# Chapter 11

# HF Yagi Arrays

Along with the dipole and the quarter-wave vertical, radio amateurs throughout the world make extensive use of the Yagi array. Hidetsugu Yagi and Shintaro Uda, two Japanese university professors, invented the Yagi in the 1920s. Uda did much of the developmental work, while Yagi introduced the array to the world outside Japan through his writings in English. Although the antenna should properly be called a *Yagi-Uda* array, it is commonly referred to simply as a *Yagi*.

The Yagi is a type of endfire multielement array. At the minimum, it consists of a single driven element and a single parasitic element. These elements are placed parallel to each other, on a supporting boom spacing them apart. This arrangement is known as a 2-element Yagi. The parasitic element is termed a *reflector* when it is placed behind the driven element, opposite to the direction of maximum radiation, and is called a *director* when it is placed ahead of the driven element. See **Fig 1**. In the VHF and UHF spectrum, Yagis employing 30 or more elements are not uncommon, with a single reflector and multiple directors. See Chapter 18, VHF and UHF Antenna Systems, for details on VHF and UHF Yagis. Large HF arrays may employ 10 or more elements, and will be covered in this chapter.

The gain and directional pattern of a Yagi array is determined by the relative amplitudes and phases of the currents induced into all the parasitic elements. Unlike the directly driven multielement arrays considered in Chapter 8, Multielement Arrays, where the designer must compensate for mutual coupling between elements, proper Yagi operation *relies on* mutual coupling. The current in each parasitic element is determined by its spacing from both the driven element and other parasitic elements, and by the tuning of the element itself. Both length and diameter affect element tuning.

For about 50 years amateurs and professionals created Yagi array designs largely by "cut and try" experimental techniques. In the early 1980s, Jim Lawson, W2PV, described in detail for the amateur audience the fundamental mathematics involved in modeling Yagis. His book *Yagi Antenna Design* is highly recommended for serious antenna designers. The advent of powerful microcomputers and sophisticated computer antenna modeling software in the mid 1980s revolutionized the field of Yagi design for the radio amateur. In a matter of minutes, a computer can

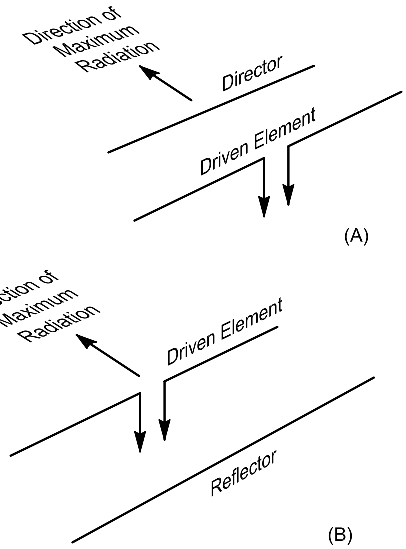


**Fig 1—Two-element Yagi systems using a single parasitic element. At A the parasitic element acts as a director, and at B as a reflector. The arrows show the direction in which maximum radiation takes place.**

try 100,000 or more different combinations of element lengths and spacings to create a Yagi design tailored to meet a particular set of high-performance parameters. To explore this number of combinations experimentally, a human experimenter would take an unimaginable amount of time and dedication, and the process would no doubt suffer from considerable measurement errors. With the computer tools available today, an antenna can be designed, constructed and then put up in the air, with little or no tuning or pruning required.

# Yagi Performance Parameters

There are three main parameters used to characterize the performance of a particular Yagi—*forward gain*, *pattern* and *drive impedance/SWR*. Another important consideration is *mechanical strength*. It is very important to recognize that each of the three electrical parameters should be characterized over the frequency band of interest in order to be meaningful. Neither the gain, SWR nor the pattern measured at a single frequency gives very much insight into the overall performance of a particular Yagi.

Poor designs have been known to reverse their directionality over a frequency band, while other designs have excessively narrow SWR bandwidths, or overly "peaky" gain response. Finally, an antenna's ability to survive the wind and ice conditions expected in one's geographical location is an important consideration in any design. Much of this chapter will be devoted to describing detailed Yagi designs that are optimized for a good balance between gain, pattern and SWR over various amateur bands, and that are designed to survive strong winds and icing.

## YAGI GAIN

Like any other antenna, the gain of a Yagi must be stated in comparison to some standard of reference. Designers of phased vertical arrays often state gain referenced to a single, isolated vertical element. See the section on "Phased Array Techniques" in Chapter 8, Multielement Arrays.

Many antenna designers prefer to compare gain to that of an *isotropic radiator in free space*. This is a theoretical antenna that radiates equally well in all directions, and by definition, it has a gain of 0 *dBi* (dB isotropic). Many radio amateurs, however, are comfortable using a dipole as a standard reference antenna, mainly because it is *not* a theoretical antenna.

In free space, a dipole does not radiate equally well in all directions—it has a figure-eight azimuth pattern, with deep nulls off the ends of the wire. In its favored directions, a free-space dipole has 2.15 dB gain compared to the isotropic radiator. You may see the term *dBd* in amateur literature, meaning gain referenced to a dipole in free space. Subtract 2.15 dB from gain in dBi to convert to gain in dBd.

Assume for a moment that we take a dipole out of "free space," and place it one wavelength over the ocean, whose saltwater makes an almost perfect ground. At an elevation angle of 15°, where sea water-reflected radiation adds in phase with direct radiation, the dipole has a gain of about 6 dB, compared to its gain when it was in free space, isolated from any reflections. See Chapter 3, The Effects of the Earth.

It is perfectly legitimate to say that this dipole has a gain of 6 dBd, although the term "dBd" (meaning "dB dipole") makes it sound as though the dipole somehow has gain over itself! Always remember that gain expressed in dBd (or dBi) refers to the *counterpart antenna in free space*. The gain of the dipole over saltwater in this example can be rated at either 6 dBd (over a dipole in free space), or as 8.15 dBi (over an isotropic radiator in free space). Each frame of reference is valid, as long as it is used consistently and clearly. In this chapter we will often switch between Yagis in free space and Yagis over ground. To prevent any confusion, gains will be stated in dBi.

Yagi free-space gain ranges from about 5 dBi for a small 2-element design to about 20 dBi for a 31-element long-boom UHF design. The length of the boom is the main factor determining the gain a Yagi can deliver. Gain as a function of boom length will be discussed in detail after the sections below defining antenna response patterns and SWR characteristics.

## RESPONSE PATTERNS—FRONT-TO-REAR RATIO

As discussed in Chapter 2, Antenna Fundamentals, for an antenna to have gain, it must concentrate energy radiated in a particular direction, at the expense of energy radiated in other directions. Gain is thus closely related to an antenna's directivity pattern, and also to the losses in the antenna. **Fig 2** shows the *E-plane* (also called *E-field,* for electric field) and *H-plane* (also called *H-field*, for magnetic field) pattern of a 3-element Yagi in free space, compared to a dipole, and an isotropic radiator. These patterns were generated using the computer program *NEC-2*, which is highly regarded by antenna professionals for its accuracy and flexibility.

In free space there is no Earth reference to determine whether the antenna polarization is horizontal or vertical, and so its response patterns are labeled as E-field (electric) or H-field (magnetic). For a Yagi mounted over ground rather than in free space, if the

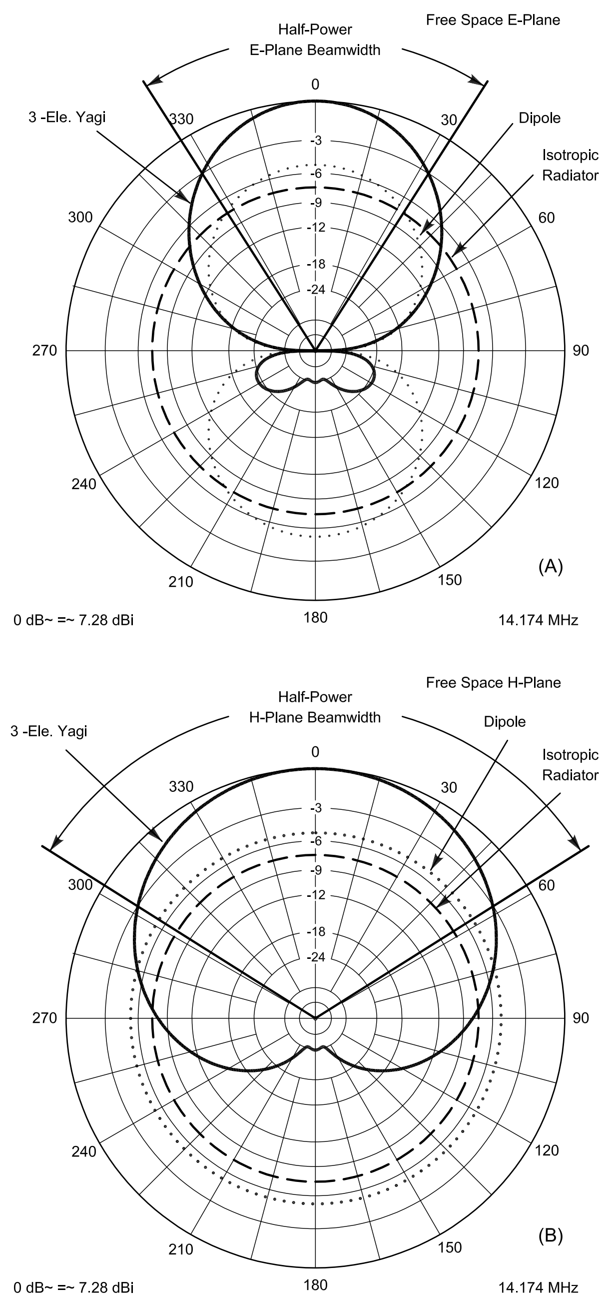


**Fig 2—E-Plane (electric field) and H-Plane (magnetic field) response patterns for 3-element 20-meter Yagi in free space. At A the E-Plane pattern for a typical 3-element Yagi is compared with a dipole and an isotropic radiator. At B the H-Plane patterns are compared for the same antennas. The Yagi has an E-Plane half-power beamwidth of 66°, and an H-Plane half-power beamwidth of about 120°. The Yagi has 7.28 dBi (5.13 dBd) of gain. The front-to-back ratio, which compares the response at 0° and at 180°, is about 35 dB for this Yagi. The front-to-rear ratio, which compares the response at 0° to the largest lobe in the rearward 180° arc behind the antenna, is 24 dB, due to the lobes at 120° and 240°.**

E-field is parallel to the earth (that is, the elements are parallel to the earth) then the antenna polarization is horizontal, and its E-field response is then usually referred to as its *azimuth* pattern. Its H-field response is then referred to as its *elevation* pattern.

Fig 2A demonstrates how this 3-element Yagi in free space exhibits 7.28 dBi of gain (referenced to isotropic), and has 5.13 dB gain over a free-space dipole. The gain is in the forward direction on the graph at 0° azimuth, and the forward part of the lobe is called the *main lobe*. For this particular antenna, the angular width of the E-plane main lobe at the half power, or 3 dB points compared to the peak, is about 66°. This performance characteristic is called the antenna's azimuthal *half-power beamwidth*.

Again as seen in Fig 2A, this antenna's response in the reverse direction at 180° azimuth is 34 dB less than in the forward direction. This characteristic is called the antenna's *front-to-back ratio*, and it describes the ability of an antenna to discriminate, for example, against interfering signals coming directly from the rear, when the antenna is being used for reception. In Fig 2A there are two sidelobes, at 120° and at 240° azimuth, which are about 24 dB down from the peak response at 0°. Since interference can come from any direction, not only directly off the back of an antenna, these kinds of sidelobes limit the ability to discriminate against rearward signals. The term *worst-case front-to-rear ratio* is used to describe the worst-case rearward lobe in the 180°-wide sector behind the antenna's main lobe. In this case, the worst-case front-to-rear ratio is 24 dB.

In the rest of this chapter the worst-case front-to-rear ratio will be used as a performance parameter, and will be abbreviated as "F/R." For a dipole or an isotropic radiator, Fig 2A demonstrates that F/R is 0 dB. Fig 2B depicts the H-field response for the same 3-element Yagi in free space, again compared to a dipole and an isotropic radiator in free space. Unlike the E-field pattern, the H-field pattern for a Yagi does not have a null at 90°, directly over the top of the Yagi. For this 3-element design, the H-field half-power beamwidth is approximately 120°.

**Fig 3** compares the azimuth and elevation patterns for a horizontally polarized 6-element 14-MHz Yagi, with a 60-foot boom mounted one wavelength over ground, to a dipole at the same height. As with any horizontally polarized antenna, the height above ground is the main factor determining the peaks and nulls in the elevation pattern of each antenna. Fig 3A shows the E-field pattern, which has now been labeled as the Azimuth pattern. This antenna has a half-power azimuthal beamwidth of about 50°, and at an elevation angle of 12° it exhibits a forward gain of 16.02 dBi, including about 5 dB of ground reflection gain over relatively poor ground, with a dielectric constant of 13 and conductivity of 5 mS/m. In free space this Yagi has a gain of 10.97 dBi.

The H-field elevation response of the 6-element Yagi has a half-power beamwidth of about 60° in free space,

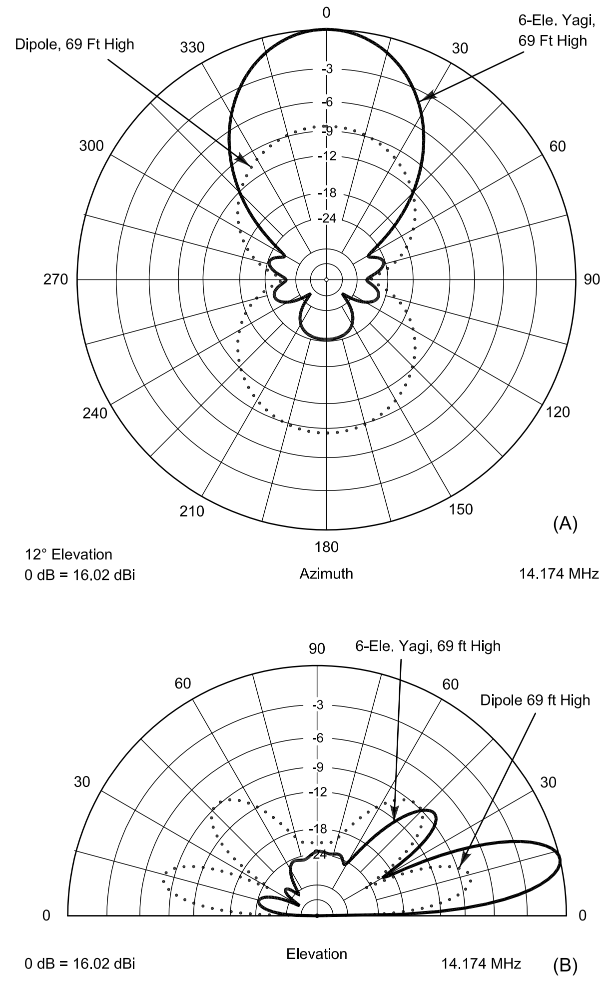


**Fig 3—Azimuth pattern for 6-element 20-meter Yagi on 60-foot long boom, mounted 60 feet over ground. At A, the azimuth pattern at 12° elevation angle is shown, compared to a dipole at the same height. Peak gain of the Yagi is 16.04 dBi, or just over 8 dB compared to the dipole. At B, the elevation pattern for the same two antennas is shown. Note that the peak elevation pattern of the Yagi is compressed slightly lower compared to the dipole, even though they are both at the same height over ground. This is most noticeable for the Yagi's second lobe, which peaks at about 40°, while the dipole's second lobe peaks at about 48°. This is due to the greater free-space directionality of the Yagi at higher angles.**

but as shown in Fig 3B, the first lobe (centered at 12° in elevation) has a half-power beamwidth of only 13° when the antenna is mounted one wavelength over ground. The dipole at the same height has a very slightly larger first-lobe half-power elevation beamwidth of 14°, since its free-space H-field response is omnidirectional.

Note that the free-space H-field directivity of the Yagi suppresses its second lobe over ground (at an elevation angle of about 40°) to 8 dBi, while the dipole's response at its second lobe peak (at about 48°) is at a level of 9 dBi.

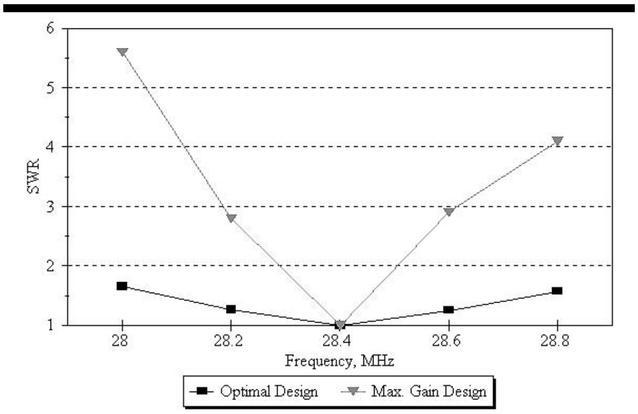


**Fig 4—SWR over the 28.0 to 28.8 MHz portion of the 10-meter band for two different 3-element Yagi designs. One is designed strictly for maximum gain, while the second is optimized for F/R pattern and SWR over the frequency band. A Yagi designed only for maximum gain usually suffers from a very narrow SWR bandwidth.**

The shape of the azimuthal pattern for a Yagi operated over real ground will change slightly as the Yagi is placed closer and closer to earth. Generally, however, the azimuth pattern doesn't depart significantly from the free-space pattern until the antenna is less than 0.5 λ high. This is just over 17 feet high at 28.4 MHz, and just under 35 feet at 14.2 MHz, heights that are not difficult to achieve for most amateurs. Some advanced computer programs can optimize Yagis at the exact installation height.

## DRIVE IMPEDANCE AND SWR

The impedance at the driven element in a Yagi is affected not only by the tuning of the driven element itself, but also by the spacing and tuning of nearby parasitic elements, and to a lesser extent by the presence of ground. In some designs that have been tuned solely for maximum gain, the driven-element impedance can fall to very low levels, sometimes less than 5 Ω. This can lead to excessive losses due to conductor resistance, especially at VHF and UHF. In a Yagi that has been optimized solely for gain, conductor losses are usually compounded by large excursions in impedance levels with relatively small changes in frequency. The SWR can thus change dramatically over a band and can create additional losses in the feed cable. **Fig 4** illustrates the SWR over the 28 to 28.8 MHz portion of the 10-meter amateur band for a 5-element Yagi on a 24-foot boom, which has been tuned for maximum forward gain at a spot frequency of 28.4 MHz. Its SWR curve is contrasted to that of a Yagi designed for a good compromise of gain, SWR and F/R.

Even professional antenna designers have difficulty accurately measuring forward gain. On the other hand, SWR can easily be measured by professional and amateur alike. Few manufacturers would probably want to advertise an antenna with the narrow-band SWR curve shown in Fig 4!

# Monoband Yagi Performance Optimization

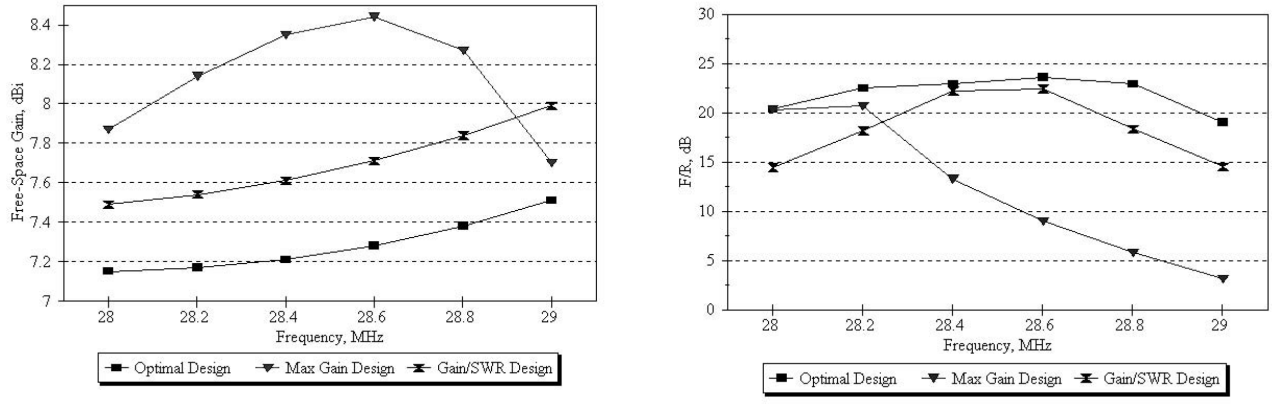
## DESIGN GOALS

The previous section discussing driven-element impedance and SWR hinted at possible design trade-offs among gain, pattern and SWR, especially when each parameter is considered over a frequency band rather than at a spot frequency. Trade-offs in Yagi design parameters can be a matter of personal taste and operating style. For example, one operator might exclusively operate the CW portions of the HF bands, while another might only be interested in the Phone portions. Another operator may want a good pattern in order to discriminate against signals coming from a particular direction; someone else may want the most forward gain possible, and may not care about responses in other directions.

Extensive computer modeling of Yagis indicates that the parameter that must be compromised most to achieve wide bandwidths for front-to-rear ratio and SWR is forward gain. However, not much gain must be sacrificed for good F/R and SWR coverage, especially on long-boom Yagis. Although 10 and 7-MHz Yagis are not rare, the HF bands from 14 to 30 MHz are where Yagis are most often found, mainly due to the mechanical difficulties involved with making sturdy antennas for lower frequencies. The highest HF band, 28.0 to 29.7 MHz, represents the largest percentage bandwidth of the upper HF bands, at almost 6%. It is difficult to try to optimize in one design the main performance parameters of gain, worst-case F/R ratio and SWR over this large a band. Many commercial designs thus split up their 10-meter designs into antennas covering one of two bands: 28.0 to 28.8 MHz, and 28.8 to 29.7 MHz. For the amateur bands below 10 meters, optimal designs that cover the entire band are more easily achieved.

## DESIGN VARIABLES

There are only a few variables available when one is designing a Yagi to meet certain design goals. The variables are:



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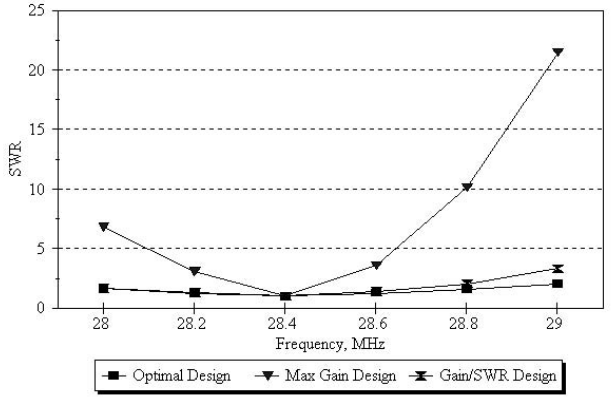

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**Fig 5—Comparisons of three different 3-element 10-meter Yagi designs using 8-foot booms. At A, gain comparisons are shown. The Yagi designed for the best compromise of gain and SWR sacrifices an average of about 0.5 dB compared to the antenna designed for maximum gain. The Yagi designed for optimal F/R, gain and SWR sacrifices an average of 1.0 dB compared to the maximum-gain case, and about 0.4 dB compared to the compromise gain and SWR case. At B, the front-to-rear ratio is shown for the three different designs. The antenna designed for optimal combination of gain, F/R and SWR maintains a F/R higher than 20 dB across the entire frequency range, while the antenna designed strictly for gain has a F/R of 3 dB at the high end of the band. At C, the three antenna designs are compared for SWR bandwidth. At the high end of the band, the antenna designed strictly for gain has a very high SWR.**

1. The physical length of the boom
2. The number of elements on the boom
3. The spacing of each element along the boom
4. The tuning of each element
5. The type of matching network used to feed the array.

## GAIN AND BOOM LENGTH

As pointed out earlier, the gain of a Yagi is largely a function of the length of the boom. As the boom is made longer, the maximum gain potential rises. For a given boom length, the number of elements populating that boom can be varied, while still maintaining the antenna's gain, provided of course that the elements are tuned properly. In general, putting more elements on a boom gives the designer added flexibility to achieve desired design goals, especially to spread the response out over a frequency band.

**Fig 5A** is an example illustrating gain versus frequency for three different types of 3-element Yagis on 8-foot booms. The three antennas were designed for the lower end of the 10-meter band, 28.0 to 28.8 MHz, based on the following different design goals:

Antenna 1: Maximum mid-band gain, regardless of F/R or SWR across the band
Antenna 2: SWR less than 2:1 over the frequency band; best compromise gain, with no special consideration for F/R over the band.
Antenna 3: "Optimal" case: F/R greater than 20 dB, SWR less than 2:1 over the frequency band; best compromise gain.

Fig 5B shows the F/R over the frequency band for these three designs, and Fig 5C shows the SWR curves over the frequency band. Antenna 1, the design that strives strictly for maximum gain, has a poor SWR response over the band, as might be expected after the previous section discussing SWR. The SWR is 10:1 at 28.8 MHz and rises to 22:1 at 29 MHz. At 28 MHz, at the low end of the band, the SWR of the maximum-gain design is more than 6:1. Clearly, designing for maximum gain alone produces an unacceptable design in terms of SWR bandwidth. The F/R for Antenna 1 reaches a high point of about 20 dB at the low-frequency end of the band, but falls to only 3 dB at the high-frequency end.

Antenna 2, designed for the best compromise of gain while the SWR across the band is held to less than 2:1, achieves this goal, but at an average gain sacrifice of 0.7 dB compared to the maximum gain case. The F/R for this design is just under 15 dB over the band. This design is fairly typical of many amateur Yagi designs before the advent of computer modeling and optimization programs. SWR can easily be measured, and experimental optimization for forward gain is a fairly straightforward procedure. By contrast, overall pattern optimization is not a trivial thing to achieve experimentally, particularly for antennas with more than four or five elements.

Antenna 3, designed for an optimum combination of F/R, SWR and gain, compromises forward gain an average of 1.0 dB compared to the maximum gain case, and about 0.4 dB compared to the compromise gain/SWR case. It achieves its design objectives of more than 20 dB F/R over the 28.0 to 28.8 MHz portion of the band, with an SWR less than 2:1 over that range.

**Fig 6A** shows the free-space gain versus frequency for the same three types of designs, but for a bigger 5-element 10-meter Yagi on a 20-foot boom. Fig 6B shows the variation in F/R, and Fig 6C shows the SWR curves versus frequency. Once again, the design that concentrates solely on maximum gain has a poor SWR curve over the band, reaching just over 6:1 toward the high end of the band. The difference in gain between the maximum gain case and the optimum design case has narrowed for this size of boom to an average of under 0.5 dB. This comes about because the designer has access to more variables in a 5-element design than he does in a 3-element design, and he can stagger-tune the various elements to spread the response out over the whole band.

**Fig 7A**, **B** and **C** show the same three types of designs, but for a 6-element Yagi on a 36-foot boom. The SWR bandwidth of the antenna designed for maximum gain has improved compared to the previous two shorter-boom examples, but the SWR still rises to more than 4:1 at 28.8 MHz, while the F/R ratio is pretty constant over the band, at a mediocre 11 dB average level. While the antenna designed for gain and SWR does hold the SWR below 2:1 over the band, it also has the same mediocre level of F/R performance as does the maximum-gain design.

The optimized 36-foot boom antenna achieves an excellent F/R of more than 22 dB over the whole 28.0 to 28.8 MHz band. Again, the availability of more elements and more space on the 36-foot long boom gives the designer more flexibility in broadbanding the response over the whole band, while sacrificing only 0.3 dB of gain compared to the maximum-gain design.

**Fig 8A**, **B**, and **C** show the same three types of 10-meter designs, but now for a 60-foot boom, populated with eight elements. With eight elements and a very long boom on which to space them out, the antenna designed solely for maximum gain can achieve a much better SWR response across the band, although the SWR does rise to more than 7:1 at the very high end of the band. The SWR remains less than 2:1 from 28.0 to 28.7 MHz, much better than for shorter-boom, maximum-gain designs. The worst-case F/R ratio is never better than 19 dB, however, and remains around 10 dB over much of the band. The antenna designed for the best compromise gain and SWR loses only about 0.1 dB of gain compared to the maximum-gain design, but does little better in terms of F/R across the band.

