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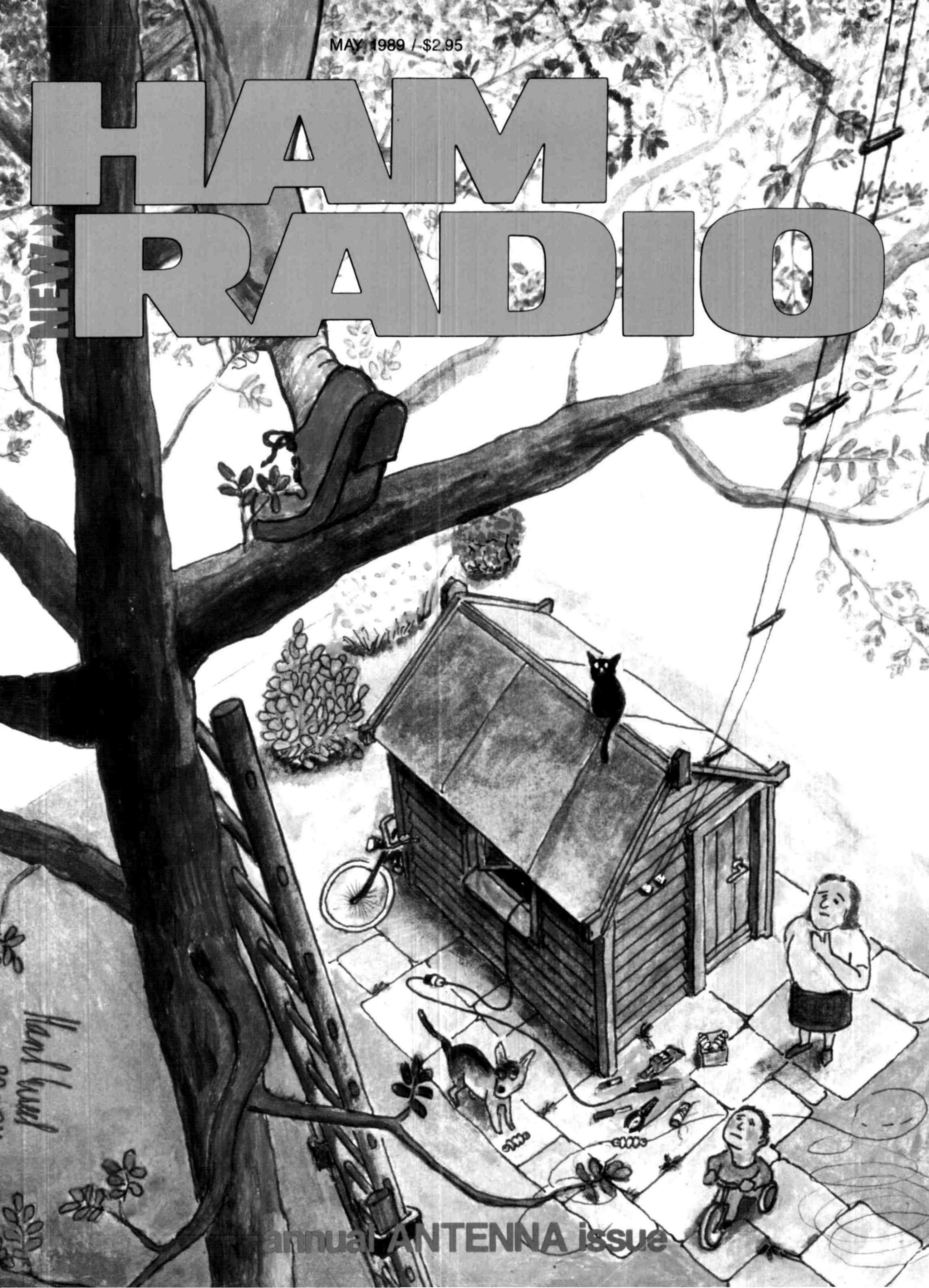

annual ANTENNA issue

IMPROVED HIGH-PERFORMANCE YAGIS FOR 432 MHZ

Obtaining the most from a design

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In the July 1987 issue of *Ham Radio* Magazine,[1] I described a high-performance 432-MHz Yagi design which I built from a Cushcraft 424B. This design improved the radiation pattern and wet weather performance of the original and offered a substantial increase in forward gain.

I gave two versions of the design. The first used 24 elements on a 17′ boom. K2OS, WA3FFC, and W7HAH now use this Yagi on EME. All of them have reported on-air EME performance improvements. A number of tropo operators have also been pleased with the results of my modification. But tropo performance is much harder to quantify and prove than EME performance. The Yagi works so well that several operators have chosen to build it from scratch. As it stands, the 24-element Mark 3 Yagi is still the final version for this boom length. I examined the possibilities of further optimization and found that I wouldn't achieve more than an additional 0.1 dB in theoretical gain. Unfortunately, I could obtain this gain increase only at the expense of pattern deterioration and increased resistive losses.

The second version of my design used a 24′ extended boom and had 32 elements. (See **Table 1** for element length and spacing dimensions.) This extended version has also been used successfully on EME, both in NC1I's 16-Yagi array and my 4-Yagi portable EME array. NC1I used the 4-Yagi array in his Rhode Island and Vermont EME DXpeditions. WA9FWD has used a similar 4 × 32 element Yagi array on EME. (He's now replaced it with an even longer 36-element model.) In the July 1987 *Ham Radio* article,[1] I mentioned that while the 24-element design was a third-generation effort, the 32-element model I described was a second-generation effort which still had room for improvement. I also gave alternative, but untested, director lengths for a potentially improved 32-element Yagi and an even longer 38-element model (both third-generation designs).

