how to design Yagi antennas

Discussion of a new Yagi design method, developed at the National Bureau of Standards, which allows you to design Yagis for your own operating requirements with optimized, reproducible gain characteristics

Have you ever wondered how to design a really good Yagi for your own requirements rather than just guessing, or using an existing design? If so, this article should be just what you are looking for. By using the information presented here you can design your own optimum Yagi for any frequency, from hf through uhf, with booms up to 4.2 wavelengths long.

Up until now, there has been little design information for Yagi antennas in the amateur literature. Kmosko and Johnson[1] designed a 13-element Yagi at 144 MHz but gave information only on that specific model. Greenblum[2] provided ranges of design values but was not specific as to exact sizes. The tables from Greenblum's article have appeared in recent *ARRL VHF Handbooks* and *Antenna Handbooks,* and several amateurs have reported good correlation using the mean values specified. Recent articles in the professional journals (such as the *IEEE Professional Group on Antennas and Propagation,* and others) have published computer-aided designs, but specific *cook-book* information is not available.

Now, for the first time, a straightforward approach to Yagi designs of various sizes and gains is available.[3] It is the result of an exhaustive study by the National Bureau of Standards in the early 1950s to explore all the major antenna types (Yagis, corner reflectors, rhombics, etc.) suitable for use on vhf

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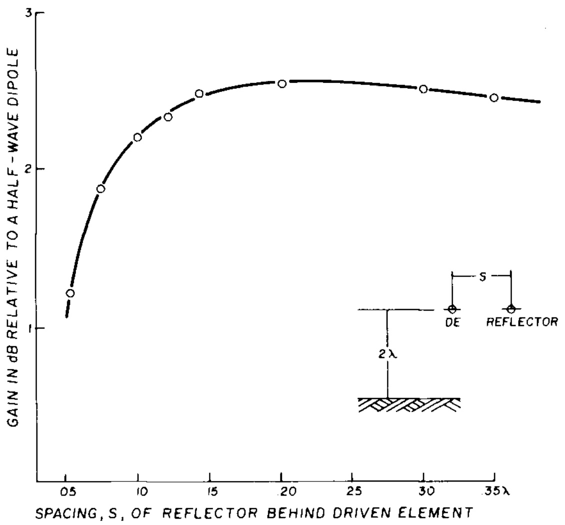

fig. 1. Gain in dB of a driven element and reflector for different spacings between elements.

ionospheric scatter. The NBS report tabulates all the design information necessary to construct six different boomlength Yagis (this portion of the project took nine man years to complete). The only known amateur use of these data are the WØEYE 432-MHz Yagi[4] and several unpublished Yagi designs by WØPW (ex WØEYE) and W1JR.

This NBS report shows the interrelationship between director and reflector diameters, lengths, and spacings, as well as the effects of a metal supporting boom. Optimum designs and gains for various boomlengths from 0.4 to 4.2 wavelengths are shown along with nomographs for designing a Yagi for your own operating requirements. Those readers who are interested in all the specifics will find the NBS publication invaluable. This article will highlight the results and present all the information necessary to design such Yagis; several working design examples will also be discussed.

reflectors

During the NBS investigation into optimum Yagi design, various reflector lengths and spacings were tried on a two-element Yagi. As can be seen from **fig. 1**, maximum gain is 2.6 dBd, peaking broadly at 0.2λ behind the driven element. Hence, all the Yagi designs presented here are optimized using this reflector spacing.

The NBS engineers tried various other reflector configurations in order to realize any possible increase in gain. The trigonal configuration shown in **fig. 2** yielded the maximum increase, 0.75 dB over a single reflector, when tested on a Yagi 4.2λ long. It should be applicable to the other designs and may be desirable if high front-to-back ratios are desired.

The heart of any Yagi design is the director. Extensive tests have shown that the diameter, length, and spacings are all interrelated. Also, it should be pointed out that these parameters become increasingly critical as the number of directors (and hence the boomlength) increase.

NBS tested various director lengths using spacings of 0.01 to 0.40λ on booms to 10λ long. Plots of these combinations show that there are optimum spacings for maximum gain. As the boomlength is increased, the optimum director spacing also increases. In addition, the gain of the antenna can be further increased if the length of each director is carefully chosen. It is noted that the diameter of the element affects its length, thicker directors being shorter than thinner ones. A comparison of maximum gain versus boomlength for uniform and optimized length directors is shown in **fig. 3**. Those readers desiring further information are referred to *NBS Technical Note 688*.[3]

A set of optimum director and reflector lengths normalized to 0.0085λ diameter elements is presented in **table 1**. These data, with respective gains noted, yield optimum performance for the six boomlengths which are shown. If a different element diameter is desired (isn't that always the case?), the elements can be scaled by using the nomograph in **fig. 4**. Element diameters from 0.001 to 0.04λ can be easily scaled as will be discussed later.

table 1. Optimized lengths of parasitic elements for Yagi antennas of six different lengths (reflector spaced 0.2λ behind driven element, element diameter 0.0085λ).

