Contents

Chapter 21

Antennas

In the world of radio, the antenna is "where the rubber meets the road!" With antennas so fundamental to communication, it is important that the amateur have a basic understanding of their function. That understanding enables effective selection and application of basic designs to whatever communications task is at hand. In addition, the amateur is then equipped to engage in one of the most active areas of amateur experimentation, antenna design. The goal of this chapter is to define and illustrate the fundamentals of antennas and provide a selection of basic designs; simple verticals and dipoles, quads and Yagi beams, and other antennas. The reader will find additional in-depth coverage of these and other topics in the *ARRL Antenna Book* and other references provided. This chapter was originally written by Chuck Hutchinson, K8CH, and has been updated by Ward Silver, NØAX. Alan Applegate, KØBG, contributed the sections on mobile antennas. The section on Radio Direction Finding Antennas was written by Joe Moell, KØOV.

21.1 Antenna Basics

This section covers a range of topics that are fundamental to understanding how antennas work and defines several key terms. (A glossary is included at the end of the chapter.) While the discussion in this section uses the dipole as the primary example, the concepts apply to all antennas.

21.1.1 Directivity and Gain

All antennas, even the simplest types, exhibit directive effects in that the intensity of radiation is not the same in all directions from the antenna. This property of radiating more strongly in some directions than in others is called the *directivity* of the antenna. Directivity is the same for receiving as transmitting.

The directive pattern of an antenna at a given frequency is determined by the size and shape of the antenna, and on its position and orientation relative to the Earth and any other reflecting or absorbing surfaces.

The more an antenna's directivity is enhanced in a particular direction, the greater the *gain* of the antenna. This is a result of the radiated energy being concentrated in some directions at the expense of others. Similarly, gain describes the ability of the antenna to receive signals preferentially from certain directions. Gain does not create additional power beyond that delivered by the feed line — it only focuses that energy.

Gain is usually expressed in decibels, and is always stated with reference to a *standard* antenna — usually a dipole or an *isotropic radiator*. An isotropic radiator is a theoretical antenna that would, if placed in the center of an imaginary sphere, evenly illuminate that sphere with radiation. The isotropic radiator is an unambiguous standard, and for that reason frequently used as the comparison for gain measurements.

When the reference for gain is the isotropic radiator in free space, gain is expressed in dBi. When the standard is a dipole, also located in *free space*, gain is expressed in dBd. Because the dipole has some gain (2.1 dB) in its favorite direction with respect to the isotropic antenna (see the next section on the dipole antenna), the dipole's gain can be expressed as 2.1 dBi. Gain in dBi can be converted to dBd by subtracting 2.1 dB and from dBd to dBi by adding 2.1 dB.

Gain also takes losses in the antenna or surrounding environment into account. For example, if a practical dipole antenna's wire element dissipated 0.5 dB of the transmitter power as heat, that specific dipole's gain with respect to an isotropic antenna would be 2.1 – 0.5 = 1.6 dBi.

21.1.2 Antenna Polarization

An electromagnetic wave has two components: an electric field and a magnetic field at right angles to each other. For most antennas, the field of primary interest is the electric, or *E-field*. The magnetic field is called the *H-field*. (The abbreviations E- and H- come from Maxwell's equations that describe electromagnetic waves.) By convention, the orientation of the E-field is the reference for determining the electromagnetic wave's *polarization*. The E-field of an electromagnetic wave can be oriented in any direction, so orientation with respect to the Earth's surface is the usual frame of reference. The wave's polarization can be vertical, horizontal, some intermediate angle, or even circular.

Antennas are considered to have polarization, too, determined by the orientation of the E-field of the electromagnetic field radiated by the antenna. Because the E-field of the radiated wave is parallel to the direction of current flow in the antenna's elements, the polarization of the wave and the orientation of the antenna elements is usually the same. For example, the E-field radiated by an antenna with linear elements is parallel to those elements, so that the polarization of the radiated wave is the same as the orientation of the elements. (This is somewhat over-simplified and additional considerations apply for elements that are not linear.) Thus a radiator that is parallel to the earth radiates a horizontally polarized wave, while a vertical antenna radiates a vertically polarized wave. If a wire antenna is slanted, it radiates waves with an E-field that has both vertical and horizontal components.

Antennas function symmetrically — a received signal will create the strongest antenna current when the antenna's elements are parallel to the E-field of the incoming wave just as the radiated wave's E-field will be strongest parallel to current in the antenna's radiating elements. This also means that for the strongest received signal, the antenna elements should have the same polarization as that of the incoming wave. Misalignment of the receiving antenna's elements with the passing wave's E-field reduces the amount of signal received. This is called *cross-polarization*. When the polarizations of antenna and wave are at right angles, very little antenna current is created by the incoming signal.

For best results in line-of-sight communications, antennas at both ends of the circuit should have the same polarization. However, it is not essential for both stations to use the same antenna polarity for ionospheric propagation or sky wave (see the **Propagation** chapter). This is because the radiated wave is bent and rotated considerably during its travel through the ionosphere. At the far end of the communications path the wave may be horizontal, vertical or somewhere in between at any given instant. For that reason, the main consideration for a good DX antenna is a low angle of radiation rather than the polarization.

Most HF-band antennas are either vertically or horizontally polarized. Although circular polarization is possible, just as it is at VHF and UHF, it is seldom used at HF. While most amateur antenna installations use the Earth's surface as their frame of reference, in cases such as satellite communication or EME the terms "vertical" and "horizontal" have no meaning with respect to polarization.

21.1.3 Current and Voltage Distribution

When power is fed to an antenna, the current and voltage vary along its length. The current is minimum at the ends, regardless of the antenna's length. The current does not actually reach zero at the current minima, because of capacitance at the antenna ends. Insulators, loops at the antenna ends, and support wires all contribute to this capacitance, which is also called the *end effect*. The opposite is true of the RF voltage. That is, there is a voltage maximum at the ends.

In the case of a half-wave antenna there is a current maximum at the center and a voltage minimum at the center as illustrated in **Fig 21.1**. The voltage and current in this case are 90° out of phase. The pattern of alternating current and voltage maxima a quarter-wavelength apart repeats every half-wavelength along a linear antenna as shown in Fig 21.1B. The phase of the current and voltage are inverted in each successive half-wavelength section.

The voltage is not zero at its minimum because of the resistance of the antenna, which consists of both the RF resistance of the wire (ohmic loss resistance) and the *radiation resistance*. The radiation resistance is the equivalent resistance that would dissipate the power the antenna radiates, with a current flowing in it equal to the antenna current at a current maximum. Radiation resistance represents the work done by the electrons in the antenna in transferring the energy from the signal source to the radiated electromagnetic wave. The loss resistance of a half-wave antenna is ordinarily small, compared with the radiation resistance, and can usually be neglected for practical purposes except in electrically small antennas, such as mobile HF antennas.

21.1.4 Impedance

The *impedance* at a given point in the antenna is determined by the ratio of the voltage to the current at that point. For example, if there were 100 V and 1.4 A of RF current at a specified point in an antenna and if they were in phase, the impedance would be approximately 71 Ω. The antenna's *feed point impedance* is the impedance at the point where the feed line is attached. If the feed point location changes, so does the feed point impedance.

Antenna impedance may be either resistive or complex (that is, containing resistance and reactance). The impedance of a *resonant* antenna is purely resistive anywhere on the antenna, no matter what value that impedance may be. For example, the impedance of a resonant half-wave dipole may be low at the center of the antenna and high at the ends, but it is purely resistive in all cases, even though its magnitude changes.

The feed point impedance is important in determining the appropriate method of matching the impedance of the antenna and the transmission line. The effects of mismatched antenna and feed line impedances are described in detail in the **Transmission Lines** chapter of this book. Some mistakenly believe that a mismatch, however small, is a serious matter. This is not true. The

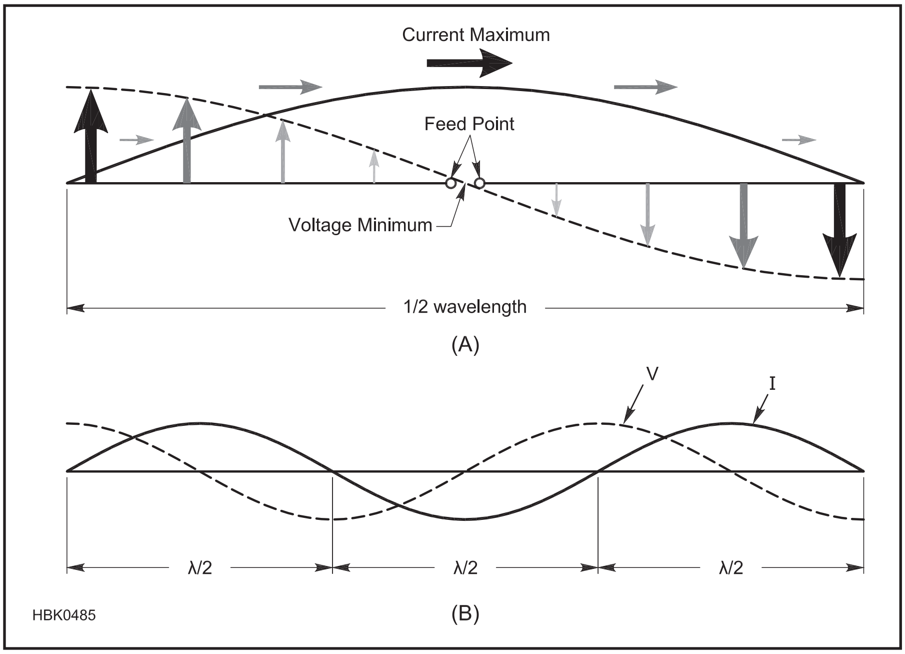


Fig 21.1 — The current and voltage distribution along a half-wave dipole (A) and for an antenna made from a series of half-wave dipoles (B).

significance of a perfect match becomes more pronounced only at VHF and higher, where feed line losses are a major factor. Minor mismatches at HF are rarely significant.

21.1.5 Impedance and Height Above Ground

The feed point impedance of an antenna varies with height above ground because of the effects of energy reflected from and absorbed by the ground. For example, a ½-λ (or half-wave) center-fed dipole will have a feed point impedance of approximately 75 Ω in free space far from ground, but **Fig 21.2** shows that only at certain electrical heights above ground will the feed point impedance be 75 Ω. The feed point impedance will vary from very low when the antenna is close to the ground to a maximum of nearly 100 Ω at 0.34-λ above ground, varying between ±5 Ω as the antenna is raised farther. The 75-Ω feed point impedance is most likely to be realized in a practical installation when the horizontal dipole is approximately ½, ¾ or 1 wavelength above ground. This is why few amateur λ/2-dipoles exhibit a center-fed feed point impedance of 75 Ω, even though they may be resonant.

Fig 21.2 compares the effects of perfect ground and typical soil at low antenna heights. The effect of height on the radiation resistance of a horizontal half-wave antenna is not drastic so long as the height of the antenna is greater than 0.2 λ. Below this height, while decreasing rapidly to zero over perfectly conducting ground, the resistance decreases less rapidly with height over actual lossy ground. At lower heights the resistance stops decreasing at around 0.15 λ, and thereafter increases as height decreases further. The reason for the increasing resistance is that more and more energy from the antenna is absorbed by the earth as the height drops below ¼ λ, seen as an increase in feed point impedance.

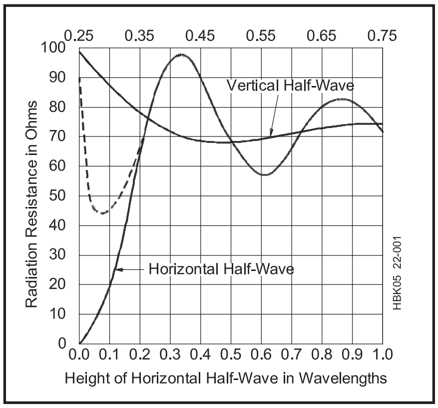


Fig 21.2 — Curves showing the radiation resistance of vertical and horizontal half-wavelength dipoles at various heights above ground. The broken-line portion of the curve for a horizontal dipole shows the resistance over *average* real earth, the solid line for perfectly conducting ground.

21.1.6 Antenna Bandwidth

The *bandwidth* of an antenna refers generally to the range of frequencies over which the antenna can be used to obtain a specified level of performance. The bandwidth can be specified in units of frequency (MHz or kHz) or as a percentage of the antenna's design frequency.

Popular amateur usage of the term antenna bandwidth most often refers to the 2:1 SWR bandwidth, such as, "The 2:1 *SWR bandwidth* is 3.5 to 3.8 MHz" or "The antenna has a 10% SWR bandwidth" or "On 20 meters, the antenna has an SWR bandwidth of 200 kHz." Other specific bandwidth terms are also used, such as the *gain bandwidth* (the bandwidth over which gain is greater than a specified level) and the *front-to-back ratio bandwidth* (the bandwidth over which front-to-back ratio is greater than a specified level).

As operating frequency is lowered, an equivalent bandwidth in percentage becomes narrower in terms of frequency range in kHz or MHz. For example, a 5% bandwidth at 21 MHz is 1.05 MHz (more than wide enough to cover the whole band) but at 3.75 MHz only 187.5 kHz! Because of the wide percentage bandwidth of the lower frequency bands 160 meters is 10.5% wide, 80 meters is 3.4% wide) it is difficult to design an antenna with a bandwidth sufficient to include the whole band.

It is important to recognize that SWR bandwidth does not always relate directly to gain bandwidth. Depending on the amount of feed line loss, an 80 meter dipole with a relatively narrow 2:1 SWR bandwidth can still radiate a good signal at each end of the band, provided that an antenna tuner is used to allow the transmitter to load properly. Broadbanding techniques, such as fanning the far ends of a dipole to simulate a conical type of dipole, can help broaden the SWR bandwidth.

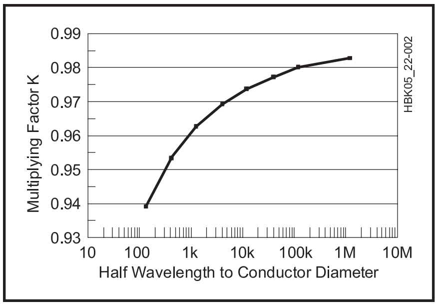


Fig 21.3 — Effect of antenna diameter on length for half-wavelength resonance, shown as a multiplying factor, K, to be applied to the free-space, half-wavelength equation.

21.1.7 Effects of Conductor Diameter

The impedance and resonant frequency of an antenna also depend on the diameter of the conductors that make up its elements in relation to the wavelength. As diameter of a conductor increases, its capacitance per unit length increases and inductance per unit length decreases. This has the net effect of lowering the frequency at which the antenna element is resonant, as illustrated in **Fig 21.3**. The larger the conductor diameter in terms of wavelength, the smaller its *length-to-diameter ratio (l/d)* and the lower the frequency at which a specific length of that conductor is ½-wavelength long electrically, in free space.

$$l / d = \frac{\lambda / 2}{d} = \frac{300}{2f \times d} \qquad (1)$$

where f is in MHz and d is in meters. For example, a ½-wavelength dipole for 7.2 MHz made from #12 AWG wire (0.081- inch dia) has an l/d ratio of

$$l / d = \frac{300}{2f \times d} =$$

$$\frac{300}{2 \times 7.2 \times \dfrac{0.081\,\text{in}}{39.37\,\text{in}/\text{m}}} = 10{,}126$$

The effect of l/d is accounted for by the factor K which is based on l/d. From Fig 21.3 an l/d ratio of 10,126 corresponds to K ≈ 0.975, so the resonant length of that ½-wave dipole would be 0.975 × (300 / 2f) = 20.31 meters instead of the free-space 20.83 meters.

Most wire antennas at HF have l/d ratios in the range of 2500 to 25,000 with K = 0.97 to 0.98. The value of K is taken into account in the classic formula for ½-wave dipole length, 468/f (in MHz). If K = 1, the formula would be 492/f (in MHz). (This is discussed further in the following section on Dipoles and the Half-Wave Antenna.)

For single-wire HF antennas, the effects of ground and antenna construction make a precise accounting for K unnecessary in practice. At and above VHF, the effects of l/d ratio can be of some importance, since the wavelength is small.

Since the radiation resistance is affected relatively little by l/d ratio, the decreased L/C ratio causes the Q of the antenna to decrease. This means that the change in antenna impedance with frequency will be less, increasing the antenna's SWR bandwidth. This is often used to advantage on the lower HF bands by using multiple conductors in a cage or fan to decrease the l/d ratio.

21.1.8 Radiation Patterns

Radiation patterns are graphic representations of an antenna's directivity. Two examples are given in **Figs 21.4** and **21.5**. Shown in polar coordinates (see the math references in the **Electrical Fundamentals** chapter for information about polar coordinates), the angular scale shows direction and the scale from the center of the plot to the outer ring, calibrated in dB, shows the relative strength of the antenna's radiated signal (gain) at each angle. A line is plotted showing the antenna's relative gain (transmitting and receiving) at each angle. The antenna is located at the exact center of the plot with its orientation specified separately.

The pattern is composed of *nulls* (angles at which a gain minimum occurs) and *lobes* (a range of angles in which a gain maximum occurs). The *main lobe* is the lobe with the highest amplitude unless noted otherwise and unless several plots are being compared, the peak amplitude of the main lobe is placed at the outer ring as a 0 dB reference point. The peak of the main lobe can be located at any angle. All other lobes are *side lobes* which can be at any angle, including to the rear of the antenna.

Fig 21.4 is an *azimuthal* or *azimuth pattern* that shows the antenna's gain in all horizontal directions (azimuths) around the antenna. As with a map, 0° is at the top and bearing angle increases clockwise. (This is different from polar plots generated for mathematical functions in which 0° is at the right and angle increases counter-clockwise.)

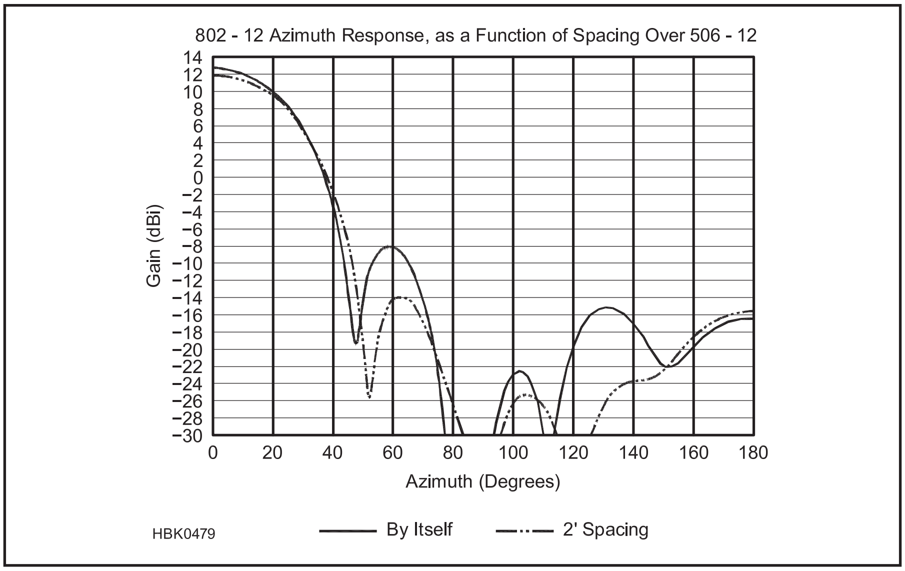


Fig 21.6 — Rectangular azimuthal pattern of an 8-element 2 meter Yagi beam antenna by itself and with another identical antenna stacked two feet above it. This example shows how a rectangular plot allows easier comparison of antenna patterns away from the main lobe.

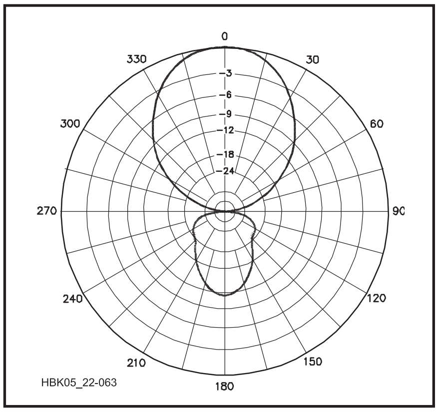


Fig 21.4 — Azimuthal pattern of a typical three-element Yagi beam antenna in free space. The Yagi's boom is along the 0° to 180° axis.

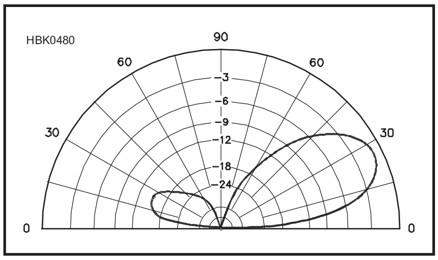


Fig 21.5 — Elevation pattern of a 3-element Yagi beam antenna placed ½-λ above perfect ground.

Fig 21.5 is an *elevation pattern* that shows the antenna's gain at all vertical angles. In this case, the horizon at 0° is located to both sides of the antenna and the zenith (directly overhead) at 90°. The plot shown in Fig 21.5 assumes a ground plane (drawn from 0° to 0°) but in free-space, the plot would include the missing semicircle with –90° at the bottom. Without the ground reference, the term "elevation" has little meaning, however.

You'll also encounter E-plane and H-plane radiation patterns. These show the antenna's radiation pattern in the plane parallel to the E-field or H-field of the antenna. It's important to remember that the E-plane and H-plane do not have a fixed relationship to the Earth's surface. For example, the E-plane pattern from a horizontal dipole is an azimuthal pattern, but if the same dipole is oriented vertically, the E-plane pattern becomes an elevation pattern.

Antenna radiation patterns can also be plotted on rectangular coordinates with gain on the vertical axis in dB and angle on the horizontal axis as shown in **Fig 21.6**. This is particularly useful when several antennas are being compared. Multiple patterns in polar coordinates can be difficult to read, particularly close to the center of the plot.

The amplitude scale of antenna patterns is almost always in dB. The scale rings can be calibrated in several ways. The most common is for the outer ring to represent the peak amplitude of the antenna's strongest lobe as 0 dB. All other points on the pattern represent *relative gain* to the peak gain. The antenna's *absolute gain* with respect to an isotropic (dBi) antenna or dipole (dBd) is printed as a label somewhere near the pattern. If several antenna radiation patterns are shown on the same plot for comparison, the pattern with the largest gain value is usually assigned the role of 0 dB reference.

The gain amplitude scale is usually divided in one of two ways. One common division is to have rings at 0, –3, –6, –12, –18, and –24 dB. This makes it easy to see where the gain has fallen to one-half of the reference or peak value (–3 dB), one-quarter (–6 dB), one-sixteenth (–12 dB), and so on. Another popular division of the amplitude scale is 0, –10, –20, –30, and –40 dB with intermediate rings or tick marks to show the –2, –4, –6, and –8 dB levels. You will encounter a number of variations on these basic scales.

RADIATION PATTERN MEASUREMENTS

Given the basic radiation pattern and scales, it becomes easy to define several useful measurements or metrics by which antennas are compared, using their azimuthal patterns. Next to gain, the most commonly-used metric for directional antennas is the *front-to-back ratio* (*F/B*) or just "front-to-back." This is the difference in dB between the antenna's gain in the specified "forward" direction and in the opposite or "back" direction. The front-to-back ratio of the antenna in Fig 21.4 is about 11 dB. *Front-to-side ratio* is also used and is the difference between the antenna's "forward" gain and gain at right angles to the forward direction. This assumes the radiation pattern is symmetric and is of most use to antennas such as Yagis and quads that have elements arranged in parallel planes. The front-to-side ratio of the antenna in Fig 21.4 is more than 30 dB. Because the antenna's rear-ward pattern can have large amplitude variations, the *front-to-rear ratio* is sometimes used. Front-to-rear uses the average of rear-ward gain over a specified angle, usually the 180° semicircle opposite the direction of the antenna's maximum gain, instead of a single gain figure at precisely 180° from the forward direction.

The antenna's *beamwidth* is the angle over which the antenna's main lobe gain is within 3 dB of the peak gain. Stated another way, the beamwidth is the angle between the directions at which the antenna's gain is –3 dB. In Fig 21.4, the antenna's main lobe beamwidth is about 54°, since the pattern crosses the –3 dB gain scale approximately 27° to either side of the peak direction. Antenna patterns with comparatively small beamwidths are referred to as "sharp" or "narrow."

An antenna with an azimuthal pattern that shows equal gain in all directions is called *omnidirectional*. This is not the same as an isotropic antenna that has equal gain in all directions, both vertical both horizontal.

21.1.9 Elevation Angle

For long-distance HF communication, the (vertical) *elevation angle* of maximum radiation, or *radiation angle*, is of considerable importance. You will want to erect your antenna so that its strongest radiation occurs at vertical angles resulting in the best performance at the distances over which you want to communicate. In general, the greater the height of a horizontally polarized antenna, the stronger its gain will be at lower vertical angles. **Fig 21.7** shows this effect at work in horizontal dipole antennas. (See the **Propagation** chapter and the *ARRL Antenna Book* for more information about how to determine the best elevation angles for communication.)

Since low radiation angles usually are most effective for long distance communications, this generally means that horizontal antennas should be high — higher is usually better. (The optimum angle for intercontinental contacts on the HF bands is generally 15° or lower.) Experience shows that satisfactory results can be attained on the bands above 14 MHz with antenna heights between 40 and 70 feet.

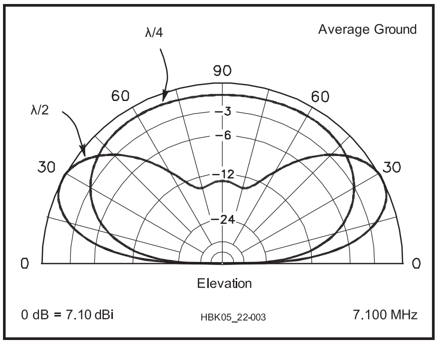


Fig 21.7 — Elevation patterns for two 40 meter dipoles over average ground (conductivity of 5 mS/m and dielectric constant of 13) at ¼-λ (33 ft) and ½-λ (66 ft) heights. The higher dipole has a peak gain of 7.1 dBi at an elevation angle of about 26°, while the lower dipole has more response at high elevation angles.

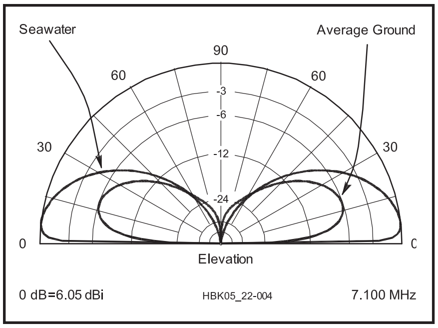


Fig 21.8 — Elevation patterns for a vertical dipole over sea water compared to average ground. In each case the center of the dipole is just over ¼-λ high. The low-angle response is greatly degraded over average ground compared to sea water, which is virtually a perfect ground.

Higher vertical angles can be useful for medium to short-range communications. For example, elevation angles between 20° and 65° are useful on the 40 and 80 meter bands over the roughly 550-mile path between Cleveland and Boston. Even higher angles may be useful on shorter paths when using these lower HF frequencies. A 75 meter dipole between 30 and 70 ft high works well for ranges out to several hundred miles.

For even shorter-range communications centered on your location, such as for emergency communications and regional nets, a very low antenna is used, generating its strongest radiation straight up. This is referred to as *Near-Vertical Incidence Skywave* (*NVIS*) communication. The antenna should be less than ¼-λ above ground and the frequency used should be below the ionosphere's critical frequency so that the signal is completely reflected back toward the ground over a wide area.

Azimuthal patterns must also specify at what elevation angle the antenna gain is measured or calculated. While an azimuthal pattern may be in the plane of the antenna (an elevation angle of 0°), for antennas located above ground, the gain will vary strongly with elevation angle.