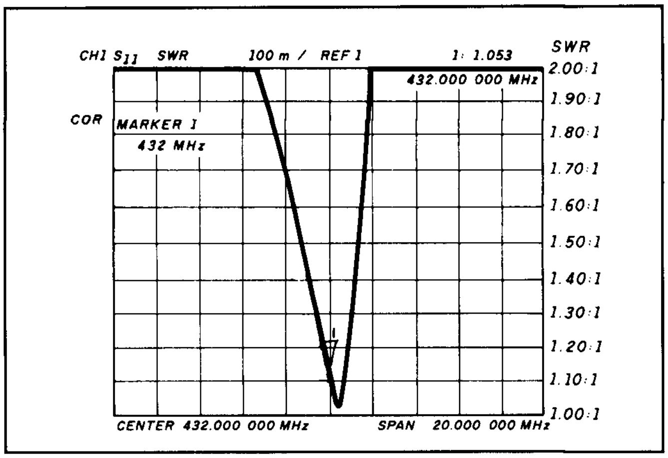
The revised design

Here are the final improved and tested dimensions for the 32-element Yagi. It's called the 32-element Mark 4 Yagi and is the fourth major revision of this design. The improvements to this 32-element Mark 4 Yagi over the earlier published version are:

- Improved radiation pattern, primarily in the rear lobes.
- Greatly improved VSWR bandwidth and wet weather performance.
- Reduced element resistive losses.
- Higher forward gain (~0.2 dB).
- Higher center frequency tuning for improved array performance.

I've also detailed a fully tested 27′6″ long model.

FIGURE 1



Resonant frequency and VSWR bandwidth of the original 32-element Mark 2 Yagi.

Why improve it?

I got the impetus for these changes while helping to assemble NC1I's 16-Yagi EME array. I had determined the driven element T match dimensions by testing a Yagi mounted on a pole in my back yard. When we started checking the driven element matches of the individual Yagis, mounted in place with the other Yagis in the 16-Yagi array, the dimensions for an acceptable VSWR didn't agree with my earlier work. A similar but lesser match problem arose in the 4-Yagi portable EME array. And, although wet weather performance of NC1I's 16-Yagi array was greatly improved over the unmodified Yagis, the wet weather VSWR performance wasn't as good as we'd hoped.

I examined a sample 32-element Yagi on a Hewlett-Packard 8753A network analyzer; it revealed a very narrow match bandwidth. As you can see in **Figure 1** (a printout of the network analyzer measurement), the under 1.2:1 VSWR bandwidth is approximately 1 MHz. The driven element is under 2:1 VSWR over a 5-MHz span. This was substantially narrower than that displayed by the 24-element Mark 3 Yagi. My attempts to improve the match bandwidth on the 32-element Mark 2 Yagi by driven element adjustments alone were unsuccessful. With the help of the network analyzer I found a "natural" match frequency with acceptable bandwidth centered at 423 MHz. Previous work on the 32-element Yagi had shown that shortening all of the elements to raise the center frequency 9 MHz would lower the gain by several tenths of a dB.

I continued my computer analysis. As described in the *Ham Radio* article, the orginal computer analysis for the version 2 Yagi was done using a variation of the WB3BGU program. Because of the limited accuracy of this program, I had to make element adjustments to control the radiation pattern. Investigations done with MININEC showed excessive currents in the first few directors. These directors were also quite long when compared with some other designs. In fact, the director string could be divided into three parts: the first few directors which were tuned too low in frequency; the middle set of directors which were tuned too high in frequency; and the last directors which were tuned close to the correct frequency, but slightly low. Further analysis and work on other long Yagi designs[2] showed that a smooth

TABLE 1

Dimensions K1FO 24', 32-element Mark 4 Yagi.

Element Spacing (inches)	Element Length (mm)	Boom	Element
1.000	348		REF
5.250	336		DE
7.875	323		D1
11.563	314		D2
16.813	309	1"	D3
23.563	305		D4
31.875	301		D5
42.125	297		D6
52.375	294		D7
62.625	292		D8
72.875	290		D9
83.125	288		D10
93.375	286	1 1/8"	D11
103.625	285		D12
113.875	284		D13
124.125	283		D14
134.375	283	1 1/4"	D15
144.625	282		D16
154.875	280		D17
165.125	279		D18
175.375	278	1 1/8"	D19
185.625	277		D20
195.875	276		D21
206.125	276		D22
216.375	275		D23
226.625	274		D24
236.875	273		D25
247.125	273	1"	D26
257.375	272		D27
267.625	272		D28
277.875	271		D29
288.125	271		D30

minor lobe pattern coincided with a good current distribution. I used this information in the 24-element Mark 3 Yagi design.

