Yagi Element Diameter
Differences Do Make a Difference

L. B. Cebik, W4RNL (SK)

I often hear a complaint: "I built my Yagi to the exact dimensions in the book (or magazine or web page). It works OK, but not nearly as good as the author claims."

About 10 years ago, this complaint often revealed that the author had over-estimated the performance of his antenna. However, in this era of precision Yagi modeling via both NEC and specialized Yagi programs, the complaint usually means something else entirely. Virtually all of the Yagi designs appearing in current radio journals list the modeled performance figures, whether they are drawn from YO, YagiMax, MININEC, or NEC. These numbers are within cumulative rounding errors of each other and, hence, any slight differences should be too small to be perceived in operation.

When the complaints are addressed to me, I usually follow up with a double-barrel question: Exactly what materials did the author specify and what materials did you use? The answers usually show differences in the element diameters and taper schedules for the elements. Hams use what they have on hand, often from antennas that are no longer operational. Broken beams can be inexpensive hamfest purchases and provide a ready source of material for a new beam. Since hams are talented adapters of old materials to new jobs, the freshly constructed beam may have significant material differences from the original published design.

So let's jump to the bottom line and then go back to fill in the space:

1. In Yagi design, changes in element diameters and taper schedules can make a significant difference in performance.

2. When contemplating "copying" a good published design with materials that differ from the original, re-model the design to determine the element lengths required by the copy.

Re-modeling is virtually the only reliable technique open to hams to optimize a beam. Few antenna builders have access to a reliable test range and test equipment that will enable them to optimize forward gain with a front-to-back peak located at a desired frequency. What hams do is generally to prune the driven element until there is a good match to the coax and accept whatever gain and front-to-back ratio emerge--often believing that the design has been optimized. This is a route to long-term disappointment for most builders, with only an occasional shot of pure luck to keep this bad practice alive.

Modeling Yagis has proven to be a much more reliable means of obtaining excellent performance from the finished product, with model-to-product deviations of 1% or less (with the most careful modeling). Whatever Yagi modeling program you prefer, it must accurately handle changes in element diameter and element diameter taper schedules. Many programs can handle these needs with ease.

Now, let's fill in the blanks and give some substance to these recommendations.

Uniform-Diameter Yagi Elements

First, let's set up a base-line of data on designs with uniform-diameter elements. To keep the task within the boundaries of easy comprehension, we shall look at only one Yagi design: a 3-element long-boom design that originated with K6STI. The outline of the Yagi appears in **Fig. 1**.

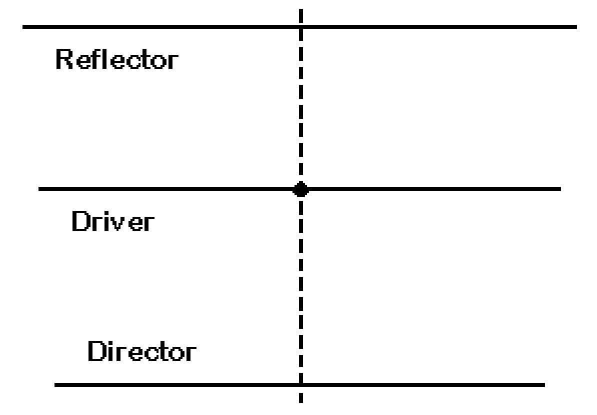

Fig. 1 Outline of Sample 3-Element Yagi

The design will be for 20 meters. All dimensions (lengths, spacings, and diameters) will be given in inches. I originally optimized the design for a frequency of 14.175 MHz, the middle of the 20-meter band, using 1" diameter aluminum elements. Here are the modeled dimensions in all of their excess decimal places.

1" diameter 3-element Yagi

Element	Length	Spacing to Reflector
Reflector	414.72"	-----
Driver	396.00"	125.46"
Director	372.60"	270.53"

I resonated the driven element within +/- 1 Ohm reactance. Using this model, I then decreased the element diameters to 0.5" and then increased them to 1.5". I held the element spacing constant to the 1" model, but changed the element lengths as a batch to arrive at resonance at the design frequency of 14.175 MHz. Here are the element lengths that resulted.

