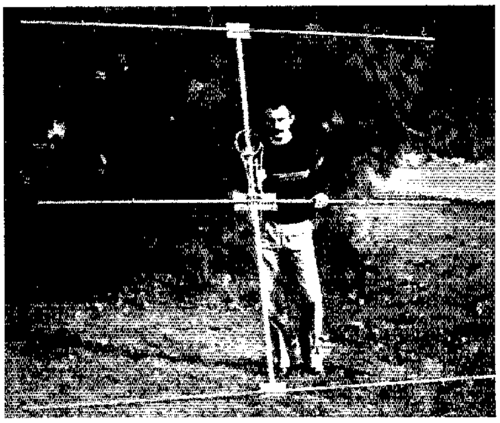
Go for the Gain, NBS Style



Ever wonder why some vhf Yagis seem to have that extra oomph? Learn about the NBS formula for success!

By Dennis J. Lusis,* W1LJ

Have you been in a vhf pileup lately? If so, then you recognize the demand for high-performance antennas. While a number of excellent commercial Yagis are available, the home builder is often left to outdated designs that provide marginal performance by today's standards. This article introduces a generation of gain-optimized Yagi antennas originally described by Viezbicke in *National Bureau of Standards Technical Note 688*.[1] These antennas have been reproduced for use in the amateur vhf and uhf bands with excellent results. Construction guidelines are provided for a 3-element, 50-MHz NBS Yagi that may be used for fixed-station or portable use. Additional data provided allows the builder to construct a larger 50-MHz array, or one for another vhf or uhf band.

The NBS Yagi

Since its conception in 1926, the Yagi-Uda antenna,[2] commonly known as the Yagi, has become the most widely utilized directive array in vhf and uhf communications. Many technical reports have been published regarding the proper tuning of Yagis. Until recently, practically no information was available regarding how element diameter, element length, spacing of the elements, boom diameter and overall length affect the gain. The National Bureau of Standards (NBS) attempted to determine these relationships in their study. Viezbicke's report describes the results of testing carried out for nearly a decade by the NBS at its Sterling, Virginia, and Table Mountain, Colorado, antenna test ranges. The results were used later by others such as Lawson and Reisert[3] who used the data to verify computer-generated models of Yagi performance. Although discrepancies exist between the Lawson and the NBS findings, the greater number of similarities between computer and empirical data add credibility to both.

NBS Test Procedures

All NBS modeling was done at 400 MHz. The test antenna was placed at the receiver end, and was separated approximately 1000 feet[4] from the transmitter and its antenna. Both antennas were mounted 3 wavelengths (λ) above ground. The test Yagi was compared to a reference dipole position 5 λ to one side, and at the same height as the Yagi. The test Yagi and the reference dipole were matched to 50 Ω and compared using a calibrated step attenuator. Gain was reproducible to within 0.2 dB throughout the test.

NBS Test Results

The NBS antenna testing provided useful information for antenna builders. Here, for the first time, experimenters could determine how dimensional aspects of their designs would interact and ultimately affect the performance of their antennas. A complete overview on how all design parameters interact is beyond the scope of this article; the reader is referred to *NBS Technical Note 688* for more detailed information. For convenience, the element dimensions yielding maximum gain for vhf and uhf Yagis are given in Tables 1 through 4. These lengths were calculated from the NBS test results. Element spacing for the various arrays are shown in Fig. 1.[5] Note that the tables specify exact boom and element diameters. Strict adherence to these dimensions will result in a Yagi of exceptionally high gain. If the builder wishes to construct a Yagi from available materials differing in size from those specified, he should consult Table 5 and the charts in Figs. 2 and 3 for conversion data.

Using the Conversion Charts

It has long been known that the diameter-to-wavelength ratio of a supporting boom affects the tuning of Yagi elements. Determining the characteristics of this effect was one of the primary objectives in the NBS study. Fig. 3 illustrates how optimum element length varies with boom diameter changes. When boom diameter increases, elements must be lengthened proportionately to remain at optimum length. For example, using 50.1 MHz as a design frequency, let us see exactly how much element length must be increased for given increases in boom and element diameter.