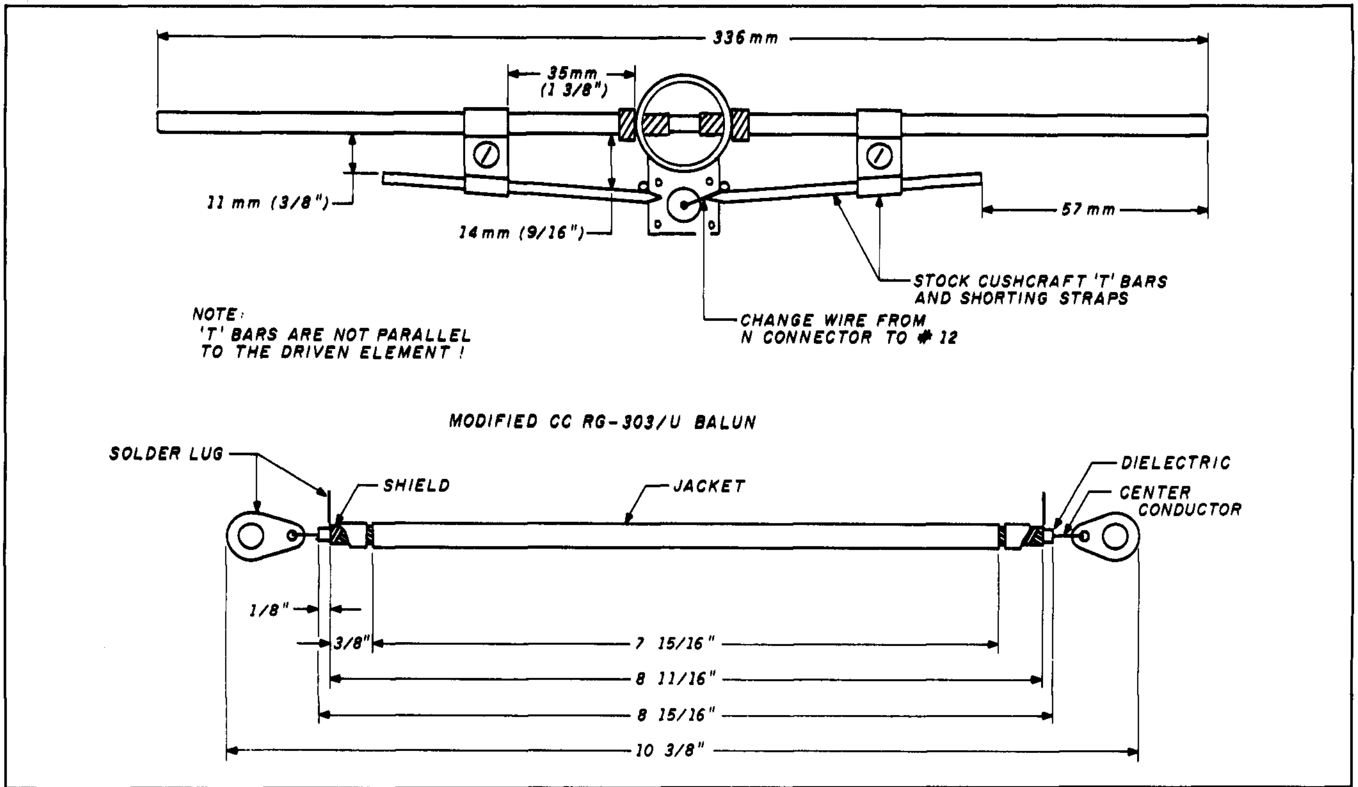
Design details

Up to this point, I'd been doing all my work on the Yagis in English dimensions. I needed an easier measurement method because I was spending considerable time building test Yagis. Metric dimensions for the element lengths were the answer. Not only is the millimeter an easier unit for working with 432-MHz Yagis, but the size of a millimeter (.039") allows for a smoother element taper — without the confusing fractional units.

All element spacings are the same as they were in the earlier versions; they are given in inches. I spent a fair amount of time looking at other spacing arrangements. It was possible to obtain slight performance improvements, but only with extensive spacing changes. These changes would make additional modification and upgrading difficult, defeating my purpose.

To make this improved design, I first converted the English lengths used in the 24-element Mark 3 Yagi to metric dimensions. Next I rounded these millimeter-sized directors to whole millimeters. Then I smoothed out the large changes in director lengths. The computer analysis on MININEC looked promising, but there was a substantial frequency

FIGURE 2



Construction detail of the 32-element Mark 4 driven element using 424B parts.

shift as a result of these manual length changes. I shortened the lengths to center the Yagi at the desired frequency.

Now I had to perform the final length optimization using MININEC. This was a painfully slow process because of the computation time required by the computer available to me at that time. A quick look at the Yagi modeling with four segments required over 2 hours; a more accurate examination using eight segments took almost 8 hours. Consequently, I was able to make only a few element adjustments each day. I'd make an overnight high-accuracy run to ensure that I was still on the right track. Fortunately, the machine I use now solves the problem over six times faster.

When I started this project 4 years ago, I was using a simple program. The original design objective was to increase the Yagi's gain while creating a clean radiation pattern. My current design process adds to the original goals with the following requirements:

- Very high forward gain per boom length.
- Very clean radiation pattern.
- Wide gain bandwidth.
- Acceptable dry and wet weather performance.
- Good driven element match bandwidth.
- Reasonably high natural driven element impedance.
- Good director current distribution.
- Low resistive losses.

Knowledgeable use of the original program can get you 80 percent of the way to a good Yagi design. But the new requirements have rendered my first program obsolete, as it is unable to get all the way to an optimum solution. More complex programs, along with the all-important post-computer optimization steps, now take you 95 percent of the way to the perfect Yagi.

After finalizing the computer-generated dimensions, I began to build and test the project. As I had already built and tested a number of Yagis, I needed to make adjustments only to the driven element and director 1.

Construction

The Yagi's mechanical layout is the same as originally described in the July 1987 *Ham Radio* article. Elements are mounted on plastic bushings which insulate them from the boom sections they extend through. The element ends are chamfered like those of the earlier Yagis. Supports keep the boom from sagging unacceptably. I suggest you review my earlier article before attempting to build these Yagis.

I compared driven element T matches constructed from the original Cushcraft parts used on the 24-element Yagi, with T matches using no. 12 T wires and a UT-141 balun like those of the 32-element Mark 2 Yagi. I obtained similar dry weather matches and match bandwidths with both driven element arrangements. Wet weather performance was slightly better with the no. 12 T wires. A slight adjustment to the balun length made it correspond to an electrical half wavelength. This improved the Yagi's pattern balance.

Figure 2 details the driven element construction using the original Cushcraft parts. Note that the balun must be shortened by 1 inch. As with the 24-element Yagi, I didn't use the original rectangular black spacers and I changed the jumper from the N connector to the T match bar to no. 12 to get a proper match. For the best match don't place the T bars parallel to the driven element.

