The Collinear Yagi Quartet

A Super Rotary for 10-Meter DX

BY A. J. F. CLEMENT,* W6KPC

This will be the third sunspot cycle in which the author has built experimental high-performance arrays for use on the 28-MHz. band.[1,2] The data collected on the arrays built during the 1948 and 1958 sunspot maxima was carefully studied and analyzed. Considerable weight was given to actual DX operating results achieved on a month-to-month basis during good and poor propagation conditions. All the while, over many years, a watchful eye was kept on what kind of antennas the v.h.f. boys were building for maximum DX results.

Out of all this, a germ of an idea began to take shape: a collinear arrangement of high-performance antennas to form a large-aperture array. As the idea grew, a number of objectives were listed:

1) The antenna should be a rotary beam.

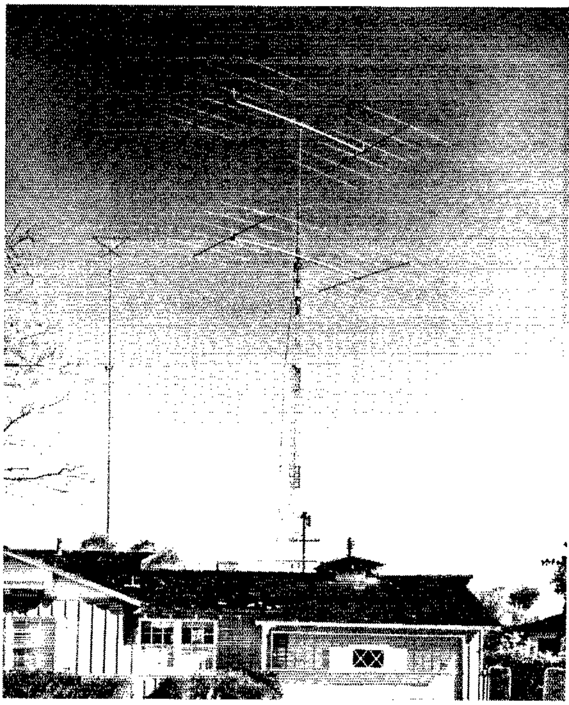
2) It should show at least 15-db. gain over a dipole.

3) To reduce QRM, the azimuth pattern width should be less than 35 degrees.

4) The vertical angle of the main lobe should not exceed 8 degrees.

5) The array should be supportable by readily-available commercial towers of best design.

The writer's experience has shown, rather conclusively, that the Yagi antenna achieves greater performance *for a given wind resistance and weight* than any other antenna design. It was decided, therefore, that a high-performance Yagi would become the basic element of the large-aperture, high-gain array.



The Collinear Yagi Quartet outlined against the sky. The top pair of elements is 108 feet above the ground. Round cross booms are made of Sitka spruce, 3½ inches in diameter at the center, tapering to 2½ inches at the ends, and are 25 feet long. The short vertical members at the ends of these booms each support a wire truss (broken up by insulators) that prevents droop in the Yagi boom.

A fairly close-spaced 6-element Yagi with balanced high-impedance feed was built and tested. It was anticipated that four of these 6-element Yagis would then be assembled into the final array. The Yagi's basic dimensions are shown in Fig. 1.

The reason for the rather close spacing was mainly mechanical; it was imperative to make all parts of the Yagi as light and thin as possible in order to cut down the wind resistance and total weight of the four that would make up the final array. It would have been better to have used a boom length of about 30 feet instead of the 25 feet shown, although close spacing can yield excellent results if great care is exercised in tuning all elements for maximum forward gain. Close spacing is bothersome, however, in that it lowers the feed-point impedance drastically; also, an unwanted amount of reactance shows up at the feed point of the driven dipole. These two irksome problems were dealt with as follows:

1) "T" matching was used to raise the feed-point impedance. The hope had been for 200 ohms, but the best that could be squeezed out of many experiments was 150 ohms. Several T-bars of various diameters, spacing and lengths were tried. Smith-chart plots were laboriously run on each try. Had a boom length of 20 feet

> ***This wouldn't be an unusual structure on 2 meters. But on 10. . . !! Needless to say, it has paid off in results.***

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[1] Clement, "The Yagi-Dagi," *QST*, September, 1951.

