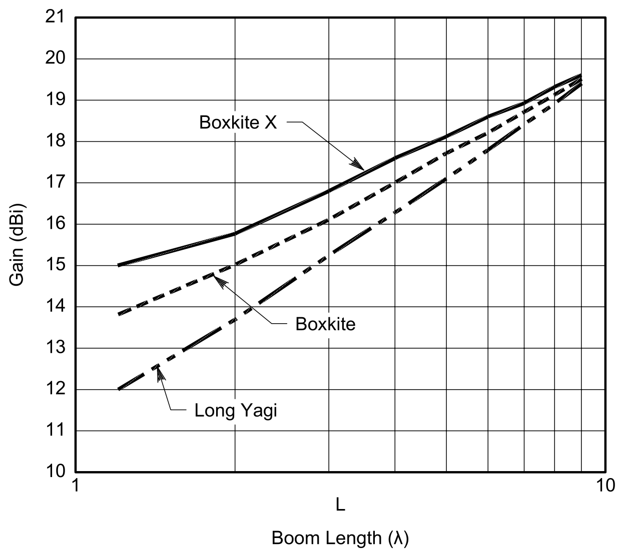

Fig 12—Yagi and Boxkite gain versus boom length.

in Fig 6, along the axis of the boom. This arrangement avoids the awkward cross over needed to maintain correct phases. One might worry about unequal coupling into the two halves of the element because of the offset between them along the Y axis. This does indeed occur but does not appear to affect the behavior of the antenna in any significant way, except as noted later.

Adding Parasitic Elements

It just so happens that the parasitic elements in a Boxkite beam can be of exactly the same form as the driven element. At *F1*, the element behaves as a short, end-loaded dipole. At *F3*, the currents in the four dipoles that make up the driven element induce currents in the four dipoles in the parasitic elements. The transmission-line sections of the parasitic elements behave as pairs of back-to-back λ/4 lines that present relatively high impedances to the ends of the four dipoles. One simplified way to look at this is that the λ/4 sections act as insulators at the third harmonic, so the four dipoles are isolated from ground and from each other. The spacing and lengths of the elements at *F3* roughly follow those of the excellent Yagis designed by K1FO, DL6WU and others. That is, there is a log taper of the element lengths and of the element spacings.[1, 2] This provides excellent gain, minimal side lobes and very good SWR characteristics. As it happens, the simulations show that these characteristics are maintained, albeit to a lesser extent, at *F1*. I was very surprised to find the feedpoint resistance at *F1* is close to 50 Ω, since the spacing of the parasitic elements is a very small fraction of a wavelength. For full- sized elements, this would mean a very low feedpoint resistance.

I have done some preliminary modeling work to compute the mutual impedance between two identical Boxkite elements as a function of the spacing between them. So far, I have no results to show, but I've noticed that the behavior of coupled Boxkite elements is notably different—and more complex—than that of coupled dipole elements, as might have been predicted. Although it is not easy to adjust a beam such as this for optimum performance in terms of gain, side-lobe level and SWR bandwidth on two bands, it is possible, as the following results will show.

During development, I was concerned that the staggered elements would cause asymmetric patterns and reduce the gain at *F3*. To resolve this, I modeled four Yagis stacked in the same way that the four sets of horizontal elements of the Boxkite are stacked. The models showed that staggering the elements does have an effect on the gain and pattern, but it is negligible. Two conventional Yagis offset along the boom axis do produce an asymmetric pattern; but here, the top pair is asymmetric in one direction and the lower pair in the opposite direction, so the resultant pattern is symmetrical. The models also showed, as expected, that increasing the horizontal stacking distance would increase the gain substantially, but this is difficult to do while maintaining enough coupling for operation at *F1*. See some remarks later on this issue.

For the prototypes, I insulated all the elements from the boom to avoid intermittent contact and boom screening problems. In theory, the centers of each of the subelements that comprise the parasitic elements can be connected together, but there is no advantage in doing this.

Prototype 2 m/70 cm Beams

I started by optimizing a two-element beam. By elements, I mean Boxkite elements, where each element has four dipoles operating at *F3*. The antenna is illustrated in Fig 7. Pattern and SWR data are shown in Figs 8 and 9 for 70 cm, and Figs 10 and 11 for 2 m. Notice that, unlike a conventional Yagi, where all elements are in the E plane, the Boxkite has elements lying in the H plane, so there are both vertical and horizontal components in the pattern because of a small amount of radiation from the transmission-line sections. To avoid confusion, the pattern plots show the total field only. This antenna has a gain of over 11 dBi at 432 MHz: The antenna behaves as a square array of four two-element Yagis stacked vertically and horizontally by 1/2λ. Although a spacing of 1/2λ is far from optimum from a gain standpoint, it does produce a very clean pattern with weak side lobes, as can be seen from Fig 8. On 2 m, the antenna is two reduced-length dipoles with very close spacing, so the gain of a little more than

[1]Notes appear on page 45.

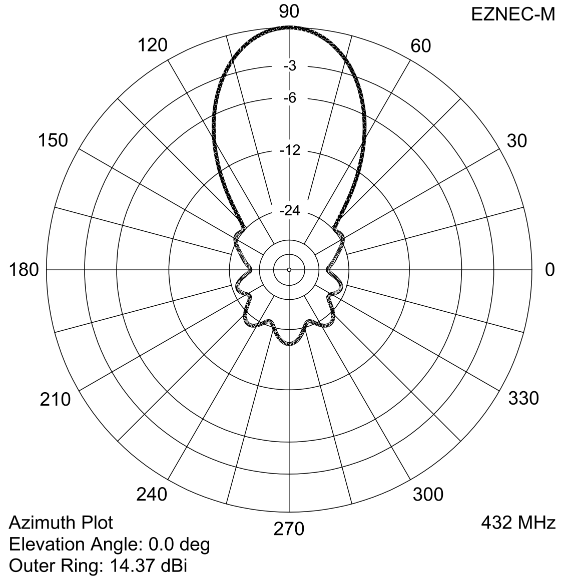

Fig 13—E-plane pattern for nine-element 1.65 λ Boxkite at 432 MHz.

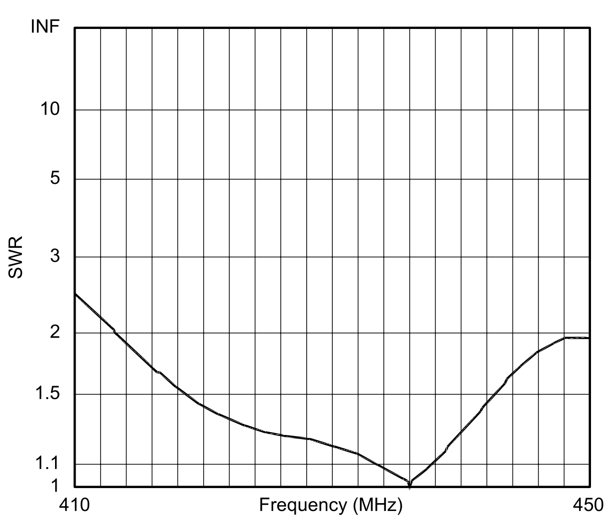

Fig 14—SWR for nine-element 1.65 λ Boxkite on 70 cm.

a dipole is expected. As can be seen from Figs 9 and 11, the SWR plots look reasonable on both bands. With Boxkites having longer booms, the SWR can be flattened substantially by tapering the directors, as is common with high-performance long-boom Yagis.

To build longer beams, elements are added in exactly the same way one would extend a Yagi, with dipoles replaced with Boxkite elements. In developing these Boxkites, I used relatively wide element spacing to provide wide SWR and gain bandwidth on 70 cm. This reduces the gain a little for a given boom length, but provides very broadband operation. Increasing the element spacing produces higher feedpoint impedances, so all the long Boxkites are designed for a feedpoint impedance of 112 Ω. (This does not apply to the two-element prototype, which has a 50-Ω feedpoint impedance.) This choice was made so that a simple balun using 75-Ω cable could be used as described later under "Baluns." I have modeled Boxkite Yagis for 2 m/70 cm for 2 through 29 elements and have measured the performance (SWR and pattern) of prototypes of most of them up to 14 elements (3.4 λ boom).

Theory says that if the stacking distance stays constant as the boom length increases, the antenna gain (as a function of boom length) will be asymptotic to that of a single Yagi. This appears to be the case; but for practical boom lengths, there still seems to be a clear gain advantage on 70 cm for the Boxkite. Fig 12 shows that the Boxkite maintains a constant length advantage of about 1.0 λ over a Yagi of the same gain. This is almost independent of the boom length. (The

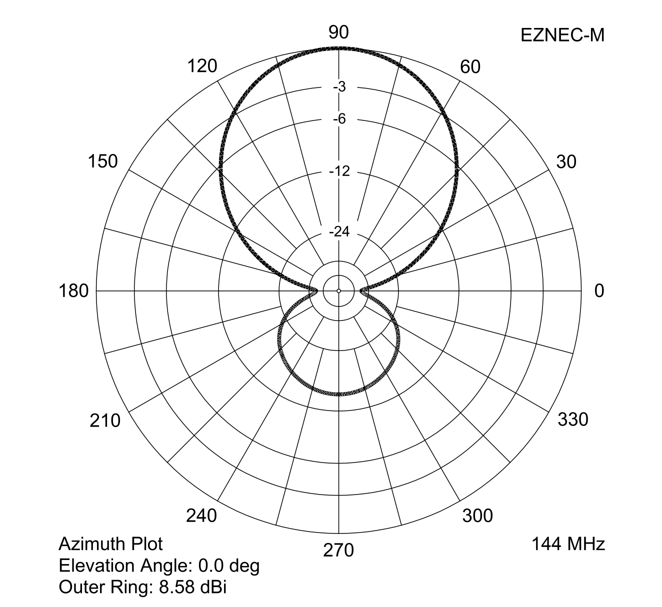

Fig 15—E-plane pattern for nine-element 1.65 λ Boxkite at 144 MHz.

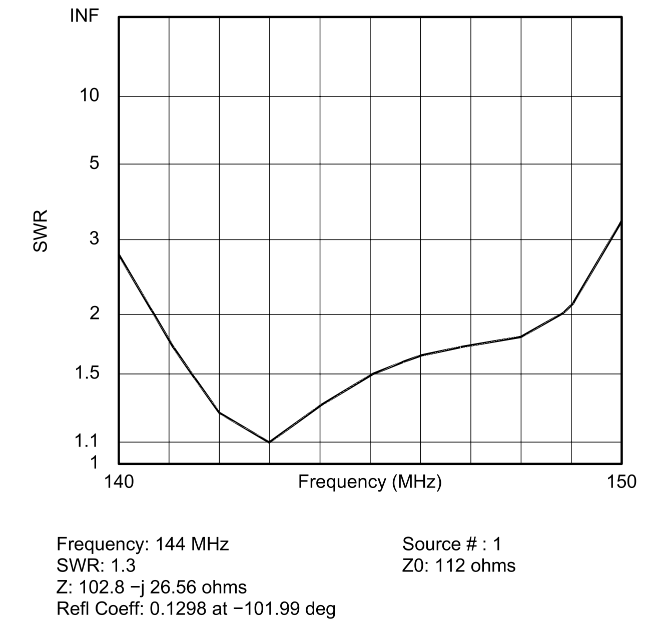

Fig 16—SWR for nine-element 1.65 λ Boxkite on 2 m.

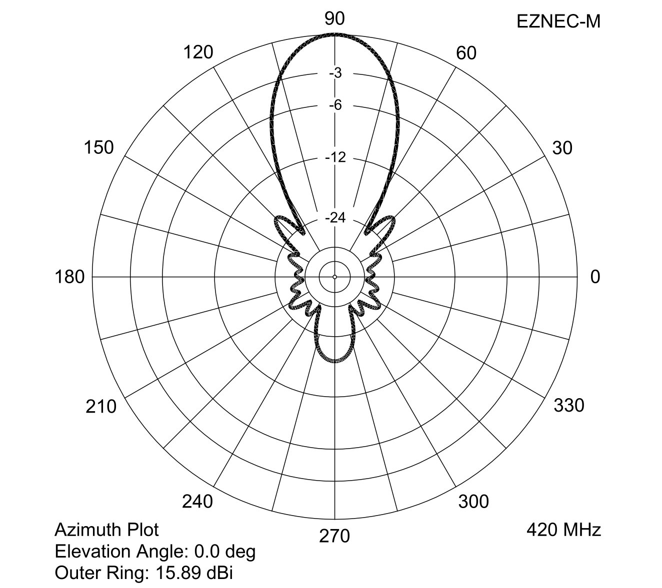

Fig 17—E-plane pattern of 14-element 3.4 λ Boxkite at 420 MHz.

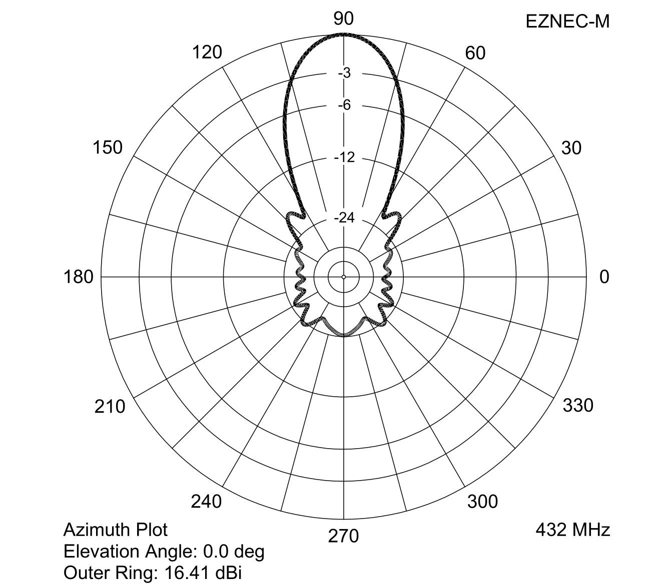

Fig 18—E-plane pattern of 14-element 3.4 λ Boxkite at 432 MHz.

Boxkite X plotted in Fig 12 is discussed later.)[3] Thus, the Boxkite gain is given approximately by:

$$G \approx 10\log[10(L_{\lambda}+1)]\ \text{dBi} \qquad \text{(Eq 1)}$$

For a contemporary, high-performance long Yagi, gain is:

$$G \approx 10\log[10L_{\lambda}]\ \text{dBi} \qquad \text{(Eq 2)}$$

On 2 m, as expected, the gain for a given boom length is less than that of a Yagi of similar length. Plots of the pattern and SWR for the nine-element Boxkite are shown in Figs 13-16. Although not shown, the pattern has low sensitivity to frequency changes, which is important because it gives an idea of the design's dimensional tolerance. One other concern is tolerance to wet weather, especially because transmission-line sections are important parts of the antenna. The approximately 1-inch spacing of the transmission-line sections is big enough so that serious detuning does not occur. All VHF/UHF Yagis detune to some extent when wet, but I have found this a minor problem with Boxkites.

Notice that all my long Boxkites have double reflectors. At first, this may seem a little odd, but the addition of the second reflector makes it much easier to optimize the SWR without affecting the F/B ratio.

A 14-element Boxkite is of considerable interest because it gives excellent performance on both 2 m and 70 cm with a very practical eight-foot boom length. Figs 17-22 show pattern and

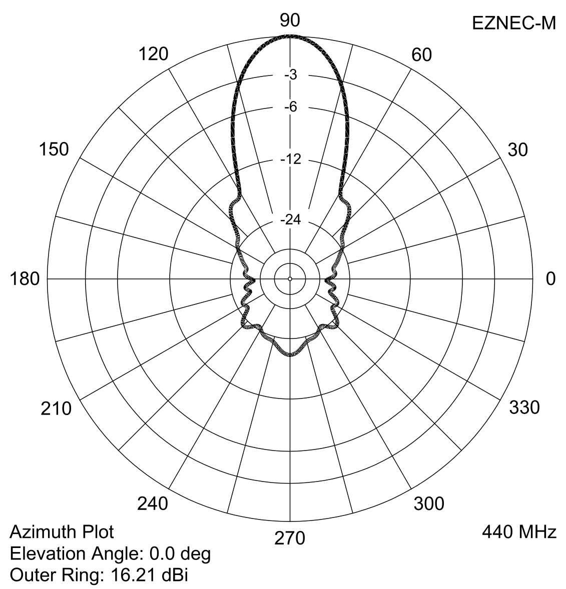

Fig 19—E-plane pattern of 14-element 3.4 λ Boxkite at 440 MHz.

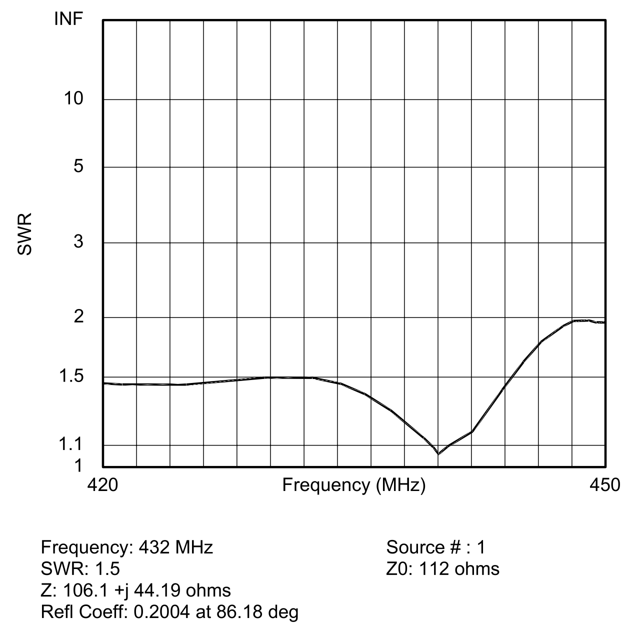

Fig 20—SWR plot for 14-element 3.4 λ Boxkite on 70 cm.

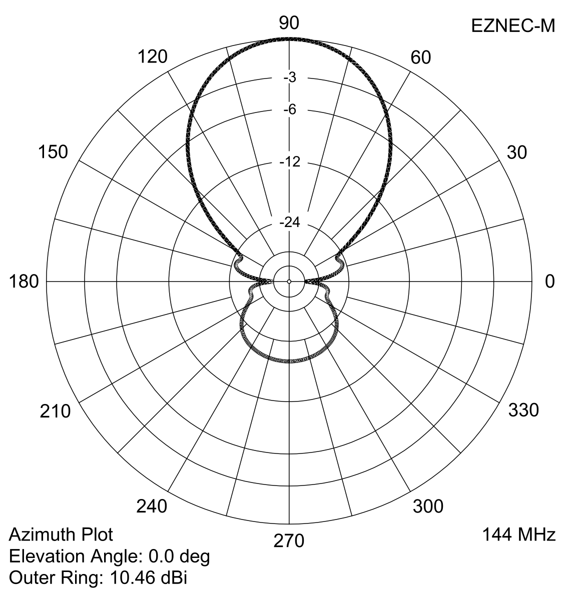

Fig 21—E-plane pattern of 14-element 3.4 λ Boxkite at 144 MHz.

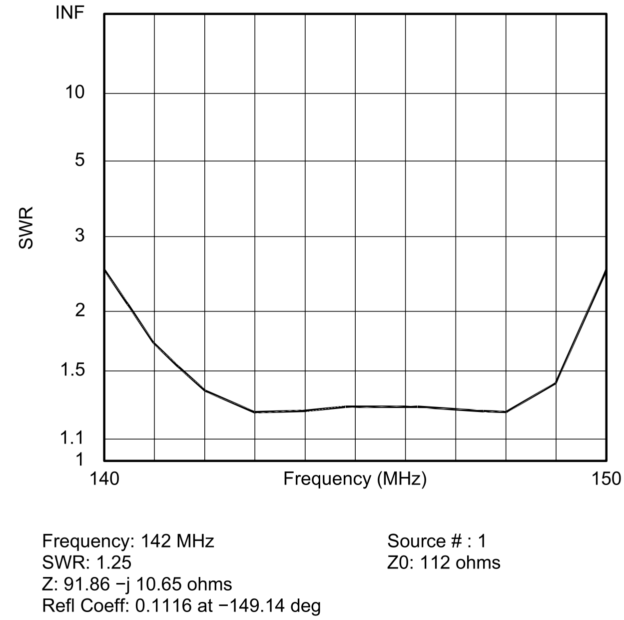

Fig 22—SWR plot for 14-element 3.4 λ Boxkite on 2 m.

SWR data. Figs 17, 18 and 19 show the E-plane patterns at 420, 432 and 440 MHz, respectively. The gain bandwidth on 70 cm at the –1 dB level is 30 MHz, or 7% of the center frequency. The 70 cm SWR plot in Fig 20 shows a 2:1 SWR bandwidth in excess of 30 MHz. Fig 21 shows the E-plane pattern at 144 MHz. Gain bandwidth on 2 m is 11 MHz, or 7.5% of the center frequency at the –1 dB level.

One might argue that a Boxkite VHF/UHF beam having polarization that is different at the two operating frequencies is of little practical value, because of cross-polarization effects in contacts with horizontally polarized antennas conventionally used for weak-signal work. However, the fact is that the Boxkite provides greater gain on a shorter boom than a conventional Yagi on the third harmonic, *and the performance on the fundamental is a bonus!*

Dimensions for the long Boxkites for 2 m/70 cm are shown in Table 1. The key to the dimensions of each subelement is shown in Fig 23. I will give some construction tips later in this article. Notice that these data are universal: The element dimensions and spacings are independent of the final boom length. Just decide what gain or boom length you want and build the antenna using the dimensions shown.

I have also modeled a nine-element Boxkite for 6 m and 2 m. This antenna has a gain of 8.6 dBi on 6 m and

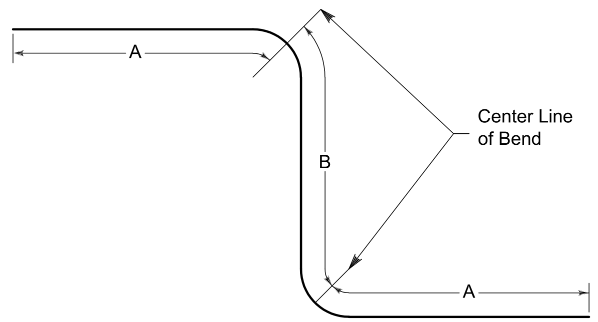

Fig 23—Key to subelement dimensions given in Table 1.