Table 1 gives a 3-element, 50-MHz Yagi boom length of 7 ft. 10 in. (0.4 λ), and a diameter of 1-1/4 in. Element diameter is 1/2 in. We would like to substitute a 2-1/2 in. diameter boom, and 3/4-in. diameter elements. To calculate the proper element lengths for any NBS Yagi, the following information must first be specified:

$$\lambda = \frac{299.01}{50.1\ \text{MHz}} = 5.97\ \text{m or } 235\ \text{in.} \qquad \text{(Eq.1)}$$

(The velocity of light is expressed as 299.01×10^6 m/sec.)

Element diameter (d): 0.75 in. Element diameter, expressed in terms of wavelength (d/λ)

$$\frac{0.75\ \text{in.}}{235\ \text{in.}/\lambda} = 0.0032\ \lambda \qquad \text{(Eq. 2)}$$

Boom diameter (D): 2.5 in. Boom diameter, expressed in terms of wavelength (D/λ)

$$\frac{2.5\ \text{in.}}{235\ \text{in.}/\lambda} = 0.0106\ \lambda \qquad \text{(Eq. 3)}$$

After calculating these values, refer to

[1]Notes appear on page 38.

*ARRL Assistant Technical Editor

Table 1

NBS 50.1 MHz Yagi Dimensions

meters = 0.3048 × feet
mm = 25.4 × inches

Boom Length	*Boom Diameter*	*Element Diameter*	*Ref*	*Driven*	*Dir. 1*	*Dir. 2*	*Dir. 3*	*Dir. 4*	*Dir. 5*	*Dir. 6*	*Dir. 7*	*Dir. 8*	*Dir. 9*	*Dir. 10*
7' 10"(0.4 λ)	1-1/4"	1/2"	9' 7-3/4"	9' 1-3/4"	9' 1 3/8"									
15' 8-1/2"(0.8 λ)	2"	3/4"	9' 7"	9' 1-3/4"	8' 9 5/8"	8' 8-7/8"	8' 9-5/8"							
23' 6-7/8"(1.2λ)	2"	3/4"	9' 7-3/4"	9' 1-3/4"	8' 10-1/4"	8' 8-7/8"	8' 8-7/8"	8' 10-1/4"						
39' 3-3/8"(2.2λ)	2"	3/4"	9' 7-3/4"	9' 1-3/4"	8' 11"	8' 8-1/8"	8' 6-1/2"	8' 4-5/8"	8' 3"	8' 3"	8' 3"	8' 3"	8' 4-5/8"	8' 6-1/2"

Table 2

NBS 144.1-MHz Yagi Dimensions

meters = 0.3048 × feet
mm = 25.4 × inches

Boom Length	*Boom Diameter*	*Element Diameter*	*Ref*	*Driven*	*Dir. 1*	*Dir. 2*	*Dir. 3*	*Dir. 4*	*Dir. 5*	*Dir. 6*	*Dir. 7*	*Dir. 8*	*Dir. 9*	*Dir. 10*	*Dir. 11*	*Dir. 12*	*Dir. 13*	*Dir. 14*	*Dir. 15*
5'5-9/16"(0.8λ)	1"	3/16"	3'4-5/8"	**3' 2-3/16"**	3'1-1/2"	3'1-3/8"	3'1-1/2"												
8'2-5/16"(1.2λ)	1"	3/16"	3'4-5/8"	**3' 2-3/16"**	3'1-1/2"	3'1-1/8"	3'1-1/8"	3'1-1/2"											
15'1/4"(2.2λ)	1 1/4"	3/16"	3'4-13/16"	**3' 2-3/16"**	3'1-15/16"	3'5/8"	3'	2'11-3/8"	2'11-3/8"	2'11-3/8"	2'11-3/8"	2'11-3/8"	3'	3'5/8"					
21'10-1/16"(3.2λ)	1 1/2"	3/16"	3'5-1/16"	**3' 2-3/16"**	3'1-15/16"	3'1-3/8"	3'13/16"	3' 3/16"	3'	2'11-5/8"	2'11-3/8"	2'11-3/8"	2'11-3/8"	2'11-3/8"	2'11-3/8"	2'11-3/8"	2'11-3/8"	2'11-3/8"	2'11-3/8"
28'8-1/8"(4.2λ)	1 1/2"	3/16"	3'4-1/2"	**3' 2-3/16"**	3'1-5/8"	3'1-5/8"	3'1-7/16"	3'11/16"	3'9/16"	3'3/16"	2'11-7/8"	2'11-5/8"	2'11-5/8"	2'11-5/8"	2'11-5/8"	2'11-5/8"	2'11-5/8"		