[2] Clement, "The Driven Beast," *QST*, May, 1958.

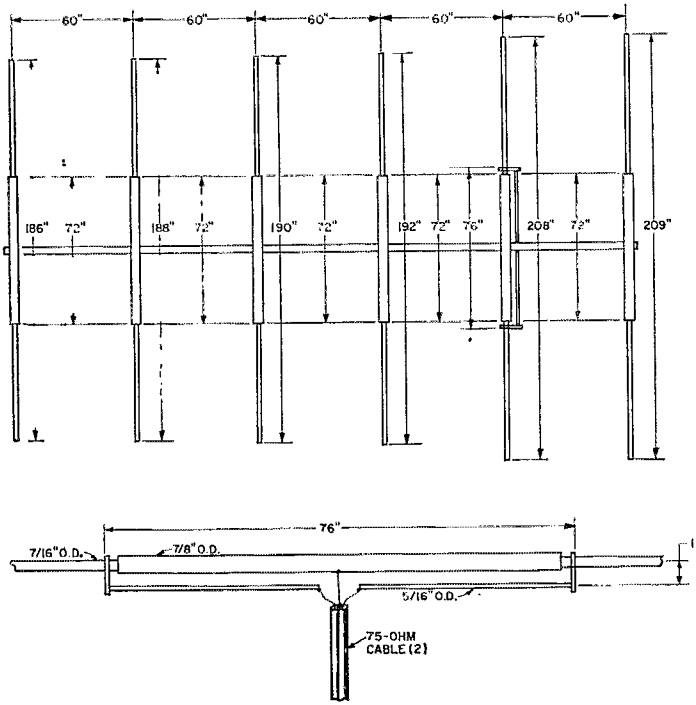

Fig. 1—Dimensional layout of the 6-element Yagi. Lower drawing shows the method of feeding the driven element. Material is seamless Dural tubing. Boom diameter is 1½ inches, 0.050-inch wall. A 4-foot solid wood insert is placed in the center part of the boom to furnish added resistance to bending.

been used 200 ohms would have been easy to attain. The main objective, of course, was to raise the resistance and to lower the reactance.

2) The reactance at the feed point had to be dealt with very carefully. The main thing to worry about was how to be sure to end up with exactly the same reactance in all four Yagis. The reason? All four Yagis must be fed exactly in phase to perform properly as an array. A ±10-degree tolerance on phase angle was set as a limit. To achieve this accuracy in phasing, only simple linear elements were used in the feed system. Only T matching and driven-dipole length juggling were used to achieve a fairly low reactance but high resistance at the feed point. As it turned out, my driven dipole had to be lengthened somewhat to yield what was desired on the Smith chart. The test setup used is shown in Fig. 2.

It must be emphasized at this point that the use of a radio-frequency bridge, or some other *accurate* way to separate reactance from resistance over the bandwidth of the antenna, is a "must." Fiddling around with s.w.r. bridges may be OK for simple antennas, but can lead one astray when working with more complex assemblies.

After about seven months of Smith charts and on-the-air testing I had a small, light (only 24 pounds), 6-element Yagi that had an effective wind area of only 3.6 square feet (this small wind area and weight is of overpowering importance, as will be seen later) and, as determined by extensive field-strength measurements during the testing period, had an indicated gain of at least 10 db. over an ordinary horizontal dipole at the same height.[3]

The Array

The final important decision of array configuration had to meet the original criteria: It could not be too bulky, too heavy or have too much wind resistance; also, it had to have a narrow pattern in azimuth and elevation and also a very low angle of radiation.