	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
1st	0.442	0.428	0.428	0.432	0.428	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
Gain relative to half-wave dipole, dB	7.1	9.2	10.2	12.25	13.4	14.2
Design curve (see fig. 4)	(A)	(C)	(C)	(B)	(C)	(D)

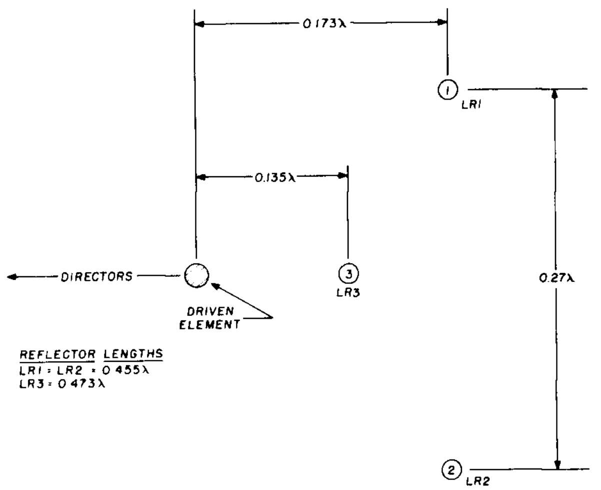

fig. 2. Trigonal reflector arrangement (three reflector elements), when used with 4.2λ Yagi, provides 0.75 dB increase in gain (lengths not corrected for boom thickness).

The element data presented in the NBS report is based on an *air* boom which, in the original tests, was simulated by a triangular plexiglass structure. After optimization was completed, various booms and materials were tested to check the effects of the test boom. All measurements verified that the designs tested on plexiglass were optimum in an air dielectric. However, attempts to repeat these results using wooden booms were dismal. According to Peter Viezbickie, the author of the NBS report, changes in moisture and directivity due to the wooden booms made repeatability almost impossible despite various coatings applied to the wood.

Metal-boom Yagis were entirely repeatable if the elements were lengthened to compensate for the boom structure. At first glance, it may seem that a constant factor could apply. However, tests conducted by NBS showed that small diameter booms (with respect to wavelength) had less effect on element lengths than larger booms. These data are plotted on **fig. 5** for boom diameters up to 0.04λ. Tests also showed that, for correction purposes, the effect of square and round booms were identical.

feed systems

Detailed feed systems are not discussed in the report. On most tests, a folded dipole using a 4:1 half-wavelength coaxial balun was followed by a stub tuner. However, any of the usual feed systems can be used.[5] Reference 6 describes how to test these matching systems.

patterns

Finally, the NBS report shows radiation patterns for the *E* and *H* planes. For the sake of brevity, only the patterns for the 1.2λ and 4.2λ Yagis are presented in this article (see **figs. 6** and **7**). You will note the symmetrical pattern, the low side lobes, and the high front-to-back ratio, all characteristics of a well-designed Yagi antenna.

Tests made by W6FZJ and WØEYE on a 15-element, 4.2λ Yagi for 432 MHz, designed with the method described in this article, showed that the antenna had about 1% vswr and 1-dB gain bandwidth, slewed to the low-frequency side of the center design frequency; performance above the center frequency fell off quite rapidly. It is estimated that the gain and vswr bandwidth for the 1.2λ Yagi is about 2%. It should be pointed out that the bandwidth of a Yagi is quite often limited by the matching and feed system, not by the basic Yagi design. In this respect most amateur beams use narrowband feed systems compared with Yagis designed for use in commercial service.

designing a yagi antenna

We will now proceed to design a 1.2λ Yagi for 50.1 MHz, a 2.2λ Yagi for 205 MHz, and a 4.2λ Yagi for

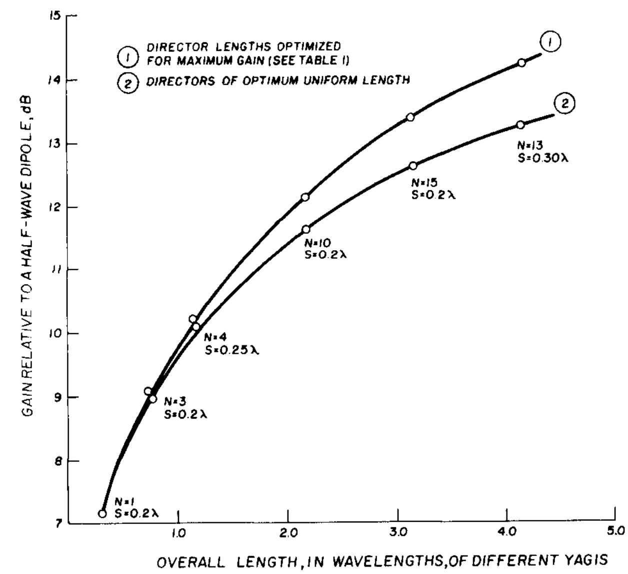

fig. 3. Gain comparison of different length Yagis, showing the relationship between directors optimized in length to yield maximum gain, and directors of optimum uniform length. *N* is the number of directors; *S* is the spacing between directors (reflector spaced 0.2λ on all antennas).

432 MHz to demonstrate how the NBS design material can be used. I actually built and tested each of these designs to verify the validity of the design data. In all cases the performance of the finished antennas matched the results reported by NBS.

The first step in any design is to choose the desired gain, compare it with the designs in **table 1**, and see if the stated boomlength is within the desired range. Next, the element diameter should be chosen to fall within the specified ranges (0.001 to 0.04λ) on the design nomograph, **fig. 4**. Finally, the boom or supporting structure should be chosen.