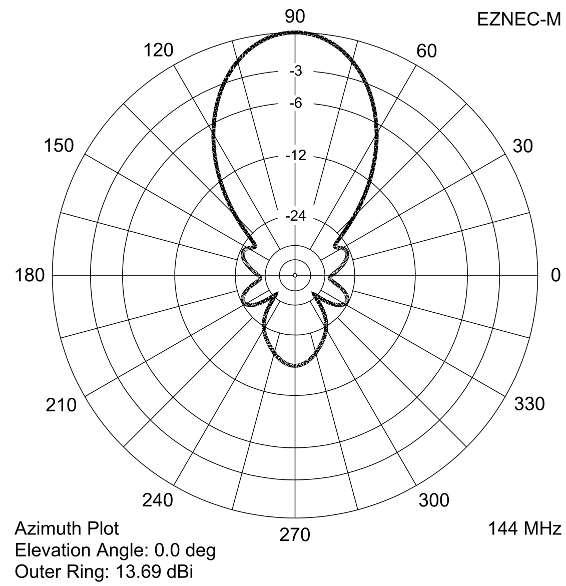

Fig 24—Nine-element 6 m/2 m Boxkite E-plane pattern at 144 MHz.

Table 1

Dimensions for 9- through 19-element Boxkites for 2 m/70 cm.

Element	Pos^n (mm)	A (mm)	B (mm)	B/2 (mm)	S (mm)	Pos^n (inches)	A (inches)	B (inches)	B/2 (inches)	S (inches)	Gain 70 cm (dBi)	Gain 2 m (dBi)	Boom Length (ft)
Ref 1	0	320	366	183	25	0	12.6	14.4	7.2	1.0			
Ref 2	140	345	366	183	25	5.51	13.6	14.4	7.2	1.0			
Driven	247	306	374	187	20	9.72	12.05	14.7	7.35	.80			
Dir 1	300	290	366	183	25	11.81	11.4	14.4	7.2	1.0			
Dir 2	410	270	366	183	25	16.14	10.65	14.4	7.2	1.0			
Dir 3	550	255	366	183	25	21.65	10.05	14.4	7.2	1.0			
Dir 4	720	250	366	183	25	28.35	9.85	14.4	7.2	1.0			
Dir 5	910	245	366	183	25	35.83	9.65	14.4	7.2	1.0			
Dir 6	1120	243	366	183	25	44.1	9.55	14.4	7.2	1.0	14.3	8.5	3'10"
Dir 7	1340	240	366	183	25	52.75	9.45	14.4	7.2	1.0	14.8	8.9	4'7"
Dir 8	1570	237	366	183	25	61.8	9.33	14.4	7.2	1.0	15.3	9.3	5'3"
Dir 9	1810	234	366	183	25	71.26	9.21	14.4	7.2	1.0	15.7	9.8	6'
Dir 10	2060	231	366	183	25	81.1	9.1	14.4	7.2	1.0	16.1	10.2	6'10"
Dir 11	2320	228	366	183	25	91.34	8.98	14.4	7.2	1.0	16.4	10.5	7'9"
Dir 12	2590	226	366	183	25	101.97	8.90	14.4	7.2	1.0	16.7	10.8	8'8"
Dir 13	2860	223	366	183	25	112.6	8.78	14.4	7.2	1.0	17.0	11.1	9'7"
Dir 14	3130	221	366	183	25	123.2	8.70	14.4	7.2	1.0	17.4	11.4	10'6"
Dir 15	3400	219	366	183	25	133.9	8.62	14.4	7.2	1.0	17.6	11.6	11'3"
Dir 16	3670	217	366	183	25	144.5	8.54	14.4	7.2	1.0	17.8	11.8	12'2"

13.7 dBi on 2 m—all on an 11-foot boom (see Figs 24-27). A conventional long Yagi would require an 18-foot boom to achieve the same gain on 2 m. I have not fully established the synthesis procedure for not-quite-harmonically-related beams, but clearly this looks promising.

Does it Work?[4]

SWR measurements of the prototype antennas agree excellently with the models. These measurements were made with an AEA SWR 121. Pattern measurements were made on my beach antenna range by (and sometimes in!) the beautiful Matanzas Inlet on the coast of Northeast Florida near St Augustine. For these measurements, I used either my trusty FT-847 or my AEA SWR 121 as the source, feeding a small Boxkite for 2 m/70 cm. The receiver was a Boonton 42BD Microwattmeter. The range was set up in accordance with guidelines given by Dick Turrin, W2IMU.[5] The measured patterns of the prototype 2, 9 and 14-element Boxkites on 2 m and 70 cm bear a very close resemblance to the simulation results, as can be seen from Figs 28-33.

The only plot that shows significant deviation from the simulation is the H-plane plot of the 14-element Boxkite on 144 MHz. I found this pattern particularly difficult to measure simply because I am a close-to-one-wave-length-long vertical element near the antenna under test! I had no such

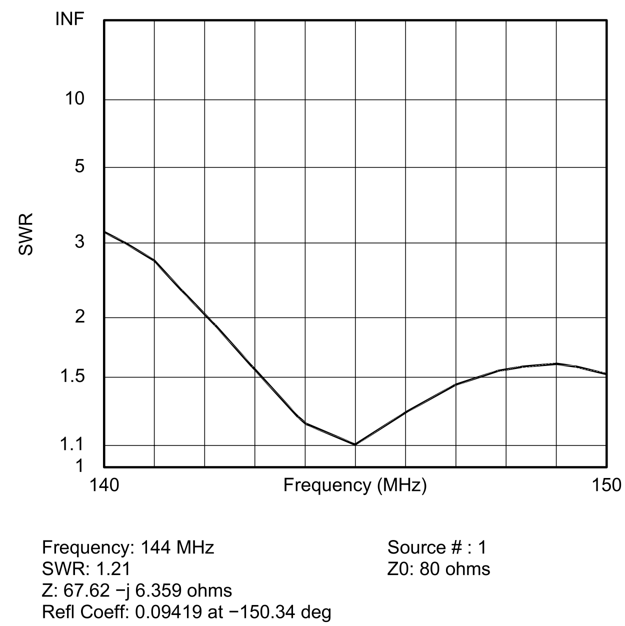

Fig 25—Nine-element 6 m/2 m Boxkite SWR on 2 m.

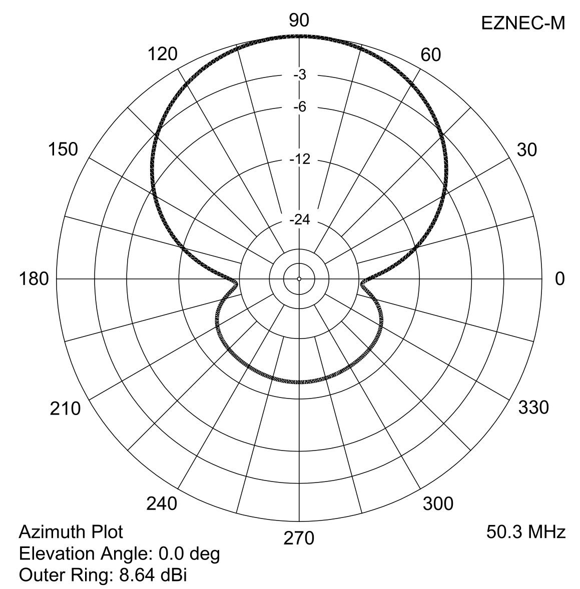

Fig 26—Nine-element 6 m/2 m Boxkite H-plane pattern at 50.3 MHz.

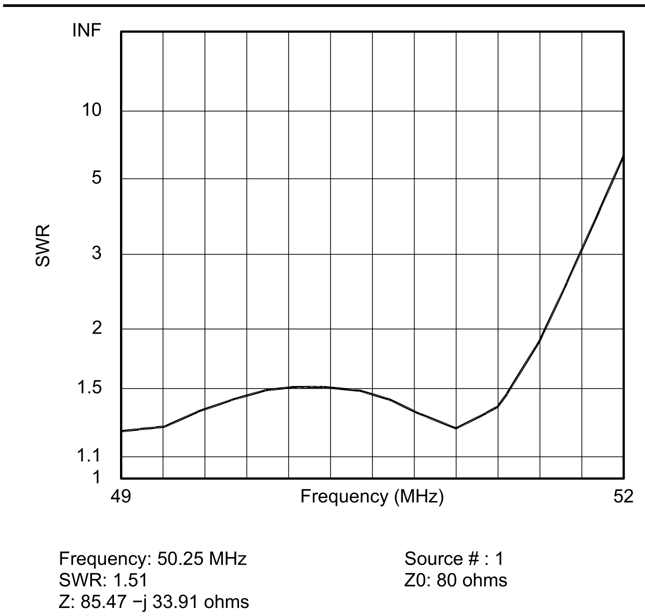

Fig 27—Nine-element 6 m/2 m Boxkite SWR on 6 m.

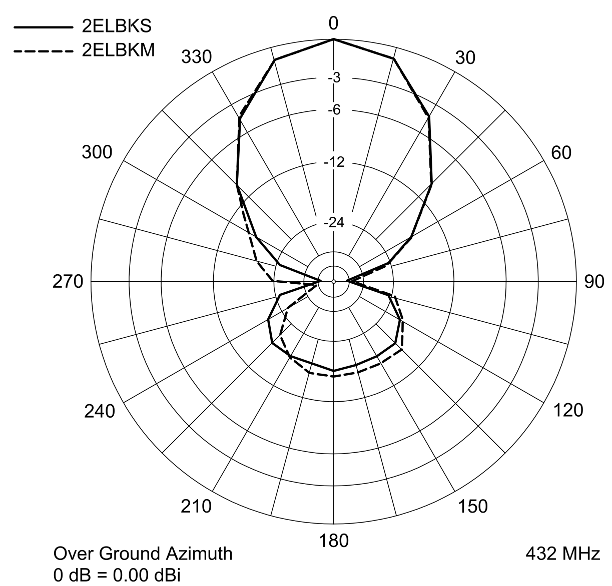

Fig 28—Simulated and measured E-plane pattern for two-element prototype Boxkite at 432 MHz.

problems with the E plane pattern on 144 MHz or either E or H plane patterns on 432 MHz.

The antennas were fed with a simple balun described later. Figs 34 and 35 show the simulated and modeled SWR plots for the 14-element Boxkite on 2 m and 70 cm, respectively. Notice the quite remarkable 2-m SWR plots!

Odd and Ends

Modeling

During the development period, I have tried to be extremely careful to check that the models produce very accurate results. I use the excellent *EZNEC pro* 3.0 software available from Roy Lewallen, W7EL. My biggest concern was that the close-spaced wires forming the transmission-line sections were being modeled accurately, so I ran some tests based on balanced twin-wire transmission-line theory. My conclusion is that, provided that an appropriate number of segments are used, the accuracy of the models for the wire diameters and spacings used in the antennas is excellent. This has been born out by the quite remarkable agreement between simulations and measurements on a wide variety of antennas.

I should point out that the 2 m/70 cm Boxkites have radius bends, and that I carefully measured the effects of this on the pattern and SWR. My conclusion is that the pattern is virtually unaffected by the 1/4-inch radius of the bend, and SWR is controlled more by the total length of each subelement, rather than by how the

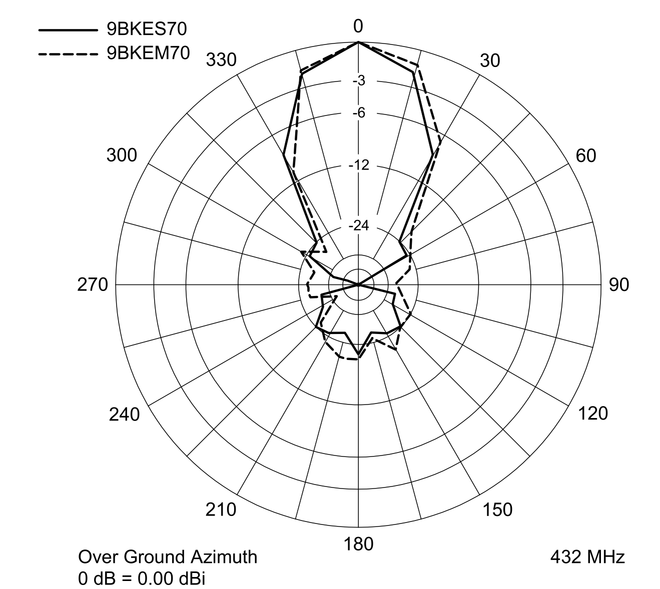

Fig 29—Simulated and measured E-plane pattern for nine-element prototype Boxkite at 432 MHz.

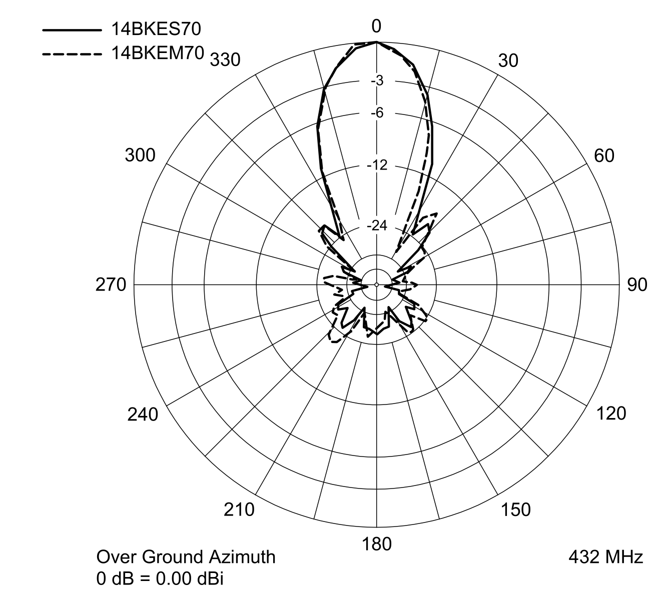

Fig 30—Simulated and measured E-plane pattern for 14-element 3.4 λ Boxkite at 432 MHz.

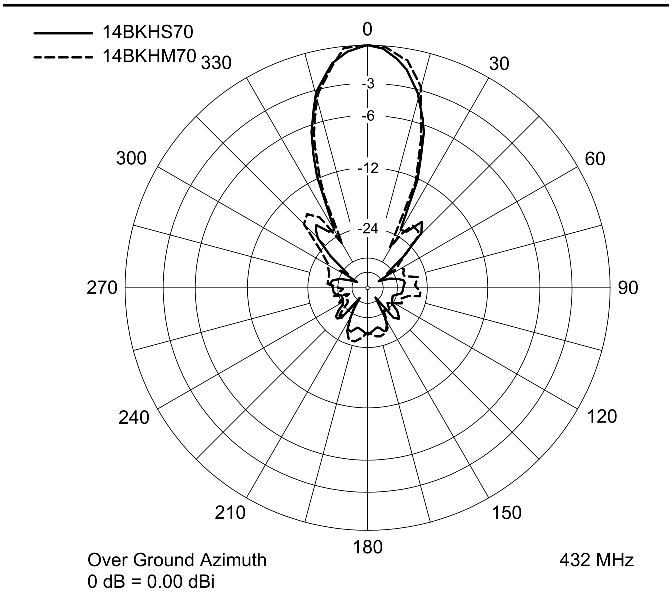

Fig 31—Simulated and measured H-plane pattern of 14-element 3.4 λ Boxkite at 432 MHz.

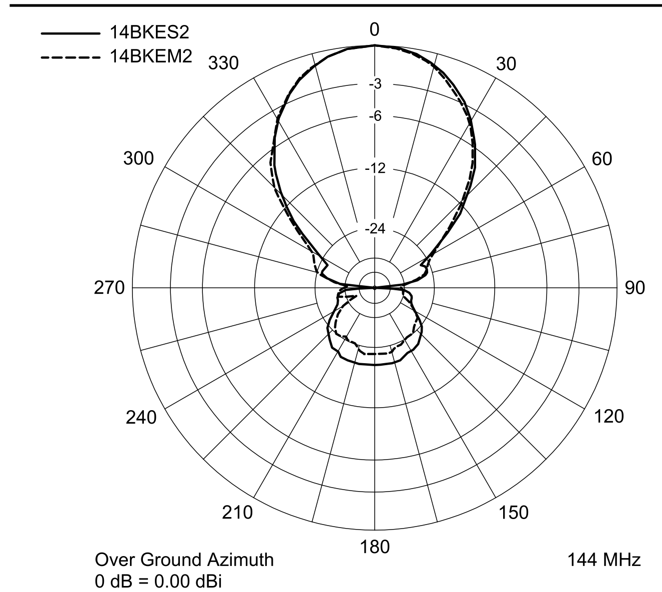

Fig 32—Simulated and measured E-plane pattern of 14-element 3.4 λ Boxkite at 144 MHz.

sector lengths are distributed. The center of a 3/16-inch diameter aluminum rod bent around a 1/4-inch radius stretches by a fraction of a millimeter: The inside of the bend contracts and the outside stretches. This means that the bend has very little effect on SWR. Hence, the prototype antennas were built by cutting the subelements exactly to the modeled length and measuring the horizontal section lengths from each subelement end to the center of the radius. This has proved a very simple and accurate way to make the subelements.

Construction Tips

Twin C dipoles can be made from any conventional antenna material, such as wire or tubing. Wire dipoles can be strung up between any convenient supports such as trees or poles. My prototypes were suspended from deck supports that are tall enough to accommodate them. Be sure that the wires in the parallel section cannot move relative to each other—otherwise, the tuning will vary.

Twin C beams can be made using any normal Yagi construction techniques, with the difference that the wings of the elements should be supported on insulators near the boom. For HF through 6 m, any reasonably sized boom will probably not cause boom-screening problems. The centers of all the nondriven subelements can be mounted without insulators directly on the boom, if desired. However, problems associated with boom screening and unreliable connections between aluminum elements and boom make this practice undesirable for antennas for 2 m and above.

The prototype Boxkites were built using readily available materials. The following is a description of how they were put together (omitting all the mistakes, of course!). The parasitic elements are mounted in polypropylene blocks cut from kitchen cutting boards available from any department store. The boom was a 1-inch square aluminum section available from most

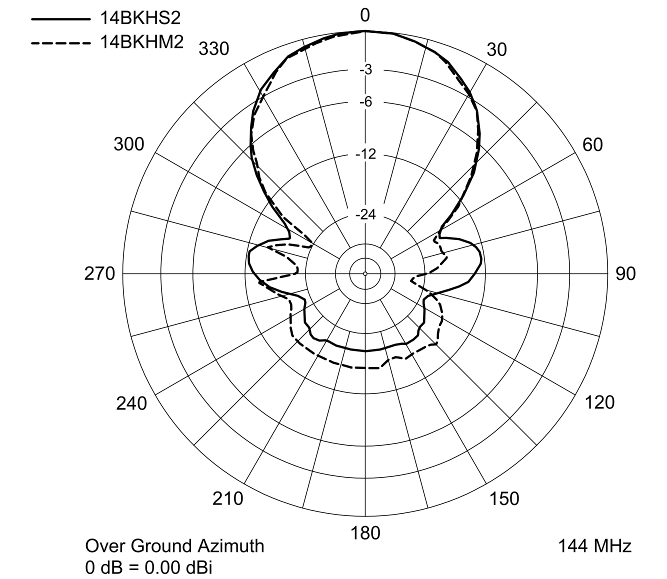

Fig 33—Simulated and measured H-plane pattern for 14-element Boxkite at 144 MHz.

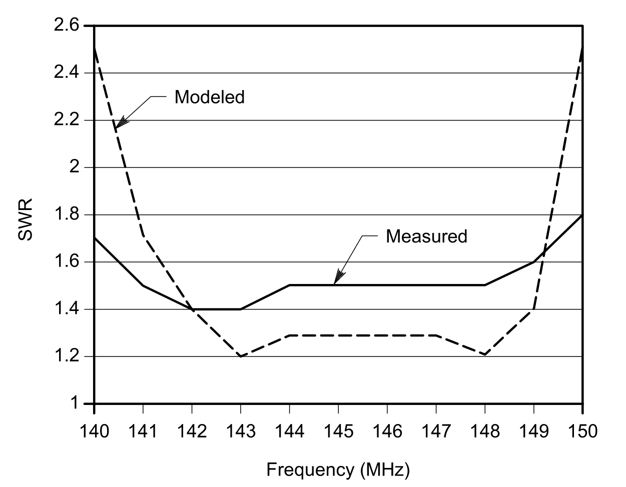

Fig 34—Simulated and measured SWR of 14-element 3.4 λ Boxkite on 2 m.

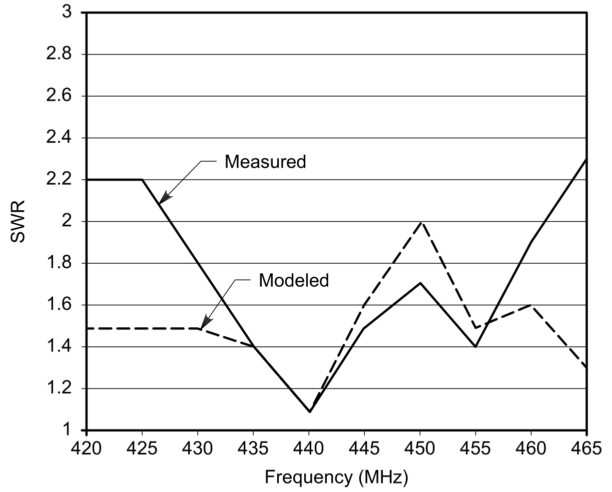

Fig 35—Simulated and measured SWR of 14-element 3.4 λ Boxkite on 70 cm.