To obtain the required narrow pattern in azimuth, collinear (side-by-side) placement of two Yagi antennas was decided upon. Fig. 3 shows the azimuthal pattern that only two ordinary collinear dipoles will produce. Fig. 4 shows the azimuthal pattern of four collinear dipoles. It was reasoned that since a single 6-element Yagi would certainly have a narrower azimuthal beam width than a pair of collinear dipoles, two 6-element Yagis placed side by side should produce about the same azimuthal pattern as shown in Fig. 4.

The optimum spacing, boom-to-boom, for two 10-db. Yagis should be about ¾ wavelength. This spacing, about 25 feet for 10 meters, should give a full 3 decibels extra gain for the two-Yagi collinear array over a single 6-element

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[3] Yagi antennas of this length (about 0.7 wavelength) have shown approximately 9-db. gain over a dipole in a number of extensive sets of measurements. See *ARRL Antenna Book* (11th edition), Figs. 4-63 and 4-68. The book *Yagi-Uda Antenna*, by Uda and Mushiake, gives 7-10 db. for 4-element and 9-11 db. for 5-element antennas measured experimentally. No element spacings are stated, but presumably were in the neighborhood of 0.25 wavelength between elements as the authors found spacings of this order to be about optimum; if so, the 4-element antenna would have been 0.75 wavelength long. — *Editor.*

Yagi antenna.[4] This 12-element combination array, then, should show a pattern close to that given in Fig. 4 and have a forward gain of approximately 13 db. Such an array could be called a "Collinear Yagi Duet."

An important consideration with respect to collinear spacing is the formation of side lobes which rob energy from the main forward lobe. Collinear spacing in excess of ¾ wavelength will cause side lobes to appear in the azimuthal pattern. Vestigial side lobes will just start to be evident when ¾-wave spacing is reached. The above considerations fixed my boom-to-boom spacing at ¾ wavelength.

To achieve even more gain, it was decided to stack two collinear Yagi duets, one pair over the other pair. This would make a 24-element array made of four 6-element Yagis, hence the "Collinear Yagi Quartet."

Stacking

The general idea in stacking antennas is to increase the aperture, or intercept area, of the array. This gives more gain; however, the ground-reflected energy will modify this as compared with the free-space gain. Fig. 5 shows how the ground-reflection factor (which applies to *any* type of horizontally-polarized antenna)[5] changes as the antenna height is increased. At a height of ½ wavelength the maximum occurs at an elevation (vertical) angle of 30 degrees; at 1 wavelength there are two maxima, one at about 4 degrees and the other at 48 degrees; and so on. Note that for each ½-wavelength increase in height a new lobe appears in the pattern, but that the lowest one keeps dropping down.

A horizontal antenna having good vertical directivity, such as a multielement Yagi, will have relatively little radiation above 30 degrees or so in the vertical plane, so the amplitudes of the higher-angle maxima in the ground-reflection patterns are of minor importance. The lowest maximum is the one of interest, as it gives rise to the useful "main lobe" in the vertical-plane pattern of the actual antenna.

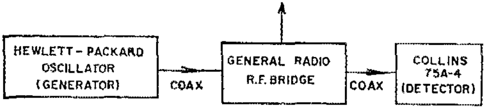

Fig. 2—Test-equipment setup for measuring antenna impedance.

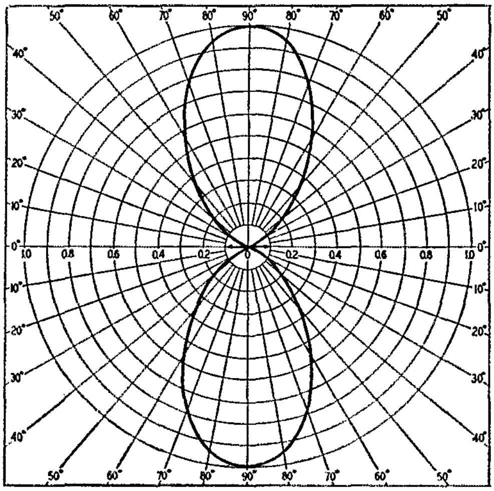

Fig. 3—E-plane pattern of two half-waves in phase, collinear.

