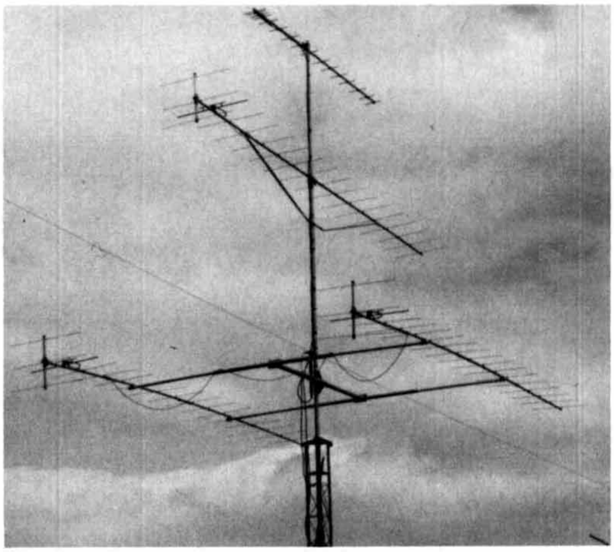
Yagi triangular array

Somewhat unconventional stack performs well mechanically and electrically



Inspired by recent articles on stacking Yagis, I decided to improve my 2-meter antenna system, which consisted of a single 19-element, horizontally polarized Yagi. Before long, I had installed another 19-element antenna above it — and with great anticipation, began making comparative checks with the new system.

Because my primary interest is in terrestrial communications, the 2.5- to 3-dB increase in gain didn't overly impress me. With a 2 x 2 array in mind, I bought two more antennas and started designing an H-frame structure. Very quickly, however, I realized how large and heavy the completed array would be. I weighed the possibilities: a tilt-over tower, with block and tackle, would allow access to the array, but would probably be unfeasible because of the antennas' size and weight. After much soul searching, I decided that a stack of four antennas, with the required H-frame, would be out of the question.

alternate stacking methods

I have, from time to time, heard mention of the diamond stacking configuration and claims of improved performance when compared with conventional rectangular stacking. Assuming reports on the diamond's performance to be correct, and seeing a triangle as half of a diamond, I concluded that a triangle would be likely to offer better performance than an inline stacked array.

Unfortunately, oddball stacking geometry such as the triangle or diamond has received little or no publicity; I've yet to find informative literature on anything but the inline stacking methods. (It would almost seem that the numeral 3 simply doesn't exist in the world of antennas. Instead, the philosophy of "double or nothing" seems to prevail.) Nevertheless, after due consideration of weight distribution on the mast and tower, I concluded that a triangle stack configuration — with two horizontally stacked antennas located at the lower level of the mast and a third Yagi mounted at the top of the mast — would best suit my needs.

Theoretically, three Yagis would provide an additional 1.75-dB gain over a pair. Subtracting the phasing harness loss from the theoretical value, a realistic gain of 4.5 dB over a single antenna should be possible. What was more important to me at this time, however, was what the plotted antenna pattern would be. How would it differ from a rectangular stack of four antennas?[2] The only way to find out would be to build the triangular array and compare the results with published articles on a four-antenna array.

optimum stacking distances

The first problem was to determine the optimum spacing required between antennas. Available stacking data apply only to a pair of antennas stacked in either of two unique locations with respect to each other. Both antennas must be located on the axis of either the E or H plane. Polarization and phasing of both must also be the same.[1,2] With triangular stacking, the two lower antennas would satisfy the above con-

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ditions. However, the upper antenna is offset, and its H plane axis does not fall upon that of either of the two below. Consequently, the spacing from it to either of the two below will differ from dimensions found in previous studies.[1,2] After a little head scratching, it became apparent that non-standard H plane stacking dimensions were still useful.

Visualize, as in **fig.1**, a pair of vertically stacked Yagis evolving through positions into a horizontal stack. For example, by keeping the lower antenna location and polarization fixed, and swinging the upper one through an arc (which defines a locus), while maintaining the same polarization as the lower one, one ends up with a horizontal stack. Each and every point along the locus will locate the movable antenna at an *optimal* distance from the fixed antenna. Also, at some point along the locus, the antenna will be equidistant to either of the two lower antenna positions (see **fig. 1**).