21.1.10 Imperfect Ground

Earth conducts, but is far from being a perfect conductor. This influences the radiation pattern of the antennas that we use. The effect is most pronounced at high vertical angles (the ones most important for short-range communications and least important for long-distance communications) for horizontal antennas. The consequences for vertical antennas are greatest at low angles, and are quite dramatic as can be clearly seen in **Fig 21.8**, where the elevation pattern for a 40 meter vertical half-wave dipole located over average ground is compared to one located over saltwater. At 10° elevation, the saltwater antenna has about 7 dB more gain than its landlocked counterpart.

An HF vertical antenna may work very well for a ham living in an area with rich soil. Ground of this type has very good conductivity. By contrast, a ham living where the soil is rocky or in a desert area may not be satisfied with the performance of a vertical HF antenna over such poorly conducting ground.

When evaluating or comparing antennas, it is also important to include the effects of ground on antenna gain. Depending on height above ground and the qualities of the ground, reflections can increase antenna gain by up to 6 dB. Because the actual installation of the antenna is unlikely to duplicate the environment in which the gain with reflections is claimed or measured, it is preferable to rely on free-space gain measurements that are independent of reflecting surfaces.

21.2 Dipoles and the Half-Wave Antenna

A fundamental form of antenna is a wire whose length is half the transmitting wavelength. It is the unit from which many more complex forms of antennas are constructed and is known as a *dipole antenna*. (The name di- meaning *two* and -pole meaning *electrical terminal* comes from the antenna having two distinct regions of electrical polarity as shown in Fig 21.1.) A dipole is resonant when it is electrically ½-λ long so that the current and voltage in the antenna are exactly 90° out of phase as shown in Fig 21.1.

The actual length of a resonant ½-λ antenna will not be exactly equal to the half wavelength of the radio wave of that frequency in free space, but depends on the thickness of the conductor in relation to the wavelength as shown in Fig 21.3. An additional shortening effect occurs with wire antennas supported by insulators at the ends because of current flow through the capacitance at the wire ends due to the end effect. Interaction with the ground and any nearby conductors also affects the resonant length of the physical antenna.

The following formula is sufficiently accurate for dipoles below 10 MHz at heights of ⅛ to ¼ λ and made of common wire sizes. To calculate the length of a half-wave antenna in feet,

$$\text{Length (ft)} = \frac{492 \times 0.95}{\text{f (MHz)}} = \frac{468}{\text{f (MHz)}} \qquad (2)$$

Example: A half-wave antenna for 7150 kHz (7.15 MHz) is 468/7.15 = 65.5 ft, or 65 ft 6 inches.

For antennas at higher frequencies and/or higher above ground, a denominator value of 485 to 490 is more useful. In any case, be sure to include additional wire for attaching to insulators and be prepared to adjust the length of the antenna once installed in its intended position.

Above 30 MHz use the following formulas, particularly for antennas constructed from rod or tubing. K is taken from Fig 21.3.

$$\text{Length (ft)} = \frac{492 \times K}{\text{f (MHz)}} \qquad (3)$$

$$\text{Length (in)} = \frac{5904 \times K}{\text{f (MHz)}} \qquad (4)$$

Example: Find the length of a half-wave antenna at 50.1 MHz, if the antenna is made of ½-inch-diameter tubing. At 50.1 MHz, a half wavelength in space is

$$\frac{492}{50.1} = 9.82\text{ ft}$$

The ratio of half wavelength to conductor diameter (changing wavelength to inches) is

$$\frac{(9.82\text{ ft} \times 12\text{ in/ft})}{0.5\text{ in}} = 235.7$$

From Fig 21.3, K = 0.945 for this ratio. The length of the antenna, from equation 3 is

$$\frac{492 \times 0.945}{50.1} = 9.28\text{ ft}$$

or 9 ft 3⅜ inches. The answer is obtained directly in inches by substitution in equation 4

$$\frac{5904 \times 0.945}{50.1} = 111.4\text{ in}$$

Regardless of the formula used to calculate the length of the half-wave antenna, the effects of ground and conductive objects within a wavelength or so of the antenna usually make it necessary to adjust the installed length in order to obtain the lowest SWR at the desired frequency. Use of antenna modeling software may provide a more accurate initial length than a single formula.

The value of the SWR indicates the quality of the match between the impedance of the antenna and the feed line. If the lowest SWR obtainable is too high, an impedance-matching network may be used, as described in the **Transmission Lines** chapter. (High SWR may cause modern transmitters with solid-state power amplifiers to reduce power output as a protective measure for the output transistors.)

21.2.1 Radiation Characteristics

The radiation pattern of a dipole antenna in free space is strongest at right angles to

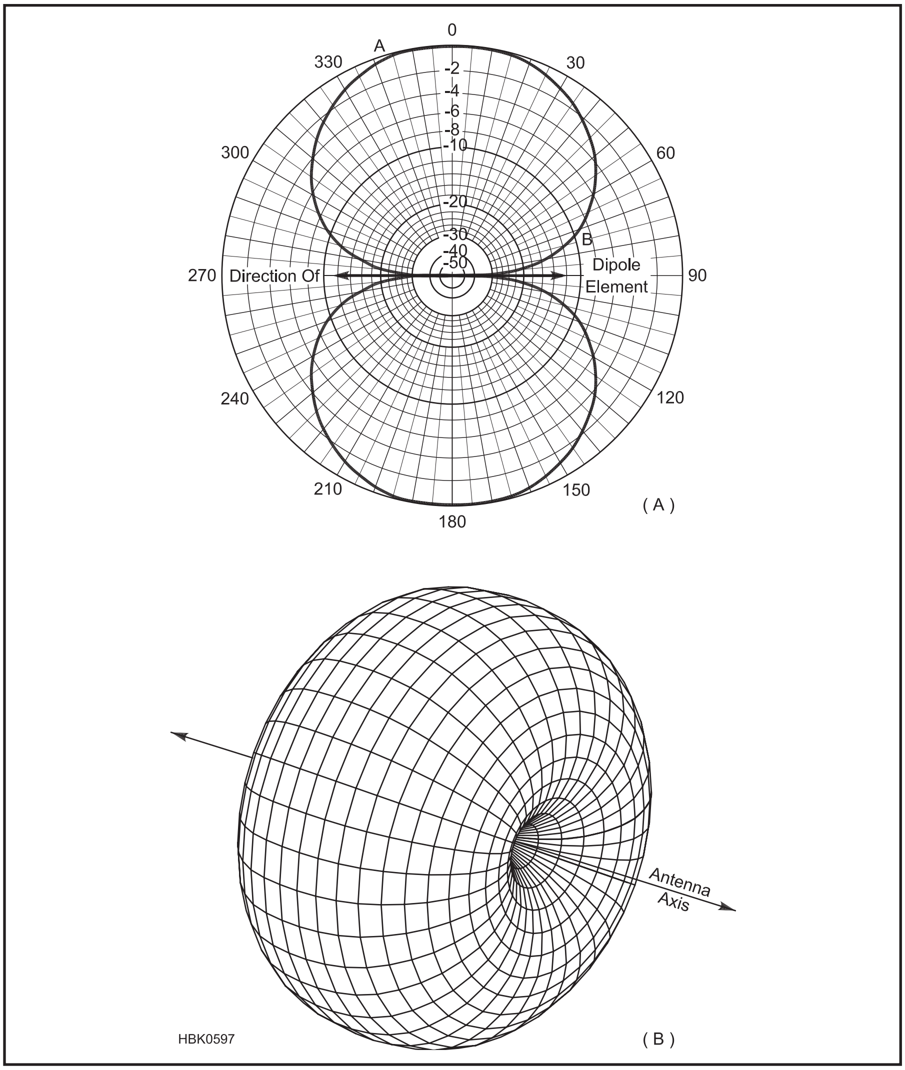


Fig 21.9 — Response of a dipole antenna in free space in the plane of the antenna with the antenna oriented along the 90° to 270° axis (A). The full three-dimensional pattern of the dipole is shown at (B). The pattern at A is a cross-section of the three-dimensional pattern taken perpendicularly to the axis of the antenna.

the wire as shown in **Fig 21.9**, a free-space radiation pattern. In an actual installation, the figure-8 pattern is less directive due to reflections from ground and other conducting surfaces. As the dipole is raised to ½-λ or greater above ground, nulls off the ends of the dipole become more pronounced. Sloping the antenna above ground and coupling to the feed line tend to distort the pattern slightly.

As a horizontal antenna is brought closer to ground, the elevation pattern peaks at a higher elevation angle as shown in Fig 21.7. **Fig 21.10** illustrates what happens to the directional pattern as antenna height changes. Fig 21.10C shows that there is significant radiation off the ends of a low horizontal dipole. For the ½-λ height (solid line), the radiation off the ends is only 7.6 dB lower than that in the broadside direction.

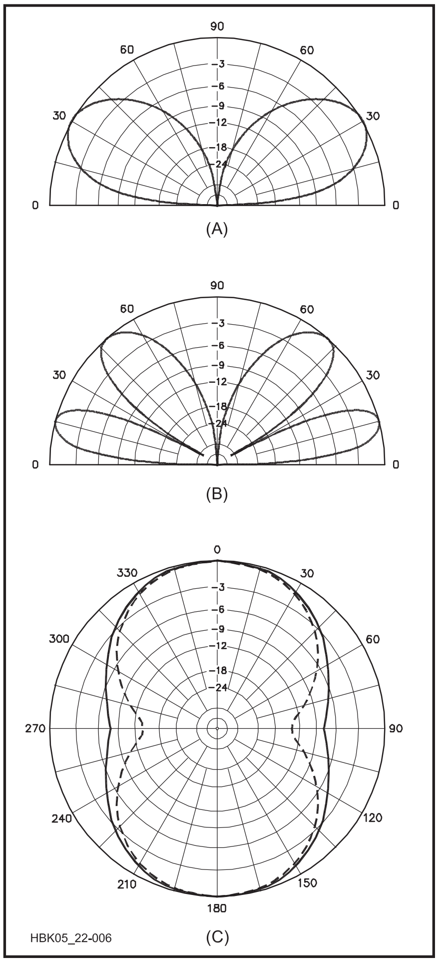


Fig 21.10 — At A, the elevation response pattern of a dipole antenna placed ½-λ above a perfectly conducting ground. At B, the pattern for the same antenna when raised to 1-λ. For both A and B, the conductor is coming out of the paper at a right angle. C shows the azimuth patterns of the dipole for the two heights at the most-favored elevation angle, the solid-line plot for the ½-λ height at an elevation angle of 30°, and the broken-line plot for the 1-λ height at an elevation angle of 15°. The conductor in C lies along the 90° to 270° axis.

Fig 21.10 also shows that for short-range communication that depends on high vertical angles of radiation (NVIS communications), a dipole can be too high. For these applications, the dipole should be installed at or below ¼-λ so that the antenna radiates strongly at high vertical angles and with little horizontal directivity.

A classic dipole antenna is ½-λ long and fed at the center. The low feed point impedance at the dipole's resonant frequency, f_0, and its odd harmonics results in a low SWR when fed with coaxial cable feed lines. The feed point impedance and resulting SWR with coaxial cable will be high at even harmonics and other frequencies.

When fed with ladder line and a wide-range impedance-matching unit, such an antenna can be used on nearly any frequency, including non-resonant frequencies. (An example of such an antenna system is presented as a project farther along in this section.)

21.2.2 Feed Methods

The feed line is attached directly to the dipole, generally at the center, where an insulator separates the antenna's conductor into two sections. This is the antenna's *feed point*. One conductor of the feed line is attached to each section. **Figs 21.11** and **21.12** show how the two types of feed lines are attached. There are numerous variations, of course. You can make your own insulators from plastic or ceramic and there are many commercial insulators available, including some with built-in coax connectors for the feed point.

A dipole can be fed (feed line attached) anywhere along its length, although the impedance of the antenna will vary as discussed earlier. One common variation is the *off-center-fed* (*OCF*) dipole where the feed point is offset from center by some amount and an impedance transformer used to match the resulting moderately-high impedance to that of coaxial cable. Another variation, shown in Fig 21.12B, is the *end-fed Zepp*, named for its original application as an antenna deployed from Zeppelin airships. The feed point impedance of a "Zepp" is quite high, requiring open-wire feed line and impedance matching techniques to deliver power effectively.

Either *coaxial cable* ("coax") or *open-wire* transmission line or feed line is used to connect the transmitter and antenna. There are pro's and con's for each type of feed line. Coax is the common choice because it is readily available, its characteristic impedance is close to that of a center-fed dipole, and it may be easily routed through or along walls and among other cables. Where a very long feed line is required or the antenna is to be used at frequencies for which the feed point impedance is high, coax's increased RF loss and low working voltage (compared to that of open-wire line) make it a poor choice. Refer to the **Transmission Lines** and **Component Data and References** chapters for information that will help you evaluate the RF loss of coaxial cable at different lengths and SWR.

Respect coax's power-handling ratings. Cables such as RG-58 and RG-59 are suitable for power levels up to 300 W with low SWR. RG-8X cable can handle higher power and there are number of variations of this type of cable. For legal-limit power or moderate SWR, use the larger diameter cable types, such as RG-8 or RG-213, that are 0.4 inches in diameter or larger. Subminiature cables, such as RG-174, are useful for very short lengths at low power levels, but the high RF losses associated with these cables make them unsuitable for most uses as antenna feed lines.

The most common open-wire transmission lines are *ladder line* (also known as *window line*) and *twin-lead*. Since the conductors are

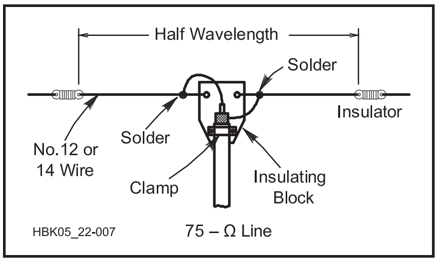


Fig 21.11 — Method of attaching feed line to the center of a dipole antenna. A plastic block is used as a center insulator. The coax is held in place by a clamp. A balun is often used to feed dipoles or other balanced antennas to ensure that the radiation pattern is not distorted. See text for explanation.

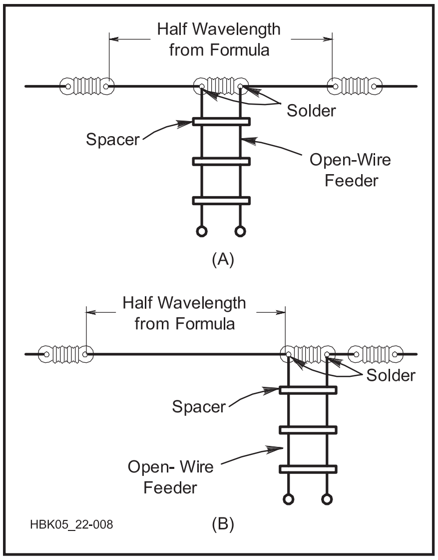


Fig 21.12 — Center-fed multiband *Zepp* antenna at A and an end-fed Zepp at B. See also Fig 21.15 for connection details.

not shielded, two-wire lines are affected by their environment. Use standoffs and insulators to keep the line several inches from structures or other conductors. Ladder line has very low loss (twin-lead has a little more), and it can stand very high voltages (created by high SWR) as long as the insulators are clean. Twin-lead can be used at power levels up to 300 W and ladder line to the full legal power limit.

The characteristic impedance of open-wire line varies from 300 Ω for twin-lead to 450 to 600 Ω for most ladder and window line. When used with ½-λ dipoles, the resulting moderate to high SWR requires an impedance-matching unit at the transmitter. The low RF losses of open-wire lines make this an acceptable situation on the HF bands.

21.2.3 Baluns

Open-wire transmission lines and center-fed dipole antennas are *balanced*, that is, each conductor or section has the same impedance to earth ground. This is different from *unbalanced* coaxial cable, in which the shield is generally connected to an earth ground at some point, generally at the transmitter. To use balanced open-wire transmission lines with unbalanced equipment — most amateur equipment is unbalanced — a *balun* is required to make the transition between the balanced and unbalanced parts of the antenna system. "Balun" is an abbreviation of "balanced-to-unbalanced," the function of the device — it allows power to be transferred between the balanced and unbalanced portions of an antenna system in either direction. The most common application of baluns is to connect an unbalanced feed line to a balanced antenna.

Because dipoles are balanced, a balun is often used at the feed point when a dipole is fed with coax. Due to the skin effect discussed in the **RF Techniques** chapter, the inside and outside of the coaxial cable shield are separate conductors at RF. This "third conductor" of a coaxial cable unbalances the symmetry of the dipole antenna when the coax is connected directly to the dipole as shown in Fig 21.11. As a result, RF current can flow on the outside of the cable shield to the enclosures of station equipment connected to the cable.

Shield currents can impair the function of instruments connected to the line (such as SWR meters and SWR-protection circuits in the transmitter). The shield current also produces some feed line radiation, which changes the antenna radiation pattern, and allows objects near the cable to affect the antenna-system performance.

The consequences may be negligible: A slight skewing of the antenna pattern usually goes unnoticed. Or, they may be significant: False SWR readings may cause the transmitter to reduce power unnecessarily; radiating coax near a TV feed line may cause strong local interference from overload. Therefore, it is better to eliminate feed line radiation whenever possible, and a balun should be used at any transition between balanced and unbalanced systems. Even so, balanced or unbalanced systems without a balun often operate with no apparent problems. For temporary or emergency stations, do not let the lack of a balun deter you from operating.

A balun can be constructed in a number of ways: the simplest being to coil several turns of coaxial cable at the antenna feed point. This creates inductance on the outer surface of the cable (the inner surface of the shield and the center conductor are unaffected) and the resulting reactance opposes RF current flow. There are other methods, such as the use of ferrite beads and cores, that are discussed in the **Transmission Lines** chapter.

21.2.4 Building Dipoles and Other Wire Antennas

The purpose of this section is to offer information on the actual physical construction of wire antennas. Because the dipole, in one of its configurations, is probably the most common amateur wire antenna, it is used in the following examples. The techniques described here, however, enhance the reliability and safety of all wire antennas.

WIRE

Choosing the right type of wire for the project at hand is the key to a successful antenna — the kind that works well and stays up through a winter ice storm or a gusty spring wind storm. What gauge of wire to use is the first question to settle; the answer depends on strength, ease of handling, cost, availability and visibility. Generally, antennas that are expected to support their own weight, plus the weight of the feed line should be made from #12 AWG wire. Horizontal dipoles, Zepps, some long wires and the like fall into this category. Antennas supported in the center, such as inverted-V dipoles and delta loops, may be made from lighter material, such as #14 AWG wire — the minimum size called for in the National Electrical Code.

The type of wire to be used is the next important decision. The wire specifications table in the **Component Data and References** chapter shows popular wire styles and sizes. The strongest wire suitable for antenna service is *copper-clad steel*, also known as *Copperweld*. The copper coating is necessary for RF service because steel is a relatively poor conductor. Practically all of the RF current is confined to the copper coating because of *skin effect*. Copper-clad steel is outstanding for permanent installations, but it can be difficult to work with because of the stiffness of the steel core.

Solid-copper wire, either hard-drawn or soft-drawn, is another popular material. Easier to handle than copper-clad steel, solid copper is available in a wide range of sizes. It is generally more expensive however, because it is all copper. Soft-drawn tends to stretch under tension, so periodic pruning of the antenna may be necessary in some cases. Enamel-coated *magnet-wire* is a suitable choice for experimental antennas because it is easy to manage, and the coating protects the wire from the weather. Although it stretches under tension, the wire may be pre-stretched before final installation and adjustment. A local electric motor rebuilder might be a good source for magnet wire.

Hook-up wire, speaker wire or even ac lamp cord are suitable for temporary installations. Almost any copper wire may be used, as long as it is strong enough for the demands of the installation.

Aluminum wire can be used for antennas, but is not as strong as copper or steel for the same diameter and soldering it to feed lines requires special techniques. Galvanized and steel wire, such as that used for electric fences, is inexpensive, but it is a much poorer conductor at RF than copper and should be avoided.

Kinking, which severely weakens wire, is a potential problem when handling any solid conductor. When uncoiling solid wire of any type — copper, steel, or aluminum — take care to unroll the wire or untangle it without pulling on a kink to straighten it. A kink is actually a very sharp twist in the wire and the wire will break at such a twist when flexed, such as from vibration in the wind.

Solid wire also tends to fail at connection or attachment points at which part of the wire is rigidly clamped. The repeated flexing from wind and other vibrations eventually causes metal fatigue and the wire breaks. Stranded wire is preferred for antennas that will be subjected to a lot of vibration and flexing. If stranded wire is not suitable, use a heavier gauge of solid wire to compensate.

Insulated vs Bare Wire

Losses are the same (in the HF region at least) whether the antenna wire is insulated or bare. If insulated wire is used, a 3 to 5% shortening from the length calculated for a bare wire is required to obtain resonance at the desired frequency. This is caused by the increased distributed capacitance resulting from the dielectric constant of the plastic insulating material. The actual length for resonance must be determined experimentally by pruning and measuring because the dielectric constant of the insulating material varies from wire to wire. Wires that might come into contact with humans or animals should be insulated to reduce the chance of shock or burns.

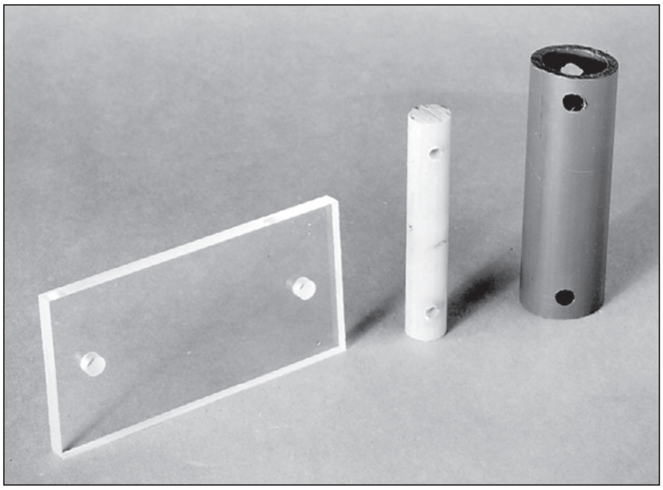
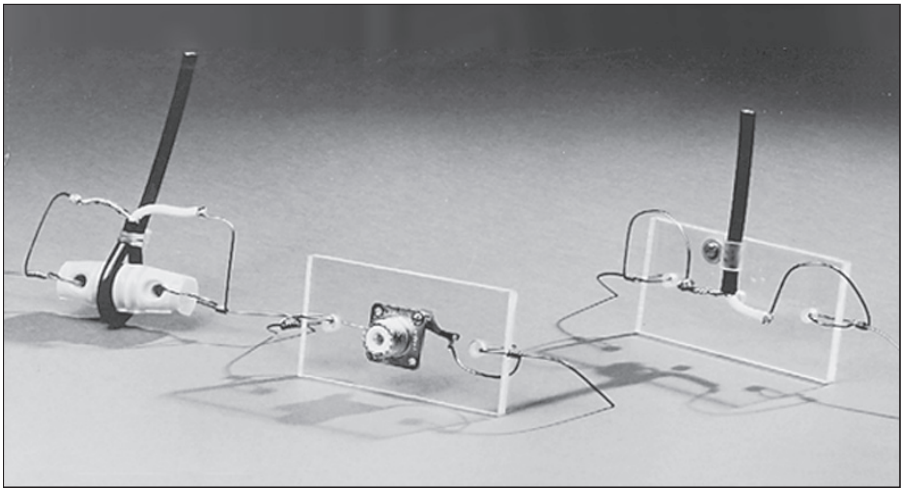


Fig 21.13 — Some ideas for homemade antenna insulators.

Fig 21.14 — Some homemade dipole center insulators. The one in the center includes a built-in SO-239 connector. Others are designed for direct connection to the feed line.



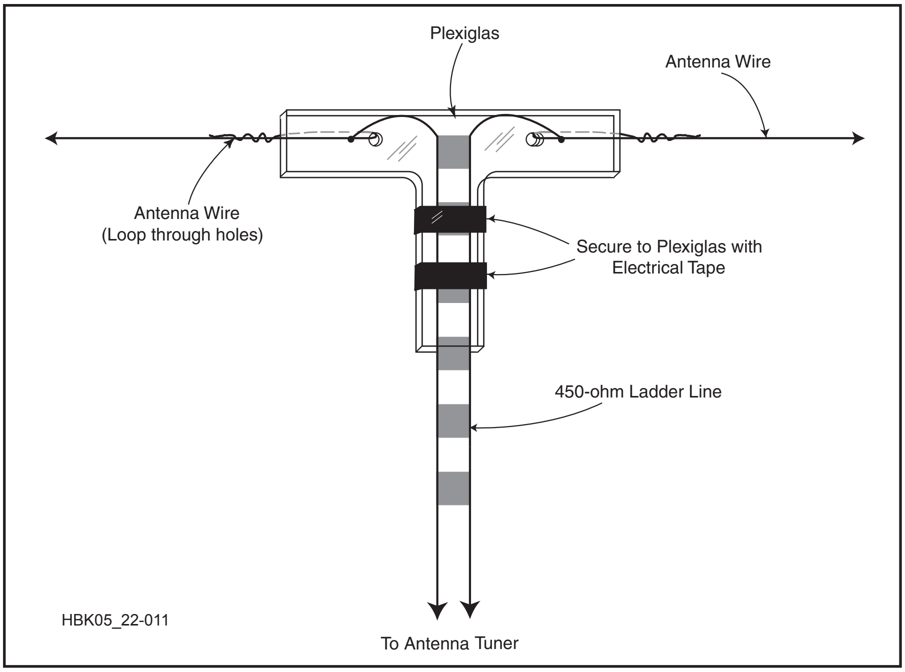


Fig 21.15 — A piece of cut Plexiglas can be used as a center insulator and to support a ladder-line feeder. The Plexiglas acts to reduce the flexing of the wires where they connect to the antenna.

INSULATORS

Wire antennas must be insulated at the ends. Commercially available insulators are made from ceramic, glass or plastic. Insulators are available from many Amateur Radio dealers. RadioShack and local hardware stores are other possible sources.

Acceptable homemade insulators may be fashioned from a variety of material including (but not limited to) acrylic sheet or rod, PVC tubing, wood, fiberglass rod or even stiff plastic from a discarded container. **Fig 21.13** shows some homemade insulators. Ceramic or glass insulators will usually outlast the wire, so they are highly recommended for a safe, reliable, permanent installation. Other materials may tear under stress or break down in the presence of sunlight. Many types of plastic do not weather well.

Most wire antennas require an insulator at the feed point. Although there are many ways to connect the feed line, there are a few things to keep in mind. If you feed your antenna with coaxial cable, you have two choices. You can install an SO-239 connector on the center insulator and use a PL-259 on the end of your coax, or you can separate the center conductor from the braid and connect the feed line directly to the antenna wire. Although it costs less to connect direct, the use of connectors offers several advantages.

Coaxial cable braid acts as a wick to soak up water. If you do not adequately seal the antenna end of the feed line, water will find its way into the braid. Water in the feed line will lead to contamination, rendering the coax useless long before its normal lifetime is up. It is not uncommon for water to drip from the end of the coax inside the shack after a year or so of service if the antenna connection is not properly waterproofed. Use of a PL-259/SO-239 combination (or other connector of your choice) makes the task of waterproofing connections much easier. Another advantage to using the PL-259/SO-239 combination is that feed line replacement is much easier, should that become necessary or desirable.

Whether you use coaxial cable, ladder line, or twin lead to feed your antenna, an often-overlooked consideration is the mechanical strength of the connection. Wire antennas and feed lines tend to move a lot in the breeze, and unless the feed line is attached securely, the connection will weaken with time. The resulting failure can range from a frustrating intermittent electrical connection to a complete separation of feed line and antenna. **Fig 21.14** illustrates several different ways of attaching the feed line to the antenna. An idea for supporting ladder line is shown in **Fig 21.15**.