Contrasted to these two designs, the antenna optimized for F/R, SWR and gain has an outstanding pattern, exhibiting an F/R of more than 24 dB across the entire

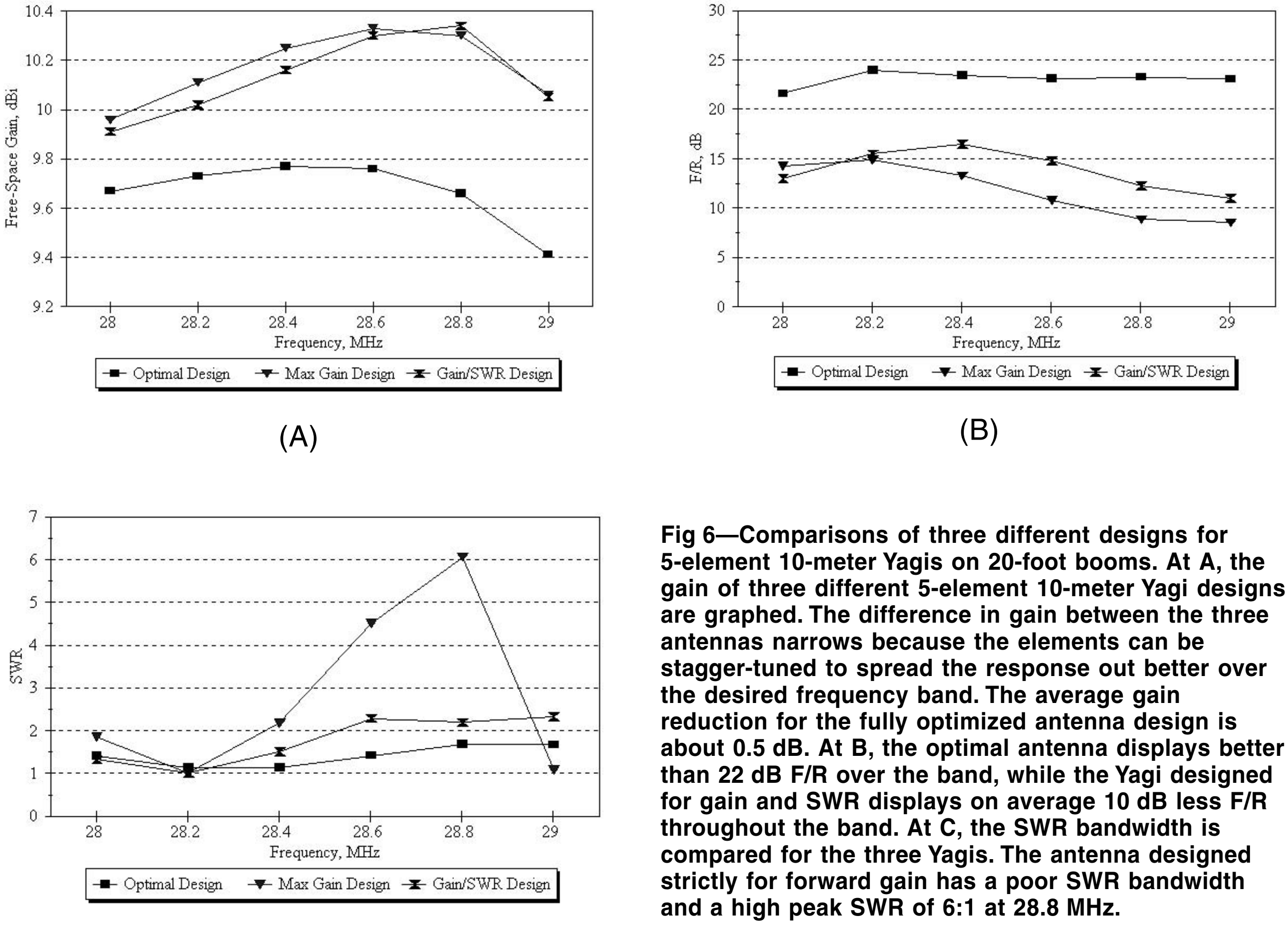

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**Fig 6—Comparisons of three different designs for 5-element 10-meter Yagis on 20-foot booms. At A, the gain of three different 5-element 10-meter Yagi designs are graphed. The difference in gain between the three antennas narrows because the elements can be stagger-tuned to spread the response out better over the desired frequency band. The average gain reduction for the fully optimized antenna design is about 0.5 dB. At B, the optimal antenna displays better than 22 dB F/R over the band, while the Yagi designed for gain and SWR displays on average 10 dB less F/R throughout the band. At C, the SWR bandwidth is compared for the three Yagis. The antenna designed strictly for forward gain has a poor SWR bandwidth and a high peak SWR of 6:1 at 28.8 MHz.**

band, while keeping the SWR below 2:1 from 28.0 to 28.9 MHz. It must sacrifice an average of only 0.4 dB compared to the maximum gain design at the low end of the band, and actually has more gain than the maximum gain and gain/SWR designs at the high-frequency end of the band.

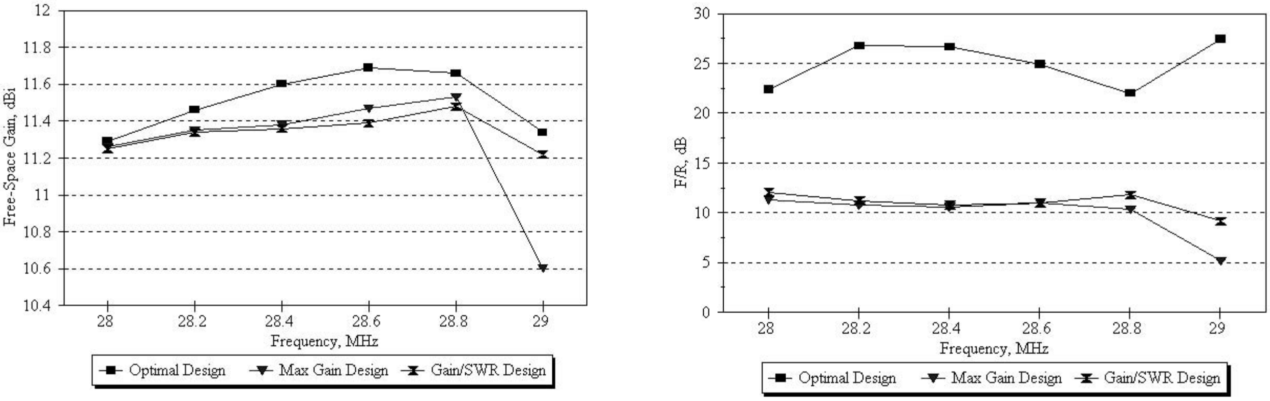
The conclusion drawn from these and many other detailed comparisons is that designing strictly for maximum mid-band gain yields an inferior design when the antenna is examined over an entire frequency band, especially in terms of SWR. Designing a Yagi for both gain and SWR will yield antennas that have mediocre rearward patterns, but that lose relatively little gain compared to the maximum gain case, at least for designs with more than three elements.

However, designing a Yagi for an optimal combination of F/R, SWR and gain results in a loss of gain less than 0.5 dB compared to designs designed only for gain and SWR. **Fig 9** summarizes the forward gain achieved for the three different design types versus boom length, as expressed in wavelength.

Except for the 2-element designs, the Yagis described in the rest of this chapter have the following design goals over a desired frequency band:

1. Front-to-rear ratio over the frequency band of more than 20 dB
2. SWR over the frequency band less than 2:1
3. Maximum gain consistent with points 1 and 2 above

Just for fun, **Fig 10** shows the gain versus boom length for theoretical 20-meter Yagis that have been designed to meet the three design goals above. The 31-element design for 14 MHz would be wondrous to behold. Sadly, it is unlikely that anyone will build one, considering that the boom would be 724 feet long! However, such a design *does* become practical when scaled to 432 MHz. In fact, a K1FO 22-element and a K1FO 31-element Yagi are the prototypes for the theoretical 14-MHz long-boom designs. See Chapter 18, VHF and UHF Antenna Systems.



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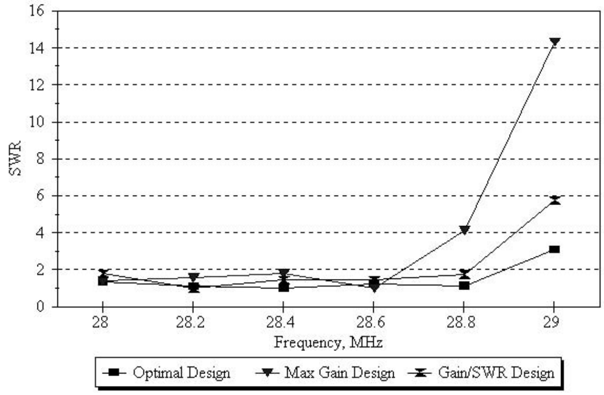

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**Fig 7—Comparisons of three different 6-element 10-meter Yagi designs on 36-foot booms. At A, gain is shown over the band. With more elements and a longer boom, the tuning can be staggered even more to make the antenna gain more uniform over the band. This narrows the gain differential between the antenna designed strictly for maximum gain and the antenna designed for an optimal combination of F/R, SWR and gain. The average difference in gain is about 0.2 dB throughout the band. At B, the F/R performance over the band is shown for the three antenna designs. The antenna designed for optimal performance maintains an average of almost 15 dB better F/R over the whole band compared to the other designs. At C, the SWR bandwidth is compared. Again, the antenna designed strictly for maximum gain exhibits a high SWR of 4:1 at 28.8 MHz, and rises to more than 14:1 at 29.0 MHz.**

## OPTIMUM DESIGNS AND ELEMENT SPACING

### Two-Element Yagis

Many hams consider a 2-element Yagi to give "the most bang for the buck" among various Yagi designs, particularly for portable operations such as Field Day. A 2-element Yagi has about 4 dB of gain over a simple dipole (sometimes jokingly called a "one-element Yagi") and gives a modest F/R of about 10 dB to help with rejection of interference on receive. By comparison, going from a 2-element to a 3-element Yagi increases the boom length by about 50% and adds another element, a 50% increase in the number of elements—for a gain increase of about 1 dB and another 10 dB in F/R.

### Element Spacing in Larger Yagis

One of the more interesting results of computer modeling and optimization of high-performance Yagis with four or more elements is that a distinct pattern in the element spacings along the boom shows up consistently. This pattern is relatively independent of boom length, once the boom is longer than about 0.3 λ.

The reflector, driven element and first director of these optimal designs are typically bunched rather closely together, occupying together only about 0.15 to 0.20 λ of the boom. This pattern contrasts sharply with older designs, where the amount of boom taken up by the reflector, driven element and first director was typically more than 0.3 λ. **Fig 11** shows the element spacings for an optimized 6-element, 36-foot boom, 10-meter design, compared to a W2PV 6-element design with constant spacing of 0.15 λ between all elements.

A problem arises with such a bunching of elements toward the reflector end of the boom—the wind loading of the antenna is not equal along the boom. Unless properly compensated, such new-generation Yagis will act like windvanes, punishing, and often breaking, the rotators trying to turn, or hold, them in the wind. One successful solution to windvaning has been to employ "dummy elements" made of PVC piping. These nonconducting elements are placed on the boom close to the last director so

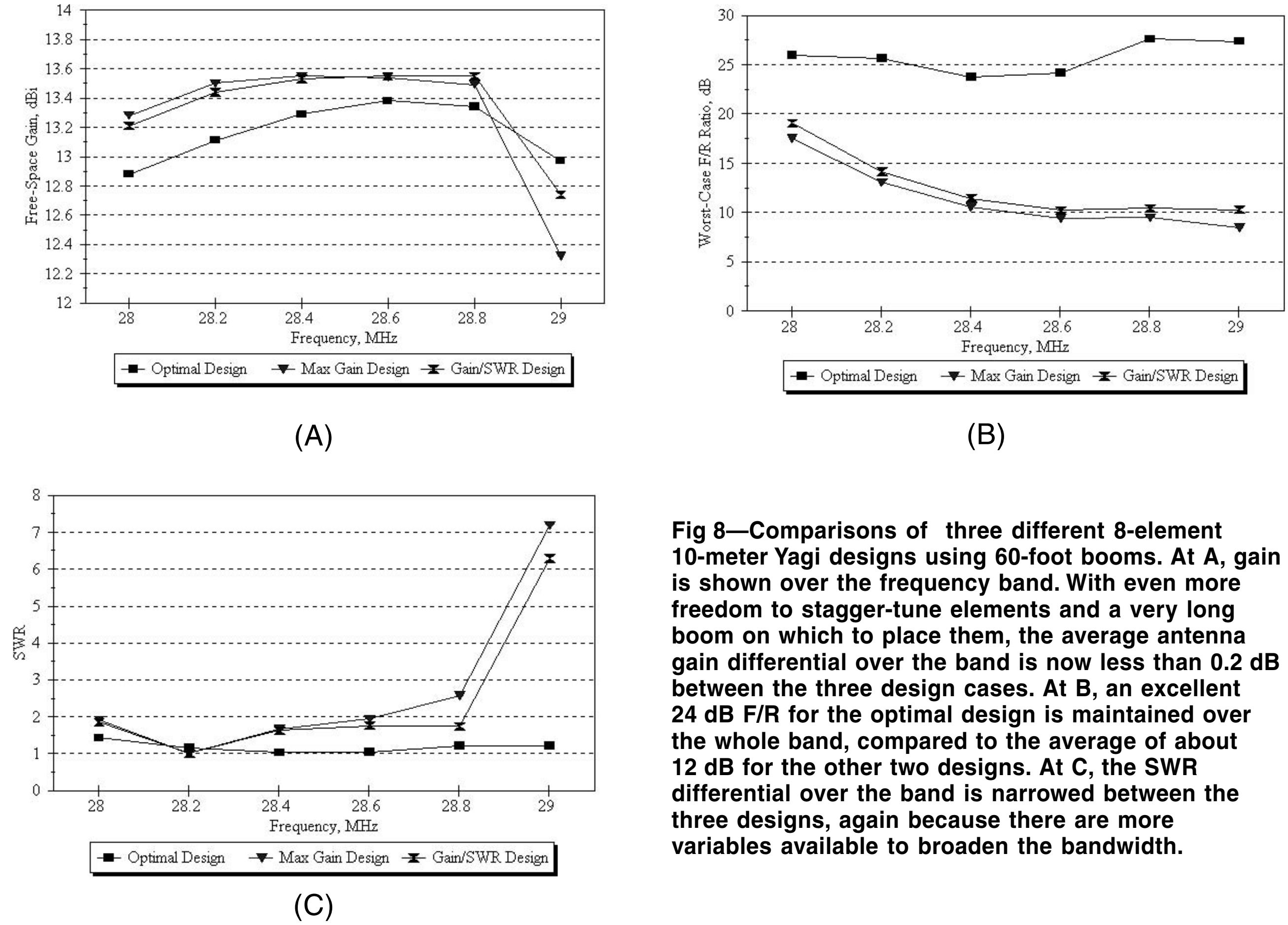

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**Fig 8—Comparisons of three different 8-element 10-meter Yagi designs using 60-foot booms. At A, gain is shown over the frequency band. With even more freedom to stagger-tune elements and a very long boom on which to place them, the average antenna gain differential over the band is now less than 0.2 dB between the three design cases. At B, an excellent 24 dB F/R for the optimal design is maintained over the whole band, compared to the average of about 12 dB for the other two designs. At C, the SWR differential over the band is narrowed between the three designs, again because there are more variables available to broaden the bandwidth.**

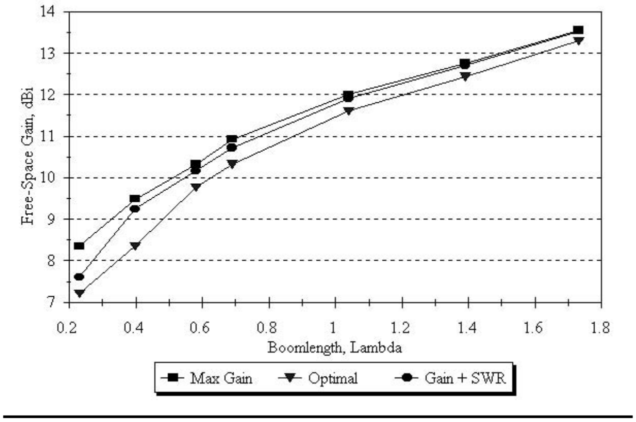


**Fig 9—Gain versus boom length for three different 10-meter design goals. The goals are: (1) designed for maximum gain across band, (2) designed for a compromise of gain and SWR, and (3) designed for optimal F/R, SWR and gain across 28.0 to 28.8 MHz portion of 10-meter band. The gain difference is less than 0.5 dB for booms longer than approximately 0.5 λ.**

the windload is equalized at the mast-to-boom bracket. In addition, it may be necessary to insert a small amount of lead weight at one end of the boom in order to balance the antenna weight.

Despite the relatively close spacing of the reflector, driven element and first director, modern optimal Yagi designs are not overly sensitive to small changes in either element length or spacing. In fact, these antennas can be constructed from design tables without excessive concern about close dimensional tolerances. In the HF range up to 30 MHz, building the antennas to the nearest $^1/_8$-inch results in performance remarkably consistent with the computations, without any "tweaking" or fine-tuning when the Yagi is on the tower.

## ELEMENT TUNING

Element tuning (or *self-impedance*) is a complex function of the effective electrical length of each element and the effective diameter of the element. In turn, the effective length and diameter of each element is related to

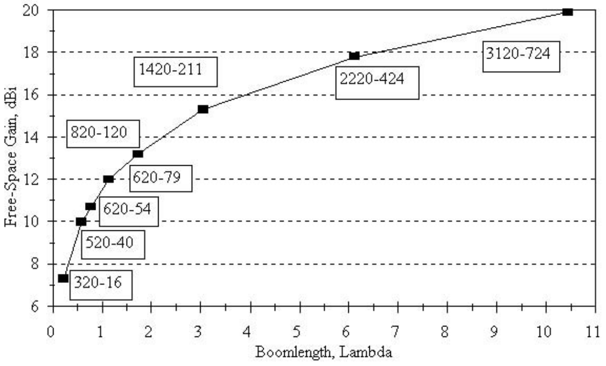


**Fig 10—Theoretical gain versus boom length for 20-meter Yagis designed for optimal combination of F/R, SWR and gain across the entire 14.0 to 14.35 MHz band. The theoretical gain approaches 20 dBi for a gigantic 724-foot boom, populated with 31 elements. Such a design on 20 meters is not too practical, of course, but can readily be achieved on a 24-foot boom on 432 MHz.**

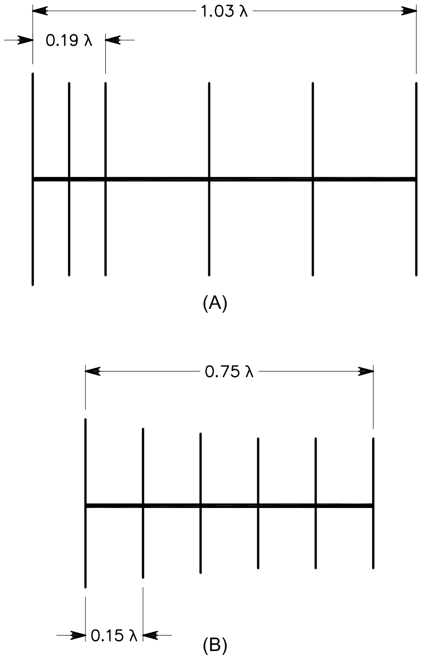


**Fig 11—Tapering spacing versus constant element spacing. At A, illustration of how the spacing of the reflector, driven element and first director (over the first 0.19 λ of the boom) of an optimally designed Yagi is bunched together compared to the Yagi at B, which uses constant 0.15 λ spacing between all elements. The optimally designed antenna has more than 22 dB F/R and an SWR less than 1.5:1 over the frequency band 28.0 to 28.8 MHz.**

the taper schedule (if telescoping aluminum tubing is used, the most common method of construction), the length of each telescoping section, the type and size of mounting bracket used to secure the element to or through the boom, and the size of the Yagi boom itself. See the section entitled "Antenna Frequency Scaling," and "Tapered Elements" in Chapter 2, Antenna Fundamentals, of this book for details about element tuning as a function of tapering and element diameter. Note especially that Yagis constructed using wire elements will perform very differently compared to the same antenna constructed with elements made of telescoping aluminum tubing.

The process by which a modern Yagi is designed usually starts out with the selection of the longest boom possible for a given installation. A suitable number of elements of a given taper schedule are then placed on this boom, and the gain, pattern and SWR are calculated over the entire frequency band of interest to the operator. Once an electrical design is chosen, the designer must then ensure the mechanical integrity of the antenna design. This involves verifying the integrity of the boom and each element in the face of the wind and ice loading expected for a particular location. The section entitled "Construction with Aluminum Tubing" in Chapter 20, Antenna Materials and Accessories, of this book shows details of tapered telescoping aluminum elements for the upper HF bands. In addition, the ARRL book *Physical Design of Yagi Antennas*, by Dave Leeson, W6NL (ex-W6QHS), describes the mechanical design process for all portions of a Yagi antenna very thoroughly, and is highly recommended for serious Yagi builders.

# Specific Monoband Yagi Designs

The detailed Yagi design tables that follow are for two taper schedules for HF Yagis covering the 14 through 30-MHz amateur bands. The heavy-duty elements are designed to survive at least 120-mph winds without icing, or 85-mph winds with 1/4-inch radial ice. The medium-duty elements are designed to survive winds greater than 80 mph, or 60-mph winds with 1/4-inch radial ice.

For 10.1 MHz, the elements shown are capable of surviving 105-mph winds, or 93-mph winds with 1/4-inch radial ice. For 7.1 MHz the elements shown can survive 93-mph winds, or 69-mph winds with 1/4-inch radial ice. For these two lower frequency bands, the elements and the booms needed are very large and heavy. Mounting, turning and keeping such antennas in the air is not a trivial task.

Each element is mounted above the boom with a heavy rectangular aluminum plate, by means of U-bolts with saddles, as shown in Fig 35 in Chapter 18, VHF and UHF Antenna Systems for a 6-meter Yagi. This method of element mounting is rugged and stable, and because the element is mounted away from the boom, the amount of element detuning due to the presence of the boom is minimal. The element dimensions given in each table already take into account any element detuning due to the boom-to-element mounting plate. For each element, the length of the tip determines the tuning, since the inner tubes are fixed in diameter and length.

### Half Elements

Each design shows the dimensions for *one-half* of each element, mounted on *one side* of the boom. The other half of each element is symmetrical, mounted on the other side of the boom. The use of a tubing sleeve inside the center portion of the element is recommended, so that the element is not crushed by the mounting U-bolts. Unless otherwise noted, each section of tubing is made of 6061-T6 aluminum tubing, with a 0.058-inch wall thickness. This wall thickness ensures that the next standard size of tubing can telescope with it. Each telescoping section is inserted 3 inches into the larger tubing, and is secured by one of the methods shown in Fig 11 in Chapter 20, Antenna Materials and Accessories.

### Matching System

Each antenna is designed with a driven-element length appropriate for a hairpin type of matching network. The driven-element's length may require slight readjustment for best match, particularly if a different matching network is used. *Do not change* either the lengths or the telescoping tubing schedule of the parasitic elements—they have been optimized for best performance and will not be affected by tuning of the driven element!

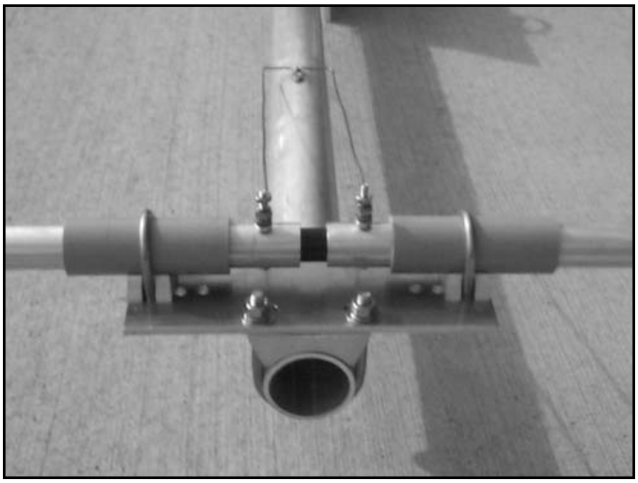


**Fig 12—Typical construction techniques for an HF Yagi. This photo shows a hairpin match on a driven element that uses a fiberglass insulator (wrapped in black vinyl tape for protection against UV). Muffler clamps and saddles mount the element to the boom, while U-bolts and saddles mount the element to the boom-to-element plate. The gray PVC sleeves insulate the element from the plate. The feed coax is connected to the two bolts that also connect to the hairpin wire. Note that the hairpin is grounded at its opposite end to dissipate static charges that might otherwise build up.**

**Fig 12** is a photograph of the driven element for a 2-element 17-meter Yagi built by Chuck Hutchinson, K8CH, for the ARRL book *Simple and Fun Antennas for Hams.* The aluminum tubing on each side of the boom was 1-inch OD, and the two pieces were mechanically joined together with a 3/4-inch OD fiberglass insulator. Chuck wound electrical tape over the insulator to protect the fiberglass from the sun's UV.

Chuck used 3-inch lengths of 1-inch sunlight-resistant PVC conduit, split lengthwise, to make the grey outer insulators for the driven element. The aluminum plates came from DX Engineering, as did the stainless-steel U-bolts and saddle clamps. These saddles ensured that the elements don't rotate on the 2-inch OD boom in the heavy winds in his part of rural Michigan.

You can see the bolts used to pin the center fiberglass insulator to the aluminum tubing, while also providing an electrical connection for the #12 hairpin wire and for the feed-line coax, which uses ferrite beads over the coax's outer vinyl jacket to make a common-mode current-type of balun (not shown in Fig 12). Note that the center of the hairpin is connected to the boom using a grounding lug for some measure of protection from static buildup.

## 10-METER YAGIS

**Fig 13** describes the electrical performance of eight optimized 10-meter Yagis with boom lengths between 6 to 60 feet. The end of each boom includes 3 inches of space for the reflector and last-director (or driven element for the 2-element designs) mounting plates. Fig 13A shows the free-space gain versus frequency for each antenna; 13B shows the front-to-rear ratio, and 13C shows the SWR versus frequency. Each antenna with three or more elements was designed to cover the lower half of the 10-meter band from 28.0 to 28.8 MHz, with SWR less than 2:1 and F/R better than 20 dB over that range.

Fig 13D shows the taper schedule for two types of 10-meter elements. The heavy-duty design can survive 125-mph winds with no icing, and 88-mph winds with $^1/_4$-inch of radial ice. The medium-duty design can handle 96-mph winds with no icing, and 68-mph winds with $^1/_4$-inch of radial ice. The element-to-boom mounting plate for these Yagis is a 0.250-inch thick flat aluminum plate, 4 inches wide by 4 inches long. Each element except for the insulated driven element, is centered on the plate, held by two stainless-steel U-bolts with saddles. Another set

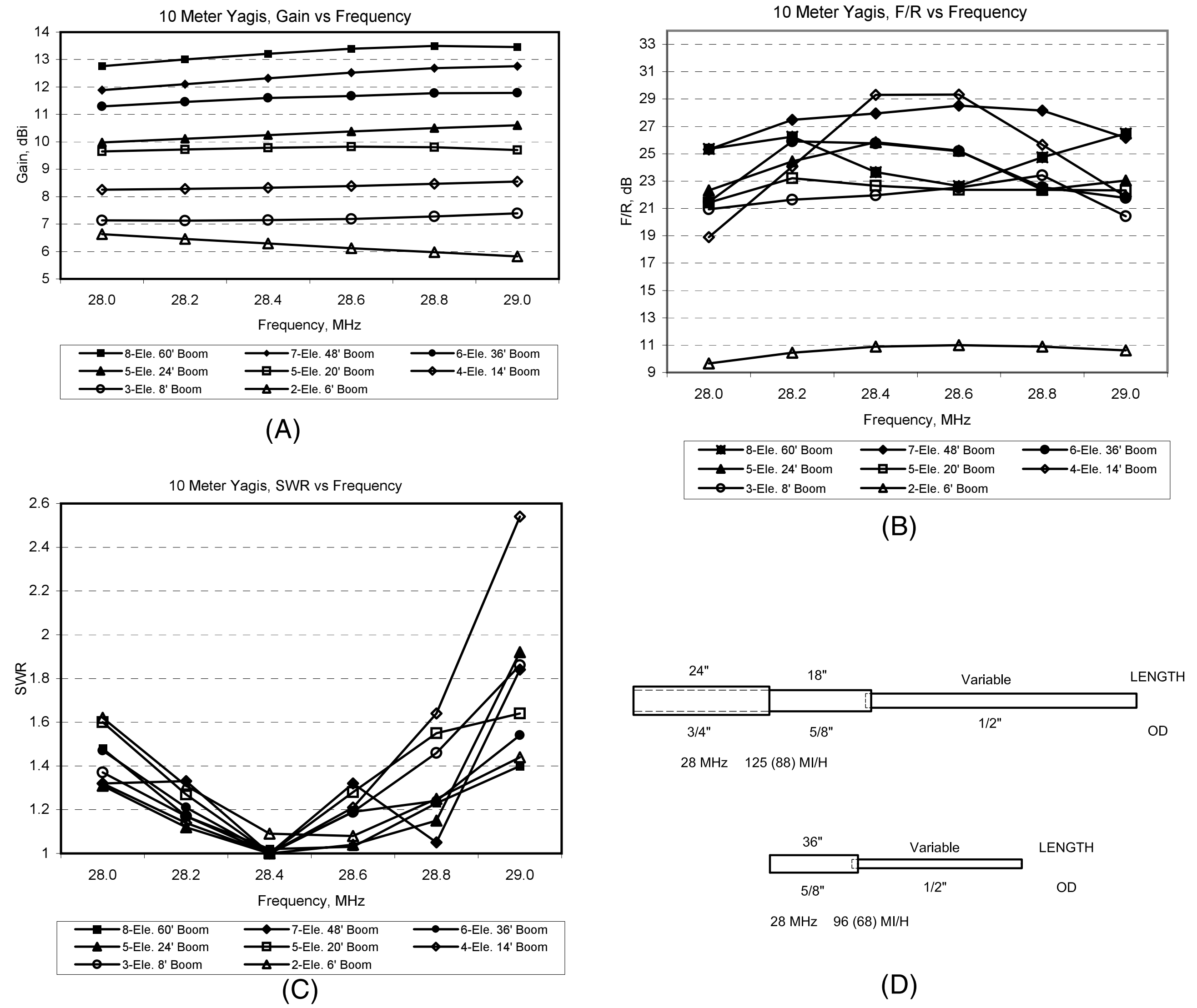


**Fig 13—Gain, F/R and SWR performance versus frequency for optimized 10-meter Yagis. At A, gain is shown versus frequency for eight 10-meter Yagis whose booms range from 6 feet to 60 feet long. Except for the 2-element design, these Yagis have been optimized for better than 20 dB F/R and less than 2:1 SWR over the frequency range 28.0 to 28.8 MHz. At B, front-to-rear ratio for these antennas is shown versus frequency, and at C, SWR is shown over the frequency range. At D, the taper schedule is shown for heavy-duty and for medium-duty 10-meter elements. The heavy-duty elements can withstand 125-mph winds without icing, and 88-mph winds with $^1/_4$-inch radial ice. The medium-duty elements can survive 96-mph winds without icing, and 68-mph winds with $^1/_4$-inch radial ice. The wall thickness for each telescoping section of 6061-T6 aluminum tubing is 0.058 inches, and the overlap at each telescoping junction is 3 inches.**