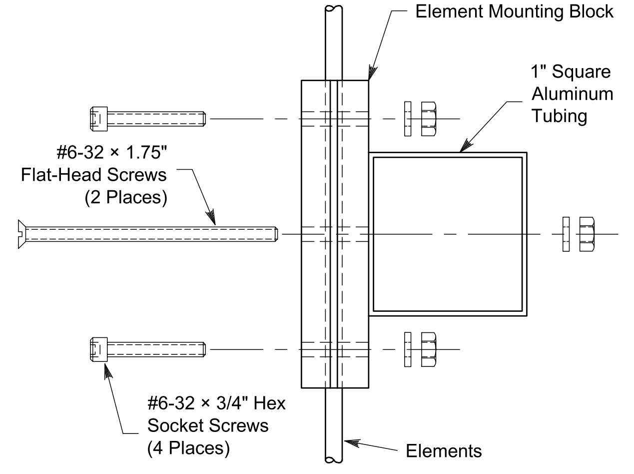

Fig 36—Method of mounting the parasitic elements.

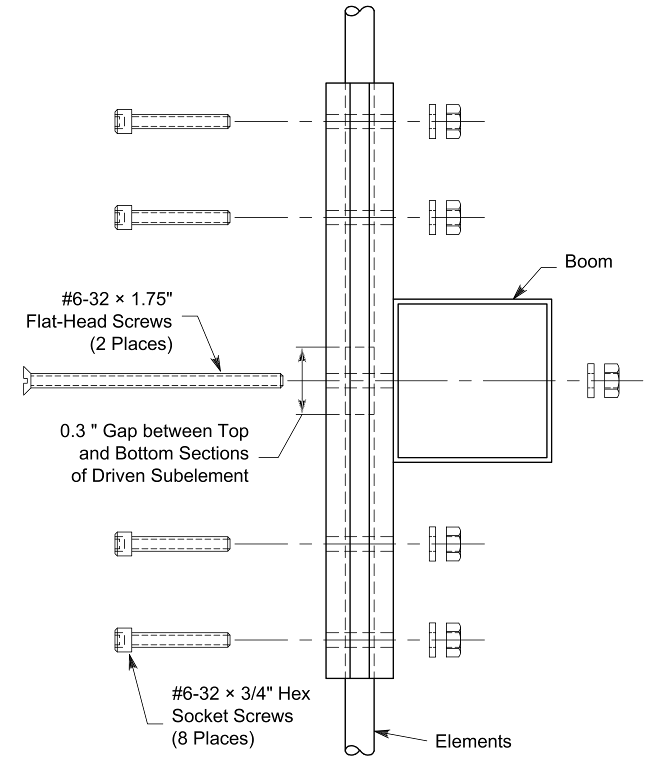

Fig 37—Method of mounting the driven element.

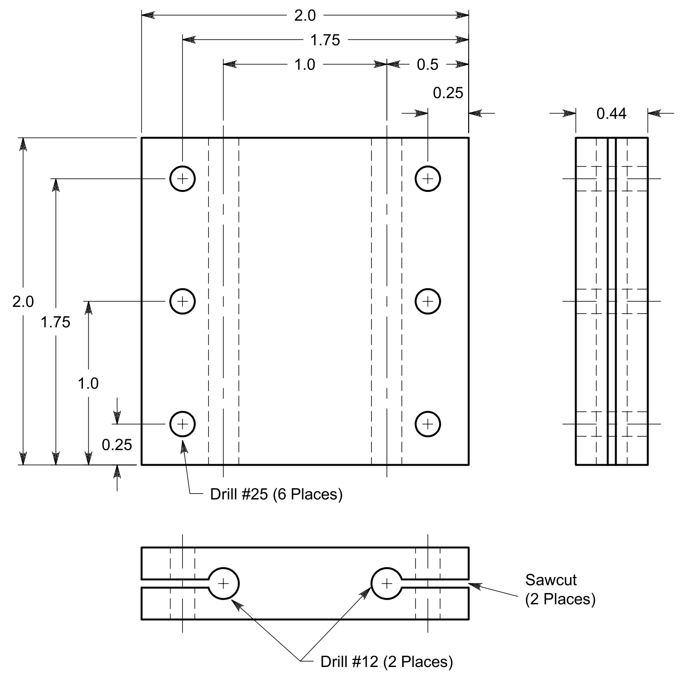

Fig 38—Parasitic-element mounting block.

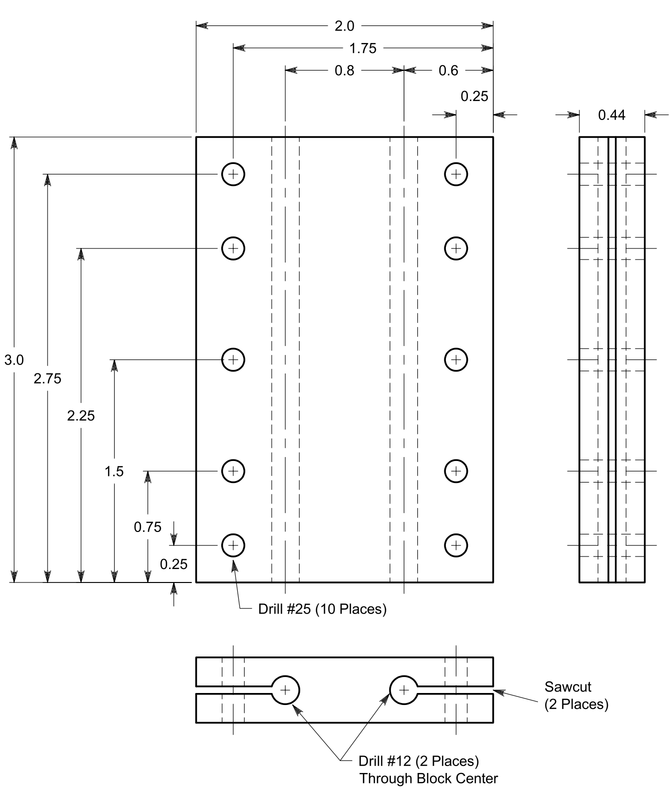

Fig 39—Driven-element mounting block.

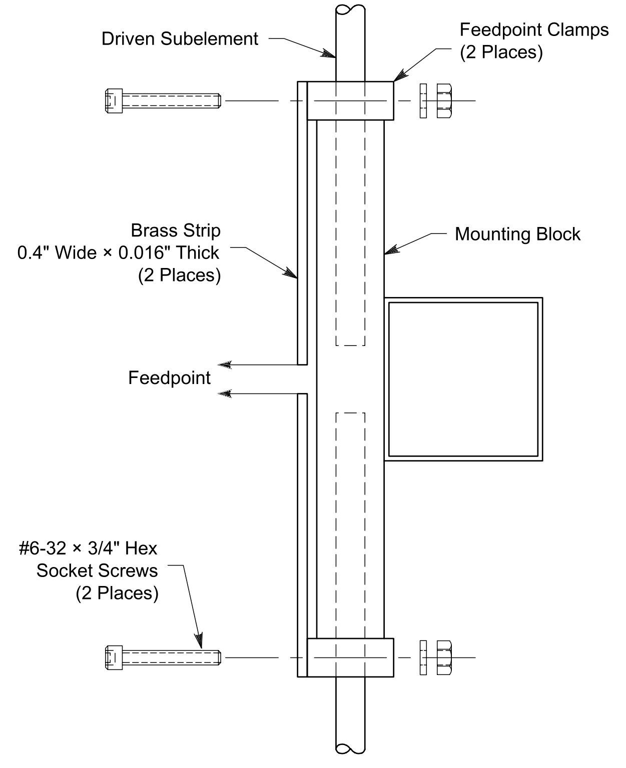

Fig 40—Feedpoint arrangement.

hardware stores. The element material is 3/16-inch aluminum rod. The bends in the elements can be formed accurately by hand-bending them around a 1/2-inch diameter mandrel (aluminum rod or tube, or even a wooden dowel, is just fine). The elements must be mounted so that they do not rotate, and this is achieved by clamping via a saw cut through the plastic blocks into the element-mounting holes. Screws through the plastic blocks then grab the elements tightly. This has worked fine for the prototypes, but they have not been exposed to the weather. If you are worried about the elements rotating, after assembling the elements to the blocks, run a suitable drill through both and install 1/16-inch tension pins.

The methods of mounting the parasitic and driven elements are shown in Figs 36 and 37, respectively. Fabrication details for the mounting blocks are shown in Figs 38 and 39. They may look a little complicated but they are easy to make. Cut out the blocks using a tenon saw: A regular hacksaw tends to produce non-square edges in this material. True up the edges with a file, and carefully mark all the holes. The vertical-element holes should be drilled using a drill press if possible to ensure that they are true. Notice that the center-to-center spacing of the driven subelements is different from that for the parasitic elements. Drill the clamping holes next, then make the saw cuts with a tenon saw. Clean up all the holes and remove any plastic burrs.

For the parasitic elements, mark out the element dimensions as shown in Table 1. Mark the positions of the block edges, equally spaced around the element center and the centers of the corner radii. Double check the total length and cut the subelement to length. Clean up the cut end with a file. Push the element through its mounting hole in the block, and locate the block roughly in the center of the element. Clamp the 1/2-inch mandrel tightly in a bench vise so that the axis of the mandrel is horizontal, and draw a short line parallel with the axis along

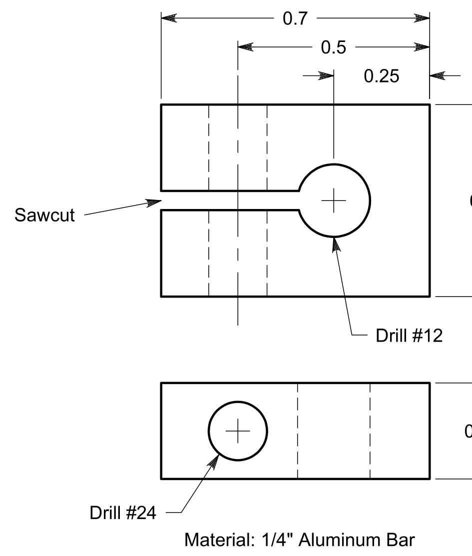

Fig 41—Feedpoint clamps.

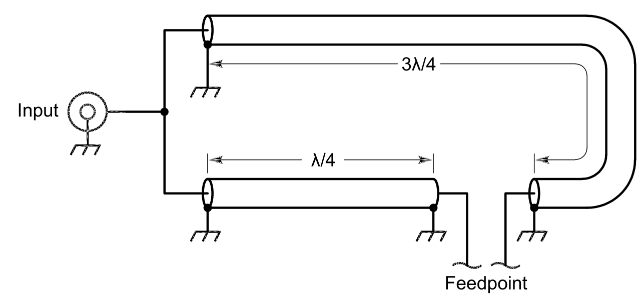

Fig 42—Dual-band balun for 2 m/70 cm Boxkites. Cut the phasing cables to the electrical length shown at 144 MHz. Use 75 Ω cable such as RG-59 or RG-6.

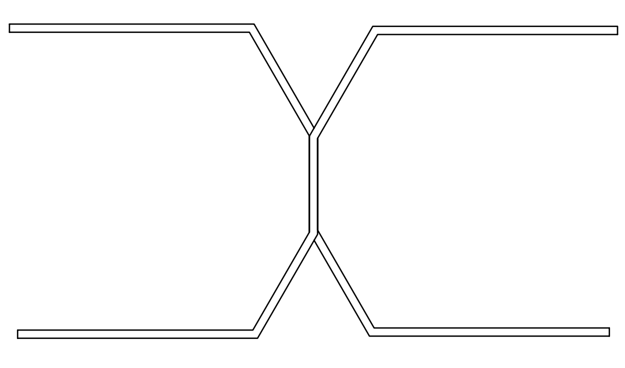

Fig 43—Boxkite X element. The two subelements are spaced along the boom by 20 mm.

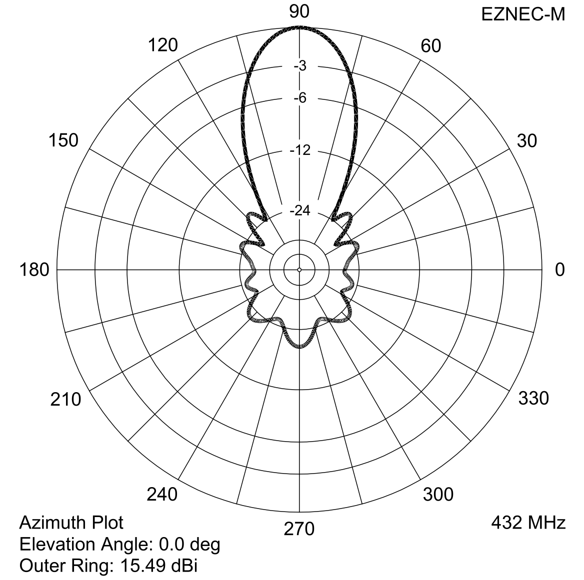

Fig 44—E-plane pattern for eight-element 1.5 λ Boxkite X at 432 MHz.

the top length of the mandrel. This provides a reference point for bending the elements. Hold the elements with your hands placed either side of the element radius center. Place the element on the mandrel so that the radius mark coincides with the reference mark on the mandrel. Check that the bend will be roughly perpendicular to the block face, and gently bend the element so that the radius mark stays in the center of the bend. Now do the same with the second bend, making sure that you bend it in the opposite direction from the first bend. Any slight error in bending can be corrected by slightly twisting the elements.

Push the second subelement rod through its mounting hole and repeat the bends. Make sure that the subelements face away from each other in the right way and that they will be square with the boom, then clamp them tightly with the #6-32 cap screws. This whole procedure sounds complicated, but it is very easy once you get the hang of it. The bends and

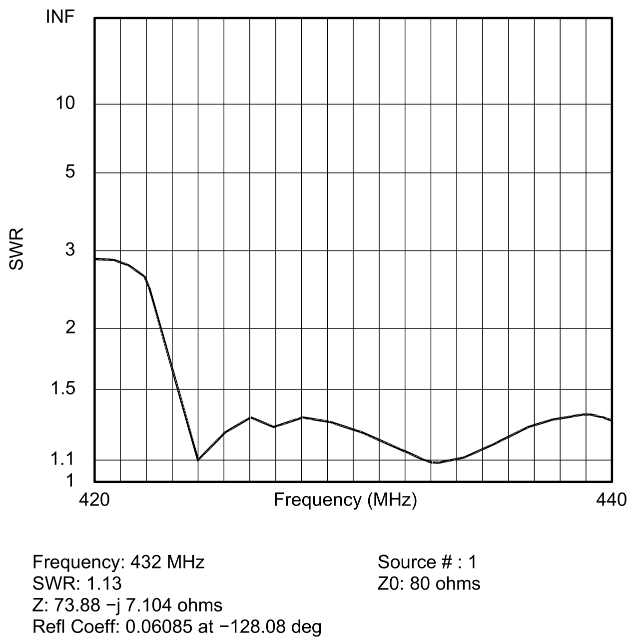

Fig 45—SWR plot for eight-element 1.5 λ Boxkite X.

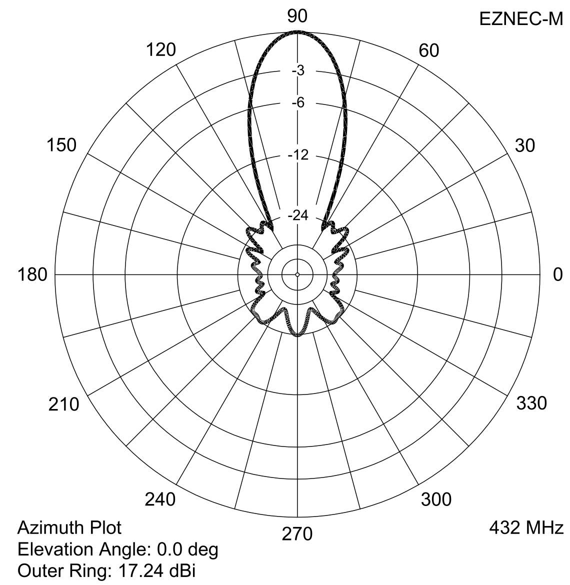

Fig 46—E-plane pattern for 13-element 3.45 λ Boxkite X.

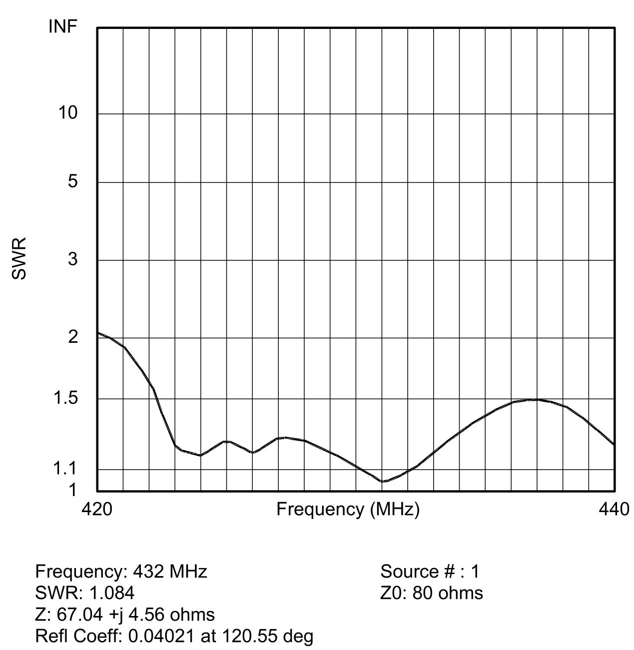

Fig 47—SWR plot of 13-element 3.45 λ Boxkite X.

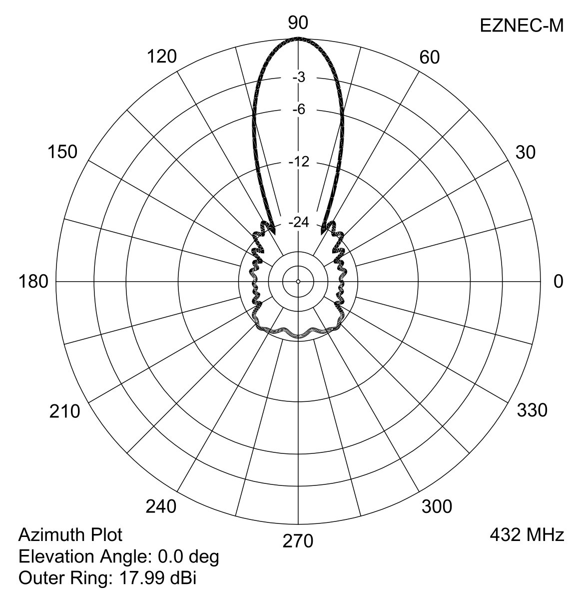

Fig 48—E-plane pattern for 17-element 4.8 λ Boxkite X.

lengths all seem to come out with sufficient accuracy.

The driven element is mounted in almost the same way, with the exception that the driven subelement is split in its center (see Fig 40). The two brass strips connect the feedpoint to the element via the element clamps (details are in Fig 41). The balun cables (see later) connect directly to the feedpoint, with their shields grounded to the boom. The lead lengths should be no more than a few millimeters. The method of mounting the driven element allows some adjustment of its length to minimize the 2 m SWR. Simply loosen the driven subelement clamp screws and move the subelement halves one way or the other to adjust for minimum SWR. This adjustment will have a minor effect on the 70-cm SWR.

Boxkites for Higher Frequencies?

Preliminary models show that scaling the 14-element 2 m/70 cm Boxkite for operation on 70 cm/23 cm works just fine. However, the devil is in the details at this frequency, so I won't believe that it is practical until I make one and verify that it works!

Baluns

The driven element is a balanced load and therefore it is preferable that it be driven via a balun. For the HF Twin C antennas, any proven 1:1 current balun will do a good job. Try to lead the feed cable away from the feed point at right angles to the plane of the antenna to reduce the current coupled into the shield of the cable. Such currents can also be reduced substantially by looping the coax through suitable ferrite toroids, which form choke baluns and reduce coupling from the antenna to the coax outer shield.

For the VHF/UHF antennas detailed here, the balun is a simple dual-band system that uses a pair of 75-Ω phasing lines cut to provide equal-amplitude, opposite-phase drive to the driven-element terminals. The principle is illustrated in Fig 42. The lines are λ/4 and ³⁄₄λ long at the fundamental. The phase difference between the outputs is 180°, and the impedance looking into the input is 50 Ω. A little thought will show that this is also true at the third harmonic. The bandwidth is adequate for both bands.

This type of balun gives a subtle theoretical advantage over the λ/2 4:1 balun that is conventionally used with a T feed for high-performance VHF/UHF Yagis. With the λ/2 balun, the SWR is sensitive to load imbalance, but with the balun used here the SWR is completely independent of load imbalance. I used a good quality RG-6 for the prototype 2 m/70 cm beams, although the loss on 70 cm is too high if you are looking for the absolute maximum gain. If you only need to use the beam on 70 cm, then the phasing lines may be reduced to one third of the lengths shown and the balun loss will be reduced. In the prototypes, the balun cables were dressed along the boom and taped to it. Be careful not to bend foam-dielectric cable too sharply.

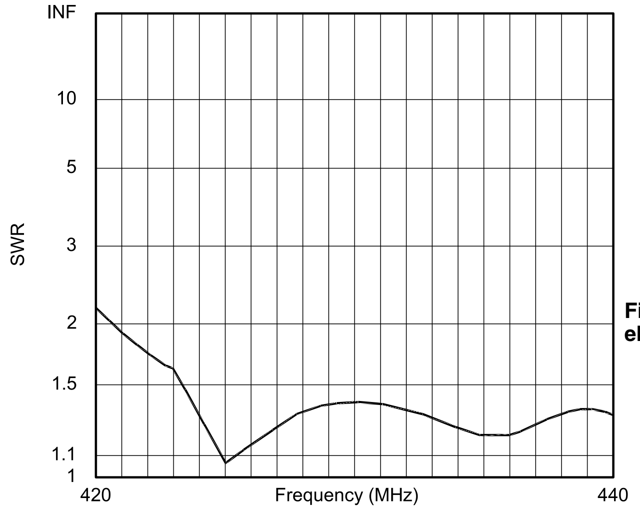

Fig 49—SWR plot of 17-element 4.8 λ Boxkite X.