PUTTING IT TOGETHER

Fig 21.16 shows details of antenna construction. Although a dipole is used for the examples, the techniques illustrated here apply to

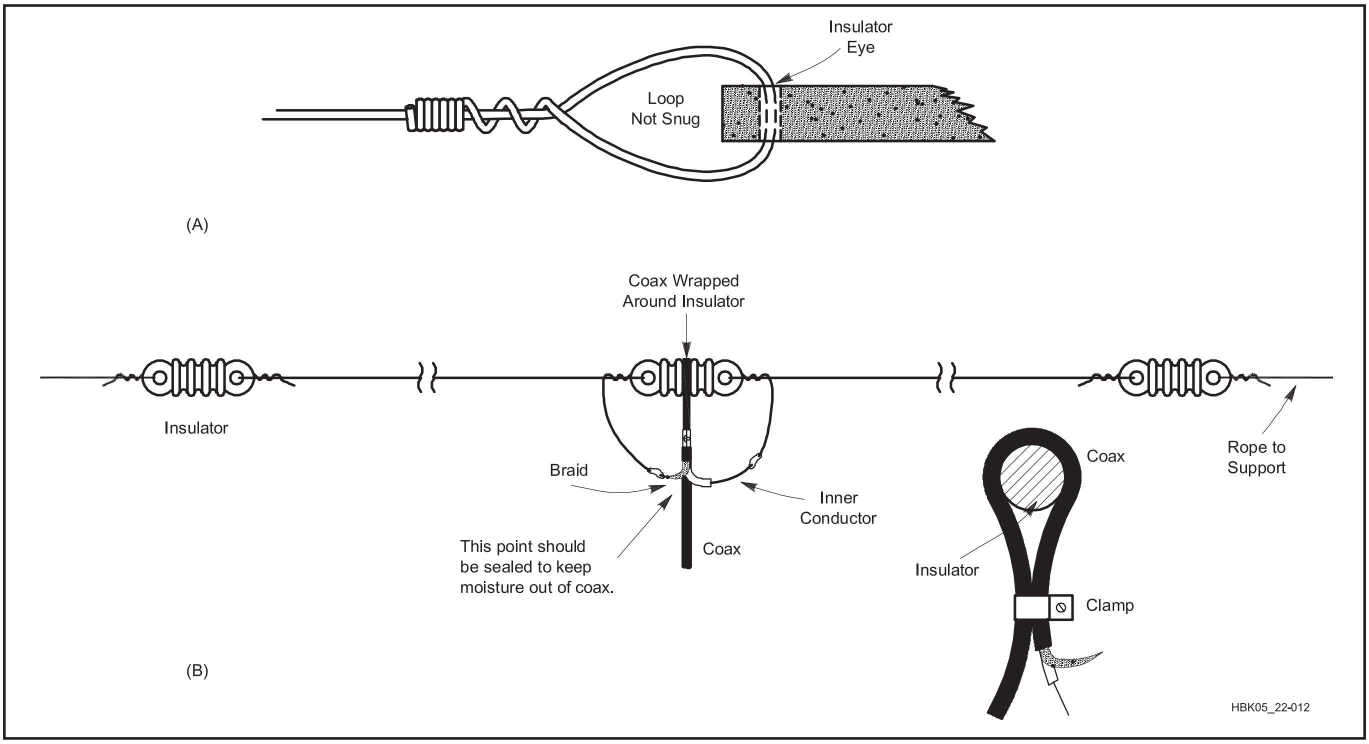


Fig 21.16 — Details of dipole antenna construction. The end insulator connection is shown at A, while B illustrates the completed antenna. This is a balanced antenna and is often fed with a balun at the feed point as described in the text.

Table 21.1
Dipole Dimensions for Amateur Bands

Freq	*Overall Length*		*Leg Length*	
(MHz)	*ft*	*in*	*ft*	*in*
28.4	16	6	8	3
24.9	18	9½	9	4¾
21.1	22	2	11	1
18.1	25	10	12	11
14.1	33	2	16	7
10.1	46	4	23	2
7.1	65	10	32	11
5.37	87	2	43	7
3.6	130	0	65	0

any type of wire antenna. **Table 21.1** shows dipole lengths for the amateur HF bands. These lengths do not include the extra wire required to attach the wire to the insulator as shown in Fig 21.16. Determine the extra amount of wire required by experimenting with the insulator you intend to use. Add twice this amount of wire to the leg lengths in Table 21.1, one extra length for each insulator.

Most dipoles require a little pruning to reach the desired resonant frequency due to the effects of ground and nearby conducting objects and surfaces. So, cut the wire to result in a constructed length 2 to 3% longer than the calculated or table length and record the constructed length with all insulators attached. (The constructed length is measured between the ends of the loops at each end of the wire.) Next, raise the dipole to the working height and find the frequency at which minimum SWR occurs. Multiply the frequency of the SWR minimum by the antenna length and divide the result by the desired f_0. The result is the finished length; trim both ends equally to reach that length and you're done. For example, if you want the SWR minimum to occur at 14.1 MHz and the first attempt with a constructed length of 33.8 ft results in an SWR minimum at 13.9 MHz, the final length for the antenna is

$$\frac{13.9}{14.1}\times 33.8 = 33.3\text{ ft}$$

In determining how well your antenna will work over the long term, how well you put the pieces together is second only to the ultimate strength of the materials used. Even the smallest details, such as how you connect the wire to the insulators (Fig 21.16A), contribute significantly to antenna longevity. By using plenty of wire at the insulator and wrapping it tightly, you will decrease the possibility of the wire pulling loose in the wind. There is no need to solder the wire once it is wrapped. There is no electrical connection here, only mechanical. The high heat needed for soldering can anneal the wire, significantly weakening it at the solder point.

Similarly, the feed line connection at the center insulator should be made to the antenna wires after they have been secured to the insulator (Fig 21.16B). This way, you will be assured of a good electrical connection between the antenna and feed line without compromising the mechanical strength. Do a good job of soldering the antenna and feed line connections. Use a heavy iron or a torch, and be sure to clean the materials thoroughly before starting the job. If possible, solder the connections at a workbench, where the best possible joints may be made. Poorly soldered or unsoldered connections will become headaches as the wire oxidizes and the electrical integrity degrades with time. Besides degrading your antenna performance, poorly made joints can even be a cause of TVI because of rectification. Spray the connections with a UV-resistant acrylic coating for waterproofing.

So that the antenna stays up after installation, keep it away from tree branches and other objects that might rub or fall on the antenna. If the supports for the antenna move in the wind, such as trees, leave enough slack in the antenna that it is not pulled overly tight in normal winds. Other options are to use pulleys and counterweights to allow the antenna supports to flex without pulling on the antenna. (This and other installation topics are covered in the *ARRL Antenna Book*.)

If made from the right materials and installed in the clear, the dipole should give years of maintenance-free service. As you build your antenna, keep in mind that if you get it right the first time, you won't have to do it again for a long time.

21.2.5 Dipole Orientation

Dipole antennas need not be installed horizontally and in a straight line. They are generally tolerant of bending, sloping or drooping. Bent dipoles may be used where antenna space is at a premium. **Fig 21.17** shows a couple of possibilities; there are many more. Bending distorts the radiation pattern somewhat and may affect the impedance as well, but compromises may be acceptable when the situation demands them. When an antenna bends back on itself (as in Fig 21.17B) some of the signal is canceled; avoid this if possible. Remember that dipole antennas are RF conductors. For safety's sake, mount all antennas away from conductors (especially power lines), combustibles and well beyond the reach of passersby.

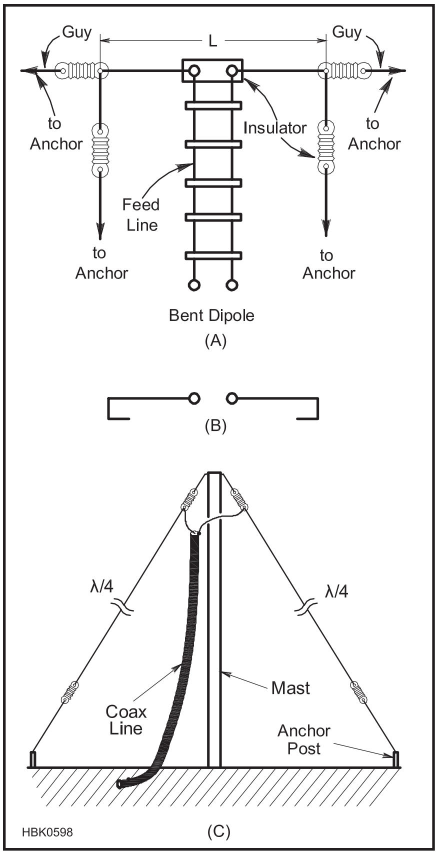


Fig 21.17 — When limited space is available for a dipole antenna, the ends can be bent downward as shown at A, or back on the radiator as shown at B. The inverted-V at C can be erected with the ends bent parallel with the ground when the available supporting structure is not high enough.

21.2.6 Inverted-V Dipole

An *inverted-V* dipole is supported at the center with a single support, such as a tree or mast. While *V* describes the shape of this antenna, this antenna should not be confused with long-wire horizontal-V antennas, which are highly directive.

The inverted-V's radiation pattern and feed point impedance depend on the *apex angle* between the legs: As the apex angle decreases, so does feed point impedance, and the radiation pattern becomes less directive. At apex angles below 90°, the antenna efficiency begins to decrease, as well.

The proximity of ground to the antenna ends will lower the resonant frequency of the antenna so that a dipole may have to be shortened in the inverted-V configuration. Losses in the ground increase when the antenna ends are close to the ground. Keeping the ends eight feet or higher above ground reduces ground loss and also prevents humans and animals from coming in contact with the antenna.

Remember that antenna current produces the radiated signal, and current is maximum at the dipole center. Therefore, performance is best when the central area of the antenna is high and clear of nearby objects.

21.2.7 Sloping Dipole

A sloping dipole is shown in **Fig 21.18**. This antenna is often used to favor one direction (the *forward direction* in the figure). With a non-conducting support and poor ground, signals off the back are weaker than those off the front. With a non-conducting mast and good ground, the response is omnidirectional. There is no gain in any direction with a non-conducting mast.

A conductive support such as a tower acts as a parasitic element. (So does the coax shield, unless it is routed at 90° from the antenna.) The parasitic effects vary with ground quality, support height and other conductors on the support (such as a beam at the top or other wire antennas). With such variables, performance is very difficult to predict.

Losses increase as the antenna ends approach the support or the ground, so the same cautions about the height of the antenna ends applies as for the inverted-V antenna. To prevent feed line radiation, route the coax away from the feed point at 90° from the antenna as far as possible.

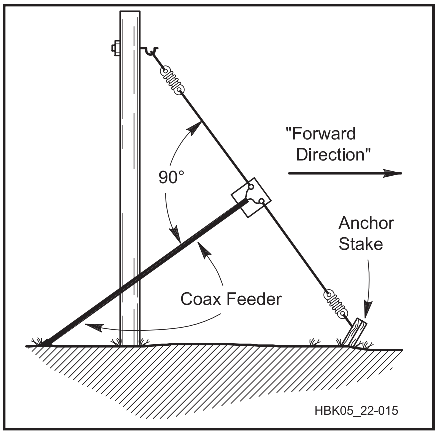


Fig 21.18 — Example of a sloping ½-λ dipole, or *full sloper*. On the lower HF bands, maximum radiation over poor to average earth is off the sides and in the *forward direction* as indicated, if a non-conductive support is used. A metal support will alter this pattern by acting as a parasitic element. How it alters the pattern is a complex issue depending on the electrical height of the mast, what other antennas are located on the mast and on the configuration of any guy wires.

21.2.8 Shortened Dipoles

Inductive loading increases the electrical length of a conductor without increasing its physical length. Therefore, we can build physically-short dipole antennas by placing inductors in the antenna. These are called *loaded dipoles*, and *The ARRL Antenna Book* shows how to design them. There are some trade-offs involved: Inductively loaded antennas are less efficient and have narrower bandwidths than full-size antennas. Generally they should not be shortened more than 50%.

21.2.9 Half-Wave Vertical Dipole (HVD)

Unlike its horizontal counterpart, which has a figure-8 pattern, the azimuthal pattern of a vertical dipole is omnidirectional. In other words, it looks like a circle. Look again at Figs 21.7 and 21.8 and note the comparison between horizontal and vertical dipole elevation patterns. These two figures illustrate the fact that performance of a horizontal dipole depends to a great extent on its height above ground. By contrast, *half-wave vertical dipole* (*HVD*) performance is highly dependent on ground conductivity and dielectric constant.

After looking at these figures, you might easily conclude that there is no advantage to an HVD. Is that really the case? Experiments at K8CH between 2001 and 2003 showed that the HVD mounted above average ground works well for long-distance (DX) contacts. Two antennas were used in the trials. The first was a 15 meter HVD with its base 14 ft above ground (feed point at 25 ft). The second (reference) antenna was a 40 meter inverted-V modified to operate with low SWR on 15 meters. The reference antenna's feed point was at 29 ft and the ends drooped slightly for an apex angle of 160°. Signals from outside North America were usually stronger on the HVD. Antenna modeling revealed the reasons for this behavior.

Fig 21.19 shows the elevation patterns for the vertical dipole and for the reference dipole at a pattern peak and at a null. The vertical dipole does not look impressive, does it? The large lobe in the HVD pattern at 48° is

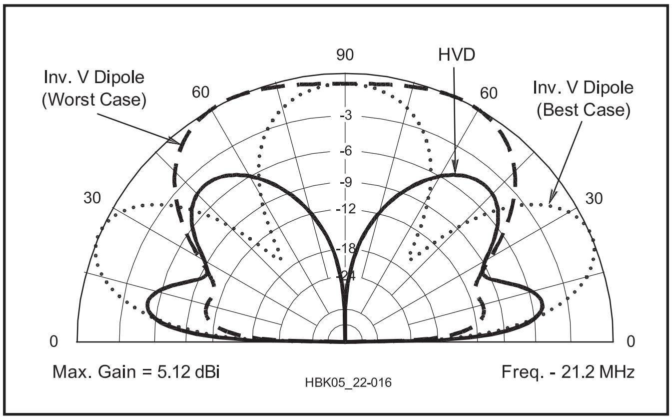


Fig 21.19 — Elevation patterns for the HVD (solid line) and the inverted-V comparison antenna in its best case (dotted line) and worst case (dashed line).

caused by the antenna being elevated 14 ft above ground. This lobe will shrink at lower heights.

Recall that the optimum elevation angles for long-distance contacts fall below 15°. Azimuthal patterns for the HVD at an elevation angle of 10° are shown in **Fig 21.20** and for 3° in **Fig 21.21**. You can clearly see in the patterns the DX potential of an HVD.

Another advantage of the HVD is its radiation resistance at low heights. Look back at Fig 21.2 at the curve for the vertical half-wave antenna. With its base just above ground, the HVD will have a radiation resistance of over 90 Ω. That can easily be turned to an advantage. Capacitive loading will lower the radiation resistance *and* shorten the antenna. It is possible to make a loaded vertical dipole that is half the height of an HVD and that has a good SWR when fed with 50-Ω coax.

21.2.10 Folded Dipoles

Fig 21.22 shows a *folded dipole* constructed from open-wire transmission line. The dipole is made from a ½-λ section of open-wire line with the two conductors connected together at each end of the antenna. The top conductor of the open-wire length is continuous from end to end. The lower conductor, however, is cut in the middle and the feed line attached at that point. Open-wire transmission line is then used to connect the transmitter.

A folded dipole has exactly the same gain and radiation pattern as a single-wire dipole. However, because of the mutual coupling between the upper and lower conductors, the feed point impedance of a single-wire dipole is multiplied by the square of the number of conductors in the antenna. In this case, there are two conductors in the antenna, so the feed point impedance is $2^2 = 4$ times that of a single-wire dipole. (A three-wire folded dipole would have a nine times higher feed point impedance and so forth.)

A common use of the folded dipole is to raise the feed point impedance of the antenna to present a better impedance match to high impedance feed line. For example, if a very long feed line to a dipole is required, open-wire feed line would be used. By raising the dipole's feed point impedance, the SWR on the open-wire line is reduced from that of a single-wire dipole fed with open-wire feed line.

A variation of the folded dipole called the *twin-folded terminated dipole* (*TFTD*) adds a resistor in the top conductor. Values of 300 to 600 Ω are used. The function of the resistor is to act as a *swamping* load, reducing the higher feed point impedances over a wide frequency range. A TFTD ½-λ long at 80 meters can be constructed to cover the entire 2-30 MHz range with SWR of 3:1 or less. The resistor dissipates some of the transmitter power (more than 50% at some frequencies!), but the improvement in SWR allows a coaxial feed line to be used without an impedance-matching unit. The increased convenience and installation outweigh the reduction in radiated signal. TFTD antennas are popular for emergency communications and where only a single HF antenna can be installed and high performance is not required.

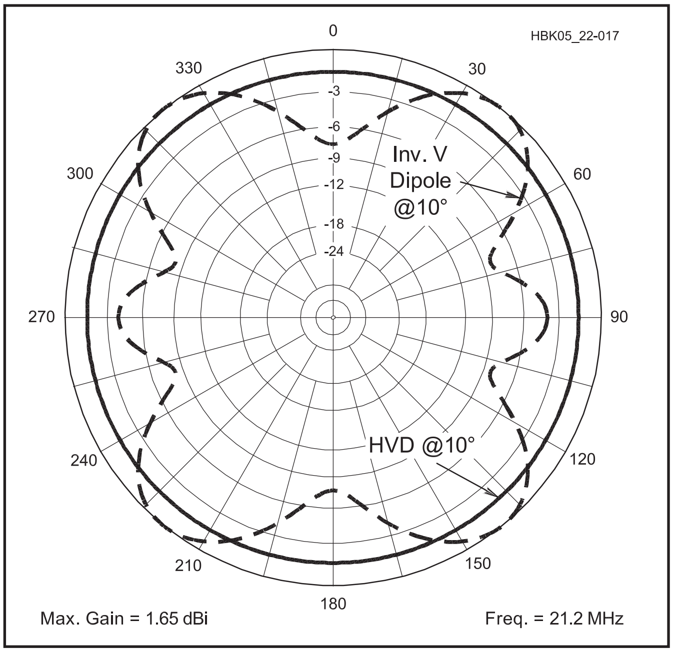


Fig 21.20 — Azimuth patterns at 10° elevation for the HVD (solid line) and inverted-V (dashed line).

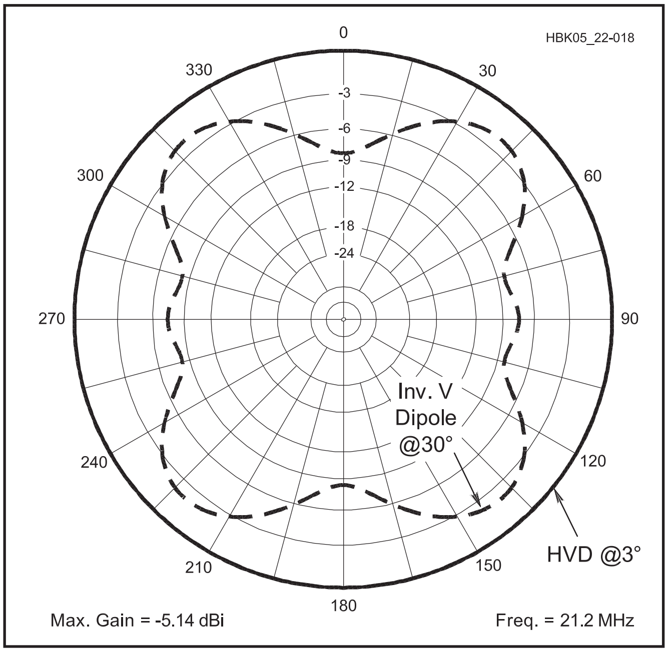


Fig 21.21 — Azimuth patterns at 3° elevation for the HVD (solid line) and the inverted-V (dashed line).

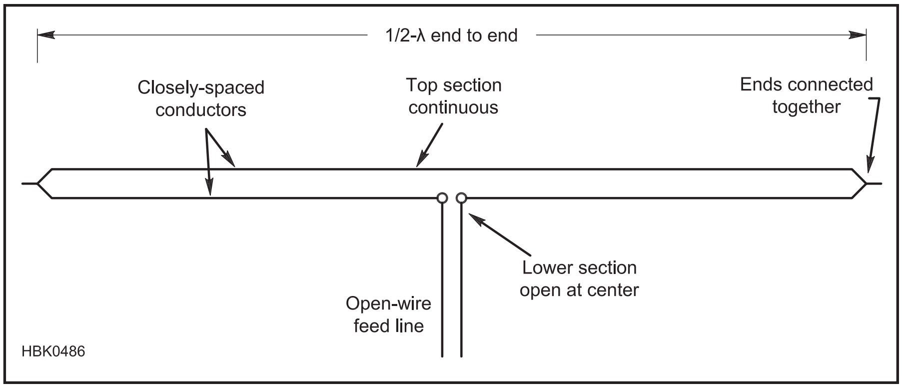


Fig 21.22 — The folded dipole is constructed from open-wire transmission line with the ends connected together. The close proximity of the two conductors and the resulting coupling act as an impedance transformer to raise the feed point impedance over that of a single-wire dipole by the square of the number of conductors used.

21.2.11 Multiband Dipole Systems

There are several ways to construct coax-fed multiband dipole systems. These techniques apply to dipoles of all orientations. Each method requires a little more work than a single dipole, but the materials don't cost much.

PARALLEL DIPOLES

Parallel dipoles as shown in **Fig 21.23** are a simple and convenient answer. Center-fed dipoles have low feed point impedances near f_0 and its odd harmonics, and high impedances at other frequencies. This lets us construct simple multiband systems that automatically select the appropriate antenna. Consider a 50-Ω resistor connected in parallel with a 5-kΩ resistor. A generator connected across the two resistors will see 49.5 Ω, and 99% of the current will flow through the 50-Ω resistor. When resonant and non-resonant antennas are connected in parallel, the same result occurs: The non-resonant antenna has a high impedance, so little current flows in it and it has little effect on the total feed point impedance. Thus, we can connect several dipoles together at the feed point, and power naturally flows to the resonant antenna.

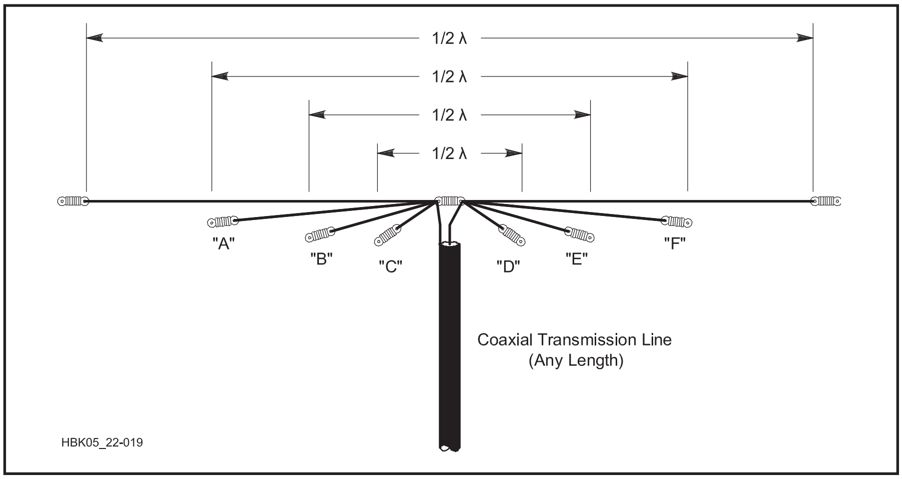


Fig 21.23 — Multiband antenna using paralleled dipoles, all connected to a common 50 or 75-Ω coax line. The ½-λ dimensions may be either for the centers of the various bands or selected for favorite frequencies in each band. The length of a ½-λ in feet is 468/frequency in MHz, but because of interaction among the various elements, some pruning for resonance may be needed on each band. See text.

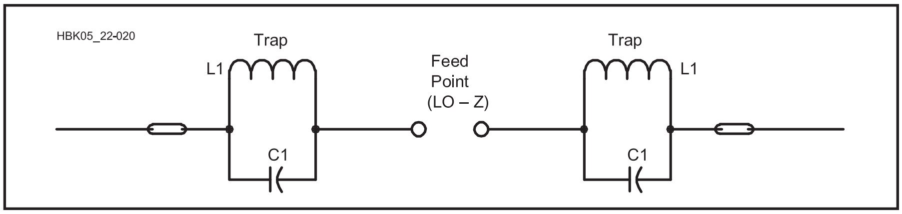


Fig 21.24 — Example of a trap dipole antenna. L1 and C1 can be tuned to the desired frequency by means of a grid-dip meter or SWR analyzer *before* they are installed in the antenna.

There are some limits, however. Wires in close proximity tend to couple due to mutual inductance. In parallel dipoles, this means that the resonant length of the shorter dipoles lengthens a few percent. Shorter antennas don't affect longer ones much, so adjust for resonance in order from longest to shortest. Mutual inductance also reduces the bandwidth of shorter dipoles, so an impedance-matching unit may be needed to achieve an acceptable SWR across all bands covered. These effects can be reduced by spreading the ends of the dipoles apart.

Also, the power-distribution mechanism requires that only one of the parallel dipoles is near resonance on any amateur band. Separate dipoles for 80 and 30 meters should not be connected in parallel because the higher band is near an odd harmonic of the lower band ($80/3 \approx 30$) and center-fed dipoles have low impedance near odd harmonics. (The 40 and 15 meter bands have a similar relationship.) This means that you must either accept the performance of the low-band antenna operating on a harmonic or erect a separate antenna for those odd-harmonic bands. For example, four parallel-connected dipoles cut for 80, 40, 20 and 10 meters (fed by a single impedance-matching unit and coaxial cable) work reasonably on all HF bands from 80 through 10 meters.

TRAP DIPOLES

Trap dipoles (also called "trapped dipoles") provide multiband operation from a coax-fed single-wire dipole. **Fig 21.24** shows a two-band trap antenna. A trap consists of inductance and capacitance in parallel with a resonant frequency on the higher of the two bands of operation. The high impedance of the trap at its resonant frequency effectively disconnects the wire beyond the trap. Thus, on the higher of the two bands of operation at which traps are resonant, only the portion of the antenna between the traps is active.

Above resonance, the trap presents a capacitive reactance. Below resonance, the trap is inductive. On the lower of the two bands of operation, then, the inductive reactance of the trap acts as a loading coil to create a shortened or loaded dipole with the wire beyond the trap.

Traps may be constructed from coiled sec-

Antenna Modeling by Computer

Modern computer programs have made it a *lot* easier for a ham to evaluate antenna performance. The elevation plots for the 135-ft long center-fed dipole were generated using a sophisticated computer program known as *NEC*, short for “Numerical Electromagnetics Code.” *NEC* is a general-purpose antenna modeling program, capable of modeling almost any antenna type, from the simplest dipole to extremely complex antenna designs. Various mainframe versions of *NEC* have been under continuous development by US government researchers for several decades.

But because it is a general-purpose program, *NEC* can be very slow when modeling some antennas — such as long-boom, multi-element Yagis. There are other, specialized programs that work on Yagis much faster than *NEC*. Indeed, *NEC* has developed a reputation for being accurate (if properly applied!), but decidedly difficult to learn and use. A number of commercial software developers have risen to the challenge and created more *user-friendly* versions. Check the ads in *QST*.

NEC uses a *Method of Moments* algorithm. The mathematics behind this algorithm are pretty formidable to most hams, but the basic principle is simple. An antenna is broken down into a set of straight-line wire *segments*. The fields resulting from the current in each segment and from the mutual interaction between segments are vector-summed in the far field to create azimuth and elevation-plane patterns.