**Table 1**

**Optimized 10-Meter Yagi Designs**

**Two-element 10-meter Yagi, 6 foot boom**

| *Element* | *Spacing* | *Heavy-Duty Tip* | *Medium-Duty Tip* |
|---|---|---|---|
| File Name | | 210-06H.YW | 210-06M.YW |
| Reflector | 0.000" | 66.000" | 71.500" |
| Driven Element | 66.000" | 57.625" | 63.000" |

**Three-element 10-meter Yagi, 8 foot boom**

| *Element* | *Spacing* | *Heavy-Duty Tip* | *Medium-Duty Tip* |
|---|---|---|---|
| File Name | | 310-08H.YW | 310-08M.YW |
| Reflector | 0.000" | 66.750" | 71.875" |
| Driven Element | 36.000" | 57.625" | 62.875" |
| Director 1 | 54.000" | 53.125" | 58.500" |
| Compensator | 12" behind Dir. 1 | 19.000" | 18.125" |

**Four-element 10-meter Yagi, 14 foot boom**

| *Element* | *Spacing* | *Heavy-Duty Tip* | *Medium-Duty Tip* |
|---|---|---|---|
| File Name | | 410-14H.YW | 410-14M.YW |
| Reflector | 0.000" | 66.000" | 72.000" |
| Driven Element | 36.000" | 58.625" | 63.875" |
| Director 1 | 36.000" | 57.000" | 62.250" |
| Director 2 | 90.000" | 47.750" | 53.125" |
| Compensator | 12" behind Dir. 2 | 22.000" | 20.500" |

**Five-element 10-meter Yagi, 24 foot boom**

| *Element* | *Spacing, inches* | *Heavy-Duty Tip* | *Medium-Duty Tip* |
|---|---|---|---|
| File Name | | 510-24H.YW | 510-24M.YW |
| Reflector | 0.000" | 65.625" | 70.750" |
| Driven Element | 36.000" | 58.000" | 63.250" |
| Director 1 | 36.000" | 57.125" | 62.375" |
| Director 2 | 99.000" | 55.000" | 60.250" |
| Director 3 | 111.000" | 50.750" | 56.125" |
| Compensator | 12" behind Dir. 3 | 28.750" | 26.750" |

**Six-element 10-meter Yagi, 36 foot boom**

| *Element* | *Spacing, inches* | *Heavy-Duty Tip* | *Medium-Duty Tip* |
|---|---|---|---|
| File Name | | 610-36H.YW | 610-36M.YW |
| Reflector | 0.000" | 66.500" | 71.500" |
| Driven Element | 37.000" | 58.500" | 64.000" |
| Director 1 | 43.000" | 57.125" | 62.375" |
| Director 2 | 98.000" | 54.875" | 60.125" |
| Director 3 | 127.000" | 53.875" | 59.250" |
| Director 4 | 121.000" | 49.875" | 55.250" |
| Compensator | 12" behind Dir. 4 | 32.000" | 29.750" |

**Seven-element 10-meter Yagi, 48 foot boom**

| *Element* | *Spacing, inches* | *Heavy-Duty Tip* | *Medium-Duty Tip* |
|---|---|---|---|
| File Name | | 710-48H.YW | 710-48M.YW |
| Reflector | 0.000" | 65.375" | 70.500" |
| Driven Element | 37.000" | 59.000" | 64.250" |
| Director 1 | 37.000" | 57.500" | 62.750" |
| Director 2 | 96.000" | 54.875" | 60.125" |
| Director 3 | 130.000" | 52.250" | 57.625" |
| Director 4 | 154.000" | 52.625" | 58.000" |
| Director 5 | 116.000" | 49.875" | 55.250" |
| Compensator | 12" behind Dir. 5 | 35.750" | 33.750" |

**Eight-element 10-meter Yagi, 60 foot boom**

| *Element* | *Spacing, inches* | *Heavy-Duty Tip* | *Medium-Duty Tip* |
|---|---|---|---|
| File Name | | 810-60H.YW | 810-60M.YW |
| Reflector | 0.000" | 65.000" | 70.125" |
| Driven Element | 42.000" | 58.000" | 63.500" |
| Director 1 | 37.000" | 57.125" | 62.375" |
| Director 2 | 87.000" | 55.375" | 60.625" |
| Director 3 | 126.000" | 53.250" | 58.625" |
| Director 4 | 141.000" | 51.875" | 57.250" |
| Director 5 | 157.000" | 52.500" | 57.875" |
| Director 6 | 121.000" | 50.125" | 55.500" |
| Compensator | 12" behind Dir. 6 | 59.375" | 55.125" |

These 10-meter Yagi designs are optimized for > 20 dB F/R, and SWR < 2:1 over frequency range from 28.000 to 28.800 MHz, for heavy-duty elements (125 mph wind survival) and for medium-duty (96 mph wind survival). For coverage from 28.8 to 29.7 MHz, subtract 2.000 inches from end of each element, but leave element spacings the same as shown here. Only element tip dimensions are shown, and all dimensions are inches. See Fig 13D for element telescoping tubing schedule. Torque compensator element is made of 2.5" OD PVC water pipe placed 12 inches behind last director. Dimensions shown for compensators is one-half of total length, centered on boom.

of U-bolts with saddles is used to secure the mounting plate to the boom.

Electrically each mounting plate is equivalent to a cylinder, with an effective diameter of 2.405 inches for the heavy-duty element, and 2.310 inches for the medium-duty element. The equivalent length on each side of the boom is 2 inches. These dimensions are incorporated in the files for the *YW* (Yagi for Windows) computer modeling program on the CD-ROM accompanying this book to simulate the effect of the mounting plate.

The second column in **Table 1** shows the spacing of each element relative to the next element in line on the boom, starting at the reflector, which itself is defined as being at the 0.000-inch reference point on the boom. The boom for antennas less than 30 feet long can be constructed of 2-inch OD tubing with 0.065-inch wall thickness. Designs larger than 30 feet long should use 3-inch OD heavy-wall tubing for the boom. Because each boom has extra space at each end, the reflector is actually placed 3 inches from the end of the boom. For example, in the 310-08H.YW design (3 elements on an 8-foot boom), the driven element is placed 36 inches ahead of the reflector, and the director is placed 54 inches ahead of the driven element.

The next columns give the lengths for the variable tips for the heavy-duty and then the medium-duty elements. In the example above for the 310-08H.YW Yagi, the heavy-duty reflector tip, made out of 1/2-inch OD tubing, sticks out 66.750 inches from the 5/8-inch OD tubing. Note that each telescoping piece of tubing overlaps 3 inches inside the piece into which it fits, so the overall length of 1/8-inch OD tubing is 69.750 inches long for the reflector. The medium-duty reflector tip has 71.875 inches protruding from the 5/8-inch OD tube, and is 74.875 inches long overall. As previously stated, the dimensions are not extremely critical, although measurement accu-

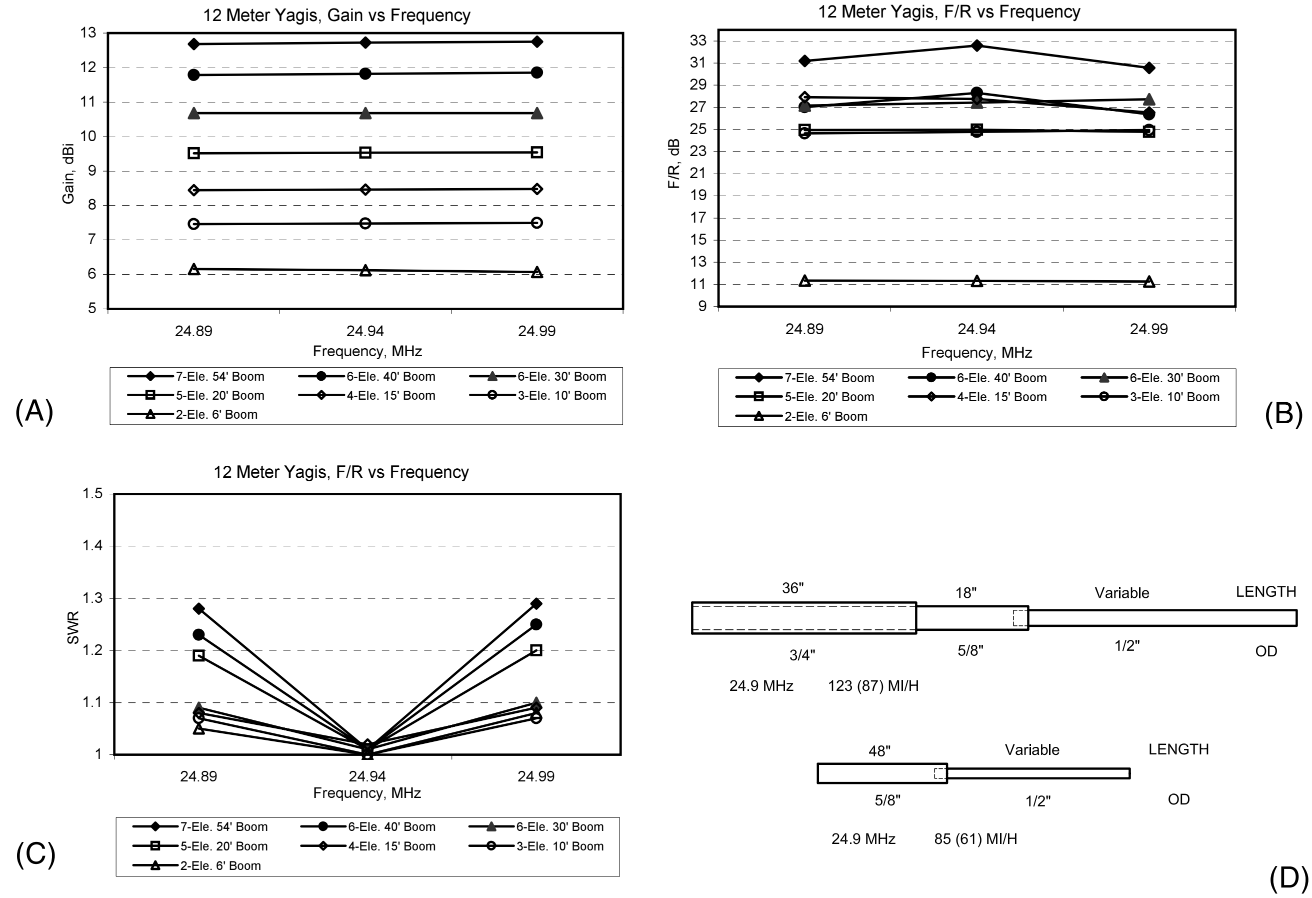


**Fig 14—Gain, F/R and SWR performance versus frequency for optimized 12-meter Yagis. At A, gain is shown versus frequency for seven 12-meter Yagis whose booms range from 6 feet to 54 feet long. Except for the 2-element design, these Yagis have been optimized for better than 20 dB F/R and less than 2:1 SWR over the narrow 12-meter band 24.89 to 24.99 MHz. At B, front-to-rear ratio for these antennas is shown versus frequency, and at C, SWR over the frequency range is shown. At D, the taper schedule for heavy-duty and for medium-duty 12-meter elements is shown. The heavy-duty elements can withstand 123-mph winds without icing, and 87-mph winds with 1/4-inch radial ice. The medium-duty elements can survive 85-mph winds without icing, and 61-mph winds with 1/4-inch radial ice. The wall thickness for each telescoping section of 6061-T6 aluminum tubing is 0.058 inches, and the overlap at each telescoping junction is 3 inches.**

## Table 2
## Optimized 12-Meter Yagi Designs

**Two-element 12-meter Yagi, 6 foot boom**

| *Element* | *Spacing* | *Heavy-Duty Tip* | *Medium-Duty Tip* |
|---|---|---|---|
| File Name | | 212-06H.YW | 212-06M.YW |
| Reflector | 0.000" | 67.500" | 72.500" |
| Driven Element | 66.000" | 59.500" | 65.000" |

**Three-element 12-meter Yagi, 10 foot boom**

| *Element* | *Spacing, inches* | *Heavy-Duty Tip* | *Medium-Duty Tip* |
|---|---|---|---|
| File Name | | 312-10H.YW | 312-10M.YW |
| Reflector | 0.000" | 69.000" | 73.875" |
| Driven Element | 40.000" | 60.250" | 65.250" |
| Director 1 | 74.000" | 54.000" | 59.125" |
| Compensator | 12" behind Dir. 1 | 13.625" | 12.000" |

**Four-element 12-meter Yagi, 15 foot boom**

| *Element* | *Spacing, inches* | *Heavy-Duty Tip* | *Medium-Duty Tip* |
|---|---|---|---|
| File Name | | 412-15H.YW | 412-15M.YW |
| Reflector | 0.000" | 66.875" | 71.875" |
| Driven Element | 46.000" | 61.000" | 66.000" |
| Director 1 | 46.000" | 58.625" | 63.750" |
| Director 2 | 82.000" | 50.875" | 56.125" |
| Compensator | 12" behind Dir. 2 | 16.375" | 14.500" |

**Five-element 12-meter Yagi, 20 foot boom**

| *Element* | *Spacing, inches* | *Heavy-Duty Tip* | *Medium-Duty Tip* |
|---|---|---|---|
| File Name | | 512-20H.YW | 512-20M.YW |
| Reflector | 0.000" | 69.750" | 74.625" |
| Driven Element | 46.000" | 62.250" | 67.000" |
| Director 1 | 46.000" | 60.500" | 65.500" |
| Director 2 | 48.000" | 55.500" | 60.625" |
| Director 3 | 94.000" | 54.625" | 59.750" |
| Compensator | 12" behind Dir. 3 | 22.125" | 19.625" |

**Six-element 12-meter Yagi, 30 foot boom**

| *Element* | *Spacing, inches* | *Heavy-Duty Tip* | *Medium-Duty Tip* |
|---|---|---|---|
| File Name | | 612-30H.YW | 612-30M.YW |
| Reflector | 0.000" | 68.125" | 73.000" |
| Driven Element | 46.000" | 61.750" | 66.750" |
| Director 1 | 46.000" | 60.250" | 65.250" |
| Director 2 | 73.000" | 52.375" | 57.625" |
| Director 3 | 75.000" | 57.625" | 62.750" |
| Director 4 | 114.000" | 53.625" | 58.750" |
| Compensator | 12" behind Dir. 4 | 30.000" | 26.250" |

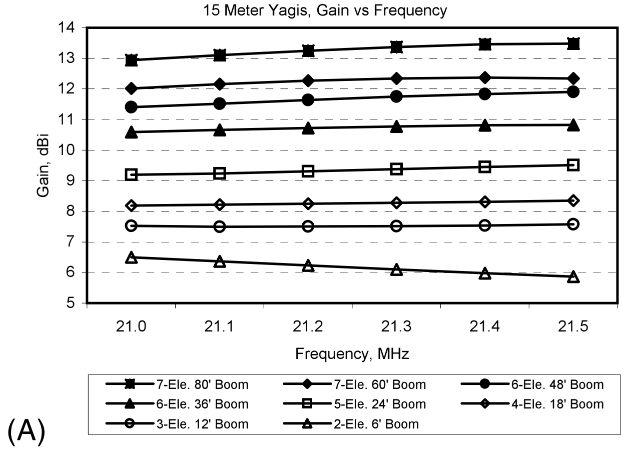
**Six-element 12-meter Yagi, 40 foot boom**

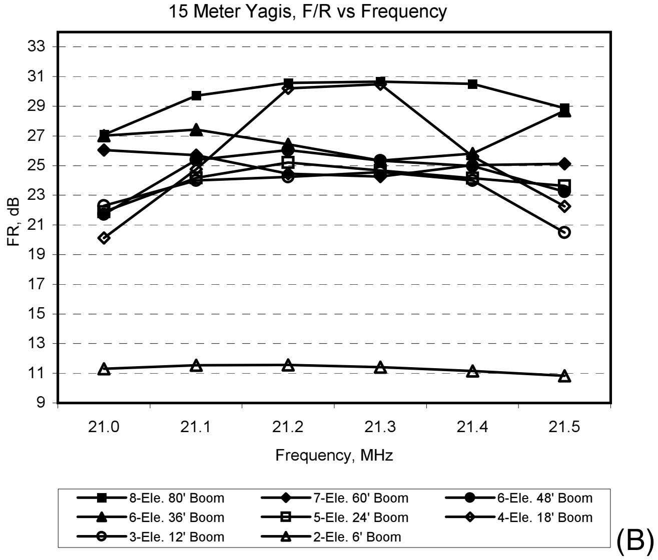
| *Element* | *Spacing, inches* | *Heavy-Duty Tip* | *Medium-Duty Tip* |
|---|---|---|---|
| File Name | | 612-40H.YW | 612-40M.YW |
| Reflector | 0.000" | 67.000" | 71.875" |
| Driven Element | 46.000" | 60.125" | 65.500" |
| Director 1 | 46.000" | 57.375" | 62.500" |
| Director 2 | 91.000" | 57.375" | 62.500" |
| Director 3 | 157.000" | 57.000" | 62.125" |
| Director 4 | 134.000" | 54.375" | 59.500" |
| Compensator | 12" behind Dir. 4 | 36.500" | 31.625" |

**Seven-element 12-meter Yagi, 54 foot boom**

| *Element* | *Spacing, inches* | *Heavy-Duty Tip* | *Medium-Duty Tip* |
|---|---|---|---|
| File Name | | 712-54H.YW | 712-54M.YW |
| Reflector | 0.000" | 68.000" | 73.000" |
| Driven Element | 46.000" | 60.500" | 65.500" |
| Director 1 | 46.000" | 56.750" | 61.875" |
| Director 2 | 75.000" | 58.000" | 63.125" |
| Director 3 | 161.000" | 55.625" | 60.750" |
| Director 4 | 174.000" | 56.000" | 61.125" |
| Director 5 | 140.000" | 53.125" | 58.375" |
| Compensator | 12" behind Dir. 5 | 43.125" | 37.500" |

These 12-meter Yagi designs were optimized for > 20 dB F/R, and SWR < 2:1 over frequency range from 24.890 to 24.990 MHz, for heavy-duty elements (123 mph wind survival) and for medium-duty (85 mph wind survival). Only element tip dimensions are shown, and all dimensions are inches. See Fig 14D for element telescoping tubing schedule. Torque compensator element is made of 2.5" OD PVC water pipe placed 12" behind last director. Dimensions shown for compensators is one-half of total length, centered on boom.





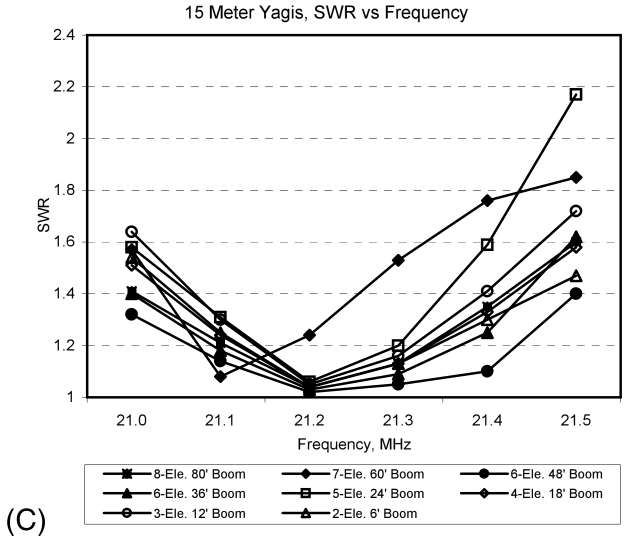
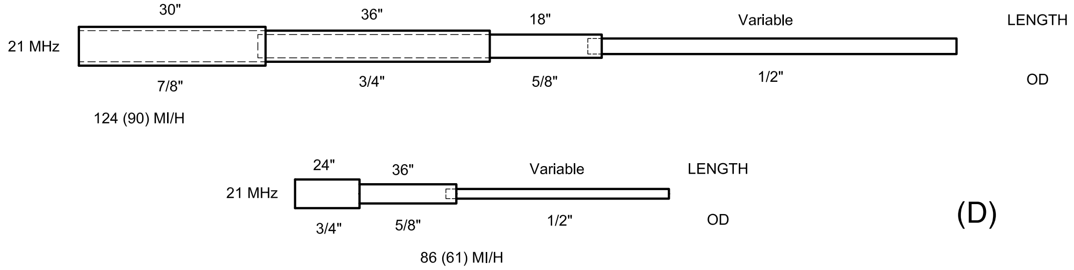


**Fig 15—Gain, F/R and SWR performance versus frequency for optimized 15-meter Yagis. At A, gain versus frequency is shown for eight 15-meter Yagis whose booms range from 6 feet to 80 feet long. Except for the 2-element design, these Yagis have been optimized for better than 20 dB F/R and less than 2:1 SWR over the frequency range 21.0 to 21.45 MHz. At B, front-to-rear ratio for these antennas is shown versus frequency, and at C, SWR over the frequency range is shown. At D, the taper schedule for heavy-duty and for medium-duty 15-meter elements is shown. The heavy-duty elements can withstand 124-mph winds without icing, and 90-mph winds with 1/4-inch radial ice. The medium-duty elements can survive 86-mph winds without icing, and 61-mph winds with 1/4-inch radial ice. The wall thickness for each telescoping section of 6061-T6 aluminum tubing is 0.058 inches, and the overlap at each telescoping junction is 3 inches.**



racy to 1/8 inch is desirable.

The last row in each variable tip column shows the length of one-half of the "dummy element" torque compensator used to correct for uneven wind loading along the boom. This compensator is made from 2.5 inches OD PVC water pipe mounted to an element-to-boom plate like those used for each element. The compensator is mounted 12 inches behind the last director, the first director in the case of the 3-element 310-08H.YW antenna. Note that the heavy-duty elements require a correspondingly longer torque compensator than do the medium-duty elements.

## 12-METER YAGIS

**Fig 14** describes the electrical performance of seven optimized 12-meter Yagis with boom lengths between 6 to 54 feet. The end of each boom includes 3 inches of space for the reflector and last director (or driven element) mounting plates. The narrow frequency width of the 12-meter band allows the performance to be optimized easily. Fig 14A shows the free-space gain versus frequency for each antenna; 14B shows the front-to-rear ratio, and 14C shows the SWR versus frequency. Each antenna with three or more elements was designed to

## Table 3
## Optimized 15-Meter Yagi Designs

**Two-element 15-meter Yagi, 6 foot boom**

| *Element* | *Spacing* | *Heavy-Duty Tip* | *Medium-Duty Tip* |
|---|---|---|---|
| File Name | | 215-06H.YW | 215-06M.YW |
| Reflector | 0.000" | 62.000" | 85.000" |
| Driven Element | 66.000" | 51.000" | 74.000" |

**Three-element 15-meter Yagi, 12 foot boom**

| *Element* | *Spacing* | *Heavy-Duty Tip* | *Medium-Duty Tip* |
|---|---|---|---|
| File Name | | 315-12H.YW | 315-12M.YW |
| Reflector | 0.000" | 62.000" | 84.250" |
| Driven Element | 48.000" | 51.000" | 73.750" |
| Director 1 | 92.000" | 43.500" | 66.750" |
| Compensator | 12" behind Dir. 1 | 34.750" | 37.625" |

**Four-element 15-meter Yagi, 18 foot boom**

| *Element* | *Spacing* | *Heavy-Duty Tip* | *Medium-Duty Tip* |
|---|---|---|---|
| File Name | | 415-18H.YW | 415-18M.YW |
| Reflector | 0.000" | 61.000" | 83.500" |
| Driven Element | 56.000" | 51.500" | 74.500" |
| Director 1 | 56.000" | 48.000" | 71.125" |
| Director 2 | 98.000" | 36.625" | 60.250" |
| Compensator | 12" behind Dir. 2 | 20.875" | 18.625" |

**Five-element 15-meter Yagi, 24 foot boom**

| *Element* | *Spacing* | *Heavy-Duty Tip* | *Medium-Duty Tip* |
|---|---|---|---|
| File Name | | 515-24H.YW | 515-24M.YW |
| Reflector | 0.000" | 62.000" | 84.375" |
| Driven Element | 48.000" | 52.375" | 75.250" |
| Director 1 | 48.000" | 47.875" | 71.000" |
| Director 2 | 52.000" | 47.000" | 70.125" |
| Director 3 | 134.000" | 41.000" | 64.375" |
| Compensator | 12" behind Dir. 3 | 40.250" | 35.125" |

**Six-element 15-meter Yagi, 36 foot boom**

| *Element* | *Spacing* | *Heavy-Duty Tip* | *Medium-Duty Tip* |
|---|---|---|---|
| File Name | | 615-36H.YW | 615-36M.YW |
| Reflector | 0.000" | 61.000" | 83.375" |
| Driven Element | 53.000" | 52.000" | 75.000" |
| Director 1 | 56.000" | 49.125" | 72.125" |
| Director 2 | 59.000" | 45.125" | 68.375" |
| Director 3 | 116.000" | 47.875" | 71.000" |
| Director 4 | 142.000" | 42.000" | 65.375" |
| Compensator | 12" behind Dir. 4 | 45.500" | 39.750" |

**Seven-element 15-meter Yagi, 48 foot boom**

| *Element* | *Spacing* | *Heavy-Duty Tip* | *Medium-Duty Tip* |
|---|---|---|---|
| File Name | | 615-48H.YW | 615-48M.YW |
| Reflector | 0.000" | 62.000" | 84.000" |
| Driven Element | 48.000" | 52.000" | 75.000" |
| Director 1 | 48.000" | 51.250" | 74.125" |
| Director 2 | 125.000" | 48.000" | 71.125" |
| Director 3 | 190.000" | 45.500" | 68.750" |
| Director 4 | 161.000" | 42.000" | 65.375" |
| Compensator | 12" behind Dir. 4 | 51.500" | 45.375" |

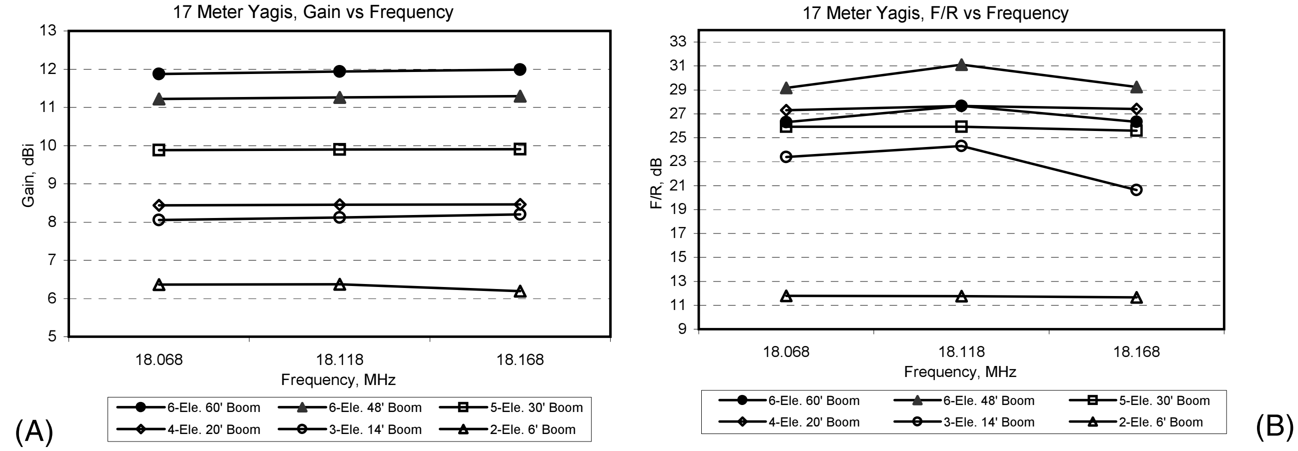
**Seven-element 15-meter Yagi, 60 foot boom**

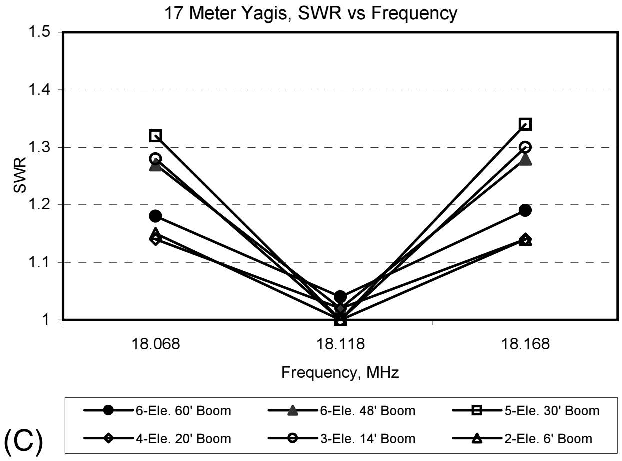
| *Element* | *Spacing* | *Heavy-Duty Tip* | *Medium-Duty Tip* |
|---|---|---|---|
| File Name | | 715-60H.YW | 715-60M.YW |
| Reflector | 0.000" | 59.750" | 82.250" |
| Driven Element | 48.000" | 52.000" | 75.000" |
| Director 1 | 48.000" | 52.000" | 74.875" |
| Director 2 | 93.000" | 49.500" | 72.500" |
| Director 3 | 173.000" | 44.125" | 67.375" |
| Director 4 | 197.000" | 45.500" | 68.750" |
| Director 5 | 155.000" | 41.750" | 65.125" |
| Compensator | 12" behind Dir. 5 | 58.500" | 51.000" |

**Eight-element 15-meter Yagi, 80 foot boom**

| *Element* | *Spacing* | *Heavy-Duty Tip* | *Medium-Duty Tip* |
|---|---|---|---|
| File Name | | 815-80H.YW | 815-80M.YW |
| Reflector | 0.000" | 62.000" | 84.000" |
| Driven Element | 56.000" | 52.500" | 75.500" |
| Director 1 | 48.000" | 51.500" | 74.375" |
| Director 2 | 115.000" | 48.375" | 71.500" |
| Director 3 | 164.000" | 45.750" | 69.000" |
| Director 4 | 202.000" | 43.125" | 66.500" |
| Director 5 | 206.000" | 44.750" | 68.000" |
| Director 6 | 163.000" | 40.875" | 64.250" |
| Compensator | 12" behind Dir. 6 | 95.000" | 83.375" |

These 15-meter Yagi designs are optimized for > 20 dB F/R, and SWR < 2:1 over entire frequency range from 21.000 to 21.450 MHz, for heavy-duty elements (124 mph wind survival) and for medium-duty (86 mph wind survival). Only element tip dimensions are shown. See Fig 15D for element telescoping tubing schedule. All dimensions are in inches. Torque compensator element is made of 2.5" OD PVC water pipe placed 12" behind last director, and dimensions shown for compensators is one-half of total length, centered on boom.