Element	0.5" Lengths	1.5" lengths
Reflector	417.80"	413.12"
Driver	398.94"	394.46"
Director	375.36"	371.16"

My reason for keeping the original spacing between elements was to make the result accord with typical amateur building practice. As we shall see, there are indications from the resulting models that this practice does not yield absolutely optimal designs. But that is jumping ahead of the story by a small bit.

The first difference of note is the gain of the three beams. See **Fig. 2**.

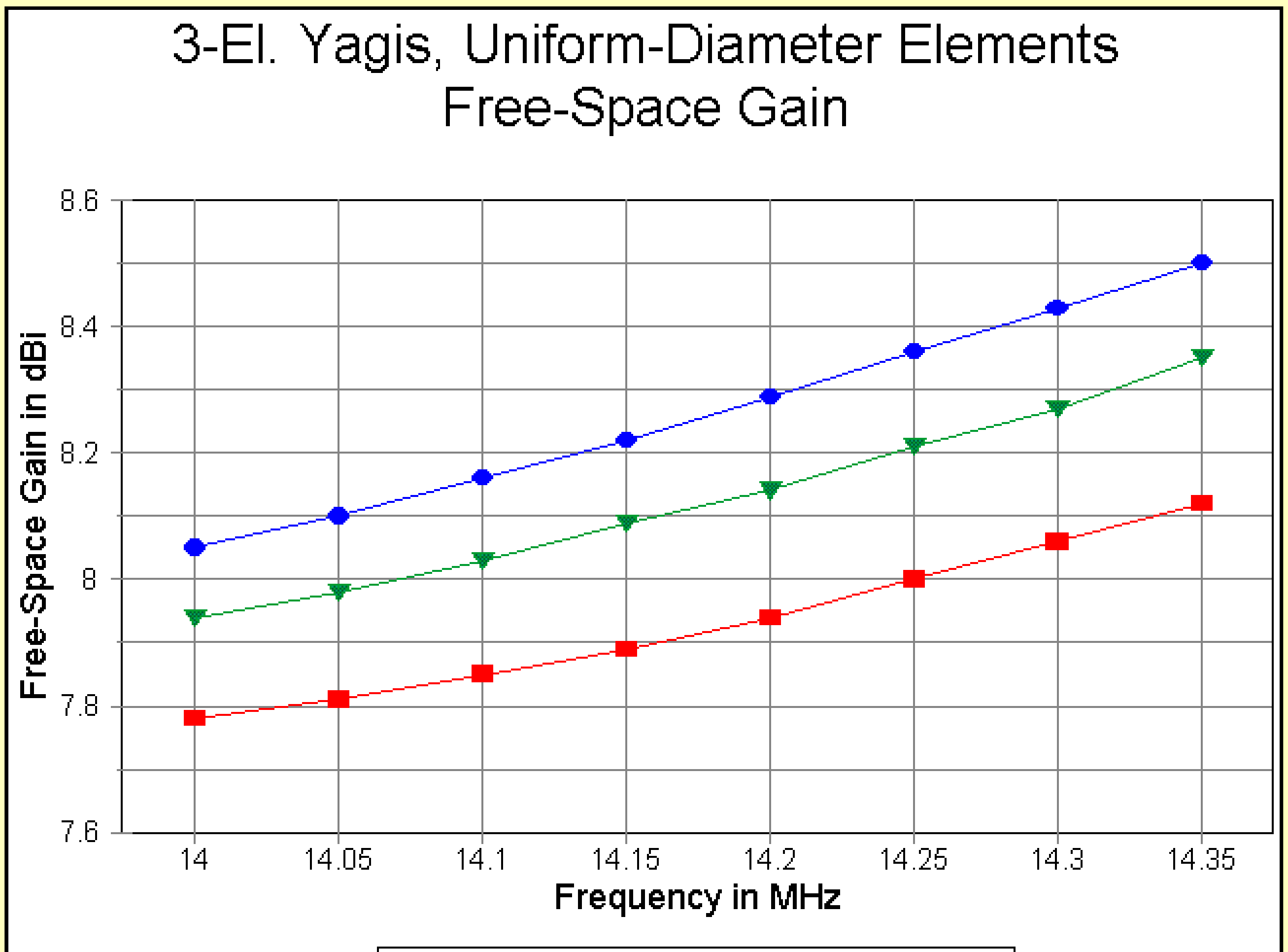

Fig. 2

Between the 0.5" and 1.5" element diameters, there is a difference of about 0.3 dB gain. However, the rate of gain increase slows down as we increase the diameter. In contrast, we see no significant differences in front-to-back ratio with increases in diameter, as evidenced by the curves in **Fig. 3**.