The most difficult part of using a *NEC*-type of modeling program is setting up the antenna’s geometry — you must condition yourself to think in three-dimensional coordinates. Each end point of a wire is represented by three numbers: an x, y and z coordinate. An example should help sort things out. See **Fig 21.A1**, showing a *model* for a 135-foot center-fed dipole, made of #14 wire placed 50 ft above flat ground. This antenna is modeled as a single, straight wire.

For convenience, ground is located at the *origin* of the coordinate system, at (0, 0, 0) feet, directly under the center of the dipole. The dipole runs parallel to, and above, the y-axis. Above the origin, at a height of 50 feet, is the dipole’s feed point. The *wingspread* of the dipole goes toward the left (that is, in the *negative y* direction) one-half the overall length, or –67.5 ft. Toward the right, it goes +67.5 ft. The *x* dimension of our dipole is zero. The dipole’s ends are thus represented by two points, whose coordinates are: (0, –67.5, 50) and (0, 67.5, 50) ft. The thickness of the antenna is the diameter of the wire, #14 gauge.

To run the program you must specify the number of segments into which the dipole is divided for the method-of-moments analysis. The guideline for setting the number of segments is to use at least 10 segments per half-wavelength. In Fig 21.A1, our dipole has been divided into 11 segments for 80 meter operation. The use of 11 segments, an odd rather than an even number such as 10, places the dipole’s feed point (the *source* in *NEC*-parlance) right at the antenna’s center and at the center of segment number six.

Since we intend to use our 135-foot long dipole on all HF amateur bands, the number of segments used actually should vary with frequency. The penalty for using more segments in a program like *NEC* is that the program slows down roughly as the square of the segments—double the number and the speed drops to a fourth. However, using too few segments will introduce inaccuracies, particularly in computing the feed point impedance. The commercial versions of *NEC* handle such nitty-gritty details automatically.

Let’s get a little more complicated and specify the 135-ft dipole, configured as an inverted-V. Here, as shown in **Fig 21.A2**, you must specify *two* wires. The two wires join at the top, (0, 0, 50) ft. Now the specification of the source becomes more complicated. The easiest way is to specify two sources, one on each end segment at the junction of the two wires. If you are using the *native* version of *NEC*, you may have to go back to your high-school trigonometry book to figure out how to specify the end points of our droopy dipole, with its 120° included angle. Fig 21.A2 shows the details, along with the trig equations needed.

So, you see that antenna modeling isn’t entirely a cut-and-dried procedure. The commercial programs do their best to hide some of the more unwieldy parts of *NEC*, but there’s still some art mixed in with the science. And as always, there are trade-offs to be made — segments versus speed, for example.

However, once you do figure out exactly how to use them, computer models are wonderful tools. They can help you while away a dreary winter’s day, designing antennas on-screen — without having to risk life and limb climbing an ice-covered tower. And in a relatively short time a computer model can run hundreds, or even thousands, of simulations as you seek to optimize an antenna for a particular parameter. Doesn’t that sound better than trying to optimally tweak an antenna by means of a thousand cut-and-try measurements, all the while hanging precariously from your tower by a climbing belt?!
— *R. Dean Straw, N6BV*

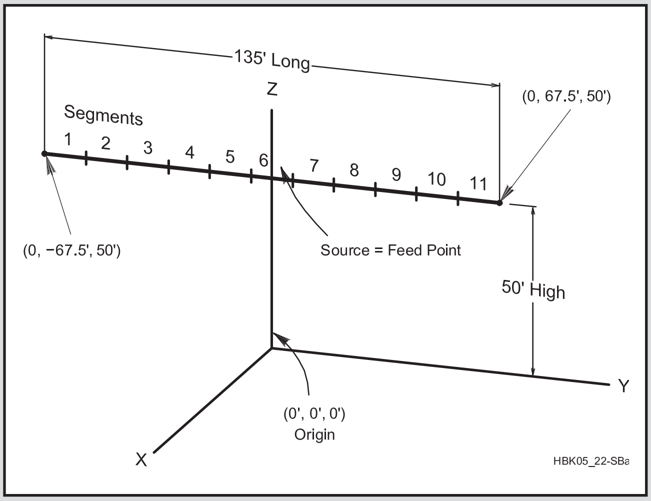


Fig 21.A1 — Model of a 135-ft center-fed dipole.

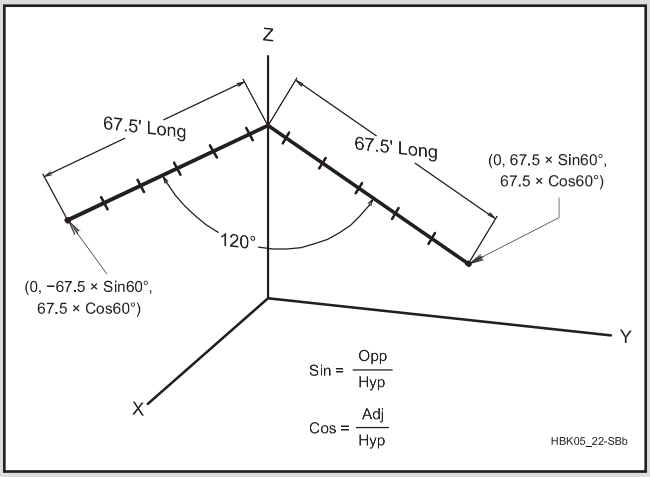


Fig 21.A2 — Model of the 135-ft dipole configured as an inverted V.

tions of coax or from discrete inductors and capacitors. (Traps are also available commercially.) Choose capacitors (C1 in the figure) that are rated for high current and voltage. Mica transmitting capacitors are good. Ceramic transmitting capacitors may work, but their values may change with temperature. Use large wire for the inductors to reduce loss. Any reactance (X_L and X_C) above 100 Ω (at f_0) will work, but bandwidth increases with reactance (up to several thousand ohms). Check trap resonance before installation. This can be done with a grid-dip meter and a receiver or with an SWR analyzer or impedance bridge.

To construct a trap antenna, build a dipole for the higher band of operation and connect the pre-tuned traps to its ends. It is fairly complicated to calculate the additional wire needed for each band, so just add enough wire to make the antenna ½-λ long on the lower band of operation, pruning it as necessary. Because the inductance in each trap reduces the physical length needed for resonance, the finished antenna will be shorter than a simple ½-λ dipole on the lower band.

21.2.12 NVIS Antennas

The use of very low dipole antennas that radiate at very high elevation angles has become popular in emergency communications ("emcomm") systems. This works at low frequencies (7 MHz and below) that are lower than the ionosphere's critical frequency — the highest frequency for which a signal traveling vertically will be reflected. (See the **Propagation** chapter.) The most common band for NVIS communication is 75 meters because the critical frequency is almost always above 4 MHz.

No special antenna construction techniques are required for NVIS antennas — just build a ½-λ dipole and install it at a height of 0.25-λ or below. 0.1-λ is often cited as the optimum height for NVIS antennas, but it is not critical.

At these low heights, the dipole's resonant frequency will be reduced because of the effects of ground. Shortening the antenna will restore the desired resonant frequency, although feed point impedance will drop.

Project: Multiband Center-Fed Dipole

An 80 meter dipole fed with ladder line is a versatile antenna. If you add a wide-range matching network, you have a low-cost antenna system that works well across the entire HF spectrum, and even 6 meters. Countless hams have used one of these in single-antenna stations and for Field Day operations.

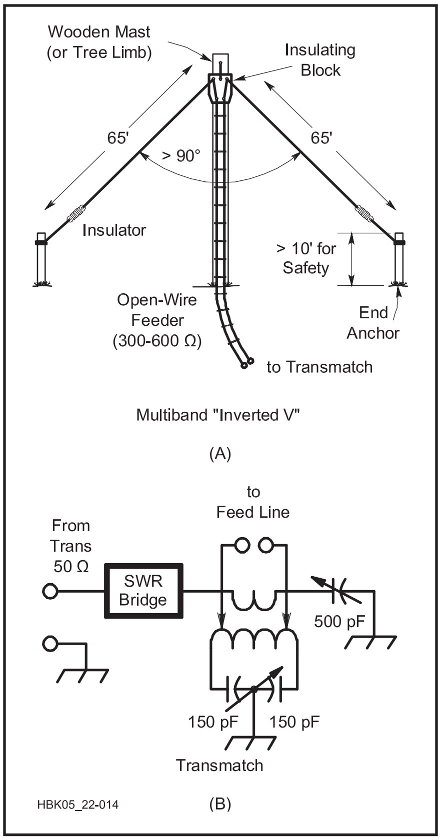


Fig 21.25 — At A, details for an inverted-V fed with open-wire line for multiband HF operation. An impedance-matching unit is shown at B, suitable for matching the antenna to the transmitter over a wide frequency range. The included angle between the two legs should be greater than 90° for best performance.

Fig 21.25A shows a typical installation for such an antenna. The inverted-V configuration is shown, lowering the total antenna length to 130 ft from the 135 ft used if the entire antenna is horizontal. Either configuration will work well. Fig 21.25B shows the schematic of an impedance-matching unit or "antenna tuner" that you can build yourself. You can also use a balanced impedance-matching unit with a balun between it and the transmitter. Many amateurs are successful in using unbalanced impedance-matching units with a balun at either the output or the input of the tuner. Don't be afraid to experiment!

This configuration is popular with other lengths for the antenna:

- 105 ft — 80 through 10 meters
- 88 ft — 80 through 10 meters
- 44 ft — 40 through 10 meters

The next lower band may also be covered if the impedance-matching unit has sufficient range, although the adjustment will be fairly sharp. Six meter coverage is possible, but depends on the station layout, length of feed line, and impedance-matching unit abilities. Again, don't be afraid to experiment!

For best results place the antenna as high as you can, and keep the antenna and ladder line clear of metal and other conductive objects. Despite significant SWR on some bands, the open-wire feed line keeps system losses low as described in the **Transmission Lines** chapter.

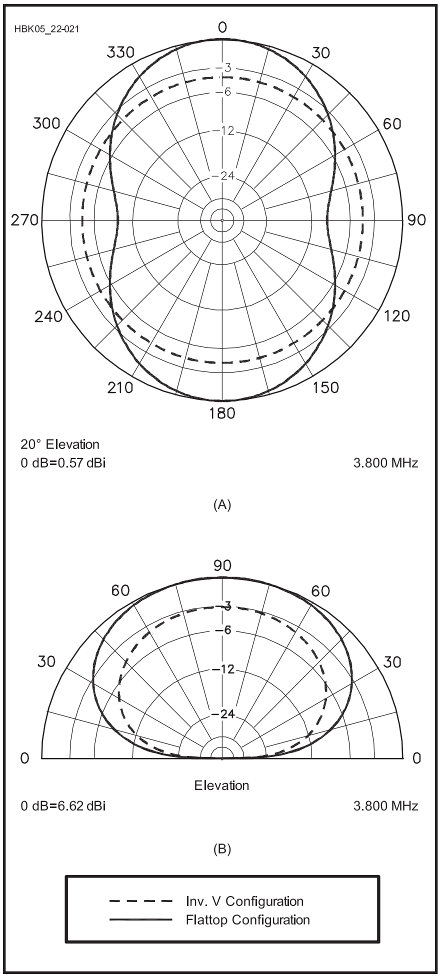


Fig 21.26 — Patterns on 80 meters for 135-ft, center-fed dipole erected as a horizontal dipole at 50 ft, and as an inverted-V with the center at 50 ft and the ends at 10 ft. The azimuth pattern is shown at A, where the conductor lies in the 90° to 270° plane. The elevation pattern is shown at B, where the conductor comes out of paper at a right angle. At the fundamental frequency the patterns are not markedly different.

ARRL staff analyzed a 135-ft dipole at 50 ft above typical ground and compared that to an inverted-V with the center at 50 ft, and the ends at 10 ft. The results show that on the 80 meter band, it won't make much difference which configuration you choose. (See **Fig 21.26**.) The inverted-V exhibits additional losses because of its proximity to ground.

Fig 21.27 shows a comparison between a 20 meter flat-top dipole and the 135-ft flat-top dipole when both are placed at 50 ft above ground. At a 10° elevation angle, the 135-ft dipole has a gain advantage. This advantage comes at the cost of two deep, but narrow,

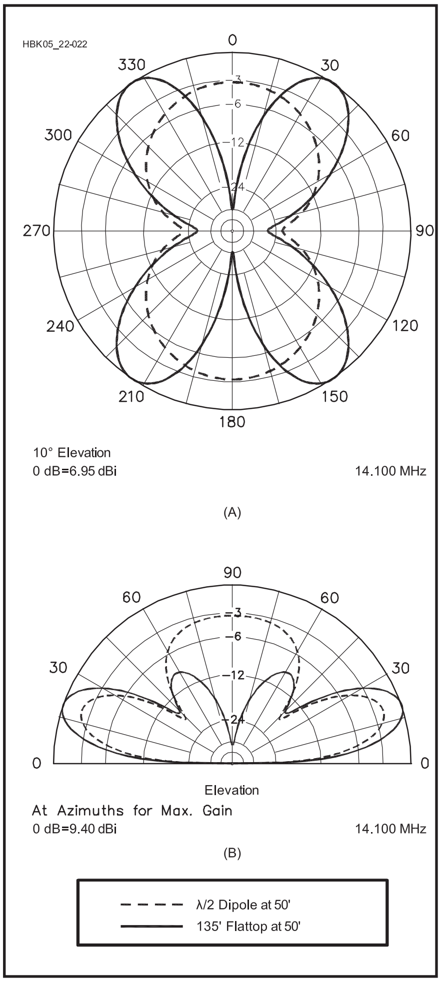


Fig 21.27 — Patterns on 20 meters comparing a standard ½-λ dipole and a multiband 135-ft dipole. Both are mounted horizontally at 50 ft. The azimuth pattern is shown at A, where conductors lie in the 90° to 270° plane. The elevation pattern is shown at B. The longer antenna has four azimuthal lobes, centered at 35°, 145°, 215°, and 325°. Each is about 2 dB stronger than the main lobes of the ½-λ dipole. The elevation pattern of the 135-ft dipole is for one of the four maximum-gain azimuth lobes, while the elevation pattern for the ½-λ dipole is for the 0° azimuthal point.

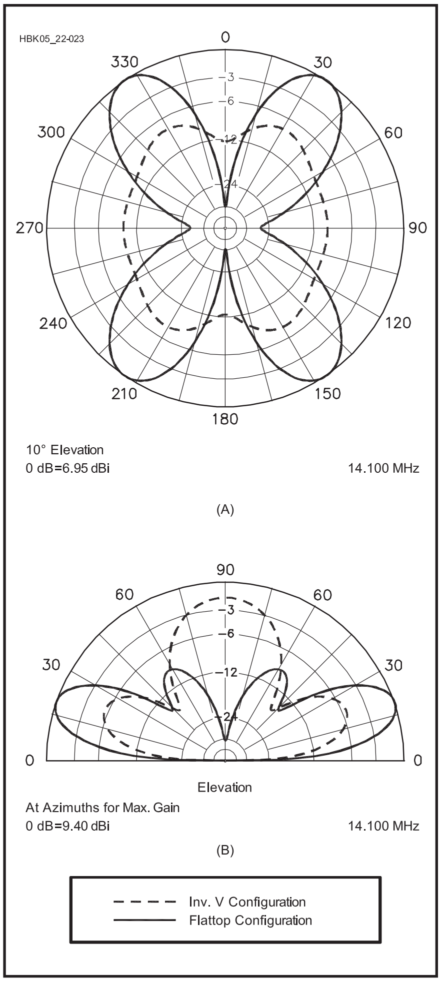


Fig 21.28 — Patterns on 20 meters for two 135-ft dipoles. One is mounted horizontally as a flat-top and the other as an inverted-V with 120° included angle between the two legs. The azimuth pattern is shown at A, and the elevation pattern is shown at B. The inverted-V has about 6 dB less gain at the peak azimuths, but has a more uniform, almost omnidirectional, azimuthal pattern. In the elevation plane, the inverted-V has a fat lobe overhead, making it a somewhat better antenna for local communication, but not quite so good for DX contacts at low elevation angles.

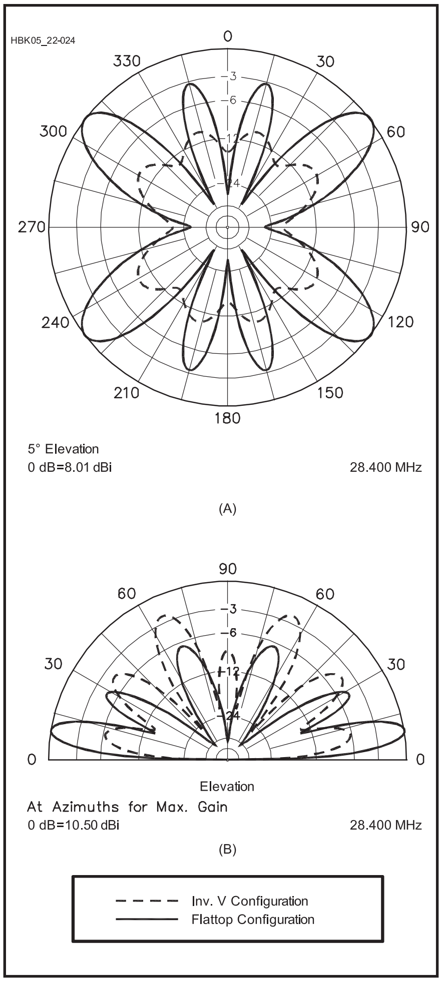


Fig 21.29 — Patterns on 10 meters for 135-ft dipole mounted horizontally and as an inverted-V, as in Fig 21.28. The azimuth pattern is shown at A, and the elevation pattern is shown at B. Once again, the inverted-V conFiguration yields a more omnidirectional pattern, but at the expense of almost 8 dB less gain than the flat-top configuration at its strongest lobes.

nulls that are broadside to the wire.

Fig 21.28 compares the 135-ft dipole to the inverted-V configuration of the same antenna on 14.1 MHz. Notice that the inverted-V pattern is essentially omnidirectional. That comes at the cost of gain, which is less than that for a horizontal flat-top dipole.

As expected, patterns become more complicated at 28.4 MHz. As you can see in **Fig 21.29**, the inverted-V has the advantage of a pattern with slight nulls, but with reduced gain compared to the flat-top configuration.

Installed horizontally, or as an inverted-V, the 135-ft center-fed dipole is a simple antenna that works well from 3.5 to 30 MHz (and on 1.8 MHz if the impedance-matching unit has sufficient range). If extremely high SWR or evidence of RF on objects at the operating position ("RF in the shack") is encountered, change the feed line length by adding or subtracting ⅛-λ at the problem frequency. A few such adjustments should yield a workable solution.

Project: 40-15 Meter Dual-Band Dipole

As mentioned earlier, dipoles have harmonic resonances at odd multiples of their fundamental resonances. Because 21 MHz is the third harmonic of 7 MHz, 7-MHz dipoles are harmonically resonant in the popular ham band at 21 MHz. This is attractive because it allows you to install a 40 meter dipole, feed it with coax, and use it without an antenna tuner on both 40 and 15 meters.

But there's a catch: The third harmonic resonance is actually higher than three times the fundamental resonant frequency. This is because there is no end effect in the center portion of the antenna where there are no insulators.

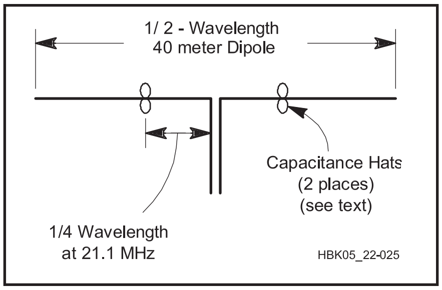


Fig 21.30 — Figure-8-shaped capacitance hats made and placed as described in the text, can make a 40 meter dipole resonate anywhere in the 15 meter band.

An easy fix for this, as shown in **Fig 21.30**, is to add capacitive loading to the antenna about ¼-λ wavelength (at 21.2 MHz) away from the feed point in both halves of the dipole. Known as *capacitance hats*, the simple loading wires shown lower the antenna's resonant frequency on 15 meters without substantially affecting resonance on 40 meters. This scheme can also be used to build a dipole that can be used on 80 and 30 meters and on 75 and 10 meters. (A project for a 75 and 10 meter dipole is included on the CD-ROM included with this book.)

Measure, cut and adjust the dipole to resonance at the desired 40 meter frequency. Then, cut two 2-ft-long pieces of stiff wire (such as #12 or #14 AWG house wire) and solder the ends of each one together to form two loops. Twist the loops in the middle to form figure-8s, and strip and solder the wires where they cross. Install these capacitance hats on the dipole by stripping the antenna wire (if necessary) and soldering the hats to the dipole about a third of the way out from the feed point (placement isn't critical) on each wire. To resonate the antenna on 15 meters, adjust the loop shapes (*not while you're transmitting!*) until the SWR is acceptable in the desired segment of the 15 meter band. Conversely, you can move the hats back and forth along the antenna until the desired SWR is achieved and then solder the hats to the antenna.

Project: W4RNL Inverted-U Antenna

This simple rotatable dipole was designed and built by L. B. Cebik, W4RNL, for use during the ARRL Field Day. For this and other portable operations we look for three antenna characteristics: simplicity, small size, and light weight. Complex assemblies increase the number of things that can go wrong. Large antennas are difficult to transport and sometimes do not fit the space available. Heavy antennas require heavy support structures, so the overall weight seems to increase exponentially with every added pound of antenna.

Today, a number of light-weight collapsible masts are available. When properly guyed, some will support antennas in the 5-10 pound range. Most are suitable for 10 meter tubular dipoles and allow the user to hand-rotate the antenna. Extend the range of the antenna to cover 20-10 meters, and you put these 20-30-foot masts to even better use. The inverted-U meets this need.

THE BASIC IDEA OF THE INVERTED-U

A dipole's highest current occurs within the first half of the distance from the feed point to the outer tips. Therefore, very little performance is lost if the outer end sections are bent. The W4RNL inverted-U starts with a 10 meter tubular dipole. You add extensions for 12, 15, 17 or 20 meters to cover those bands.

You only need enough space to erect a 10 meter rotatable dipole. The extensions hang down. **Fig 21.31** shows the relative proportions of the antenna on all bands from 10 to 20 meters. The 20 meter extensions are the length of half the 10 meter dipole. Therefore, safety dictates an antenna height of at least 20 feet to keep the tips above 10 feet high. At any power level, the ends of a dipole have high RF voltages, and we must keep them out of contact with human body parts.

Not much signal strength is lost by drooping up to half the overall element length straight down. What is lost in bidirectional gain shows up in decreased side-nulls. **Fig 21.32** shows the free-space E-plane (azimuth) patterns of the inverted-U with a 10 meter horizontal section. There is an undetectable decrease in gain between the 10 meter and 15 meter versions. The 20 meter version shows a little over a half-dB gain decrease and a signal increase off the antenna ends.

The real limitation of an inverted-U is a function of the height of the antenna above ground. With the feed point at 20 ft above ground, we obtain the elevation patterns

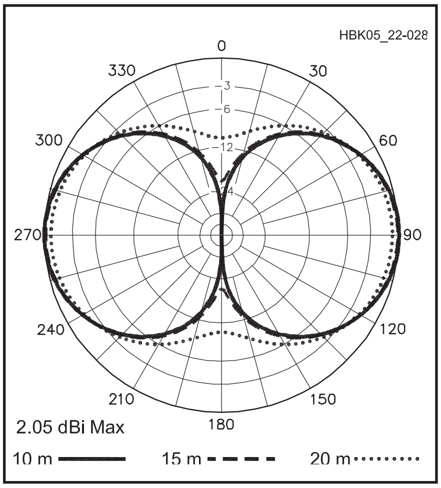


Fig 21.32 — Free-space E-plane (azimuth) patterns of the inverted-U for 10, 15, and 20 meters, showing the pattern changes with increasingly longer vertical end sections.

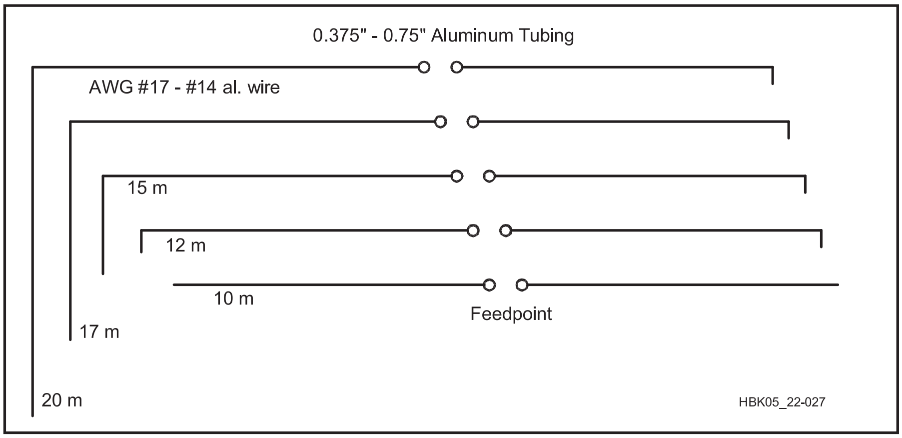


Fig 21.31 — The general outline of the inverted-U field dipole for 20 through 10 meters. Note that the vertical end extension wires apply to both ends of the main 10 meter dipole, which is constant for all bands.

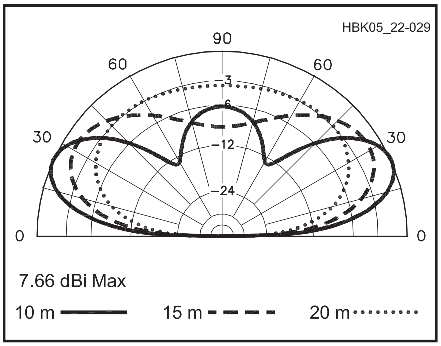


Fig 21.33 — Elevation patterns of the inverted-U for 10, 15, and 20 meters, with the antenna feed point 20 ft above average ground. Much of the decreased gain and higher elevation angle of the pattern at the lowest frequencies is due to its ever-lower height as a fraction of a wavelength.

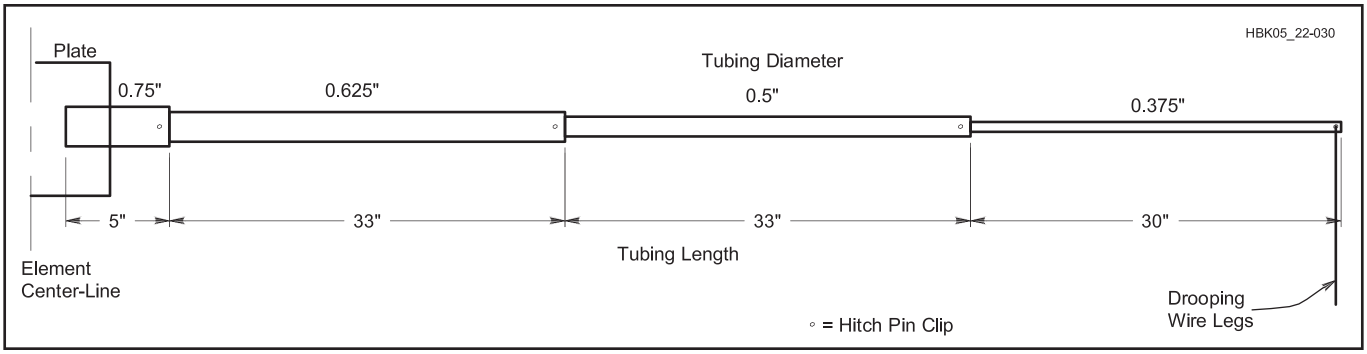


Fig 21.34 — The general tubing layout for the inverted-U for each half element. The opposite side of the dipole is a mirror image of the one shown.

shown in **Fig 21.33**. The 10 meter pattern is typical for a dipole that is about ⅝ λ above ground. On 15, the antenna is only 0.45 λ high, with a resulting increase in the overall elevation angle of the signal and a reduction in gain. At 20 meters, the angle grows still higher, and the signal strength diminishes as the antenna height drops to under 0.3 λ. Nevertheless, the signal is certainly usable. A full-size dipole at 20 meters would show only a little more gain, and the elevation angle would be similar to that of the invert U, despite the difference in antenna shape. If we raise the inverted-U to 40 feet, the 20 meter performance would be very similar to that shown by the 10 meter elevation plot in Fig 21.29.