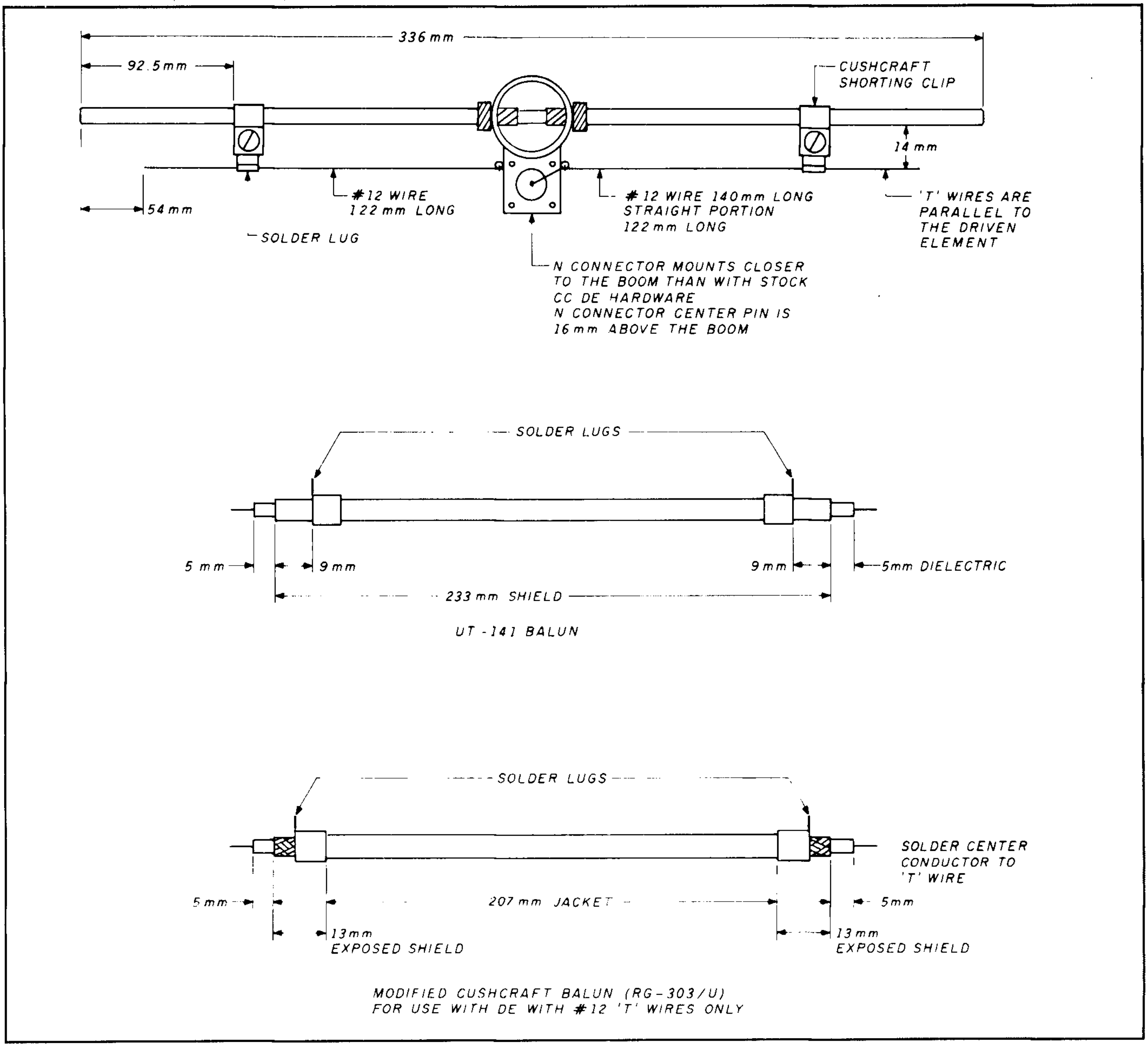
The second version of the driven element is shown in **Figure 3**. It uses no. 12 T wires in place of the original 3/16" diameter T bars. This allows for a greater natural impedance setup. I prefer this arrangement because the shorting straps are farther out on the driven element, away from the high-current point. I tried baluns made from UT-141 solid copper shield coax and RG-303 (like the original 424B) with similar results. If you make the balun from RG-303 you'll need to use a set of dimensions different from those used with the first driven element arrangement. I thought it was desirable to eliminate the original solder lugs and solder the center conductor directly to the T match wires instead.

Performance

The computed E and H plane patterns for the 32-element Mark 4 Yagi in **Figure 4** show a very smooth lobe structure. The first sidelobes are 1 dB stronger than those in the original version. This seemed an acceptable tradeoff for a smoother overall lobe structure and significantly lower rear and mid-H plane lobes, in combination with higher overall gain. Calculated gain on MININEC is 17.9 dBd (20.1 dBi). Because of program inaccuracies and resistive losses, the real gain of the Yagi is closer to 17.8 dBd (19.9 dBi) — still an excellent figure for the boom length. DJ9BV examined the Yagi design using the more sophisticated NEC program. His results gave an excellent pattern correlation. The NEC-calculated gain figure of 17.8 dBd (19.9 dBi) also agrees closely with antenna measurements.

On the antenna range, the new model consistently measures about 0.2 dB higher than the earlier 24' long version. It also measures about 0.4 dB higher than my "high-gain" reference Yagi, the KLM 432-30 LBX. This places the real-

FIGURE 3



Construction detail of the 32-element Mark 4 driven element using no. 12 T wires. Further details for modifying the Cushcraft Balun for use with the no. 12 T wire match.

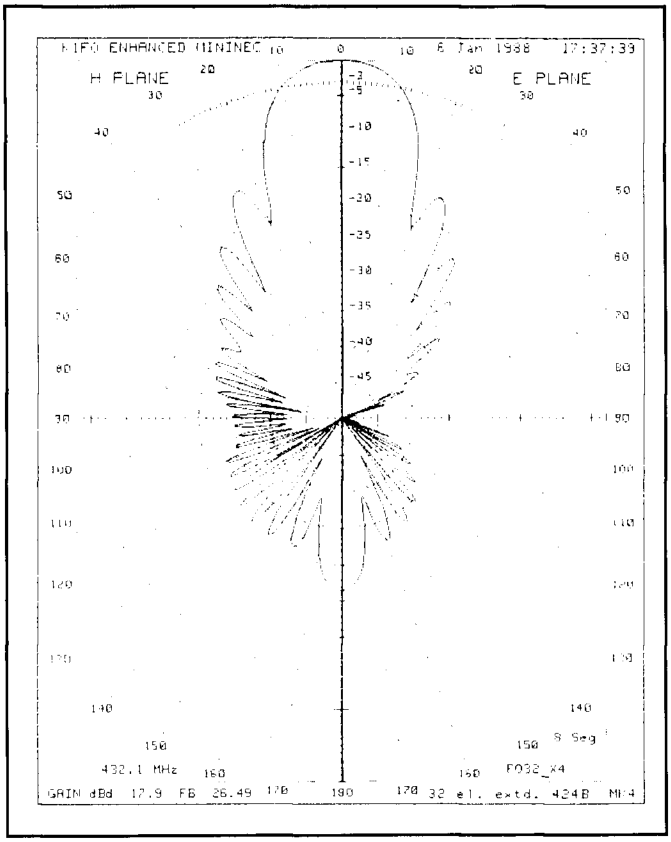
world gain of the new 32-element Mark 4 Yagi at about 17.8 dBd (19.9 dBi). Earlier measurements with the Mark 2 Yagi were slightly optimistic; the real-world gain for this version was about 17.5 dBd. (This has also been confirmed by NEC analysis.)