Table 3

NBS 220.1-MHz Yagi Dimensions

meters = 0.3048 × feet
mm = 25.4 × inches

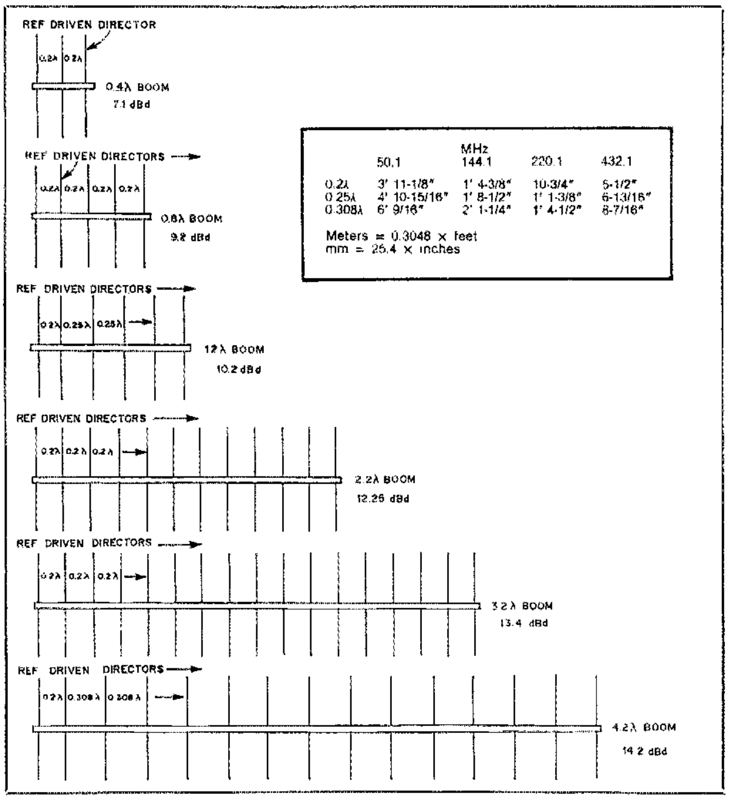
Boom Length	*Boom Diameter*	*Element Diameter*	*Ref*	*Driven*	*Dir. 1*	*Dir. 2*	*Dir. 3*	*Dir. 4*	*Dir. 5*	*Dir. 6*	*Dir. 7*	*Dir. 8*	*Dir. 9*	*Dir. 10*	*Dir. 11*	*Dir. 12*	*Dir. 13*	*Dir. 14*	*Dir. 15*
3'6-15/16"(0.8λ)	1"	3/16"	2'2-1/16" 2'2-3/4"	2'1"	1'11-13/16" 2'1/2"	1'11-11/16" 2'3/8"	1'11-13/16" 2'1/2"												
5'4-3/8"(1.2λ)	1"	3/16"	2'2-1/16" 2'2-3/4"	2'1"	1'11-13/16" 2'1/2"	1'11-9/16" 2'1/4"	1'11-9/16" 2'1/4"	1'11-3/16" 2'1/2"											
9'10"(2.2λ)	1"	3/16"	2'2-1/16" 2'2-3/4"	2'1"	2'1/16" 2'3/4"	1'11-5/16" 2'1/16"	1'10-15/16" 1'11-5/8"	1'10-1/2" 1'11-1/4"	1'10-1/8" 1'10-7/8"	1'10-1/8" 1'10-7/8"	1'10-1/8" 1'10-7/8"	1'10-1/8" 1'10-7/8"	1'10-1/2" 1'11-1/4"	1'10-15/16" 1'11-5/8"					
14'3-11/16"(3.2λ)	1 1/4"	3/16"	2'2-1/16" 2'3"	2'1"	1'11-13/16" 2'3/4"	1'11-9/16" 2'7/16"	1'10-15/16" 1'11-7/8"	1'10-1/2" 1'11-7/16"	1'10-5/16" 1'11-1/4"	1'10-1/8" 1'11"	1'9-7/8" 1'10-13/16"	1'9-7/8" 1'10-13/16"	1'9-7/8" 1'10-13/16"	1'9-7/8" 1'10-13/16"	1'9-7/8" 1'10 13/16"	1'9-7/8" 1'10-13/16"	1'9-7/8" 1'10 13/16"	1'9-7/8" 1'10-13/16"	1'9 7/8" 1'10 13/16"
18'9-5/16"(4.2λ)	1 1/2"	3/16"	2'1-11/16" 2'2-3/4"	2'1"	1'11-5/8" 2'11/16"	1'11-5/8" 2'11/16"	1'11-7/16" 2'1/2"	1'10-7/8" 2'	1'10-3/4" 1'11-13/16"	1'10-1/2" 1'11-9/16"	1'10-5/16" 1'11-3/8"	1'10-1/8" 1'11-3/16"	1'10-1/8" 1'11-3/16"	1'10-1/8" 1'11-3/16"	1'10-1/8" 1'11-3/16"	1'10-1/8" 1'11-3/16"	1'10-1/8" 1'11 3/16"		