It is obvious that two identical antennas stacked at different heights above ground cannot have their main lobes at exactly the same elevation angle. For example, if two Yagis are stacked ½ wavelength apart and the lower of the two is ½ wavelength high, its ground reflection factor will maximize at 30 degrees, while the maximum for the upper antenna, at a height of one wavelength, will occur at about 14 degrees. But as the heights are progressively increased, the main lobes will tend toward coincidence. To get really good coincidence, the upper antenna should be up about 3 wavelengths and the lower one up at, say, 2⅜ wavelengths (⅝-wavelength separation). For this case calculation shows that the theoretical ground-reflection factors are 4.75 degrees for the top antenna and 6.5 degrees for the bottom one — less than 2 degrees separation.[6]

The reader can now understand why the Collinear Yagi Quartet was designed so that the upper duet of collinear Yagi antennas was placed at a height of 3 wavelengths while the bottom duet was placed almost as high, at 2⅜ wave-lengths. This is 103 feet (at 28.6 MHz.) for the top pair and 81 feet for the bottom pair above ground. (Imagine what this would be on 20 meters — 206 and 162 feet, to be exact! One can see why stacking is, in general, less beneficial on 20 meters but very effective indeed on 10 meters when 100-foot-high antennas are used.)

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[4] This is based on unpublished work to which the author had access. There is relatively little in the literature on this point. One reference (Fishenden and Wiblin, "Design of Yagi Aerials," *Proc. IEEE* (London), Part III, January 1949) states that "mutual effects are usually found to be unimportant at spacings greater than 1½λ . . . and the gain of *N* units is approximately *N* times the gain of a single unit. — *Editor.*

[5] Reproduced from the *ARRL Antenna Book*, page 46. These patterns are plots of the formula 2 sin (h sin β), where h is the height in electrical degrees and B is the vertical angle in degrees above horizontal. The formula is based on the assumption that the ground is perfectly conducting. — *Editor.*

[6] This helps in visualizing what is going on in the construction of the composite pattern. The customary method of calculating the overall pattern is to take the average height of the two antennas and apply the ground-reflection factor for that height. In the above example, using this method shows that the ground-reflection factor maximizes at 5.3 degrees for the composite antenna (average height = 2-11/16 wavelengths). This method is applicable at any height. However, if the factors for the individual antennas are not reasonably close to coincidence there is some sacrifice of possible gain, as the author points out. — *Editor.*

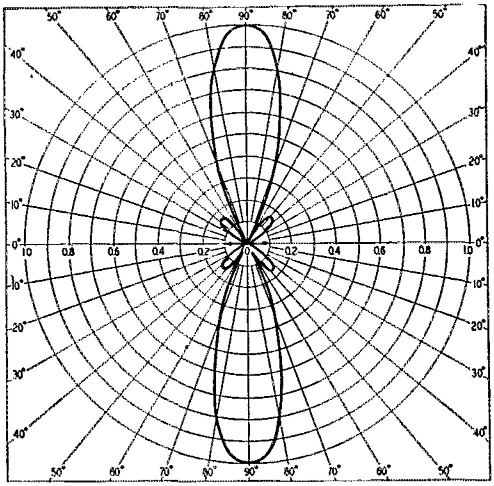

Fig. 4—E-plane pattern of four half-waves in phase, collinear.

One may wonder why ⅝ wavelength was chosen as the stacking distance, vertically, between the Duets. It turns out that ⅝ wavelength is not a bad compromise between the optimum distance of 1.0 wavelength[7] on one hand and a host of mechanical problems on the other hand. At 1.0 wavelength, the added gain due to stacking is in excess of 3 db., while at ⅝ wavelength one can still achieve about 3 db. of gain by having lobe coincidence as described above. *General rule:* Vertical stacking distance = ¾ of boom length.[8]

Even at ⅝ wavelength the upper mast becomes large and heavy. In my case the mast was made of high-strength aircraft steel tubing having a wall thickness of over ¼ inch. Imagine what this mast would have to be made of if the spacing had been 1 wavelength. The entire array ended up weighing about 700 pounds, including motor, indicator, mast, booms, feed lines, and antennas. A Tri-Ex LM470HD free-standing crank-up tower was selected to support this big array.