Frequency: 432 MHz
SWR: 1.34
Z: 82.92 −j 23.5 ohms
Refl Coeff: 0.1439 at −74.72 deg

Source # : 1
Z0: 80 ohms

Boom Effects

As with most VHF/UHF Yagis, a metallic boom affects the feedpoint impedance and, to a lesser extent, the pattern. For the 2 m/70 cm two-element beam, I found that the two bands are affected differently. With the elements mounted through the center of 0.4-inch-thick insulators on top of the 1-inch square boom, the resonant frequency on 2 m was shifted up by about 2%. (The distance from the centers of the elements to the boom is only 0.2 inch.) I finally tracked this down to a reduction of the coupling coefficient caused by boom screening, and as pointed out earlier this increases the resonant frequency. It does not materially affect the pattern or gain, so any correction for boom effect need be applied to the driven element only. On 70 cm, the combined screening effect and the extra capacitance from the feedpoint to the boom also increase the resonant frequency by a little less than 2%, but has a beneficial effect of flattening the SWR curve somewhat.

The boom effect appears to be a problem only for Boxkites using few elements, such as the two-element beam. This is because the SWR bandwidth is narrow and the boom effect primarily affects the SWR center frequency: Any changes can easily produce an unacceptably high SWR. The gain bandwidth is wide enough that pattern and gain changes caused by boom effect seem to be quite small. For the longer beams, where conventional broadband techniques adapted from Yagi design allow a much wider SWR bandwidth, the effect appears to be negligible, unless you are looking for the perfect 1:1 on your favorite frequency!

I must confess that the boom effect on my prototype two-element 2 m/70 cm beam caused me more aggravation than it should have. My prototype eight-element Boxkite for 2 m/70 cm has elements mounted through the boom and the effects are negligible.

Mounting to the Mast

When a Boxkite is oriented to produce horizontal polarization on the fundamental, there appears to be no problem using a conventional metallic mast and clamp. The mast is not close to, or in line with, the vertical elements, so there is very little interaction between mast and antenna.

When oriented for vertical polarization on the fundamental, a metallic mast is problematic. A solution is to use a short plastic or fiberglass mast. Don't forget that the feed cable, if dressed down the mast, will affect antenna operation unless decoupled every few inches with ferrite toroids to suppress braid currents.

Wind Load and Weight

To compare the weight of a Boxkite to that of conventional Yagis, I added the weights of K1FO Yagi designs for 70 cm and 2 m that would produce the same gain as a 14-element, 3.4-λ Boxkite on the two bands. My quick calculations of the relative weight of a Boxkite show that, for the same boom and element materials and sizes, the Boxkite weighs approximately 11% less than the two Yagis combined.

As for wind load, the advantage again lies with the Boxkite. I assumed the two Yagis were horizontally polarized, and that the Boxkite was horizontally polarized on 70 cm. According to my sums, again when using similar size and shapes for the boom and elements, a 14-element, 3.4 λ Boxkite has a wind load that is 88% of the Yagis'. This is mostly because the Boxkite has a significantly shorter total boom length, and the boom is a major contributor to the wind load.

Boxkite X

As a final note before I summarize, while I was developing the Boxkite, I recalled the "Multibeam" that was produced by J-Beam in the United Kingdom a few years back. It has some resemblance to the Boxkite, with the exception that the driven element and reflector appear to be skeleton slots. Each director consists of four separate directors insulated from each other. I have not seen any reports on the antenna performance, so I modeled an "X beam" for 70 cm based on a stretched out Boxkite element (see Fig 43). All elements have the same form. The total length of each subelement is about the same as for a Boxkite, but the X shape moves the dipole sections further apart in the horizontal plane, while shifting them slightly closer together vertically. I expected that the wider horizontal spacing would improve the gain over that of a Boxkite. It does this nicely, with a very good pattern, but the coupling between the subelements is too small to allow operation on 2 m. The pattern and SWR plots of 8, 13 and 17-element versions of this antenna, which I call the Boxkite X (for want of a better name) are shown in Figs 44-49. The eight-element antenna has a boom length of 3 feet 6 inches and the gain of a conventional Yagi that is over 7 feet long. Boxkite X performance versus length is shown in Fig 27. For all practical boom lengths, it maintains a length advantage over a conventional long-boom Yagi of about 1.8 λ, or about 4 feet on 70 cm and over 12 feet on 2 m. The gain of a Boxkite X is given approximately by:

$$G \approx 10\log\left[10(L_\lambda + 1.8)\right] \text{dBi} \quad \text{(Eq 3)}$$

Gain bandwidth for all practical Boxkite X antennas for 70 cm is about 20 MHz, and the SWR bandwidth is over 20 MHz.

The feedpoint impedance of the Boxkite X series is about 80 Ω, and a simple T match and λ/2 balun combination is probably the easiest way to feed them. I have not yet built a Boxkite X prototype, so I won't give dimensions here. If there is sufficient interest, I will write a follow-up article on Boxkite X construction.

Summary

These articles have introduced a wide range of antennas that are based on a novel basic dipole element. The element has applications from the low HF bands up through UHF and even higher. Since I finished these articles, I have completed more development of Boxkites. I have built and tested an 18-element Boxkite for 23 cm/70 cm with excellent results. I have also learned how to provide identical polarization on the two bands and have modeled Boxkites using this method for operation on 2 m/6 m, 70 cm/2 m, 23 cm/70 cm and 9 cm/23 cm. I have also built and tested prototypes for 2 m / 6 m, 23 cm / 70 cm and 9 cm / 23 cm having the same polarization on both bands. The results of this further development will be reported in a follow-up article, I hope in the not-too-distant future.

Notes

[1]G. Hoch, DL6WU, "Yagi Antennas for UHF/SHF," *ARRL UHF/Microwave Experimenter's Manual*, ARRL, 1990.

[2]S. Powlishen, K1FO, "An Optimum Design for 432 MHz Yagis," ARRL UHF/Microwave Experimenters Manual, ARRL 1990.

[3]Using data from reference 5 as representative, and from Zack Lau, W1VT, "RF, A Small 70-cm Yagi," *QEX*, Jul/Aug 2001, pp 55-59.

[4]This is what my mother says a lot when rooting around in garage sales.

[5] R. Straw, N6BV Ed, *ARRL Antenna Book*, 19th edition, (Newington, Connecticut: ARRL, 2000). □□

Boxkite Yagis—Part 2

Design notes for high-performance single- and dual-band Boxkite Yagis

By Brian Cake, KF2YN

Introduction

In the first two articles, I described the basic theory behind Twin Cs and Boxkites, and gave some constructional data on the limited number of prototypes that I had built. At that stage in the development the dual-band Boxkite had different polarization on the two operating frequencies, and I felt that it was worth further effort to investigate the possibility of providing similar polarization sense on both bands. This has indeed proved to be the case, and dual-band Boxkites with the same polarization sense on both bands have been designed for 6 m/2 m, 2 m/70 cm, 70 cm/23 cm, 33 cm/13 cm, 23 cm/9 cm and 6 cm/9 cm. For these bands some interesting antennas have been designed, and practical tests on 6 m/2 m, 70 cm/23 cm and 23 cm/9 cm prototypes show that the model is remarkably accurate both in terms of pattern and SWR prediction. I have also attempted to improve the mechanical design both by moving to a folded dipole feed where appropriate and by simplifying construction, while at the same time providing a much more positive method for preventing rotation of the elements.

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The directivity (gain) of the dual-band Boxkites with the same polarization on both bands is remarkably close to that of published data for state of the art long Yagis designed by K1FO and DL6WU. From the published K1FO data[1], the expression that gives the gain of a given boom length Yagi is as follows, and is within 0.3 dB of the published data:

$$G \approx 10\log[9.1(L_\lambda + 0.6)] \text{ for } L_\lambda \geq 1$$

where *G* is the antenna gain in dBi (same as directivity for zero loss) and L_λ is the Yagi length in wavelengths

Comparison of Boxkite gains with Yagi gains having the same boom length will use the expression above as the reference gain in this article. Also note that all the models used include skin effect losses in the elements, which are 6061-T6 aluminum in every case.

As far as single band Boxkites are concerned (referred to as Boxkite Xs in the second article) I have more data to share with you that shows that they have between 2.2 and 2.6 λ advantage in terms of boom length over contemporary long Yagis having the same gain, and this advantage is to first order independent of length. Naturally this has a more profound effect on boom length on the lower VHF bands, such as 2 meters.

I will discuss how to stack both dual band and single band Boxkites, and in a couple of cases compare Box kite and stacked Boxkite gain with theoretical supergain limits.

I think you will see from the data presented that these antennas are capable of quite remarkable performance, even in the dual-band versions.

Dual-band Boxkites having the same polarization on both operating frequencies

From the theory presented in the second article, remember that the Boxkite driven-element has three useful frequencies, with the lower two, designated f_1 and f_2, being the result

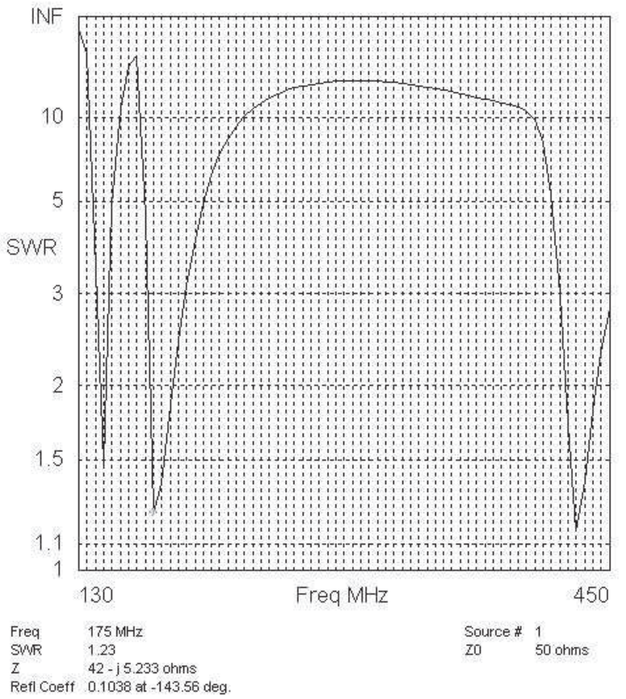

Fig 1—SWR plot for 2-element Boxkite for 2 m and 70 cm with s= 16 mm.

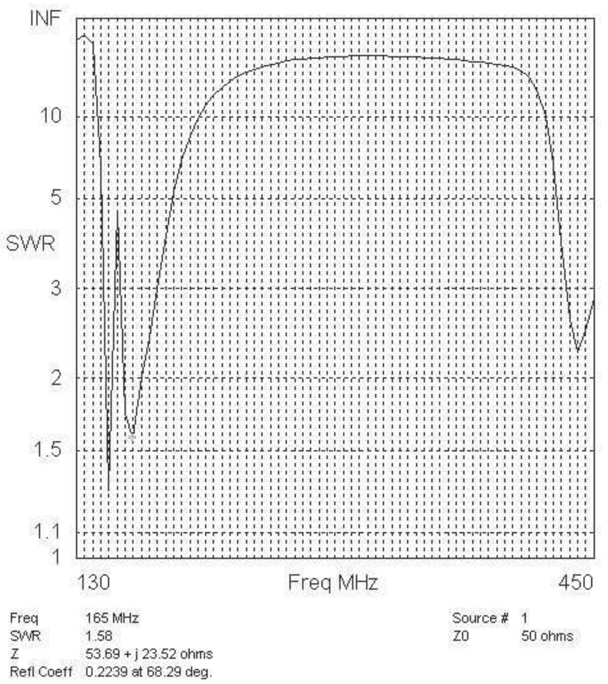

Fig 3—2-element Boxkite for 2 and 70 cm with s=35 mm.

of over-coupling between the two sub-elements. The upper operating frequency, f_3, is close to three times the self-resonant frequency of one sub-element. Also, remember that the current phases at f_1 are such that the resultant field polarization is vertical; at f_2 the polarization is horizontal, and at f_3 the polarization is again horizontal. Fig 1 shows an SWR plot for a Boxkite 2-element Yagi designed for operation on 2 m and 70 cm, with vertical polarization on 2 m and horizontal on 70 cm. The three resonances can be seen clearly. The first resonance, f_1, at the extreme left of the plot, produces vertical polarization. The second resonance, f_2, produces horizontal polarization, as does the third resonance, f_3, which is at the extreme right of the plot. In this case, f_1 is at 145 MHz; f_2 is at 175 MHz and f_3 is at 432 MHz. Thus the ratio between f_3 and f_2 is about 2.5:1. We now note that there are some microwave bands that have non-integer frequency ratios, for example 9 cm/ 23 cm (3456 MHz and 1296 MHz) where the ratio is 2.67:1;

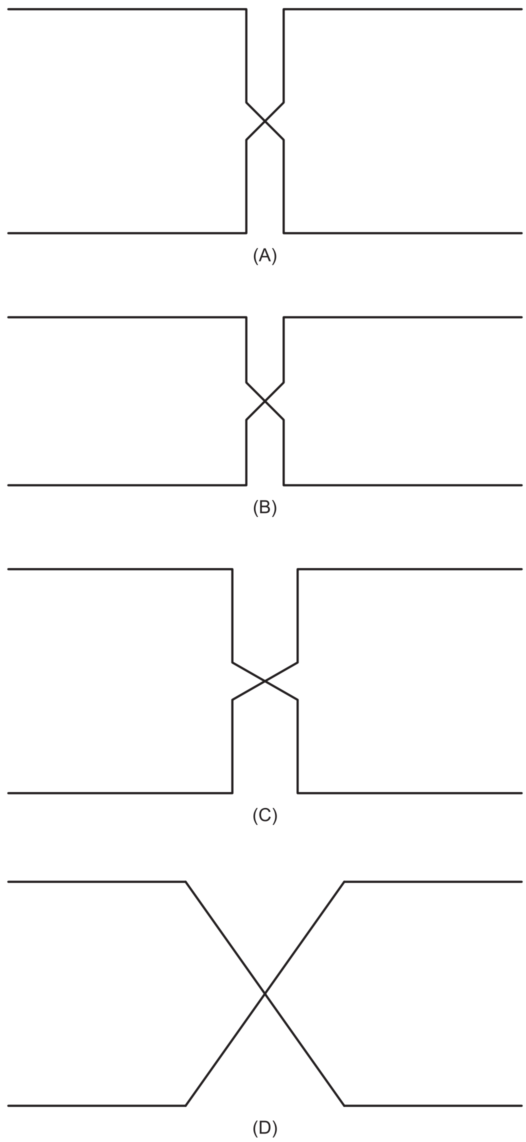

Fig 2A thru 2D—Methods of adjusting the coupling between Boxkite sub-elements.

13 cm/33 cm (2304 MHz and 902 MHz), where the ratio is 2.55; and 6 cm/13 cm (5.7 GHz and 2.304 GHz) where the ratio is 2.49. The first and second resonances, f_1 and f_2, are varied by changing the coupling between the two sub-elements while maintaining the same sub-element total length. If the coupling is reduced, then f_1 and f_2 move closer together. Conversely, increasing the coupling moves f_1 and f_2 further apart. In both cases, f_2 moves relative to f_3 (which stays relatively constant as the coupling is changed), so different ratios between f_3 and f_2 can

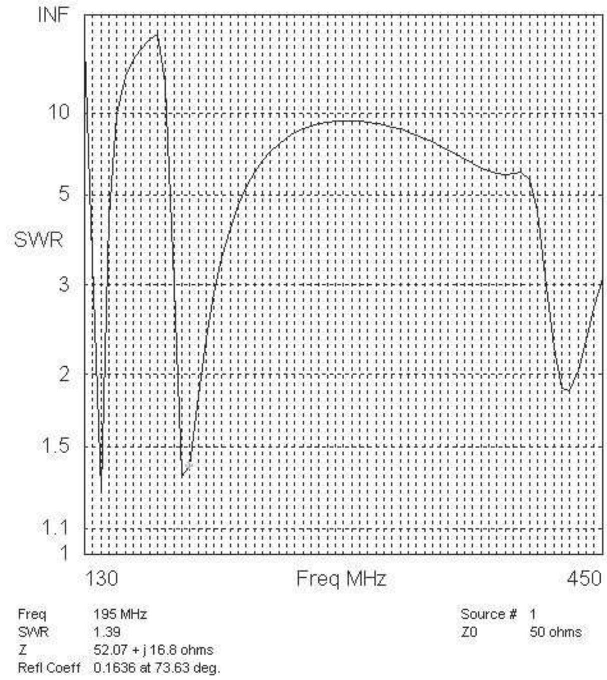

Fig 4—2-element Boxkite for 2 m and 70 cm with s=8 mm.

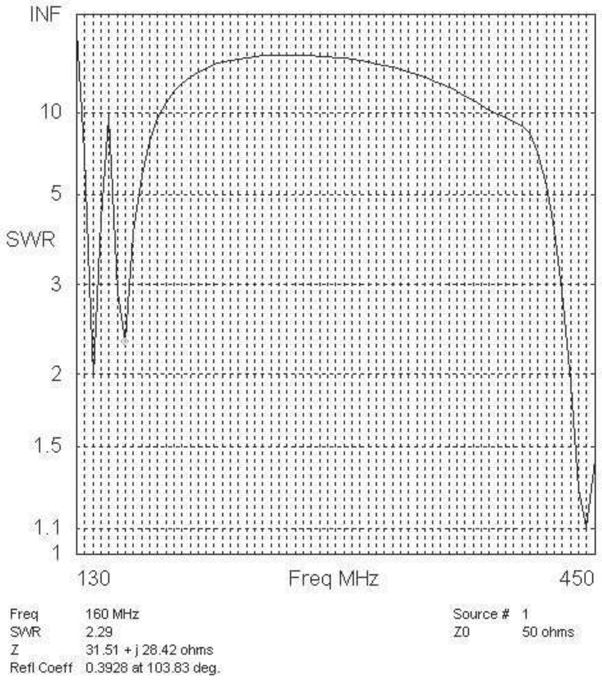

Fig 5—2-element Boxkite for 2 m and 70 cm with s=16 mm and transmission lines = +- 120mm.

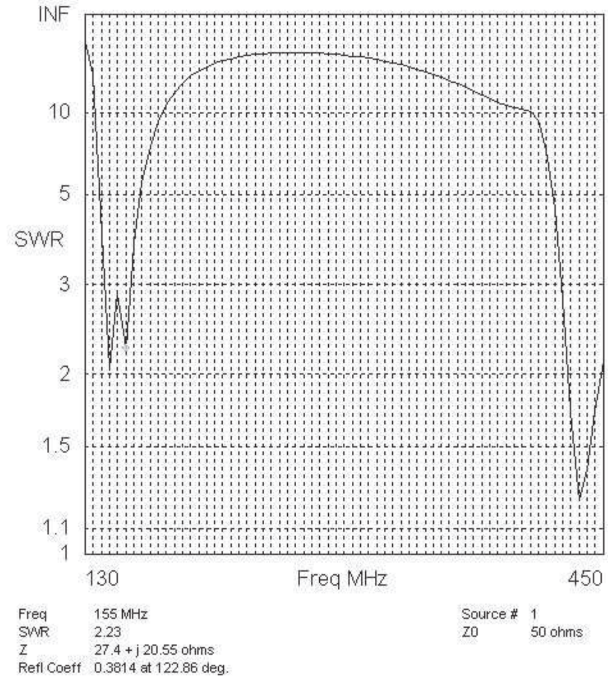

Fig 6—2-element Boxkite for 2 m and 70 cm with s=25 mm and transmission lines = +- 120 mm.

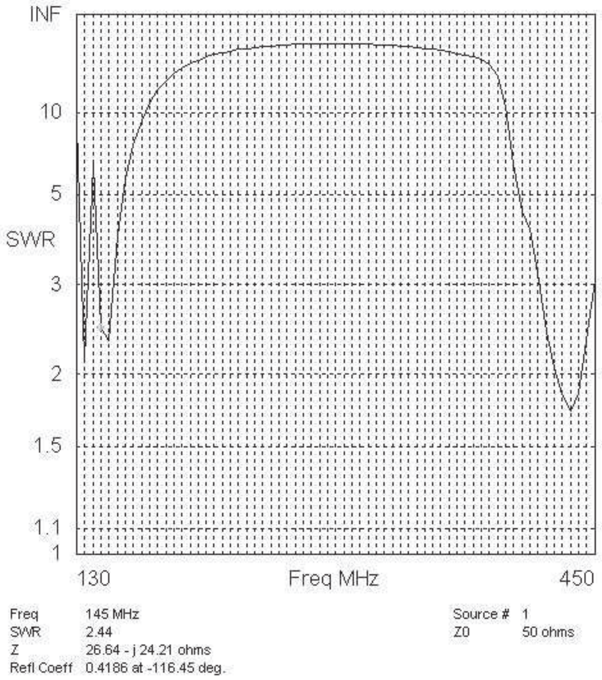

Fig 7—2-element Boxkite for 2 m and 70 cm with s=16 mm and ends of transmission lines spaced by 100 mm.

be achieved simply by changing the coupling between the sub-elements.

There are three methods by which the coupling between the sub-elements may be changed, and these are shown in Fig 2. Note that for clarity I have placed the crossover in the center of the vertical parallel sections. These sections will be referred to as "transmission line" sections because that is their function at f_3. Fig 2A shows the basic Boxkite structure, with the transmission lines a half wavelength long. We can reduce the coupling by reducing the length of the transmission lines, while maintaining resonance by increasing the length of the horizontal sections, as shown in Fig 2B. This also produces higher gain at f_3 but we have to be careful not to overdo it or the sidelobes at f_3 will suffer. We can also reduce the coupling by increasing the spacing between the transmission lines, as shown in Fig 2C. This changes the characteristic impedance of the transmission line so it also changes the drive-point impedance at f_3. Finally, we can separate the ends of the transmission lines as shown in Fig 2D. This increases both the impedance of the transmission line and the spacing of the horizontal sections. In practice some combination of all these methods will produce a practical design, but modeling is currently the only way of ending up with a working design. In practice, for Boxkite Xs, a short vertical section is used at the center of the transmission lines to support the-elements on a square boom.