E and H optimum spacing differs

If optimum spacing for E and H plane were identical, the locus would be a 90-degree arc of a circle, with its radius equal to the optimum spacing dimension. However, the E and H plane optimum values are *not* equal, and studies have shown that optimum spacing, in a particular plane, depends on beamwidth in that plane. The greater the beamwidth, the closer the

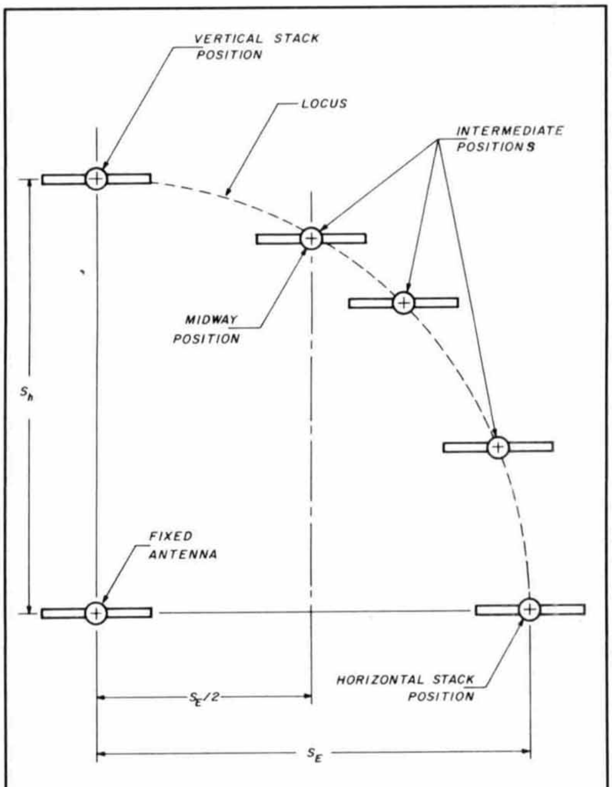

fig. 1. Vertical-to-horizontal stack orientation.

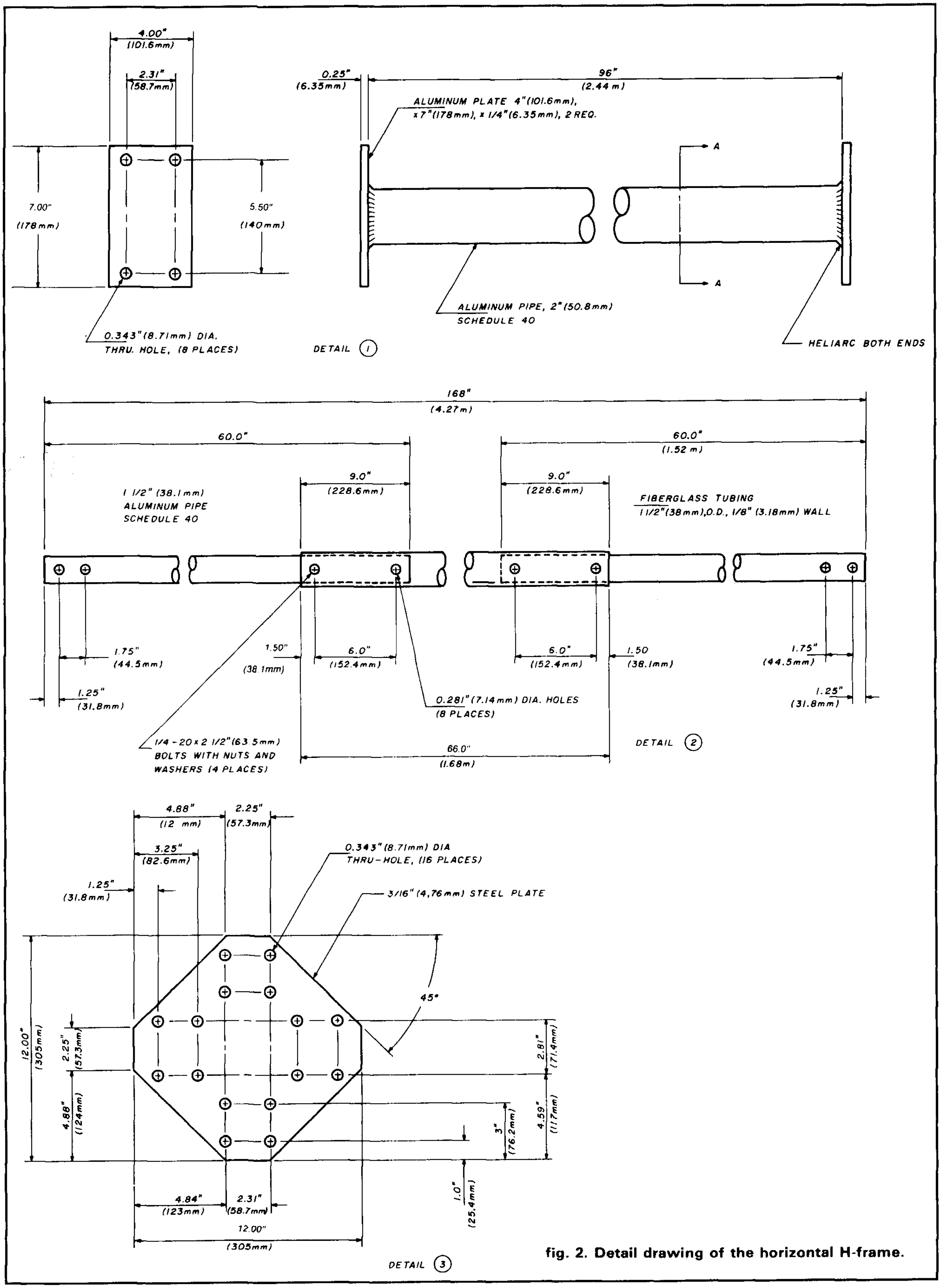

fig. 2. Detail drawing of the horizontal H-frame.