Phasing and Feeding

The four Yagi antennas are fed as shown in Fig. 6. Notice that double 75-ohm coax pairs go three half waves from the balun to the two upper collinear Yagis. Also, only two half waves of double 75-ohm coax pairs go from the balun to the bottom collinear Duet; also, these two lower lines are transposed at the balun. The balun transforms from a balanced 50-ohm line on the antenna side to an unbalanced 50-ohm line on the transmitter side. The 150-ohm antennas are all "transported" electrically to the unbalanced side of the balun and are then effectively paralleled.

Four 150-ohm impedances, when paralleled, give a resulting impedance of 37.5 ohms. When

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[7] Kasper, "Optimum Stacking Spacings in Antenna Arrays," *QST*, April, 1958. Data from this article also is in the *ARRL Antenna Book* (Fig. 4-64 in the 11th edition). — *Editor.*

[8] Orr, *The VHF Handbook*, 1st edition, page 112. (The Uda-Mushiake book mentioned in Footnote 3 shows an experimentally-measured stacking gain of 3 db. with two 5-element antennas stacked ½ wavelength apart. For this array, the authors state that the gain is maximum when this spacing "is nearly equal to a half-wavelength." — *Editor.)*

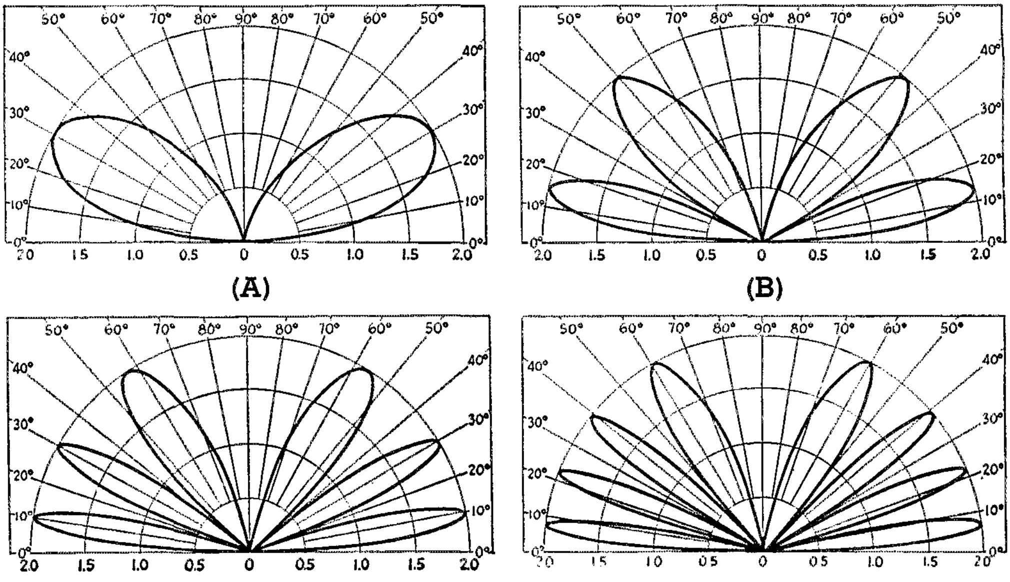

Fig. 5—Factors by which the vertical pattern of a horizontal antenna is multiplied when the antenna is above perfectly-conducting ground. A: height ½ wavelength; B: 1 wavelength; C: 1½ wavelengths; D: 2 wavelengths. See *ARRL Antenna Book*, Figs. 2-26 through 2-37, for patterns at intermediate heights.

the actual input impedance was measured it was found to be about 42 ohms. From 28.0 MHz. to 29.0 MHz. the v.s.w.r. never exceeded 1.8:1, with about 1.3:1 at 28.6 MHz.