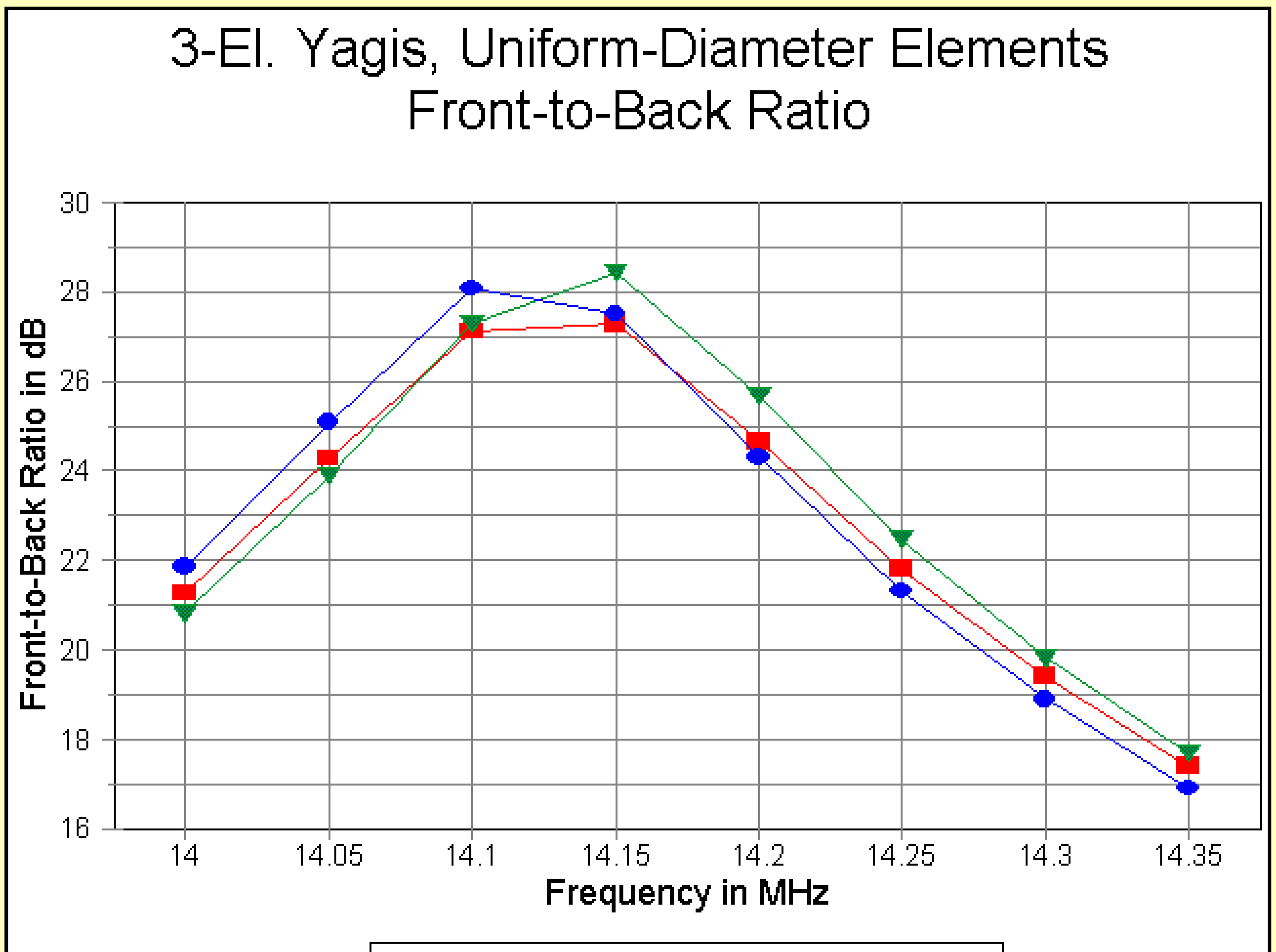

Fig. 3

Peak front-to-back ratio occurs between 14.1 and 14.15 MHz for this design. The seeming oddity of the front-to-back peaks in the graph stems from something a bit more subtle in the array behavior. The peak front-to-back for the 0.5" diameter element model occurs almost exactly at 14.125 MHz. The peak for the 1" diameter model occurs closer to 14.15 MHz, while the corresponding peak for the 1.5" models occurs closer to 14.1 MHz. The slight differences result from the fact that the variant models (relative to the 1" base-line version) were not optimized fully in terms of element spacing as well as element length. Changing element diameter does have an impact--even if only a small one--on all operating parameters, including the frequency at which certain values peak.