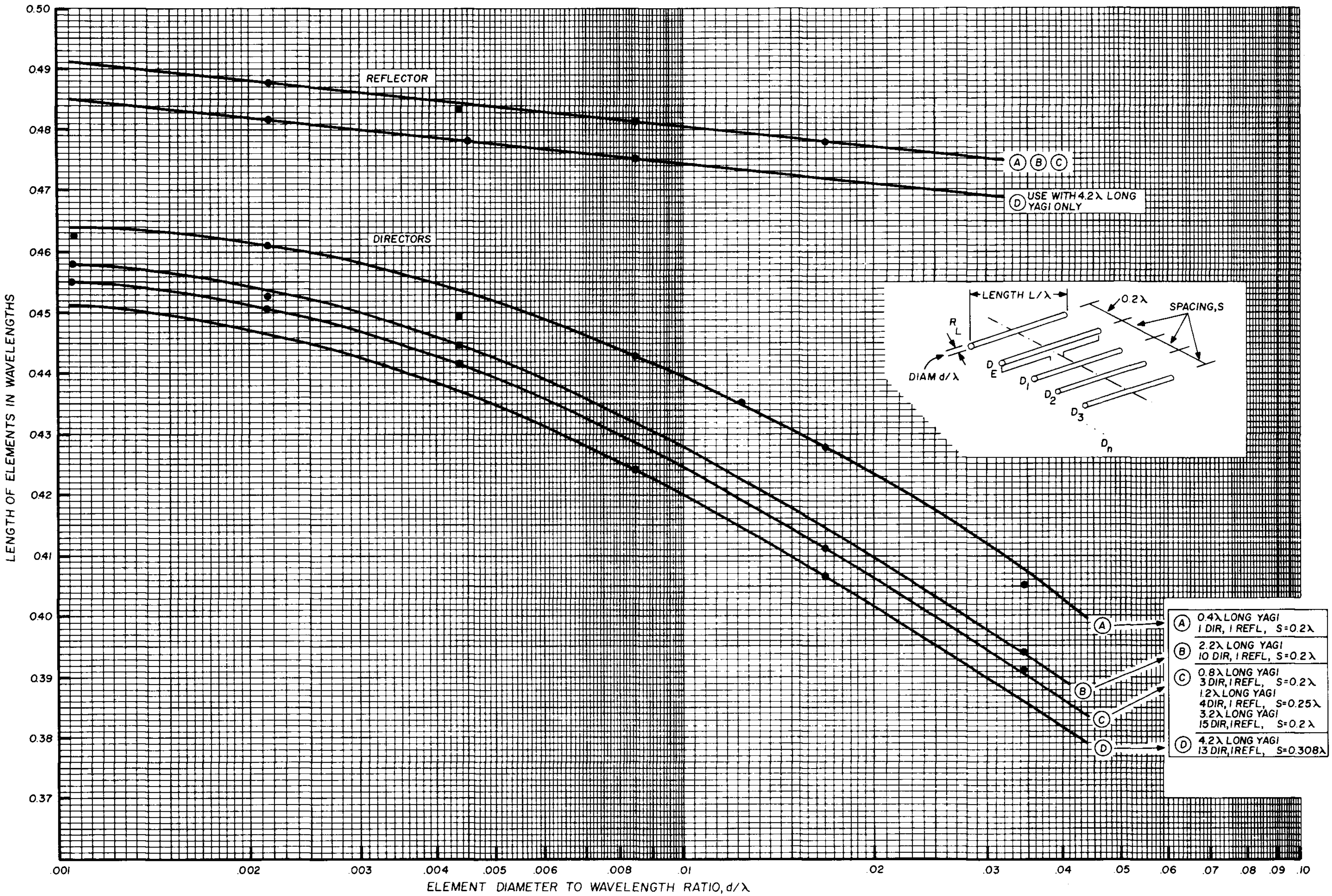

fig. 4. Yagi antenna design nomograph showing the relationship between element diameter to wavelength ratio (d/λ), and element length for different antennas. Detailed procedure for using this chart is presented in the text.