Experimental Data
The Pattern

After the Collinear Yagi Quartet had been in use for ten months Cameron Pierce, W6QY, and I measured the azimuthal (horizontal) pattern. About ten miles away from W6KPC is a mountain range. It is a clear shot from the Collinear Yagi Quartet to the ridge of this range. Fortunately, Dale Hoppe, W6VSS, owns a QTH right on top of this mountain. Cam and Dale set up a KWM-2 and a dipole on the mountaintop.

Back at W6KPC the Collinear Yagi Quartet was pointed directly at the QTH of W6VSS and attenuator No. 1, Fig. 7, was set so that the S meter on the Collins 75S3-B at W6KPC read exactly S9 with the KWM-2 at W6VSS turned on. This No. 1 attenuator was never again touched; it was used *only* to set the received signal to S9 with the antenna head-on to the W6VSS source.

Next, the antenna array was rotated ten degrees off the line to W6VSS. The S meter dropped off slightly, so it was brought back up to S9 by cutting out resistance units in the second precision attenuation decade box. Next, the array was rotated another 10 degrees (now a total of 20 degrees off W6VSS); resistance was cut out of box No. 2. This process was repeated every 10 degrees around the whole azimuthal circle. At each 10-degree stop the amount of attenuation removed from box No. 2 was tabulated.

At this point it is important to note that what was being tabulated was *db. of attenuation*, a precise item. This attenuation table was then converted to a table of volts *vs.* angle. Field strength is, of course, measured in volts, not attenuation. In the process of conversion, the new tabulation was also "normalized;" the largest voltage being set equal to unity. This final table was then plotted on a standard azimuthal chart to yield a field-strength diagram. The resulting pattern is shown in Fig. 8. Both the forward and rear lobes show a pattern width at the half-power point (0.707 on the voltage scale) of 28 degrees. The beautiful shape of the forward lobe shows why Collinear Yagi Duets are here to stay as DX antennas.

The reason for the rather large rear lobe is simple: The individual Yagis were tuned for maximum forward gain, *not* for maximum front-to-back ratio. One will also notice, however, that the rear lobe is down 6 db. from the front lobe; this means that on the nose the power radiated to the rear is only one quarter of the power radiated in front — a cheap price to pay for a 28-degree front lobe and no side lobes.

Gain

Antenna gain can be determined approximately if one knows the horizontal and vertical field-strength patterns of the antenna's main lobe and knows that the minor lobes are small compared with the main lobe. Based on carefully-conducted measurements of the horizontal pattern and some assumptions with respect to the main lobe's vertical pattern, the author feels confident that the Collinear Yagi Quartet has a real gain of the order of 16 db.[9] This gain is effective at an elevation angle of only 6 degrees.

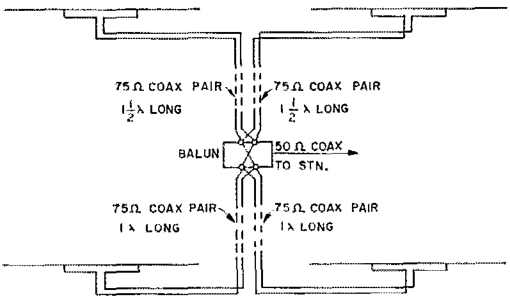

Fig. 6—Method of feeding the four Yagis in the Quartet. Note that the twin 75-ohm transmission-line lengths are not drawn to scale. Line lengths are electrical; i.e., physical length in wavelengths times velocity factor. The 50-ohm balun (made by Telrex) is connected for 1-to-1 impedance ratio.