As examples of these methods of changing f_2, first we look at increasing the spacing, s, between the transmission lines. The plot in Fig 1 is for s= 16 mm. Fig 3 shows the SWR plot for the same 2-element Boxkite with s= 35 mm. The resonances are now at 150, 162.5 and 440 MHz. As expected, f_2 has shifted downwards. Note also that the SWR at f_3 has increased because of the increase in the characteristic impedance of the transmission lines. Fig 4 shows the result of reducing s to 8 mm in the same 2-element Boxkite. Here the resonances are at 140, 187.5 and 427.5 MHz, and the SWR at f_3 has again risen because of the change in transmission line impedance.

So we can see that f_2 can be changed simply by changing s, although in practice the achievable range for f_2 is rather

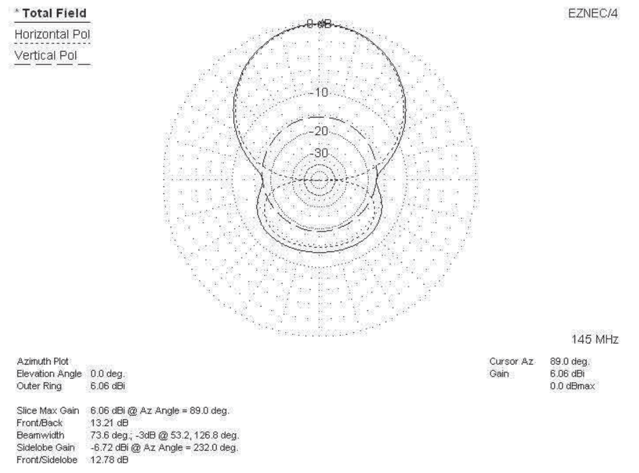

Fig 8—E-plane pattern of 2-element Boxkite for 2 m and 70 cm at 145 MHz s=16 mm and transmission line end spacing = 100 mm.

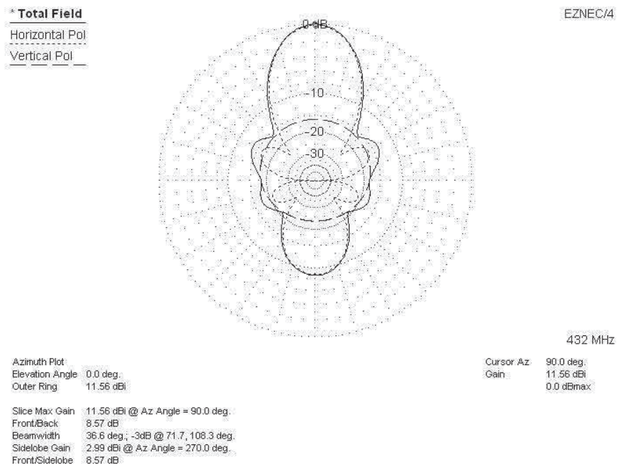

Fig 9—E-plane pattern of 2-element Boxkite for 2 m and 70 cm at 432 MHz s=16 mm and transmission line end spacing = 100 mm.

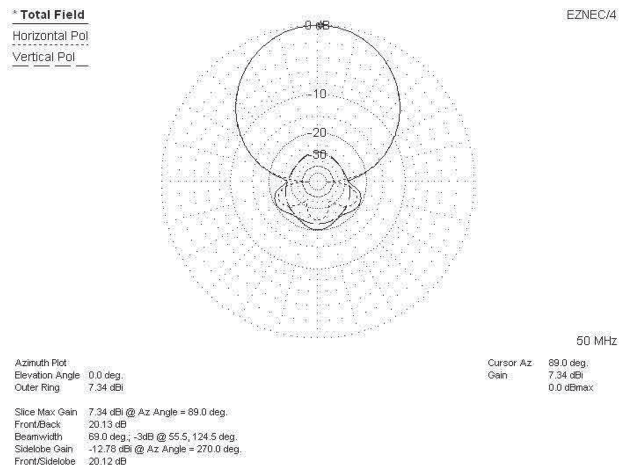

Fig 10—E-plane pattern of a 3-element Boxkite for 6 m and 2 m at 50 MHz.

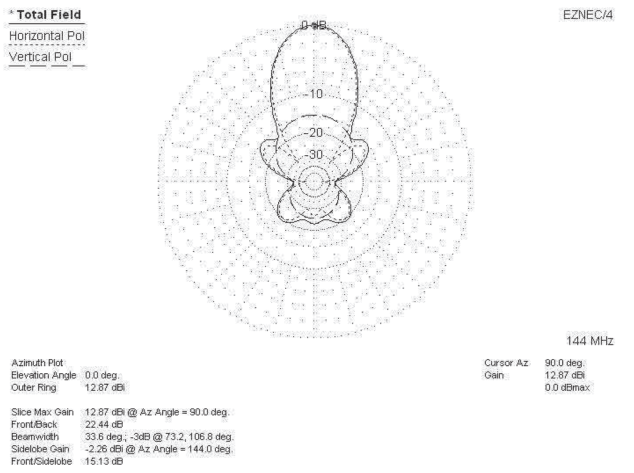

Fig 11—E-plane pattern of a 3-element Boxkite for 6 m and 2 m at 144 MHz.

restricted because of the need to avoid spacing that is too close for comfort at one extreme and spacing that is too large compared with the operating wavelength at the other. Now we will look at reducing the length of the transmission lines. Fig 5 shows the same 2-element Boxkite with s=16 mm but with the transmission line length reduced from +- 183 mm to +-120 mm, and with the length of the horizontal sections increased to maintain resonance at f_3. The resonances are at 142.5, 157.5 and 445 MHz. By combining the two methods of reducing coupling shown above we can further reduce f_2, as shown in Fig 6. This is a plot for s= 25 mm and transmission line length =+-120 mm. The resonances are at 145, 155 and 437.5 MHz. However, the pattern at f_3 becomes unacceptable because the horizontal sections are now too long. As an example of the third method of reducing the coupling, Fig 7 shows the SWR plot for a 2-element Boxkite with s=16 mm but with "crossed" transmission lines such that the inner ends of the horizontal sections are spaced by 100 mm. Resonances are at 135, 145 and 432.5 MHz, so this is a potential 2 m/70 cm beam, although as can be seen in Figs 8 and 9, the patterns need work! Although these patterns are far from perfect, they were enough to encourage more work. The result, after the burning of

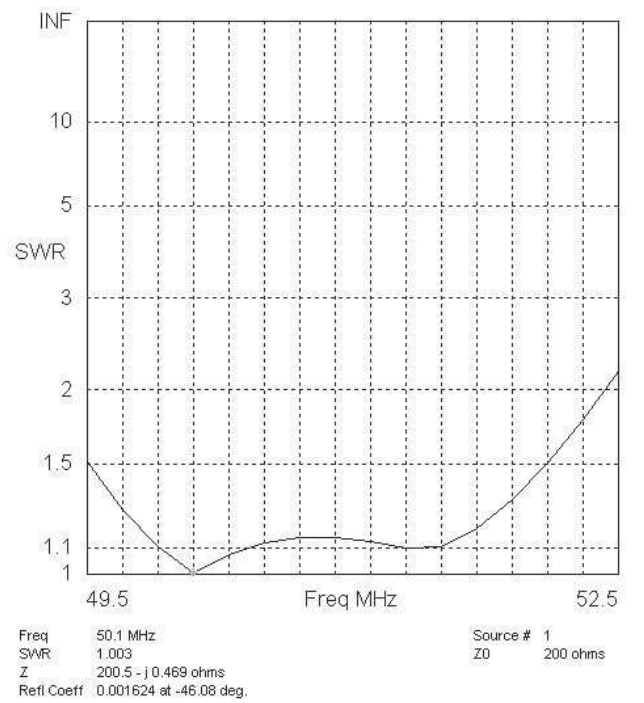

Fig 12—SWR plot for the 3-element Boxkite on the 6 m band.

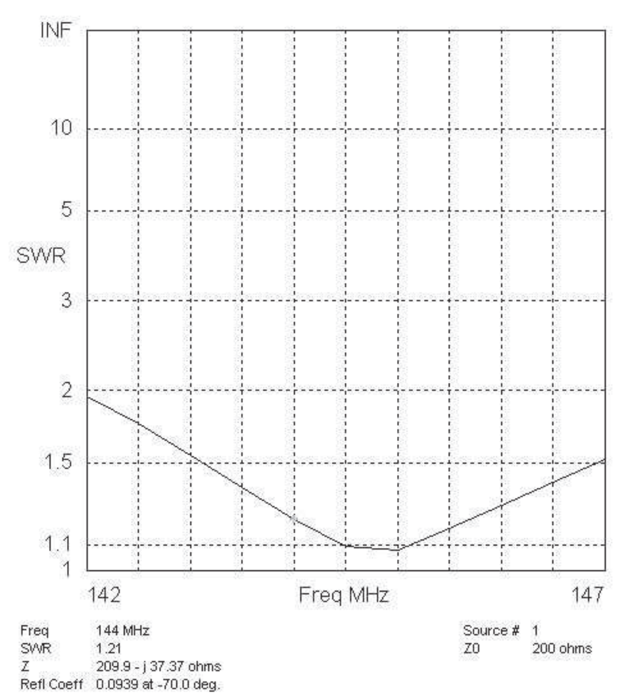

Fig 13—SWR plot of the 3-element Boxkite on the 2 m band.

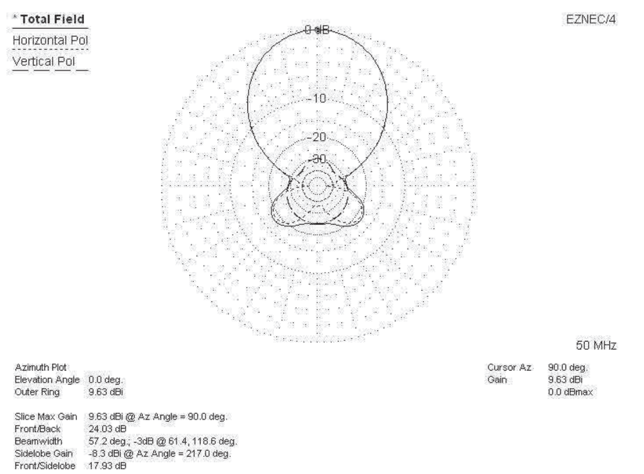

Fig 14—E-plane pattern for the 6-element Boxkite for 6 m and 2 m at 50 MHz.

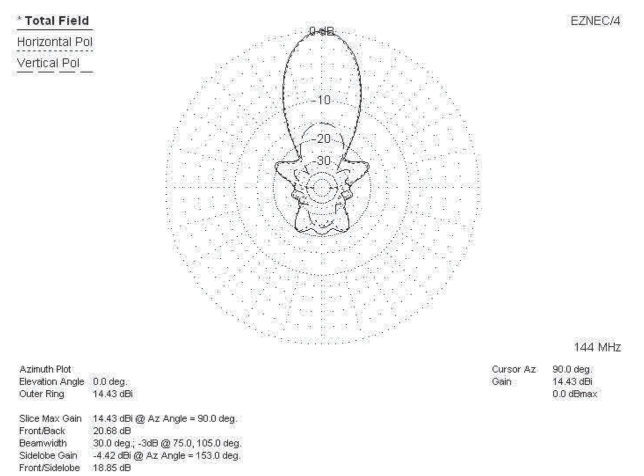

Fig 15—E-plane pattern for the 6-element Boxkite for 6 m and 2 m at 144 MHz.

much midnight oil, and the squirting of much test RF across the Matanzas Inlet, will be shown in the following examples. I will show the modeled results for many antennas first, then I will go on with general comments and some comments on the reasons for the observed behavior of some antennas.

Dual-band Boxkites

Boxkites for 6 m and 2 m

I have fully developed 2 versions of the 6 m and 2 m Boxkites, the first has 3-elements and the second 6-elements. The 3-element version has a boom length of 33 inches and a maximum "wingspan" of 101 inches. The E-plane patterns at 50 MHz and 144 MHz are shown in Figs 10 and 11 respectively. The –1 dB gain-bandwidth is 6 MHz on 6 meters and 10 MHz on 2 meters. As is usual for conventional Yagis, F/B ratio and sidelobe levels deteriorate at the –1 dB band edges. Note that a contemporary high performance Yagi would need a boom length of 1.5 λ, or 124 inches, for the same gain on 2 m. The turning radius is not much reduced compared to a conventional Yagi because of the "wingspan". Fig 12 shows the SWR of the Box kite in the 6 meter band. The antenna has a folded dipole feed (the fed sub-element is simply doubled with a horizontal spacing of 1 inch, and the ends connected to form a "bent" folded dipole). Design feed im-

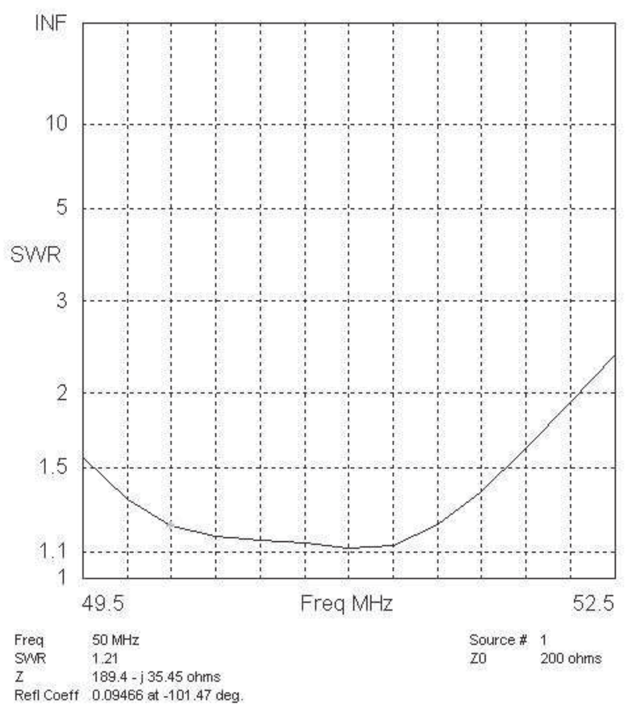

Fig 16—SWR plot for the 6-element Boxkite for 6 m and 2 m in the 6 m band.

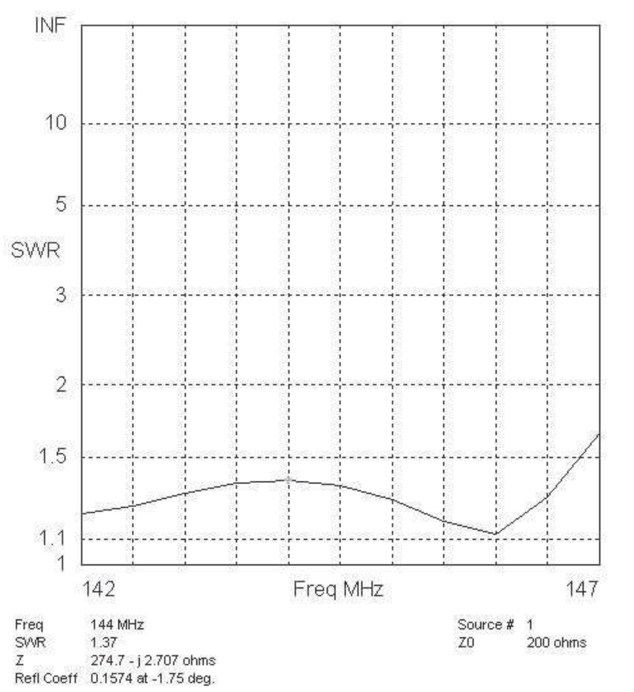

Fig 17—SWR plot for the 6-element Boxkite for 6 m and 2 m in the 2 m band.

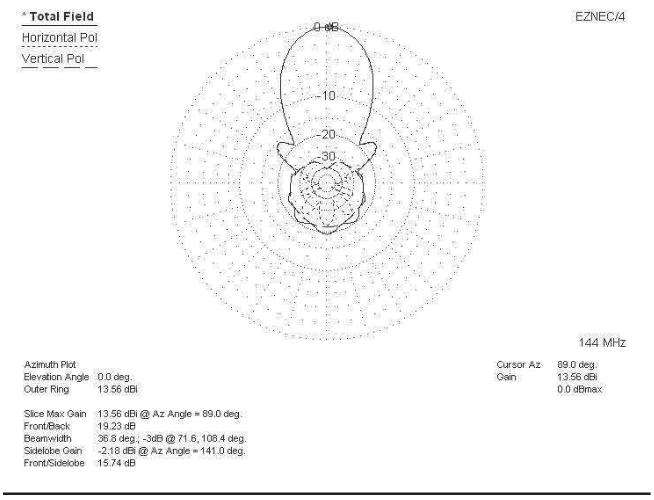

Fig 18—E-plane pattern of the 20-element Boxkite for 2 m and 70 cm at 144 MHz.

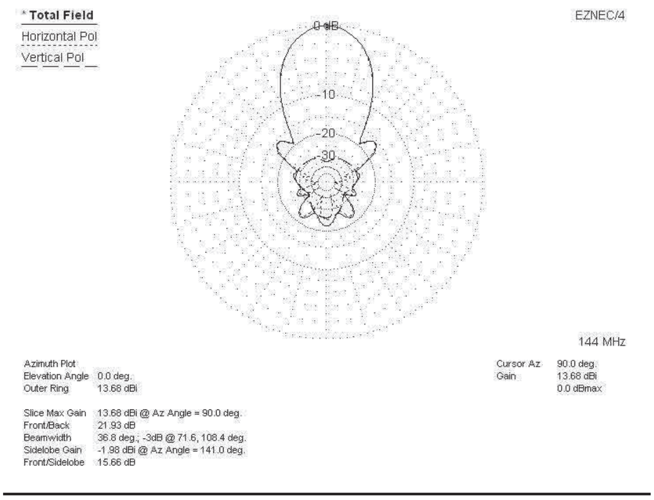

Fig 19—E-plane plot of 21-element Boxkite for 2 m and 70 cm, with third vertical reflector.

pedance is 200 ohms, and the antenna is fed with 50-ohm cable via a simple dual-band 1:4 balun. Fig13 shows the SWR curve on 2 m. It shows an SWR of less than 2:1 from 142 MHz to greater than 147 MHz. I have built a prototype of this antenna, and it is shown in Photo 1. Because of materials that I had to hand, the transmission lines are made of $^{1}/_{2}$ inch aluminum and the horizontal-elements are of $^{1}/_{4}$ inch aluminum, although ideally $^{1}/_{2}$ inch material should be used for both. The SWR curve on both bands is close to the predictions of the model, but I have not yet done a pattern test. On-air tests are notoriously unreliable but the front-to-back ratio and sidelobe levels seem to be good.

Now for the 6-element version. Figs 14 and 15 show the E-plane pattern at 50 MHz and 144 MHz respectively. The boom length on 144 MHz is 1.6 λ, or 11 feet 2 inches, with a "wingspan" of 8 feet 6 inches. A contemporary high performance Yagi would need a boom length of 2.4 λ, or over 16 feet, for the same gain on 2 m. On 6 m the gain is about what we would expect for the same boom length in a conventional Yagi. SWR plots on 6 m and 2 m are shown in Figs 16 and 17 respectively.

Boxkites for 2 m and 70 cm

Fig 18 shows the E-plane pattern for a 20-element Boxkite at 144 MHz. Note

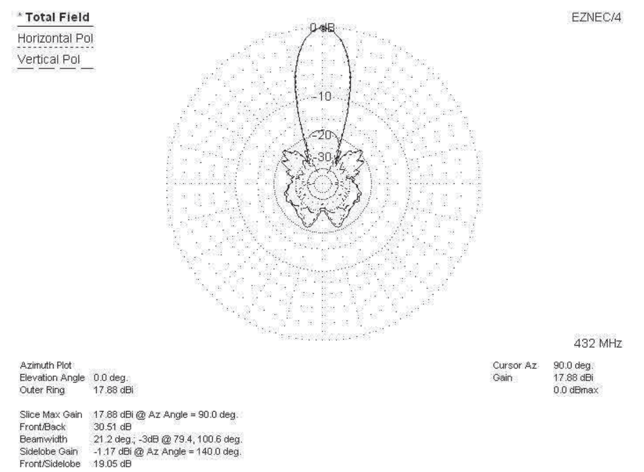

Fig 20—E-plane pattern of the 21-element Boxkite for 2 m and 70 cm at 432 MHz.

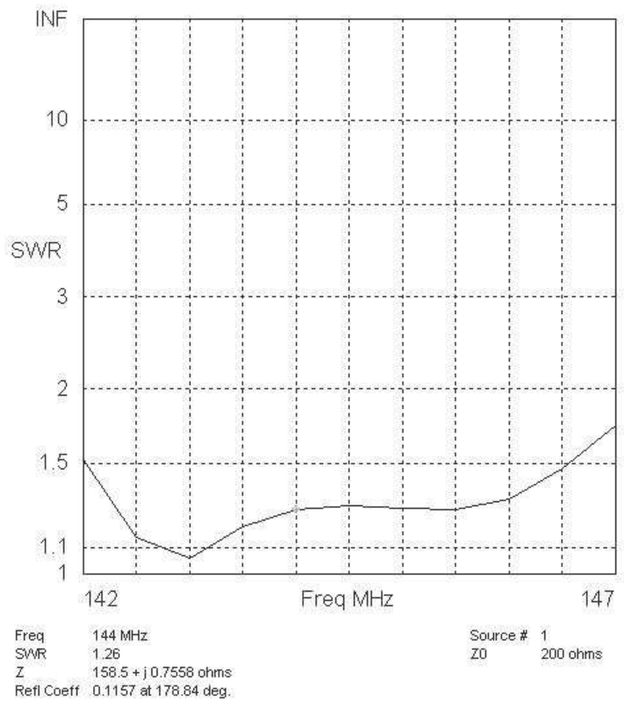

Fig 21—SWR plot of the 21-element Boxkite for 2 m and 70 cm in the 2 m band.