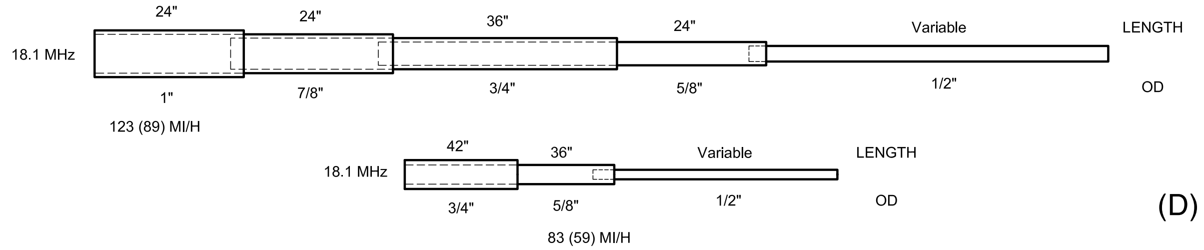


**Fig 16—Gain, F/R and SWR performance versus frequency for optimized 17-meter Yagis. At A, gain versus frequency is shown for six 17-meter Yagis whose booms range from 6 feet to 60 feet long. Except for the 2-element design, these Yagis have been optimized for better than 20 dB F/R and less than 2:1 SWR over the narrow 17-meter band 18.068 to 18.168 MHz. At B, front-to-rear ratio for these antennas is shown versus frequency, and at C, SWR over the frequency range is shown. At D, the taper schedule for heavy-duty and for medium-duty 10-meter elements is shown. The heavy-duty elements can withstand 123-mph winds without icing, and 89-mph winds with 1/4-inch radial ice. The medium-duty elements can survive 83-mph winds without icing, and 59-mph winds with 1/4-inch radial ice. The wall thickness for each telescoping section of 6061-T6 aluminum tubing is 0.058 inches, and the overlap at each telescoping junction is 3 inches.**

cover the narrow 12-meter band from 24.89 to 24.99 MHz, with SWR less than 2:1 and F/R better than 20 dB over that range.

Fig 14D shows the taper schedule for two types of 12-meter elements. The heavy-duty design can survive 123-mph winds with no icing, and 87-mph winds with 1/4 inch of radial ice. The medium-duty design can handle 85-mph winds with no icing, and 61-mph winds with 1/4 inch of radial ice. The element-to-boom mounting plate for these Yagis is a 0.375 inch thick flat aluminum plate, 5 inches wide by 6 inches long.

Electrically, each mounting plate is equivalent to a cylinder, with an effective diameter of 2.945 inches for the heavy-duty element, and 2.857 inches for the medium-duty element. The equivalent length on each side of the boom is 3 inches. As usual, the torque compensator is mounted 12 inches behind the last director.

## 15-METER YAGIS

**Fig 15** describes the electrical performance of eight optimized 15-meter Yagis with boom lengths between 6 feet to a spectacular 80 feet. The end of each boom includes 3 inches of space for the reflector and last-director (or driven element) mounting plates. Fig 15A shows the free-space gain versus frequency for each antenna; 15B shows the worst-case front-to-rear ratio, and 15C shows the SWR versus frequency. Each antenna with three or more elements was designed to cover the full 15-meter band from

**Table 4**
**Optimized 17-meter Yagi Designs**

**Two-element 17-meter Yagi, 6 foot boom**

| *Element* | *Spacing* | *Heavy-Duty Tip* | *Medium-Duty Tip* |
|---|---|---|---|
| File Name | | 217-06H.YW | 217-06M.YW |
| Reflector | 0.000" | 61.000" | 89.000" |
| Driven Element | 66.000" | 48.000" | 76.250" |

**Three-element 17-meter Yagi, 14 foot boom**

| *Element* | *Spacing* | *Heavy-Duty Tip* | *Medium-Duty Tip* |
|---|---|---|---|
| File Name | | 317-14H.YW | 317-14M.YW |
| Reflector | 0.000" | 61.500" | 91.500" |
| Driven Element | 65.000" | 52.000" | 79.500" |
| Director 1 | 97.000" | 46.000" | 73.000" |
| | 12" behind Dir. 1 | 12.625" | 10.750" |

**Four-element 17-meter Yagi, 20 foot boom**

| *Element* | *Spacing* | *Heavy-Duty Tip* | *Medium-Duty Tip* |
|---|---|---|---|
| File Name | | 417-20H.YW | 417-20M.YW |
| Reflector | 0.000" | 61.500" | 89.500" |
| Driven Element | 48.000" | 54.250" | 82.625" |
| Director 1 | 48.000" | 52.625" | 81.125" |
| Director 2 | 138.000" | 40.500" | 69.625" |
| Compensator | 12" behind Dir. 2 | 42.500" | 36.250" |

**Five-element 17-meter Yagi, 30 foot boom**

| *Element* | *Spacing* | *Heavy-Duty Tip* | *Medium-Duty Tip* |
|---|---|---|---|
| File Name | | 517-30H.YW | 517-30M.YW |
| Reflector | 0.000" | 61.875" | 89.875" |
| Driven Element | 48.000" | 52.250" | 80.500" |
| Director 1 | 52.000" | 49.625" | 78.250" |
| Director 2 | 93.000" | 49.875" | 78.500" |
| Director 3 | 161.000" | 43.500" | 72.500" |
| Compensator | 12" behind Dir. 3 | 54.375" | 45.875" |

**Six-element 17-meter Yagi, 48 foot boom**

| *Element* | *Spacing* | *Heavy-Duty Tip* | *Medium-Duty Tip* |
|---|---|---|---|
| File Name | | 617-48H.YW | 617-48M.YW |
| Reflector | 0.000" | 63.000" | 90.250" |
| Driven Element | 52.000" | 52.500" | 80.500" |
| Director 1 | 51.000" | 45.500" | 74.375" |
| Director 2 | 87.000" | 47.875" | 76.625" |
| Director 3 | 204.000" | 47.000" | 75.875" |
| Director 4 | 176.000" | 42.000" | 71.125" |
| Compensator | 12" behind Dir. 4 | 68.250" | 57.500" |

**Six-element 17-meter Yagi, 60 foot boom**

| *Element* | *Spacing* | *Heavy-Duty Tip* | *Medium-Duty Tip* |
|---|---|---|---|
| File Name | | 617-60H.YW | 617-60M.YW |
| Reflector | 0.000" | 61.250" | 89.250" |
| Driven Element | 54.000" | 54.750" | 83.125" |
| Director 1 | 54.000" | 52.250" | 80.750" |
| Director 2 | 180.000" | 46.000" | 74.875" |
| Director 3 | 235.000" | 44.625" | 73.625" |
| Director 4 | 191.000" | 41.500" | 70.625" |
| Compensator | 12" behind Dir. 4 | 62.875" | 53.000" |

These 17-m Yagi designs are optimized for > 20 dB F/R, and SWR < 2:1 over entire frequency range from18.068 to 18.168 MHz, for heavy-duty elements (123 mph wind survival) and for medium-duty (83 mph wind survival). Only element tip dimensions are shown. All dimensions are in inches. Torque compensator element is made of 2.5" OD PVC water pipe placed 12" behind last director, and dimensions shown for compensators is one-half of total length, centered on boom.

21.000 to 21.450 MHz, with SWR less than 2:1 and F/R ratio better than 20 dB over that range.

Fig 15D shows the taper schedule for two types of 15-meter elements. The heavy-duty design can survive 124-mph winds with no icing, and 90-mph winds with $^1/_4$ inch of radial ice. The medium-duty design can handle 86-mph winds with no icing, and 61-mph winds with $^1/_4$ inch of radial ice. The element-to-boom mounting plate for these Yagis is a 0.375-inch thick flat aluminum plate, 5 inches wide by 6 inches long.

Electrically, each mounting plate is equivalent to a cylinder, with an effective diameter of 3.0362 inches for

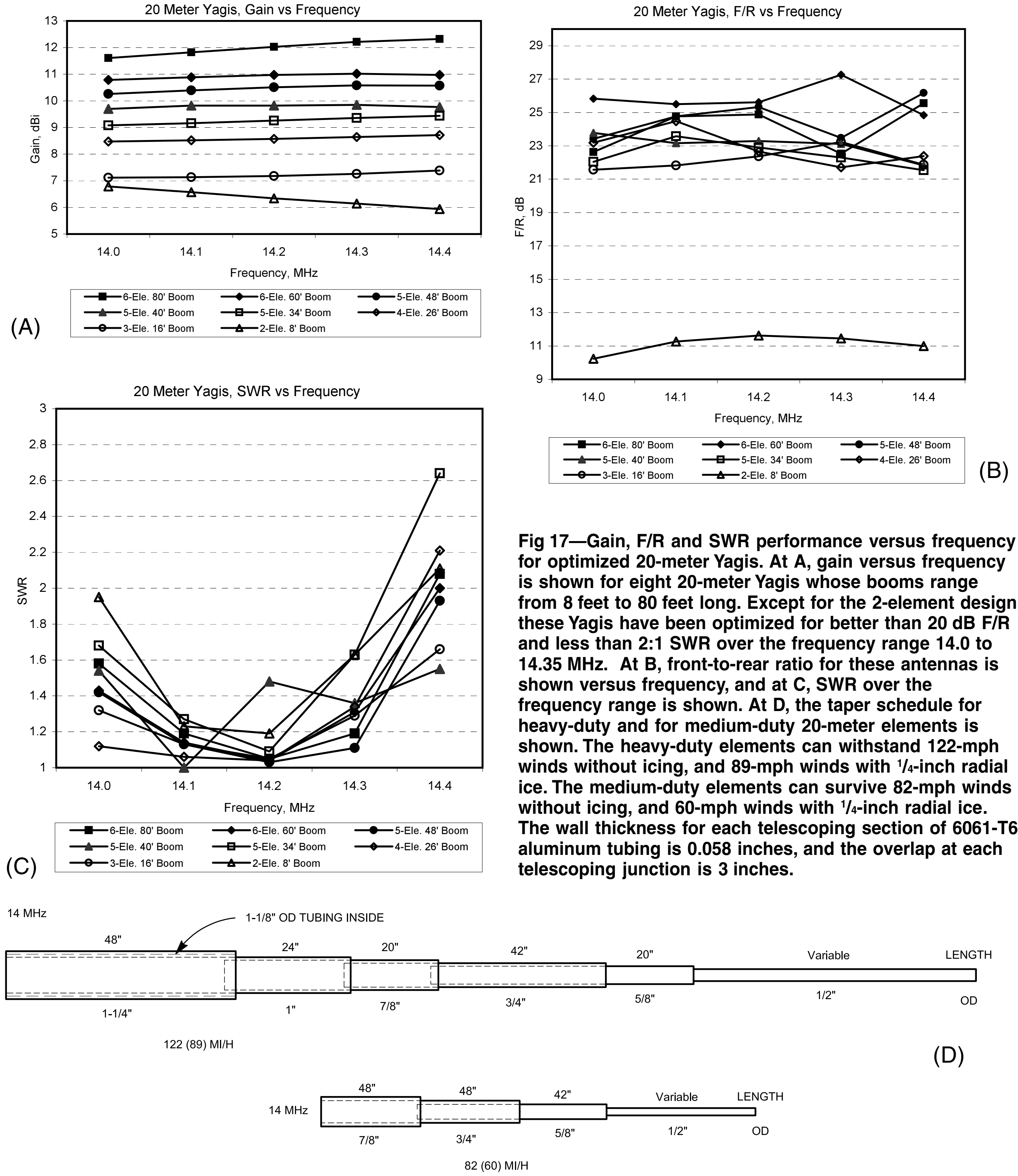


**Fig 17—Gain, F/R and SWR performance versus frequency for optimized 20-meter Yagis. At A, gain versus frequency is shown for eight 20-meter Yagis whose booms range from 8 feet to 80 feet long. Except for the 2-element design, these Yagis have been optimized for better than 20 dB F/R and less than 2:1 SWR over the frequency range 14.0 to 14.35 MHz. At B, front-to-rear ratio for these antennas is shown versus frequency, and at C, SWR over the frequency range is shown. At D, the taper schedule for heavy-duty and for medium-duty 20-meter elements is shown. The heavy-duty elements can withstand 122-mph winds without icing, and 89-mph winds with $^1/_4$-inch radial ice. The medium-duty elements can survive 82-mph winds without icing, and 60-mph winds with $^1/_4$-inch radial ice. The wall thickness for each telescoping section of 6061-T6 aluminum tubing is 0.058 inches, and the overlap at each telescoping junction is 3 inches.**

the heavy-duty element, and 2.9447 inches for the medium-duty element. The equivalent length on each side of the boom is 3 inches. As usual, the torque compensator is mounted 12 inches behind the last director.

## 17-METER YAGIS

**Fig 16** describes the electrical performance of six optimized 17-meter Yagis with boom lengths between 6 to a heroic 60 feet. As usual, the end of each boom includes 3 inches of space for the reflector and last director (or driven element) mounting plates. Fig 16A shows the free-space gain versus frequency for each an-

**Table 5**

**Optimized 20-Meter Yagi Designs**

**Two-element 20-meter Yagi, 8 foot boom**

| *Element* | *Spacing* | *Heavy-Duty Tip* | *Medium-Duty Tip* |
|---|---|---|---|
| File Name | | 220-08H.YW | 220-08M.YW |
| Reflector | 0.000" | 66.000" | 80.000" |
| Driven Element | 90.000" | 46.000" | 59.000" |

**Three-element 20-meter Yagi, 16 foot boom**

| *Element* | *Spacing* | *Heavy-Duty Tip* | *Medium-Duty Tip* |
|---|---|---|---|
| File Name | | 320-16H.YW | 320-16M.YW |
| Reflector | 0.000" | 69.625" | 81.625" |
| Driven Element | 80.000" | 51.250" | 64.500" |
| Director 1 | 106.000" | 42.625" | 56.375" |
| Compensator | 12" behind Dir. 1 | 33.375" | 38.250" |

**Four-element 20-meter Yagi, 26 foot boom**

| *Element* | *Spacing* | *Heavy-Duty Tip* | *Medium-Duty Tip* |
|---|---|---|---|
| File Name | | 420-26H.YW | 420-26M.YW |
| Reflector | 0.000" | 65.625" | 78.000" |
| Driven Element | 72.000" | 53.375" | 65.375" |
| Director 1 | 60.000" | 51.750" | 63.875" |
| Director 2 | 174.000" | 38.625" | 51.500" |
| Compensator | 12" behind Dir. 2 | 54.250" | 44.250" |

**Five-element 20-meter Yagi, 34 foot boom**

| *Element* | *Spacing* | *Heavy-Duty Tip* | *Medium-Duty Tip* |
|---|---|---|---|
| File Name | | 520-34H.YW | 520-34M.YW |
| Reflector | 0.000" | 68.625" | 80.750" |
| Driven Element | 72.000" | 52.250" | 65.500" |
| Director 1 | 71.000" | 45.875" | 59.375" |
| Director 2 | 68.000" | 45.875" | 59.375" |
| Director 3 | 191.000" | 37.000" | 51.000" |
| Compensator | 12" behind Dir. 3 | 69.250" | 56.250" |

**Five-element 20-meter Yagi, 40 foot boom**

| *Element* | *Spacing* | *Heavy-Duty Tip* | *Medium-Duty Tip* |
|---|---|---|---|
| File Name | | 520-40H.YW | 520-40M.YW |
| Reflector | 0.000" | 68.375" | 80.500" |
| Driven Element | 72.000" | 53.500" | 66.625" |
| Director 1 | 72.000" | 51.500" | 64.625" |
| Director 2 | 139.000" | 48.375" | 61.750" |
| Director 3 | 191.000" | 38.000" | 52.000" |
| Compensator | 12" behind Dir. 3 | 69.750" | 56.750" |

**Five-element 20-meter Yagi, 48 foot boom**

| *Element* | *Spacing* | *Heavy-Duty Tip* | *Medium-Duty Tip* |
|---|---|---|---|
| File Name | | 520-48H.YW | 520-48M.YW |
| Reflector | 0.000" | 66.250" | 78.500" |
| Driven Element | 72.000" | 53.000" | 66.000" |
| Director 1 | 88.000" | 50.500" | 63.750" |
| Director 2 | 199.000" | 47.375" | 60.875" |
| Director 3 | 211.000" | 39.750" | 53.625" |
| Compensator | 12" behind Dir. 3 | 70.325" | 57.325" |

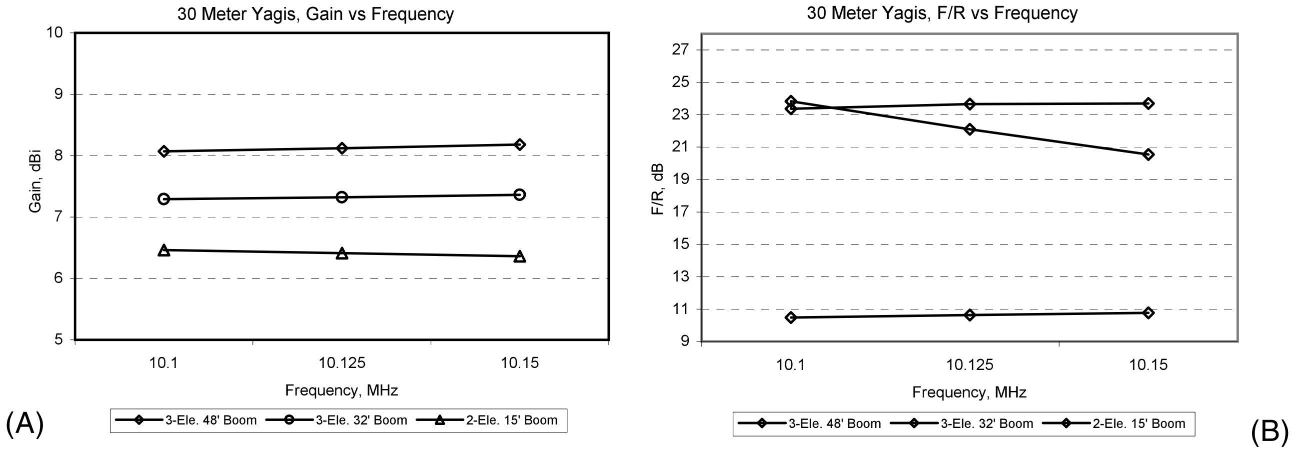
**Six-element 20-meter Yagi, 60 foot boom**

| *Element* | *Spacing* | *Heavy-Duty Tip* | *Medium-Duty Tip* |
|---|---|---|---|
| File Name | | 620-60H.YW | 620-60M.YW |
| Reflector | 0.000" | 67.000" | 79.250" |
| Driven Element | 84.000" | 51.500" | 65.000" |
| Director 1 | 91.000" | 45.125" | 58.750" |
| Director 2 | 130.000" | 41.375" | 55.125" |
| Director 3 | 210.000" | 46.875" | 60.375" |
| Director 4 | 199.000" | 39.125" | 53.000" |
| Compensator | 12" behind Dir. 4 | 72.875" | 59.250" |

**Six-element 20-meter Yagi, 80 foot boom**

| *Element* | *Spacing* | *Heavy-Duty Tip* | *Medium-Duty Tip* |
|---|---|---|---|
| File Name | | 620-80H.YW | 620-80M.YW |
| Reflector | 0.000" | 66.125" | 78.375" |
| Driven Element | 72.000" | 52.375" | 65.500" |
| Director 1 | 122.000" | 49.125" | 62.500" |
| Director 2 | 229.000" | 44.500" | 58.125" |
| Director 3 | 291.000" | 42.625" | 56.375" |
| Director 4 | 240.000" | 38.750" | 52.625" |
| Compensator | 12" behind Dir. 4 | 78.750" | 64.125" |

These 20-meter Yagi designs are optimized for > 20 dB F/R, and SWR < 2:1 over entire frequency range from 14.000 to 14.350 MHz, for heavy-duty elements (122 mph wind survival) and for medium-duty (82 mph wind survival). Only element tip dimensions are shown. See Fig 17 for element telescoping tubing schedule. All dimensions are in inches. Torque compensator element is made of 2.5" OD PVC water pipe placed 12" behind last director, and dimensions shown for compensators is one-half of total length, centered on boom.



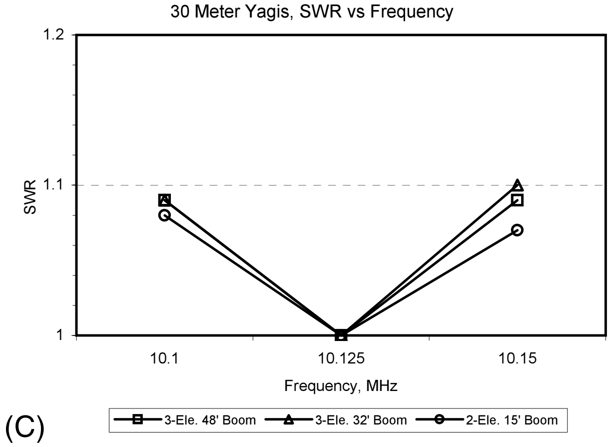
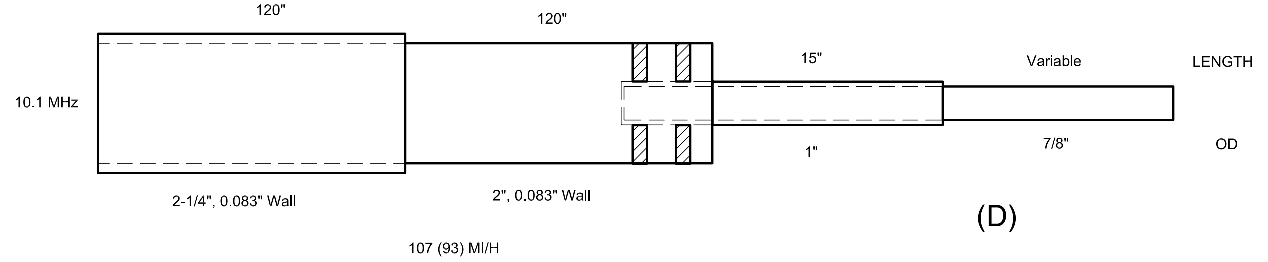


**Fig 18—Gain, F/R and SWR performance versus frequency for optimized 30-meter Yagis. At A, gain versus frequency is shown for three 30-meter Yagis whose booms range from 15 feet to 34 feet long, and which have been optimized for better than 10 dB F/R and less than 2:1 SWR over the frequency range 10.1 to 10.15 MHz. At B, front-to-rear ratio for these antennas is shown versus frequency, and at C, SWR over the frequency range is shown. At D, the taper schedule is shown for heavy-duty 30-meter elements, which can withstand 107-mph winds without icing, and 93-mph winds with $^1/_4$-inch radial ice. Except for the 2$^1/_4$-inch and 2-inch sections, which have 0.083 inch thick walls, the wall thickness for the other telescoping sections of 6061-T6 aluminum tubing is 0.058 inches, and the overlap at the 1 inch telescoping junction with the $^7/_8$-inch section is complete. The 2-inch section utilizes two machined aluminum reducers to accommodate the 1-inch tubing.**



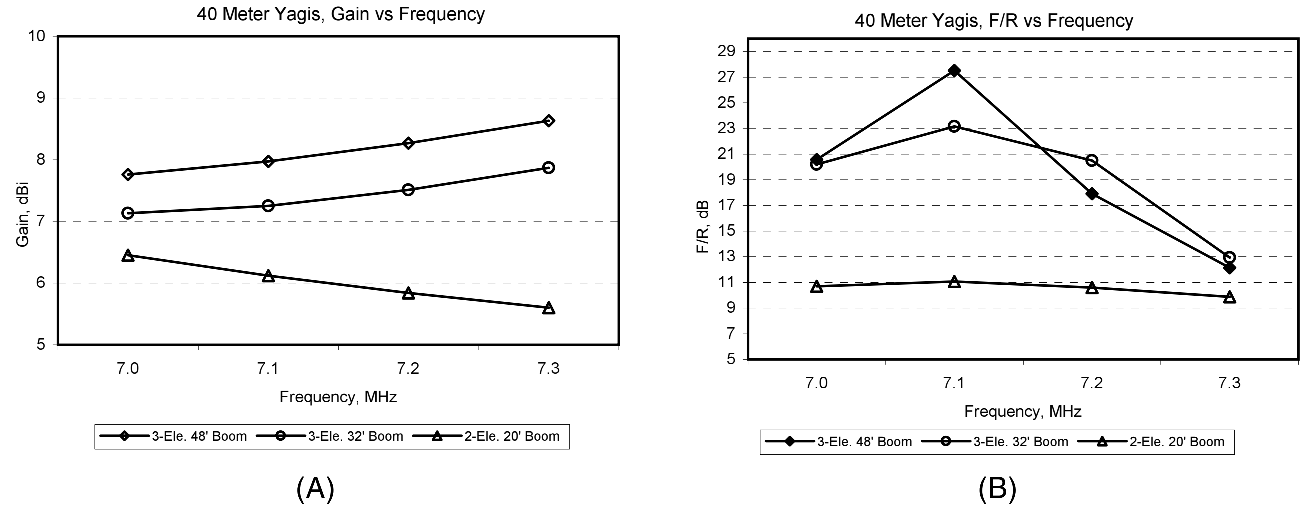
tenna; 16B shows the worst-case front-to-rear ratio, and 16C shows the SWR versus frequency. Each antenna with three or more elements was designed to cover the narrow 17-meter band from 18.068 to 18.168 MHz, with SWR less than 2:1 and F/R ratio better than 20 dB over that range.

Fig 16D shows the taper schedule for two types of 17-meter elements. The heavy-duty design can survive 123-mph winds with no icing, and 83-mph winds with $^1/_4$-inch of radial ice. The medium-duty design can handle 83-mph winds with no icing, and 59-mph winds with ¼ inch of radial ice.

The element-to-boom mounting plate for these Yagis is a 0.375-inch thick flat aluminum plate, 6 inches wide by 8 inches long. Electrically, each mounting plate is equivalent to a cylinder, with an effective diameter of 3.5122 inches for the heavy-duty element, and 3.3299 inches for the medium-duty element. The equivalent length on each side of the boom is 4 inches. As usual, the torque compensator is mounted 12 inches behind the last director.

## 20-METER YAGIS

**Fig 17** describes the electrical performance of eight optimized 20-meter Yagis with boom lengths between 8 to a giant 80 feet. As usual, the end of each boom includes 3 inches of space for the reflector and last director (driven element) mounting plates. Fig 17A shows the free-space gain versus frequency for each antenna; 17B shows the front-to-rear ratio, and 17C shows the SWR versus frequency. Each antenna with three or more ele-



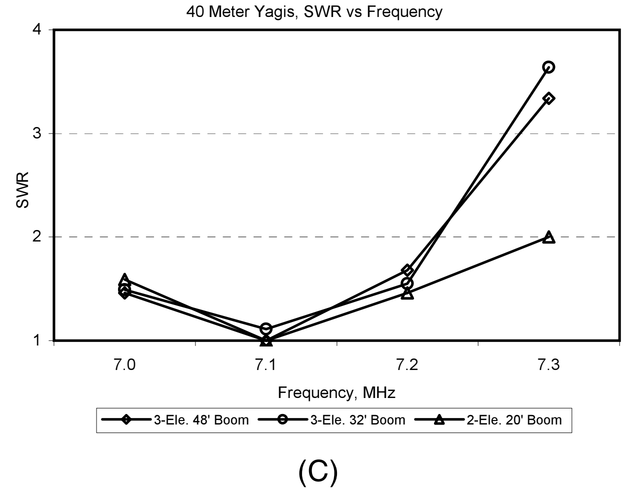
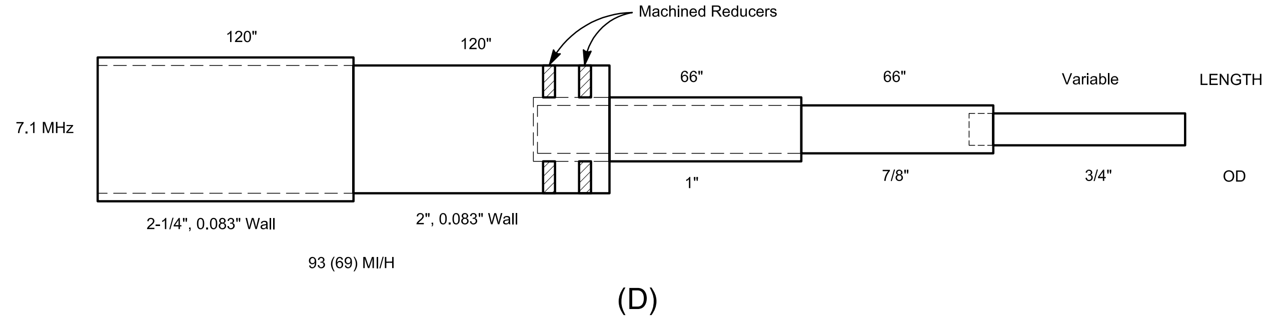


**Fig 19—Gain, F/R and SWR performance versus frequency for optimized 40-meter Yagis. At A, gain versus frequency is shown for three 40-meter Yagis whose booms range from 20 feet to 48 feet long, and which have been optimized for better than 10 dB F/R and less than 2:1 SWR over the frequency range 7.0 to 7.2 MHz. At B, front-to-rear ratio for these antennas is shown versus frequency, and at C, SWR over the frequency range is shown. At D, the taper schedule is shown for heavy-duty 40-meter elements, which can withstand 107-mph winds without icing, and 93-mph winds with $\frac{1}{4}$-inch radial ice. Except for the $2\frac{1}{4}$-inch and 2-inch sections, which have 0.083 inch thick walls, the wall thickness for the other telescoping sections of 6061-T6 aluminum tubing is 0.058 inches, and the overlap at the end telescoping junction is 3 inches. The 2-inch section utilizes two machined aluminum reducers to accommodate the 1-inch tubing.**



ments was designed to cover the complete 20-meter band from 14.000 to 14.350 MHz, with SWR less than 2:1 and F/R ratio better than 20 dB over that range.