Array temperature is an important parameter on EME and for high-performance tropo stations. Array noise is the combination of noise received by the array (manmade or natural) and the noise generated from resistive losses in the material used to make it. DJ9BV calculated that an array of four of the 32-element Mark 4 Yagis pointed at cold sky has a noise temperature of 25K. This figure is 5K lower than the original Yagi design — a significant number on EME. Array noise measurements, using earth to cold sky and stellar sources to cold sky, place the array temperature somewhat higher than the calculations. Measured array temperatures for four Yagis arranged 2 × 2 are about 30K for the new Mark 4 Yagi, and about 37K for the old version.

To calculate the overall system temperature, you have to add the phasing line, relay, and balun losses, and the receive system noise temperature to the array noise. For a high-performance EME system with very low loss phasing lines (like the Andrew Heliax™ and a 25K preamplifier), this reduced array temperature would provide an additional 0.5-dB signal-to-noise improvement on receive over the original 32-element Yagis. Including the additional gain of the improved design, you can expect to hear your own moon echoes almost 1 dB stronger — a significant improvement for no array size increase.

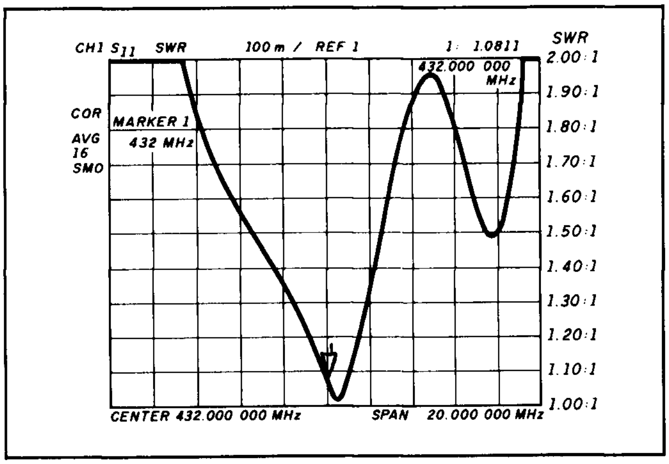
Figure 5 is a network analyzer plot of the driven element match. When you compare this with **Figure 1** (the same plot for the original 32-element Yagi) you can see that the

FIGURE 4



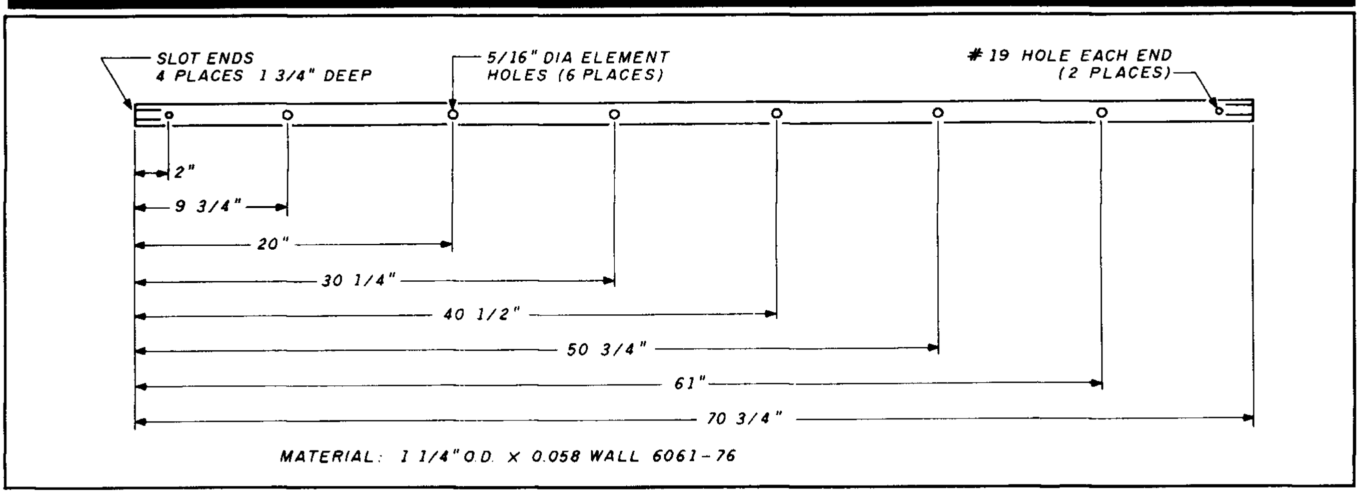
Calculated E and H plane patterns for the K1FO 32-element Mark 4 Yagi.

FIGURE 5



Resonant frequency and VSWR bandwidth of the improved 32-element Mark 4 Yagi.

FIGURE 6



Element mounting dimensions for the center section of the boom for the 36-element extended modified 424B Mark 4 Yagi.

match bandwidth is much broader. On the 32-element Mark 4 Yagi, the SWR is now less than 1.2:1 for almost 2.5 MHz. This is 2-1/2 times wider than the original. The SWR is less than 2:1 over 16 MHz, or more than 3 times greater than the earlier version.

With the revised dimensions, the 32-element Yagi behaves well when wet. The VSWR curve shifts down in frequency approximately 2 MHz under simulated heavy rain conditions. This raises the SWR to a still acceptable 1.35:1 when the antenna is very wet. This is a significant improvement over the 32-element Mark 2 Yagi, which would show about a 2.2:1 VSWR in heavy rain.

Proper stacking distances for the 32-element Mark 4 Yagi are 82 inches in the E plane and 78 inches in the H. At these distances, the stacking gain (before phasing line losses and mechanical errors are factored in) is over 2.9 dB in each plane. A 4-Yagi EME array using low-loss phasing lines would have 23.3 dBd (25.5 dBi) array gain. This is more than adequate to work a number of different 432-MHz EME stations. An 8-bay 32-element Yagi array has enough gain to give you a standout EME signal.

A longer 36-element version

NC1I did his portable EME operations in the summer, usually the worst time of year for EME. Although the original 4 × 32 element Yagi array performed well, I wanted a little extra performance without having to add more Yagis. I chose the 27-1/2′ length because it was the minimum size increase which would make a significant performance improvement. (See **Table 2** for element length and spacing details.)