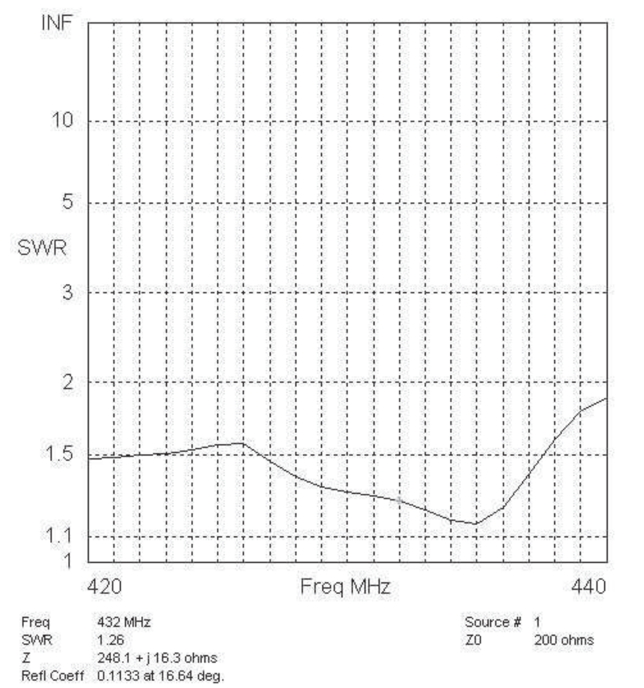

Fig 22—SWR plot for the 21-element Boxkite for 2 m and 70 cm in the 70 cm band.

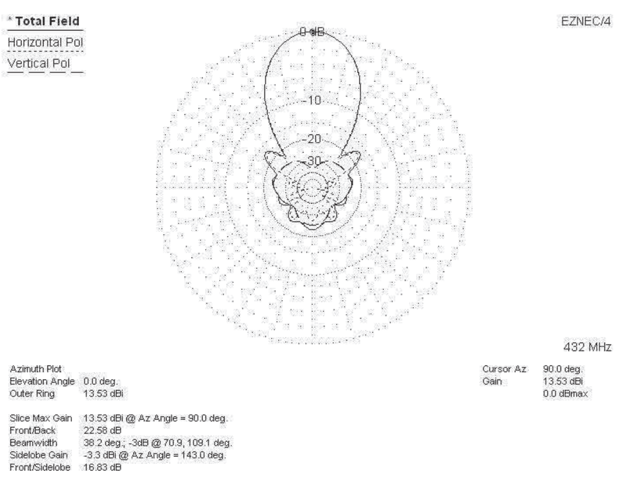

Fig 23—E-plane pattern of the 21-element Boxkite for 70 cm and 23 cm at 432 MHz.

that the most significant rear sidelobes at 144 MHz are vertically polarized. This seems to be a characteristic of Boxkites having an operating frequency ratio of near 3:1, and is caused by unequal currents in the driven-element transmission lines. In order to achieve a frequency ratio of 3:1, the coupling between the driven sub-element and its un-driven parasitic sub-element has to be reduced until the pair is operating in a region where the coupling between them is relatively weak, so the currents in the transmission lines are not equal, and are not in antiphase. A simple solution to this problem is to add a conventional vertical reflector at about 0.2 λ behind the driven-element. The resulting pattern is shown in Fig 19, and we see a substantial improvement in the rear lobes. Note that this fix is not needed for Boxkites where the frequency ratios are less than 3:1, or for single band Boxkites. The pattern at 432 MHz is shown in Fig 20. The antenna is 13 feet 6 inches long and on both 2 m and 70 cm has approximately the same gain as an equal-boom-length Yagi. SWR plots for 2 m and 70 cm are shown in Figs. 21 and 22 respectively.

Boxkites for 70 cm and 23 cm

Patterns for a 21-element Boxkite for 70 and 23 cm are shown in Figs. 23 and 24. The antenna is 4 feet 6 inches long. The gain on 70 cm is the same as a Yagi

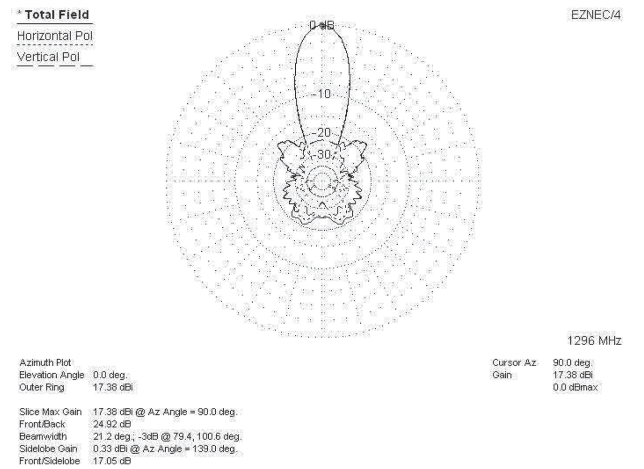

Fig 24—E-plane pattern of the 21-element Boxkite for 70 cm and 23 cm at 1296 MHz.

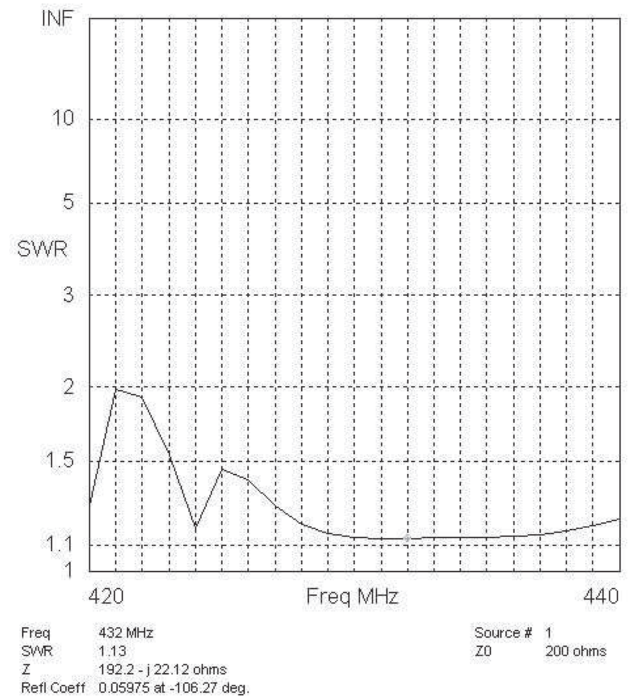

Fig 25—SWR plot for the 21-element Boxkite for 70 cm and 23 cm in the 70 cm band.

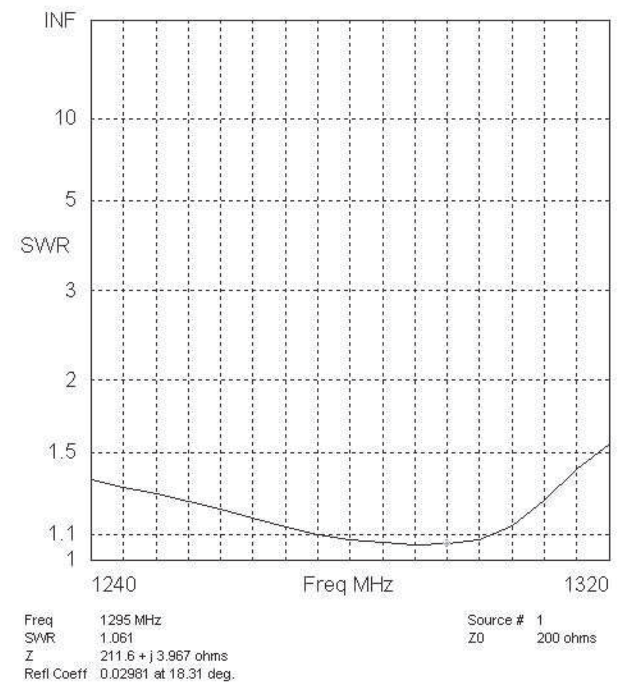

Fig 26—SWR plot for the 21-element Boxkite for 70 cm and 23 cm in the 23 cm band.

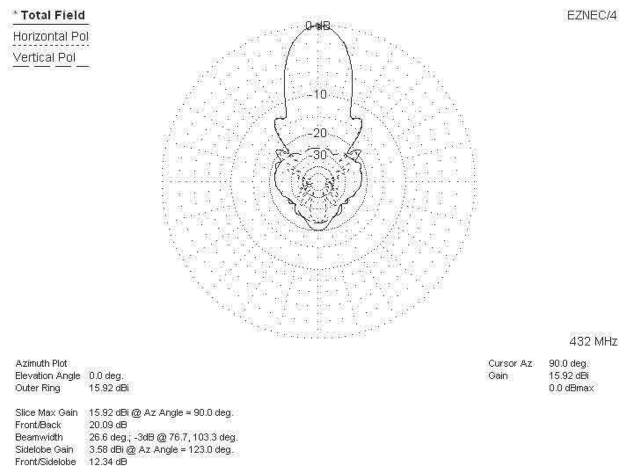

Fig 27—E-plane pattern of the 39-element Boxkite for 70 cm and 23 cm at 432 MHz.

having the same boom length, and on 23 cm the Boxkite gain is about 1 dB more than that of an equal-length Yagi. The –1 dB gain-bandwidth extends from 1270 MHz to 1325 MHz, and from 423 MHz to 455 MHz. SWR plots are shown in Figs. 25 and 26. I have built and tested two prototypes of the antenna above, but without the third (vertical) reflector. Both of them have performed, both in terms of measured pattern and SWR, very closely to the model predictions. The first of these used round $^{3}/_{16}$ inch diameter aluminum sub-elements mounted via conventional Delryn insulators mounted through a round boom. As expected I had problems with element rotation, although even large element rotation does not appear to impact the performance in a serious way. The second prototype uses square element material mounted to a square boom via custom polycarbonate insulators that lock the elements in place. This mounting method is very rugged, but requires either machining the mounting blocks, or having them injection molded. I am looking into the latter possibility. The prototype antenna is shown in Photo 2.

Now for a longer 23/70 cm Boxkite. The plots for a 39-element Boxkite are shown in Figs. 27 thru 30. This antenna is 9 feet 6 inches long. The gain on 70 cm is within 0.4 dB of that expected for an equal length Yagi, and

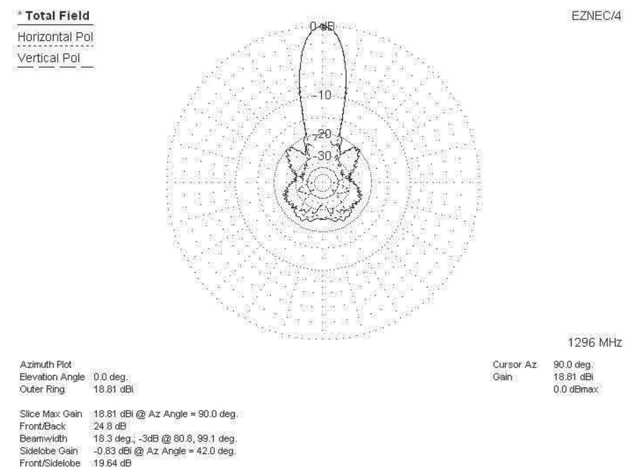

Fig 28—E-plane pattern of the 39-element Boxkite for 70 cm and 23 cm at 1296 MHz.

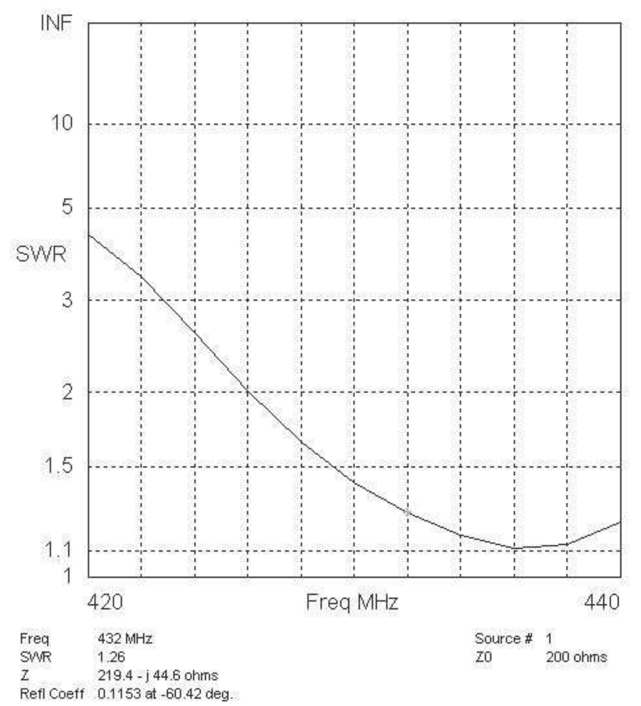

Fig 29—SWR plot of the 39-element Boxkite for 70 cm and 23 cm in the 70 cm band.

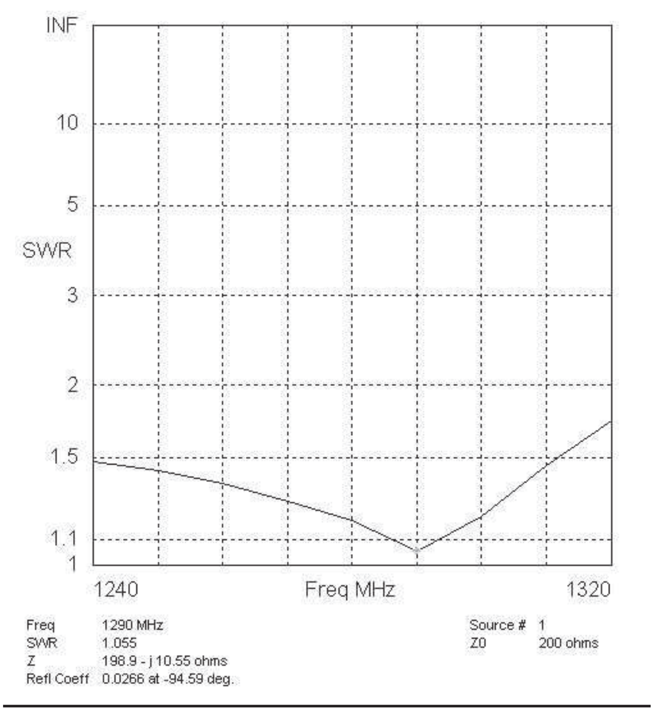

Fig 30—SWR plot for the 39-element Boxkite for 70 cm and 23 cm in the 23 cm band.

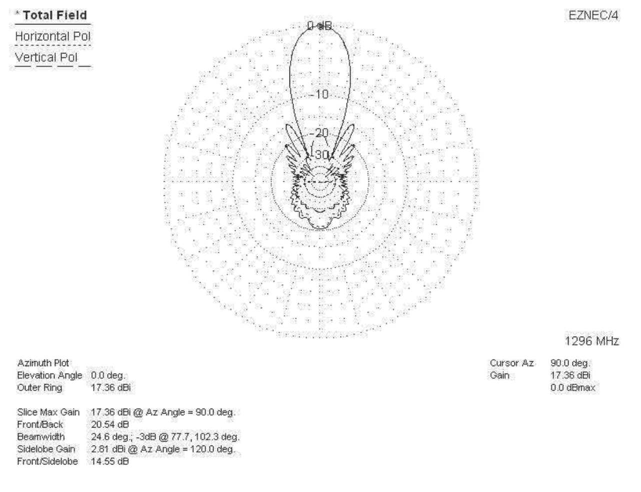

Fig 31—E-plane pattern of the 56-element Boxkite for 23 cm and 9 cm at 1296 MHz.

on 23 cm is about 1.5 dB less than an equal length Yagi. These gains can be improved somewhat by reducing the SWR bandwidth.

Boxkites for 23 and 9 cm

Data for a 56-element Boxkite for 23 and 9 cm are shown in Figs 31 thru 34. The antenna is 5 feet 6 inches long, and uses $^{1}/_{16}$ inch diameter elements. The feed element is not folded, and the nominal feed-point impedance is designed to be 50 ohms. Because of the non-harmonic relationship between 3456 MHz and 1296 MHz, the Boxkite uses reduced-length transmission lines to reduce coupling between the sub-elements, and the elements are of the non-X variety. The expected gain for a long Yagi with the same boom length at 3456 MHz is 22.5 dBi, and we are at 21.9 dBi. At 1296 MHz these numbers are 18.5 dBi and 17.4 dBi respectively. See later for some comments on this. The –1 dB gain-bandwidth is from 3400 to 3550 MHz, and, remarkably, from 1180 to 1390 MHz, or 16% of the center frequency. The reason for this is that, as can be seen from the SWR curve in Fig 33, there are two minima in the SWR plot, one at 1200 MHz and one at 1300 MHz. At 1300 MHz the polarization is horizontal, and at 1200 MHz it is vertical, with equal vertical and horizontal field magnitude at about 1235 MHz. The gain-bandwidth

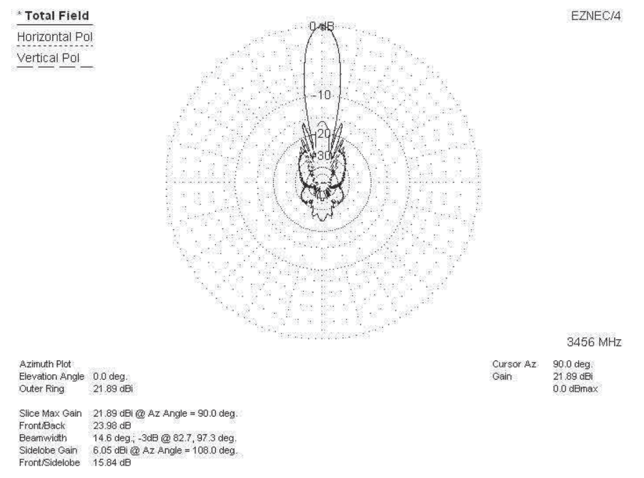

Fig 32—E-plane pattern of the 56-element Boxkite for 23 cm and 9 cm at 3456MHz.

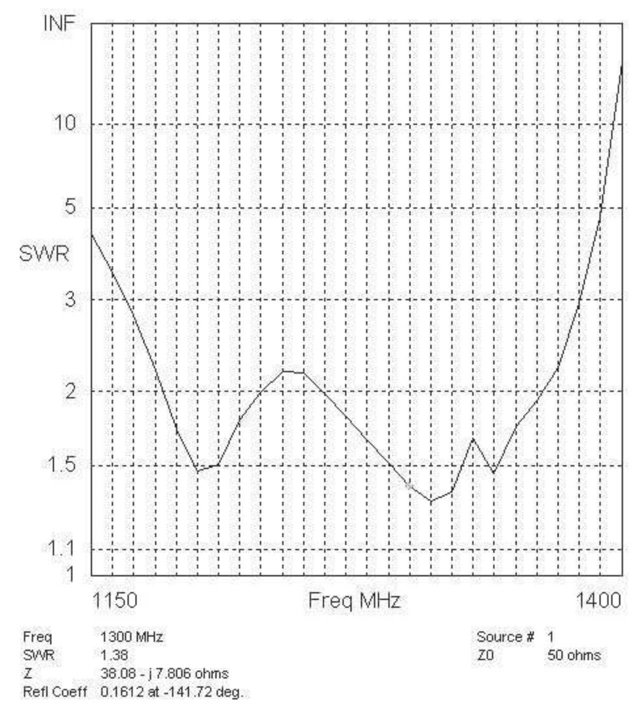

Fig 33—SWR of the 56-element Boxkite for 23 cm and 9 cm on 23 cm.

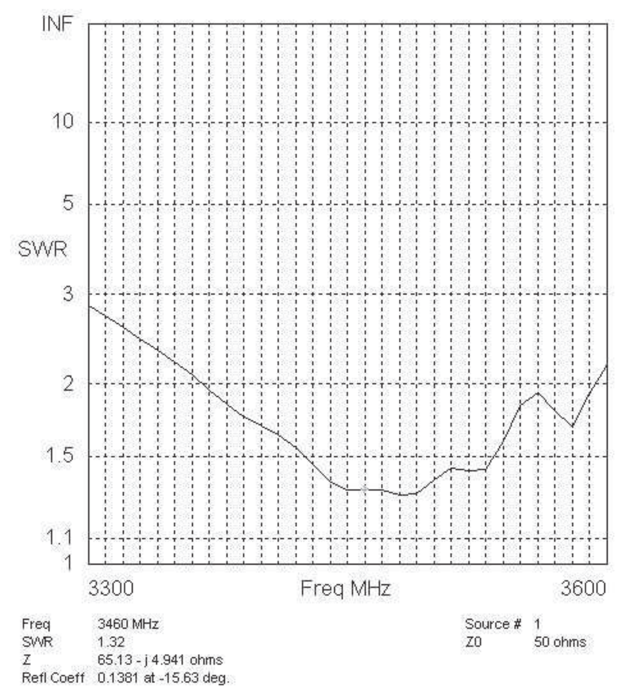

Fig 34—SWR of the 56-element Boxkite for 23 cm and 9 cm at 9 cm.