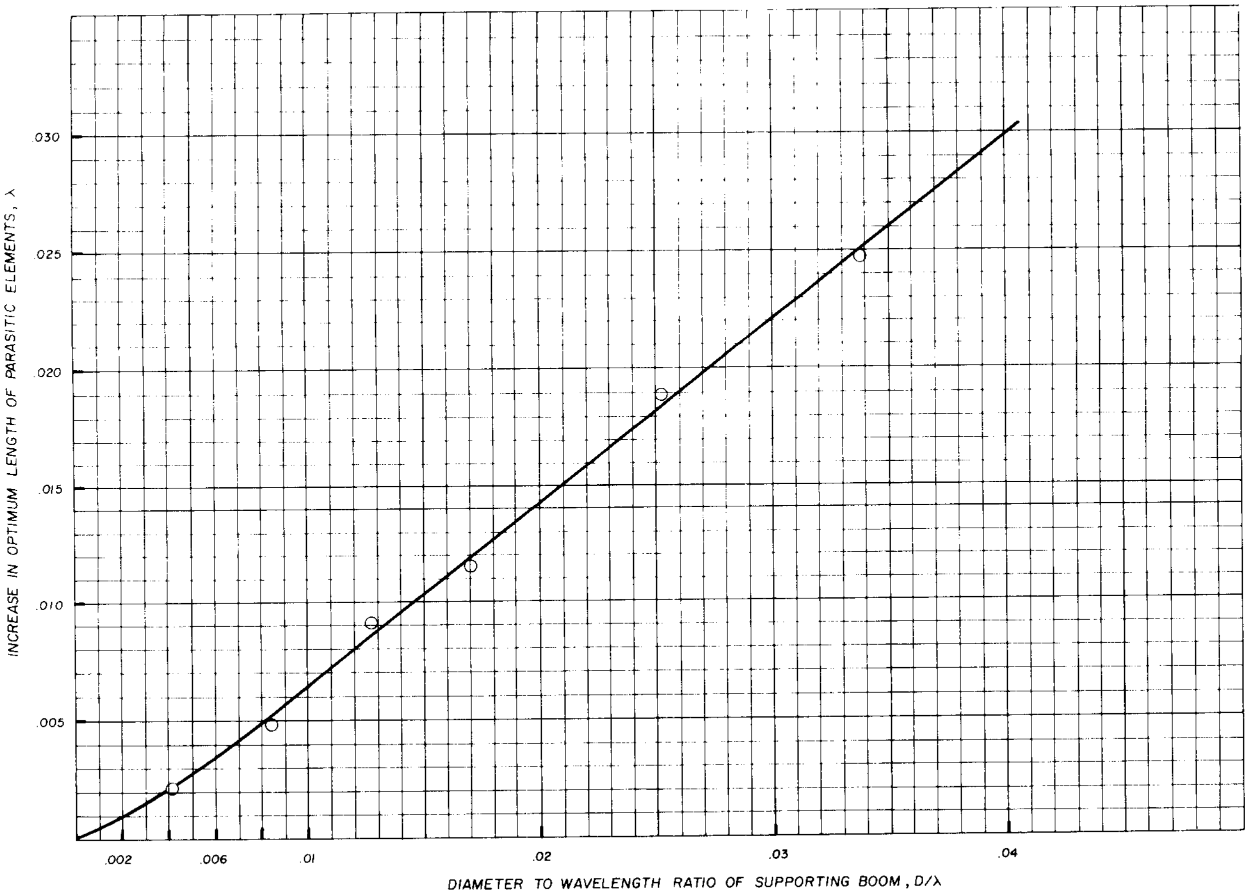

fig. 5. Graph showing the effect of a supporting metal boom on the length of the parasitic elements.

Example 1. It is desired to build a 6-meter Yagi with 10.2 dBd gain, using 0.5 inch (13mm) diameter elements mounted on insulating blocks above a 1.5 inch (38mm) diameter boom. This is the 1.2λ design in **table 1**.

The formula for wavelength is

$$L = \frac{11803}{F} \ (inches) \quad \textbf{(1)}$$

$$L = \frac{29980}{F} \ (cm) \quad \textbf{(2)}$$

where L = length
F = frequency in MHz

Frequency	50.1 MHz
Wavelength	235.6 inches (5.98 meters)
Element diameter (d/λ)	0.0021λ
Reflector spacing	47 inches or 120 cm (0.2λ)
Director spacings	59 inches or 150 cm (0.25λ)
Boom diameter	not important, discussed later
Overall length	283 inches (approximately 24 feet) or 7.2 meters (1.2λ)

1. Plot the lengths of the parasitic elements for the 1.2λ design from **table 1** on the design nomograph

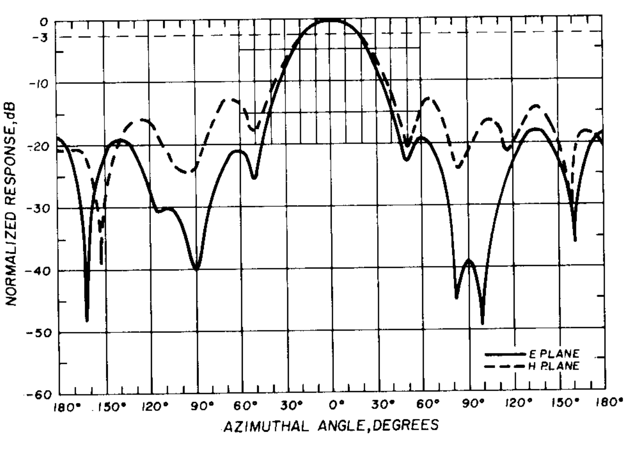

fig. 6. Radiation patterns of a 6-element, 1.2λ long Yagi, built with the dimensions shown in table 1. Beamwidth of the *E* plane is 40 degrees; *H* plane beamwidth is 42 degrees.

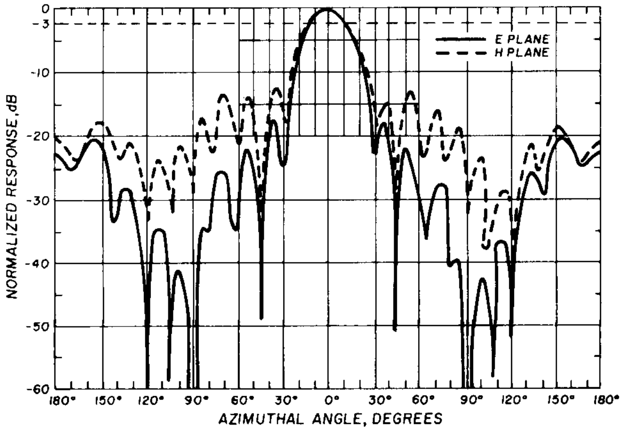

fig. 7. Radiation patterns of a 15-element, 4.2λ long Yagi. Beamwidth of the ***E*** **plane is 26 degrees;** ***H*** **plane beamwidth is 29 degrees.**

(see **fig. 8**) for parasitic elements with a diameter, $d/\lambda = 0.0085\lambda$.

$$L_R = 0.482\lambda$$
$$L_{D1} = L_{D4} = 0.428\lambda$$
$$L_{D2} = L_{D3} = 0.420\lambda$$