The feed point impedance of the inverted-U remains well within acceptable limits for virtually all equipment, even at 20 feet above ground. Also, the SWR curves are very broad, reducing the criticalness of finding exact dimensions, even for special field conditions.

BUILDING AN INVERTED-U

Approach the construction of an inverted-U in 3 steps: 1) the tubing arrangement, 2) the center hub and feed point assembly, and 3) the drooping extensions. A parts list appears in **Table 21.2**.

The Aluminum Tubing Dipole for 10 Meters

The aluminum tubing dipole consists of three longer sections of tubing and a short section mounted permanently to the feed point plate, as shown in **Fig 21.34**. Let's consider each half of the element separately. Counting from the center of the plate — the feed point — the element extends five inches using ¾-inch aluminum tubing. Then we have two 33-inch exposed tubing sections, with an additional three inches of tubing overlap per section. These sections are ⅝- and ½-inch diameter, respectively. The outer section is 30 inches long exposed (with at least a three-inch overlap) and consists of ⅜-inch diameter tubing.

Since the ⅝- and ½-inch sections are 36 inches long, you can make the outer ⅜-inch section the same overall length and use more overlap, or you can cut the tubing to 33 inches and use the 3-inch overlap. Three inches of overlap is sufficient to ensure a strong junction, and it minimizes excess weight. However, when not in use, the three outer tubing sections will nest inside each other for storage, and a 36-inch length for the outer section is a bit more convenient to un-nest for assembly. Keep the end hitch pin on the ⅜ inch tubing as an easy way of pulling it into final position. You may use the readily available 6063-T832 aluminum tubing that nests well and has a long history of antenna service.

The only construction operation that you need to perform on the tubing is to drill a hole at about the center of each junction to pass a hitch pin clip. Obtain hitch pin clips (also called hairpin cotter pin clips in some literature) that fit snugly over the tubing. One size will generally handle about two or three tubing sizes. This antenna uses 3⁄32 (pin diameter) by 2⅝-inch long clips for the ¾- to ⅝-inch and the ⅝- to ½-inch junctions, with 3⁄32 by 1⅝-inch pins for the ½- to ⅜-inch junction and for the final hitch pin clip at the outer end of the antenna. Drill the ⅛-inch diameter holes for the clips with the adjacent tubes in position relative to each other. Tape the junction temporarily for the drilling. Carefully de-burr the holes so that the tubing slides easily when nested.

The hitch pin clip junctions, shown in **Fig 21.35**, hold the element sections in position. Actual electrical contact between sections is made by the overlapping portions of the tube. Due to the effects of weather, junctions of this type are not suitable for a permanent installation, but are completely satisfactory for short-term use. Good electrical contact requires clean, dry aluminum surfaces, so do not use any type of lubricant to assist the nesting and un-nesting of the tubes. Instead, clean both the inner and outer surfaces of the tubes before and after each use.

Hitch pin clips are fairly large and harder to lose in the grass of a field site than most

Table 21.2
Parts List for the Inverted-U

Amount	*Item*	*Comments*
6'	0.375" OD aluminum tubing	2 - 3' pieces
6'	0.5" OD aluminum tubing	2 - 3' pieces
6'	0.625" OD aluminum tubing	2 - 3' pieces
10"	0.75" OD aluminum tubing	2 - 5" pieces
4"	0.5" nominal (⅝" OD) CPVC	
50'	Aluminum wire AWG #17	
8	Hitch pin clips	Sized to fit tubing junctions.
1	4" by 4" by ¼" Lexan plate	Other materials suitable.
2	SS U-bolts	Sized to fit support mast
2	Sets SS #8/10 1.5" bolt, nut, washers	SS = stainless steel
2	Sets SS #8 1" bolt, nut, washers	
2	Sets SS #8 0.5" bolt, nut, washers	
1	Coax connector bracket, 1⁄16" aluminum	See text for dimensions and shape
1	Female coax connector	
2	Solder lugs, #8 holes	
2	Short pieces copper wire	From coax connector to solder lugs

Note: 6063-T832 aluminum tubing is preferred and can be obtained from such outlets as Texas Towers (**www.texastowers.com**). Lexan (polycarbonate) is available from such sources as McMasters-Carr (**www.mcmasters.com**), as are the hitch pin clips (if not locally available). Other items should be available from local home centers and radio parts stores.

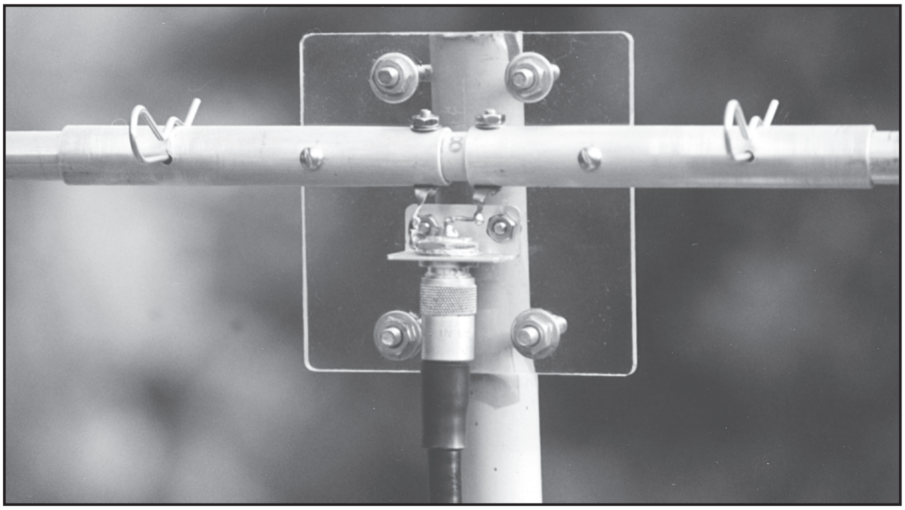


Fig 21.35 — A close-up of the element mounting plate assembly, including the hitch pin clips used to secure the next section of tubing.

nuts and bolts. To avoid losing the clips, attach a short colorful ribbon to the loop end of each clip.

Each half element is 101 inches long, for a total 10 meter dipole element length of 202 inches (16 ft 10 inches). Length is not critical within about one inch, so you may pre-assemble the dipole using the listed dimensions. However, if you wish a more precisely tuned element, tape the outer section in position and test the dipole on your mast at the height that you will use. Adjust the length of the outer tubing segments equally at both ends for the best SWR curve on the lower 1 MHz of the 10 meter band. Even though the impedance will be above 50 Ω throughout the band, you should easily obtain an SWR curve under 2:1 that covers the entire band segment.

The Center Hub: Mounting and Feed Point Assembly

Construct the plate for mounting the element and the mast from a 4 × 4 × ¼-inch-thick scrap of polycarbonate (trade name Lexan), as shown in **Fig 21.36**. You may use other materials so long as they will handle the element weight and stand up to field conditions.

At the top and bottom of the plate are holes for the U-bolts that fit around the mast. Since masts may vary in diameter at the top, size your U-bolts and their holes to suit the mast.

The element center, consisting of two five-inch lengths of ¾-inch aluminum tubing, is just above the centerline of the plate (to allow room for the coax fitting below). ½-inch nominal CPVC has an outside diameter of about ⅝ inch and makes a snug fit inside the ¾-inch tubing. The CPVC aligns the two aluminum tubes in a straight line and allows for a small (about ½ inch) gap between them. When centered between the two tubes, the CPVC is the same width as the plate. A pair of 1.5-inch #8 or #10 stainless steel bolts — with washers and a nut — secures the element to the plate.

Note in the sketch that you may insert the ⅝-inch tube as far into the ¾-inch tube as it will go and be assured of a three-inch overlap. Drill all hitch pin clip holes perpendicular to the plate. Although this alignment is not critical to the junctions of the tubes, it is important to the outer ends of the tubes when you use the antenna below 10 meters.

Mount a single-hole female UHF connector on a bracket made from a scrap of 1⁄16-inch-thick L-stock that is 1 inch on a side. Drill the UHF mounting hole first, before cutting the L-stock to length and trimming part of the mounting side. Then drill two holes for ½-inch long #8 stainless steel bolts about 1 inch apart, for a total length of L-stock of about 1.5 inches. The reason for the wide strip is to place the bolt heads for the bracket outside the area where the mast will meet the plate on the back side. Note in Fig 21.36 that the bracket nuts are on the bracket-side of the main plate, while the heads face the mast. The bracket-to-plate mounting edge of the bracket needs to be only about ¾ inch wide, so you may trim that side of the L-stock accordingly.

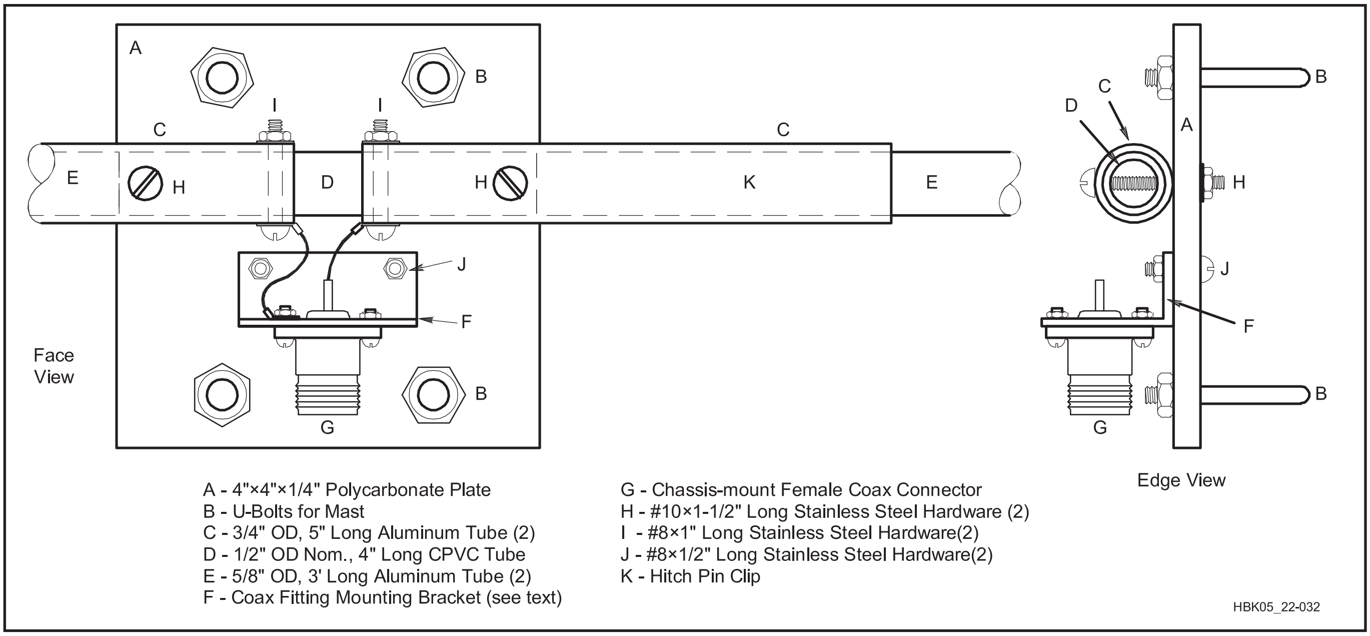


Fig 21.36 — The element and feed point mounting plate, with details of the construction used in the prototype.

Table 21.3
Inverted-U Drooping Wire Lengths

Band (meters)	*Wire Length (inches)*
10	n/a
12	15.9
15	37.4
17	62.0
20	108.0

Note: The wire length for the drooping ends is measured from the end of the tubular dipole to the tip for #17 AWG wire. Little change in length occurs as a function of the change in wire size. However, a few inches of additional wire length is required for attachment to the element.

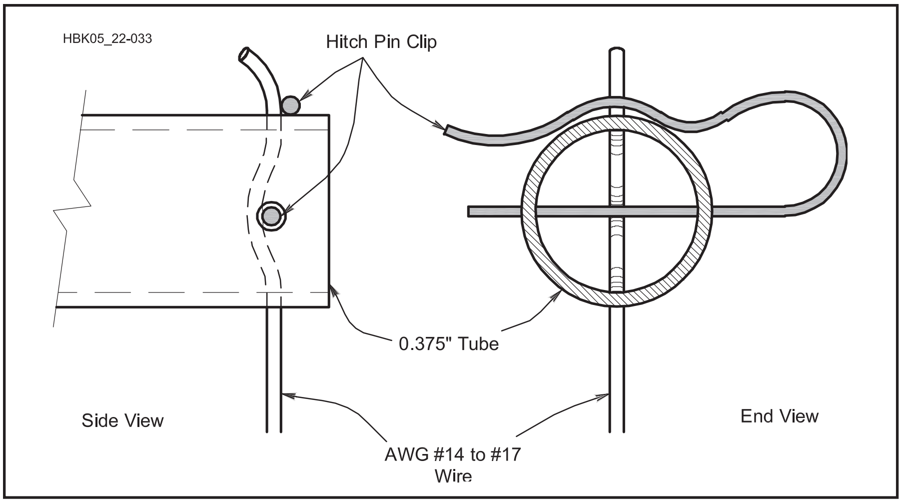


Fig 21.37 — A simple method of clamping the end wires to the ⅜-inch tube end using a hitch pin clip.

With the element center sections and the bracket in place, drill two holes for one-inch long #8 stainless steel bolts at right angles to the mounting bolts and as close as feasible to the edges of the tubing at the gap. These bolts have solder lugs attached for short leads to the coax fitting. Solder lugs do not come in stainless steel, so you should check these junctions before and after each use for any corrosion that may require replacement.

With all hardware in place, the hub unit is about 4 × 10 × 1 inch (plus U-bolts). It will remain a single unit from this point onward, so that your only field assembly requirements will be to extend tubing sections and install hitch pin clips. You are now ready to perform the initial 10 meter resonance tests on your field mast.

The Drooping Extensions for 12-20 Meters

The drooping end sections consist of aluminum wire. Copper is usable, but aluminum is lighter and quite satisfactory for this application. **Table 21.3** lists the approximate lengths of each extension *below* the element. Add three to five inches of wire — less for 12 meters, more for 20 meters — to each length listed.

Common #17 AWG aluminum electric fencing wire works well. Fence wire is stiffer than most wires of similar diameter, and it is cheap. Stiffness is the more important property, since you do not want the lower ends of the wire to wave excessively in the breeze, potentially changing the feed point properties of the antenna while it is in use.

When stored, the lengths of wire extensions for 12 and 15 meters can be laid out without any bends. However, the longer extensions for 17 and 20 meters will require some coiling or folding to fit the same space as the tubing when nested. Fold or coil the wire around any kind of small spindle that has at least a two-inch diameter (larger is better). This measure prevents the wire from crimping and eventually breaking. Murphy dictates that a wire will break in the middle of an operating session. So carry some spare wire for replacement ends. All together, the ends require about 50 ft of wire.

Fig 21.37 shows the simple mounting scheme for the end wires. Push the straight wires through a pair of holes aligned vertically to the earth and bend the top portion slightly. To clamp the wire, insert a hitch pin clip though holes parallel to the ground, pushing the wire slightly to one side to reach the far hole in the tube. The double bend holds the wire securely (for a short-term field operation), but allows the wire to be pulled out when the session is over or to change bands.

Add a few inches to the lengths given in Table 21.3 as an initial guide for each band. Test the lengths and prune the wires until you obtain a smooth SWR curve below 2:1 at the ends of each band. Since an inverted-U antenna is full length, the SWR curves will be rather broad and suffer none of the narrow bandwidths associated with inductively loaded elements. **Fig 21.38** shows typical SWR curves for each band to guide your expectations.

You should not require much, if any, adjustment once you have found satisfactory lengths for each band. So you can mark the wire when you finish your initial test adjustments. However, leave enough excess so that you can adjust the lengths in the field.

Do not be too finicky about your SWR curves. An initial test and possibly one adjustment should be all that you need to arrive at an SWR value that is satisfactory for your equipment. Spending half of your operating time adjusting the elements for as near to a 1:1 SWR curve as possible will rob you of valuable contacts without changing your signal strength is any manner that is detectable.

Changing bands is a simple matter. Remove the ends for the band you are using and install the ends for the new band. An SWR check and possibly one more adjustment of the end lengths will put you back on the air.

FINAL NOTES

The inverted-U dipole with interchangeable end pieces provides a compact field antenna. All of the parts fit in a 3-ft long bag. A drawstring bag works very well. **Fig 21.39** shows the parts in their travel form. When assembled and mounted at least 20 feet up (higher is even better), the antenna will compete with just about any other dipole mounted at the same height. But the inverted-U is lighter than most dipoles at frequencies lower than 10 meters. It also rotates easily by hand — assuming that you can rotate the mast by hand. Being able to broadside the dipole to your target station gives the inverted-U a strong advantage over a fixed wire dipole.

With a dipole having drooping ends, safety is very important. Do not use the antenna unless the wire ends for 20 meters are higher than any person can touch when the antenna is in use. Even with QRP power levels, the RF voltage on the wire ends can be dangerous. With the antenna at 20 feet at its center, the ends should be at least 10 feet above ground.

Equally important is the maintenance that you give the antenna before and after each use. Be sure that the aluminum tubing is clean — both inside and out — when you nest and un-nest the sections. Grit can freeze the sections together, and dirty tubing can prevent good electrical continuity. Carry a few extra hitch pin clips in the package to be sure you have spares in case you lose one.

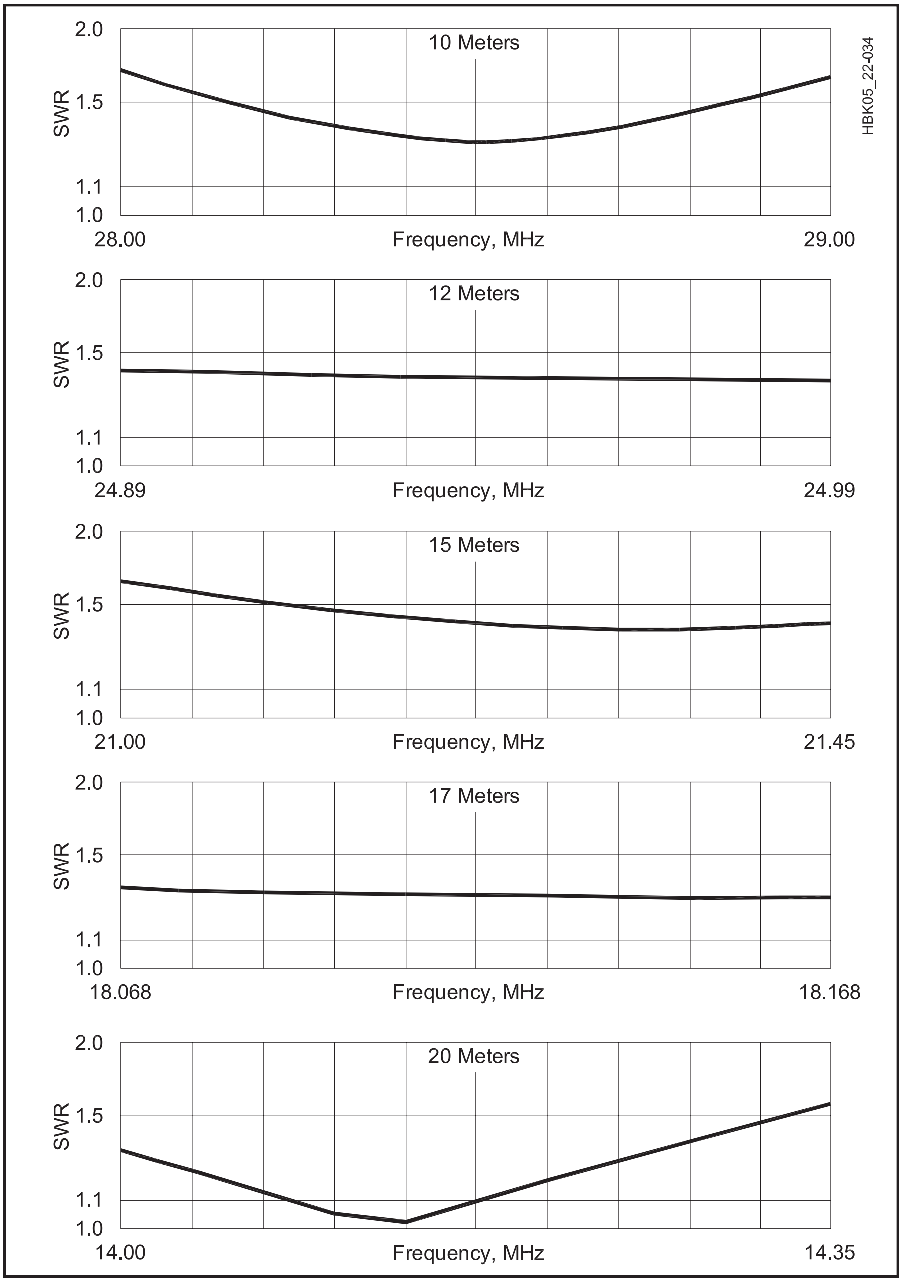


Fig 21.38 — Typical 50-Ω SWR curves for the inverted-U antenna at a feed point height of 20 ft.

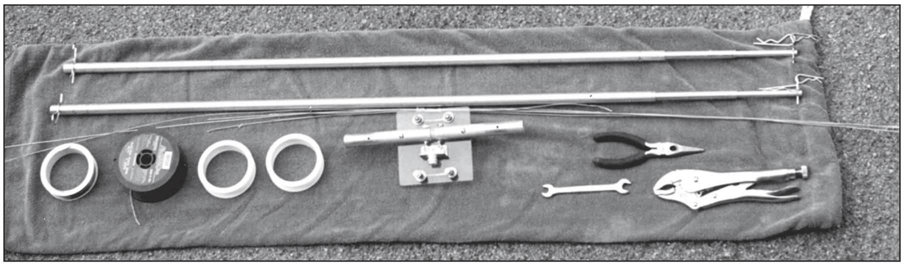


Fig 21.39 — The entire inverted-U antenna parts collection in semi-nested form, with its carrying bag. The tools stored with the antenna include a wrench to tighten the U-bolts for the mast-to-plate mount and a pair of pliers to help remove end wires from the tubing. The pliers have a wire-cutting feature to help replace a broken end wire. A pair of locking pliers makes a good removable handle for turning the mast. The combination of the locking and regular pliers helps to uncoil the wire extensions for any band; give them a couple of sharp tugs to straighten the wire.

Scaling Up the Inverted-U

To inverted-U's rotatable dipole can be scaled up by as much as a factor of three with correspondingly heavier mounting plate and tubing diameters. This results in a rotatable dipole that can be used as low as 30 meters with excellent performance. A full-sized dipole is a very efficient antenna and will hold its own with two-element Yagis at comparable heights.

Suitable tubing and mounting hardware can be obtained by scavenging pieces from old tri-band HF Yagis that have been damaged or taken out of service. Metal boom-to-mast plates can be used if the antenna elements are insulated by enclosing them in a piece of exterior plastic electrical conduit whose inside diameter is a close match to the element's outside diameter. Cut a ¼-inch slot along the length of the conduit so that it can be compressed around the element by the U-bolt or muffler clamp.

Project: Two W8NX Multiband, Coax-Trap Dipoles

Over the last 60 or 70 years, amateurs have used many kinds of multiband antennas to cover the traditional HF bands. The availability of the 30, 17 and 12 meter bands has expanded our need for multiband antenna coverage.

Two different antennas are described here. The first covers the traditional 80, 40, 20, 15 and 10 meter bands, and the second covers 80, 40, 17 and 12 meters. Each uses the same type of W8NX trap — connected for different modes of operation — and a pair of short capacitive stubs to enhance coverage. The W8NX coaxial-cable traps have two different modes: a high- and a low-impedance mode. The inner-conductor windings and shield windings of the traps are connected in series for both modes. However, either the low- or high-impedance point can be used as the trap's output terminal. For low-impedance trap operation, only the center conductor turns of the trap windings are used. For high-impedance operation, all turns are used, in the conventional manner for a trap. The short stubs on each antenna are strategically sized and located to permit more flexibility in adjusting the resonant frequencies of the antenna.

80, 40, 20, 15 AND 10 M DIPOLE

Fig 21.40 shows the configuration of the 80, 40, 20, 15 and 10 meter antenna. The radiating elements are made of #14 AWG stranded copper wire. The element lengths are the wire span lengths in feet. These lengths do not include the lengths of the pigtails at the balun, traps and insulators. The 32.3-ft-long inner 40 meter segments are measured from the eyelet of the input balun to the tension-relief hole in the trap coil form. The 4.9-ft segment length is measured from the tension-relief hole in the trap to the 6-ft stub. The 16.l-ft outer-segment span is measured from the stub to the eyelet of the end insulator.

The coaxial-cable traps are wound on PVC pipe coil forms and use the low- impedance output connection. The stubs are 6-ft lengths of ⅛-inch stiffened aluminum or copper rod hanging perpendicular to the radiating elements. The first inch of their length is bent 90° to permit attachment to the radiating elements by large-diameter copper crimp connectors. Ordinary #14 AWG wire may be used for the stubs, but it has a tendency to curl up and may tangle unless weighed down at the end. You should feed the antenna with 75-Ω coax cable using a good 1:1 balun.

This antenna may be thought of as a modified W3DZZ antenna (see the References) due to the addition of the capacitive stubs. The length and location of the stub give the antenna designer two extra degrees of freedom to place the resonant frequencies within the amateur bands. This additional flexibility is particularly helpful to bring the 15 and 10 meter resonant frequencies to more desirable locations in these bands. The actual 10 meter resonant frequency of the original W3DZZ antenna is somewhat above 30 MHz, pretty remote from the more desirable low frequency end of 10 meters.

80, 40, 17 AND 12 M DIPOLE

Fig 21.41 shows the configuration of the 80, 40, 17 and 12 meter antenna. Notice that the capacitive stubs are attached immediately outboard after the traps and are 6.5 ft long, ½-ft longer than those used in the other antenna. The traps are the same as those of the other antenna, but are connected for the high-impedance parallel-resonant output mode. Since only four bands are covered by this antenna, it is easier to fine tune it to precisely the desired frequency on all bands. The 12.4-ft tips can be pruned to a particular 17 meter frequency with little effect on the 12 meter frequency. The stub lengths can be pruned to a particular 12 meter frequency with little effect on the 17 meter frequency. Both such pruning adjustments slightly alter the 80 meter resonant frequency. However, the bandwidths of the antennas are so broad on 17 and 12 meters that little need for such pruning exists. The 40 meter frequency is nearly independent of adjustments to the capacitive stubs and outer radiating tip elements. Like the first antennas, this dipole is fed with a 75-Ω balun and feed line.

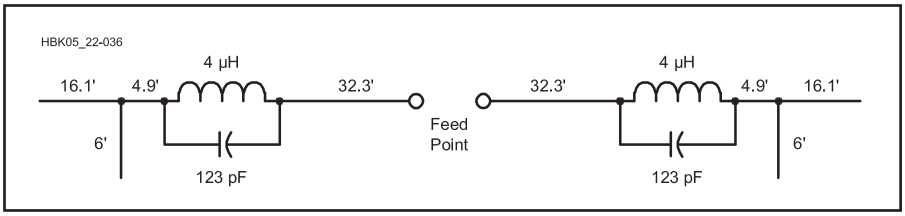


Fig 21.40 — A W8NX multiband dipole for 80, 40, 20, 15 and 10 meters. The values shown (123 pF and 4 µH) for the coaxial-cable traps are for parallel resonance at 7.15 MHz. The low-impedance output of each trap is used for this antenna.