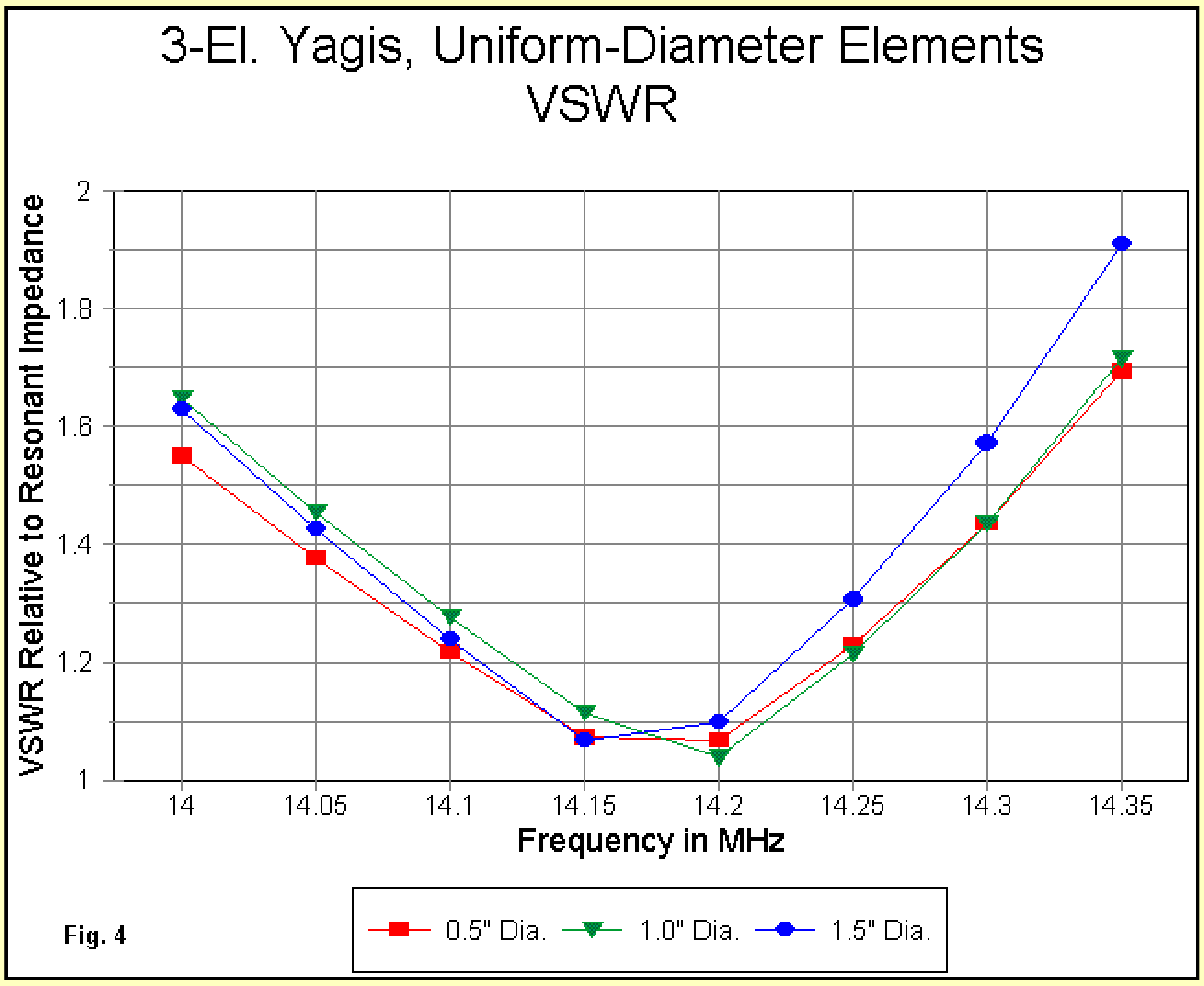

Fig. 4

A similar set of slight variances occurs with respect to the VSWR curves in **Fig. 4**, all of which are referenced to the resonant impedance of each model. Interestingly, the 0.5" diameter model has the broadest curve. However, this curve is partly a function of the fact that the feedpoint impedance at resonance is highest for the smallest diameter elements. In fact, the following table of band-edge and band-center performance figures is also instructive.

Element Diameter **Frequency MHz**	**Free-Space Gain dBi**	**Front-to-Back Ratio dB**	**Feedpoint Z R +/-jX Ohms**	**VSWR (resonance)**
Element Diameter: 0.5"				
14.0	**7.70**	**21.3**	**30.6 - j 13.2**	**1.55**
14.175	**7.91**	**26.1**	**29.6 - j 0.1**	**1.00**
14.35	**8.12**	**17.4**	**26.6 + j 14.6**	**1.69**
Element Diameter: 1.0"				
14.0	**7.94**	**20.8**	**27.0 - j 13.3**	**1.65**
14.175	**8.11**	**27.3**	**25.7 - j 0.9**	**1.03**
14.35	**8.35**	**17.7**	**22.9 + j 13.0**	**1.72**
Element Diameter: 1.5"				
14.0	**8.05**	**21.9**	**24.8 - j 11.7**	**1.63**
14.175	**8.25**	**26.0**	**23.1 + j 0.3**	**1.01**
14.35	**8.50**	**16.9**	**20.3 + j 14.0**	**1.91**

As we increase the element diameter, the differential in gain between the low and high ends of the band increases--from a low of 0.34 dB to a high of 0.45 dB. The decrease in the resistive component of the feedpoint impedance with increases in element diameter is also apparent. Moreover, as the element diameter increases, the differential between the low and high ends of the band also increases--from 3.95 to 4.5 Ohms. In contrast, the spread of reactance from one end of the band to the other decreases with an increase in element diameter--from 27.88 down to 25.65 Ohms.

Although these changes are very small and would not affect general operation of any version of the array, the directions and rates of change are indicative of beam performance as we change element sizes. Noting these changes can aid in analyzing what may be occurring when the time comes to field adjust an array based upon some initial measurements. It always makes good sense to note trends--however small--in the performance of modeled antennas as one does spot or swept frequency checks.

Stepped-Diameter Elements

At 20 meters, common construction practice calls for stepped diameter elements, that is, elements that are composed of descending diameters of tubing as one works from the beam center-line outward. Since the element diameter decreases toward the outer ends, the element always acts shorter than its physical length. Otherwise put, a stepped-diameter (also called a tapered-diameter) element must be physically longer than a corresponding uniform-diameter element serving the same function.

The tapering schedules used for elements in amateur arrays cover a wide territory. The normal 20-meter element may use from 4 to 6 sections, with diameters ranging from 1.25" to 0.375". We shall examine just 4 samples of tapering schedules, as shown in **Fig. 5**.