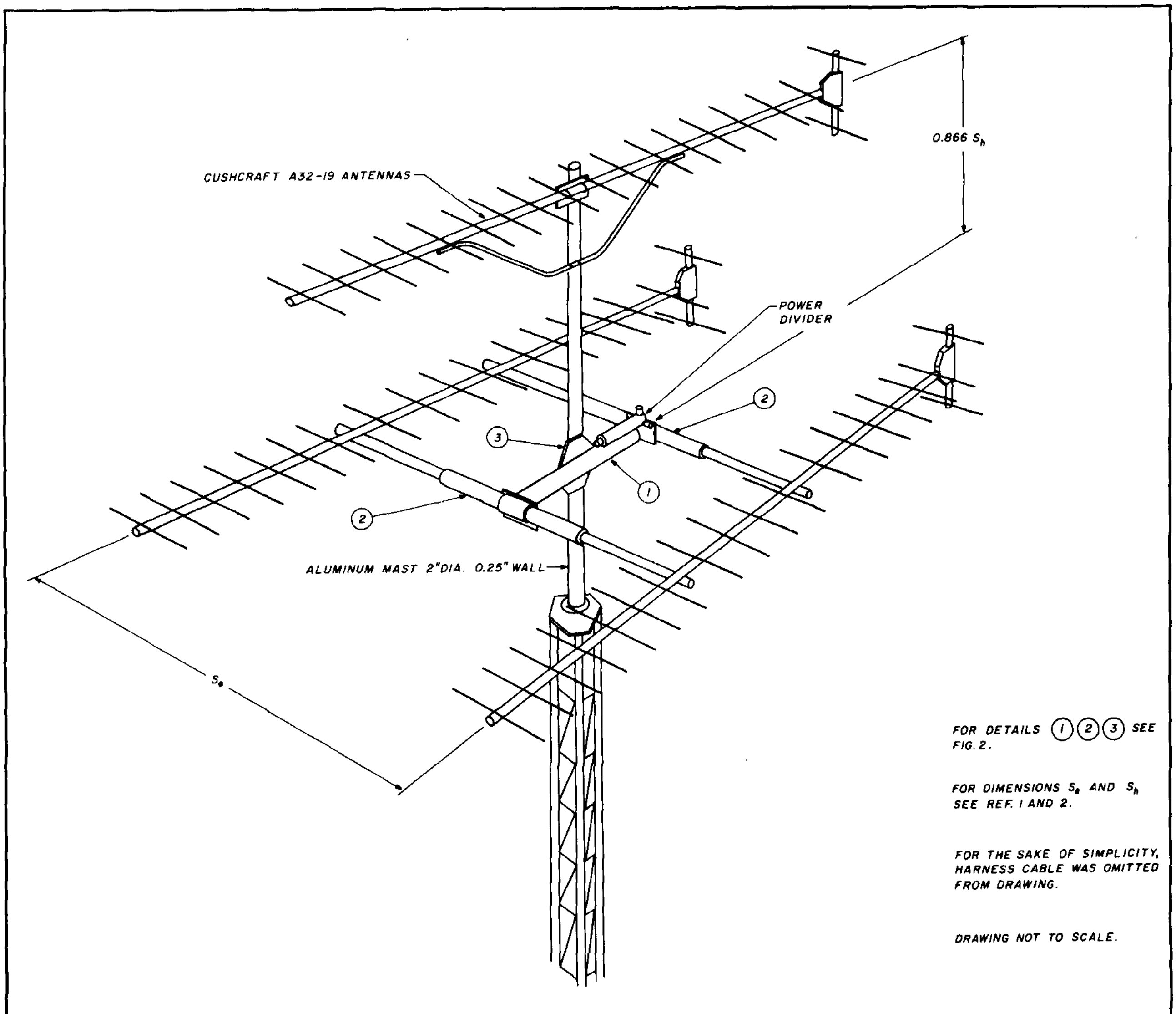

fig. 3. The Yagi triangle.