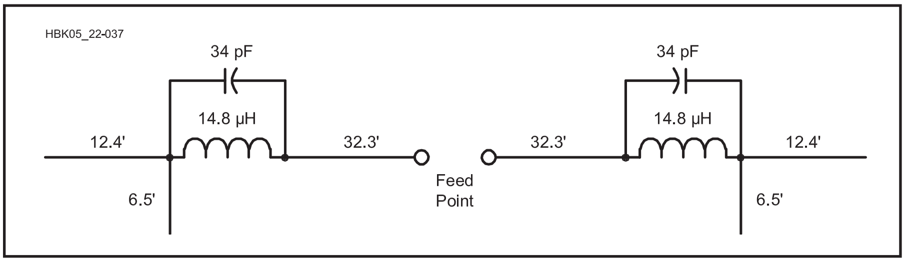


Fig 21.41 — A W8NX multiband dipole for 80, 40, 17 and 12 meters. For this antenna, the high-impedance output is used on each trap. The resonant frequency of the traps is 7.15 MHz.

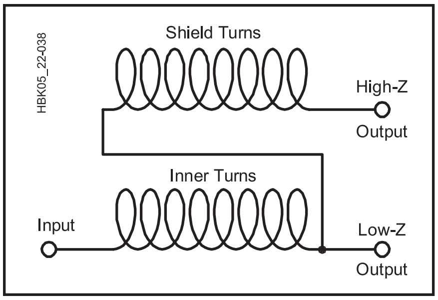


Fig 21.42 — Schematic for the W8NX coaxial-cable trap. RG-59 is wound on a 2⅜-inch OD PVC pipe.

Fig 21.42 shows the schematic diagram of the traps. It illustrates the difference between the low and high-impedance modes of the traps. Notice that the high-impedance terminal is the output configuration used in most conventional trap applications. The low-impedance connection is made across only the inner conductor turns, corresponding to one-half of the total turns of the trap. This mode steps the trap's impedance down to approximately one-fourth of that of the high-impedance level. This is what allows a single trap design to be used for two different multiband antennas.

Fig 21.43 is a drawing of a cross-section of the coax trap shown through the long axis of the trap. Notice that the traps are conventional coaxial-cable traps, except for the

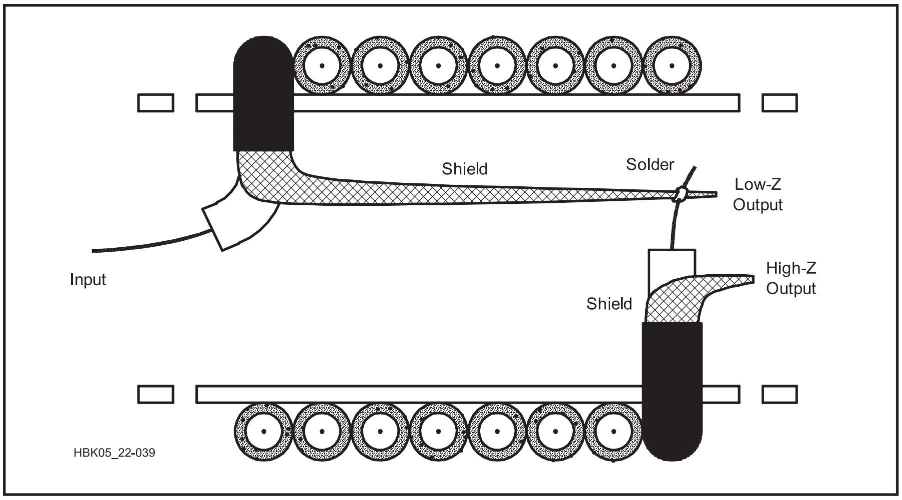


Fig 21.43 — Construction details of the W8NX coaxial-cable trap.

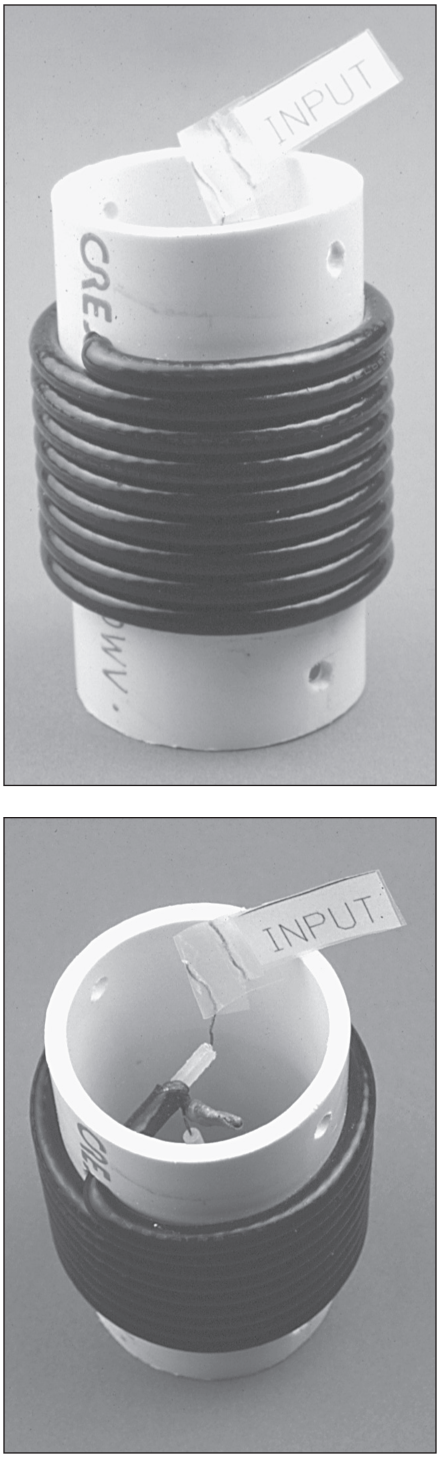


Fig 21.44 — Other views of a W8NX coax-cable trap.

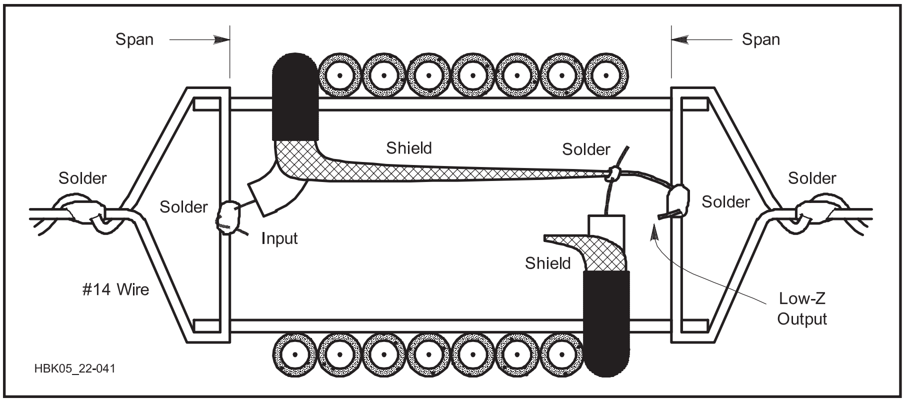


Fig 21.45 — Additional construction details for the W8NX coaxial-cable trap.

added low-impedance output terminal. The traps are 8¾ close-spaced turns of RG-59 (Belden 8241) on a 2⅜-inch-OD PVC pipe (schedule 40 pipe with a two-inch ID) coil form. The forms are 4⅛ inches long. Trap resonant frequency is very sensitive to the outer diameter of the coil form, so check it carefully. Unfortunately, not all PVC pipe is made with the same wall thickness. The trap frequencies should be checked with a dip meter and general-coverage receiver and adjusted to within 50 kHz of the 7150 kHz resonant frequency before installation. One inch is left over at each end of the coil forms to allow for the coax feed-through holes and holes for tension-relief attachment of the antenna radiating elements to the traps. Be sure to seal the ends of the trap coax cable with RTV sealant to prevent moisture from entering the coaxial cable.

Also, be sure that you connect the 32.3-ft wire element at the start of the inner conductor winding of the trap. This avoids detuning the antenna by the stray capacitance of the coaxial-cable shield. The trap output terminal (which has the shield stray capacitance) should be at the outboard side of the trap. Reversing the input and output terminals of the trap will lower the 40 meter frequency by approximately 50 kHz, but there will be negligible effect on the other bands.

Fig 21.44 shows a coaxial-cable trap. Further details of the trap installation are shown in **Fig 21.45**. This drawing applies specifically to the 80, 40, 20, 15 and 10 meter antenna, which uses the low-impedance trap connections. Notice the lengths of the trap pigtails: three to four inches at each terminal of the trap. If you use a different arrangement, you must modify the span lengths accordingly. All connections can be made using crimp connectors rather than by soldering. Using a crimping tool instead of a soldering iron allows easier access to the trap's interior.

PERFORMANCE

The performance of both antennas has been very satisfactory. W8NX uses the 80, 40, 17 and 12 meter version because it covers 17 and 12 meters. (He has a tri-band Yagi for 20, 15 and 10 meters.) The radiation pattern on 17 meters is that of 3⁄2-wave dipole. On 12 meters, the pattern is that of a 5⁄2-wave dipole. At his location in Akron, Ohio, the antenna runs essentially east and west. It is installed as an inverted-V, 40 ft high at the center, with a 120° included angle between the legs. Since the stubs are very short, they radiate little power and make only minor contributions to the radiation patterns. In theory, the pattern has four major lobes on 17 meters, with maxima to the northeast, southeast, southwest and northwest. These provide low-angle radiation into Europe, Africa, South Pacific, Japan and Alaska. A narrow pair of minor broadside lobes provides north and south coverage into Central America, South America and the polar regions.

There are four major lobes on 12 meters, giving nearly end-fire radiation and good low-angle east and west coverage. There are also three pairs of very narrow, nearly broadside, minor lobes on 12 meters, down about 6 dB from the major end-fire lobes. On 80 and 40 meters, the antenna has the usual figure-8 patterns of a half-wave-length dipole.

Both antennas function as electrical half-wave dipoles on 80 and 40 meters with a low SWR. They both function as odd-harmonic current-fed dipoles on their other operating frequencies, with higher, but still acceptable, SWR. The presence of the stubs can either raise or lower the input impedance of the antenna from those of the usual third and fifth harmonic dipoles. Again W8NX recommends that 75-Ω, rather than 50-Ω, feed line be used because of the generally higher input impedances at the harmonic operating frequencies of the antennas.

The SWR curves of both antennas were carefully measured using a 75 to 50-Ω transformer from Palomar Engineers inserted at the junction of the 75-Ω coax feed line and a 50-Ω SWR bridge. The transformer is required for accurate SWR measurement if a 50-Ω SWR bridge is used with a 75-Ω line. Most 50-Ω rigs operate satisfactorily with a 75-Ω line, although this requires different tuning and load settings in the final output stage of the rig or antenna tuner. The author uses the 75 to 50-Ω transformer only when making SWR measurements and at low power levels. The transformer is rated

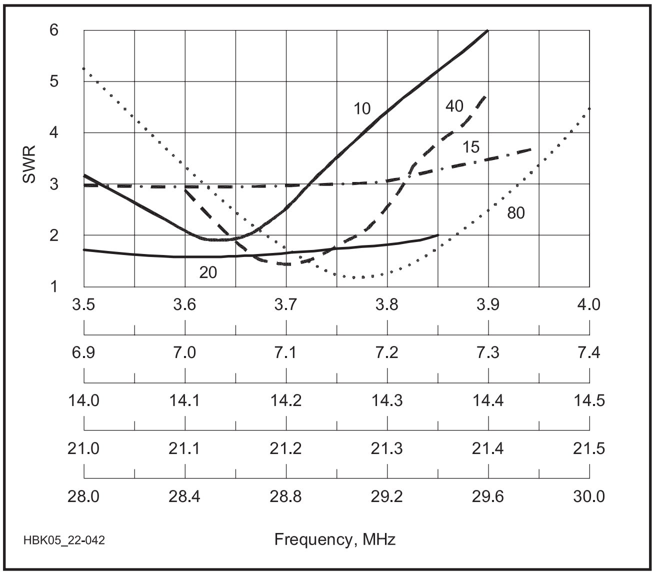


Fig 21.46 — Measured SWR curves for an 80, 40, 20, 15 and 10 meter antenna, installed as an inverted-V with 40-ft apex and 120° included angle between legs.

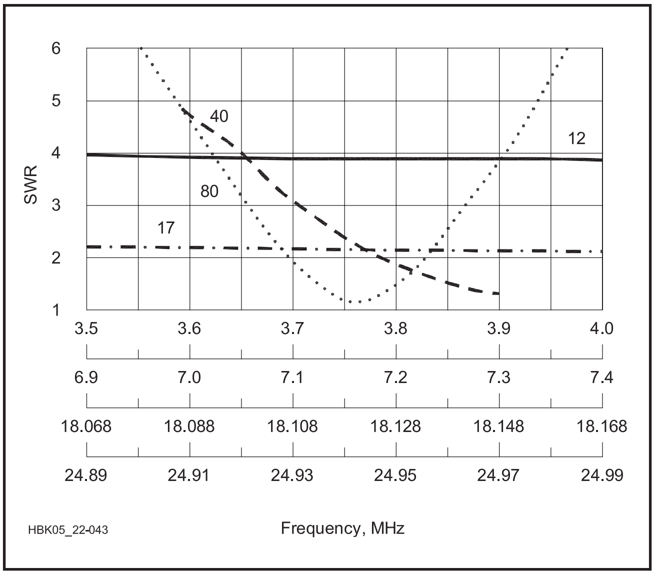


Fig 21.47 — Measured SWR curves for an 80, 40, 17 and 12 meter antenna, installed as an inverted-V with 40-ft apex and 120° included angle between legs.

for 100 W, and when he runs his 1-kW PEP linear amplifier the transformer is taken out of the line.

Fig 21.46 gives the SWR curves of the 80, 40, 20, 15 and 10 meter antenna. Minimum SWR is nearly 1:1 on 80, 1.5:1 on 40, 1.6:1 on 20, and 1.5:1 on 10 meters. The minimum SWR is slightly below 3:1 on 15 meters. On 15 meters, the stub capacitive reactance combines with the inductive reactance of the outer segment of the antenna to produce a resonant rise that raises the antenna input resistance to about 220 Ω, higher than that of the usual ½-wavelength dipole. An antenna tuner may be required on this band to keep a solid-state final output stage happy under these load conditions.

Fig 21.47 shows the SWR curves of the 80, 40, 17 and 12 meter antenna. Notice the excellent 80 meter performance with a nearly unity minimum SWR in the middle of the band. The performance approaches that of a full-size 80 meter wire dipole. The short stubs and the low-inductance traps shorten the antenna somewhat on 80 meters. Also observe the good 17 meter performance, with the SWR being only a little above 2:1 across the band.

But notice the 12 meter SWR curve of this antenna, which shows 4:1 SWR across the band. The antenna input resistance approaches 300 Ω on this band because the capacitive reactance of the stubs combines with the inductive reactance of the outer antenna segments to give resonant rises in impedance. These are reflected back to the input terminals. These stub-induced resonant impedance rises are similar to those on the other antenna on 15 meters, but are even more pronounced.

Too much concern must not be given to SWR on the feed line. Even if the SWR is as high as 9:1 *no destructively high voltages will exist on the transmission line.* Recall that transmission-line voltages increase as the square root of the SWR in the line. Thus, 1 kW of RF power in 75-Ω line corresponds to 274 V line voltage for a 1:1 SWR. Raising the SWR to 9:1 merely triples the maximum voltage that the line must withstand to 822 V. This voltage is well below the 3700-V rating of RG-11, or the 1700-V rating of RG-59, the two most popular 75-Ω coax lines. Voltage breakdown in the traps is also very unlikely. As will be pointed out later, the operating power levels of these antennas are limited by RF power dissipation in the traps, not trap voltage breakdown or feed line SWR.

TRAP LOSSES AND POWER RATING

Table 21.4 presents the results of trap Q measurements and extrapolation by a two-frequency method to higher frequencies above resonance. W8NX employed an old, but recently calibrated, Boonton Q meter for the measurements. Extrapolation to higher-frequency bands assumes that trap resistance losses rise with skin effect according to the square root of frequency, and that trap dielectric losses rise directly with frequency. Systematic measurement errors are not increased

Table 21.4
Trap Q

Frequency (MHz)	3.8	7.15	14.18	18.1	21.3	24.9	28.6
High Z out (Ω)	101	124	139	165	73	179	186
Low Z out (Ω)	83	103	125	137	44	149	*155*

Table 21.5
Trap Loss Analysis: 80, 40, 20, 15, 10 Meter Antenna

Frequency (MHz)	3.8	7.15	14.18	21.3	28.6
Radiation Efficiency (%)	96.4	70.8	99.4	99.9	100.0
Trap Losses (dB)	0.16	1.5	0.02	0.01	0.003

Table 21.6
Trap Loss Analysis: 80, 40, 17, 12 Meter Antenna

Frequency (MHz)	3.8	7.15	18.1	24.9
Radiation Efficiency (%)	89.5	90.5	99.3	99.8
Trap Losses (dB)	0.5	0.4	0.03	0.006

by frequency extrapolation. However, random measurement errors increase in magnitude with upward frequency extrapolation. Results are believed to be accurate within 4% on 80 and 40 meters, but only within 10 to 15% at 10 meters. Trap Q is shown at both the high- and low-impedance trap terminals. The Q at the low-impedance output terminals is 15 to 20% lower than the Q at the high-impedance output terminals.

W8NX computer-analyzed trap losses for both antennas in free space. Antenna-input resistances at resonance were first calculated, assuming lossless, infinite-Q traps. They were again calculated using the Q values in Table 21.4. The radiation efficiencies were also converted into equivalent trap losses in decibels. **Table 21.5** summarizes the trap-loss analysis for the 80, 40, 20, 15 and 10 meter antenna and **Table 21.6** for the 80, 40, 17 and 12 meter antenna.

The loss analysis shows radiation efficiencies of 90% or more for both antennas on all bands except for the 80, 40, 20, 15 and 10 meter antenna when used on 40 meters. Here, the radiation efficiency falls to 70.8%. A 1-kW power level at 90% radiation efficiency corresponds to 50-W dissipation per trap. In W8NX's experience, this is the trap's survival limit for extended key-down operation. SSB power levels of 1 kW PEP would dissipate 25 W or less in each trap. This is well within the dissipation capability of the traps.

When the 80, 40, 20, 15 and 10 meter antenna is operated on 40 meters, the radiation efficiency of 70.8% corresponds to a dissipation of 146 W in each trap when 1 kW is delivered to the antenna. This is sure to burn out the traps — even if sustained for only a short time. Thus, the power should be limited to less than 300 W when this antenna is operated on 40 meters under prolonged key-down conditions. A 50% CW duty cycle would correspond to a 600-W power limit for normal 40 meter CW operation. Likewise, a 50% duty cycle for 40 meter SSB corresponds to a 600-W PEP power limit for the antenna.

The author knows of no analysis where the burnout wattage rating of traps has been rigorously determined. Operating experience seems to be the best way to determine trap burn-out ratings. In his own experience with these antennas, he's had no traps burn out, even though he operated the 80, 40, 20, 15 and 10 meter antenna on the critical 40 meter band using his AL-80A linear amplifier at 600-W PEP output. He did not make a continuous, key-down, CW operating tests at full power purposely trying to destroy the traps!

Some hams may suggest using a different type of coaxial cable for the traps. The dc resistance of 40.7 Ω per 1000 feet of RG-59 coax seems rather high. However, W8NX has found no coax other than RG-59 that has the necessary inductance-to-capacitance ratio to create the trap characteristic reactance required for the 80, 40, 20, 15 and 10 meter antenna. Conventional traps with wide-spaced, open-air inductors and appropriate fixed-value capacitors could be substituted for the coax traps, but the convenience, weatherproof configuration and ease of fabrication of coaxial-cable traps is hard to beat.

Project: Extended Double-Zepp For 17 Meters

Although the Extended Double-Zepp (EDZ) antenna shown in **Fig 21.48** has several attractive features, it is rarely used by hams, perhaps out of concern over the Zepp's high feed point impedance. The antenna's overall length is 1.28 λ and its pattern is bidirectional broadside to the antenna. The SWR of the antenna is low enough near the design frequency that it can be fed with coax and an impedance-matching unit or open-wire line can be used for wider range and multiband use. This project describes an EDZ for 17 meters.

The Zepp antenna (a half-wave dipole, fed at one end) was introduced earlier in this section. The Zepp can be modified in two ways. The first is to double the length of the antenna and feed it in the middle, making a *double-Zepp*. This creates a one-wavelength dipole, with the expected high feed point impedance and about 1.6 dBd gain. A ½-λ center-fed dipole operated on its second harmonic is effectively a double-Zepp. The second modification is to extend the double-Zepp to be 0.64-λ (close to ⅝-λ) long on each side of the feed point. The feed point is then no longer at a high-impedance point on the antenna. This creates the extended, double-Zepp. (The EDZ is described in more detail in the *ARRL Antenna Book*.)

The overall length of the EDZ is calculated as follows:

$$\frac{984}{f\,(\text{MHz})} \times 1.28 = \text{length in feet} \qquad (5)$$

Using this formula, an 18.1 MHz EDZ is 69.6 feet (69 feet, 7 inches.) long. The EDZ has 3 dBd of gain in a figure-8 pattern of two major lobes broadside to the antenna and four minor lobes at smaller angles to the axis of the antenna. The feed point impedance is approximately 140 Ω.

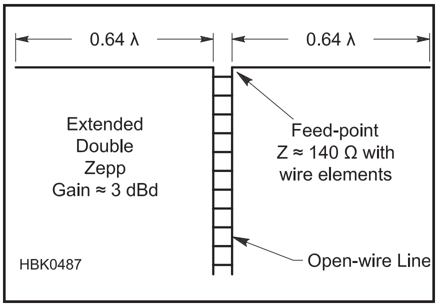


Fig 21.48 — The Extended Double-Zepp antenna consists of two 0.64-λ sections placed end to end and fed in the middle. The high-impedance points of the antenna have been moved away from the feed point, lowering feed point impedance. The antenna has gain of approximately 3 dBd broadside to the antenna.

The EDZ is useful at lower frequencies, as well. On 20 meters, the 17-meter EDZ is just slightly longer than the double-Zepp, with 1.6 to 2 dBd of gain and a rather high feed point impedance of several hundred ohms. On 40 meters, the antenna is a slightly long ½-λ dipole. If your antenna tuner has sufficient range, the antenna can also serve as a shortened dipole for 75/80 meters. At these lower frequencies, the antenna's radiation pattern is a single lobe, broadside to the antenna.

On higher frequencies, the pattern continues to split into more lobes. For example, on 15 meters, there are four lobes at approximately 45° from the antenna axis. On 10 meters, where the antenna is approximately two full-wavelengths long, the pattern is similar, with the lobes a bit closer to the antenna axis and smaller lobes beginning to appear.

Some hams use a 4:1 impedance transformer to reduce the feed point impedance and improve SWR as the operating frequency moves away from the design frequency. This works best if the antenna is to be used on a single band. However, if the antenna is to be used on multiple bands, a better solution is to use open-wire feed line and an antenna tuner. If you wish to operate on a frequency at which the feed point impedance is high, use a feed line length near an odd multiple of a quarter-wavelength long, presenting a lower impedance to your antenna tuner that may be easier to match.

(This project is based on a "Hints and Kinks" item by Bob Baird, W7CSD, from the January 1992 issue of *QST*.)

21.3 Vertical (Ground-Plane) Antennas

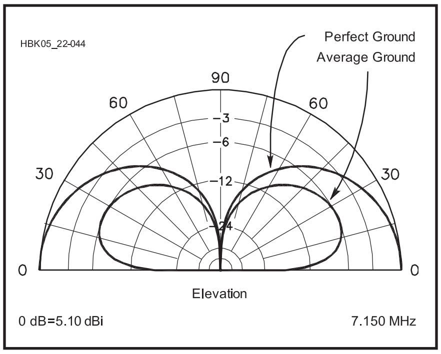


Fig 21.49 — Elevation patterns for two quarter-wave vertical antennas over different ground. One vertical is placed over perfect ground, and the other is placed over average ground. The far-field response at low elevation angles is greatly affected by the quality of the ground — as far as 100 λ away from the vertical antenna.

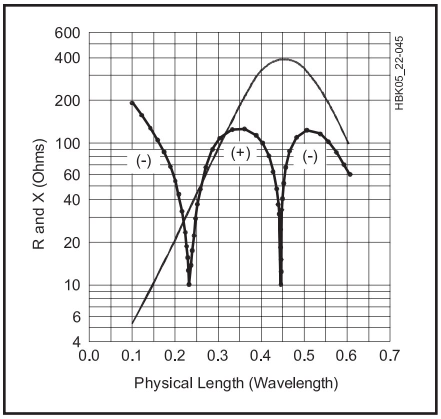


Fig 21.50 — Radiation resistance (solid curve) and reactance (dotted curve) of vertical antennas as a function of their electrical height.

One of the more popular amateur antennas is the *vertical*. It usually refers to a single radiating element erected vertically over the ground. A typical vertical is an electrical ¼-λ long and is constructed of wire or tubing. The vertical antenna is more accurately named the *ground plane* because it uses a conductive surface (the ground plane) to create a path for return currents, effectively creating the "missing half" of a ½-λ antenna. Another name for this type of antenna is the *monopole* (sometimes *unipole*).

The ground plane can be a solid, conducting surface, such as a vehicle body for a VHF/UHF mobile antenna. At HF, this is impractical and systems of *ground radials* are used; wires laid out on the ground radially from the base of the antenna. One conductor of the feed line is attached to the vertical radiating element of the antenna and the remaining conductor attached to the ground plane.

Single vertical antennas are omnidirectional radiators. This can be beneficial or detrimental, depending on the situation. On transmission there are no nulls in any direction, unlike most horizontal antennas. However, QRM on receive can't be nulled out from the directions that are not of interest unless multiple verticals are used in an array.

Ground-plane antennas need not be mounted vertically. A ground-plane antenna can operate in any orientation as long as the ground plane is perpendicular to the radiating element. Other considerations, such as minimizing cross-polarization between stations, may require a specific mounting orientation though. In addition, due to the size of HF antennas, mounting them vertically is usually the most practical solution.

A vertical antenna can be mounted at the Earth's surface, in which case it is a *ground-mounted vertical*. The ground plane is then constructed on the surface of the ground. A vertical antenna and the associated ground plane can also be installed above the ground. This often reduces ground losses, but it is more difficult to install the necessary number of radials. *Ground-independent* verticals are often mounted well above the ground because their operation does not rely on a ground plane.

21.3.1 Ground Systems

When compared to horizontal antennas, verticals also suffer more acutely from two main types of losses — *ground return losses* for currents in the near field, and *far-field ground losses*. Ground losses in the near field can be minimized by using many ground radials. This is covered in the sidebar, "Optimum Ground Systems for Vertical Antennas."

Far-field losses are highly dependent on the conductivity and dielectric constant of the earth around the antenna, extending out as far as 100 wavelengths from the base of the antenna. There is very little that someone can do to change the character of the ground that far away — other than moving to a small island surrounded by saltwater! Far-field losses greatly affect low-angle radiation, causing the radiation patterns of practical vertical antennas to fall far short of theoretical patterns over *perfect ground*, often seen in classical texts.