Table 4

NBS 432.1-MHz Yagi Dimensions

meters = 0.3048 × feet
mm = 25.4 × inches

Boom Length	*Boom Diameter*	*Element Diameter*	*Ref*	*Driven*	*Dir. 1*	*Dir. 2*	*Dir. 3*	*Dir. 4*	*Dir. 5*	*Dir. 6*	*Dir. 7*	*Dir. 8*	*Dir. 9*	*Dir. 10*	*Dir. 11*	*Dir. 12*	*Dir. 13*	*Dir. 14*	*Dir. 15*
2'8-13/16"(1.2λ)	1"	3/16"	1'1-15/16"	**1' 23/32"**	1'17/32"	1'11/32"	1'11/32"	1"17/32"											
5'1/8"(2.2λ)	1"	3/16"	1'1-15/16"	**1' 23/32"**	1'21/32"	1'3/16"	1'	11-3/4"	11-17/32"	11-17/32"	11-17/32"	11-17/32"	11-3/4"	1'					
7'3-15/32"(3.2λ)	1"	3/16"	1'1-15/16"	**1' 23/32"**	1'9/16"	1'11/32"	1'	11-3/4"	11-5/8"	11-17/32	11-13/32"	11-13/32"	11-13/32"	11-13/32"	11-13/32"	11-13/32"	11-13/32"	11-13/32"	11-13/32"
9'6 25/32"(4.2λ)	1"	3/16"	1'1-3/4"	**1' 23/32"**	1'7/16"	1'7/16"	1'11/32"	1'	11-7/8"	11-3/4"	11 5/8"	11-17/32"	11-17/32"	11-17/32"	11-17/32"	11-17/32"	11-17/32"		



	MHz 50.1	144.1	220.1	432.1
0.2λ	3' 11-1/8"	1' 4-3/8"	10-3/4"	5-1/2"
0.25λ	4' 10-15/16"	1' 8-1/2"	1' 1-3/8"	6-13/16"
0.308λ	6' 9/16"	2' 1-1/4"	1' 4-1/2"	8-7/16"

Meters = 0.3048 × feet
mm = 25.4 × inches

Fig. 1 — Element spacing for the various Yagi arrays, in terms of boom wavelength.