Fig 17D shows the taper schedule for two types of 20-meter elements. The heavy-duty design can survive 122-mph winds with no icing, and 89-mph winds with $\frac{1}{4}$ inch of radial ice. The medium-duty design can handle 82-mph winds with no icing, and 60-mph winds with $\frac{1}{4}$ inch of radial ice. The element-to-boom mounting plate for these Yagis is a 0.375-inch thick flat aluminum plate, 6 inches wide by 8 inches long. Electrically, each mounting plate is equivalent to a cylinder, with an effective diameter of 3.7063 inches for the heavy-duty element, and 3.4194 inches for the medium-duty element. The equivalent length on each side of the boom is 4 inches. As usual, the torque compensator is mounted 12 inches behind the last director.

## 30-METER YAGIS

**Fig 18** describes the electrical performance of three

**Table 6**
**Optimized 30-Meter Yagi Designs**

**Two-element 30-meter Yagi, 15 foot boom**

| *Element* | *Spacing* | *Heavy-Duty Tip* |
|---|---|---|
| File Name | | 230-15H.YW |
| Reflector | 0.000" | 50.250" |
| Driven Element | 174.000" | 14.875" |

**3-element 30-meter Yagi, 22 foot boom**

| *Element* | *Spacing* | *Heavy-Duty Tip* |
|---|---|---|
| File Name | | 330-22H.YW |
| Reflector | 0.000 | 59.375 |
| Driven Element | 135.000 | 35.000 |
| Director 1 | 123.000 | 19.625 |

**Three-element 30-meter Yagi, 34 foot boom**

| *Element* | *Spacing* | *Heavy-Duty Tip* |
|---|---|---|
| File Name | | 330-34H.YW |
| Reflector | 0.000" | 53.750" |
| Driven Element | 212" | 29.000" |
| Director 1 | 190" | 14.500" |

These 30-m Yagi designs are optimized for > 10 dB F/R, and SWR < 2:1 over entire frequency range from 10.100 to 10.150 MHz for heavy-duty elements (105 mph wind survival). Only element tip dimensions are shown. See Fig 18D for element telescoping tubing schedule. All dimensions are in inches. No torque compensator element is required.

**Table 7**
**Optimized 40-Meter Yagi Designs**

**Two-element 40-meter Yagi, 20 foot boom**

| *Element* | *Spacing* | *Heavy-Duty Tip* |
|---|---|---|
| File Name | | 240-20H.YW |
| Reflector | 0.000" | 85.000" |
| Driven Element | 234.000" | 35.000" |

**Three-element 40-meter Yagi, 32 foot boom**

| *Element* | *Spacing* | *Heavy-Duty Tip* |
|---|---|---|
| File Name | | 340-32H.YW |
| Reflector | 0.000" | 90.750" |
| Driven Element | 196.000" | 55.875" |
| Director 1 | 182.000" | 33.875" |

**Three-element 40-meter Yagi, 48 foot boom**

| *Element* | *Spacing* | *Heavy-Duty Tip* |
|---|---|---|
| File Name | | 340-48H.YW |
| Reflector | 0.000" | 81.000" |
| Driven Element | 300.000" | 45.000" |
| Director 1 | 270.000" | 21.000" |

These 40-m Yagi designs are optimized for > 10 dB F/R, and SWR < 2:1 over low-end of frequency range from 7.000 to 7.200 MHz, for heavy-duty elements (95 mph wind survival). Only element tip dimensions are shown. See Fig 19D for element telescoping tubing schedule. All dimensions are in inches. No wind torque compensator is required.

optimized 30-meter Yagis with boom lengths between 15 to 34 feet. Because of the size and weight of the elements alone for Yagis on this band, only 2-element and 3-element designs are described. The front-to-rear ratio requirement for the 2-element antenna is relaxed to be greater than 10 dB over the band from 10.100 to 10.150 MHz, while that for the 3-element designs is kept at greater than 20 dB over that frequency range.

As usual, the end of each boom includes 3 inches of space for the reflector and last director mounting plates. Fig 18A shows the free-space gain versus frequency for each antenna; 18B shows the worst-case front-to-rear ratio, and 18C shows the SWR versus frequency.

Fig 18D shows the taper schedule for the 30-meter elements. Note that the wall thickness of the first two sections of tubing is 0.083 inches, rather than 0.058 inches. This heavy-duty element design can survive 107-mph winds with no icing, and 93-mph winds with 1/4 inch of radial ice. The element-to-boom mounting plate for these Yagis is a 0.500-inch thick flat aluminum plate, 6 inches wide by 24 inches long. Electrically, each mounting plate is equivalent to a cylinder, with an effective diameter of 4.684 inches. The equivalent length on each side of the boom is 12 inches. These designs require no torque compensator.

## 40-METER YAGIS

**Fig 19** describes the electrical performance of three optimized 40-meter Yagis with boom lengths between 20 to 48 feet. Like the 30-meter antennas, because of the size and weight of the elements for a 40-meter Yagi, only 2-element and 3-element designs are described. The front-to-rear ratio requirement for the 2-element antenna is relaxed to be greater than 10 dB over the band from 7.000 to 7.300 MHz, while the goal for the 3-element designs is 20 dB over the frequency range of 7.000 to 7.200 MHz. It is exceedingly difficult to hold the F/R greater than 20 dB over the entire 40-meter band without sacrificing excessive gain with a 3-element design.

As usual, the end of each boom includes 3 inches of space for the reflector and last director mounting plates. Fig 19A shows the free-space gain versus frequency for each antenna; 19B shows the front-to- rear ratio, and 19C shows the SWR versus frequency.

Fig 19D shows the taper schedule for the 40-meter elements. Note that the wall thickness of the first two sections of tubing is 0.083 inches, rather than 0.058 inches. This element design can survive 93-mph winds with no icing, and 69-mph winds with 1/4 inch of radial ice. The element-to-boom mounting plate for these Yagis is a 0.500-inch thick flat aluminum plate, 6 inches wide by 24 inches long. Electrically each mounting plate is equivalent to a cylinder, with an effective diameter of 4.684 inches. The equivalent length on each side of the boom is 12 inches. These designs require no torque compensator.

# Modifying Monoband Hy-Gain Yagis

Enterprising amateurs have long used the Telex Communications Hy-Gain "Long John" series of HF monobanders as a source of top-quality aluminum and hardware for customized Yagis. Often-modified older models include the 105BA for 10 meters, the 155BA for 15 meters, and the 204BA and 205BA for 20 meters. Newer Hy-Gain designs, the 105CA, 155CA and 205CA, have been redesigned by computer for better performance.

Hy-Gain antennas have historically had an excellent reputation for superior mechanical design, and Hy-Gain proudly points out that many of their monobanders are still working after more than 30 years. In the older designs the elements were purposely spaced along the boom to achieve good weight balance at the mast-to-boom bracket, with electrical performance as a secondary goal. Thus, the electrical performance was not necessarily optimum, particularly over an entire amateur band. Newer Hy-Gain designs are electrically superior to the older ones, but because of their strong concern for weight-balance are still not optimal by the definitions used in this chapter.

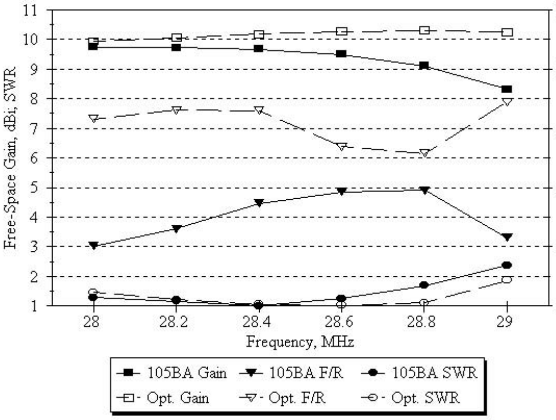


**Fig 20—Gain, F/R and SWR over the 28.0 to 28.8 MHz range for original and optimized Yagis using Hy-Gain hardware. Original 105BA design provided excellent weight balance at boom-to-mast bracket, but compromised the electrical performance somewhat because of non-optimum spacing of elements. Optimized design requires wind torque-balancing compensator element, and compensating weight at director end of boom to rebalance weight. The F/R ratio over the frequency range for the optimized design is more than 23 dB. Each element uses the original Hy-Gain taper schedule and element-to-boom clamp, but the length of the tip is changed per Table 8.**

**Table 8**

**Optimized Hy-Gain 20-Meter Yagi Designs**

**Optimized 204BA, Four-element 20-meter Yagi, 26 foot boom**

| *Element* | *Spacing* | *Element Tip* |
|---|---|---|
| File Name | | BV204CA.YW |
| Reflector | 0.000" | 56.000" |
| Driven Element | 85.000" | 52.000" |
| Director 1 | 72.000" | 61.500" |
| Director 2 | 149.000" | 50.125" |

**Optimized 205CA, Five-element 20-meter Yagi, 34 foot boom**

| *Element* | *Spacing* | *Element Tip* |
|---|---|---|
| File Name | | BV205CA.YW |
| Reflector | 0.000" | 62.625" |
| Driven Element | 72.000" | 53.500" |
| Director 1 | 72.000" | 63.875" |
| Director 2 | 74.000" | 61.625" |
| Director 3 | 190.000" | 55.000" |

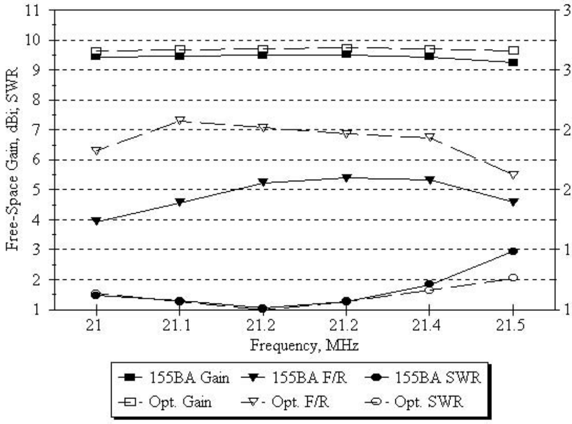


**Fig 21—Gain, F/R and SWR over the 21.0 to 21.45 MHz band for original and optimized Yagis using Hy-Gain hardware. Original 155BA design provided excellent weight balance at boom-to-mast bracket, but compromised the electrical performance somewhat because of non-optimum spacing of elements. Optimized design requires wind torque-balancing compensator element, and compensating weight at director end of boom to rebalance weight. The F/R ratio over the frequency range for the optimized design is more than 22 dB. Each element uses the original Hy-Gain taper schedule and element-to-boom clamp, but the length of the tip is changed per Table 9.**

**Table 9**

**Optimized Hy-Gain 15-Meter Yagi Designs**

**Optimized 155BA, Five-element 15-meter Yagi, 24 foot boom**

| *Element* | *Spacing* | *Element Tip* |
|---|---|---|
| File Name | | BV155CA.YW |
| Reflector | 0.000" | 64.000" |
| Driven Element | 48.000" | 65.500" |
| Director 1 | 48.000" | 63.875" |
| Director 2 | 82.750" | 61.625" |
| Director 3 | 127.250" | 55.000" |

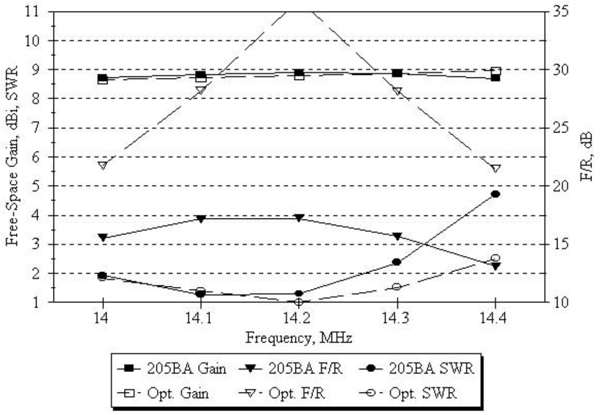


**Fig 22—Gain, F/R and SWR over the 14.0 to 14.35 MHz band for original and optimized Yagis using Hy-Gain hardware. Original 205BA design provided good weight balance at boom-to-mast bracket, but compromised the electrical performance because of non-optimum spacing of elements. Optimized design requires wind torque-balancing compensator element, and compensating weight at director end of boom to rebalance weight. The F/R ratio over the frequency range for the optimized design is more than 23 dB, while the original design never went beyond 17 dB of F/R. Each element uses the original Hy-Gain taper schedule and element-to-boom clamp, but the length of the tip is changed per Table 10.**

**Table 10**
**Optimized Hy-Gain 10-Meter Yagi Designs**

**Optimized 105BA, Five-element 10-meter Yagi, 24 foot boom**

| *Element* | *Spacing, inches* | *Element Tip* |
|---|---|---|
| File Name | | BV105CA.YW |
| Reflector | 0.000" | 44.250" |
| Driven Element | 40.000" | 53.625" |
| Director 1 | 40.000" | 52.500" |
| Director 2 | 89.500" | 50.500" |
| Director 3 | 112.250" | 44.750" |

With the addition of wind torque-compensation dummy elements, and with extra lead weights, where necessary, at the director end of the boom for weight-balance, the electrical performance can be enhanced, using the same proven mechanical parts.

**Fig 20** shows the computed gain, F/R ratio and SWR for a 24-foot boom, 10-meter optimized Yagi (modified 105BA) using Hy-Gain hardware. **Fig 21** shows the same for a 26-foot boom 15-meter Yagi (modified 155BA), and **Fig 22** shows the same for a 34-foot boom (modified 205BA) 20-meter Yagi. **Tables 8** through **10** show dimensions for these designs. The original Hy-Gain taper schedule is used for each element. Only the length of the end tip (and the spacing along the boom) is changed for each element.

# Multiband Yagis

So far, this chapter has discussed monoband Yagis—that is, Yagis designed for a single Amateur-Radio frequency band. Because hams have operating privileges on more than one band, multiband coverage has always been very desirable.

## INTERLACING ELEMENTS

In the late 1940s, some experimenters tried interlacing Yagi elements for different frequencies on a single boom, mainly to cover the 10 and 20-meter bands (at that time the 15-meter band wasn't yet available to hams). The experimenters discovered, to their considerable chagrin, that the mutual interactions between different elements tuned to different frequencies are very difficult to handle.

Adjusting a lower-frequency element usually results in interaction with higher-frequency elements near it. In effect, the lower-frequency element acts like a retrograde reflector, throwing off the effectiveness of the higher-frequency directors nearby. Element lengths and the spacing between elements can be changed to improve performance of the higher-frequency Yagi, but the resulting compromise is rarely equal to that of an optimized monoband Yagi. A reasonable compromise for portable operation may be found in Chapter 15, Portable Antennas, by VE7CA.

## TRAPPED MULTIBANDERS

Multiband Yagis using a single boom can also be made using traps. Traps allow an element to have multiple resonances. See Chapter 7, Multiband Antennas, for details on trap designs. Commercial vendors have sold trapped antennas to hams since the 1950s and surveys show that after simple wire dipoles and multiband verticals, trapped triband Yagis are the most popular antennas in the Amateur Radio service.

The originator of the trapped tribander was Chester Buchanan, W3DZZ, in his Mar 1955 *QST* article, "The Multimatch Antenna System." On 10 meters this rather unusual tribander used two reflectors (one dedicated and one with traps) and two directors (one dedicated and one with traps). On 20 and 15 meters three of the five elements were active using traps. The W3DZZ tribander employed 12 traps overall, made with heavy wire and concentric tubular capacitors to hold down losses in the traps. Each trap was individually fine tuned after construction before mounting it on an element.

Another example of a homemade tribander was the 26-foot boom 7-element 20/15/10-meter design described by Bob Myers, W1XT (ex-W1FBY) in Dec 1970 *QST*. The W1FBY tribander used only two sets of traps in the driven element, with dedicated reflectors and directors for each frequency band. Again, the traps were quite robust in this design to minimize trap losses, using 7/16-inch aluminum tubing for the coils and short pieces of RG-8 coax as high-voltage tuning capacitors.

Only a relatively few hams actually built tribanders for themselves, mainly because of the mechanical complexity and the close tolerances required for such antennas. The traps themselves must be constructed quite accurately for reproducible results, and they must be carefully weatherproofed for long life in rain, snow, and often polluted or corrosive atmospheres.

### Christmas Tree Stacks

Another possible method for achieving multiband coverage using monoband Yagis is to stack them in a "Christmas tree" arrangement. See **Fig 23**. For an installation covering 20, 15 and 10 meters, you could mount on the rotating mast just at the top of the tower the 20-meter monobander. Then perhaps 9 feet above that you would mount the 15-meter monobander, followed by the 10-meter monoband Yagi 7 feet further up on the mast. Another configuration would be to place the 10-meter Yagi in between the lower 20-meter and upper 15-meter Yagis. Whatever the arrangement, the antenna in the middle of such a Christmas-tree always suffers the most interaction from the lowest-frequency Yagi.

Dave Leeson, W6NL (ex-W6QHS), mentions that the 10-meter Yagi in his closely stacked Christmas Tree (15 meters at the top, 10 meters in the middle, and 20 meters at the bottom of the rotating mast) loses "substantial gain" because of serious interaction with the 20-meter antenna. (N6BV and K1VR calculated that the free-space gain in the W6NL stack drops to 5 dBi, compared to about 9 dBi with no surrounding antennas.) Monobanders are *definitely not* universally superior to tribanders in multiband installations. In private conversations, W6NL has indicated that he would not repeat this kind of short Christmas Tree installation again.

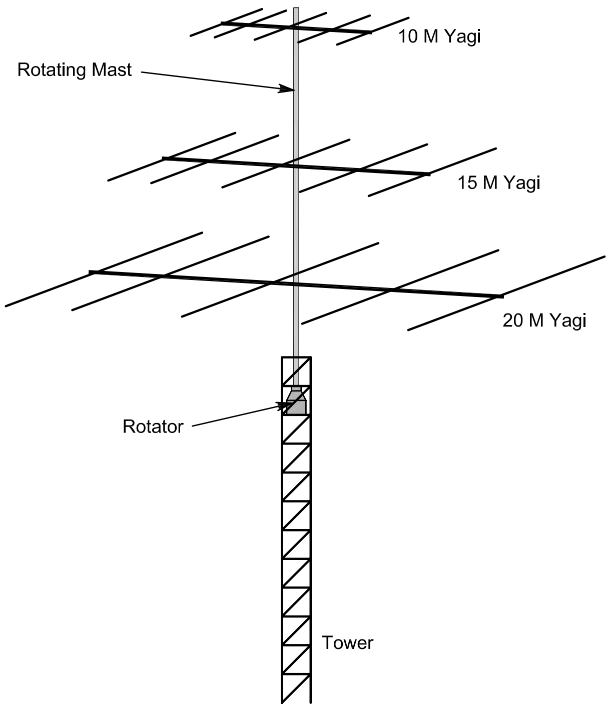


**Fig 23—"Christmas Tree" stack of 20/15/10-meter Yagis spaced vertically on a single rotating mast.**

### Forward Staggering

Some hams have built multiband Yagis on a common boom, using a technique called *forward staggering*. This means that that most (or all) of the higher-frequency elements are placed in front of any lower-frequency elements—in other words, most of the elements are not interlaced. Richard Fenwick, K5RR, described his triband Yagi design in Sep 1996 *QEX* magazine. This uses forward-stagger and open-sleeve design techniques and was optimized using several sophisticated modeling programs.

Fenwick's tribander used a 57-foot, 3-inch OD boom to hold 4 elements on 20 meters, 4 elements on 15 meters and 5 elements on 10 meters. **Fig 24** shows the element placement for the K5RR tribander. Most hams, of course, don't have the real-estate or the large rotator needed to turn such a large, but elegant solution to the interaction problem!

#### Force 12 C3 "Multi-Monoband" Triband Yagi

Antenna manufacturer Force 12 also uses forward-stagger layouts and patented combinations of open- and closed-sleeve drive techniques extensively in their product line of multiband antennas, which they call "multi-monoband Yagis." **Fig 25** shows the layout for the popular Force 12 C3 triband Yagi. The C3 uses no traps, thereby avoiding any losses due to traps. The C3 consists of three 2-element Yagis on an 18-foot boom, using full-sized elements designed to withstand high winds.

The C3 feed system employs open-sleeves, where the 20-meter driver element is fed with coax through a common-mode current balun and parasitically couples to the closely spaced 15-meter driver and the two 10-meter drivers to yield a feed-point impedances close to 50 Ω on all three bands. See the section on open-sleeve dipoles in Chapter 7, Multiband Antennas.

Note the use of the forward-stagger technique in the C3, especially on 10 meters. To reduce interaction with

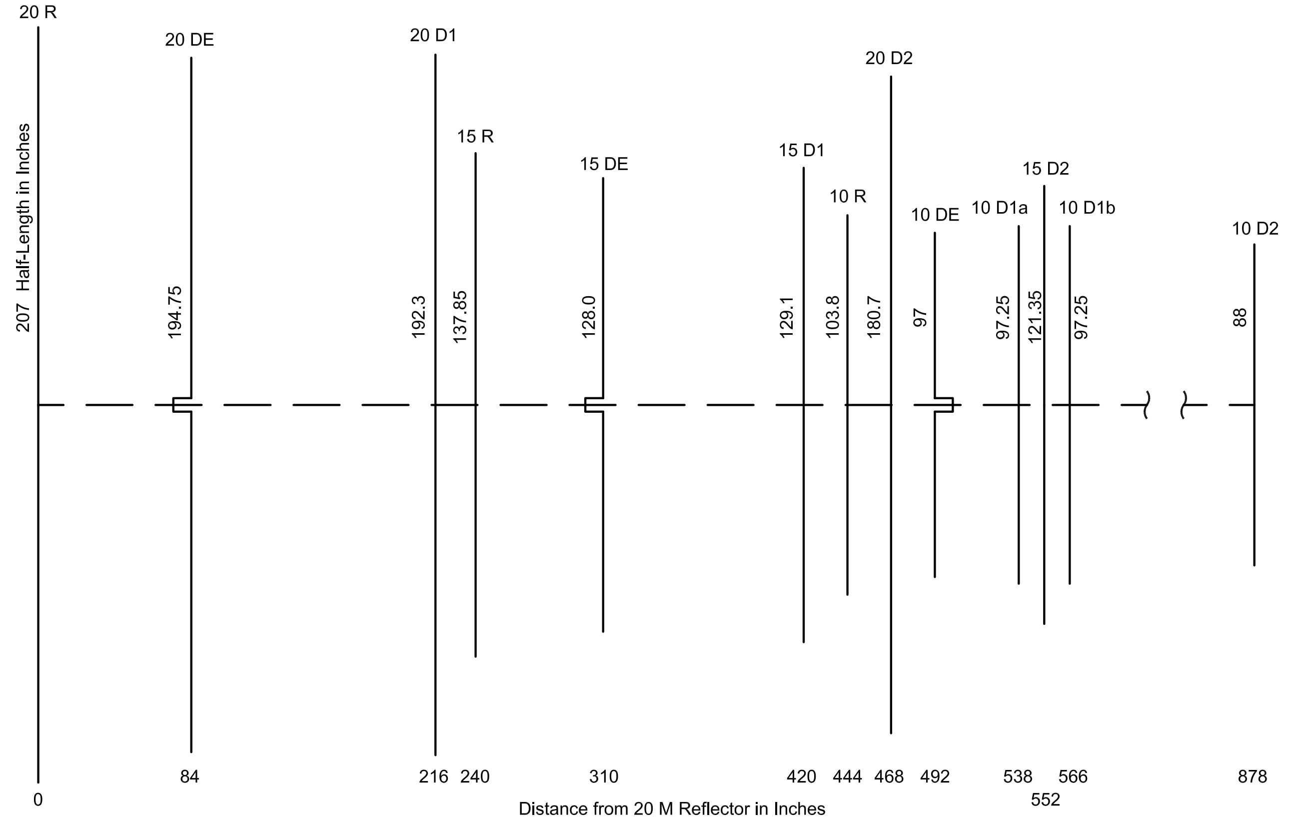


**Fig 24—Dimensions of K5RR's trapless tribander using "forward stagger" and open-sleeve techniques to manage interaction between elements for different frequencies.**

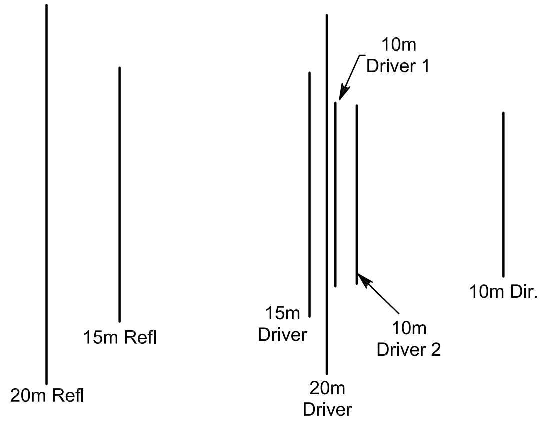


**Fig 25—Layout of Force 12 C3 multiband Yagi. Note that the 10-meter (driver/director) portion of the antenna is "forward staggered" ahead of the 15-meter (reflector/driver) portion, which in turn is placed ahead of the 20-meter (reflector/driver) portion. The antenna is fed at the 20-meter driver, which couples parasitically to the 15-meter driver and the two 10-meter drivers.**

the lower-frequency elements behind it, the 10-meter portion of the C3 is mounted on the boom ahead of all the lower-frequency elements, with the main 10-meter parasitic element (#7) acting as a director. The lower-frequency elements behind the 10-meter section act as retrograde reflectors, gaining some improvement of the gain and pattern compared to a monoband 2-element Yagi. A simplified *EZNEC* model of the C3 is included on the CD-ROM accompanying this book.

On 15 meters, the main parasitic element (#2) is a dedicated reflector, but the other elements ahead on the boom act like retrograde directors to improve the gain and pattern somewhat over a typical 2-element Yagi with a reflector. On 20 meters, the C3 is a 2-element Yagi with a dedicated reflector (#1) at the back end of the boom.

The exact implementation of any Yagi, of course, depends on the way the elements are constructed using telescoping aluminum tubing. The C3 type of design is no exception.

# Stacked Yagis

Monoband parasitic arrays are commonly stacked either in broadside or collinear fashion to produce additional directivity and gain. In HF amateur work, the most common broadside stack is a vertical stack of identical Yagis on a single tower. This arrangement is commonly called a *vertical stack*. At VHF and UHF, amateurs often employ collinear stacks, where identical Yagis are stacked side-by-side at the same height. This arrangement is called a *horizontal stack*, and is not usually found at HF, because of the severe mechanical difficulties involved with large, rotatable side-by-side arrays.

**Fig 26** illustrates the two different stacking arrangements. In either case, the individual Yagis making up the stack are generally fed in phase. There are times, however, when individual antennas in a stacked array are purposely fed out of phase in order to emphasize a particular elevation pattern. See Chapter 17, Repeater Antenna Systems, for such a case where elevation pattern steering is implemented for a repeater station.

Let's look at the reasons hams stack Yagis:

- For more gain
- For a wider elevation footprint in a target geographical area
- For azimuthal diversity—two or more directions at once
- For less fading
- For less precipitation static

## STACKS AND GAIN

**Fig 27** compares the elevation responses for three antenna systems of 4-element 15-meter Yagis. The response for the single Yagi at a height of 120 feet peaks at an elevation of about 5°, with a second peak at 17° and a third at 29°. When operated by itself, the 60-foot high Yagi has its first peak at about 11° and its second peak beyond 34°.

The basic principle of a vertically stacked HF array is that it takes energy from higher-angle lobes and concentrates that energy into the main elevation lobe. The main lobe of the 120/60-foot stack peaks about 7° and is about 2 dB stronger than either the 60- or 120-foot antenna by itself. The shape of the left-hand side of the stack's main lobe is determined mainly by the 120-foot antenna's response. The right-hand side of the stack's main lobe is "stretched" rightwards (toward higher angles) mainly by the 60-foot Yagi, while the shape follows the curve of the 120-foot Yagi.

Look at the second and third lobes of the stack, which appear about 18° and 27°. These are about 14 dB down from the stack's peak gain, showing that energy has indeed been extracted from them. By contrast, look at the levels of the second and third lobes for the individual Yagis at 60 and 120 feet. These higher-angle lobes are almost as strong as the first lobes.