2. However, our element diameters are 0.0021λ so the element lengths must be adjusted. Draw a vertical line from 0.0021λ on the horizontal axis on the nomograph. This intersects the compensated lengths for the reflector and directors 1 and 4:

$$L_{R'} = 0.488\lambda$$
$$L_{D1'} = L_{D4'} = 0.451\lambda$$

3. Using a pair of dividers (or a compass), measure the distance between director 1 (D1) and director 2 (D2) determined in **step 1**. Transpose this distance from the point established in **step 2** to the left along the 1.2λ Yagi curve to 0.0021λ to determine the compensated length for directors 2 and 3:

$$L_{D2'} = L_{D3'} = 0.446\lambda$$

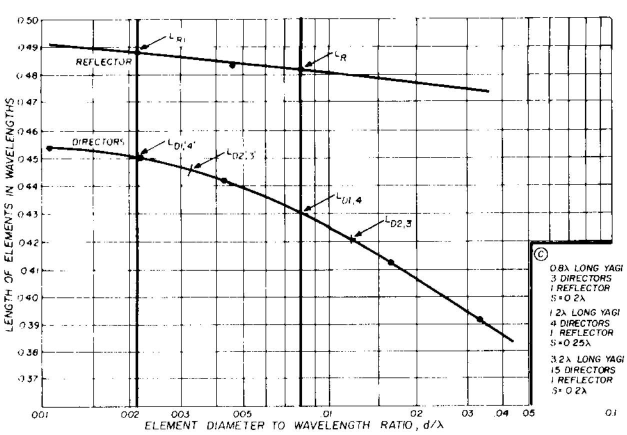

fig. 8. Use of the Yagi design curves (fig. 4) to determine the element lengths for a 6-element, 50.1-MHz Yagi on a boom 1.2λ long (see example 1 in text).

When I built this antenna I decided to use large element insulating blocks which I purchased from Swan Antennas (now KLM). Therefore, it wasn't necessary to put the elements through the boom. Since the wavelength is long with respect to the chosen boom diameter, I didn't feel that any boom correction was necessary. This was verified by subsequent tests. When the boom diameter represents a substantial portion of the operating wavelength, however, a correction for the boom diameter is required; this will be discussed in *example 3*.

The reflector and director lengths for the 50.1-MHz Yagi are as follows:

Reflector	0.488λ = 115 inches (2.92m)
Director 1	0.451λ = 106.25 inches (2.70m)
Director 2	0.446λ = 105.06 inches (2.67m)
Director 3	0.446λ = 105.06 inches (2.67m)
Director 4	0.451λ = 106.25 inches (2.70m)

The approximate length of the driven element can be calculated from

$$L = \frac{5500}{F} \text{ (inches)} \quad (3)$$

$$L = \frac{13970}{F} \text{ (cm)} \quad (4)$$

where L = length
F = frequency in MHz

Therefore, at 50.1 MHz, the length of the driven element is 109.75 inches or 2.79 meters. For simplicity I decided to use a gamma match and to attach the driven element to the boom with a U bolt. During the matching adjustments the driven element was short-

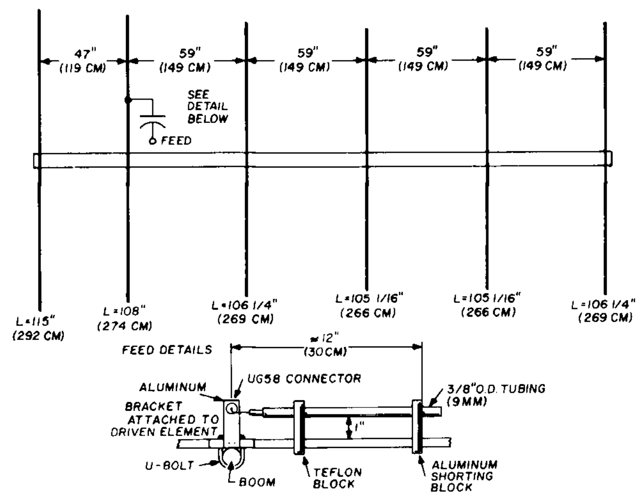

fig. 9. Layout of a 6-element Yagi for 50.1 MHz on a 1.2λ boom. All elements are ½ inch (13mm) OD aluminum tubing, mounted on insulating blocks attached to a 1½ inch (38mm) OD aluminum boom. The gamma capacitor is approximately 12 inches (30cm) of RG-8/U coaxial cable with the outer jacket and shield removed, then inserted in a 3/8-inch (10mm) diameter tube.

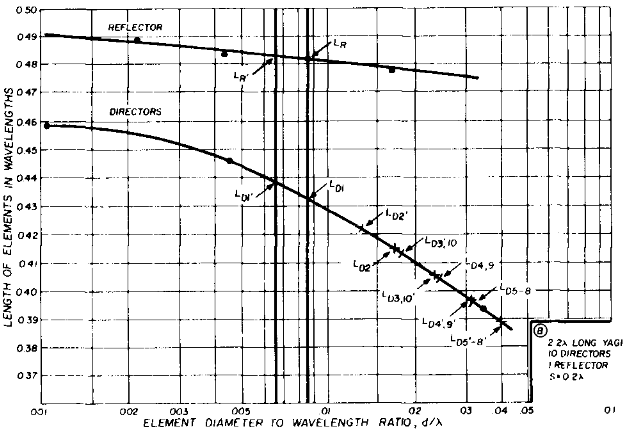

fig. 10. Use of the Yagi design curves (fig. 4) to determine the parasitic element lengths for a 12-element 205.25-MHz Yagi on a boom 2.2λ long (example 2).

ened to 108 inches (2.74m) for optimum vswr (the length of the driven element is not critical for maximum gain, as will be discussed later).

The completed 6-meter Yagi is shown in **fig. 9**. On-the-air receiving tests at W1JR have shown the 3 dB beamwidth to be between 40-45 degrees, while all sidelobes were at least 15 dB down; the front-to-back ratio was 18 dB. This agrees closely with the published NBS data.

