Some Notes on FM BC Antennas
Part 2: A Few Possible Yagi Beam Designs

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Suppose we decide that we need--whatever the reason--a directional beam in order to search for and enhance the reception of distant FM broadcast band stations. What are our choices? In the realm of antennas that we might build for ourselves, there is the Yagi-Uda beam and the log periodic dipole array (LPDA). As well, there are esoteric antennas normally outside the scope of home construction, as well as some over-hyped commercial offerings.

Before looking at some other options, let's first examine the most popular antenna choice, especially for the listener who may wish to build his or her own antenna: the Yagi. We shall first orient ourselves toward this interesting and useful antenna type. Then, we shall look at a number of different designs. This episode will be filled with many tables, hopefully informative ones, but we shall stop short of actually trying to build a Yagi antenna. That subject will be worth an entire episode in itself.

Some Yagi Basics

The Yagi-Uda array--or simply the Yagi--appeared in the late 1920s. However, it did not become popular for many communications uses until after World War II with the advent of television. As we entered the 1990s, computer antenna modeling software appeared in civilian circles, and the design of Yagi antennas reached new heights of performance and advertising honesty. Most Yagis available to communications services today begin life as a computer model.

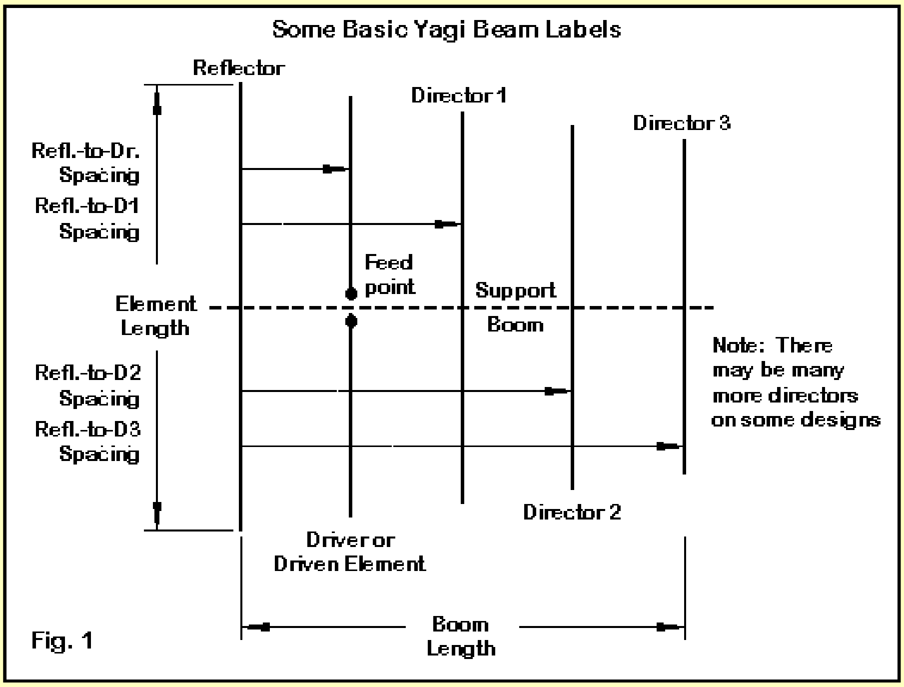


Fig. 1

Fig. 1 will give us an orientation to some of the key dimensions and operative terminology associated with the Yagi. Note that there is only one feedpoint for the antenna, on the driver or driven element. All of the other elements are parasitic. They derive their function to form the Yagi's directional characteristics from the coupling of energy to and from adjacent elements.

Relative to the main forward lobe of the antenna, elements to the rear of the driver are called reflectors. Elements forward of the driver are called directors. As we have come to better understand the function of the elements, these names have become simply conventional designators and the label does not necessarily indicate the exact function. It is unwise to try to apply anything like a flashlight and lens analogy to the Yagi. Nonetheless, reflector elements are normally longer than the driver and directors are shorter. However, it is not necessary for the directors to be progressively shorter in any simplistic way. A Yagi designer will place an element and set its length to maximize performance without regard to its length relative to surrounding elements.

There are three sets of critical dimensions with respect to Yagi design. One of them is the diameter of the elements. Every element that changes its diameter also affects its position in the array and its length. Hence, for the designs that we shall examine in detail, changing the element diameter to some more convenient material may well destroy the performance of the antenna.

The second set of dimensions of critical importance is the element length. As we have seen, length will depend on element diameter--and also upon its position in the array. The third group is element position. There are several conventions for listing element position. In this episode, we shall designate position by the distance forward of the reflector.