Table 5

Optimized Lengths of Parasitic Elements For Yagi Antennas of Six Different Lengths

	Length of Yagi in Wavelengths 0.4	0.8	1.20	2.2	3.2	4.2
Length of Reflector λ	0.482	0.482	0.482	0.482	0.482	0.475
Lenth of Director, λ 1st	0.442	0.482	0.482	0.432	0.482	0.424
2nd		0.424	0.420	0.415	0.420	0.424
3rd		0.428	0.420	0.407	0.407	0.420
4th			0.428	0.398	0.398	0.407
5th				0.390	0.394	0.403
6th				0.390	0.390	0.398
7th				0.390	0.386	0.394
8th				0.390	0.386	0.390
9th				0.398	0.386	0.390
10th				0.407	0.386	0.390
11th					0.386	0.390
12th					0.386	0.390
13th					0.386	0.390
14th					0.386	
15th					0.386	
Spacing Between Directors, in λ	0.20	0.20	0.25	0.20	0.20	0.308
NBS Claimed Gain Relative to Half-Wave Dipole in dB	7.1	9.2	10.2	12.25	13.4	14.2
Design Curve (See Fig. 2)	(A)	(C)	(C)	(B)	(C)	(D)

Element diameter = 0.0085λ
Reflector Spaced 0.2λ behind driven element

Table 5, which provides the optimized lengths of parasitic elements for Yagis of six different boom lengths, as shown in Fig. 1. (Note that these values are based on a specific element d/λ of 0.0085, and are not yet compensated for boom diameter.) Find the Yagi boom length that you want to work with at the top of Table 5. In our case, it is 0.4 λ. The numbers 0.482 and 0.442 listed below represent the lengths of the reflector and the director, respectively. Mark these two values on the graph found in Fig. 2. These points should be placed along reflector and director design curves "A" which correspond to the 0.4-λ Yagi. Notice that both points fall exactly on the vertical design reference line at d/λ = 0.0085.

To determine what our element lengths should be, refer back to Eq. 2. This equation states that our Yagi has an element d/λ of 0.0032. Draw a vertical line on the graph in Fig. 2 from the point d/λ = 0.0032, found on the horizontal axis. Since both the reflector and the director points fall exactly on the vertical line d/λ = 0.0085 in the design example, it is a simple matter to determine our "new" element lengths. Mark the two points where the vertical line d/λ = 0.0032 intersects reflector and director design curves "A." The element lengths may now be read from the scale on the left:

Ref. = 0.487 λ
Dir. = 0.457 λ

This example, using the 3-element, 0.4-λ Yagi is quite simple because both the director and reflector points fall directly on the vertical design-reference line. Element lengths for the five longer Yagis require a slightly different technique to be determined. Take the 5-element, 0.8-λ antenna, for example. Because this antenna has multiple directors (of varying lengths) there will be more than one point to plot along director design curve "C." It is first necessary to plot all the points and, using a set of dividers, measure the distance between each point on the design curve and the vertical reference line at d/λ = 0.0085. You must then transpose these distances away from the new vertical line that represents your particular Yagi element d/λ. Just be sure to mark the distance off on the proper side of the line, for some points will lie to the left, and others to the right! Also, be sure to plot the new points on the proper design curve "A"-"D." After all points have been plotted, the new element lengths may be read directly from the scale on the left, as in the previous example.

So far, the procedure I have outlined deals strictly with compensation that is necessary because of varying element diameter. Boom diameter also has a considerable effect on optimum element length. The NBS Yagi is not complete without taking this into account.