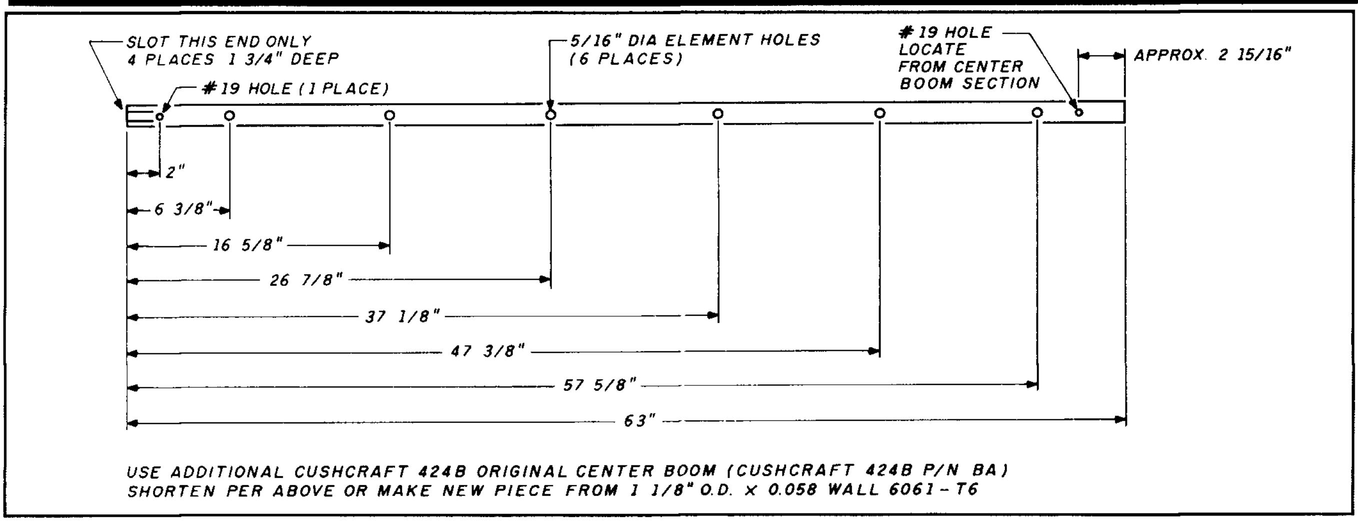
Electrically, the design is virtually identical to the 32-element Mark 4 Yagi. Mechanically, the changes are a little more detailed. I built a 6′ long 1-1/4″ diameter center boom section from scratch for the long Yagi. I reinforced this new center section with a 1-3/8″ outer diameter, 0.058″ wall thickness, 24″ long piece of 6061-T6 aluminum tubing. The 1-3/8″ diameter tube is centered at the mast mounting point. This arrangement gives you a very rugged (though slightly heavy) boom section.

TABLE 2

Dimensions K1FO 36-element Yagi 27′4-1/8″ boom.

Element Spacing (inches)	Element Length (mm)	Boom Diameter	Element
1.000	347		REF
5.250	327		DE
7.875	322		D1
11.563	313		D2
16.813	308		D3
23.563	304	1″	D4
31.875	300		D5
42.125	296		D6
52.375	293		D7
62.625	291		D8
72.875	289		D9
83.125	287		D10
93.375	285		D11
103.625	284	1 1/8″	D12
113.875	283		D13
124.125	282		D14
134.375	282	1 1/4″	D15
144.625	282		D16
154.875	281	1 3/8″	D17
165.125	279		D18
175.375	278	1 1/4″	D19
185.625	277		D20
195.875	275		D21
206.125	275		D22
216.375	274		D23
226.625	274	1 1/8″	D24
236.875	273		D25
247.125	273		D26
257.375	272		D27
267.625	271		D28
277.875	270		D29
288.125	270		D30
298.375	269	1″	D31
308.625	269		D32
318.875	268		D33
329.125	268		D34

FIGURE 7



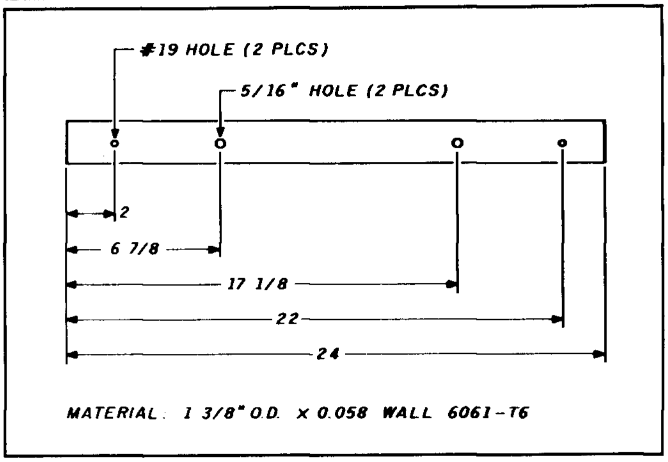
Detail for the new no. 2 rear boom section for the 36-element extended Mark 4 Yagi.

Though the doubled-up center piece may seem like overkill, it's very easy to bow a 0.058" wall tube when you tighten the mast bracket U bolts. A few degrees of bend in the boom may not be noticeable on a short Yagi, but when you translate this bend to a 27-1/2' long boom it becomes a significant curvature.

The new center boom section is detailed in **Figure 6**. **Figure 7** describes boom section no. 2 (between the rear and the middle section). You can make this second boom section from a spare 424B original center section, or from scratch. Just follow the drawing and use 1-1/8" diameter × 0.058" wall aluminum tube. The center boom reinforcing piece is shown in **Figure 8**.