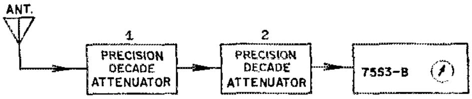

Fig. 7—Equipment setup at W6KPC for making pattern measurements. The measurements were made on a constant-output transmitter located about 10 miles away in line-of-sight.

Results

Results are all that really count. The Quartet's combination of high gain and low takeoff angle really produces results, making extremely long hops possible from the F_2 layer. Since the Quartet was erected last spring, I have been able to work long-haul DX stations both earlier and later than other 10-meter stations in the Los Angeles

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[9] The method of calculating gain mentioned above is based on a formula in which three assumptions are inherent: (1) horizontal and vertical beam widths are approximately the same; (2) the amplitudes of secondary lobes are negligible; and (3) the beam is narrow (errors become appreciable when the beam width exceeds 20 degrees). The formula has the form Gain = $N/\theta_1\theta_2$, where θ_1 and θ_2 are the horizontal and vertical beam widths in degrees and N is a number that varies with different sources. Jasik's *Antenna Engineering Handbook*, McGraw-Hill, gives $N = 30{,}000$; Lindsay, in "Quads and Yagis," *QST*, May, 1968, used $N = 40{,}000$. In both cases the gain is over an isotropic antenna, or 2.14 db. greater than over a half-wave dipole. For a beam width of 28 degrees, $N = 30{,}000$ gives a power gain of 38 while $N = 40{,}000$ gives a gain of 51. These are, respectively, 15.8 and 17.1 db. over isotropic. A similar array using stacked collinear 6-element Yagis, but with wider element spacing and greater spacing between Yagis, described in the paper referred to in Footnote 4, was said to have a gain of 15 db. over a half-wave dipole. — *Editor*.

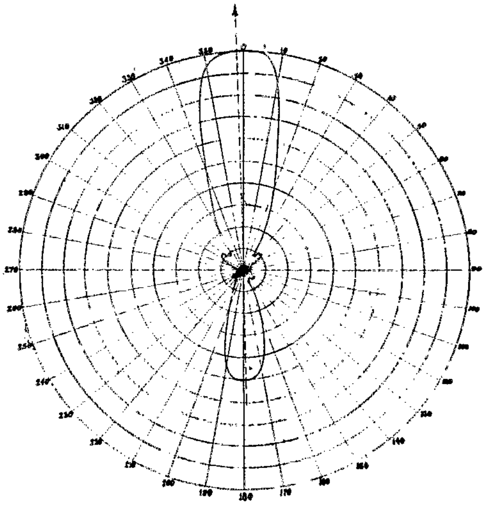


Fig.8—Measured horizontal field-strength pattern of the Collinear Yagi Quartet.

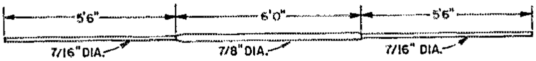
area; in other words, the array is both a band opener and a band closer. Not infrequently, W6KPC would be the only West Coast station being heard by the DX station. The most power ever used was 700 watts p.e.p. from a Collins KWS-1.

All this winter, using 600 watts p.e.p., and working at 27.820 MHz., A6KPC (Army MARS) used the Quartet (s.w.r. = 2.5:1) to handle consistently, day by day, phone-patch messages from GIs in Vietnam to their relatives here at home. So far (January 25, 1969) I have not missed contacting the Vietnam Net a single day, except for the very few week ends when I have been away from home.

DX includes such rare and choice morsels as follows:

YJ8BW
5W1AT
ZB2A
VQ9JW
6W8DY
ZD3D
TU2CF
9L1KZ
SV1AE
LX1JW
9U5HI
CR6LX
XW8BX
XW8BS
VQ8CC
UP2OV
ET3USA
ET3REL
IS1SCB
HA2KRB
ZD5X
SL3ZV
VP8JJ
XD5V
YO2BI/7
EA9AQ
ZC4MO
9H1M
4X4SO
5A4TH
UO5BZ
UV3AAE
LA1MB
VR1P
ZS3HT
GD3RFK
ZB2A
OD5BZ
YO2BB
IT1EUR
CN8HD
UV3AAM
6W8DY
YO9CN
ZD5V
VK9TG
ZD7DI
OH2SB

Appendix



1) In the typical 10-meter element shown above in the drawing consider the 6′ 0″ center section first. The projected area is diameter × length:

= $\frac{7}{8}$″ × (6 × 12″) = $\frac{7}{8}$″ × 72″
= 63.0 square inches.