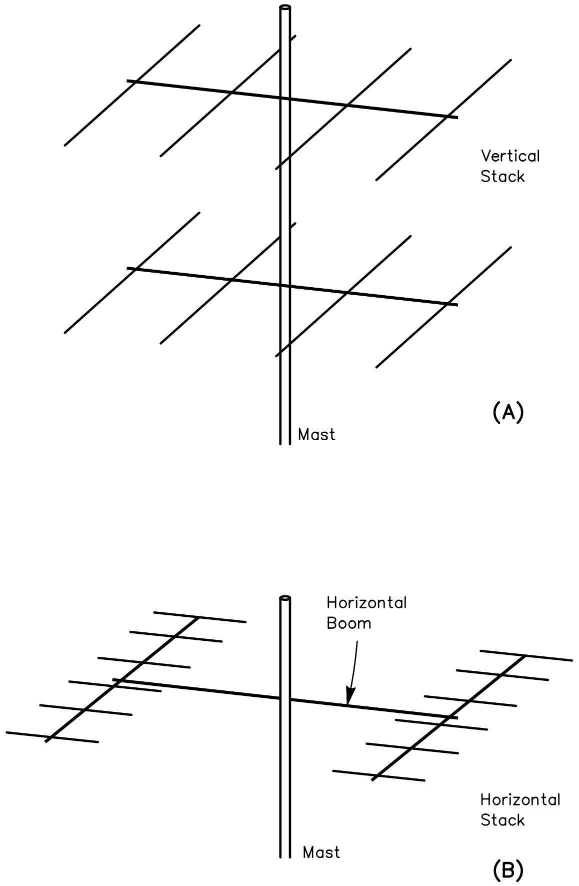


**Fig 26—Stacking arrangements. At A, two Yagis are stacked vertically (broadside) on the same mast. At B, two Yagis are stacked horizontally (collinear) side-by-side. At HF the vertical stack is more common because of mechanical difficulties involved with large HF antennas stacked side-by-side, whereas at VHF and UHF the horizontal stack is common.**

The stack squeezes higher-angle energy into its main elevation lobe, while maintaining the frontal lobe azimuth pattern of a single Yagi. This is the reason why many state-of-the-art contest stations are stacking arrays of relatively short-boom antennas, rather than stacking long-boom, higher-gain Yagis. A long-boom HF Yagi narrows the azimuthal pattern (and the elevation pattern too), making pointing the antenna more critical and making it more difficult to spread a signal over a wide azimuthal area, such as all of Europe and Asiatic Russia at one time.

## STACKS AND WIDE ELEVATION FOOTPRINTS

Detailed studies using sophisticated computer models of the ionosphere have revealed that coverage

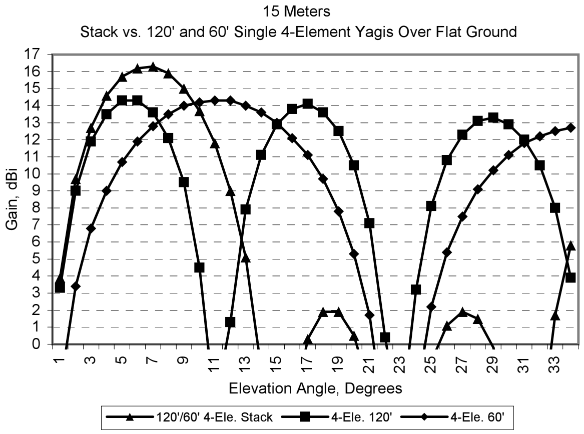


**Fig 27—Comparison of elevation patterns on 15 meters for a stack of 4-element Yagis at 120 and 60 feet and individual Yagis at those two heights. The shape of the stack's response is determined mainly by that of the top antenna.**

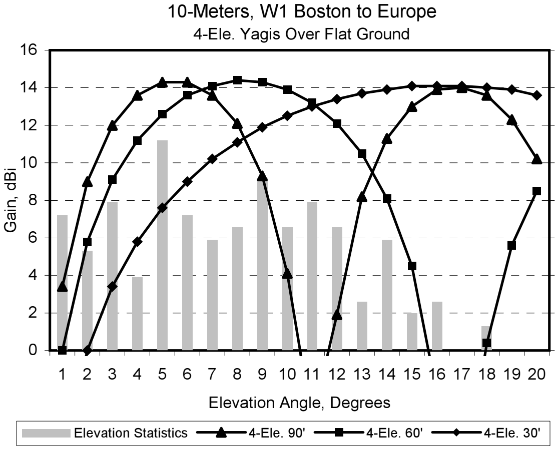


**Fig 28—Comparison of elevation patterns and elevation-angle statistics for individual 10-meter TH7DX tribanders mounted over flat ground aiming from New England to Europe. No single antenna can cover the wide range of angles needed—from 1° to 18°.**

of a wide range of elevation angles is necessary to ensure consistent DX or contest coverage on the HF bands. These studies have been conducted over all phases of the 11-year solar cycle, and for numerous transmitting and receiving QTHs throughout the world.

Chapter 23, Radio Wave Propagation, covers these studies in more detail, and the CD-ROM accompanying this book contains a huge number of elevation-angle statistical tables for locations all around the world. The *HFTA* (HF Terrain Assessment) program on the CD-ROM can not only compute antenna elevation patterns over irregular local terrain, but it can compare them directly to the elevation-angle statistics for a particular target geographic area.

### A 10-Meter Example

**Fig 28** shows the 10-meter elevation-angle statistics for the New England path from Boston, Massachusetts, to all of the continent of Europe. The statistics are overlaid with the computed elevation response for three individual 4-element Yagis, at three heights: 90, 60 and 30 feet above flat ground. In terms of wavelength, these heights are 2.60 λ, 1.73 λ and 0.86 λ high.

You can see that the 90-foot high Yagi covers the lower elevation angles best, but it has a large null in its response centered at about 11°. This null puts a big hole in the coverage for some 22% of all the times the 10-meter band is open to Europe. At those angles where the 90-foot Yagi exhibits a null, the 60-foot Yagi would be effective, and so would the 30-foot Yagi. If that is the only antenna you have, the 90-foot high Yagi would be too high for good coverage of Europe from New England.

The peak statistical elevation angle into Europe is 5°, and this occurs about 11% of all the times the 10-meter band is open to Europe from Boston. At an elevation of 5° the 30-foot high Yagi would be down almost 7 dB compared to the 90-foot high Yagi, but at 11° the 90-foot Yagi would be more than 22 dB down from the 30-foot Yagi. There is no single height at which one Yagi can optimally cover all the necessary elevation angles, especially to a large geographic area such as Europe—although the 60-foot high antenna is arguably the best compromise for a single height. To cover all the possibilities to Europe, however, you need a 10-meter antenna system that can cover equally well the entire range of elevation angles from 1° to 18°.

**Fig 29** compares elevation-angle statistics for two 10-meter paths from New England to Europe and to Japan. The elevation angles needed for communications with the Far East are very low. Overlaid on Fig 29 for comparison are the elevation responses over flat ground for three different antenna systems, using identical 4-element Yagis:

- Three Yagis, stacked at 90, 60 and 30 feet
- Two Yagis, stacked at 70 and 40 feet
- One Yagi at 90 feet.

The best coverage of all the necessary angles on 10 meters to Europe is with the stack of three Yagis at 90/60/30 feet. The two-Yagi stack at 70 and 40 feet comes in a close second to Europe, and for elevation angles higher than about 9° the 70/40-foot stack is actually superior to the 90/60/30-foot stack.

Both of the stacks illustrated here give a wider *elevation footprint* than any single antenna, so that all the angles can be covered automatically without having to switch from higher to lower antennas manually. This is perhaps the major benefit of using stacks, but not the only

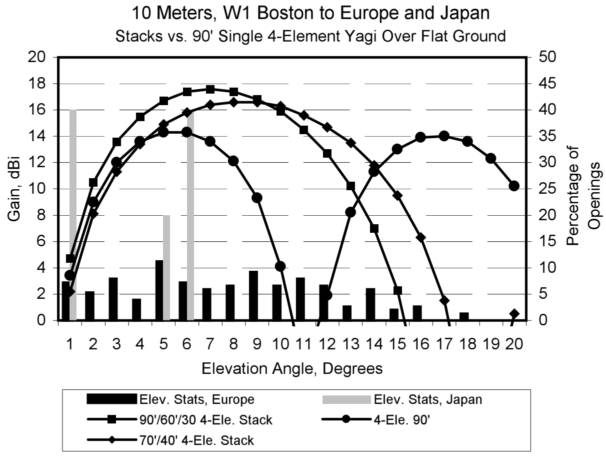


**Fig 29—Combinations of 4-element Yagis over flat ground. The elevation-angle statistics into Japan from New England (Boston) are represented by the black vertical bars, while the grey vertical bars represent the elevation-angle statistics to Europe. The 90/60/30-foot stack has the best *elevation footprint* into Japan, although the 70/40-foot stack performs well also.**

one, as we'll see.

To Japan, the necessary range of elevation angles is considerably smaller than that needed to a larger geographic target area like Europe. The 90/60/30-foot stack is still best on the basis of having higher gain at low angles, although the two-Yagi stack at 70 and 40 feet is a good choice too. Note that the single 90-foot high Yagi's performance is very close to the 70/40-foot stack of two Yagis at low angles, but the two-Yagi stack is superior to the single 90-foot antenna for angles higher than about 5° on 10 meters.

## A 15-Meter Example

The situation is similar on 15 meters from New England to Europe. On 15 meters, the range of angles needed to fully cover Europe is 1° to 28°. This large range of angles makes covering all the angles even more challenging. Ken Wolff, K1EA, a devoted contest operator and the author of the famous *CT* contest logging program, put it very clearly when he wrote in the bulletin for the Yankee Clipper Contest Club:

"Suppose you have 15-meter Yagis at 120 feet and 60 feet, but can feed only one at a time. A 15-meter beam at 120 feet has its first maximum at roughly 5° and the first minimum at 10°. The Yagi at 60 feet has a maximum at 10° and a minimum at 2°. At daybreak, the band is just opening, signals are arriving at 3° or less and the high Yagi outperforms the low one by 5-10 dB. Late in the morning, western Europeans are arriving at angles of 10° or more, while UA6 is still arriving at 4-5°. Western Europe can be 20-30 dB louder on the low antenna than the high! What to do? Stack em!"

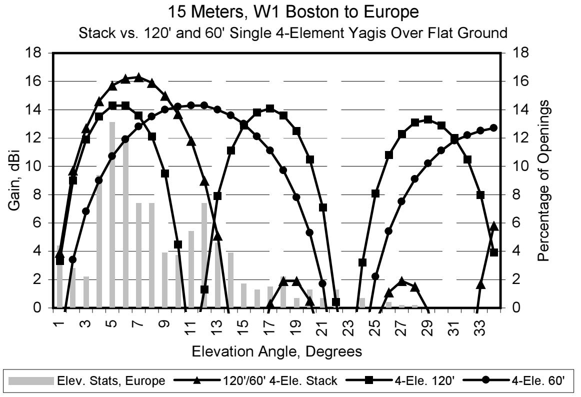


**Fig 30—Comparison of elevation patterns for K1EA's illustration about 15-meter Yagis mounted over flat ground, with elevation-angle statistics to Europe added. The stack at 120 and 60 feet yields a better footprint over the range of 3° to 11° at its half-power points, better than either antenna by itself.**

**Fig 30** illustrates K1EA's scenario, showing the elevation statistics to Europe from Massachusetts and the elevation responses for a 120- and a 60-foot high, 4-element Yagi, both over flat ground, together with the response for both antennas operated as vertical stack. The half-power beamwidth of the stack's main lobe is 6.9°, while that for the 120-foot antenna by itself is 5.5° and that for the 60-foot antenna by itself is 11.1°. The half-power beamwidth numbers by themselves can be deceiving, mainly because the stack starts out with a higher gain. A more meaningful observation is that the stack has equal to or more gain than either of the two individual antennas from 1° to about 10°.

Is such a stack of 15-meter Yagis at 120 and 60 feet optimal for the New England to Europe path? No, it isn't, as we'll explore later, but the stack is clearly better than either antenna by itself for the scenario K1EA outlined above.

## A 20-Meter Example

Take a look now at **Fig 31**, which overlays elevation-angle statistics for Europe (gray vertical bars) and Japan (black vertical bars) from Boston on 20 meters, plus the elevation responses for four different sets of antennas mounted over flat ground. Just for emphasis, the highest antenna is a 200-foot high 4-Element Yagi. It is clearly too high for complete coverage of all the needed angles into Europe. A number of New England operators have verified that this is true—a really high Yagi will open the 20-meter band to Europe in the morning and may shut it down in the afternoon, but during the middle of the day the high antenna gets soundly beaten by lower antennas.

To Japan, however, from New England the range of angles needed narrows considerably on 20 meters,

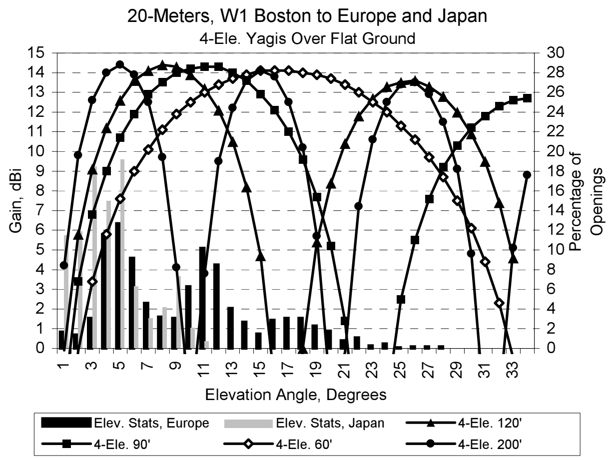


**Fig 31—Comparison of elevation patterns for individual 20-meter Yagis over flat ground, compared with the range of elevation angles needed on this band from New England to Europe (gray bars) and to Japan (black bars). For fun, the response of a 200-foot high Yagi is included—this antenna is far too high to cover the needed range of angles to Europe because of its deep nulls at critical angles, like 10°. But the 200 footer is great into Japan!**

from 1° to only 11°. For these angles, the 200-foot Yagi is the best antenna to work Japan from New England on 20 meters.

This is true provided that the antenna is aiming out over flat ground. The actual, generally irregular, terrain in various directions can profoundly modify the takeoff angles favored by an antenna system, particularly on steep hills. There will be more discussion on this important topic later on.

## SPARE ME THE NULLS!

Now, let's look closely at some other 20-meter antennas in Fig 28, the ones at 120 and 60 feet. At an elevation angle of 8° the difference in elevation response between the 60- and 120-foot high Yagis is just over 3 dB. Can you really notice a change of 3 dB on the air? Signals on the HF bands often rise and fall quickly due to fading, so differences of 2 or 3 dB are difficult to discern. Consequently, the difference between a Yagi at 120 feet and one at 60 feet may be difficult to detect at elevation angles covered well by both antennas. But a *deep null* in the elevation response is very noticeable.

Back in 1990, when editor Dean Straw, N6BV, put up his 120-foot tower in Windham, New Hampshire, his first operational antenna was a 5-element triband Yagi, with 3 elements on 40 and 4 elements on both 20 and 15 meters. Just as the sun was going down on a late August day Straw finished connecting the feed line in the shack. The antenna seemed to be playing like it should, with a good SWR curve and a good pattern when it was rotated. So N6BV/1 called a nearby friend, John Dorr, K1AR, on the telephone and asked him to get on the air to make some signal comparisons on 20 meters into Europe.

Straw was shocked that every European they worked that evening said his signal was several S units weaker than K1AR's. Dorr was using a 4-element 20-meter monobander at 90 feet, which at first glance should have been comparable to Straw's 4-element antenna at 120 feet. But N6BV really shouldn't have been so shocked—in New England, the elevation angles from Europe late in the day on 20 meters are almost always higher than 11°, and that is true for the entire solar cycle.

The N6BV/1 station was located on a small hill, while K1AR was located on flat terrain towards Europe. The elevation response for N6BV/1's 120-foot high Yagi fell right into a deep null at 11°. This was later confirmed many times in the following eight years that the N6BV/1 station was operational. During the early morning opening on 20 meters into Europe, the top antenna was always very close to or equal to the stack of three TH7DX tribanders at 90/60/30 feet on the same tower. But in the afternoon the top antenna was *always* decidedly worse than the stack, so much so that Straw often wondered whether something had gone wrong with the top antenna!

So what's the moral to this short tale? It's simple: *The gain you can achieve, while useful, is not so important as the deep nulls you can avoid by using a stack.*

## STACKING DISTANCES BETWEEN YAGIS

So far, we've examined stacks as a means of achieving more gain over an individual Yagi, while also matching the antenna system's response to the range of elevation angles needed for particular propagation paths. Most importantly, we seek to avoid nulls in the elevation response. Earlier we asked whether a 120/60-foot stack was optimal for the path from New England to Europe on 15 meters. Let's examine how the stacking distance between individual antennas affects the performance of a stack.

**Fig 32** shows overlays of various combinations of 15-meter Yagis. Just for reference, a plot for a single 60-foot high Yagi is also included. Let's start by looking at the most widely spaced stack in the group: the 120/30-foot stack. Here, the spacing is obviously too large, since the second lobe is actually stronger than the first lobe. In terms of wavelength, the 90-foot spacing between antennas in this stack is 1.94 λ, a large spacing indeed.

There is a great deal of folklore and superstition among amateurs about stacking distances for HF arrays. For years, high-performance stacked Yagi arrays have been used for weak-signal DXing on the VHF and UHF bands. The most extreme example of weak-signal work is EME work (Earth-Moon-Earth, also called *moonbounce*) because of the huge path losses incurred on the way to and from the Moon. The most successful arrays used for

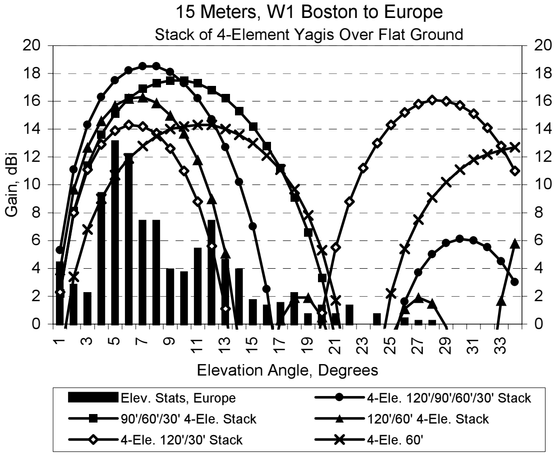


**Fig 32—Various stacks towards Europe from New England for 15-meters. The stack at 120 and 30 feet is clearly suboptimal, since the second lobe is higher than the first lobe. The 120/60-foot stack is better in this regard, but is still not as good a performer as the 90/60/30-foot stack. It's debatable whether going to four Yagis in the 120/90/60/30-foot stack is a good idea because it drops below the performance of the 90/60/30-foot stack at about 10° in elevation. The exact distance between practical HF Yagis is not critical to obtain the benefits of stacking. For a stack of tribanders at 90, 60 and 30 feet, the distance in wavelengths between individual antennas is 0.87 λ at 28.5 MHz, 0.65 λ at 21.2 MHz, and 0.43 λ at 14.2 MHz.**

moonbounce have low sidelobe levels and very narrow frontal lobes that give huge amounts of gain. The low sidelobes help minimize received noise, since the receive levels for signals that do manage to bounce off the Moon and return to Earth are exceedingly weak.

But HF work is different from moonbounce in that rigorously trying to minimize high-angle lobes is far less crucial at HF, where we've already shown that the main goal is to achieve gain over a wide elevation-plane footprint without any disastrous nulls in the pattern. The gain gradually increases as spacing in terms of wavelength is increased between individual Yagis in a stack, and then decreases slowly once the spacing is greater than about 1.0 λ. The difference in gain between spacings of 0.5 λ to 1.0 λ for a stack of typical HF Yagis amounts to only a fraction of a decibel. Stacking distances on the order of 0.6 λ to 0.75 λ give best gain commensurate with good patterns.

While the stack at 120/60 feet in Fig 32 doesn't have the second-lobe-stronger problem the 120/30-foot stack has, 60 feet between antennas is 1.29 λ, again outside the normal range of HF stack spacings. As a consequence, the 120/60-foot stack doesn't cover the range of elevation angles as well as it could, and is inferior to both the 90/60/30-foot stack and the 120/90/60/30-foot stack. The 120/60-foot two-Yagi stack needs at least one more antenna placed in-between to spread out the elevation-range coverage and to provide more gain.

It could be debated, but the 90/60/30-foot stack seems optimal for coverage of all the angles into Europe from New England on 15 meters. Note that the 30-foot spacing between Yagis is 0.65 λ on 21.2 MHz, right in the middle of the range of typical stack spacings.

### Switching Out Yagis in the Stack

Still, the extra gain that is available at low elevation angles from a 120/90/60/30-foot high, four-Yagi stack in Fig 32 is alluring. For those statistically possible, but less likely, occasions when the elevation angle is higher than about 12°, it would be advantageous to switch out the top 120-foot Yagi and operate with only the lower three Yagis in a stack. (This also allows the top antenna to be rotated in another direction, an aspect we'll explore later.) There are even times when the incoming angles are really high and when the top two antennas might be switched out to create a 60/30-foot stack. Later in this chapter we'll explore flexible circuitry for such stack switching.

### Stacking Distance and Lobes at HF

Let's look a little more closely at how a stack achieves gain and a wide elevation footprint. **Fig 33** shows a rectangular X-Y graph of the elevation response from 0° to 180° for two 3-element 15-meter Yagis (with 12-foot booms) spaced 30 feet apart (0.65 λ at 21.2 MHz), but mounted at two different heights: 95/65 and 85/55 feet. The rectangular plot gives more resolution than is possible on a polar plot. Note that the heights shown represent typical stacking heights on 15 meters—there's nothing magic about these choices. The free-space H-Plane pattern for the 30-foot spaced stack is also shown for reference.

The worst-case overhead elevation lobe, which ranges from about 60° to 120° in elevation (±30° from straight overhead at 90°), is about 14.7 dB down for the 95/65-foot stack. The overhead lobe peaks broadly at an elevation angle of about 82°. The overhead lobe for the lower 85/55-foot stack occurs at an elevation of about 64°, where it is 19 dB down.

The F/B for both 3-element sets of heights is about 15 dB, well down from the excellent 32 dB F/B for each Yagi by itself. The degradation of F/B is mainly due to mutual coupling to its neighbor in the stack.

The ground-reflection pattern in effect "modulates" the free-space pattern of the individual Yagi, but in a complex and not always intuitive manner. This is quite evident for the 85/55-foot stack at near-overhead angles. In this region things become complicated indeed, because the fourth and fifth lobes due to ground reflections are interacting with the free-space pattern of the stack.

Because the spacing remains constant at 30 feet for

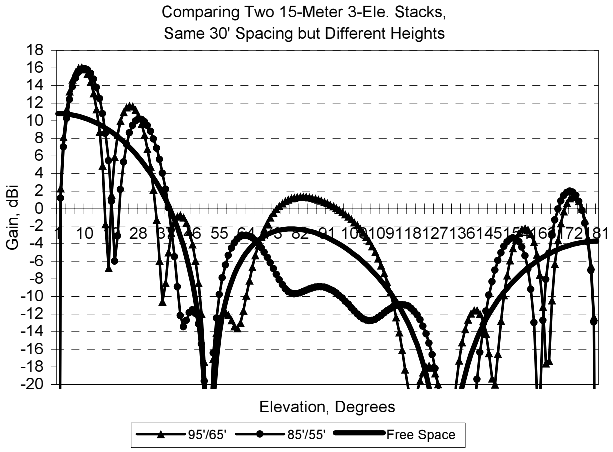


**Fig 33—Rectangular plot comparing two 15-meter stacks of 3-element Yagis—each antenna is spaced 30 feet from its partner, but at different heights. The lobes are a complicated function of the antenna height, not the spacing, since that remains constant.**

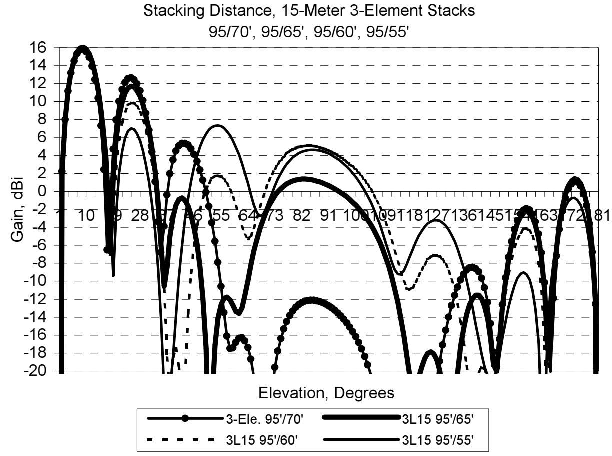


**Fig 34—Four spacing scenarios for two 3-element 15-meter Yagis. Things get very complicated. The optimal spacing in terms of stacking gain is 30 feet, which is 0.65 λ. The near-overhead lobes turn out to be ugly looking, but unimportant for skywave propagation.**

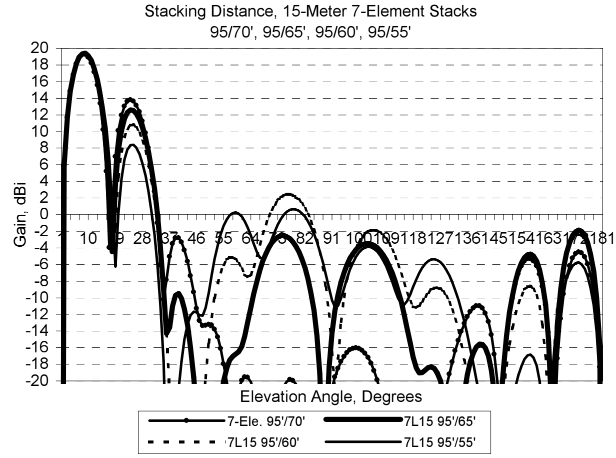


**Fig 35—Four spacing scenarios for two large 7-element 15-meter Yagis (on 64-foot booms). Again, a 0.65 λ spacing (30 feet) provides the most stacking gain.**

these pairs of antennas, however, the main determinant for the upper-elevation angle lobes is the distance of the horizontally polarized antennas above the ground, not the spacing between them.

### Changing the Stack Spacing

**Fig 34** demonstrates just how complicated things get for four different spacing scenarios. Here, the lower Yagi in the stack is moved down in 5-foot increments from the 95/70 feet level, to 95/65, 95/60 and 95/55 feet. The closest spacing, 25 feet in the 95/70-foot stack, yields nominally the "cleanest" pattern in the overhead region from 60° to 120°. The worst-case overhead lobe for the 95/70-foot stack is down 28 dB from peak. The F/B is again about 15 dB.

The worst case overhead lobe for the widest spacing, 40 feet in the 95/55-foot stack, is about 11 dB down from peak. The F/B has increased marginally, but is still only about 16 dB. It is difficult to pinpoint directly whether the spacing or the height above ground is the major determinant for the various lobe amplitudes for the 3-element stack. We'll soon look closely at whether the overhead lobe is important or not for HF work.

### Longer Boom Length and Stack Spacing

**Fig 35** shows the same type overlay of elevation plots, but this time for two 7-element 15-meter Yagis on gigantic 64-foot booms. These Yagis are also spaced 30 feet apart (0.65 λ at 21.2 MHz), mounted at the same four sets of heights in Fig 34. As you'd expect, the free-space elevation pattern for a stacked pair of 7-element Yagis on 64-foot booms is narrower than that for a stacked pair of 3-element Yagis on 12-foot booms. The intrinsic F/B of the longer Yagi is also better than the F/B of the shorter antenna. As a result, all lobes beyond the main lobe of the stacked 7-element pair are lower for both sets of heights than their 3-element counterparts. The worst-case overhead lobe for the 7-element 95/65-foot pair is about 22 dB down at 76° and the F/B at 172° is greater than 21 dB for all four sets of heights.

**Table 11** summarizes the main performance characteristics for four sets of stacked Yagis. The first entry for each boom length is for the Yagi by itself at a height of 95 feet. Stacked configurations are next listed in order of gain. The column labeled "Worst lobe, dB re Peak" is the

**Table 11**
**Example, Spacing Between 15–Meter Yagis**

| *Antenna* | *Peak Gain dBi* | *Worst Lobe dB re Peak* | *Worst Lobe Angle,°* | *F/B dB* | *Overhead Lobe dB re Peak* |
|---|---|---|---|---|---|
| **3–Ele., 12' boom** | | | | | |
| By itself 95' | 13.2 | –0.9 | 21 | 28.8 | –17.5 |
| 95'/65' (Δ 30') | 16.08 | –4.5 | 25 | 14.9 | –14.7 |
| 95'/60' (Δ 35') | 16.01 | –6.2 | 24 | 15.1 | –10.9 |
| 95'/70' (Δ 25') | 15.81 | –3.2 | 24 | 14.8 | –28 |
| 95'/55' (Δ 40') | 15.71 | –8.7 | 24 | 16.4 | –11 |
| 95'/75' (Δ 20') | 15.34 | –2.3 | 23 | 16.3 | –17.2 |
| **4–Ele., 18' boom** | | | | | |
| By itself 95' | 13.92 | –1 | 21 | 28.3 | –20.4 |
| 95'/65' (Δ 30') | 16.63 | –4.5 | 23 | 18.5 | –17.3 |
| 95'/60' (Δ 35') | 16.6 | –6.2 | 24 | 18.2 | –13.1 |
| 95'/55' (Δ 40') | 16.36 | –8.7 | 24 | 19.8 | –13.2 |
| 95'/70' (Δ 25') | 16.36 | –3.3 | 24 | 20.4 | –31.8 |
| 95'/75' (Δ 20') | 15.92 | –2.5 | 23 | 25.9 | –19 |
| **5–Ele., 23' boom** | | | | | |
| By itself 95' | 14.26 | –1.1 | 21 | 27.9 | –22.3 |
| 95'/65' (Δ 30') | 16.86 | –4.6 | 24 | 20.8 | –19 |
| 95'/60' (Δ 35') | 16.86 | –6.3 | 24 | 20.7 | –14.4 |
| 95'/55' (Δ 40') | 16.67 | –8.8 | 24 | 23.5 | –14.4 |
| 95'/70' (Δ 25') | 16.59 | –3.4 | 24 | 24.9 | –34.4 |
| 95'/75' (Δ 20') | 16.18 | –2.6 | 23 | 34.3 | –20.2 |
| **7–Ele., 64' boom** | | | | | |
| By itself 95' | 17.93 | –2.2 | 21 | 28.9 | –17.1 |
| 95'/65' (Δ 30') | 19.39 | –6.9 | 24.3 | 21.4 | –21.9 |
| 95'/60' (Δ 35') | 19.38 | –8.6 | 24 | 21.4 | –16.9 |
| 95'/55' (Δ 40') | 19.29 | –10.9 | 24 | 25.0 | –18.6 |
| 95'/70' (Δ 25') | 19.26 | –5.5 | 23 | 24 | –35.3 |
| 95'/75' (Δ 20') | 19.08 | –4.6 | 23 | 27 | –23.4 |

amplitude of the second lobe due to ground reflections, and the elevation angle of that second lobe is listed as well.