Example 2. During the summer of 1973, when I was W6FZJ, transpacific tests to Hawaii were conducted on 220 and 432 MHz. Television video carriers seemed like a good propagation indicator so I designed a converter for Channel 12 on Mt. Haleakela on Maui. Since I had no good designs for a moderate gain Yagi with low sidelobes (to discriminate against Channel 12 TV stations in California), I chose the NBS 2.2λ Yagi design using 3/8 inch (1cm) diameter elements.

Frequency	205.25 MHz
Wavelength	57.5 inches (1.46 meters)
Element diameter (d/λ)	0.0065λ
Reflector spacings	11.5 inches or 29.2 cm (0.2λ)
Director spacings	11.5 inches or 29.2cm (0.2λ)
Boom diameter	not important, discussed later
Overall length	126.5 inches or 3.21 meters (2.2λ)

1. Plot the director element lengths for the 2.2λ Yagi design from **table 1** on the design nomograph (see **fig. 10**) for $d/\lambda = 0.0085$.

$L_R = 0.482\lambda$
$L_{D1} = 0.432\lambda$
$L_{D2} = 0.415\lambda$
$L_{D3} = L_{D10} = 0.407\lambda$
$L_{D4} = L_{D9} = 0.398\lambda$
L_{D5} through $L_{D8} = 0.390\lambda$

2. Since the chosen element diameters are 0.0065λ, draw a vertical line from 0.0065λ on the horizontal on the nomograph. This intersects the compensated length for the reflector and the first detector:

$L_{R'} = 0.483\lambda$
$L_{D'} = 0.4375\lambda$

3. Using a pair of dividers, measure the distance be-

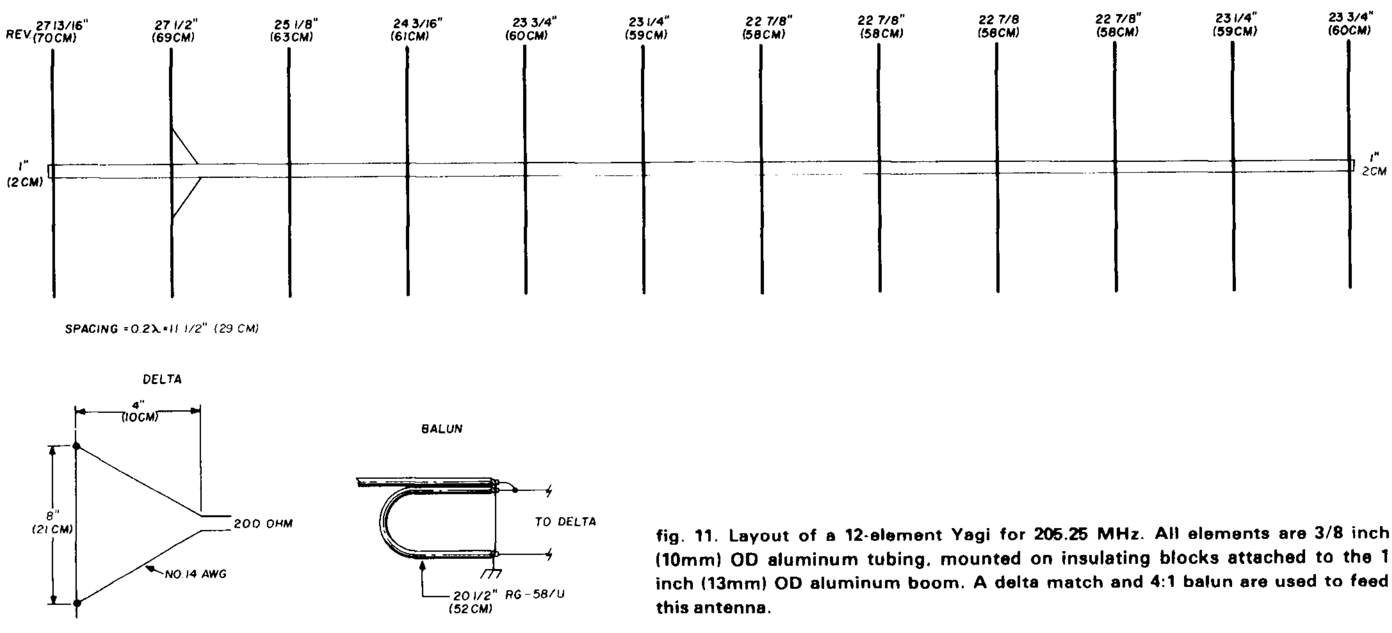

fig. 11. Layout of a 12-element Yagi for 205.25 MHz. All elements are 3/8 inch (10mm) OD aluminum tubing, mounted on insulating blocks attached to the 1 inch (13mm) OD aluminum boom. A delta match and 4:1 balun are used to feed this antenna.

tween director 1 (D1) and director 2 (D2) determined in **step 2**. Transpose this distance from the point established in **step 2** to the left along the 2.2λ curve to determine the compensated length of director 2 ($L_{D'} = 0.421\lambda$). Now span the distance between directors 1 and 3 (D1 and D3) with the dividers, and move this dimension along the curve, making sure to reference D1′ (at the 0.0065 line). Follow this same procedure until all directors have been scaled. The remaining director lengths are as follows:

$$L_{D3'} = L_{D10'} = 0.414\lambda$$
$$L_{D4'} = L_{D9'} = 0.405\lambda$$
$$L_{D5'} \text{ through } L_{D8'} = 0.398\lambda$$

As in the case of the 6-meter Yagi, I decided to use element insulators which I purchased from KLM Electronics. Since the elements are mounted well above the boom, an element correction factor was not applied. The reflector and director lengths for the 205.25 MHz Yagi are as follows:

Reflector	0.483 = 27-13/16 inches (70.6cm)
Director 1	0.4375λ = 25-1/8 inches (63.9cm)
Director 2	0.421λ = 24-3/16 inches (61.5 cm)
Directors 3 and 10	0.414λ = 23-3/4 inches (60.5cm)
Directors 4 and 9	0.405λ = 23-1/4 inches (59.2cm)
Directors 5 - 8	0.398λ = 22-7/8 inches (58.1cm)

You will note that these lengths have been slightly rounded off. The NBS report states that tolerances of 0.003λ should be maintained (0.173 inch or 4.4mm at 205.25 MHz). Furthermore, tests made by WØEYE

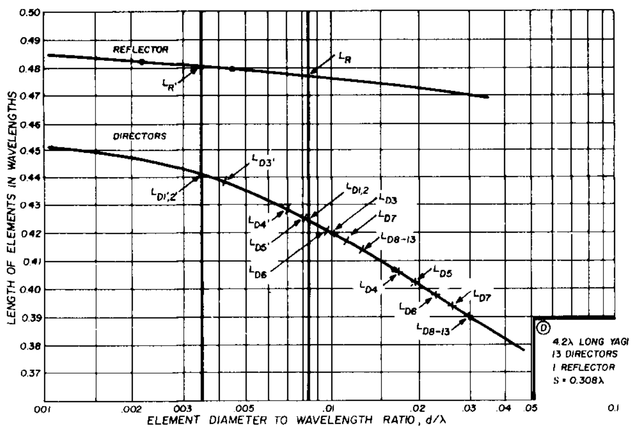

fig. 12. Use of the Yagi design curves (fig. 4) to determine the parasitic element lengths for a 15-element Yagi for 432 MHz; boom is 4.2λ long (example 3).

and W6FZJ in 1973 clearly showed that the gain and radiation pattern of a Yagi antenna degrades quite rapidly on the high side of the design frequency, but much more slowly on the low side. Therefore, if you must round off to a standard dimension, it is better to

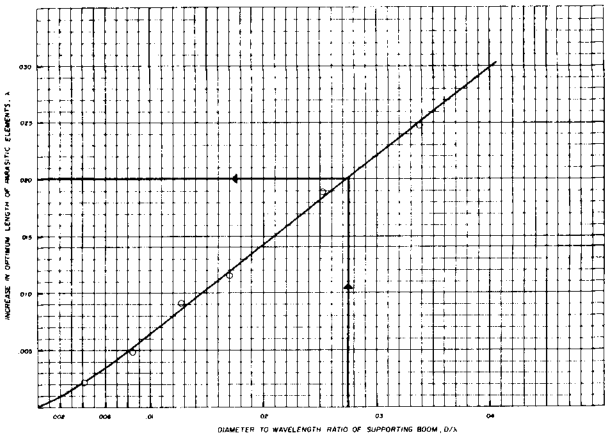

fig. 13. Supporting boom correction factor for the 15-element 432-MHz Yagi. Boom diameter is 0.0275λ (3/4 inch or 1.9cm at 432 MHz); length of each parasitic element must be increased to 0.2λ.

cut the director elements slightly shorter — not longer. Reflector length, on the other hand, should be rounded off on the long side. The element lengths for the Channel 12 Yagi were shortened to the nearest 1/16 inch, or only about 0.001λ.

For simplicity I decided to use a delta matching system and a 4:1 balun on this antenna. The driven element length was calculated using **eq. 3**. During final tests using the procedures outlined in reference 6 the driven element was extended slightly to obtain a 1:1 vswr. The length of the driven element is not a critical factor as long as the driven element is always shorter than the reflector.

The final design for the 205.25-MHz Yagi is shown in **fig. 11**. The desired discrimination to other Channel 12 television stations was achieved. This antenna is now in use at W1JR for indicating tropo, meteor shower, and aurora openings.

Example 3. The transpacific tropo tests mentioned in the previous example required an easily transportable antenna for the 432-MHz system to be installed at KH6BZF's station in Hawaii. I decided to use four 4.2λ Yagis similar to the WØEYE type[4] and stack them accordingly. The humidity and salt air are high in Hawaii so the elements were mounted through the boom using knurled 3/32-inch (2.4mm) diameter brass rods; this is similar to the method used on the W6FZJ extended, expanded collinear array described in *QST*.[7]

For the sake of brevity, **steps 1, 2,** and **3** will not be repeated here. However, the marked up nomograph for the 4.2λ 432-MHz Yagi is shown in **fig. 13;**

Since I decided to mount the elements through a metal boom, the elements must be lengthened to