The distance of the most forward director from the reflector is the element boom length. When building a Yagi, select a boom a little bit longer than this measurement in order to have room to hold any mounting hardware and perhaps to cap the boom ends.

Why element diameter, length, and position are so interactive is an interesting question that could take us a book to answer. In the context of our entry into Yagi-land, let's just note that changes in any of the dimensions will change the level and distribution of energy coupled into and out of any given element. Any change in one element ripples throughout the array and ends up changing the performance of the array as a whole.

There are a number of performance specifications that are of considerable interest in Yagi design. **Fig. 2** illustrates some new and old ones.

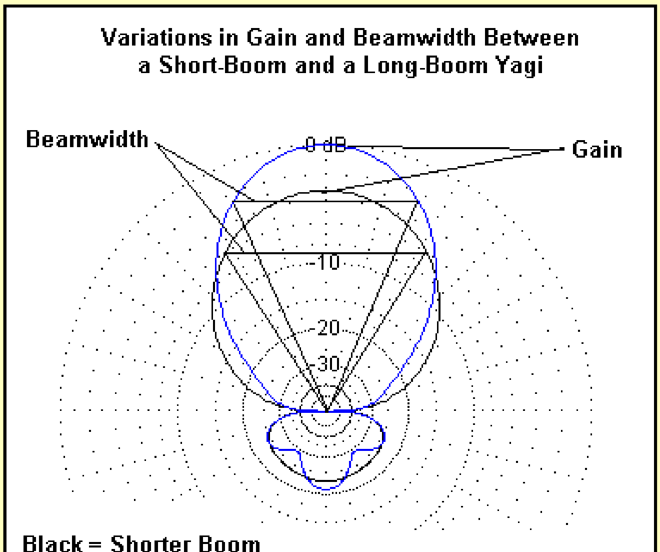


Fig. 2

The maximum forward gain of a Yagi is largely a matter of its boom length--up to a limit. Of course, for a given boom length, we need to have some sort of minimum element population. Once we meet those criteria, the longer the boom, the higher the maximum forward gain. **Fig. 2** shows the azimuth patterns of a shorter-boom and a longer-boom Yagi, and the gain differential is readily apparent.

A second basic property of Yagis is the beamwidth. We normally measure beamwidth between points on each side of the direction of maximum strength or sensitivity (or power gain in transmitting terms). We extend our measurement on either side of that heading until the radiated power is 1/2 the level in the maximum power direction. For receiving, the signal is at half strength. The angle between those two points is the beamwidth of the antenna. In general, the higher the maximum forward power or receiving sensitivity of a beam antenna, the narrower the beamwidth. High gain, narrow beam antennas are better at rejecting stations near to the heading of the desired station. However, the narrow beamwidth makes them more finicky to aim.

We may often use more than the minimum number of elements on a given boom length to achieve a desired gain. That decision results from wanting to tailor other characteristics. For a given boom length and gain level, the fewer the elements, the narrower the operating bandwidth of the antenna. Operating bandwidth often refers to the frequency coverage over which the antenna maintains its gain, front-to-back ratio, and matched feedpoint impedance, since these are either reasons for using the antenna or conditions necessary to its effective use.

The Yagi is inherently a narrow-bandwidth antenna. In most Yagi designs, the gain tends to change continuously. If we have 1 or more directors, the gain goes up with frequency until it reaches a peak. Then it rapidly descends and, at a certain frequency, the pattern actually reverses so that the antenna is most sensitive to the rear. In most designs, by the time we reach that pattern-reversal frequency, the feedpoint impedance has changed radically enough to make the antenna unmatchable to the remainder of the overall antenna system.

The front-to-back ratio is a measure of how well signals are rejected when their direction is in the rear quadrants of the antenna. The most conventional measure simply compares the maximum forward gain to the gain in exactly the opposite direction. We can record the difference in dB as the front-to-back ratio. Some designers take note of the fact that the rear pattern often has lobes, some of which are stronger that the sensitivity to the exact rear of the main lobe. So they use a worst-case value for the entire rear quadrants in making the comparison. Still others average the strength of all of the rearward radiation or sensitivity and make the comparison with that figure. In this episode, as a matter of convenience, we shall use the most conventional figure, the 180-degree front-to-back ratio.

What Shall We Look For in a Yagi?

The needs of FM listeners who also may wish to build their own antennas are as varied as the types of antennas themselves. Some want something simple that will still give a boost to the desired signal and some rejection of unwanted signals. At the opposite end of the spectrum are listeners who wish maximum gain and maximum unwanted signal rejection regardless of the challenge level in constructing the desired antenna. We shall sample both types of antennas.