Referring to Eq. 3, we know that our boom D/λ = 0.0106. The graph in Fig. 3

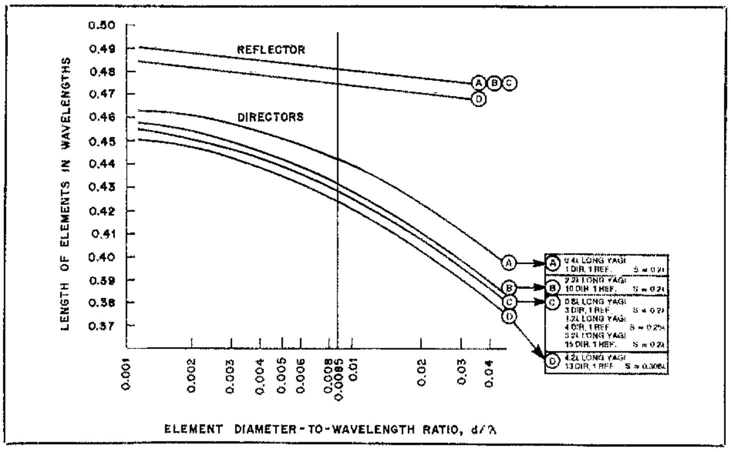


Fig. 2 — Curves showing the relationship between element diameter-to-wavelength ratio and the element length for different Yagi arrays.

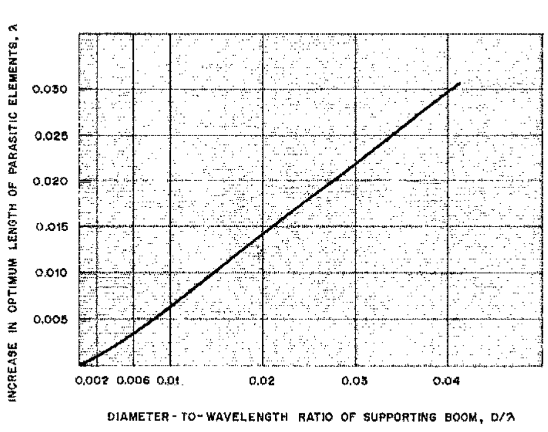


Fig. 3 — Curve showing the effect of a supporting boom on the length of Yagi elements.

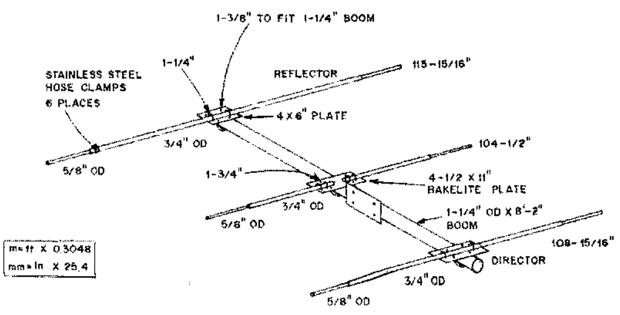


Fig. 4 — Dimensional drawing of the 3-element, 50-MHz Yagi described in the text.

indicates that, with this boom D/λ, it is necessary to lengthen all elements by 0.0065 λ to remain at optimum length. Simply add this amount to the previously determined element lengths for our 3-element, 50-MHz Yagi. The final, optimum parasitic element lengths are:

Ref. = 0.487 λ + 0.0065λ = 0.4935λ
0.4935λ × 235 in./λ = 115.97 in.

Dir. = 0.457λ + 0.0065λ = 0.4635λ
0.4635λ × 235 in./λ = 108.92 in.

No mention is made concerning driven-element length, because the choice of matching system exerts considerable influence on it. Standard methods for determining driven-element lengths can be used, or the measurements found in Tables 1 through 4 can be used as starting points. An in-depth discussion of driven element/feed systems may be found in *The ARRL Antenna Book.*[6]

The W1LJ NBS Yagi

To illustrate the procedures described in this article, I constructed a 3-element Yagi for the 50-MHz band. No special attempt was made to procure materials of the exact dimensions called for in Table 1. A quick look through the ARRL laboratory junk box turned up enough scrap aluminum for the project. Elements were fashioned from 3/4-inch OD tubing, with short pieces of 5/8-inch OD tubing telescoped in the ends for fine adjustment. Overall dimensions can be seen in Fig. 4. Boom-to-element clamps were made of scrap heavy-gauge aluminum plate, U-bolts and plated muffler clamps. Likewise, the boom-to-mast plate was made from aluminum plate — only heavier gauge than used on the element clamps. Construction details can be seen in Fig. 5. The 8-ft 2-in.-long boom was salvaged from a piece of 1-1/4 inch OD heavy wall aluminum electrical conduit.