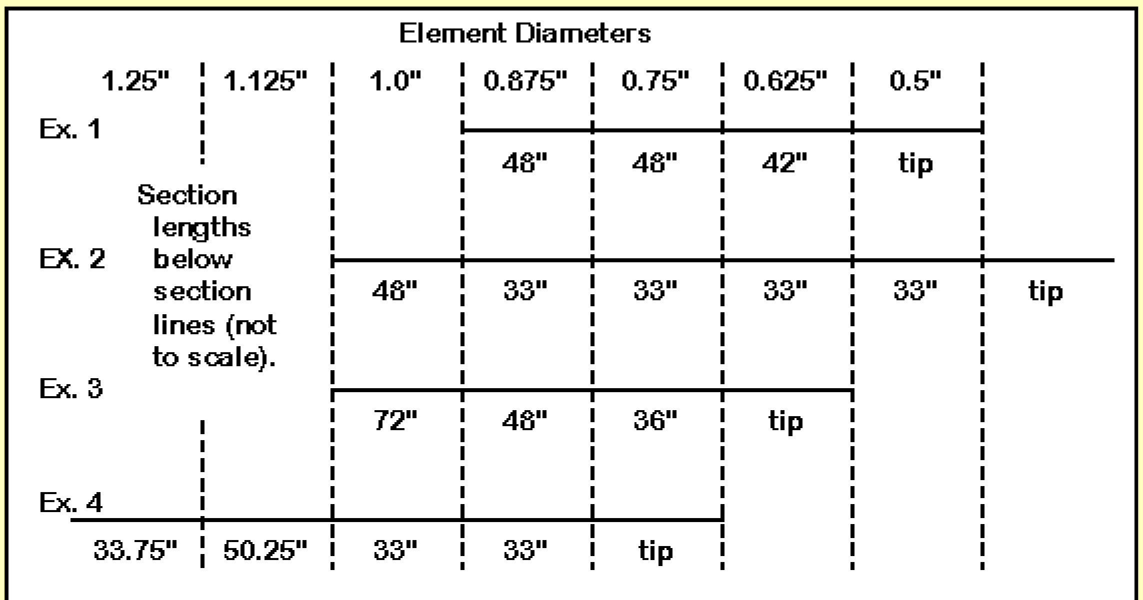

Fig. 5 Outlines of 4 Sample Element Tapering Schedules

The figure shows the 4 examples as functions of regular decreases in diameter. Only half-elements are shown, since normal practice would make the missing side simply the mirror image of what is shown. In many, but not all beams, the inner sections will all have the same section lengths, with only the tip making up the differences among the reflector, driver, and director. However, in a number of commercial and personal designs, the tapering schedule may vary from one element to the next, as dictated by element stress analysis.

Fig. 5 lists the lengths of the individual sections for each of the 4 examples we shall explore. Although this procedure makes a compact chart, it does not give a good sense of the section proportions among the examples. To give some idea of how section proportions may vary from one design to another, **Fig. 6** shows two of the examples sketched with proportional divisions.

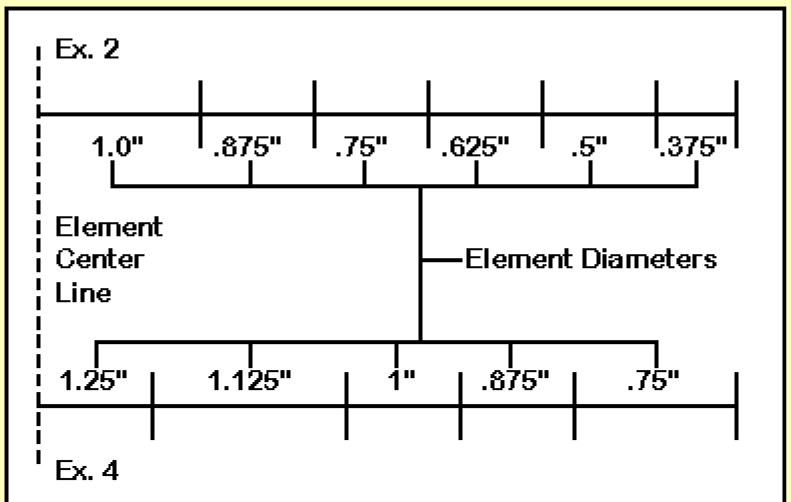

Fig. 6 A Sample of Element Section Proportions

It is readily apparent that the sections within an element may be short or long, close to equal or very unequal, fat or thin. Every variation in the element construction changes the equivalent uniform diameter of the element and the equivalent electrical length.