What everyone wants is a single antenna that covers the entire FM band with smooth, even performance across the entire band. If we stick to Yagis, you may not be able to realize that desire in a conventional design. However, we shall show you how close we might come to that goal.

One requisite for a good receiving antenna is a reasonably good match between the antenna feedpoint and the feedline. All of the antennas that we shall explore will--within their operating passbands--provide a good match to 50-Ohm coaxial cable. This means a 50-Ohm SWR value of 2:1 or less across the passband. In one case, we shall reduce the peak SWR value to under 1.3:1. The results for the antenna builder and installer are the following ones. If you have 50-Ohm coaxial cable, use it and connect it directly (with the correct connector) to the input of the receiver. It will not matter even a little that the receiver has a 75-Ohm input impedance: the difference is too small to make a difference in overall antenna system performance. If you have "cable company" coax (75-Ohm material with good weathering characteristics), feel free to use it. Again, the SWR on the line will be too small to create any losses that could be noticed by the listener. If you want to use TV twinlead of very good quality and know how to install it correctly, then you may use a 4:1 transformer at both ends of the line and still have a successful system.

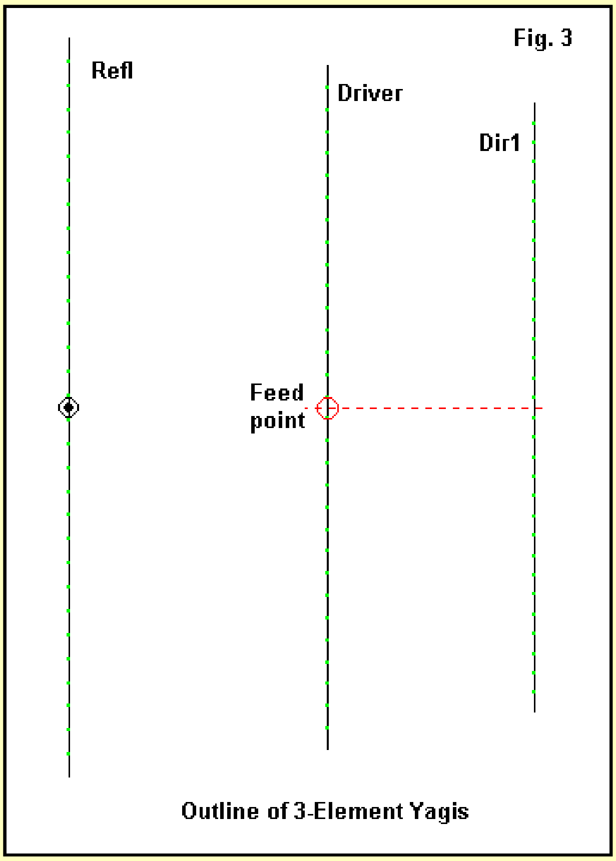
A word about the gain values we shall use to characterize Yagi performance. We shall report the gain in free-space terms using the dBi standard. A free-space dipole has a gain of 2.15 dBi. For any two horizontal antennas placed over real ground, the reflections from the ground will add about 5.5 dB to the free-space figure. Hence, a dipole will have about 7.6 dBi gain at reasonable heights. A Yagi with a free space gain of 6 dBi will have a gain of about 11.5 dBi over ground. Although the numbers have changed, the advantage over the dipole (nearly 4 dB) does not change. Hence, the use of free-space figures allows us to compare one antenna with another with confidence.

Now we are ready to explore a few Yagi designs, beginning with some very simple ones.

3-Element Yagis

A typical Yagi of conventional design has a bandwidth of about 3% or so, where we define the bandwidth as the difference between the upper and lower limits of operating frequency divided by the median frequency between the two, times 100, of course, to arrive at a percentage. Since the middle of the FM broadcast band is nearly 100 MHz, such designs would give us only about 3 MHz of bandwidth. Unless we had a very confined interest in the FM band, it would take nearly 7 antennas to cover the band.

By careful design--and the sacrifice of some forward gain--it is possible to more than double the operating bandwidth of even so simple an antenna as a 3-element Yagi. In the process, we may still use conventional element materials, such a 0.25" diameter aluminum. In fact, except for the last of our Yagi designs, all of the antennas in this episode will use quarter-inch aluminum.