Besides the 3- and 7-element designs discussed above, we've also added 4- and 5-element designs in Table 11. Over the range of stacking distances between 20 and 40 feet on 15 meters (0.43 λ to 0.86 λ), the peak gain for the 3-element stacks changes less than 0.75 dB, with the 30-foot spacing exhibiting the highest gain. The differences between peak gains versus stacking distance become smaller as the boom length increases. For example, for the 64-foot boom Yagi, the gain varies 19.39 – 19.08 = 0.31 dB for stack spacings from 20 to 40 feet.

In other words, changing the spacing from 20 to 40 feet (0.43 λ to 0.86 λ) doesn't change the gain significantly for boom lengths from 12 to 64 feet (0.26 λ to 1.38 λ). From the point of view of gain, the vertical spacing between individual antennas in an HF stack is not critical.

The worst-case lobes (generally speaking, the second lobe due to ground reflections) are highest for a Yagi operated by itself. After all, a single Yagi doesn't benefit from the redistribution of energy from higher-angle lobes into the main lobe that a stack gives. Thus, the 3-element, 12-foot boom Yagi by itself at 95 feet would have a second lobe at 21° that is only 0.9 dB down from the main lobe, while the stack of two such antennas at a 30-foot (0.65 λ) spacing at 95/65 feet would have a second lobe down 4.5 dB. As the spacing between antennas in a vertical stack increases, the second lobe is suppressed more, up to 8.7 dB at a 40-foot (0.86 λ) spacing.

Since the free-space elevation pattern for a 3-element Yagi is wider than that for a 7-element Yagi, the second lobe due to ground reflection will be somewhat reduced. This is true for all longer-boom antennas operating by themselves over ground. Used in stacks, the second lobe's amplitude will vary depending on spacing between antennas, but they range only about 6 dB.

The front-to-back ratio will also tend to increase with longer boom lengths on a properly designed Yagi. Table 11 shows that the F/B is somewhat better for closer spacings between antennas in a stack, a rather non-intuitive result, considering that the mutual coupling should be greater for closer antennas. For example, the 5-element Yagi stack with a 20-foot spacing has a exceptional F/B of 34.3 dB, compared to a F/B of 21.4 dB with the 30-foot spacing distance that gives nominally the most gain. High values of F/B, however, rarely hold over a wide frequency range because of the very critical phasing relationships necessary to get a deep null, so the difference between 34.3 and 21.4 dB would rarely be noticeable in practice.

The near-overhead lobe structure (between 60º to 120º in elevation) tends also to be lower for smaller stack spacings—for all boom lengths—peaking in this example at a spacing of 25 feet for the boom lengths considered here. Since the peak gain actually occurs with smaller spacing between Yagis in this 7-element stack, even relatively large and messy looking overhead lobes are not subtracting from the stacking gain. In the next section we'll now examine whether this overhead lobe is important or not.

### Are Higher-Angle Lobes Important?

We've already shown that the exact spacing between HF Yagis is not critical for stacking gain. Further, the heights (and hence spacing) of the individual Yagis in a stack interact in a complicated fashion to determine higher-angle lobes.

Let's examine the relevance of such higher-angle lobes for stacked HF Yagis, this time in terms of interference reduction on receive. As Chapter 23, Radio Wave Propagation, points out, few DX signals arrive at elevation angles greater than about 30°. In fact, DX signals only propagate at elevation angles in the range from 1° to 30° on all the bands where operators might reasonably expect to stack Yagis—nominally from 7 to 29.7 MHz.

You should remember that the definition of the *critical frequency* for HF propagation is the highest frequency for which a wave launched directly overhead at 90° elevation is reflected back down to Earth, rather than being lost into outer space. The maximum critical frequency for extremely high levels of solar flux is about 15 MHz. In other words, high overhead angles do not propagate signals on the upper HF bands.

However, some domestic signals do arrive at relatively high elevation angles. Let's look at some scenarios where higher angles might be encountered and how the elevation patterns of typical HF stacks affect these signals. Let's examine a situation where a medium-range interfering station is on the same heading as a more distant target station.

We'll examine a typical scenario involving stations in Atlanta, Boston and Paris. The heading from Atlanta to Paris is 49º, the same heading as Atlanta to Boston. In other words, the Atlanta station would have to transmit over (and listen through) a Boston station for communication with Paris. The distance between Atlanta and Boston is about 940 miles, while the distance from Atlanta to Paris is about 4350 miles. Ground wave signals obviously cannot travel either of these distances at 21 MHz (ground wave coverage is less than about 10 miles at this frequency), and so the propagation between Atlanta to Boston and Atlanta to Paris will be entirely by means of the ionosphere.

Let's evaluate the situation on 15 meters in the month of October. We'll assume a smoothed sunspot number (SSN) of 100 and that each station puts 1500 W of power into theoretical isotropic antennas that have +10 dBi of gain at all elevation and azimuth angles. [We use such theoretical isotropic antennas because they make it easier to work in *VOACAP*. We will factor in real-world stacks later.] *VOACAP* predicts that the signal from Boston will be S9 + 8 dB in Atlanta at 1400 UTC, arriving at an elevation angle of 21.3º on a single $F_2$ hop. This elevation angle is higher than commonly encountered angles for DX signals, but it is still far away from near-overhead angles.

The signal from Paris into Atlanta is predicted to be about S6 for the same theoretical isotropic antennas, at an incoming elevation angle of 6.4º on three $F_2$ hops. The S6 level validates the rule-of-thumb that each extra hop loses approximately 10 dB of signal strength, assuming that each S unit is about 4 dB, typical for modern receivers.

Now look at **Fig 36**, which shows the response for a stack of 3-element Yagis at 90/60/30 feet over flat ground, along with the response for a similar stack of 7-element Yagis. Again, we'll assume that all three stations are using such 3-element 90/60/30-foot stacks. The stations in Atlanta and Boston point their stacks into Europe and the Parisian station points his stack towards the USA. The gain of the Atlanta array at 6.4º into Paris will be about 16 dBi, or 6 dB more than the isotropic array with its +10 dBi of gain selected for use in *VOACAP*. Similarly, the French station's transmitted signal will enjoy a 6 dB gain advantage over the isotropic array used in the *VOACAP* calculation, and thus the French signal into Atlanta will now be S6 + 12 dB, or about S9.

By comparison, the interfering signal from Boston into Atlanta will be reduced by the rearward pattern of his array, which will launch a signal at 180º – 21.3º = 158.7º in elevation at the single $F_2$ mode from Boston to Atlanta. From Fig 33, the Boston station's gain at this rearward elevation is going to drop from the isotropic's +10 dBi of gain down to –11 dBi, a drop of 21 dB. The signal into the Atlanta receiver will also be reduced by the pattern of the Atlanta array on receive, which has a gain of about 0 dBi at 21.3º, compared to the isotropic's +10 dBi gain at 6.4º, a net drop of 10 dB.

Thus, the Boston station's signal will drop by about 21 + 10 = 31 dB, bringing the interfering signal from Boston, which would be S9 + 8 dB for isotropic antennas, down to about S3 due to the combined effects of the arrays. This is a very significant reduction in interference. But you will note that the reduction has nothing to

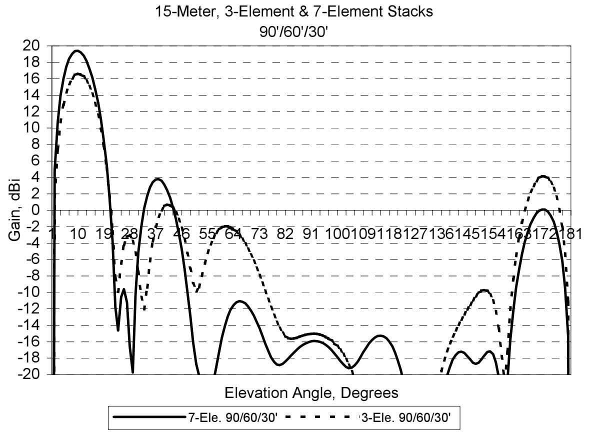


**Fig 36—Stacks of three 3-element and 7-element Yagis on 15 meters at 90/60/30 feet heights. The F/B for the 7-element stack is superior to the 3-element stack mainly because the F/B is intrinsically better for the long-boom design.**

do with the near-overhead lobes, dealing as it does with the trailing edge of the main lobe and the F/B lobe.

### Even Higher Elevation Angles

Now let's evaluate a station that is even closer to Boston, say a station in Philadelphia. The heading from Philadelphia to Paris is 53° and the distance is 3220 miles. On the same day in October as above, *VOACAP* predicts a signal strength of S8 from Paris to Philadelphia, at a 2.7° elevation angle on two $F_2$ hops. Again, the *VOACAP* computations assume isotropic antennas with +10 dBi gain at all three stations. The gain of the 3-element stacks at both ends of the circuit at 2.7° is also about +10 dBi, so the signal level from Paris to Philadelphia would be S8 with the 3-element stacks.

Now *VOACAP* computes the elevation angle from Philadelphia to Boston as 56.3°, on one $F_2$ hop launched at an azimuth of 53°, well within the azimuthal beamwidth of the stack. *VOACAP* says the predicted signal strength for isotropic antennas with +10 dBi of gain is less than S1!

What's happening here? Boston and Philadelphia are within the "skip" region on 21 MHz and signals are skipping right over Boston from Philadelphia (and vice versa). Actual signals would be much weaker than they would be with theoretical isotropic antennas because of the actual patterns of the transmitting and receiving stacks. At an elevation angle of 56.3° the receiving stack would have a gain of –10 dBi, while at an elevation of 180° – 56.3° = 123.7° the transmitting stack would be down to –10 dBi as well. The net reduction for the stacks compared to isotropics with +10 dBi gain each would be 40 dB, putting the interfering signal well into the receiver noise.

You can safely say that near-overhead angles don't enter into the picture, simply because signals at intermediate distances are in the ionospheric skip zone and interfering signals are very weak in that zone already.

Even in situations where having a poor front-to-back ratio might be beneficial—because it alerts stations tuning across your signal that you are occupying that frequency—the ionosphere doesn't cooperate for intermediate-distance signals that are in the skip zone. Often two stations may be on the same frequency without either knowing that the other is there.

### Ground Wave?

What happens, you might wonder, for ground-wave signals? Let's look at a situation where the interfering station is in the same direction as the desired target, but is only 5 miles away. Unfortunately, his signal is S9 + 50 dB. Even reducing the level by 30 dB, a huge number, is still going to make his signal 20 dB stronger than signals from your desired target location! There is not much you can do about ground-wave signals and fretting about optimizing stack heights to discriminate against local signals is generally futile.

### Stacking Distances for Multiband Yagis

By definition, a stack of multiband Yagis (such as a "tribander" covering 20/15/10 meters) has a constant vertical spacing between antennas in terms of feet or meters, but not in terms of wavelength. Tribanders are no different than monobanders in terms of optimal spacing between individual antennas. Again, the difference in gain between spacings of 0.5 λ and 1.0 λ for a stack of triband Yagis amounts to only a fraction of a decibel. Furthermore, the main practical constraint that limits choice of stacking distances between any kind of Yagis, multiband or monoband, is the spacing between guy wire sets on the tower itself.

### Summary, Stacking Distances

In short, let us summarize that there is nothing magical about stacking distances for practical HF Yagis—a good rule-of-thumb is a stacking distance of 0.65 λ. This is 23 feet on 10 meters, 30 feet on 15 meters and 45 feet on 20 meters for monoband stacks. Practically speaking, however, you've only got limited places where you can mount antennas on the tower—mainly where guy wires allow you to place them. This is especially applicable if you wish to rotate lower antennas on the tower, where you must clear the guys from up above.

## STACKS AND FADING

The following is derived from an article by Fred Hopengarten, K1VR, and Dean Straw, N6BV, in a Feb 1994 *QST* article. Using stacked Hy-Gain TH7DXs or TH6DXXs at their respective stations, they have solicited a number of reports from stations, mainly in Europe, to compare various combinations of antennas in stacks and as single antennas. The peak gain of the stack is usually just a little bit higher than that for the best of the single antennas, which is not surprising. Even a large stack has no more than about 6 dB of gain over a single Yagi at a height favoring the prevailing elevation angle. Fading on the European path can easily be 20 dB or more, so it is very confusing to try to make definitive comparisons. They have noticed over many tests that the stacks are much less susceptible to fading compared to single Yagis. Even within the confines of a typical SSB bandwidth, frequency-selective fading occasionally causes the tonal quality of a voice to change on both receive and transmit, often dramatically becoming fuller on the stacks, and tinnier on the single antennas. This doesn't happen all the time, but is often seen. They have also observed often that the depth of a fade is less, and the period of fading is longer, on the stacks compared to single antennas.

Exactly *why* stacks exhibit less fading is a fascinating subject, for which there exist a number of speculative ideas, but little hard evidence. Some maintain that stacks outperform single antennas because they can afford *space diversity* effects, where by virtue of the difference in physical placement one antenna will randomly pick up signals that another one in another physical location might not hear.

This is difficult to argue with, and equally difficult to prove scientifically. A more plausible explanation about why stacked Yagis exhibit superior fading performance is that their narrower frontal elevation lobes can discriminate against undesired propagation modes. Even when band conditions favor, for example, a very low 3° elevation angle on 10 or 15 meters from New England to Western Europe, there are signals, albeit weaker ones, that arrive at higher elevation angles. These higher-angle signals have traveled longer distances on their journey through the ionosphere, and thus their signal levels and their phase angles are different from the signals traversing the primary propagation mode. When combined with the dominant mode, the net effect is that there is both destructive and constructive fading. If the elevation response of a stacked antenna can discriminate against signals arriving at higher elevation angles, then in theory the fading will be reduced. Suffice it to say: In practice, stacks do reduce fading.

## STACKS AND PRECIPITATION STATIC

The top antenna in a stack is often much more affected by rain or snow precipitation static than is the lower antenna. N6BV and K1VR have observed this phenomenon, where signals on the lower antenna by itself are perfectly readable, while S9+ rain static is rendering reception impossible on the higher antenna or on the stack. This means that the ability to select individual antennas in a stack can sometimes be extremely important.

## STACKS AND AZIMUTHAL DIVERSITY

*Azimuthal diversity* is a term coined to describe the situation where one of the antennas in a stack is purposely pointed in a direction different from the main direction of the stack. During most of the time in a DX contest from the East Coast, the lower antennas in a stack are pointed into Europe, while the top antenna is often rotated toward the Caribbean or Japan. In a stack of three identical Yagis, the first-order effect of pointing one antenna in a different direction is that one-third of the transmitter power is diverted from the main target area. This means that the peak gain is reduced by 1.8 dB, not a very large amount considering that signals are often 10 to 20 dB over S9 anyway when the band is open from New England to Europe.

**Fig 37** shows the 3D pattern of a pair of 4-element Yagis fed in-phase at 95 and 65 feet, but where the lower antenna has been rotated 180° to fire in the –X direction. The backwards lobe peaks at a higher elevation angle because the antenna doing the radiating in this direction is lower on the tower. The forward lobe peaks at a lower angle because its main radiator is higher.

## THE N6BV/1 ANTENNA SYSTEM—BRUTE FORCE FEEDING

The N6BV/1 system in Windham, New Hampshire, was located on the crest of a small hill about 40 miles from Boston, and could be characterized as a good, but not dominant, contesting station. A number of top-10 contest results were achieved from that station in the 1990s before N6BV returned to California.

There was a single 120-foot high Rohn 45 tower, guyed at 30-foot intervals, with a 100-foot horizontal spread from tower base to each guy point so there was sufficient room for rotation of individual Yagis on the tower. Each set of guy wires employed heavy-duty insulators at 57-foot intervals, to avoid resonances in the 80 through 10-meter amateur bands. There were five Yagis on the tower. A heavy-duty 12-foot long steel mast with 0.25-inch walls was at the top of the tower, turned by an Orion 2800 rotator. Two thrust bearings were used above the rotator, one at the top plate of the tower itself, and the other about 2 feet down in the tower on a modified rotator shelf plate. The two thrust bearings allowed the rotator to be removed for service.

At the top of the mast, 130 feet high, was a 5-element, computer-optimized 10-meter Yagi, which was a modified Create design on a 24-foot boom. The element tuning was modified from the stock antenna in order to achieve higher gain and a better pattern over the band. At the top of the tower (120-foot level) was mounted a Create 714X-3 triband Yagi. This was a large tribander, with a 32-foot boom and five elements. Three elements were active on 40 meters, four were active on 20 meters and four were active on 15 meters. The 40-meter elements were loaded with coils, traps and

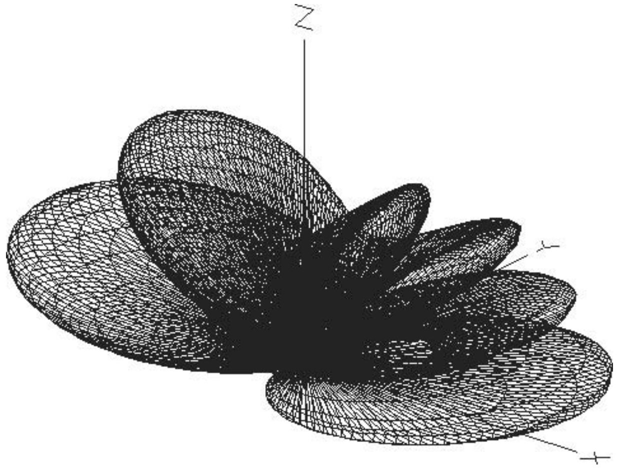


**Fig 37—3D representation of the pattern for two 4-element 15-meter Yagis, with the top antenna at 95 and the bottom at 65 feet, but pointed in the opposite direction.**

capacitance hats, and were approximately 46 feet long. A triband 20/15/10-meter Hy-Gain TH7DX tribander was fixed into Europe at the 90-foot level on the tower, just above the third set of guys.

At the 60-foot level on the tower, just above the second set of guys, there was a "swinging-gate" side-mount bracket, made by DX Engineering of Oregon. A Hy-Gain *Tailtwister* rotator turned a TH7DX on this side mount. (Note that both the side mount and the element spacings of the TH7DX itself prevented full rotation around the tower—about 280° of rotation was achieved with this system.) At the 30-foot level, just above the first set of guys, was located the third TH7DX, also fixed on Europe.

All five Yagis were fed with equal lengths of Belden 9913 low-loss coaxial cable, each measured with a noise bridge to ensure equal electrical characteristics. At each feed point a ferrite-bead choke balun (using seven large beads) was placed on the coax. All five coaxial cables went to a relay switch box mounted at the 85-foot level on the tower. **Fig 38** shows the schematic for the switch box, which was fed with 250 feet of 75-Ω, 0.75-inch OD Hardline coaxial cable.

The stock DX Engineering remote switch box was modified by adding relay K6, so that either the 130-foot or the 120-foot rotating antenna could be selected through a second length of 0.75-inch Hardline going to the shack. This created a *Multiplier* antenna, independent of the *Main* antennas. A second band could be monitored in this fashion while calling CQ using the main antennas on another band. Band-pass filters were required at the multiplier receiver to prevent overload from the main transmitter.

The 0.75-inch Hardline had very low losses, even when presented with a significant amount of SWR at the switch-box end. This was important, because unlike K1VR's system, no attempt was made at N6BV to maintain a constant SWR when relays K1 through K5 were switched in or out. This seemingly cavalier attitude came about because of several factors. First, there were many

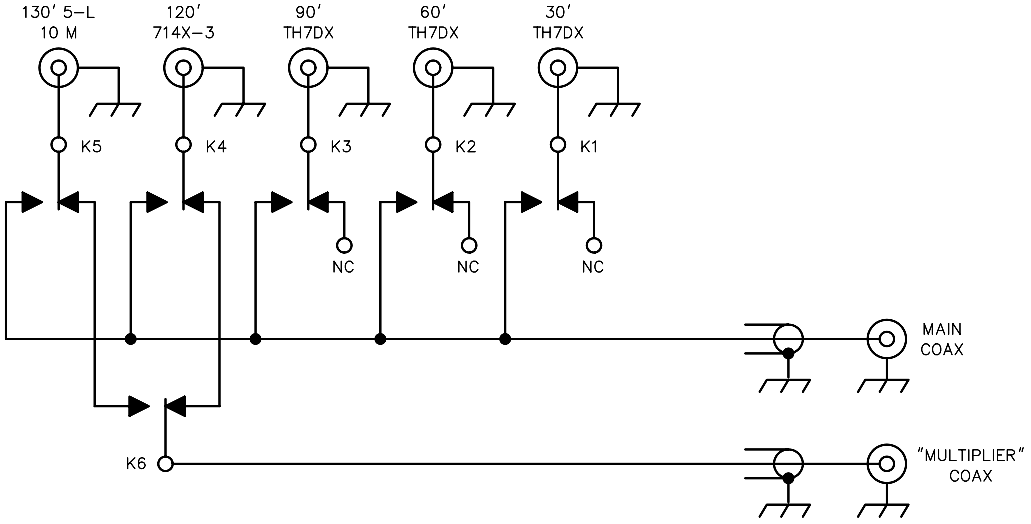


**Fig 38—N6BV/1 switch box system. This uses a modified DX Engineering remote switch box, with relay K6 added to allow selection of either of the two top antennas (5-element 10-meter Yagi or 40/20/15-meter triband 714X-3) as a "multiplier" antenna. There is no special provision for SWR equalization when any or all of the Yagis are connected in parallel as a stack fed by the Main coaxial cable. Each of the five Yagis is fed with equal lengths of flexible Belden 9913 coax, so phasing can be maintained on any band. The Main and "Multiplier" coaxes going to the shack are 0.75" OD 75-Ω Hardline cables.**

different combinations of antennas that could be used together in this system. Each relay coil was independently controlled by a toggle switch in the shack. N6BV was unable to devise a matching system that did not become incredibly complex because of the numerous impedance combinations used over all the five bands.

Second, the worst-case additional transmission line loss due to a 4:1 SWR mismatch when four antennas were connected in parallel on 10 meters was only 0.5 dB. It was true that the linear amplifier had to be retuned slightly when combinations of antennas were switched in and out, but this was a small penalty to pay for the reduced complexity of the switching and matching networks. The 90/60/30-foot stack into Europe was used for about 95% of the time during DX contests, so the small amount of amplifier retuning for other antenna combinations was considered only a minor irritation.

## WHY TRIBANDERS?

Without a doubt, the most common question K1VR and N6BV have been asked is: "Why did you pick *tribanders* for your stacks?" Triband antennas were chosen with full recognition that they are compromise antennas. Other enterprising amateurs have built stacked tribander arrays. Bob Mitchell, N5RM, is a prominent example, with his so-called *TH28DX* array of four TH7DX tribanders on a 145-foot-high rotating tower. Mitchell employed a rather complex system of relay-selected tuned networks to choose either the upper stacked pair, the lower stacked pair or all four antennas in stack. Others in Texas have also had good results with their tribander stacks. Contester Danny Eskenazi, K7SS, has very successfully used a pair of stacked KT-34XA tribanders for years.

A major reason why tribanders were used is that over the years both authors have had good results using TH6DXX or TH7DX antennas. They are ruggedly built, mechanically and electrically. They are able to withstand New England winters without a whimper, and their 24-foot long booms are long enough to produce significant gain, despite trap-loss compromises. Amateurs speculating about trap losses in tribanders freely bandy about numbers between 0.5 and 2 dB. Both N6BV and K1VR are comfortable with the lower figure, as are the Hy-Gain engineers.

Consider this: If 1500 W of transmitter power is going into an antenna, a loss of 0.5 dB amounts to 163 W. This would create a significant amount of heat in the six traps that are on average in use on a TH6DXX, amounting to 27 W per trap. If the loss were as high as 1 dB, this would be 300 W total, or 50 W per trap. Common sense says that if the overall loss were greater than about 0.5 dB, the traps would act more like big *firecrackers* than resonant circuits! A long-boom tribander like the TH6DXX or TH7DX also has enough space to employ elements dedicated to different bands, so the compromises in element spacing usually found on short-boom 3 or 4-element tribanders can be avoided.

Another factor in the conscious choice of tribanders was first-hand frustration with the serious interaction that can result from stacking monoband antennas closely together on one mast in a Christmas Tree configuration. N6BV's worst experience was with the ambitious 10 through 40-meter Christmas Tree at W6OWQ in the early 1980s. This installation used a Tri-Ex SkyNeedle tubular crankup tower with a rotating 10-foot-long heavy-wall mast. The antenna suffering the greatest degradation was the 5-element 15-meter Yagi, sandwiched 5 feet below the 5-element 10-meter Yagi at the top of the mast, and 5 feet above the full-sized 3-element 40-meter Yagi, which also had five 20-meter elements interlaced on its 50-foot boom.

The front-to-back ratio on 15 meters was at best about 12 dB, down from the 25+ dB measured with the bottom 40/20-meter Yagi removed. No amount of fiddling with element spacing, element tuning or even orientation of the 15-meter boom with respect to the other booms (at 90° or 180°, for example) improved its performance. Further, the 20-meter elements had to be lengthened by almost a foot *on each end of each element* in order to compensate for the effect of the interlaced 40-meter elements. It was a lucky thing that the tower was a motorized crankup, because it went up and down hundreds of times as various experiments were attempted!

Interaction due to close proximity to other antennas in a short Christmas Tree can definitely destroy carefully optimized patterns of individual Yagis. Nowadays, such interaction can be modeled using a computer program such as *EZNEC* or *NEC*. A gain reduction of as much as 2 to 3 dB can easily result due to close vertical spacing of monobanders, compared to the gain of a single monoband antenna mounted in the clear. Curiously enough, at times such a reduction in gain can be found even when the front-to-back ratio is not drastically degraded, or when the front-to-back occasionally is actually *improved*.

If you plan on stacking monoband Yagis—for example, putting only 15-meters Yagis on a single tower, with your other monoband stacks on other towers—do make sure you model the system to see if any interactions occur. You may be quite surprised.

Finally, in the N6BV/1 installation, triband antennas were chosen because the system was meant to be as simple as possible, given a certain desired level of performance, of course. Triband antennas make for less mechanical complexity than do an equivalent number of monobanders. There were five Yagis on the N6BV/1 tower, yielding gain from 40 to 10 meters, as opposed to using 12 or 13 monobanders on the tower.

## THE K1VR ARRAY: A MORE ELEGANT APPROACH TO MATCHING

The K1VR stacked array is on a 100-foot high Rohn

25 tower, with sets of guy wires at 30, 60 and 90 feet, made of nonconducting Phillystran. Phillystran is a nonmetallic Kevlar rope covered by black polyethylene to protect against the harmful effects of the sun's ultraviolet rays. A caution about Phillystran: Don't allow tree branches to rub against it. It is designed to work in tension, but unlike steel guy wire, it does not tolerate abrasion well.

Both antennas are Hy-Gain TH6DXX tribanders, with the top one at 97 feet and the bottom one at 61 feet. The lower antenna is rotated by a Telex Ham-M rotator on a homemade swinging-gate side mount, which allows it to be rotated 300° around the tower without hitting any guy wires or having an element swing into the tower. At the 90-foot point on the tower, a 2-element 40-meter Cushcraft Yagi has been mounted on a RingRotor so it can be rotated 360° around the tower.

After several fruitless attempts trying to match the TH6DXX antennas so that either could be used by itself or together in a stack, K1VR settled on using a relay-selected broadband toroidal matching transformer. When both triband antennas are fed together in parallel as a stack, it transforms the resulting 25-Ω impedance to 50 Ω. The transformer is wound on a T-200A powdered-iron core, available from Amidon, Palomar Engineering or Ocean State Electronics. Two lengths of twin RG-59 coax (sometimes called Siamese or WangNet), four turns each, are wound on the core. Two separate RG-59 cables could be used, but the Siamese-twin cable makes the assembly look much more tidy. The shields of the RG-59 cables are connected in series, and the center conductors are connected in parallel. See **Fig 39** for details.