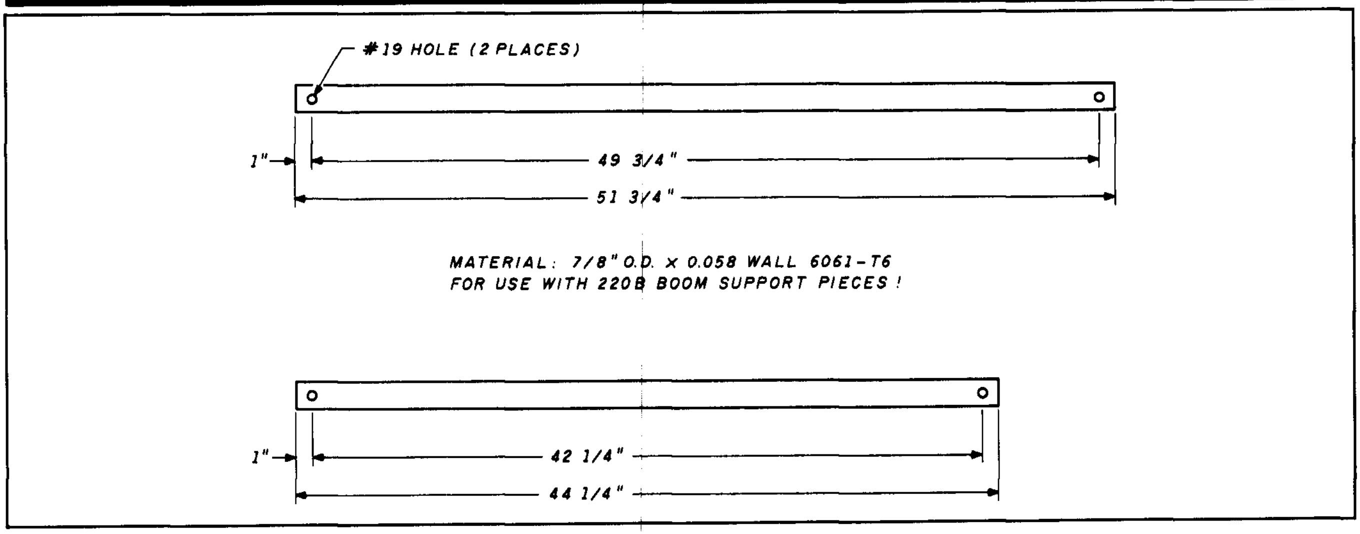
I made new pieces for the boom supports so I could extend them. I positioned the mast mounting point for the boom supports 30" from the boom. This creates a large enough angle and prevents overstressing the supports. Like the earlier Yagis, I used old-style Cushcraft 220B bent support pieces with longer homemade center sections. **Figure 9** shows these new boom support splice pieces. Cushcraft has since changed the design of their boom supports. If you don't want to make your own supports from scratch, Cushcraft 4218-XL boom supports will do the job.

FIGURE 8



Detail for reinforcing the center boom section of the 36-element extended Mark 4 Yagi.

FIGURE 9



Detail for the boom support pieces on the 36-element extended Mark 4 Yagi.

Electrical changes

You'll notice that the element lengths start out 1 mm shorter than on the 32-element Mark 4 Yagi. I changed the length to keep the gain center frequency in the right place. Remember that the Yagi's center frequency oscillates up and down as you add directors. Tapered designs like this one minimize the effect, but the trait still exists.

The driven element was easy to set up for both a good SWR at 432 MHz and a minimum centered above 432 MHz. This is the best way to ensure good wet weather performance. The match bandwidth on the 36-element model is actually better than on the 32. The driven element match on the 36-element Yagi also was relatively insensitive to the balun length — another good sign. The driven element for the 36-element Yagi is outlined in **Figure 10**.

Stacking the 36-element Yagi

At a 12-wavelength boom length a good Yagi will have a nearly symmetrical pattern. You can see from the calculated pattern in **Figure 11** how the H plane is starting to show nulls at 90 degrees in the pattern, similar to the E plane. The −3 dB beamwidth is still slightly wider in the H plane, even at this long boom length. This indicates that optimum spacings will be close but not quite equal in both planes.

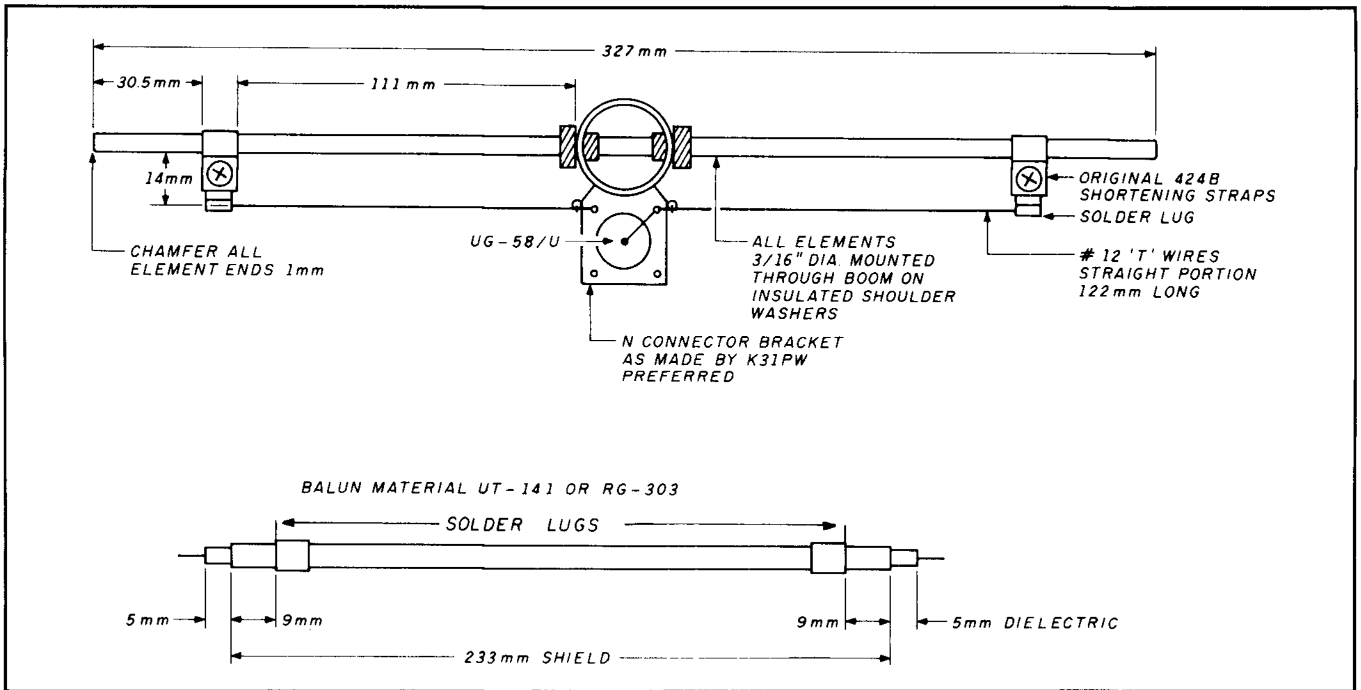
The optimum spacings for the 36-element Yagi are 87" in the E plane and 85" in the H plane. At these spacings the theoretical stacking gain in each plane is 2.9 dB.