Fig 21.49 shows the elevation pattern response for two different 40 meter quarter-wave verticals. One is placed over a theoretical infinitely large, infinitely conducting ground. The second is placed over an extensive radial system over average soil, having a conductivity of 5 mS/m and a dielectric constant of 13. This sort of soil is typical of heavy clay found in pastoral regions of the US mid-Atlantic states. At a 10° elevation angle, the real antenna losses are almost 6 dB compared to the theoretical one; at 20° the difference is about 3 dB. See *The ARRL Antenna Book* chapter on the effects of ground for further details.

While real verticals over real ground are not a magic method to achieve low-angle radiation, cost versus performance and ease of installation are incentives that inspire many antenna builders. For use on the lower frequency amateur bands — notably 160 and 80 meters — it is not always practical to erect a full-size vertical. At 1.8 MHz, a full-sized quarter-wave vertical is 130 ft high. In such instances it is often necessary to accept a shorter radiating element and use some form of loading.

Fig 21.50 provides curves for the physical height of verticals in wavelength versus radiation resistance and reactance. Although the plots are based on perfectly conducting ground, they show general trends for installations where many radials have been laid out to make a ground screen. As the radiator is made shorter, the radiation resistance decreases — with 6 Ω being typical for a 0.1-λ high antenna. The lower the radiation resistance, the more the antenna efficiency depends on ground conductivity and the effectiveness of the ground screen. Also, the bandwidth decreases markedly as the length is reduced toward the left of the scale in Fig 21.50. It can be difficult to develop suitable matching networks when radiation resistance is very low.

Generally a large number of shorter radials results in a better ground system than a few longer ones. For example, eight ¼-λ radials are preferred over four ¼-λ radials. Optimum radial lengths are described in the sidebar.

The conductor size of the radials is not especially significant. Wire gauges from #4 to #20 AWG have been used successfully by amateurs. Copper wire is preferred, but where soil is low in acid (or alkali), aluminum wire can be used. The wires may be bare or insulated, and they can be laid on the earth's surface or buried a few inches below ground. Insulated wires will have greater longevity by virtue of reduced corrosion and dissolution from soil chemicals.

When property dimensions do not allow a classic installation of equally spaced radial wires, they can be placed on the ground as space permits. They may run away from the antenna in only one or two compass directions. They may be bent to fit on your property. Hardware cloth and chicken wire are also quite effective, although the galvanizing must be of high-quality to prevent rapid rusting.

A single ground rod, or group of them bonded together, is seldom as effective as a collection of random-length radial wires.

All radial wires should be connected together at the base of the vertical antenna. The electrical bond needs to be of low resistance. Best results will be obtained when the wires are soldered together at the junction point. When a grounded vertical is used, the ground wires should be affixed securely to the base of the driven element.

Ground return losses are lower when vertical antennas and their radials are elevated above ground, a point that is well-known by those using ground plane antennas on their roofs. Even on 160 or 80 meters, effective vertical antenna systems can be made with as few as four ¼ λ long radials elevated 10 to 20 feet off the ground.

Optimum Ground Systems for Vertical Antennas

A frequent question brought up by old-timers and newcomers alike is: "So, how many ground radials do I *really* need for my vertical antenna?" Most hams have heard the old standby tales about radials, such as "if a few are good, more must be better" or "lots of short radials are better than a few long ones."

John Stanley, K4ERO, eloquently summarized a study he did of the professional literature on this subject in his article "Optimum Ground Systems for Vertical Antennas" in December 1976 *QST*. His approach was to present the data in a sort of "cost-benefit" style in **Table 21.A**, reproduced here. John somewhat wryly created a new figure of merit—the total amount of wire needed for various radial configurations. This is expressed in terms of wavelengths of total radial wire.

Table 21.A
Optimum Ground-System Configurations

Configuration Designation	*A*	*B*	*C*	*D*	*E*	*F*
Number of radials	*16*	*24*	*36*	*60*	*90*	*120*
Length of each radial in wavelengths	0.1	0.125	0.15	0.2	0.25	0.4
Spacing of radials in degrees	22.5	15	10	6	4	3
Total length of radial wire installed, in wavelengths	1.6	3	5.4	12	22.5	48
Power loss in dB at low angles with a quarter-wave radiating element	3	2	1.5	1	0.5	0*
Feed point impedance in ohms with a quarter-wave radiating element	52	46	43	40	37	35

Note: Configuration designations are indicated only for text reference.

*Reference. The loss of this configuration is negligible compared to a perfectly conducting ground.

The results almost jumping out of this table are:

- If you can only install 16 radials (Case A), they needn't be very long — 0.1 λ is sufficient. You'll use 1.6 λ of radial wire in total, which is about 450 feet at 3.5 MHz.
- If you have the luxury of laying down 120 radials (Case F), they should be 0.4 λ long, and you'll gain about 3 dB over the 16-radial case. You'll also use 48 λ of total wire—For 80 meters, that would be about 13,500 feet!
- If you can't put out 120 radials, but can install 36 radials that are 0.15 λ long (Case C), you'll lose only 1.5 dB compared to the optimal Case F. You'll also use 5.4 λ of total wire, or 1,500 feet at 3.5 MHz.
- A 50-Ω SWR of 1:1 isn't necessarily a good thing — the worst-case ground system in Case A has the lowest SWR.

Table 21.A represents the case for "Average" quality soil, and it is valid for radial wires either laid on the ground or buried several inches in the ground. Note that such ground-mounted radials are detuned because of their proximity to that ground and hence don't have to be the classical quarter-wavelength that they need to be were they in "free space."

In his article John also made the point that ground-radial losses would only be significant on transmit, since the atmospheric noise on the amateur bands below 30 MHz is attenuated by ground losses, just as actual signals would be. This limits the ultimate signal-to-noise ratio in receiving.

So, there you have the tradeoffs — the loss in transmitted signal compared to the cost (and effort) needed to install more radial wires. You take your pick.

21.3.2 Full-Size Vertical Antennas

When it is practical to erect a full-size ¼-λ vertical antenna, the forms shown in **Fig 21.51** are worthy of consideration. The example at A is the well-known *vertical ground plane*. The ground system consists of four above-ground radial wires. The length of the driven element and ¼-λ radials is derived from the standard equation

$$L\ (\text{ft}) = \frac{234}{f\ (\text{MHz})} \qquad (6)$$

With four equidistant radial wires drooped at approximately 30° (Fig 21.51A), the feed point impedance is roughly 50 Ω. When the radials are at right angles to the radiator (Fig 21.51B) the impedance approaches 36 Ω.

Besides minimizing ground return losses, another major advantage in this type of vertical antenna over a ground-mounted type is that the system can be elevated well above nearby conductive objects (power lines, trees, buildings and so on). When drooping radials are used, they can also serve as guy wires for the mast that supports the antenna. The coax shield braid is connected to the radials, and the center conductor to the driven element.

The *Marconi* vertical antenna shown in Fig 21.51C is the classic form taken by a ground-mounted vertical. It can be grounded at the base and *shunt fed*, or it can be isolated from ground, as shown, and *series fed*. As always, this vertical antenna depends on an effective ground system for efficient performance. If a perfect ground were located below the antenna, the feed impedance would be near 36 Ω. In a practical case, owing to imperfect ground, the impedance is more likely to be in the vicinity of 50 Ω.

Vertical antennas can be longer than ¼-λ, too. ⅜-λ, ½-λ, and ⅝-λ verticals can all be used with good results, although none will present a 50-Ω feed point impedance at the base. Non-resonant lengths have become popular for the same reasons as non-resonant horizontal antennas; when fed with low-loss feed line and a wide-range impedance matching unit, the antenna can be used on multiple bands. Various matching networks, described in the **Transmission Lines** chapter, can be employed. Antenna lengths above ½-λ are not recommended because the radiation pattern begins to break up into more than one lobe, developing a null at the horizon at 1-λ.

A gamma-match feed system for a grounded ¼-λ vertical is presented in Fig 21.51D. (The gamma match is also discussed in the **Transmission Lines** chapter.) Some rules of thumb for arriving at workable gamma-arm and capacitor dimensions are to make the rod length 0.04 to 0.05 λ, its diameter ⅓ to

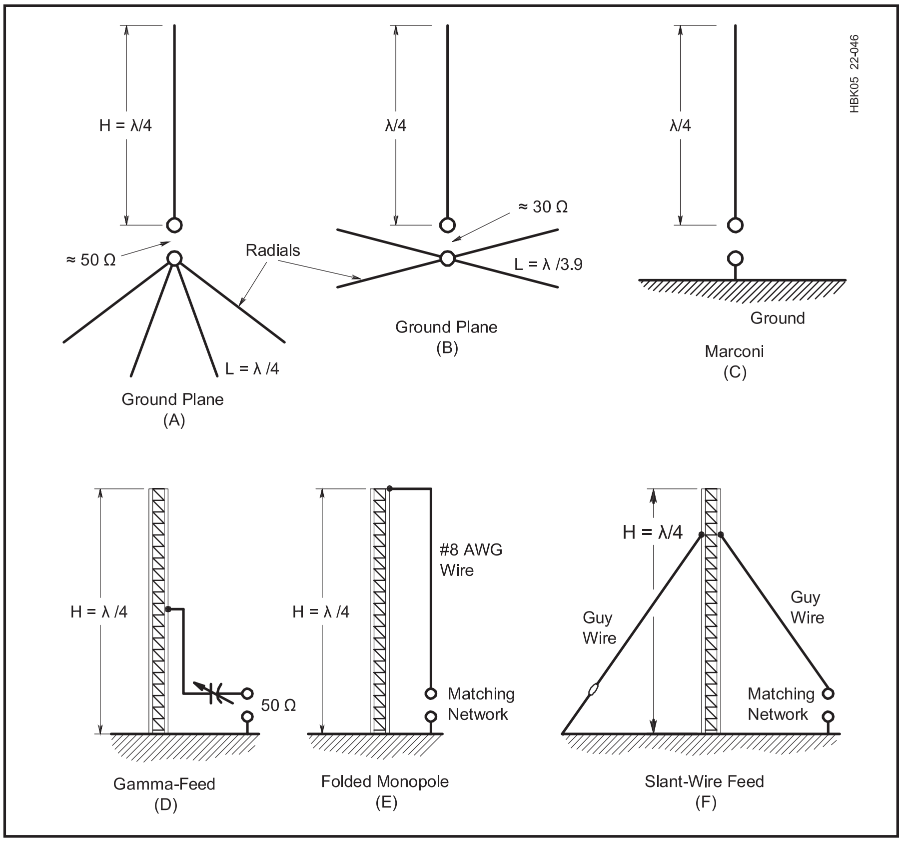


Fig 21.51 — Various types of vertical antennas.

½ that of the driven element and the center-to-center spacing between the gamma arm and the driven element roughly 0.007 λ. The capacitance of C1 at a 50-Ω matched condition will be about 7 pF per meter of wavelength. The absolute value of C1 will depend on whether the vertical is resonant and on the precise value of the radiation resistance. For best results, make the radiator approximately 3% shorter than the resonant length.

Amateur antenna towers lend themselves to use as shunt-fed verticals, even though an HF-band beam antenna is usually mounted on the tower. The overall system should be close to resonance at the desired operating frequency if a gamma feed is used. The HF-band beam will contribute somewhat to *top loading* of the tower. The natural resonance of such a system can be checked by dropping a #12 or #14 AWG wire from the top of the tower (connecting it to the tower top) to form a folded monopole (Fig 21.51E). A four- or five-turn link can be inserted between the lower end of the drop wire and the ground system. A dip meter is then inserted in the link to determine the resonant frequency.

If the tower is equipped with guy wires, they should be broken up with strain insulators to prevent unwanted loading of the vertical. In such cases where the tower and beam antennas are not able to provide ¼-λ resonance, portions of the top guy wires can be used as top-loading capacitance. Experiment with the guy-wire lengths (using the dip-meter technique) while determining the proper dimensions.

A folded-monopole is depicted in Fig 21.51E. This system has the advantage of increased feed point impedance. Furthermore, an impedance-matching unit can be connected between the bottom of the drop wire and the ground system to permit operation on more than one band. For example, if the tower is resonant on 80 meters, it can be used as shown on 160 and 40 meters with reasonable results, even though it is not electrically long enough on 160 to act as a full-size antenna. The drop wire need not be a specific distance from the tower, but you might try spacings between 12 and 30 inches.

The method of feed shown at Fig 21.51F is commonly referred to as *slant-wire feed*. The guy wires and the tower combine to provide quarter-wave resonance. A matching network is placed between the lower end of one guy wire and ground and adjusted for an SWR of 1:1. It does not matter at which level on the tower the guy wires are connected, assuming that the impedance-matching unit is capable of effecting a match to 50 Ω.

21.3.3 Physically Short Verticals

A group of short vertical radiators is presented in **Fig 21.52**. Illustrations A and B are for top and center loading. A capacitance hat is shown in each example. The hat should be as large as practical to increase the radiation resistance of the antenna and improve the bandwidth. The wire in the loading coil is chosen for the largest gauge consistent with ease of winding and coil-form size. The larger wire diameters will reduce the resistive (I^2R) losses in the system. The coil-form material should have a medium or high dielectric constant. Phenolic or fiberglass tubing is entirely adequate.

A base-loaded vertical is shown at C of Fig 21.52. The primary limitation is that the high current portion of the vertical exists in the coil rather than the driven element. With center loading, the portion of the antenna below the coil carries high current, and in the top-loaded version the entire vertical element carries high current. Since the high-current part of the antenna is responsible for most of the radiating, base loading is the least effective of the three methods. The radiation resistance of the coil-loaded antennas shown is usually less than 16 Ω.

A method for using guy wires to top load a short vertical is illustrated in Fig 21.52D. This system works well with gamma feed. The loading wires are trimmed to provide an electrical quarter wavelength for the overall system. This method of loading will result in a higher radiation resistance and greater bandwidth than the systems shown at A through C. If an HF or VHF array is at the top of the tower, it will simply contribute to the top loading.

A three-wire monopole is shown in Fig 21.52E. Two #8 AWG drop wires are connected to the top of the tower and brought to ground level. The wires can be spaced any convenient distance from the tower — normally 12 to 30 inches from the sides. C1 is adjusted for best SWR. This type of vertical has a fairly narrow bandwidth, but because C1 can be motor driven and controlled from the operating position, frequency changes can be accomplished easily. This technique will not be suitable for matching to 50-Ω line unless the tower is less than an electrical quarter wavelength high.

A different method for top loading is shown in Fig 21.52F. Barry Boothe, W9UCW, described this method in December 1974 *QST*. An extension is used at the top of the tower to create an electrical quarter-wavelength vertical. L1 is a loading coil with sufficient inductance to provide antenna resonance. This type of antenna lends itself to operation on 160 meters.

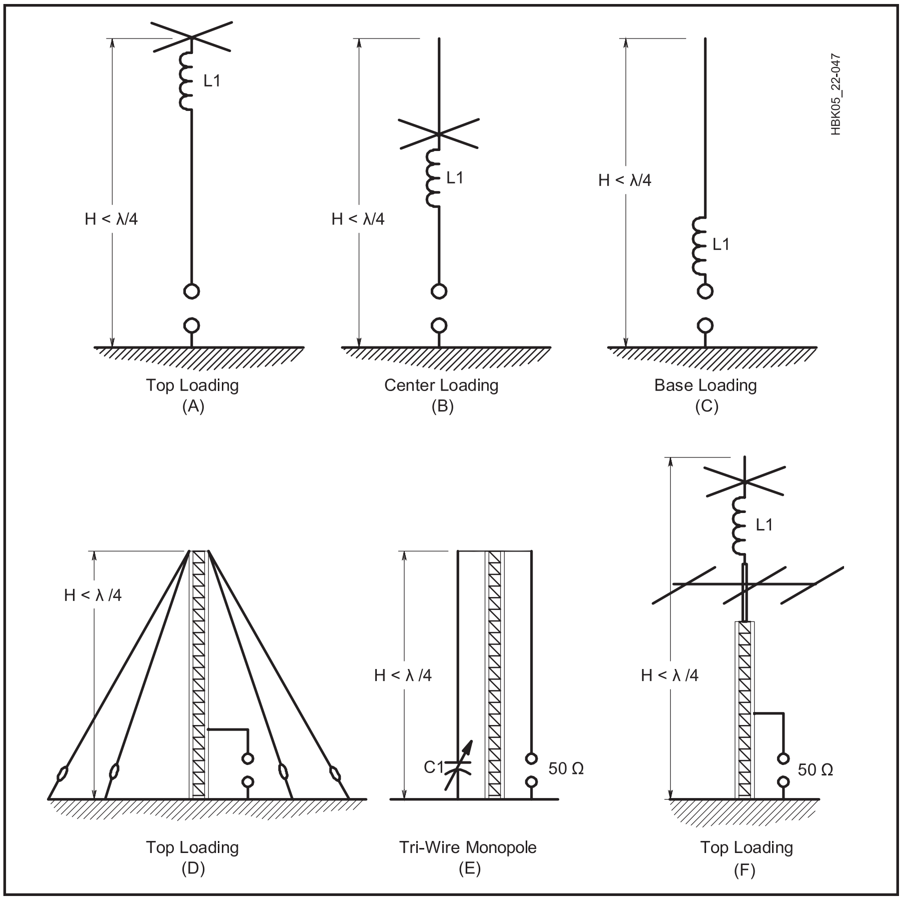


Fig 21.52 — Vertical antennas that are less than one-quarter wavelength in height.

Project: Top-Loaded Low-Band Antenna

The short, top-loaded vertical antenna described here by Dick Stroud, W9SR, is of interest to hams with limited space or who are portable operators. It has been used on 40, 80 and 160 meters. The antenna uses a single 10-ft TV mast section for the vertical radiator, along with a capacitance hat, loading coil and short top mast. The overall height is less than 15 ft, as seen in **Fig 21.53**. The capacitance hat and loading coil assembly can be used with longer vertical radiators with changes to the coil inductance.

CAPACITANCE HAT

The capacitance hat consists of a hub that mounts to the top mast above the coil and six elements made from aluminum rod. The machining, drilling and tapping of the hub assembly can be done by nearly any machine shop if you don't have the facilities. Be sure to use stainless steel hardware throughout. (Thanks to Fred Gantzer, W0AWD, for building the original hub.)

The hub is made of two pieces of ½-inch thick aluminum as shown in **Fig 21.54**. The two pieces (Fig 21.55A and B) are bolted together to form the hub, which slides over the 1⅛-inch top mast. It is held in place with three 10-32 screws, as shown in Fig 21.54C. The six elements of the capacitance hat are made from 3⁄16-inch aluminum rod, each 4.5 ft long. These are held in place with 6-32 screws.

LOADING COIL

The coil form is made from fiberglass tubing available from Small Parts, Inc. A 6-inch length of 1.25-inch OD fiberglass tubing (part no. LFT-125/16-30) is centered over a 10-inch length of 1-inch OD tubing (part no. LFT-125/20-30). The tubes telescope tightly and it may be necessary to lightly sand the smaller tube for a smooth fit.

The loading coil is wound on the 1.25-inch OD fiberglass tube, as shown in Fig 21.54D.

Fig 21.53 — W9SR's short vertical uses top loading and a capacitance hat with a 10-ft TV mast to make a compact antenna for 160, 80 or 40 meters.

After the coil is optimized, it is covered with a length of shrink sleeving for weather protection. Coil winding information in the drawing is for use with a 10-ft mast.

The bottom section of the coil assembly fits directly into the tapered upper section of the TV mast and the exposed upper fiberglass section of the coil assembly fits into a 2.5-ft long, 1.125-inch OD, aluminum upper mast. Stainless 8-32 screws join the pieces together and also provide a connection point for the loading coil wires. If you use a painted steel mast, be sure to remove paint from the connection point, and then weather-seal it after adjustment is complete.

The capacitance hat hub slides over the upper mast and is held in place with three screws. The hub is about 6 inches above the coil, but the location can be moved to change the resonance of the antenna slightly.

The completed capacitance hat and loading coil assembly are shown in **Fig 21.55**. A dab of Glyptol (exterior varnish or Loctite also works) locks the screws in place once adjustments have been made and the antenna is ready for installation.

The coaxial feed line attaches to the bottom of the TV mast. Again, use an 8-32 screw for attachment and clean any paint from the metal. To match the antenna to a 50-Ω transmission line, a small parallel (shunt) inductance is needed at the base. The inductor is air-wound with #16 AWG wire (see **Table 21.7**).

Table 21.7
Shunt Inductor Winding Details

Band	*Turns*
160 m	10 turns #16 AWG, spaced ⅛ inch
80 m	8.75 turns #16 AWG, spaced ⅛ inch
40 m	7.5 turns #16 AWG, spaced ⅛ inch

Note: All inductors are air wound, 1.75 inch ID. Dimensions shown are for use with 10 ft mast.

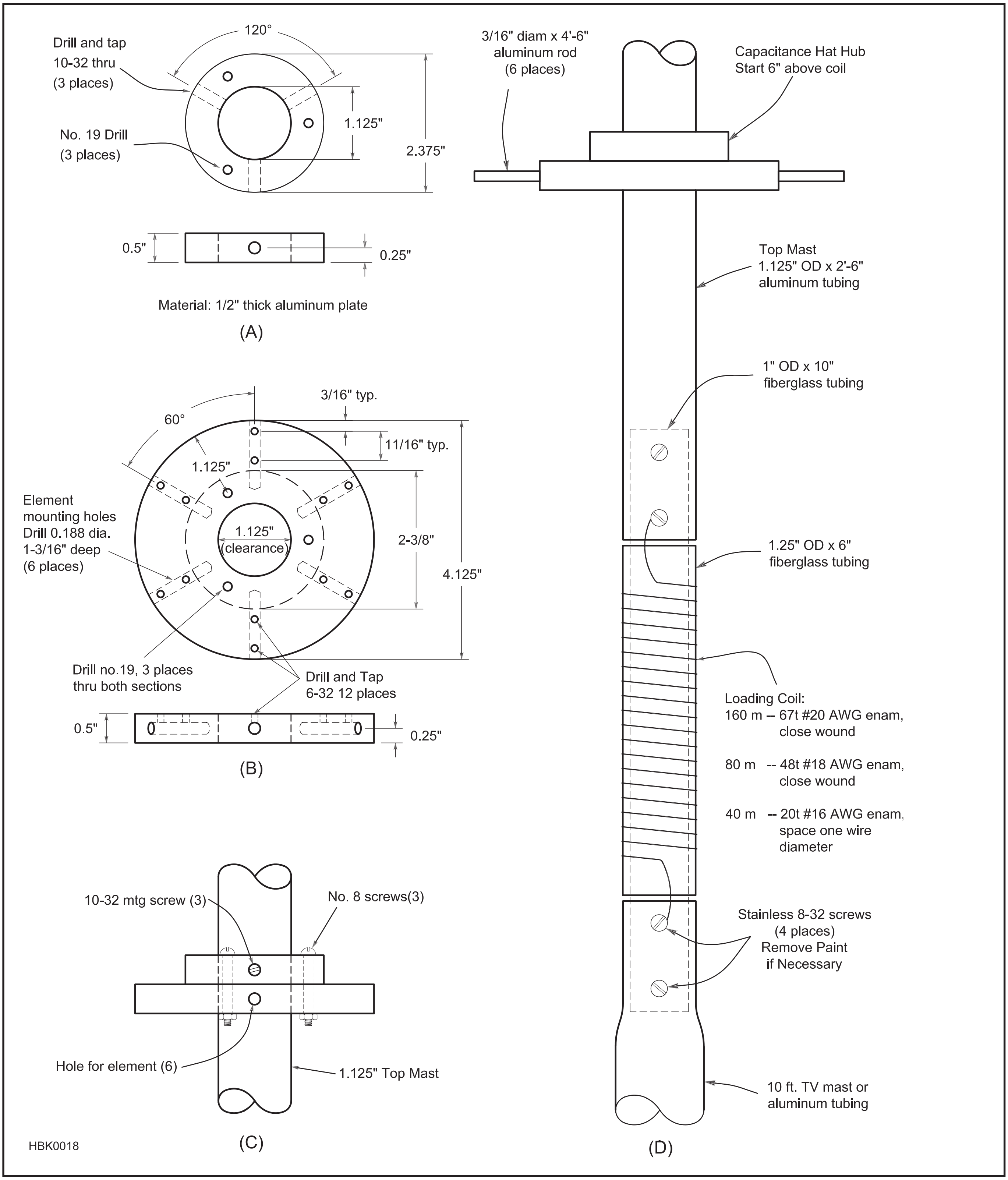


Fig 21.54 — Construction details for the capacitance hat. The hub is made from two pieces of ½-inch aluminum plate (A and B). It's attached to the mast as shown in C. The six elements are made from 4.5-ft lengths of 3⁄16-inch aluminum rod. Loading coil details are shown in D.

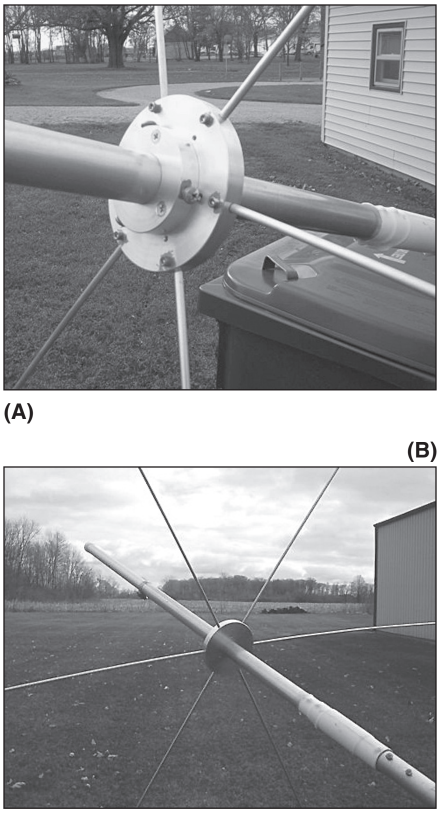


Fig 21.55 — The completed capacitance hat assembly is shown at A, and B shows a view of the upper mast assembly with the loading coil and capacitance hat.

MOUNTING THE ANTENNA

A glass beverage bottle serves well as the base insulator, with the neck of the bottle fitting snugly into the TV mast. To support the base insulator, drill a hole large enough to accept the base of the bottle in the center of a 2 × 6 board about 14 inches long. Nail a piece of ¼-inch plywood over the bottom to keep the bottle from slipping through. To keep the base support board from moving around, drill a couple of holes and secure it to the ground with stakes.

The antenna is top-heavy and will need to be guyed. A simple insulated guy ring can be made from a 2-inch PVC coupling and placed on the mast just below the loading coil. The PVC is locked to the mast with three ¼-20 bolts. They are 1-inch long and have nuts on the inside and outside of the PVC. Three ¼-inch holes are drilled for the guy lines, made from lengths of 3/16-inch non-absorbent rope.

OPERATION

On-air results with a 10-ft mast have been very good, even with low power. The ground system for the early tests was nothing more than an 8-ft ground rod hammered into Hoosier soil. With this setup, and using about 90 W, many DX contacts were made over one week's time and stateside contacts were plentiful.

There is plenty of room to experiment however. Performance could be improved by using an extended radial system or raised and insulated radials. (Expect much better performance over average ground with a system of radials) Two, or even three, mast sections could be used with additional guys and proper loading coil inductance. If you use multiple masts, be sure to make a good electrical connection at the joints. The upper assembly is now permanently used to top load a 60-ft pole for transmitting on 160 meters.

21.3.4 Cables and Control Wires on Towers

Most vertical antennas of the type shown in Fig 21.51 and 21.52C-E consist of towers, usually with HF or VHF beam antennas at the top. The rotator control wires and the coaxial feeders to the top of the tower will not affect antenna performance adversely. In fact, they become a part of the composite antenna. To prevent unwanted RF currents from following the wires into the shack, simply dress them close to the tower legs and bring them to ground level. (Running the cables inside the tower works even better.) This decouples the wires at RF. The wires should then be routed along the earth surface (or buried underground) to the operating position. It is not necessary to use bypass capacitors or RF chokes in the rotator control leads if this is done, even when maximum legal power is employed.