spacing.[1] The one feature all Yagis seem to have in common is greater beamwidth in the H plane than in the E plane. Consequently, H plane spacing will be less than the E plane's. The locus in this case is an arc of an ellipse. (To visualize an ellipse, picture a hoop rotated about its diameter and viewed at an angle.) Put into usable terms, E plane spacing is the value recommended by Joe Reisert, W1JR[1] and Steve Powlishen, K1FO.[2] Their tabulated data includes the most popular antennas in use today. The vertical stacking dimension is 86.6 percent of the optimum H plane dimension or $S = 0.866\ S_H$ where S_H is the optimum H plane stacking dimension recommended for inline stacking.[1,2]

horizontal H-frame construction

Horizontal stacking of horizontally polarized antennas requires the use of dielectric material in the immediate vicinity of the Yagi elements. A minimum distance of 1/2 wavelength of metal-free structure is recommended, or 1/4 wavelength beyond the active element tips.[3] Detail drawings for the structural parts used to assemble the H-frame are shown in **fig. 2**. The Cushcraft A32-19 antennas used in the Yagi triangle normally require boom supports supplied by the manufacturer; these are not necessary when mounted on this horizontal H-frame. The upper antenna, however, must be mounted in accordance with the manufacturer's recommendations (see **fig. 3**). Within reasonable limits, variations in frame design are certainly permissible.

If antennas other than those shown are used, changes in the overall length of items 1 and 2 might be required. Should it be necessary to make such adjustments, remember that the fiberglass support arms of the H-frame must be located midway between

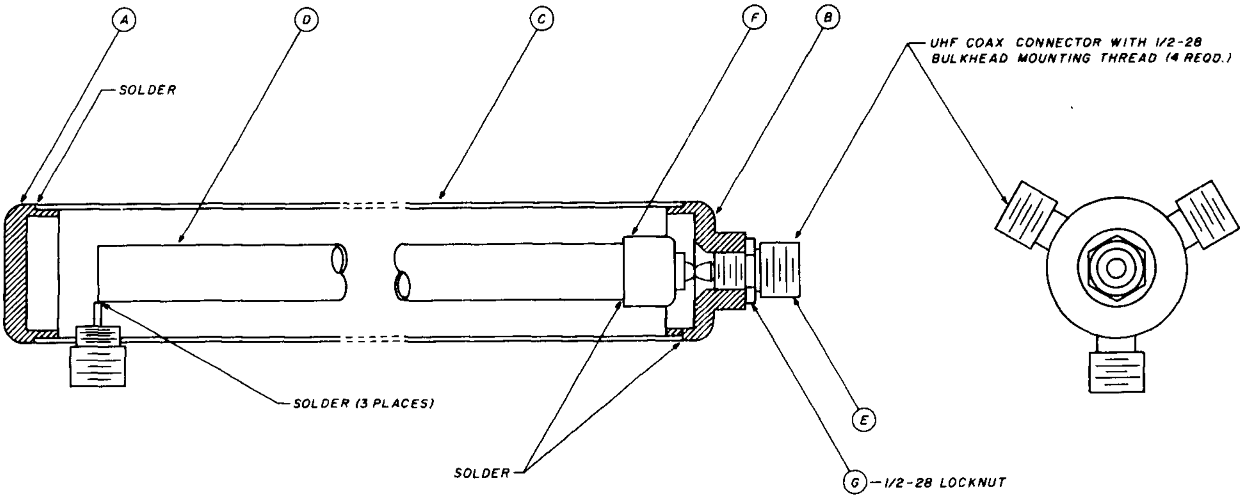

fig. 4A. Sectional view, 144-MHz three-way power divider.

the director elements of the antennas as shown in **fig. 3**.

material sources

I made use of readily available material. A local metal fence supply dealer stocked aluminum pipe and was also equipped with Heliarc welding facilities, which became very useful while constructing the H-frame. The 1-1/2 inch diameter fiberglass tubing, available in 5-foot lengths and used for satellite antenna work, was purchased from my local Amateur Radio dealer.

Because the inside diameter of the 1-1/2 inch aluminum pipe measures slightly more than 1-1/2 inches, it was necessary to shim the fiberglass tubing with glass filament tape to achieve a tight fit. The assembled frame and the three Yagis mounted on top of the tower are shown in **fig. 3**. All that remained at this point was choosing a feedline and deciding on a power divider method. A 50-ohm impedance, 7/8-inch hardline had already been installed with the previous array. The phasing harness and feedline around the rotator used more flexible RG-8U.