Yagi modeling programs that effectively handle stepped-diameter elements generally perform calculations on a uniform-diameter element of equivalent electrical length to the stepped-diameter version. Most commonly, the Leeson corrections are used to give very accurate predictions of array performance, based on his work in *The Physical Design of Yagi Antennas*.

This facility to create electrically equivalent uniform-diameter elements makes it relatively straight forward to formulate element dimensions for 3-element Yagis have the same spacing as used in our earlier models, but using each of the taper schedules shown in **Fig. 5**. The procedure is simply a matter of making each element tip long enough so that the corrected uniform-diameter element ends up the same length as in the original design. We shall use as our design standard the 1" diameter model with which we began. However, along the way, we shall note that the uniform-diameter element generated by applying the correction factor will vary from element to element and model to model--and this factor will have a bearing on the array performance projections. Let's proceed through the examples in the order given, which corresponds to a progression from the slimmest to the fattest equivalent uniform diameter elements. We shall also speak in terms of half-element lengths (or half-lengths, for short).

Example 1: The example uses the smallest diameter elements in a regular progression. Let's remember that the half-lengths for the 1" uniform-diameter model were 207.36", 198.00", and 186.30", working from the reflector to the director. To achieve electrical lengths equal to these, the stepped-diameter elements must be considerably longer, as shown in the following table. Refer to **Fig. 5** for the lengths of inner sections of the elements.

Example 1

Element	**Half-Element Length**	**Tip Length**	**Equiv. dia.**
Reflector	**213.00"**	**75.00"**	**0.670"**
Driver	**204.20"**	**66.20"**	**0.680"**
Director	**191.35"**	**53.35"**	**0.694"**

These elements are between 5" and 6" longer than the uniform-diameter elements of the original model. Note also that the equivalent diameter for each element differs as a function of the differing tip lengths and their proportion of the whole element. Hence, the director, with the shortest tip, is effectively the electrically fattest element of the group.

To certify performance, the following table shows the band-edge and band-center performance predicted for this array.

Frequency MHz	**Free-Space Gain dBi**	**Front-to-Back Ratio dB**	**Feedpoint Z R +/-jX Ohms**	**VSWR (resonance)**
14.0	**7.84**	**18.3**	**29.0 - j 13.1**	**1.57**
14.175	**7.98**	**27.9**	**28.5 - j 0.6**	**1.02**
14.35	**8.18**	**19.6**	**26.0 + j 13.4**	**1.64**

With one exception, the performance predictions fall between those for the 0.5" and 1" diameter models earlier explored. The front-to-back curve suggests that further work is possible with respect to bringing the curve more into alignment with the earlier models, although it seems very reasonably symmetrical across the band.

Example 2: The second example uses a very aggressive 6-section element ranging from 1" at the center to 3/8" at the outer end. The relatively short tips will give this element an electrically fatter equivalent diameter than the element we just surveyed. The data is as follows.

Example 2

Element	**Half-Element Length**	**Tip Length**	**Equiv. dia.**
Reflector	**216.25"**	**36.25"**	**0.707"**
Driver	**206.70"**	**26.70"**	**0.726"**
Director	**193.30"**	**13.30"**	**0.753"**

Despite the larger equivalent diameter, relative to the first example, the aggressive element taper requires elements that are 2 to 3 inches longer to achieve the same equivalent length. In short, how the taper is implemented has a strong bearing on the required physical length for a given electrical performance. Had the elements been set to the uniform-diameter lengths, the resulting beam would not have performed anywhere near to expectations. The performance data of the revised model appears in the following table.

Frequency MHz	**Free-Space Gain dBi**	**Front-to-Back Ratio dB**	**Feedpoint Z R +/-jX Ohms**	**VSWR (resonance)**
14.0	**7.87**	**18.9**	**28.3 - j 13.6**	**1.62**
14.175	**8.02**	**28.2**	**27.6 - j 0.9**	**1.04**
14.35	**8.23**	**18.9**	**25.0 + j 13.1**	**1.65**

As expected, the larger equivalent diameter of the elements (relative to Example 1) provides slight numeric (but insignificant operational) increases in gain and slightly lower values for the feedpoint resistance.