A 3-element Yagi, as outlined in **Fig. 3**, can cover about 1/3 of the FM band. Hence, if one is only interested in the lowest part of the band, where many (but not all) public radio stations broadcast, and if only modest gain is required, then a single 3-element Yagi may be perfectly satisfactory--and quite easy to build out of home center materials. Should we wish to cover the entire FM band, we might stack three of these light-weight antennas at about 5' intervals on a single mast. Separate feedlines are required for each antenna. However, one might install a switch near the receiver to select the antenna suited to the part of the band under search.

The designs are not suitable for interlacing on one boom. Indeed, the design of interlaced Yagis is a complicated affair due to the complex interactions of the elements with each other.

The following table presents the dimensions for 3 3-element Yagis that together cover the entire FM band.

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3-Element Yagis: Dimensions

All Elements 0.25" diameter aluminum. Element Length in inches. Element Spacing from Reflector in inches. Spacing to D1 = Boom Length

	Low: 88-95 MHz		Mid: 95-102 MHz		High: 102-108 MHz	
	Space	Length	Space	Length	Space	Length
Ref	----	66.39	----	61.67	----	57.85
Dr	23.12	61.44	21.48	57.07	20.15	53.54
D1	41.74	54.62	38.78	50.74	36.38	47.60

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Note that the longest boom length--for the lowest portion of the band--is just over 41" or well under 4'. As we shall see in the next episode--devoted to home construction techniques--the antenna is well within basement and garage shop capabilities. Since the longest element is under 6', common materials are suitable for the task. The driver is forward of the center of the overall boom length, so mounting will not be a significant problem.

For a Yagi with about a 7% bandwidth, the little 3-element Yagi design provides fairly even performance across its passband. The following table lists typical performance values for the passband (not the overall FM band) for the lowest and highest frequencies covered, as well as the center frequency of the passband. There will be slight variations from one version to the next, so these values are typical rather than absolute.

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3-Element Yagi Performance

Lo = Low end of passband (88 or 95 or 102 MHz)

Mid = Middle of passband (91.5 or 98.5 or 105 MHz)
Hi = High end of passband (95 or 102 or 108 MHz)
Gain = Free-space gain in dBi
Front-Back = 180-degree front-to-back ratio in dB

	Lo	Mid	Hi
Gain	**6.9**	**6.9**	**7.3**
Front-Back	**15**	**20**	**19**

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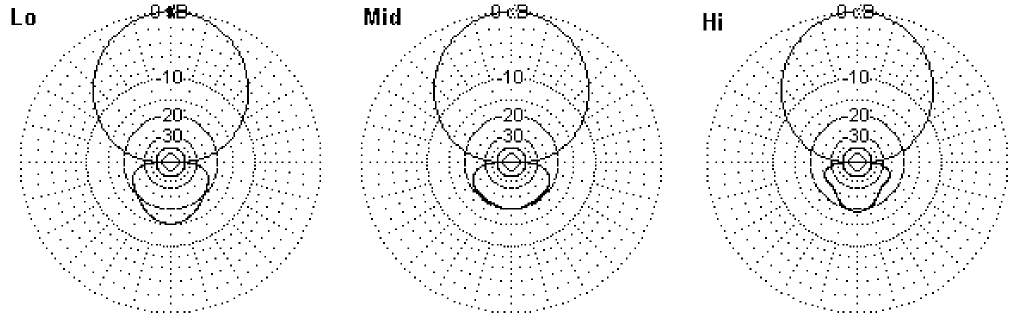
The antenna provides almost 5 dB more gain than a dipole at the same height, along with excellent reduction of signal sensitivity to the rear of the antenna. Another way to view the performance is to examine azimuth patterns for the antenna. **Fig. 4** provides us with typical patterns at the same passband intervals as those in the table.



Azimuth Patterns for Each 3-Element Yagi Fig. 4

For those who need only modest gain, the simplicity of the 3-element Yagi is difficult to beat.

4-Element Yagis

For just a few more inches of boom length, we may increase the gain of our Yagi by over a dB. The gain improvement will cost us one more element, as shown in **Fig. 5**.