Use good quality cable for the harness. Each leg must be cut to equal electrical lengths, preferably from the same run of cable. Each antenna must be parallel to the others — elements as well as booms — and the most forward director element of all three Yagis must be located within the same vertical plane. Otherwise, the wavefront launched by any one individual antenna will be out of phase with the others, resulting in lower gain, greater sidelobes, and possible multipath propagation. Phasing lines, besides being equal in length, should be kept as short as possible, especially at higher frequencies. Mounting the power divider as shown in **fig. 3** allows shorter harness leads.

three-way power divider

Obtaining a three-way power divider meant building one from scratch, because I couldn't locate any commerical units. So I went back to the books and set off on a thorough search of local supply houses for appropriate hardware.

To my knowledge, two methods for power splitting are commonly used. Most popular is the transformation of impedance by the use of a single 1/4 wavelength of coaxial transmission line. A common input port is located at one end and the required number of output ports at the other end. The characteristic surge impedance is determined as the mean value between transmitter output impedance and the parallel combined load impedance presented by the three antennas. Manufacturers of communications equipment have standardized their products for use with 50-ohm coaxial line. This simplifies the mathematics to determine power divider impedance when using more than one Yagi. Reduced to its simplest form, the equation for characteristic surge impedance for the above power divider becomes:[4-8]

$$Z = \frac{Z_o}{\sqrt{n}} = \frac{50}{\sqrt{n}} \qquad (1)$$

where n = number of antennas in array, Z_o = impedance of each antenna and equals the transmitter output impedance of 50 ohms.

Using **eqn. 1**, the characteristic impedance is:

$$Z = \frac{50}{\sqrt{3}} = 28.9 \text{ ohms}$$

To determine the proper diameter ratio for coaxial line

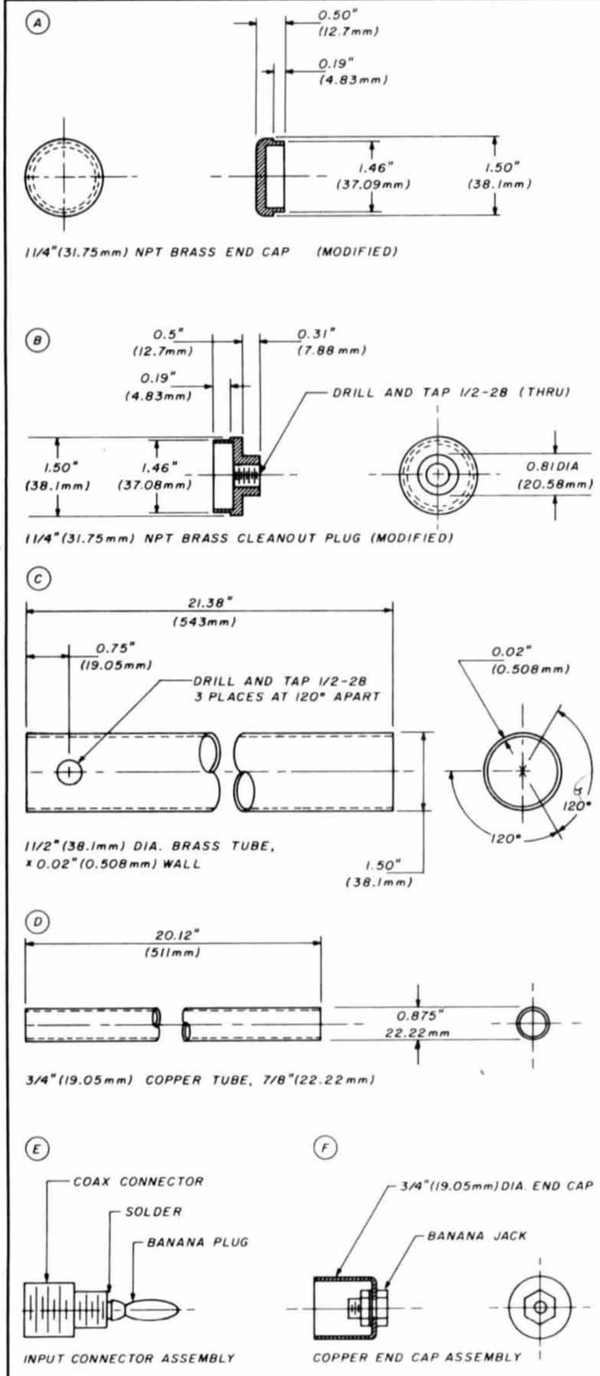

fig. 4B. Details of 144-MHz three-way power divider.

with the above impedance, the following relationship is used:

$$a/b = antilog \frac{Z}{138} = 1.62 \qquad (2)$$

a = Inside diameter of outer conductor
b = Outside diameter of inner conductor
Z = Characteristic surge impedance of coaxial line in the power divider.

The above diameter ratio (a/b) can be closely satisfied by using standard 3/4-inch diameter copper plumbing tubing (which actually measures 7/8 inch diameter) and 1-1/2 inch diameter brass tubing with 0.02-inch wall, normally used for kitchen sink drains. It can be purchased without the usual nickel plating at most plumbing supply stores.