Feed System

A hairpin feed system was chosen for the Yagi.[7] Because it is balanced, this type of feed tends to prevent pattern skewing and unwanted side lobes. Details of the hairpin construction can be seen in Fig. 6.

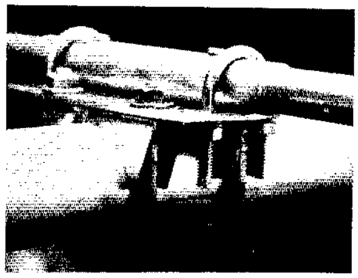


Fig. 5 — Photograph illustrating the element-to-boom clamp. Heavy-gauge scrap aluminum, U-bolts and plated muffler clamps were used to make up the assembly.

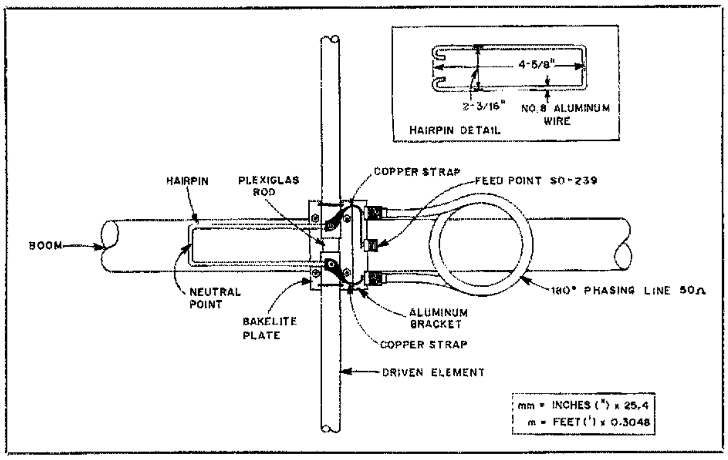


Fig. 6 — Detail of the hairpin matching and the feed system used with the 3-element, 50-MHz Yagi. Coaxial phasing-line lengths are discussed in the text.

The driven element and the feed assembly are insulated from the boom through the use of a 3/16-inch-thick bakelite mounting plate. Plexiglas rod is used as an insulator between the two halves of the driven element. An aluminum bracket is used to mount the three SO-239 connectors to the bakelite plate. The hairpin is made from no. 8 aluminum grounding wire, and is connected across the split element halves. The hairpin is electrically neutral at the exact center, and either may be fastened to the boom at this point or allowed to hang freely. A coaxial 1/2-λ phasing line is also connected across the driven element halves to provide a 180-degree phase shift between them. For cable with a 0.8 velocity factor, the phasing line should be 7 ft, 10-3/8 in.; for cable with a 0.66 velocity factor, 6 ft, 5-3/4 in. These phasing-line lengths will remain constant for any of the 50-MHz Yagis in Table 1. Hairpin and driven-element length must be determined experimentally for Yagis with different numbers of elements. It should be noted that with a hairpin match the driven element will be considerably shorter than specified in Table 1. Both parasitic elements were lengthened slightly from the Table 1 dimensions, as previously determined.