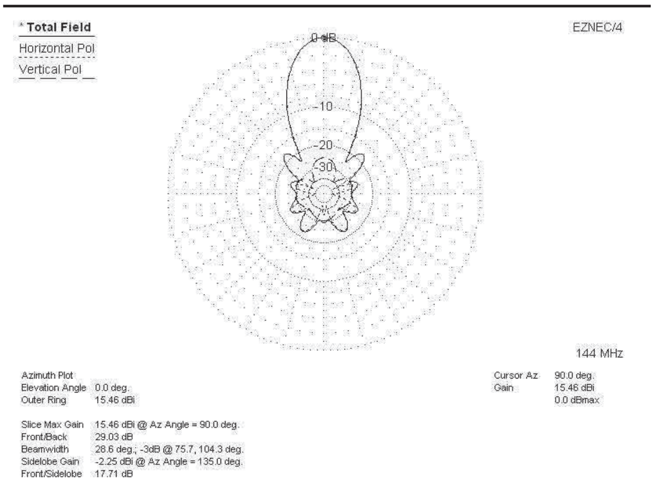

Fig 35—E-plane pattern of the 7-element Boxkite X for 2 m.

noted above is referenced to the sum of the vertical and horizontal fields. However, it is interesting to note that, at the frequency where the horizontal and vertical fields are equal, the antenna is radiating a circularly polarized field. This is because there is zero phase delay between the feed-point and the vertical-elements (the transmission lines) in the transmitting antenna, but approximately 90º phase shift from the feed-point to the horizontal-elements because of the transmission lines. If an identical receiving antenna is used there is zero phase shift from the vertical-elements to the feed-point, and 90º from the horizontal-elements. So the polarization sense is the same in each, and the broadband expectations are met. The polarization sense may be changed by switching the feed-point from one of the driven-element transmission lines to the other. The vertical phase is independent of which transmission line is fed, because the currents in the two transmission lines are in phase, but the horizontal phase changes. I checked this (in the model) by rotating a dipole receiving antenna in the far field, and found that, at 1235 MHz, indeed the received signal is virtually independent of rotation angle. Also, when using identical 56-element Boxkites for transmitting and receiving, the –1 dB gain-bandwidth extends from 1210 to 1380 MHz, if the transmission line phasing is correct as noted above.

Note that the ratio of the two operating frequencies for this antenna is 3456/1296 = 2.67. I have built a prototype 3-element 23/9 cm antenna and it is shown in Photo 3. It performs very closely to the model predictions, even though I did not use a balun. In order to decouple the feed cable outer sheath from the antenna, I believe that a pair of concentric sleeve baluns would probably work just fine, but I have not tried them.

Single-band Boxkites (Boxkite X)

A 7-element Boxkite X for 2 meters

If we restrict operation to f_3, and optimize for that, we end up with the Boxkite X versions. As an example, a 7-element Boxkite X for 2 meters has performance shown in Figs. 35 and 36. The boom length is 8 feet, and the “wing-span” is 8 feet 4 inches. A conventional Yagi would need a boom length of 3.3λ, or 22.5 feet, for the same gain. The relative turning radii are approximately 5.7 feet and 11 feet respectively. The –1 dB gain-bandwidth is 7 MHz, with a gain peak of 15.5 dBi at 147 MHz. It is interesting to note that the supergain limit for this antenna at 144 MHz is 15.9 dBi,

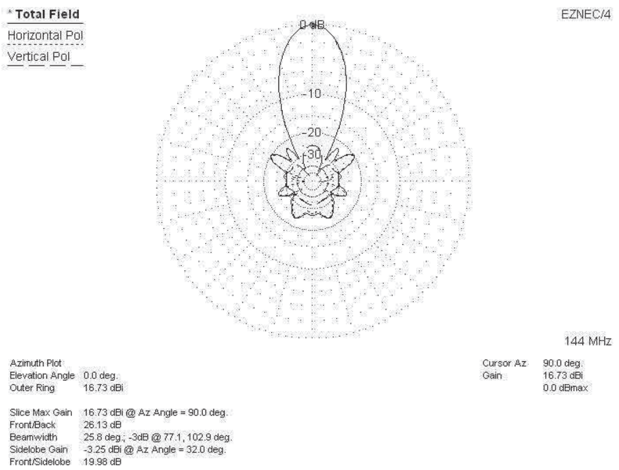

Fig 37—E-plane pattern for 10-element Boxkite X for 2 m.

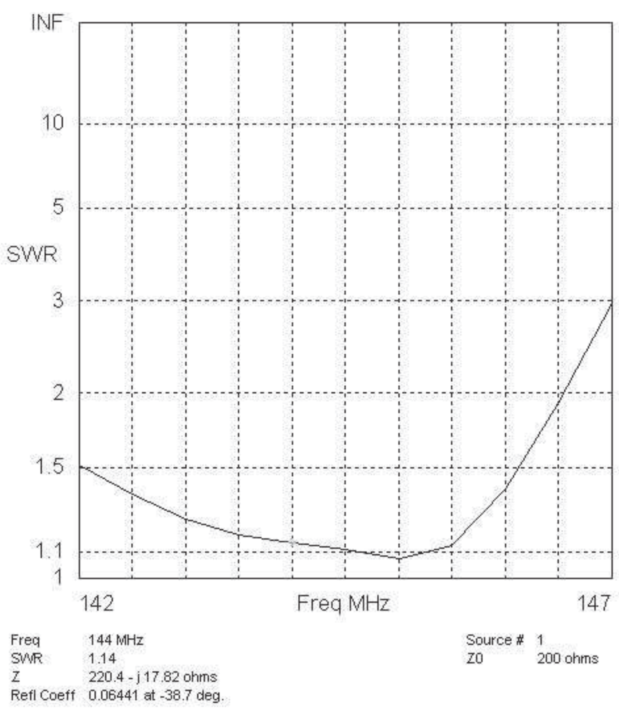

Fig 36—SWR plot for the 7-element Boxkite X for 2 m.

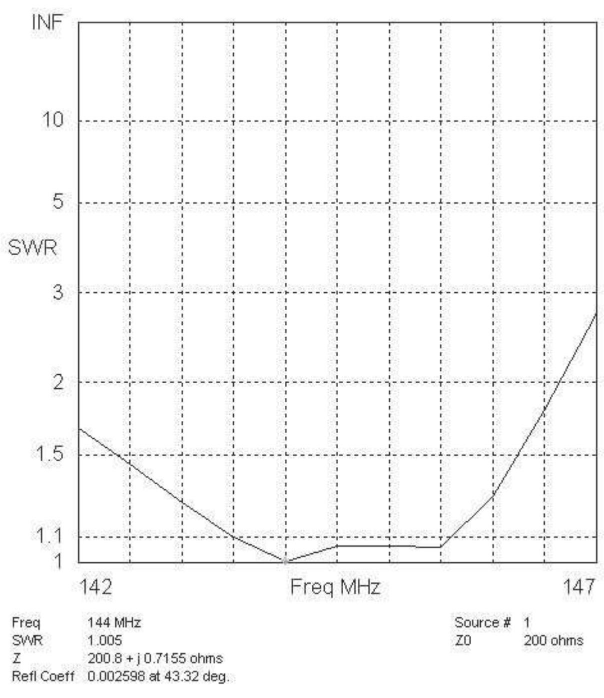

Fig 38—SWR of 10-element Boxkite X for 2 m.

so we are within 0.4 dB of this. See under "stacking Box kites" later for notes about supergain.

A 10-element Boxkite X for 2 meters

Fig 37 shows the E-plane pattern for the 10-element version. The SWR plot is shown in Fig 38. The –1 dB gain-bandwidth is over 6 MHz. The boom length is 14 feet (2 λ) and a conventional Yagi would need a boom length of 4.5 λ, or over 30 feet, for the same gain.

The turning radii are approximately 8 feet and 15 feet respectively. A stack of four of these Boxkites, spaced 160 inches in the E-plane and 145 inches in the H-plane, provides 22.4 dBi gain. The Boxkite stack has roughly half the boom length of the Yagi stack for the same gain. It can be seen that the Boxkite X design provides a major advantage, in terms of boom length, over a conventional Yagi.

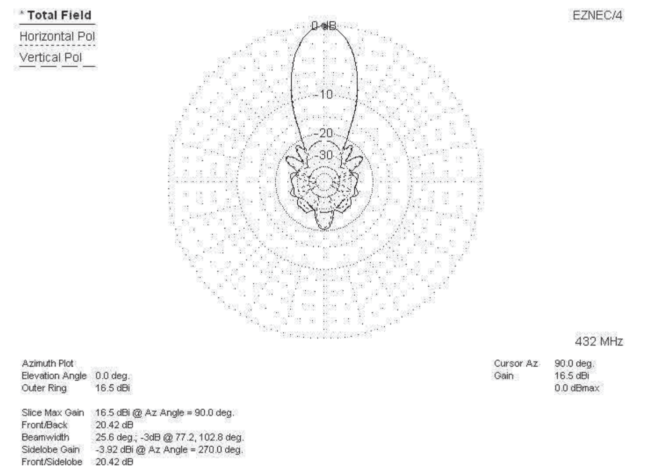

Fig 39—E-plane pattern for the 10-element Boxkite for 70 cm at 432 MHz.

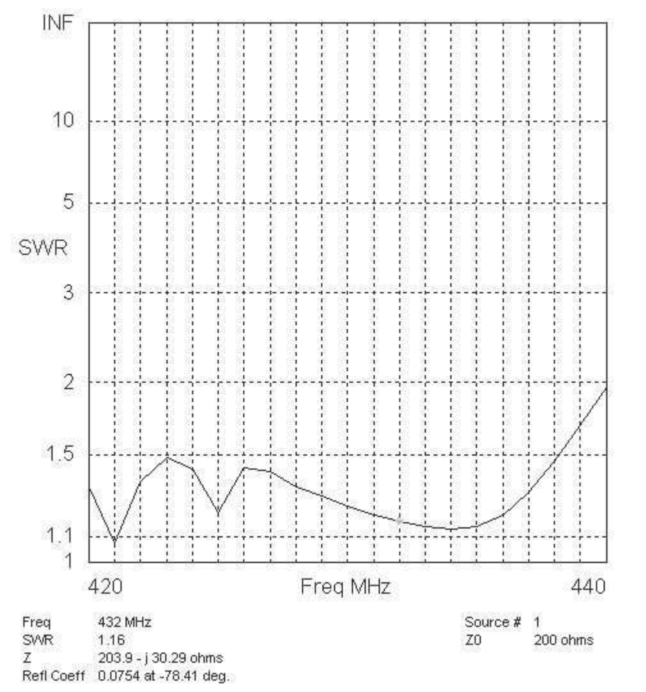

Fig 40—SWR of 10-element Boxkite X for 70 cm.

A 10-element Boxkite X for 70 cm

The pattern for this antenna is shown in Fig 39. The antenna is less than 5 feet long and has the same gain as a conventional Yagi that is about 10 feet long. The –1 dB gain-bandwidth is 20 MHz, with a gain peak at 435 MHz. The SWR plot is shown in Fig 40.

20-element Boxkite X for 70 cm

The plots for this antenna are shown in Figs 41 and 42. The antenna is 13 feet long and has the same gain as a 19 foot Yagi.

From the above few examples, it can be seen that the 10-element 70 cm Boxkite X has a boom length advantage over a conventional high performance long Yagi of 5 feet or 2.2 λ, and the 20-element version has a length advantage of 6 feet or 2.6 λ. For the 2 m versions, the boom length advantage is approximately 15 feet or 2.2 λ.

20-element Boxkite X for 23 cm

Box kite Xs for 23 cm still maintain similar boom length advantages, in terms of wavelengths, but of course a 2.5 to 3 λ advantage over a Yagi is only a little over 27 inches, so one can argue that the added complication of the Boxkite X is not worth the effort. However, I have included data for two Boxkites for this band for completeness. For bands above 23 cm, the advantage becomes negligible for any reasonable boom length. Plots for this antenna are shown in Figs. 43 and 44. This antenna is 53 inches long and has the same gain as a Yagi 73 inches long. The boom length advantage over a Yagi is 2.2 λ.

34-element Boxkite X for 23 cm

This antenna is 91 inches, or 10 λ, long and has the gain of a 13.1 λ (119 inches) Yagi. Plots are shown in Figs. 45 and 46.

Discussion

The modeled data for dual-band Boxkites shows that these are perfectly practical, and this is supported by measurements on prototypes. The difficulty with designing

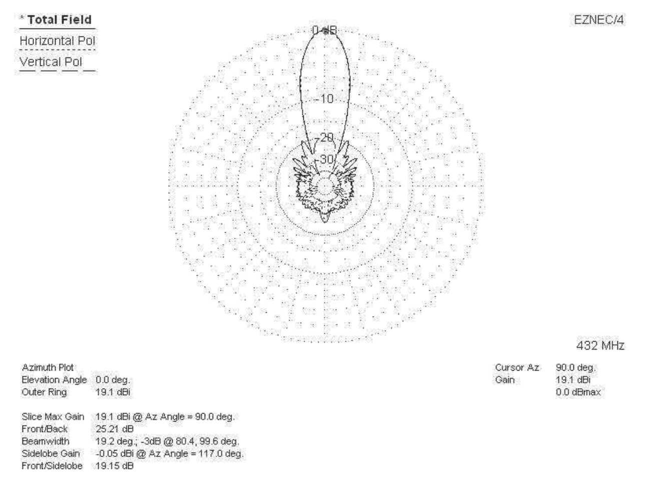

Fig 41—E-plane pattern of the 20-element Boxkite X for 70 cm.

Boxkites, however, is significantly greater than for Yagis because of their three dimensional nature. For a regular contemporary long Yagi for the VHF/UHF/microwave bands, the variables are the element diameter, the element lengths, and the element spacings (ignoring matching problems). These are optimized on one band only. For a dual-band Boxkite, the variables are the element diameter, the sub-element geometry (which is not necessarily the same for all sub-elements), the spacing of the sub-elements, the spacing of the sub-element pairs and the sub-element lengths. These have to be optimized on two bands, and the feed-point impedance has to be the same on both bands if complex matching networks are to be avoided. Although this seems to be a daunting task, the foregoing data shows that the results can be reasonably good, if not perfect.

One of the problems I encountered was that of understanding why it was that the antenna performance at f_2, in terms of pattern and gain, was so good when the geometry seemed to be all wrong. In particular, the director spacing is much smaller than for conventional Yagis, and it appeared that the director lengths were nowhere near optimum. However, I believe I have at least the glimmer of an idea as to why this should be so. I will only consider the horizontal/horizontal polarization case: the vertical/horizontal case is quite different and I think of limited interest.

First we'll consider the director spacing at f_2, which is set by the spacing requirement at f_3. This spacing is about 0.36 λ for the 21-element Boxkites at f_3 for directors far from the feed-point, so for dual-band Boxkites where f_3 is 3 times f_2, the spacing at f_2 is 0.12 λ. Although this is very close spacing, it turns out that it is not a problem. An excellent article by Emerson[2] points out that the more (correctly phased) directors that a Yagi has, the better. To check this, I took the 21-element 23 cm/70 cm Boxkite, left the first five directors in place, and removed every other director. The gain on 70 cm dropped by 0.1 dB with virtually no change in the pattern, and, remarkably, the SWR curve remained very good. Then I removed two out of three directors, while retaining the first five directors, and the gain on 70 cm dropped by 0.9 dB compared to the original, again with a very good SWR curve and unchanged pattern. In both cases of course the performance on 23 cm was strongly affected. So it seems that the close spacing on 70 cm really is not important either from the standpoint of gain or feed-point impedance. Now let's consider the geometric differences between the elements on the two bands. Consider Fig 47, which shows a director sub-element pair. Note that, at both f_2 and f_3, there is a voltage node at the center of the

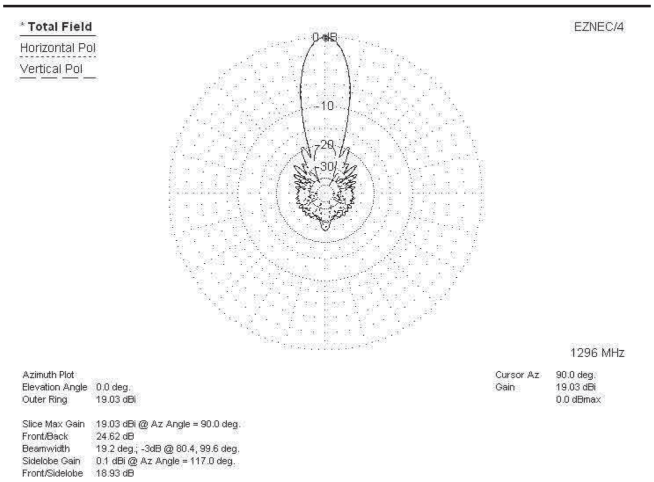

Fig 43—E-plane pattern of the 20-element Boxkite X for 23 cm.

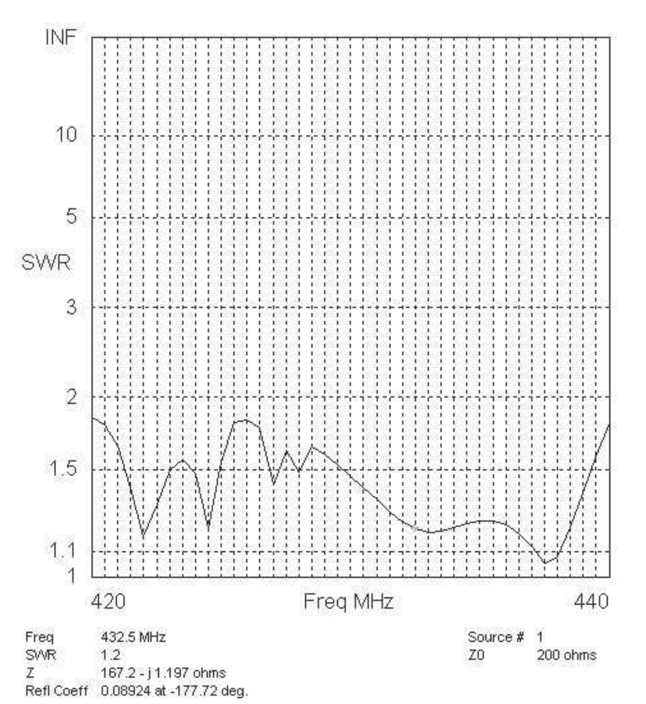

Fig 42—SWR of 20-element Boxkite X for 70 cm.

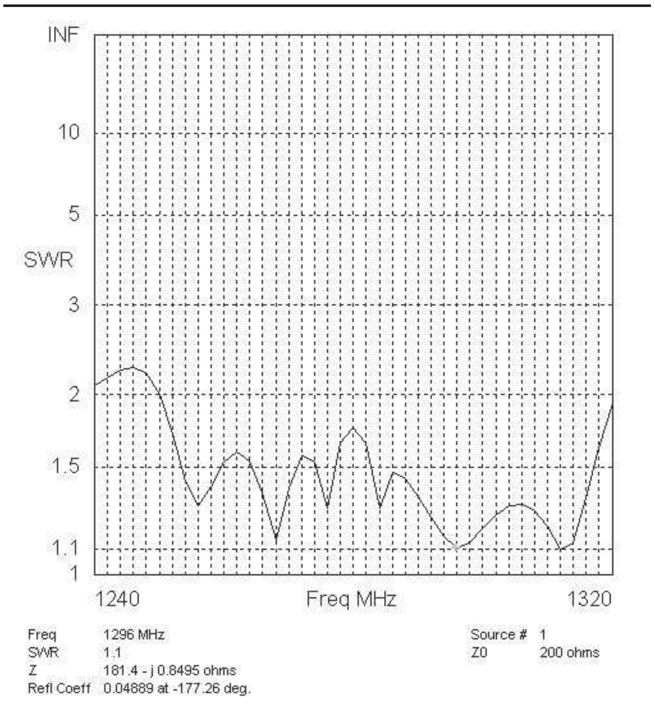

Fig 44—SWR of the 20-element Boxkite X for 23 cm.

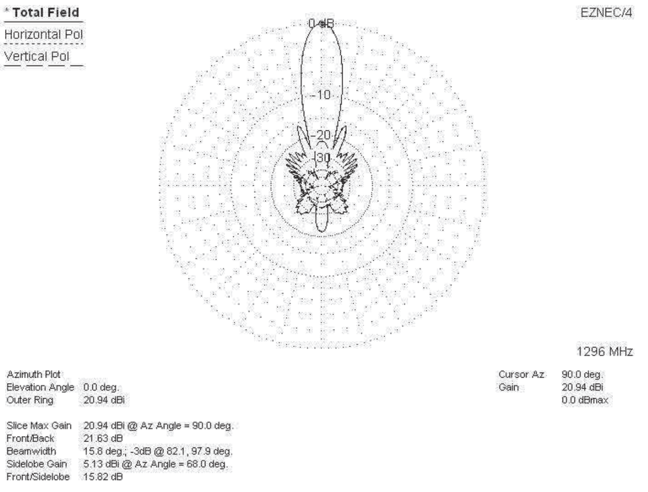

Fig 45—E-plane pattern of the 34-element Boxkite X for 23 cm.

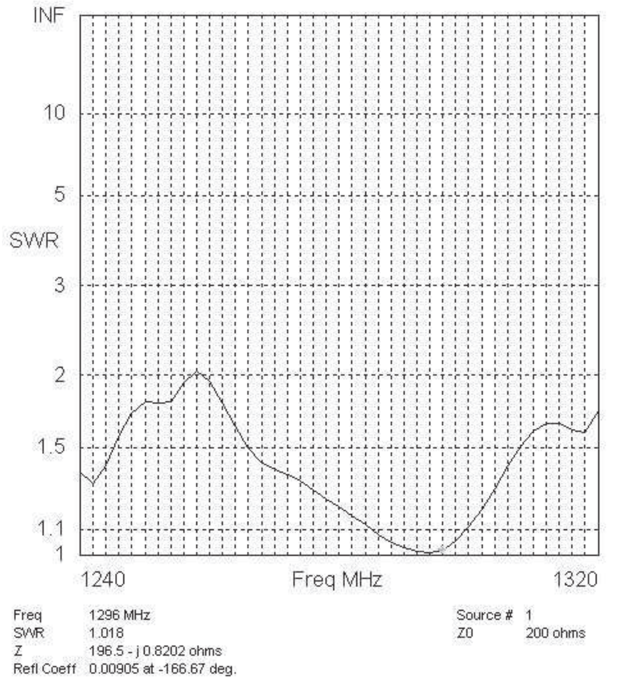

Fig 46—SWR of the 34-element Boxkite X for 23 cm.