To cap each end of the 1/4-wavelength line, it's necessary to machine 1-1/4 inch NPT brass cleanout plugs and end caps to the dimensions shown in the detail and assembly drawing for the three-way power divider (**fig. 4**).

Suitable connectors for this application are the familiar UHF type with 1/2-28 thread mounting capability. Amphenol 83-875 or equivalent can be used. By removing the snap ring, the connector can be dismantled and soldered to the body of the divider. Otherwise, excessive heat will destroy the insulator insert. To simplify assembly, it was necessary to include what at first would seem to be two unnecessary steps: first, the addition of a banana plug and jack at the input end of the line, to allow for adjusting the position of the inner conductor when you're soldering to output ports; and second, the drilling of three tapped holes (1/2-28) at the output end to hold coax connectors in place while you solder them to the 1-1/2 inch diameter brass tubing.

The power divider shown in **figs. 5** and **6** is the 432 MHz version of the above. Also, a scaled-down H-frame for a 432-MHz Yagi triangle is shown in **fig. 7**. (Although the antennas shown aren't representative of 144-MHz proportions, the reader may find the photos helpful nevertheless.) For further harness detail, see **fig. 8A**. The alternate power divider method (**fig. 8B**) requires 86.7-ohm impedance transformation sections of coaxial line in each leg of harness to the antennas.

$$Z = Z_0\sqrt{n} \quad (3)$$

A 1/4 wavelength of RG-62/U cable whose impedance is 93 ohms should work well. However, transmitter power must be limited to a couple of hundred watts. With higher power, use of RG-63/U is recommended. The velocity factor for both cables is 86 percent, which makes the overall length (including connectors) of the 1/4-wavelength sections 17 inches.

A three-way "T" junction must be used at the feed point. A weathertight metal junction box with closely spaced coaxial connectors will easily satisfy the short junction lead lengths required at the distribution point. A variation of the above division method is shown in **fig. 8C**. The three 1/4-wavelength sections as well as the three 50-ohm harness cables are replaced with equal lengths of RG-62/U. The three lengths, however, must be odd multiples of 1/4 wavelength each.

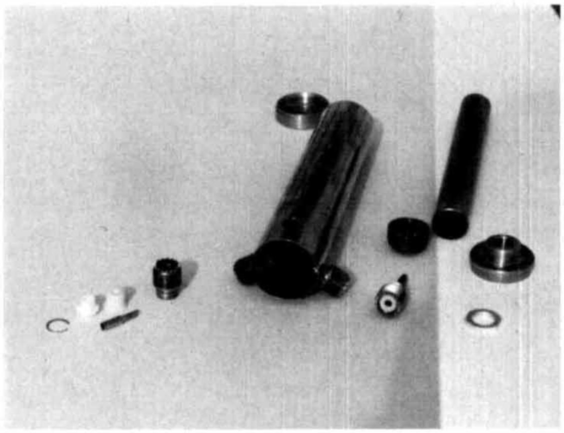

fig. 5A. Three-way power divider before assembly.

fig. 5B. Three-way power divider output ports.

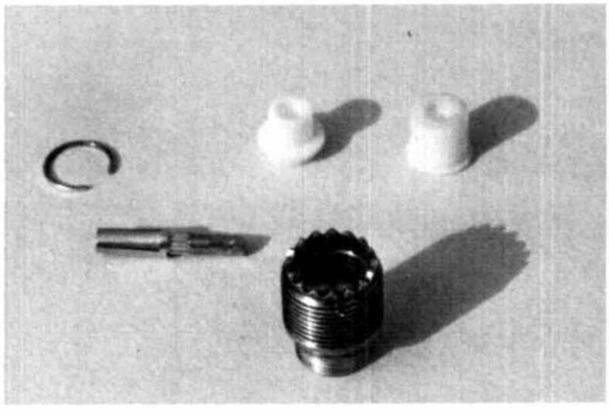

fig. 5C. Dismantled Amphenol coax connector.

Before connecting the harness to the power divider, best results will be obtained if each antenna is separately adjusted for best SWR using that leg (i.e, the same length) of feedline intended for the harness.

After adjustments have been made, connect the power divider to the antennas and feedline. Measure the SWR of the assembled array. In some cases, the

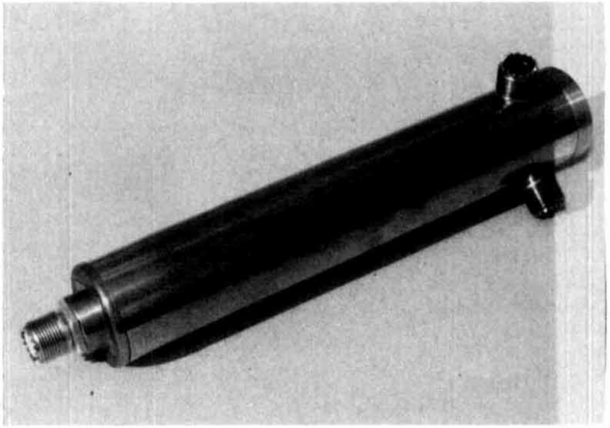

fig. 6. Assembled three-way power divider.