Performance

Upon completion, the 3-element NBS Yagi was installed at a 75-foot level above the ARRL Hq. building. The Hq. operators' club station, W1INF, was used to test and evaluate the antenna. A quick check indicated a good match at 1.25:1 VSWR. Delivering under 10 watts to the antenna, it took only a few minutes to see the exceptional performance the Yagi would provide. My first contact was a 6-to 10-meter crossband QSO with SM6PU! A few moments later the Yagi was rotated west, and a score of W6 and W7 stations were contacted. All signal reports from the West Coast were 59+. Not bad for less than 10 watts! A week of casual operating with never more than 50 watts to the antenna snagged the following prefixes: TF, HK, 8P6, T32, XE, KL7, EL, C5 and my best DX — AH8 in American Samoa! Although my signal was not quite as strong as those of the "kilowatt boys," I was never far behind in the pileups. In short, the gain seems very good, especially when one considers how small the Yagi is. The NBS data claims a gain of 7.1 dB over a dipole. Keep in mind that the NBS Yagi is optimized for maximum gain. The claimed front-to-back ratio is between 15 and 20 dB — not an extremely high figure, but acceptable for most vhf work. An outstanding feature of this Yagi is the clean and symmetrical pattern, which may prove to be a more valuable measure of performance than front-to-back ratio.

I would like to thank ARRL Hq. staff members Gerry Hull, AK4L, Pete O'Dell, KB1N, and Bernie Glassmeyer, W9KDR. They provided much help in constructing, tuning and installing the 3-element, 50-MHz Yagi.

Notes

[1]P. Viezbicke, "Yagi Antenna Design," NBS Technical Note 688, U.S. Department of Commerce, Washington, DC., Dec. 1976.
[2]H. Yagi and S. Uda, *Proceedings of the Imperial Academy*, Feb. 1926.
[3]J. Lawson, "Yagi Antenna Design: Experiments Confirm Computer Analysis," *Ham Radio*, Feb. 1980, pp. 19-27. J. Reisert, "How to Design Yagi Antennas," *Ham Radio*, Aug. 1977.
[4]m = ft × 0.3048; mm = in. × 25.4.
[5]Tables 1 through 4 and Fig. 1 are taken from *The Radio Amateur's Handbook*, 59th ed. (Newington: ARRL, 1981).
[6,7]G. Hall, ed., *The ARRL Antenna Book*, 14th ed. (Newington: ARRL, 1982), Chapter 5.

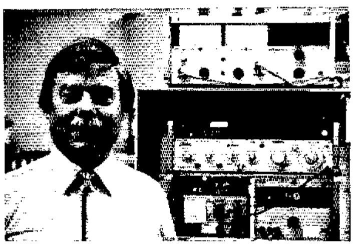
Strays

TA PROFILES

☐ ARRL Technical Advisor Roy Hejhall, K7QWR, joined our official consultant family five years ago. During this period, his expertise in rf-power semiconductor devices and circuits has been invaluable to the League and to Amateur Radio. He has contributed many articles for *QST*, and is the recipient of a Cover Plaque award (*QST*, March 1972). Roy has also written technical articles for leading professional publications, and has been a technical speaker at ARRL conventions and at numerous radio-club meetings and hamfests.

Licensed as WØTRH in 1954, Roy now holds an Advanced class license. Vhf and uhf fm (including linked remote-base systems) are his primary interests in Amateur Radio. He is a Life Member of ARRL, with memberships in QCWA, the Arizona Repeater Association, the Motorola Amateur Radio Club and the Saguaro Amateur Remote Base Association.

Roy received his BS degree from the U.S. Naval Academy. He now resides in Phoenix, Arizona, and is the principal staff engineer for the Motorola Semiconductor Products Sector. For 20 years he has been involved in product-development engineering (vhf and uhf bipolar and field-effect power transistors), starting as a member of the engineering team that introduced the first 15-W, 50-MHz transistor (the 2N2947). Roy enjoys music, photography and sharing his Amateur Radio activities with his XYL (WB7RPB). — *Marian Anderson, WB1FSB*



We don't know whether K7QWR's big smile was caused by a recent success in some job-related work with the test gear in the picture, or if it's because the 5 o'clock whistle just blew and he's thinking of firing up his fm mobile rig. But Roy smiles a lot, and he is definitely one of the "good guys."

I would like to get in touch with . . .

☐ owners of Collins KWM-380 rigs who are using Alpha amplifiers. Andrew Caughey, Jr., W8QIT, 15256 Levan Rd., Livonia, MI 48154.