Next, consider the tip section (on one end only):

= $\frac{7}{16}$″ × (5.5 × 12″) = $\frac{7}{16}$″ × 66″
= 28.875 square inches.

There are two tips, so 2 × 28.875 sq. in. = 57.75 square inches.

The total area of one element is 63.0 + 57.8 = 120.8 square inches. As there are six elements, 6 × 120.8 = 724.8 square inches.

Civil-engineering codes allow the use of only $\frac{2}{3}$ of the projected area if the elements are cylindrical (which they are). This simply says that a cylinder is more streamlined, and has only $\frac{2}{3}$ the wind resistance that a flat plate, strip, or square element would have. We can, therefore, *reduce* our 724.8 square inches to two thirds of this value:

= $\frac{2}{3}$ × 724.8 = 478.37 sq in.
= 2.32 ft^2 effective wind area.

My real antenna has elements of different lengths, hence my effective area of 3.6 square feet. The boom, broadside, has less area, so is ignored.

The elements were stressed by me for bending and found to be good for 100 mph winds.

2) Now, consider the 25-foot-long by 3-inch-diameter wooden beam that holds the upper two 6-element Yagis apart by $\frac{3}{4}$ wavelength. The wood beam tapers from 3½-inch diameter at the center to 2½-inch diameter at each end. This gives it an average diameter of 3.0 inches.

Beam area = 3″ × (12 × 25″)
= 900 square inches (projected area)
$\frac{2}{3}$ × 900 = 600 square inches (effective wind area)
= 4.16 square feet.

3) Now, consider the vertical mast separating the stacks. The upper part of this mast is 2 inches in diameter (OD) and is 6 feet 0 inches long. The projected area is

(6 × 12″) × 2″ = 144 square inches
= 1.0 square foot.

The lower mast is 3 inches in diameter and is 16 feet 0 inches out of the tower.

(16 × 12″) × 3 = 576 square inches
= 4.0 square feet projected area.

Adding the two together gives

1.0 + 4.0 = 5.0 square feet.

The effective wind area of the mast is

$\frac{2}{3}$ × 5.0 = 3.3 square feet.

4) The bending moment, M_A, at the top of the tower (bottom of the mast) for the antennas alone is

M_A = Area × Wind Pressure (40 lb per ft^2) × distance.

In our case we have two antennas (we ignore the bottom bay, as it has no mast):

2 × 3.6 = 7.2 square feet of antenna up 22 feet (264 inches).

7.2 × 30 lb/ft^2 × 264 inches = 7.2 × 30 × 264
= 5700 in. lb (contribution of two Yagis).

5) The bending moment, M_B, caused by wind drag on the 25-ft wood beam:

M_B = 4.16 ft^2 × 30 lb/ft^2 × 22 ft (264 inches)
= 4.16 × 30 × 264
= 32950 inch pounds.

6) For the contribution of the mast, assume the center of pressure to be halfway up the mast (this is conservative):

(M_M = 3.3 ft^2 × 30 lb/ft^2 × 11 ft (132 in.)
= 3.3 × 30 × 132
= 13200 in. lb.

7) The total combined moment on the mast's base is:

$M = M_A + M_B + M_M$
= 57000 – 33000 + 13000
= 103000 inch pounds.

8) From appropriate tables, one selects a mast that will withstand this amount of bending moment. My mast (SAE 4130 Aircraft Steel) is 3 inches OD, ¼-inch wall, and is good for a moment of 130000 inch pounds.