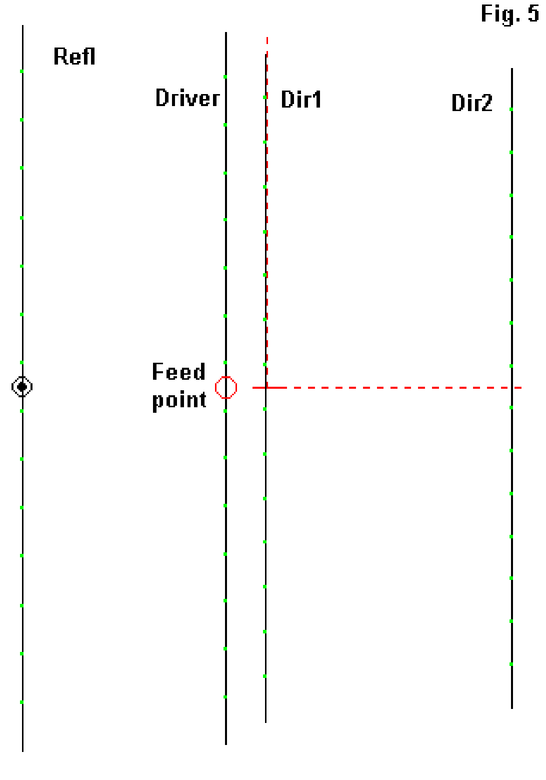


Fig. 5
Outline of 4-Element Yagis

The element placement of the 4-element Yagi is quite different than that for the smaller 3-element array. The driven element is closer to the reflector, and the first director is very close to the driver. In fact, it is so close, that for the upper part of the passband, it tends to carry more current and to dominate performance. You may also note that designing a Yagi is not simply a matter of tacking on another element. Not only does the spacing of elements differ from the smaller array, but as well the element lengths are also different, even though we are using the same diameter material (0.25" diameter aluminum rods or tubes).

Perhaps the one drawback to the 4-element design is the fact that the first director is virtually on the center point of the boom. However, the antenna is so light, when properly made, that setting the mounting point a few inches ahead of the first director should create no major mechanical problems in the wind and weather.

The following table lists the dimensions for this type of Yagi, again using 3 antennas to cover the entire FM band.

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4-Element Yagis: Dimensions

All Elements 0.25" diameter aluminum. Element Length in inches. Element Spacing from Reflector in inches. Spacing to D2 = Boom Length

	Low: 88-95 MHz		Mid: 95-102 MHz		High: 102-108 MHz	
	Space	Length	Space	Length	Space	Length
Ref	----	64.36	----	60.39	----	55.79
Dr	17.93	63.29	16.82	59.38	15.54	54.86
D1	21.45	59.15	20.13	55.51	18.60	51.28
D2	43.21	56.70	40.55	53.21	37.46	49.15

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For each version of the antenna, the boom length is only about 2" longer than required for the 3-element Yagi--and still well under 4'. The version for the high end of the FM band is just over 3' long.

As the following table of typical performance values shows, for each part of the passband of each antenna, we increase the forward gain over the 3-element beam, with an average advantage of 6 dB over a dipole at the same height.

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4-Element Yagi Performance

Lo = Low end of passband (88 or 95 or 102 MHz)
Mid = Middle of passband (91.5 or 98.5 or 105 MHz)
Hi = High end of passband (95 or 102 or 108 MHz)
Gain = Free-space gain in dBi
Front-Back = 180-degree front-to-back ratio in dB

	Lo	Mid	Hi
Gain	7.8	8.1	8.4
Front-Back	14	20	11

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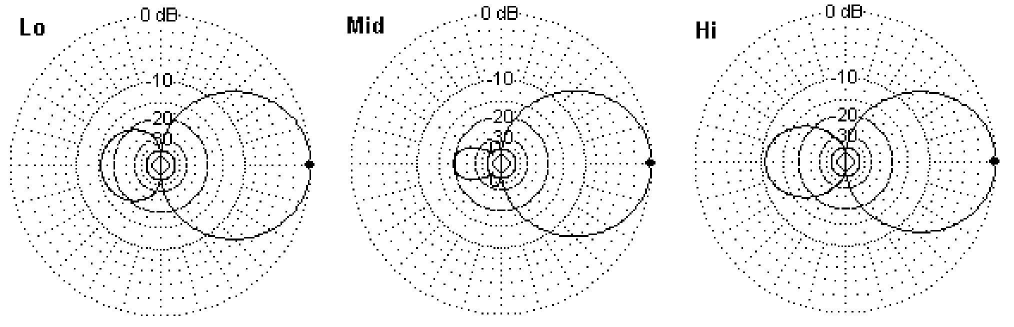
The 4-element Yagi does not have the nearly equal front-to-back ratio across the band that we obtained for the smaller beam. Perhaps the decision as to which of the two designs may be more suitable may, in the end, depend on the need for gain vs the need for reducing the strength of signals from the rear of the antenna. **Fig. 6**, which shows the azimuth patterns for each antenna at low, middle, and high frequencies within its passband, may be useful in visualizing performance and thus making the decision easier.