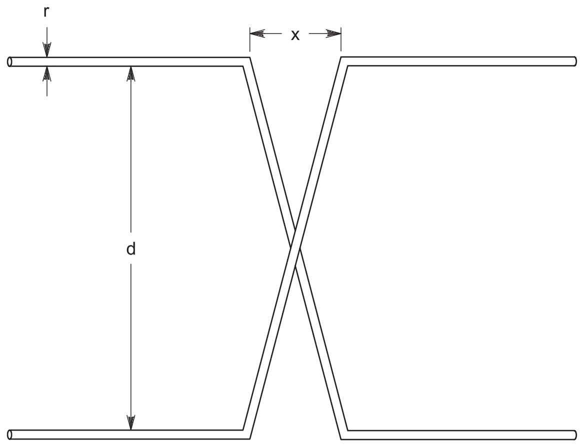

Fig 47—Geometry of a Boxkite director.

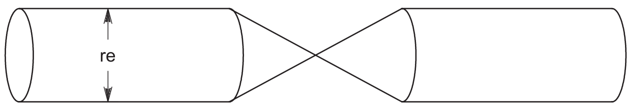

Fig 48—Equivalent Boxkite director.

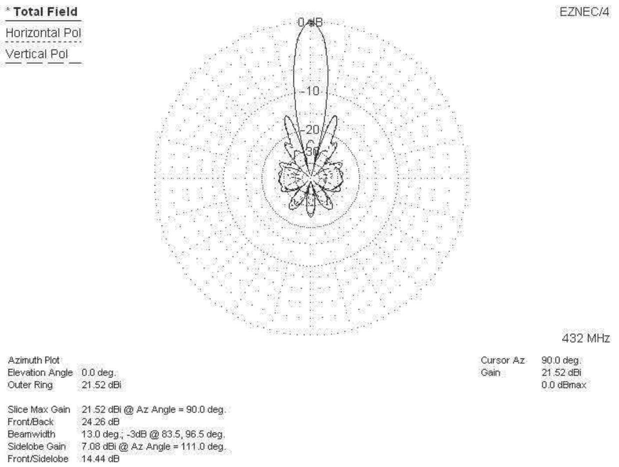

Fig 49—E-plane pattern of a 4 stack of 10-element Boxkite Xs for 70 cm.

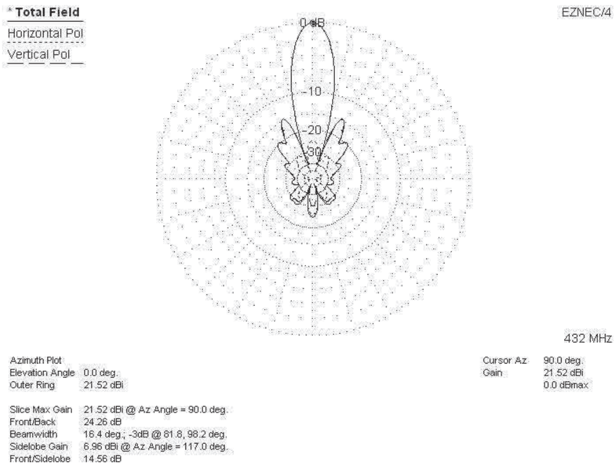

Fig 50—H-plane pattern of 4 stack of 10-element Boxkite Xs for 70 cm.

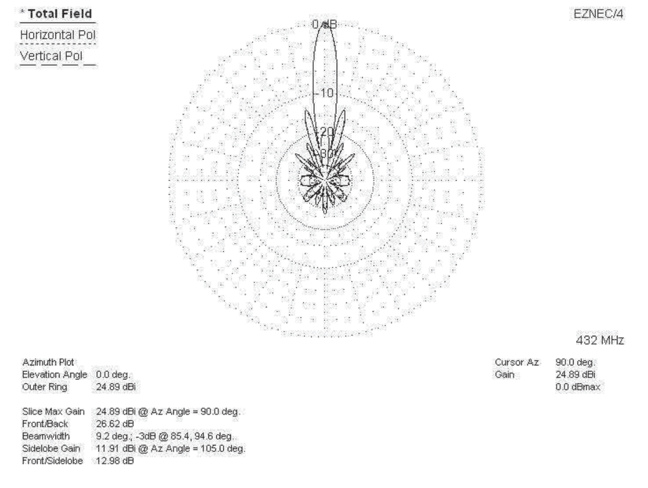

Fig 51—E-plane pattern of 4 20-element Boxkite Xs.

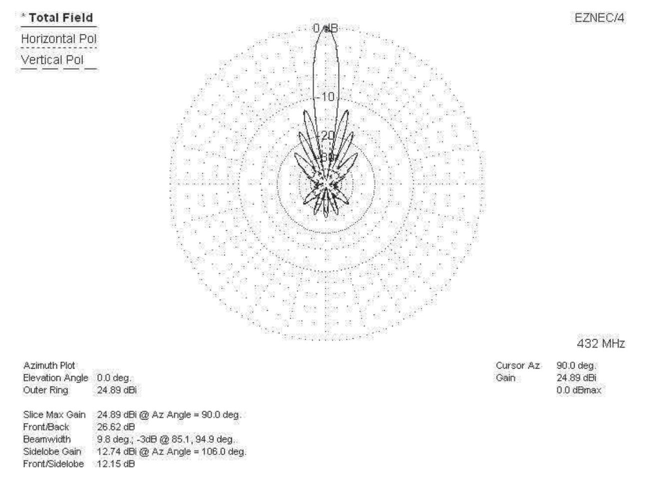

Fig 52—H-plane plot of 4 20-element Boxkite Xs for 70 cm.

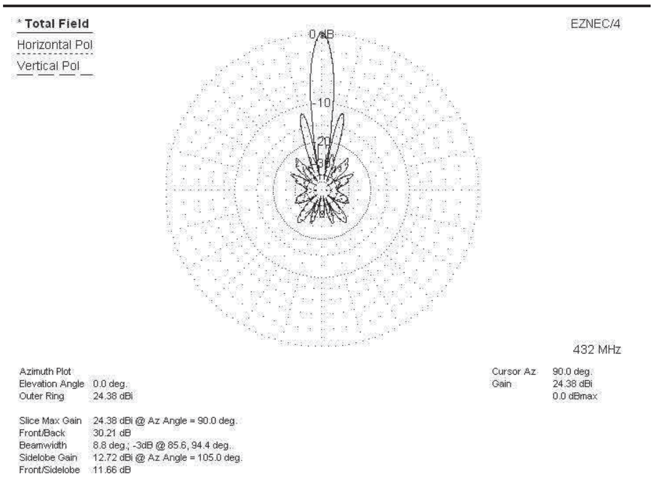

Fig 53—E-plane pattern of a 5 stack of 21-element Boxkites for 2 m and 70 cm at 432 MHz.

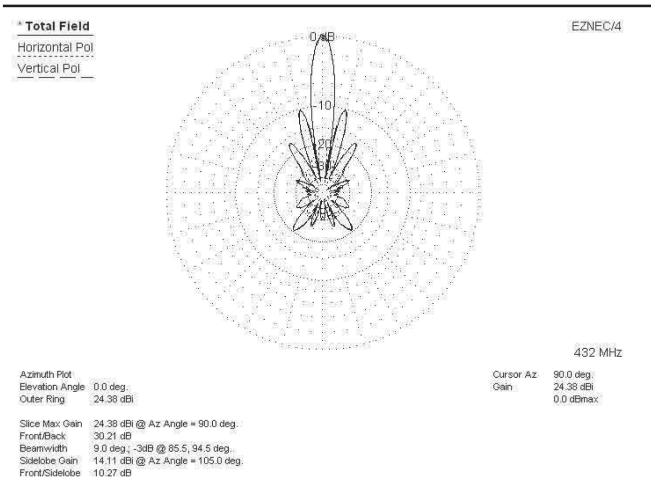

Fig 54—H-plane plot of 5 stack of 21-element Boxkites for 2 m and 70 cm at 432 MHz.

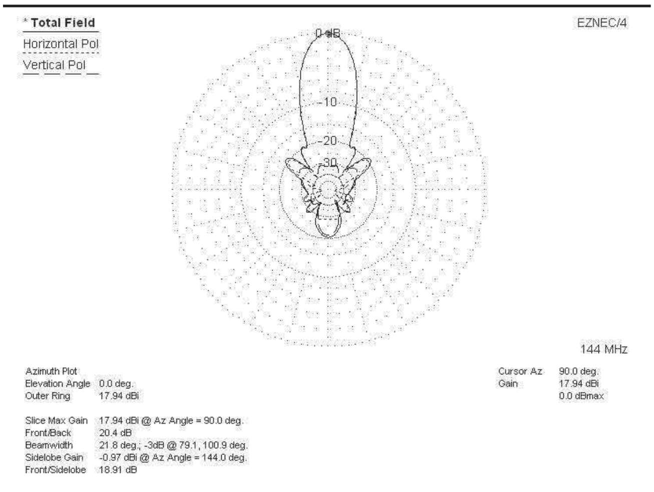

Fig 55—E-plane pattern of 5 stack of 21-element Boxkites for 2 m and 73 cm at 144 MHz.

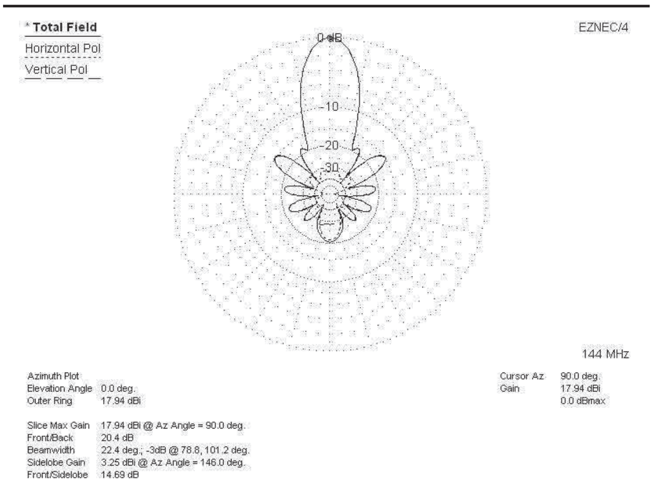

Fig 56—H-plane pattern of 5 stack of 21-element Boxkites for 2 m and 70 cm at 144 MHz.

transmission lines, so we can consider them to be connected together at this point. At f_3, as explained earlier, the element behaves as a stacked quad of approximately λ/2 dipoles insulated from each other by λ/4 shorted stubs. At f_2 the currents in the horizontal sections of the elements are in phase, so the sub-elements can be replaced by a single element having a radius equivalent to that of the spaced elements. See Fig 48. (The transition at the center is almost certainly a lot more complex than illustrated, but I hope you will get the point).

In order to achieve the maximum gain for a surface-wave antenna, which a Boxkite is when the length is several wavelengths or more, it is necessary to optimize the phase delay along the antenna. This is determined by the spacing and diameter of the equivalent directors. The equivalent radius of two identical parallel wires is given by[3]

$$r_e \quad \sqrt{rd} \qquad \text{Eq 1}$$

where r_e is the equivalent radius of the two sub-elements, r is the radius of the sub-elements and d is the center-to-center spacing of the sub-elements

For the 21-element Boxkite for 23 and 70 cm, d is approximately λ/6 on 70 cm (4.6 inches) and is set by the requirement that it be roughly λ/2 on 23 cm. The diameter of the elements is set by mechanical considerations, and in the example antenna is the equivalent diameter of 0.1875 inches square extrusion, which is 0.22 inches. On 23 cm, the element diameter to wavelength ratio, d_e/λ, is 0.024, so from available charts[4] relating-element length to d_e/λ, the length of the directors needs to be somewhere in the region of 0.41 λ for the first director and 0.35 λ for the final director, the latter being dependent on the antenna length. The spacing between the fanned out upper and lower ends of the transmission lines on the 20-element Box kite for 23 and 70 cm is 1.4 inches (0.15 λ at 23 cm) so the total antenna width is twice the director length plus 0.15 λ, or 1.05 λ for the first director and 0.89 λ for the final director, in terms of λ on 23 cm. On 70 cm this translates to .35 λ and .3 λ respectively. For a relatively thin element diameter this would be far too short to provide effective director action. However, on 70 cm the effective diameter of the element is much greater than it is on 23 cm. From (1), r_e=0.7 inches, or d_e/λ =.05. If we now look at design curves[3] relating antenna length to the phase shift along the antenna needed for maximum gain, we find that, again for the 21-element Boxkites, the boom length at f_2 is

$$L \approx 2\lambda \qquad \text{Eq 2}$$

For a boom length of 2 λ, then for maximum gain

$$\frac{\lambda}{\lambda_z} \quad 1.13 \qquad \text{Eq 3}$$

where λ is the free space wavelength and λ_z is the wavelength along the antenna surface

The surface wavelength is determined by the spacing of the directors and by their reactance, which is determined by their diameter and length. Curves relating these parameters are given in ref. 3, and show that, for d_e/λ= .05, and s/λ = .12 (where s is the director spacing), the director length required to achieve the necessary surface wave velocity is 0.32 λ. This is close to that determined above from considerations of the required dimensions at f_3, given that the data for surface wave antennas assumes that the all the directors are equally spaced and of equal diameter (note however that I have ignored the effect of the conical center sections of the equivalent director). This is why the performance on the two bands is better than might have been expected. Despite this, I have not found it possible to maintain the high gain of a single band Box kite at f_3 while maintaining good pattern and gain at f_2. From the modeled results, it seems that the best that can be done is to produce directivity on each of the two bands that is close to that of a contemporary long Yagi having the same boom length. The "fat" elements at f_2 help to produce high gain-bandwidth and SWR bandwidth at that frequency.

Stacking Boxkites

Like Yagis, Boxkites can be stacked horizontally and/or vertically to give increased gain. For single band Boxkites, there are no more difficulties than there are with stacking Yagis. Depending on the application, we can stack for maximum gain or for moderate gain with low sidelobes. As an example, Figs 49 and 50 show the E-plane and H-plane patterns respectively for a stack of 4 10-element Boxkite Xs for 70 cm. The individual Yagi gain is 16.4 dBi, and it can be seen that the total gain of the stack is 21.8 dBi, which is close to the maximum that can be achieved with reasonably low sidelobes. Stacking distance is 53 inches by 46 inches. This is not necessarily optimum, but illustrates what can be achieved. The array is contained in a cube that is approximately 70 inches wide by 60 inches tall by 58 inches long.

Photo 1—Prototype 3-element Boxkite for 6 m and 2 m.

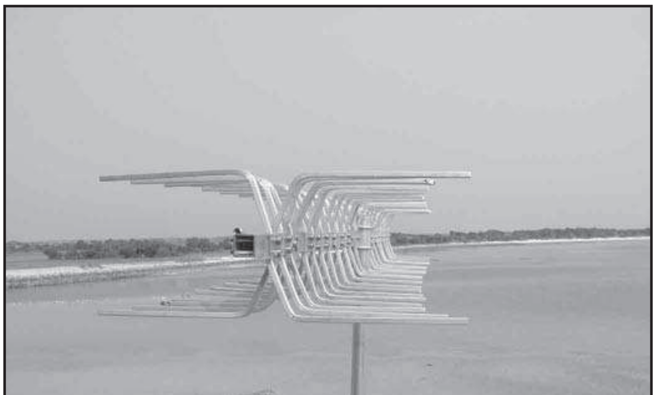

Photo 2—Prototype 20-element Boxkite for 70 cm and 23 cm.

It is interesting to note how close this comes to the supergain limit. An antenna possesses supergain when its directivity is higher than a fundamental limit imposed by the dimensions of its enclosing sphere[5]. If the antenna is in the supergain region, all sorts of woes occur, such as high losses from very high antenna currents, and high Q resulting in narrow bandwidths. The supergain limit is given by

$$G_{\max} \le \left(\frac{2\pi A}{\lambda}\right)^2 + \frac{4\pi A}{\lambda} \qquad \text{Eq 4}$$

where A is the radius of the enclosing sphere and G_{max} is the maximum allowable gain without entering the supergain region

For our stacked 10-element 70 cm Boxkite Xs, the radius of the enclosing sphere is 53 inches, or 1.9 λ, from which G_{max} is 22.4 dBi. Our stacked gain is 21.8 dBi, so we are in the interesting situation where the stacked Boxkite X produces almost the maximum gain achievable for its enclosed volume without entering the supergain region.

Figs 51 and 52 show the results of stacking four 20-element 70 cm Boxkite Xs. The stacking distances are 75 inches (1.9 m) in the E-plane and 72 inches (1.8 m) in the H-plane. This antenna provides sufficient gain for serious moon bounce work[6]. Its dimensions are roughly 6 feet by 6 feet by 13 feet long.

Stacking dual-band Box kites is not quite so simple. The optimum stacking distance for Yagis is:

$$D_{opt} = \frac{\lambda}{2\sin\frac{\varphi}{2}} \qquad \text{Eq 5}$$

where φ is the half-power beamwidth, and for long Yagis

$$D_{opt} \approx \frac{57\lambda}{\varphi} \qquad \text{Eq 6}$$

Also, for long Yagis, the E and H-plane beamwidths are virtually equal. The gain is given approximately by:

$$G \approx \frac{42{,}000}{\varphi_E \varphi_H} \approx \frac{42000}{\varphi^2} \qquad \text{Eq 7}$$

The gain is also proportional to the length, L, of the Yagi:

$$G \approx \frac{10L}{\lambda} \qquad \text{Eq 8}$$

The above expression is approximately true for dual-band Boxkites so

$$D_{opt} \approx 0.9\sqrt{L\lambda}$$

For a given length, the optimum spacing is proportional to the square root of the wavelength. For two operating frequencies that are a factor three apart, this means that the optimum spacing is root three different for the two frequencies. However, setting the stacking distance to give maximum gain at f_3 will not produce the maximum stacking gain achievable at f_2. Conversely, setting the stacking distance at f_2 for maximum gain will produce an over stacked condition at f_3, with consequent very large sidelobes. With a rectangular stack of four Boxkites this is indeed true. However, if we slightly under stack at f_2, then put a fifth Boxkite right in the middle of the array, we can overcome this problem. Figs. 53 thru 56 show the patterns for a stack of five 21-element Box kites for 2 m and 70 cm, with the four outer antennas spaced 90 inches apart both vertically and horizontally, and the fifth antenna centered in the square. These patterns are very reasonable on both bands, and are almost certainly not optimized. There are other geometries that provide good performance, for example a triangular arrangement of three Boxkites with a fourth set in the center of the triangle also gives a good pattern and gain.

For the *big guns*, a stack of four of the above antennas, spaced 160 inches in both E and H-planes provides the very high directivity required for moonbounce work. The gain at 432 MHz is 30 dBi with a beamwidth of 4.2°, and on 144 MHz the gain is 23 dBi with a beamwidth of 12°. For the 2 m/70 cm and 70 cm/23 cm Boxkites, where the frequency ratio is three, the individual Box kites may be driven by a conventional power splitter that is a quarter wavelength long at f_2, and this will also work at f_3. Although it is quite unlikely that such a dual-band stacked array gives the ultimate in performance on both bands, especially in terms of G/T, it is nevertheless intriguing to be able to consider a dual-band Yagi-based moonbounce antenna.

Summary

I hope I have shown that Boxkites have some unique advantages over conventional Yagis on the VHF, UHF and microwave bands. The ability to use one antenna on two bands, which do not have to be harmonically related, with virtually no compromise in performance, has the advantage that only a single feeder is necessary. The single band Boxkites have a length advantage over conventional Yagis that is, to first order, independent of length. On 2 meters a single band Boxkite has the same gain as a regular Yagi that is approximately 15 feet longer. Although not as easy to construct as regular Yagis, all the antennas described are not difficult to make, and I hope to have kits of parts available in the near future.

In the next article I will provide detailed constructional data for some of the Boxkite Yagis, along with mea-

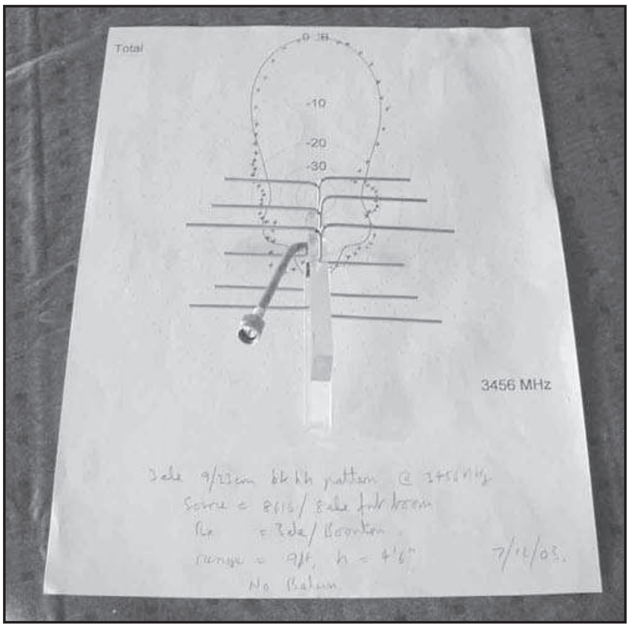

Photo 3—Prototype 3-element Boxkite for 23 cm and 9 cm, along with modeled and measured pattern at 3456 MHz.

surements of SWR and pattern made on the prototypes.

I must confess that the most important lesson I have learned from the endeavor that produced the Boxkite designs, and others as yet unpublished, is that even with technology that is over a hundred years old, there is still plenty of room for innovation. It is also an awful lot of fun!

Notes

[1]S. Powlishen, K1FO, *The ARRL Handbook for Radio Amateurs*, 76th edition, ARRL, 1999.

[2]D. Emerson, AA7FV, "The Gain of an Endfire Array". *ARRL Antenna Compendium*, Volume 5, ARRL 1996.

[3]R. Johnson. *Antenna Engineering Handbook*, 3rd edition, McGraw-Hill Inc, 1961.

[4]G. Hoch, DL6WU, "Yagi antennas for UHF/VHF", *UHF/Microwave Handbook*, ARRL, 1990.

[5]R. Haviland, W4MB, "Supergain Antennas", *Communications Quarterly*, Summer 1992.

[6]R. Turrin, W2IMU, and A. Katz, K2UYH, "Earth-Moon-Earth (EME) Communications", *ARRL UHF/Microwave Handbook*, ARRL, 1990.