Example 3: The third example begins at the element center with the same diameter tubing as in the preceding example. However, by using longer lengths of each tubing size, the element needs only 4 sections, with a minimum diameter of 5/8". For this example, we should expect shorter required element lengths and a fatter equivalent diameter.

Example 3

Element	**Half-Element Length**	**Tip Length**	**Equiv. dia.**
Reflector	**212.25"**	**56.25"**	**0.851"**
Driver	**202.80"**	**46.80"**	**0.862"**
Director	**190.36"**	**34.36"**	**0.878"**

With equivalent element diameters in the vicinity of 7/8", the calculated performance of this array should approach that of the full 1" array.

Frequency MHz	**Free-Space Gain dBi**	**Front-to-Back Ratio dB**	**Feedpoint Z R +/-jX Ohms**	**VSWR (resonance)**
14.0	**7.91**	**20.3**	**27.7 - j 13.2**	**1.62**
14.175	**8.08**	**27.7**	**26.5 - j 0.7**	**1.03**
14.35	**8.30**	**18.0**	**23.8 + j 13.3**	**1.71**

The performance table does not disappoint us, as this element arrangement replicates closely in almost every detail the corresponding table for our initial design. (Note that this correspondence is only of electrical interest and does not represent a recommendation for the tapering schedule in the example.)

Example 4: The last example presents a very beefy element indeed. It centers at 1.25" in diameter and uses 5 sections, with a long 3/4" diameter tip. Although the equivalent uniform diameter is larger than that of the preceding example, this fact alone does not dictate element length overall. In fact, the required element lengths of this last example are actually a tiny bit larger than those of Example 3.

Example 4

Element	**Half-Element Length**	**Tip Length**	**Equiv. dia.**
Reflector	**212.50"**	**62.50"**	**0.988"**
Driver	**203.00"**	**53.00"**	**1.000"**
Director	**190.85"**	**40.85"**	**1.020"**

The reason for the "longer" elements lies in the tapering schedule. The corrected elements calculate for each section diameter and length. The 5-section taper shows a larger gradient of decrease than for Example 3, and hence requires longer elements than had the element simply followed the schedule of Example 3 with larger diameter elements.

Frequency MHz	**Free-Space Gain dBi**	**Front-to-Back Ratio dB**	**Feedpoint Z R +/-jX Ohms**	**VSWR (resonance)**
14.0	**7.97**	**21.7**	**26.7 - j 11.9**	**1.59**
14.175	**8.15**	**26.3**	**25.2 + j 0.6**	**1.02**
14.35	**8.35**	**17.0**	**22.3 + j 14.8**	**1.87**

As expected, the fatter equivalent elements yield the highest gain of all our examples, along with the lowest feedpoint resistance values.

We should remember that none of these examples has been further optimized with respect to spacing and additional tweaking of element lengths to achieve the absolute best performance curves. Instead, they were simply equalized to the length dimensions of the original design sample.

Moreover, whatever the performance differences among the models, none of the element tapering schedules is endorsed or recommended. That task would require a more detailed stress analysis using software like YagiStress by Kurt Andress. Moreover, the final selection of an element taper may involve trade-offs with respect to size and weight, not to mention the use of available materials.

Rather, the exercises have been designed to demonstrate the importance--indeed, the necessity--of re-modeling a Yagi design whenever we propose to alter the element tapering schedule of the initial design. We encountered a number of phenomenon related to the electrical equivalents of stepped-diameter elements, and the end results were not always intuitively obvious.

The electrical performance of a stepped-diameter element depends not only on the sizes of tubing used along the way, but as well on the aggressiveness of the taper and lengths of each section within the whole element. The only safe way to ensure that a substitute element is correctly sized for the task at hand is to model it. An hour's work with one of the Yagi modeling packages can save a lot of hard and uncertain work up on the tower and a lot of disappointment down the road.

Go to Main Index