Azimuth Patterns for Each 4-Element Yagi Fig. 6

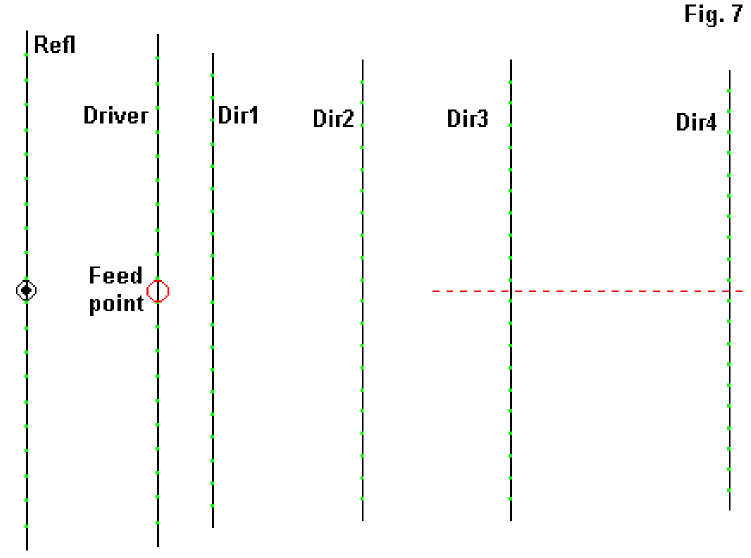
Both the 3- and the 4-element Yagis are simple antennas with good performance for their physical size. Both provide a good match (SWR less than 2:1) across their passbands for a 50-Ohm coaxial cable transmission line.

However, some listeners may require both higher gain and a narrower beam angle to satisfy their needs.

6-Element Yagis

In a longer Yagi, we generally cannot cover the entire FM band in 3 steps. We shall require 4 steps and hence, 4 Yagis to do the job. For our pains in this category, we shall obtain beams with about 10 dBi gain (about 8 dB better than a dipole) and an excellent match to common 50-Ohm coaxial cable--with an SWR of better than 1.3:1. **Fig. 7** shows the outline of our 6-element Yagis.

Fig. 7



Outline of 6-Element Yagis

The designs are optimized wide-band antenna (OWA) Yagis, which have found use on both the HF and VHF amateur bands. The longest version uses a boom that is a little over 7' long, still within manageable size for a fairly light-weight installation. The following table provides the dimensions for each of the four versions needed to cover all of the FM band.

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6-Element Yagis: Dimensions

All Elements 0.25" diameter aluminum. Element Length in inches. Element Spacing from Reflector in inches. Spacing to D4 = Boom Length

	Low: 88-93 MHz		Mid-1: 93-98 MHz	
	Space	**Length**	**Space**	**Length**
Ref	**----**	**65.36**	**----**	**62.03**
Dr	**16.53**	**64.37**	**15.68**	**61.08**
D1	**23.37**	**59.71**	**22.17**	**56.66**
D2	**42.30**	**58.13**	**40.14**	**55.16**
D3	**60.83**	**58.13**	**57.73**	**55.16**
D4	**88.41**	**55.61**	**83.90**	**52.77**

	Mid-2: 98-103 MHz		High: 103-108 MHz	
	Space	**Length**	**Space**	**Length**
Ref	**----**	**59.02**	**----**	**56.29**
Dr	**14.92**	**58.12**	**14.23**	**55.43**
D1	**21.10**	**53.91**	**20.12**	**51.41**
D2	**38.19**	**52.48**	**36.42**	**50.05**
D3	**54.92**	**52.48**	**52.38**	**50.05**
D4	**79.83**	**50.23**	**76.13**	**47.89**

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Like the 3- and 4-element beams, the OWA Yagi designs shown here have a 50-Ohm feedpoint impedance. Actually, the feedpoint resistance and reactance wander a bit, or the SWR would be a perfect 1:1 across the passband. However, no other Yagi design comes closer to the ideal than the OWA Yagi within its 5% operating passband.

The following table provides typical performance figures for each of the 4 antenna designs in the dimensions table.

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6-Element Yagi Performance

Lo = Low end of passband (88 or 93 or 98 or 103 MHz)
Mid = Middle of passband (90.5 or 95.5 or 100.5 or 105.5 MHz)
Hi = High end of passband (93 or 98 or 103 or 108 MHz)
Gain = Free-space gain in dBi
Front-Back = 180-degree front-to-back ratio in dB