Performance of the 36-element Yagi

The calculated pattern for the 36-element Yagi (**Figure 11**) is quite similar to the 32-element Mark 4 Yagi. The sidelobe structure is almost identical. The main lobe E and H plane beamwidths are about 1 degree narrower than the 32-element Yagi at 18 × 18.5 degrees.

Measured gain of the 36-element Yagi is approximately

FIGURE 10



Detail of the driven element of the 36-element Yagi using the no. 12 T wire match. Total boom length is 27′ 4-1/8″.

0.6 dB higher than the 32-element Mark 4 Yagi at 18.3 dBd or 20.5 dBi. Array temperature is even better than the shorter Yagis at a calculated 24K. Measurements indicate an array temperature under 30K.

Of course, on-the-air performance is what counts. WA9FWD reported a significant improvement when he upgraded from four of the 32-element Mark 2 Yagis to four of the 36-element model.

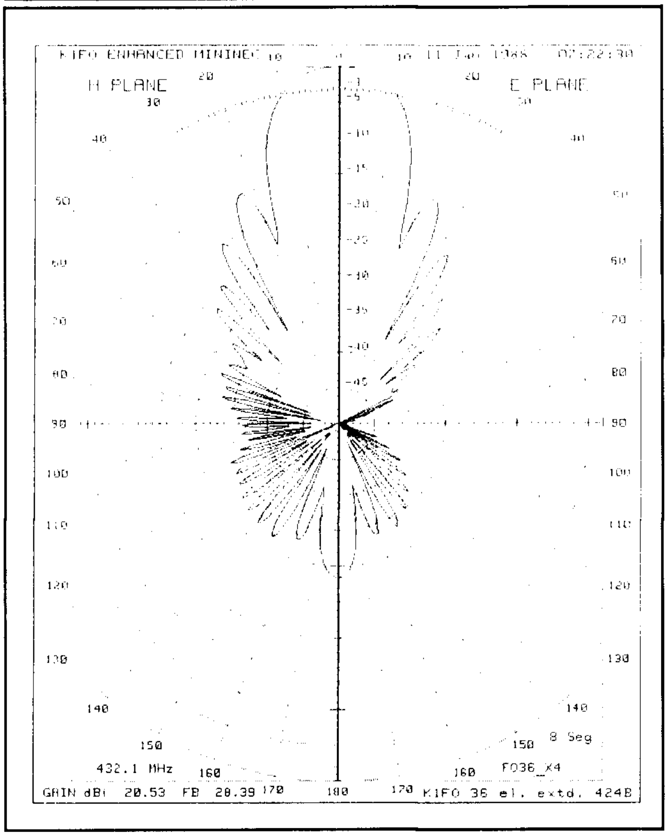
NC1I and I recently rebuilt our portable EME array to use four of the new 36-element models. The old array was 4 × 32 element Mark 2 Yagi. The new array seems to follow the predicted improvements. Measured sun noise is up 1.5 dB from the best we measured with the old array. The new array uses the same phasing lines, power divider, and preamp as the old one. The sun noise improvement is in the expected range. Gain of the 36-element Yagi is 0.8 dB higher than the 32-element Mark 2. Signal-to-noise improvement due to noise pickup and resistive losses is calculated to be over 0.5 dB. The sum, 1.3 dB, is close to the measured 1.5-dB improvement.

We first tested the new array at W1NY during the January VHF contest. We made a total of 15 EME QSOs in only 5 hours of EME operation, all with a bad antenna relay! After the contest we fixed the relay and activated the array the following weekend. We had 16 hours of EME operation spaced over the two weekends. We made 34 EME QSOs with 26 different stations, all on random. Echoes were noticeably better with the new array.

Conclusion

A top performing 432-MHz Yagi must have a proper balance of several desirable characteristics:

FIGURE 11



Calculated E and H plane patterns for the K1FO 36-element Mark 4 Yagi.

- High forward gain for the boom length.
- Excellent sidelobe structure.
- Good gain bandwidth.
- Good driven element SWR bandwidth.
- Low resistive losses.

Once you've defined these electrical traits, you must contruct your Yagi so that it will not only work in the real world, but stay up and retain that performance for many years. The K1FO 32 and 36-element Yagis have an excellent balance of these design goals, especially when you consider that they can be made easily from an existing commercial Yagi and its spare parts.

The 4-element (41" long) Yagi extension appears to be worth the effort. During initial operation with the 36-element Yagi arrays, it seemed we finally had an array that was better than a 4-Yagi array was supposed to be. As any given Yagi design is extended, its driven element impedance and rear lobe structure oscillate up and down. At a length of 27-1/2', the pattern and driven element are in optimal combination. If you plan to build a long 432-MHz Yagi from scratch, I suggest that you take a serious look at the 36-element model.

The results of the computer analysis suggest that the design could be extended still further with good results. But keep in mind that the boom would have to be extended by more than the same percent of boom change when going from 32 to 36 elements for another 0.5-dB gain. You'd need to add at least five more elements, possibly six, to see an equivalent improvement. This would make the boom almost 32 feet long. Since the 36-element Yagi weighs over 12 pounds and has a wind area of over 3 square feet, an even longer Yagi may quickly become unmanageable. A very long object also develops quite a momentum when it's moved. This added inertia requires a large increase in the mechanical strength of the array's stacking frame.

Acknowledgment

I'd like to thank Rainer Bertelsmeier, DJ9BV, for his NEC analysis and array temperature calculations of my Yagi designs. hr

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1. Steve Powlishen, K1FO, "High-Performance Yagis for 432 MHz," *Ham Radio*, July 1987, page 8.
2. Steve Powlishen, K1FO, "An Optimum Design for 432-MHz Yagis, Part 1," *QST*, December 1987, page 20.

MARCH WINNERS

Congratulations to George Gorsline, VE3FIU, our March sweeps winner and Rick Littlefield, K1BQT, author of March's most popular WEEKENDER — "Solo-16 Acoustic CW Speaker." Both will receive a copy of *The Radio Handbook* by Bill Orr, W6SAI.

Our WEEKENDER sweepstakes ends with the April issue. You still have a chance to send your April evaluation cards and win. The winners of the April sweeps will be announced in the June issue of *Ham Radio*.

Thanks to all of you who sent in your cards. Your comments have been invaluable to us!

Terry Northup, KA1STC