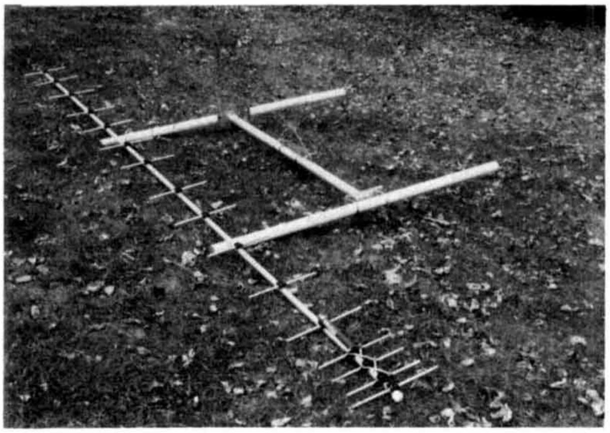

fig. 7. Horizontal H-frame for 432-MHz Yagi triangle.

final SWR measurement will appear to be better than that of the individual Yagis. Offhand this would seem to indicate an improvement to the system; however, this may not necessarily be so since the SWR measurements, other than 1:1, simply indicate the presence of a reactive load. The reactance, which can be either inductive or capacitive, depends upon how far the operating frequency is from the center frequency of the antenna and on the adjustment of the matching device at the individual antennas.[4] The inductive reactance of one antenna can cancel out, in part or completely, the capacitive reactance of another so that the resulting sum can be less than that of the individual antenna. Other than becoming more broadband (i.e., having lower *Q*), this does not imply that gain performance of the stacked array will be enhanced in any way. The SWR, as previously measured at the *individual* antennas, still exists and should be adjusted for the lowest ratio attainable or the maximum forward gain will be degraded accordingly. Once assured that the individual as well as the overall system SWR measurements are satisfactory, the Yagi triangle is ready for use.

E plane plot

The E plane plot shown in **fig. 9** indicates a half-power, 15-degree beamwidth. This was determined by the 48.5-percent method described by Gunther Hoch, DL6WU.[2] A comparison of the E plane plot of four stacked NBS-17 antennas with that of the Yagi triangle shows very little variation.[2] In fact, the front-to-back response seems to be better with the triangle. This might be attributed to the trigon reflectors on the Cushcraft A32-19 antennas used in the Yagi triangle.

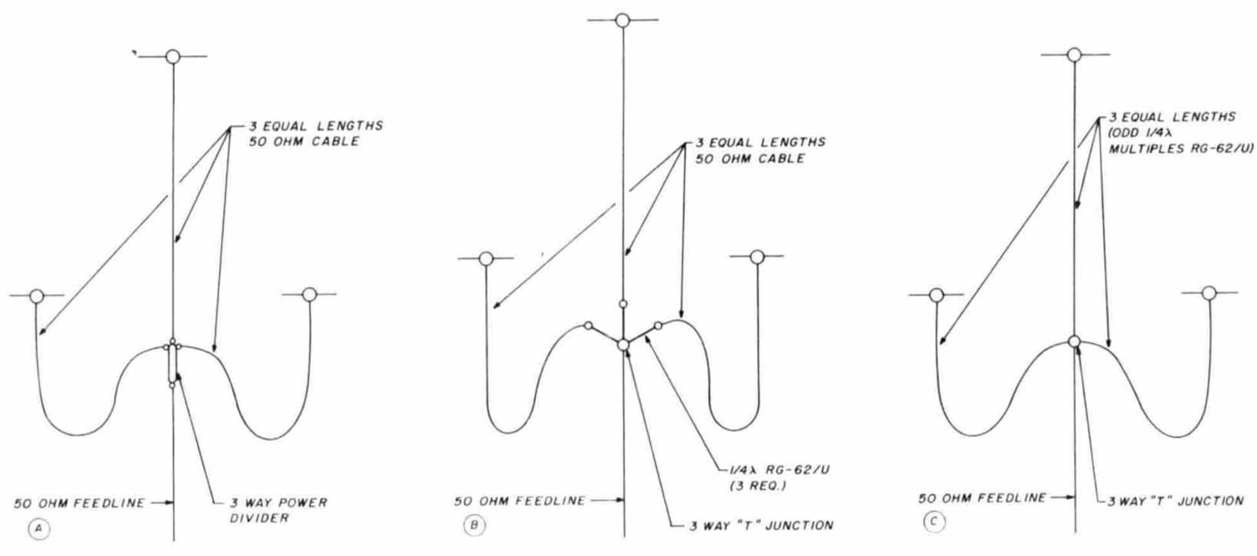

fig. 8. Alternate power divider and harness methods.