	Lo	Mid	Hi
Gain	**9.9**	**10.2**	**10.1**
Front-Back	**15**	**27**	**21**

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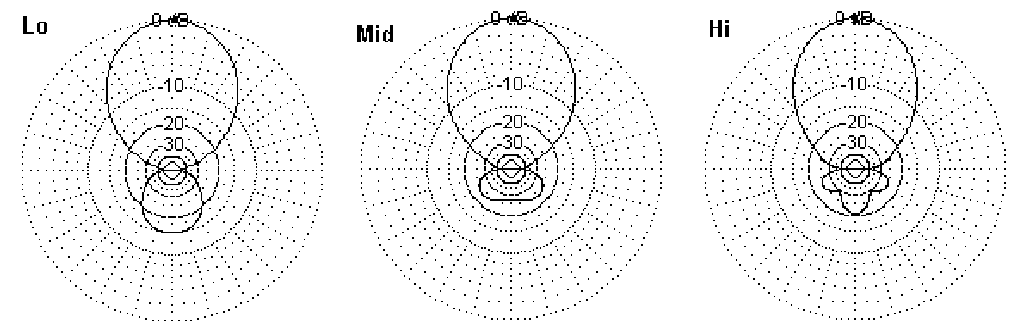
The forward gain varies by only 0.3 dB across the operating passband. The front-to-back ratio shows a minimum of 15 dB, with higher values across most of the passband. As the azimuth patterns in **Fig. 8** demonstrate, the pattern is clean and well behaved everywhere in the passband.

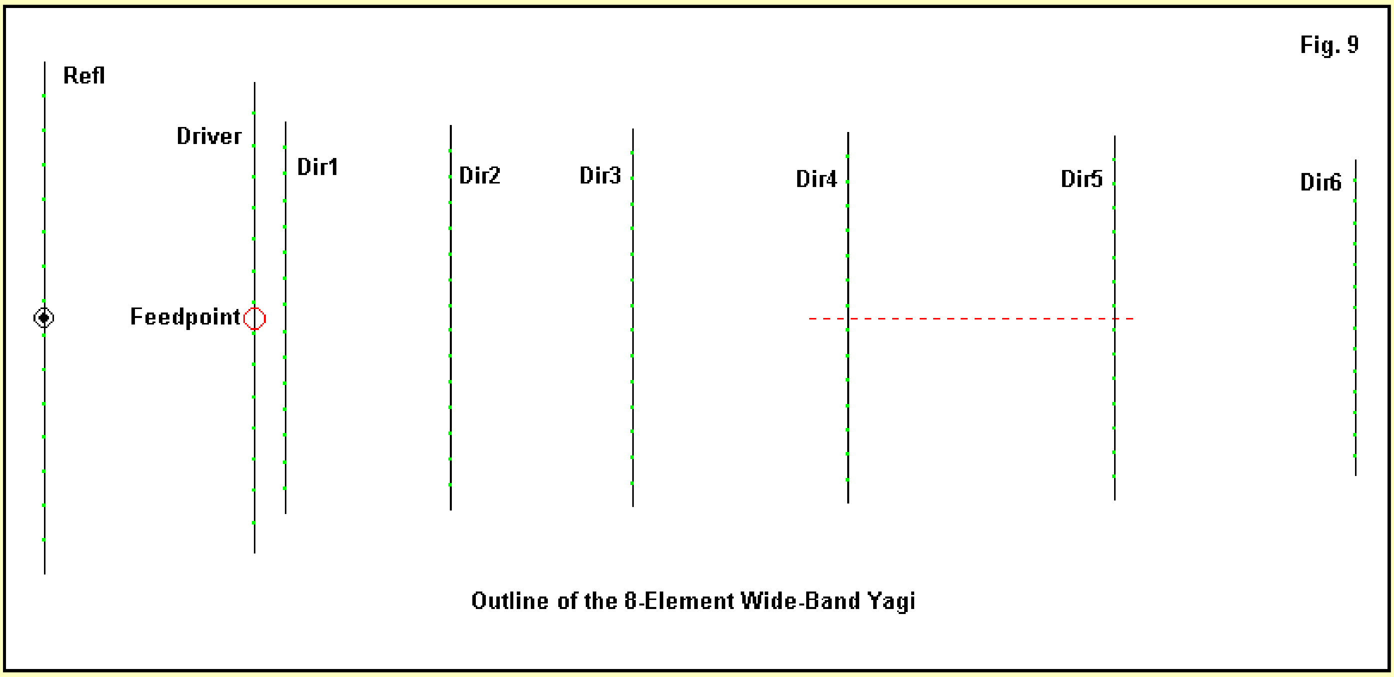


Azimuth Patterns for Each 6-Element Yagi Fig. 8

As we try to increase antenna gain, the boom length tends to increase faster than the gain. We virtually doubled the boom length to add 2 dB of gain relative to the 4 element Yagi. It is possible to design Yagis with higher gain and still have about the same operating passband. However, their length may quickly outstrip our ability to support the antenna. The 6-element OWA Yagi will likely have a self-supporting boom. That is to say, we shall not need additional trussing to keep the boom from sagging and from snapping with the first high wind or ice of the season. However, by the time we reach about 10' of boom length, added truss-work will likely be advisable, unless we are prepared to use weightier boom tubes with thicker walls. Then, we acquire a new problem of supporting a much greater mass. If we wish to go to the trouble of using a truss with a lighter boom or using a heavier boom, then perhaps we should obtain something more than simply another dB of gain.