**Fig 40** shows the schematic of the K1VR switch box, which is located in the shack. Equal electrical lengths of 50-Ω Hardline are brought from the antennas into the shack and then to the switch box. Inside the box, the relay contacts were soldered directly to the SO-239 chassis connectors to keep the wire lengths down to the absolute minimum. K1VR used a metal box that was larger than

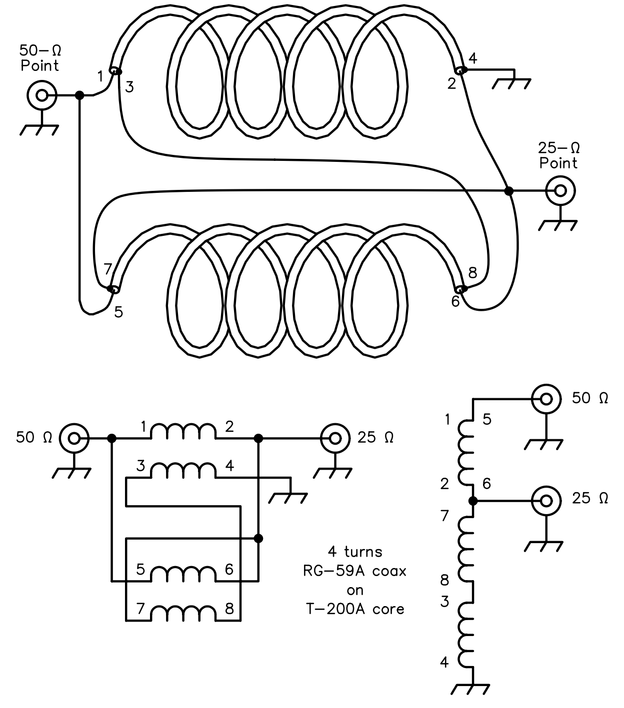


**Fig 39—Diagram for matching transformer for K1VR stacked tribander system. The core is powdered iron-core T-200A, with four turns of two RG-59A or "Siamese" coax cables. Center conductors are connected in parallel and shields are connected in series to yield 0.667:1 turns ratio, close to desired 25-Ω to 50-Ω transformation.**

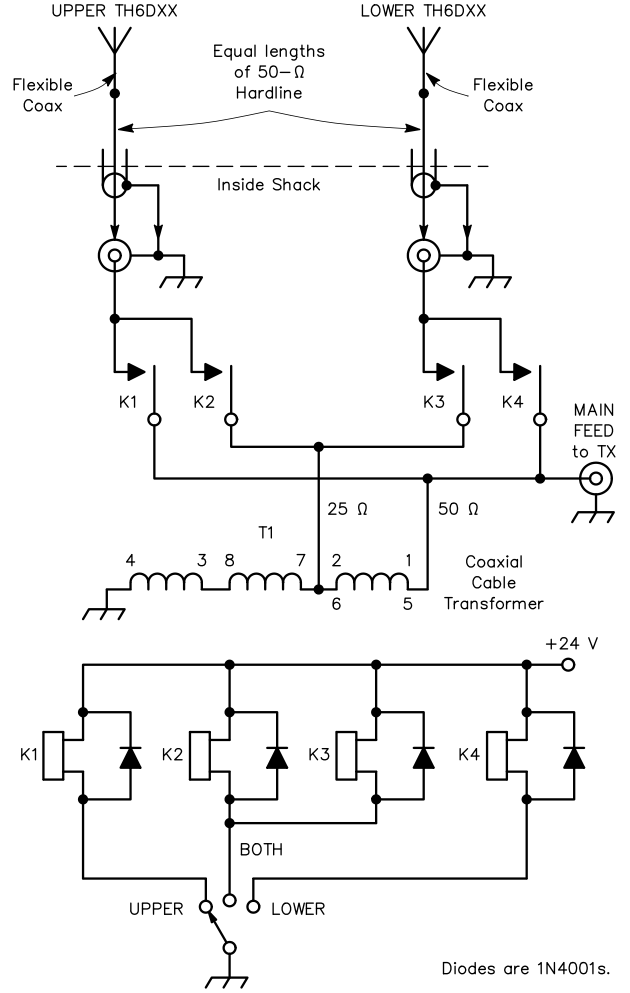


**Fig 40—Relay switch box for K1VR stacked tribander system. Equal lengths of 50-Ω Hardline (with equal lengths of flexible 50-Ω cable at each antenna to allow rotation) go to the switch box in the shack. The SWR on all three bands for Upper, Lower or Both switch positions is very close to constant.**

might appear necessary because he wanted to mount the toroidal transformer with plenty of clearance between it and the box walls. The toroid is held in place with a piece of insulation foam board. Before placing the switch box in service, the system was tested using two 50-Ω dummy loads, with equal lengths of cable connected in parallel to yield 25 Ω. The maximum SWR measured was 1.25:1 at 14 MHz, 1.3:1 at 21 MHz and 1.15:1 at 28 MHz, and the core remained cold with 80 W of continuous output power.

One key to the system performance is that K1VR made the electrical lengths of the two hardlines the same (within 1 inch) by using a borrowed TDR (time domain reflectometer). Almost as good as Hardline, K1VR points out, would be to cut exactly the same length of cable from the same 500-foot roll of RG-213. This eliminates manufacturing tolerances between different rolls of cable.

K1VR's experience over the last 10 years has been that at the beginning of the 10 or 15-meter morning opening to Europe the upper antenna is better. Once the band is wide open, both antennas are fed in phase to cast a bigger shadow, or footprint, on Europe. By mid-morning, the lower antenna is better for most Europeans, although he continues to use the stack in case someone is hearing him over a really long distance path throughout Europe. He reports that it is always very pleasant to be called by a 4S7 or HS0 or VU2 when he is working Europeans at a fast clip!

## SOME SUGGESTIONS FOR STACKING TRIBANDERS

It is unlikely that many amateurs will try to duplicate exactly K1VR's or N6BV's contest setups. However, many hams already have a tribander on top of a moderately tall tower, typically at a height of about 70 feet. It is not terribly difficult to add another, identical tribander at about the 40-foot level on such a tower. The second tribander can be pointed in a fixed direction of particular interest (such as Europe or Japan), or it can be rotated around the tower on a side mount or a Ring Rotor. If guy wires get in the way of rotation, the antenna can usually be arranged so that it is fixed in a single direction.

Insulate the guy wires at intervals to ensure that they don't shroud the lower antenna electrically. A simple feed system consists of equal-length runs of surplus 0.5-inch 75-Ω Hardline (or more expensive 50-Ω Hardline, if you are really obsessed by SWR) from the shack up the tower to each antenna. Each tribander is connected to its respective Hardline feeder by means of an equal length of flexible coaxial cable, with a ferrite choke balun, so that the antenna can be rotated.

Down in the shack, the two hardlines can simply be switched in and out of parallel to select the upper antenna only, the lower antenna only, or the two antennas as a stack. See **Fig 41**. Any impedance differences can be handled as stated previously, simply by retuning the linear amplifier, or by means of the internal antenna tuner (included in most modern transceivers) when the transceiver is run barefoot. The extra performance experienced in such a system will be far greater than the extra decibel or two that modeling calculates.

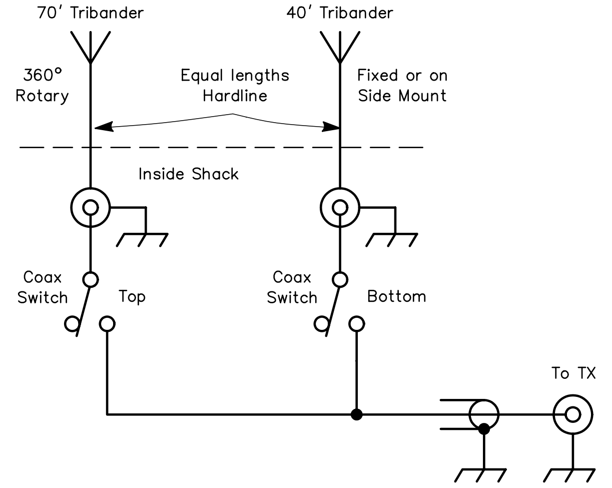


**Fig 41—Simple feed system for 70/40-foot stack of tribanders. Each tribander is fed with equal lengths of 0.5-inch 75-Ω Hardline cables (with equal lengths of flexible coax at the antenna to allow rotation), and can be selected singly or in parallel at the operator's position in the shack. Again, no special provision is made in this system to equal SWR for any of the combinations.**

## THE WX0B APPROACH TO STACK MATCHING AND FEEDING

Earlier we mentioned how useful it would be to switch various antennas in or out of a stack, depending on the elevation angles that need to be emphasized at that moment. Jay Terleski, WX0B, of Array Solutions has designed switchable matching systems, called *StackMatches*, for stacks of monoband or multiband Yagis.

The StackMatch uses a 50-Ω to 22.25-Ω broadband transmission-line transformer to match combinations of up to three Yagis in a stack. See **Fig 42** for a schematic of the StackMatch. For selection of any 50-Ω Yagi by itself, no matching transformer is needed and Relay IN routes RF directly to the common bus going to Relay 1, 2 and 3. For selection of two Yagis together the parallel impedance is 50/2 = 25 Ω and Relay IN routes RF to the matching transformer. The SWR is 25/22.25 = 1.1:1. For three Yagis used together, the parallel impedance is 50/3 = 16.67 Ω, and the SWR is 22.25/16.67 = 1.3:1.

The broadband transformer consists of four trifilar turns of #12 enamel-insulated wire wound on a Ferrite Corporation FT-240 2.4-inch OD core made of #61

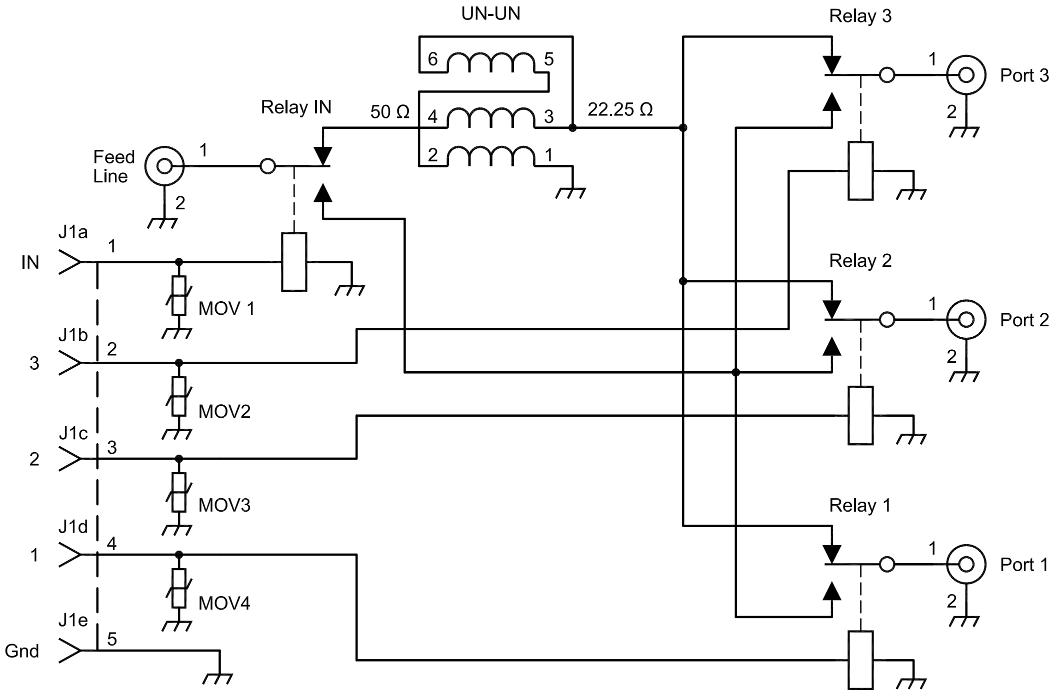


**Fig 42—Schematic of WX0B's StackMatch 2000 switchbox, which uses a broadband transmission line transformer using trifilar #12 enamel-insulated wires. (*Courtesy Array Solutions.*)**

material ($\mu = 125$). WX0B uses 10-A relays enclosed in plastic cases to do the RF switching, selected by a control box at the operating position. (10-A relays can theoretically handle $10\ A^2 \times 50\ \Omega = 5000$ W.) **Fig 43** shows a photo of the transmission-line transformer and StackMaster PCB.

The control/indicator box uses a diode matrix to switch various combinations of antennas in/out of the stack. Three LEDs lined up vertically on the front panel indicate which antennas in a stack are selected.

## "BIP/BOP" OPERATION

The contraction "BIP" means "both in-phase," while "BOP" means "both out-of-phase." BIP/BOP refer to stacks containing two Yagis, although the term is commonly used for stacks containing more than two Yagis. In theory, feeding a stack with the antennas out-of-phase will shift the elevation response higher than in-phase feeding.

**Fig 44** shows a rectangular plot comparing BIP/BOP operation of two 3-element 15-meter Yagis at heights of 2 λ and 1 λ (93 and 46 feet) over flat ground. The BOP pattern is the higher-angle lobe and the two lobes cross over about 14°. The maximum amplitude of the BOP stack's gain is about ½ dB less than the BIP pair. For reference, the pattern of a single 46-foot high Yagi is overlaid on the pattern for the stacks.

The most common method for feeding one Yagi 180° out-of-phase is to include an extra electrical half wavelength of feed-line coax going to one of the antennas. This method obviously works on a single frequency band and thus is not applicable to stacks of multiband Yagis, such as tribanders. For such multiband stacks, feeding only the lower antenna(s)—by switching out higher antenna(s) in the stack—is a practical method for achieving better coverage at medium or high elevation angles.

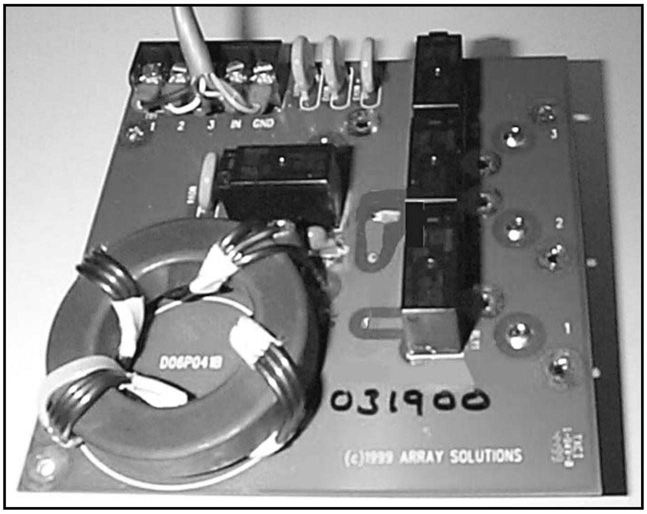


**Fig 43—Inside view of StackMatch. (*Photo courtesy Array Solutions.*)**

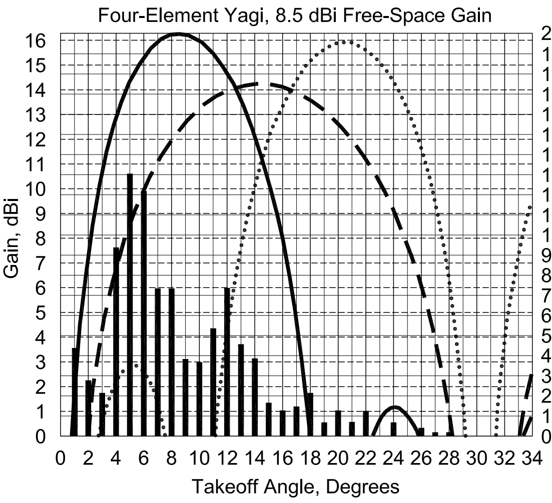


**Fig 44—*HFTA* screen shot of "BIP/BOP" operation of two 4-element 15-meter Yagis at 93 and 46 feet above flat ground. The elevation response in BOP (both out-of-phase) operation is shifted higher, peaking at about 21°, compared to the BIP (both in-phase) operation where the peak is at 8°. The dashed line is response of single Yagi at 46 feet.**

## STACKING DISIMILAR YAGIS

So far we have been discussing vertical stacks of identical Yagis. Less commonly, hams have successfully stacked dissimilar Yagis. For example, consider a case where two 5-element 10-meter Yagis are placed 46 and 25 feet above flat ground, with a 7-element 10-meter Yagi at 68 feet on the same tower. See **Fig 45**, which is a schematic of the layout for this stack. Note that the driven element for the top 7-element Yagi is well behind the vertical plane of the driven elements for the two 5-element Yagis. This offset distance must be compensated for with a phase shift in the drive system for the top Yagi.

**Fig 46** shows the elevation-pattern responses for uncompensated (equal-length feed lines) and the compensated (additional 150° of phase shift to top Yagi) stacks. These patterns were computed using *EZNEC ARRL*, which is included with this book. Not only is about 1.7 dB of maximum gain lost, but the peak elevation angle is shifted upwards by 11° from the optimal takeoff angle of 8°—where some 10 dB of gain is also lost. Without compensation, this is a severe distortion of the stack's elevation pattern.

For RG-213 coax, the extra length needed to provide an additional 150° of phase shift = 150°/360° λ = 0.417 λ = 9.53 feet at 28.4 MHz. This was computed using the program *TLW* (Transmission Line for Windows) included on the CD-ROM accompanying this book.

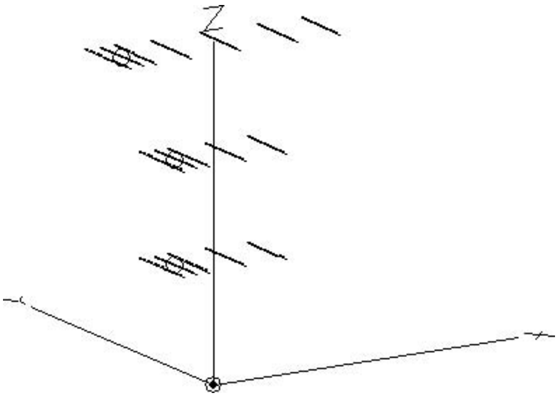


**Fig 45—Stacking dissimilar Yagis. In this case a 7-element 10-meter Yagi is stacked over two 5-element Yagis. Note the displacement of the 7-element Yagi's driven element compared to the position of the two 5-element Yagis. This leads to an undesired phase shift for the higher antenna.**

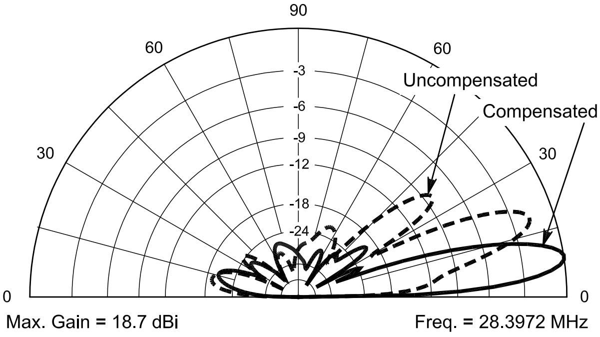


**Fig 46—Comparison of elevation responses for 7/5/5-element 10-meter stacks, with and without compensation for driven-element offset.**

It is not always possible to compensate for dissimilar Yagis in a stack with a simple length of extra coax, so you should be sure to model such combinations to make sure that they work properly. A safe alternative, of course, is to stack only identical Yagis, feeding all of them with equal lengths of coax to ensure in-phase operation.

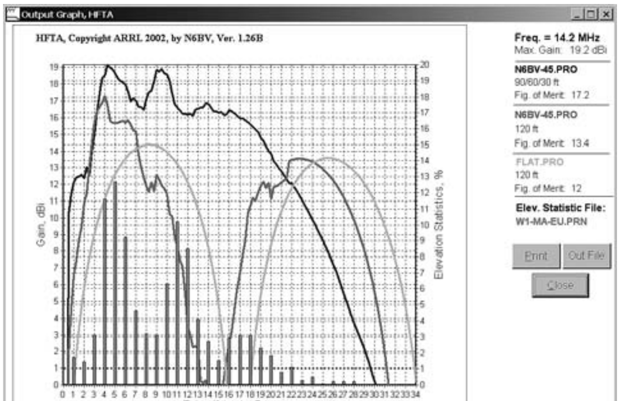
# Real-World Terrain and Stacks

So far, the stacking examples shown have been for flat ground. Things can become a lot more complicated when you deal with real-world irregular terrains! See Chapter 3, The Effects of Ground, for a description of the *HFTA* (High Frequency Terrain Assessment) program that is included with this book.

**Fig 47** shows the *HFTA*-computed 20-meter elevation responses towards Europe (at an azimuth of 45°) for three antennas at the N6BV/1 location in Windham, New Hampshire. Overlaid as a bar graph are the elevation-angle statistics for the path to all of Europe from New England (Massachusetts). The stack at 90/60/30 feet clearly covers all the angles needed best at 14 MHz. The N6BV 120-foot Yagi has a severe null in the region from about 7° to about 20°, with the deepest part of that null occurring at about 13° and is roughly comparable to the 90/60/30-foot stack between 2° to 7°.

In practice, the 120-foot Yagi was indeed comparable to the stack during morning openings to Europe on 20 meters, when the elevation angles are typically about 5°. In the New England afternoon, when the elevation angles typically rise to about 11°, the 120-foot Yagi was always distinctly inferior to the stack.

For reference, the response of a single 120-foot high Yagi over flat ground is also shown. Note that the N6BV 120-foot high Yagi has about 3 dB more gain at a 5° takeoff angle than does its flatland counterpart. This additional gain is due to the focusing effects of the local terrain, which had about a 3° downwards slope towards Europe.



Output Graph, HFTA

HFTA, Copyright ARRL 2002, by N6BV, Ver. 1.26B

Freq. = 14.2 MHz
Max. Gain: 19.2 dBi

N6BV-45.PRO
90/60/30 ft
Fig. of Merit: 17.2

N6BV-45.PRO
120 ft
Fig. of Merit: 13.4

FLAT.PRO
120 ft
Fig. of Merit: 12

Elev. Statistic File:
W1-MA-EU.PRN

**Fig 47—*HFTA* screen shot showing how complicated things become when real-world irregular terrain is analyzed. This is the 20-meter elevation pattern for the N6BV/1 station location in Windham, NH, for the 90/60/30-foot stack of triband TH7DX Yagis and a 4-element Yagi at 120 feet on the same tower. For comparison, the response of a 120-foot Yagi over flat ground is also included.**

**Fig 48** shows the *HFTA*-computed 15-meter elevation responses towards Europe for the 90/60/30-foot stack at 90/60/30 feet at N6BV/1, compared to the same 120-foot high Yagi and a 90/60/30-foot stack, but this time over flat ground. Again, the N6BV/1 terrain towards Europe has a significant effect on the gain of the stack compared to that of an identical stack over flat ground. In fact, the peak gain of 20.1 dBi at a 4° elevation angle is close to moon-bounce levels.

## OPTIMIZING OVER LOCAL TERRAIN

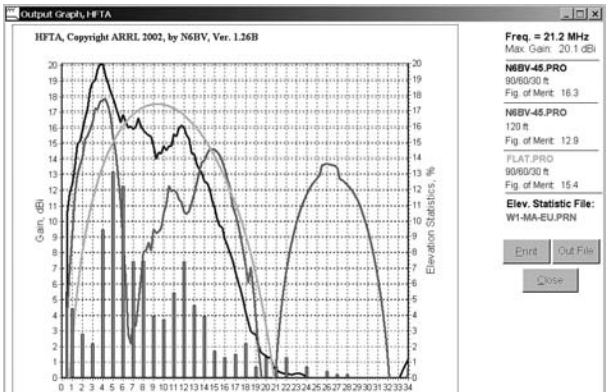
There are only a small number of possibilities to optimize an installation over local terrain:

- Change the antenna height(s) above ground.
- Stack two (or more) Yagis.
- Change the spacing between stacked Yagis.
- Move the tower back from a cliff (or a hill).
- BIP/BOP (Both In Phase/Both Out of Phase).

The *HFTA* program on the CD-ROM accompanying this book can be used, together with Digital Elevation Model (DEM) topographic data available on the Internet, to evaluate all these options.

## SO NEAR, YET SO FAR

It is sometimes very surprising to compare elevation responses for different towers located at various points on the same property, particularly when that prop-



Output Graph, HFTA

HFTA, Copyright ARRL 2002, by N6BV, Ver. 1.26B

Freq. = 21.2 MHz
Max. Gain: 20.1 dBi

N6BV-45.PRO
90/60/30 ft
Fig. of Merit: 16.3

N6BV-45.PRO
120 ft
Fig. of Merit: 12.9

FLAT.PRO
90/60/30 ft
Fig. of Merit: 15.4

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**Fig 48—*HFTA* screen shot showing the 15-meter elevation pattern for the N6BV/1 station location in Windham, NH, for the 90/60/30-foot stack of triband TH7DX Yagis and a 4-element Yagi at 120 feet on the same tower. For comparison, the response of a 120-foot Yagi over flat ground is also included.**

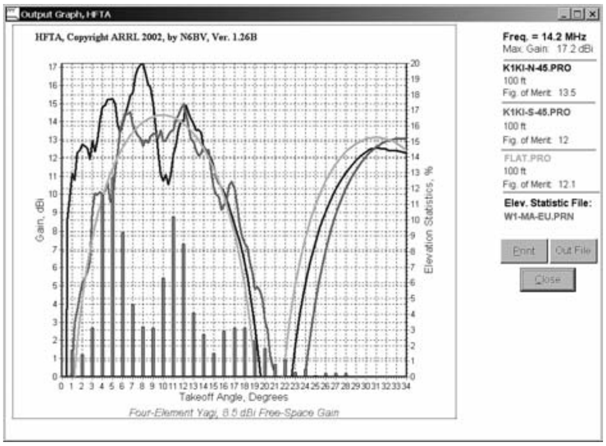

**Fig 49—*HFTA* screen shot showing the 20-meter elevation pattern for K1KI's North and South towers, with 100-foot high 4-element Yagis pointing into Europe at an azimuth of 45°. The responses are surprisingly different for two towers separated by only 600 feet.**

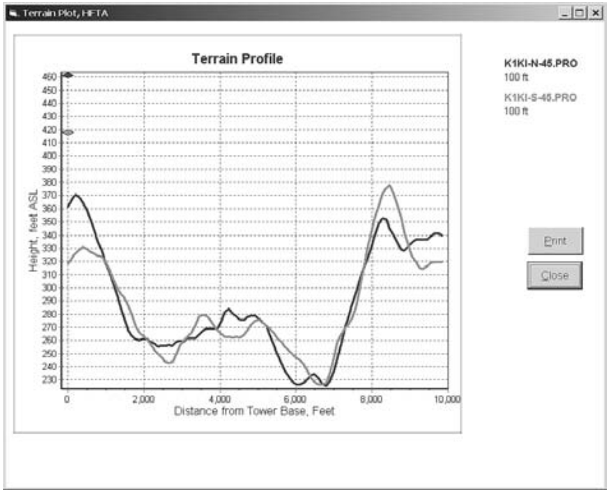

**Fig 50—K1KI's terrain profiles for the North and South towers at an azimuth of 45° into Europe.**

erty is located in the mountains. **Fig 49** shows the computed elevation responses for three 100-foot high 14-MHz Yagis over three terrains towards Europe: from the North tower at K1KI's location in West Suffield, Connecticut, from the South tower at K1KI, and over flat ground. The elevation response from the South tower follows that over flat ground well, while the response from the North tower is quite a bit stronger at low elevation angles—about 1.5 dB on average, as the Figure of Merit shows from *HFTA*.

**Fig 50** shows the reason why this happens—the terrain from the North tower slopes down quickly towards Europe, while the terrain from the South tower goes out almost 900 feet before starting to fall off. These two towers are about 600 feet apart.

# Moxon Rectangle Beams

LB Cebik, W4RNL, has written extensively about the *Moxon rectangle*, an antenna invented by Les Moxon, G6XN, derived from a design by VK2ABQ. The Moxon rectangle beam takes less space horizontally than a conventional 2-element Yagi design, yet it offers nearly the same amount of gain and a superior front-to-back ratio. And as an additional benefit, the drive-point impedance is close to 50 Ω, so that it doesn't need a matching section.

For example, rather than a "wingspan" of 17 feet for the reflector in a conventional 2-element 10-meter Yagi, the Moxon rectangle is 13 feet wide, a saving of almost 25%. The Moxon rectangle W4RNL created for *The ARRL Antenna Compendium, Vol 6*, had an SWR less than 2:1 from 28.0 to 29.7 MHz, with a gain over ground of 11 dBi. It had a F/B of 15 dB at 28.0 MHz, more than 20 dB at 28.4 MHz, and 12 dB at 29.7 MHz.

The Moxon rectangle relies on controlling the spacing (hence controlling the coupling) between the ends of the driven element tips and the ends of the reflector tips, which are both bent toward each other. See **Fig 51**, which shows the general outline for W4RNL's 10-meter aluminum Moxon rectangle. The tips of the elements are kept a fixed distance from each other by PVC spacers. The closed rectangular mechanical assembly gives some rigidity to the design, keeping it stable in the wind. W4RNL described other Moxon rectangle designs using wire elements in June 2000 *QST*.

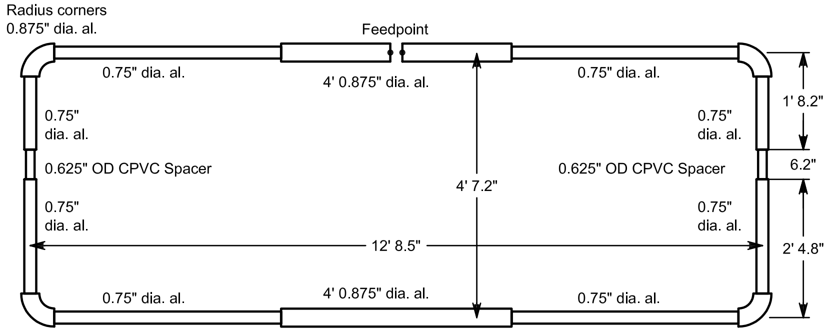

**Fig 51—General outline of the 10-meter aluminum Moxon rectangle, showing tubing dimensions.**