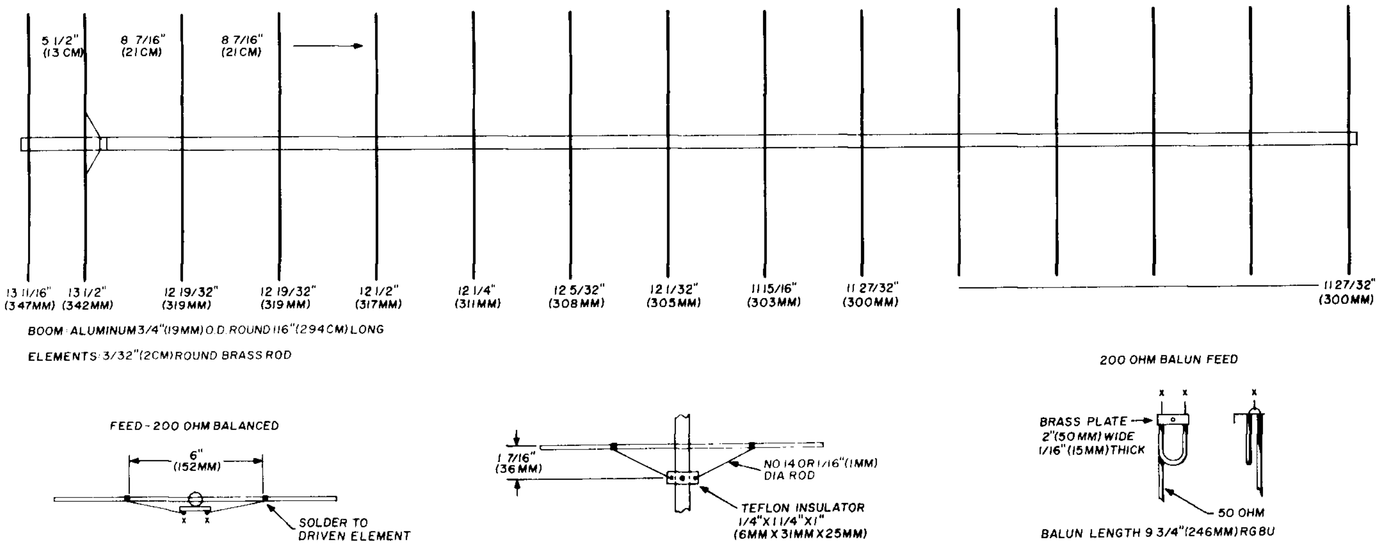

fig. 14. Layout of the 15-element 432-MHz Yagi on a 4.2λ boom. All elements are 3/32 inch (2.4mm) OD brass rod; elements are knurled and tapped into under-size holes in the 3/4 inch (1.9mm) aluminum boom. Element spacing of all directors is 8-7/16 inches (21.4cm); reflector is 5½ inches (14cm) behind the driven element. Details of the delta matching system and 4:1 balun are also shown.

compensate for the shortening effect of the boom.

Frequency	432 MHz
Wavelength	27.32 inches (69.40 cm)
Element diameter (d/λ)	0.00343λ
Reflector spacing	5-1/2 inches or 13.9cm (0.2λ)
Director spacing	8-7/16 inches or 21.4 cm (0.308λ)
Boom diameter	3/4 inch or 1.9cm (0.0275λ)
Overall length	115 inches or 2.915 meters (4.2λ)

$L_{R'} = 0.480\lambda$
$L_{D1'} = L_{D2'} = 0.441\lambda$
$L_{D3'} = 0.438\lambda$
$L_{D4'} = 0.428\lambda$
$L_{D5'} = 0.425\lambda$
$L_{D6'} = 0.421\lambda$
$L_{D7'} = 0.417\lambda$
$L_{D8'}$ through $L_{D13'} = 0.414\lambda$

To determine the corrected element length, first convert the boom diameter (3/4 inch or 1.9cm in this case) to wavelength (d/λ) or approximately 0.0275λ. Draw a vertical line from 0.0275λ on the boom correction nomograph (see **fig. 13**) to the DATA line. Move to left-hand axis and read the correction factor; 0.02λ for this antenna. Add this length correction factor to all elements as shown below.

Note that all the director lengths have been rounded off to the *short* side, as in **example 2**. The driven element length was calculated with **eq. 3**, but a better match was obtained when it was extended to 13½ inches (34.3cm); a delta match with a 4:1 balun was used. The final design for the 432-MHz Yagi is shown in **fig. 14**.

This antenna stacks well at 1.6λ in the H plane, and 1.8λ in E plane. As tested at NBS, this quad Yagi array yielded 19.6 dBd. A one-way 432-MHz contact was attained between KH6BZF and W6FZJ in July, 1973 (don't ask me why it wasn't two-way because I'll cry loudly). During October, 1973, using only 200

Reflector	0.480 + 0.02 = 0.500	13-11/16 inches	(34.7cm)
Directors 1 and 2	0.441 + 0.02 = 0.461	12-19/32 inches	(32.0cm)
Director 3	0.438 + 0.02 = 0.458	12-1/2 inches	(31.8cm)
Director 4	0.428 + 0.02 = 0.448	12-1/4 inches	(31.1cm)
Director 5	0.425 + 0.v2 = 0.445	12-5/32 inches	(30.9cm)
Director 6	0.421 + 0.02 = 0.441	12-1/32 inches	(30.6cm)
Director 7	0.417 + 0.02 = 0.437	11-15/16 inches	(30.3cm)
Directors 8 - 13	0.414 + 0.02 = 0.434	11-27/32 inches	(30.1cm)

watts and this array, EME signals from KH6BZF were copied and identified at W6FZJ. KH6BZF now uses this setup on Oscar 7, Mode B.

This article has presented a new and relatively precise way to consistently design and build Yagi antennas with optimum, reproducible gain characteristics — selecting a boomlength to suit your own requirements. Three design examples have shown Yagi antennas with demonstrated performance. If construction tolerances are held to 0.003λ maximum (0.001λ preferred), you should be able to design your own Yagis with the same excellent results. As pointed out earlier, director elements should be slightly shortened, while reflectors should be lengthened when rounding off the calculated dimensions.

Before actually starting to build a given design, double check your mathematics and scaling; it will pay off a 100-fold in time saved (and frustration). In those cases where the numbers in **table 1** do not agree exactly for the first director, reference at 0.0085 (d/λ) on the chart. The feed methods are not critical, and attention to the details outlined in references 5 and 6 should fill any voids in this article.

In closing, I would especially like to thank Don Hilliard, WØPW (ex WØEYE), who first introduced me to this information, and to Peter Viezbickie who, after much prodding by Don and myself, finally published this wealth of information. Now you, too, can be an expert in designing your own Yagi antennas.

references

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