An 8-Element, Long-Boom, Wide-Band Yagi

For the adventurous antenna builder, I shall add one more Yagi design to this collection. It has 8 elements on a 14' boom. Instead of 0.25" diameter rods, the elements are 0.75" tubing--which seems fitting to the larger boom material required. Regardless of the boom, the element diameter is necessary if we are to obtain the chief benefit of the design: the ability to cover the entire FM band with one Yagi. **Fig. 9** shows the antenna outline.



The center of weight of the array is forward of director 5. The exact position will depend on the ratio of boom weight to element weight. The principle of operation is a modification of the OWA principle in which the first director is very close to the driven element. Indeed, for the upper half of the FM band, the first director controls performance more than the driver. The following table shows the dimensions.

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8-Element Wide-Band Yagi: Dimensions

All Elements 0.75" diameter aluminum. Element Length in inches. Element Spacing from Reflector in inches. Spacing to D6 = Boom Length

	Space	Length
Ref	----	65.37
Dr	26.76	60.14
D1	30.86	50.11
D2	51.82	49.20
D3	75.17	48.52
D4	102.50	47.61
D5	136.67	46.70
D6	167.42	40.55

. . . .

As notable as the close spacing between the driver and the first director is the fact that the forward directors become very short. Director 6 is only about 3/8 of a wavelength long at the mid-band frequency (98 MHz). The combination of the feed system, the element lengths, and the long boom length does net us a Yagi with an operating passband of more than 20% and less than 2:1 50-Ohm SWR across the band.

We cannot expect a Yagi with such a wide operating passband to have as even a set of performance values as its narrow-band cousins. The following table samples performance at the bottom, middle, and top of the entire FM band.

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8-Element Wide-Band Yagi Performance

Gain = Free-space gain in dBi Frequency in MHz
Front-Back = 180-degree front-to-back ratio in dB

Frequency	88	98	108
Gain	9.2	10.3	11.2
Front-Back	14	17	12

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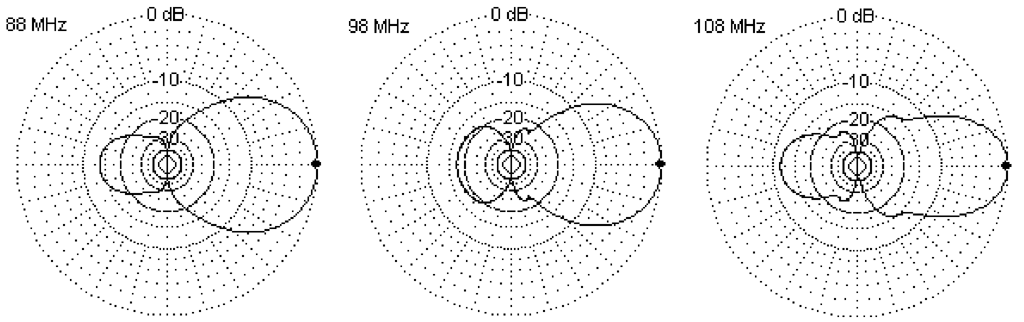
The gain shows a rising value across the band, with the peak value in the 103-105-MHz range. Front-to-back performance is modest compared to some of the narrow-band designs, but still adequate in all but severe cases of strong rearward signals.



Azimuth Patterns of the Wide-Band FM Yagi (88-108 MHz) Fig. 10

As shown in **Fig. 10**, the wide-band design does not have the well-behaved or smooth patterns that we typically associate with narrow-band designs. Nevertheless, the overall design does what it claims: it covers the entire FM band with good gain and adequate front-to-back values, along with a satisfactory match to 50-Ohm coaxial cable. The cost is a long boom and fat elements.

We have at our disposal an array of FM band Yagis. All are technically wide-band designs, but only one is wide enough to cover the entire band. We have not covered all of the possible antennas that we might use on the FM band, but first we must pause for an important question.

How would we go about building one or more of these Yagi designs? That is our next episode in the FM saga.

Go to Main Index