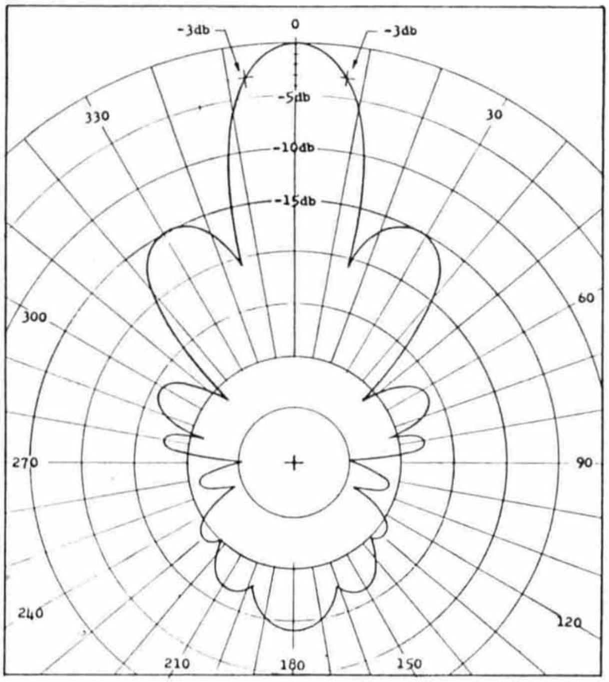

fig. 9. E plane plot.

No attempt was made to plot the H plane pattern, since no facilities to do so were available. It's my guess that the pattern would very much resemble that of two vertically stacked A32-19 antennas. Since I expect to duplicate the Yagi triangle at higher frequencies in the near future, a smaller array will be more manageable for the setup required to make H plane measurements.

antenna rotators and resolution

As the gain of a beam antenna system is increased, the beamwidth gets smaller until the point at which the resolving capability of the rotating system reaches a practical limit.

Most rotators available for Amateur use are geared to rotate at 1 rpm. The indicator on the control unit is graduated in divisions of 5 degrees. This means that rotation occurs at a rate of 6 degrees per second, or to put it in more dramatic terms, *less than one second per division*. A 15-degree segment (three divisions) will be scanned in 2.5 seconds.

To fix a beam heading, the antenna rotation between first nulls on either side of the main lobe shouldn't take less than 5 to 6 seconds. A main lobe with 15-degree beamwidth will have approximately 30 degrees between first nulls. Therefore, 1-rpm rotators will perform at the limit of their resolution capability. Antennas with beamwidths less than 15 degrees should be rotated with slower-speed devices. Aircraft prop-pitch motors are often used for this purpose. Manufacturers of one or two commercial rotators available for Amateur use claim dual speed, but the load capability of these units isn't sufficient for the size of the 144-MHz antenna array that would require the lower speed.

Used with 1-rpm rotators, antennas with less than 15-degree beamwidth require rocking the rotation back and forth several times to attain true beam heading. The problem is further compounded because of play (backlash) inherent in all such devices.

Still another resolution gremlin is the inertia that builds up during antenna rotation, causing long-boom Yagis to whip laterally when rotation is suddenly stopped. Many of these antennas have boom braces to keep them from sagging. However, the brace does little or nothing for the side motion. Heavy gusts of wind will also cause lateral flexing with these antennas. Though the two lower antennas of the Yagi triangle aren't prone to this problem because of the H-frame construction, the upper antenna does occasionally do a little dancing. Polypropylene guys from the upper antenna to the H-frame should remedy this problem.

Rotation at 1 rpm seems like a long enough period of time for a complete 360-degree turn of the antenna, and many of us — myself included — wouldn't relish the thought of extending the time. Therefore, antenna arrays with beamwidths of 15 degrees, or perhaps by stretching a point or two, even 14 degrees, should satisfy the resolution capability limits of 1-rpm rotators. This Yagi triangle is such an antenna.

performance

The triangle-stacked Cushcraft A32-19 antennas certainly perform better than the original dual stack. The theoretical 1.75-dB increase in signal seems to mock the theoretical 3 dB originally obtained while using the dual stack. QRP signals, unheard before, are now Q5 copy. Reports on my signal are almost always complimentary.

Raising or lowering the tower with the triangle stack is a one-man operation. Repeated inquiries about the triangle stack seem to indicate that others would like to give it a try. Anyone interested in a totally different approach for stacking Yagis will find building the Yagi triangle a worthy and rewarding effort.

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