21.3.5 Multiband Trap Verticals

The two-band trap vertical antenna of **Fig 21.56** operates in much the same manner as a trap dipole or trap Yagi. The notable difference is that the vertical is one-half of a dipole. The radial system (in-ground or above-ground) functions as a ground plane for the antenna, and provides an equivalent for the missing half of the dipole. Once again, the more effective the ground system, the better will be the antenna performance.

Trap verticals usually are designed to work as ¼-λ radiators. The portion of the antenna below the trap is adjusted as a ¼-λ radiator at the higher proposed operating frequency. That is, a 20/15 meter trap vertical would be a resonant quarter wavelength at 15 meter from the feed point to the bottom of the trap. The trap and that portion of the antenna above the trap (plus the 15 meter section below the trap) constitute the complete antenna during 20 meter operation. But because the trap is in the circuit, the overall physical length of the vertical antenna will be slightly less than that of a single-band, full-size 20 meter vertical.

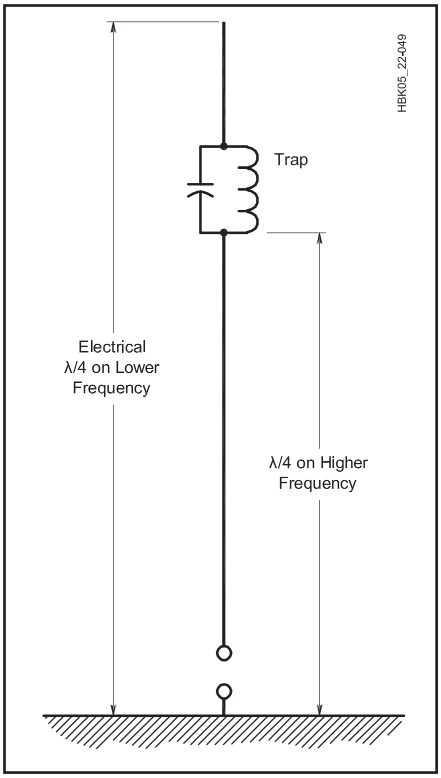


Fig 21.56 — A two-band trap vertical antenna. The trap should be resonated by itself as a parallel resonant circuit at the center of the operating range for the higher frequency band. The reactance of either the inductor or the capacitor range from 100 to 300 Ω. At the lower frequency the trap will act as a loading inductor, adding electrical length to the total antenna.

Recent "ground-independent" multiband vertical antennas also have traps, but are designed to be electrically longer than ¼-λ. A common electrical length, is 3/8 λ, for example. The "traps" in these antennas are generally not parallel-LC circuits as described above. A variety of techniques are used with both parallel-LC traps and short resonant structures similar to stubs being used to change the antenna's electrical length at different frequencies.

TRAPS

The trap functions as the name implies: the high impedance of the parallel resonant circuit "traps" the 15 meter energy and confines it to the part of the antenna below the trap. (See the **Electrical Fundamentals** chapter for more information on resonant LC circuits.) During 20 meter operation it allows the RF energy to reach all of the antenna. The trap in this example is tuned as a parallel resonant circuit to 21 MHz. At this frequency it electrically disconnects the top section of the vertical from the lower section because it presents a high impedance at 21 MHz, blocking 21 MHz current. Generally, the trap inductor and capacitor have a reactance of 100 to 300 Ω. Within that range it is not critical.

The trap is built and adjusted separately from the antenna. It should be resonated at the center of the portion of the band to be operated. Thus, if one's favorite part of the 15 meter band is between 21.0 and 21.1 MHz, the trap should be tuned to 21.05 MHz.

Resonance is checked by using a dip meter and detecting the dipper signal in a calibrated receiver. An SWR analyzer can also be used. Once the trap is adjusted it can be installed in the antenna, and no further adjustment will be required. It is easy, however, to be misled after the system is assembled: Attempts to check the trap resonance in the antenna will suggest that the trap has moved much lower in frequency (approximately 5 MHz lower in a 20/15 meter vertical). This is because the trap is now part of the overall antenna, and the resultant resonance is that of the total antenna. Measure the trap's resonant frequency separately from the rest of the antenna.

Multiband operation is quite practical by using the appropriate number of traps and tubing sections. The construction and adjustment procedure is the same, regardless of the number of bands covered. The highest frequency trap is always closest to the feed end of the antenna, and the lowest frequency trap is always the farthest from the feed point. As the operating frequency is progressively lowered, more traps and more tubing sections become a functional part of the antenna.

Traps should be weatherproofed to prevent moisture from detuning them. Several coatings of high dielectric compound, such as polystyrene Q Dope or Liquid Electrical Tape, are effective. Alternatively, a protective sleeve of heat-shrink tubing can be applied to the coil after completion. The coil form for the trap should be of high insulating quality and be rugged enough to sustain stress during periods of wind.

21.4 T and Inverted-L Antennas

This section covers variations on the vertical antenna. **Fig 21.57** shows a flat-top T vertical. The T is basically a shortened ¼-λ vertical with the flat-top T section acting as capacitive loading to length the antenna electrically. Dimension H should be as large as possible (up to ¼-λ) for best results. The horizontal section, L, is adjusted to a length that provides resonance. Maximum radiation is polarized vertically despite the horizontal top-loading wire because current in each horizontal half creates out-of-phase radiation that cancels.

A variation of the T antenna is depicted in **Fig 21.58**. This antenna is commonly referred to as an *inverted-L* and is basically a 5⁄16-λ vertical bent in the middle so that the top section runs parallel to the ground. Similarly to the T antenna, the vertical section should be as long as possible. L is then added to provide an electrical 5⁄16-λ overall.

Because the horizontal section does carry some current, there will be some horizontally-polarized radiation at high angles. This is often considered desirable because it provides local and regional coverage. The horizontal section need not be perfectly horizontal — sloping the wire at a shallow angle from horizontal does not greatly affect antenna performance. This allows the inverted-L to be constructed with a single vertical support.

A sidearm or a length of line attached to a tower can be used to support the vertical section of the T or inverted-L antenna. (Keep the vertical section of the antennas as far from the tower as is practical. Certain combinations of tower height and top loading can create a resonance that interacts severely with the antennas — a 70-ft tower and a 5-element Yagi, for example.)

Both the T and inverted-L antennas are ground-plane antennas and require a good ground system to be effective. If the T or inverted-L are used with a very good ground system, the feed-point impedance will approach 35-40 Ω so that the SWR approaches 1.4:1. The inverted-L is constructed longer than resonance as illustrated in Fig 21.58 so that the feed point resistance increases to 50 Ω plus some inductive reactance due to the extra length. A series capacitor at the feed point then cancels the reactance, leaving a 50-Ω impedance suitable for direct connection by coaxial cable.

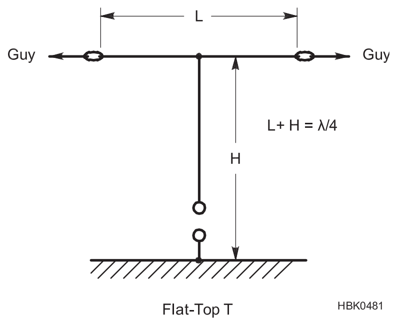


Fig 21.57 — The T antenna is basically a shortened ¼-λ vertical with the flat-top T section acting as capacitive loading to length the antenna electrically.

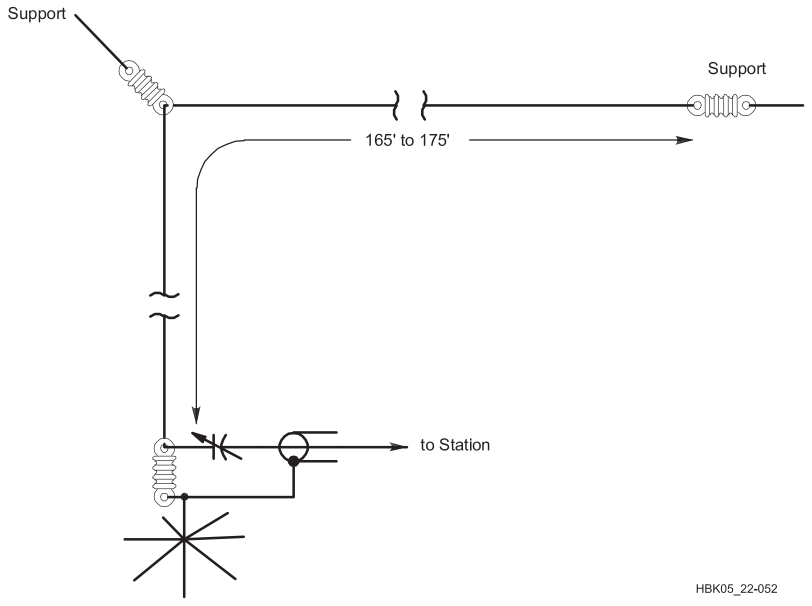


Fig 21.58 — The inverted-L antenna designed for the 1.8 MHz band. Overall wire length is 165 to 175 ft. The variable capacitor has a maximum capacitance of 500 to 800 pF.

21.5 Slopers and Vertical Dipoles

21.5.1 Half-Sloper Antenna

Many hams have had excellent results with *half-sloper* antennas, while others have not had such luck. Investigations by ARRL Technical Advisor John S. Belrose, VE2CV, have brought some insight to the situation through computer modeling and antenna-range tests. The following is taken from VE2CV's Technical Correspondence in Feb 1991 *QST*, pp 39 and 40. Essentially, the half-sloper is a top-fed vertical antenna that uses the structure at the top of the tower plane (such as a grounded Yagi antenna) as a ground plane and the tower acts as a reflector.

For half-slopers, the input impedance, the resonant length of the sloping wire and the antenna pattern all depend on the tower height, the angle (between the sloper and tower) the type of Yagi and the Yagi orientation. Here are several configurations extracted from VE2CV's work:

At 160 meters — use a 40 meter beam on top of a 95-ft tower with a 55° sloper apex angle. The radiation pattern varies little with Yagi type. The pattern is slightly cardioid with about 8 dB front-to-back ratio at a 25º takeoff angle (see Fig 21.59B and C). Input impedance is about 50 Ω.

At 80 meters — use a 20 meter beam on top of a 50-ft tower with a 55° sloper apex angle. The radiation pattern and input impedance are similar to those of the 160 meter half-sloper.

Table 21.8
HVD Dimensions

Length using 0.875-inch aluminum tubing

MHz	*Feet*	*Inches*
18.11	33	11
21.2	22	0
24.94	18	9
28.4	16	5

These lengths should divided by two to determine the length of the dipole legs

At 40 meters — use a 20 meter beam on top of a 50-ft tower with a 55° sloper apex angle. The radiation pattern and impedance depend strongly on the azimuth orientation of the Yagi. Impedance varies from 76 to 127 Ω depending on Yagi direction.

Project: Half-Wave Vertical Dipole (HVD)

Chuck Hutchinson, K8CH, describes a 15 meter vertical dipole (HVD) that he built for the ARRL book, *Simple and Fun Antennas for Hams*. The performance of this antenna, with its base at 14 ft, compares favorably with a horizontal dipole at 30 ft when making intercontinental QSOs.

CONSTRUCTION OF A 15 METER HVD

The 15 meter HVD consists of four 6-ft lengths of 0.875-inch aluminum tube with 0.058 wall thickness. In addition there are two 1-ft lengths of 0.75-inch tubing for splices, and two one-foot lengths of 0.75-inch fiberglass rod for insulators. See **Table 21.8** for dimensions.

Start by cutting off 1 foot from a 6-ft length of 0.875-inch tubing. Next, insert six inches of one of the 1-foot-long 0.75-inch tubes into the machine-cut end of your tubing and fasten the tubes together. Now, slide an end of a 6-ft length of 0.875 tube over the protruding end of the 0.75 tube and fasten them together. Repeat this procedure with the remaining 0.875-inch tubing.

You should now have two 11-ft-long elements. As you can see in **Fig 21.60**, K8CH was temporarily out of aluminum pop rivets, so he used sheet metal screws. Either will work fine, but pop rivets can easily be drilled out and the antenna disassembled if you ever want to make changes.

Because hand-made cuts are not perfectly square, put those element ends at the center of the antenna. Slip these cut ends over the

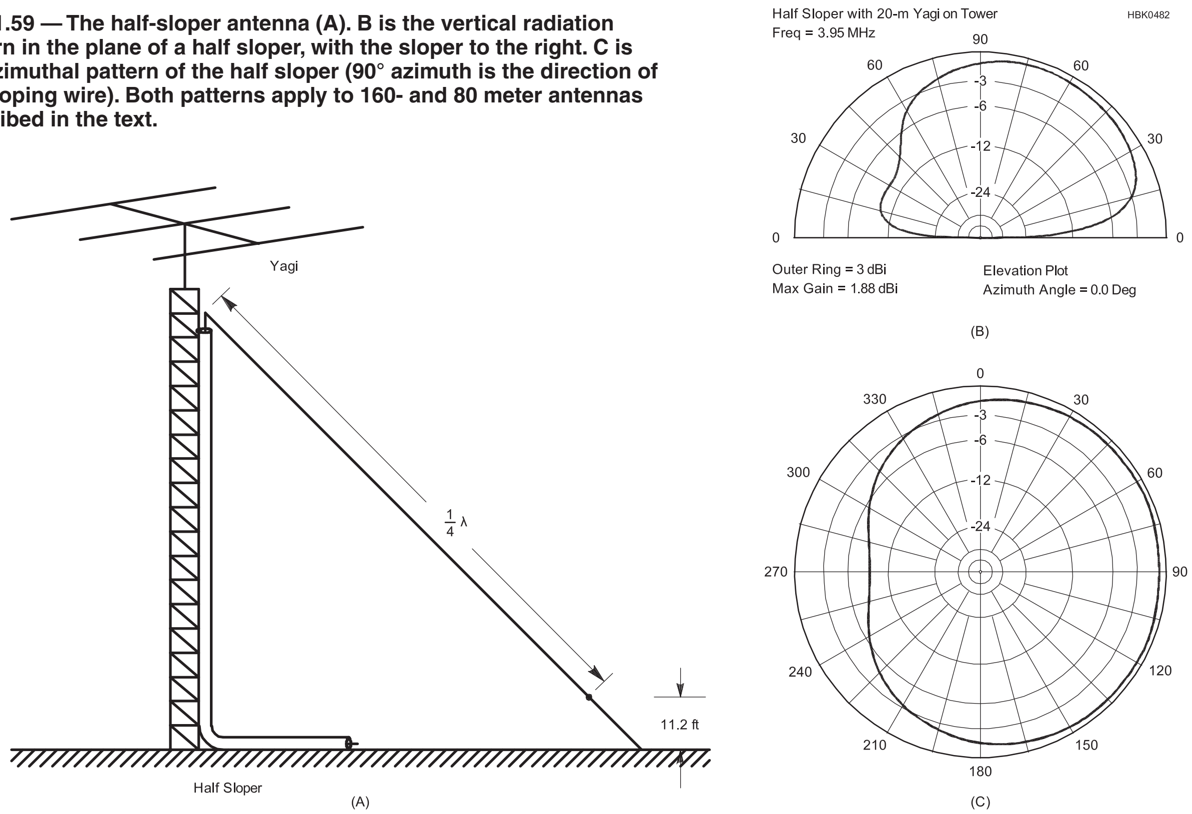


Fig 21.59 — The half-sloper antenna (A). B is the vertical radiation pattern in the plane of a half sloper, with the sloper to the right. C is the azimuthal pattern of the half sloper (90° azimuth is the direction of the sloping wire). Both patterns apply to 160- and 80 meter antennas described in the text.

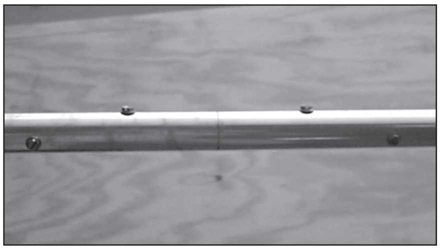


Fig 21.60 — Element splice uses a 1-ft length of 0.75-inch tubing inserted into the 0.875-inch sections to join them together. Self-tapping sheet-metal screws are used in this photo, but aluminum pop rivets or machine screws with washers and nuts can be used.

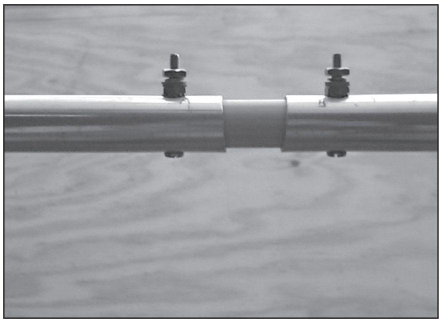


Fig 21.61 — The center insulator of the 15 meter HVD is a 1-ft length of 0.75-inch fiberglass rod. Insulator and elements have been drilled to accept #8 hardware.

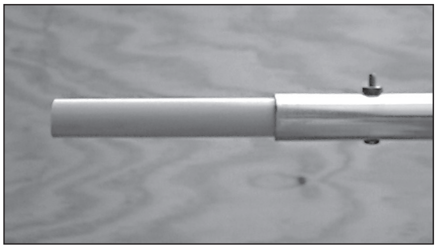


Fig 21.62 — The HVD base insulator is a 1-ft length of 0.75-inch fiberglass rod.

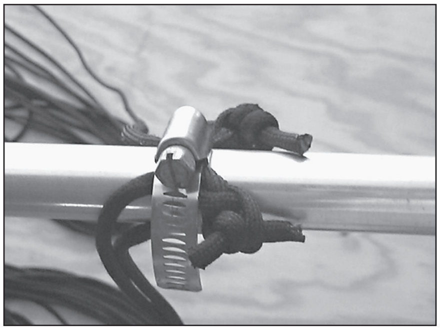


Fig 21.63 — Guys are made of Dacron line that is attached to the HVD by a stainless-steel worm-screw-type hose clamp. A self-tapping sheet-metal screw (not visible in the photo) prevents the clamp from sliding down the antenna.

Fig 21.65 — The HVD installed at K8CH. An eye screw that is used for securing one of the guy lines is visible in the foreground. You can also see the two choke baluns that are used in the feed system (see text).

ends of a 1-ft length of 0.75-inch fiberglass rod. This rod serves as the center insulator. Leave about a 1-inch gap at the center. Drill aluminum and fiberglass for #8 hardware as shown in **Fig 21.61**.

Now, slip half of the remaining 1-ft length of 0.75-inch fiberglass rod into one end the dipole. (This end will be the bottom end or base.) Drill and secure with #8 hardware. See **Fig 21.62**.

The final step is to secure the guy wires to your vertical. You can see how K8CH did that in **Fig 21.63**. Start by drilling a pilot hole and then drive a sheet metal screw into the antenna about a foot above the center. The purpose of that screw is to prevent the clamp and guys from sliding down the antenna.

The guys are clean lengths of 3⁄16-inch Dacron line. (The Dacron serves a dual purpose: it supports the antenna vertically, and it acts as an insulator.) Tie secure knots into the guy ends and secure these knotted ends to the antenna with a stainless-steel worm-screw-type hose clamp. Take care to not over tighten the clamps. You don't want the clamp to slip (the knots and the sheet-metal screw will help), but you especially don't want to cut your guy lines. Your antenna is ready for installation.

Fig 21.64 — At K8CH, the HVD base insulator sits in this saddle-shaped wooden fixture. This was photo was taken before the fixture was painted—a necessary step to protect against the weather.

INSTALLATION

Installation requires two things. First, a place to sit or mount the base insulator. Second, you need anchors for the support guys.

K8CH used a piece of 2 × 6 lumber to make a socket to hold the HVD base securely in place. He drilled a ¾-inch-deep hole with a ¾-inch spade bit. A couple of pieces of 2 × 2 lumber at the ends of the base form a saddle which nicely straddles the ridge at the peak of his garage roof. You can see this in **Fig 21.64**. The dimensions are not critical. Paint your base to protect it from the weather.

BALUN

This antenna needs a common-mode choke balun to ensure that stray RF doesn't flow on the shield of the coax. (See the **Transmission Lines** chapter for more information on choke baluns.) Unlike a horizontal dipole, don't consider it an option to omit the common-mode choke when building and installing an HVD.

You can use 8 ft of the RG-213 feed line wound into 7 turns for a balun. Secure the turns together with electrical tape so that each turn lies parallel with the next turn, forming a solenoid coil. Secure the feed line and balun to one of the guy lines with UV-resistant cable ties.

Because the feed line slants away from the antenna, you'll want to do *all* that you can to eliminate common-mode currents from the feed line. For that reason, make another balun about 11.5 ft from the first one. This balun also consists of 8 ft of the RG-213 feed line wound into 7 turns. See **Fig 21.65** for a photo of the installed antenna.

Project: Compact Vertical Dipole (CVD)

An HVD for 20 meters will be about 33 ft tall, and for 30 meters, it will be around 46 ft tall. Even the 20 meter version can prove to be a mechanical challenge. The compact vertical dipole (CVD), designed by Chuck Hutchinson, K8CH, uses capacitance loading to shorten the antenna. Starting with the 15 meter HVD described in the previous project, Chuck added capacitance loading wires to lower the resonance to 30 meters. Later, he shortened the wires to move resonance to the 20 meter band. This project describes those two CVDs.

PERFORMANCE ISSUES

Shortened antennas frequently suffer reduced performance caused by the shortening. A dipole that is less than ½-λ in length is a compromise antenna. The issue becomes how much is lost in the compromise. In this case there are two areas of primary interest, radiation efficiency and SWR bandwidth.

Table 21.9
CVD Loading Wires
Length using #14 AWG insulated copper wire

Band	*Feet*	*Inches*	
30 m	6	0	Top & Bottom
20 m	4	2¼	Top
20 m	3	½	Bottom

Radiation Efficiency

Capacitance loading at the dipole ends is the most efficient method of shortening the antenna. Current distribution in the high-current center of the antenna remains virtually unchanged. Since radiation is related directly to current, this is the most desirable form of loading. Computer modeling shows that radiation from a 30 meter CVD is only 0.66 dB less than that from a full-size 30 meter HVD when both have their bases 8 ft above ground. The angle of maximum radiation shifts up a bit for the CVD. Not a bad compromise when you consider that the CVD is 22-ft long compared to the approximately 46-ft length of the HVD.

SWR and SWR Bandwidth

Shortened antennas usually have lower radiation resistance and less SWR bandwidth than the full-size versions. The amount of change in the radiation resistance is related to the amount and type of loading (shortening), being lower with shorter the antennas. This can be a benefit in the case of a shortened vertical dipole. In Fig 21.2 you can see that vertical dipoles have a fairly high radiation resistance. With the dipole's lower end ⅛-λ above ground, the radiation resistance is roughly 80 Ω. In this case, a shorter antenna can have a better SWR when fed with 50-Ω coax.

SWR bandwidth tends to be wide for vertical dipoles in general. A properly designed CVD for 7 MHz or higher should give you good SWR (1.5:1 or better) across the entire band!

As you can see, in theory the CVD provides excellent performance in a compact package. Experience confirms the theory.

CONSTRUCTION

To convert the K8CH 15 meter HVD to 20 or 30 meters, you'll need to add four loading wires at the top and four more at the bottom of the HVD. The lengths are shown in **Table 21.9**. The upper wires droop at a 45° angle and the lower wires run horizontally. The antenna is supported by four guy lines. See **Fig 21.66**. You can connect the wires to the vertical portion with #8 hardware. Crimp and solder terminals on the wire ends to make connections easier. The technique is illustrated in **Fig 21.67**.

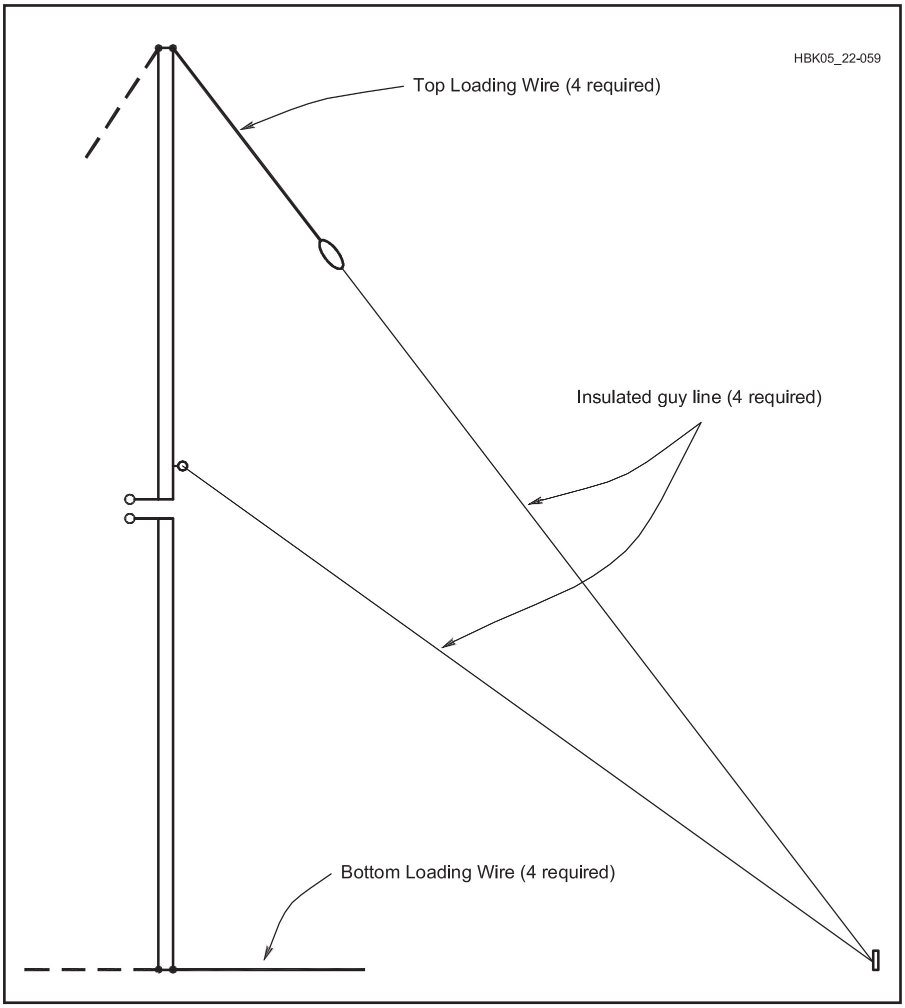


Fig 21.66 — The CVD consists of a vertical dipole and loading wires. Only one set of the four loading wires and only one guy line is shown in this drawing. See text for details.

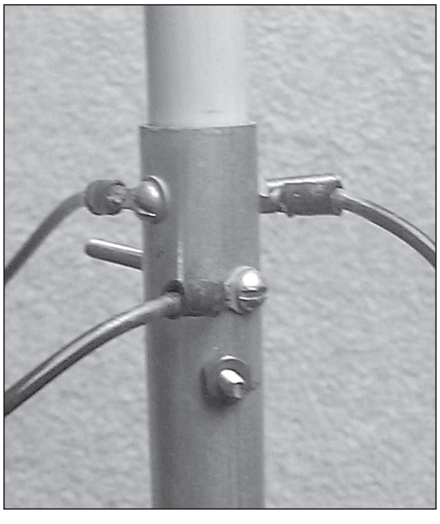


Fig 21.67 — CVD loading wires can be attached using #8 hardware. Crimp and solder terminals on the wire ends to make connections easier.

The upper loading wires can be extended with insulated line and used for additional guying. The lower wires are extended with insulated line and fasten to the guy lines so that the lower wires run horizontally.

Prune the lower wires for best SWR across the band of interest. The K8CH CVD has its base at 14 ft. This antenna has an SWR of less than 1.2:1 on 30 meters and less than 1.3:1 across the entire 20 meter band.

EXPERIENCE

The 30 meter CVD was compared to a ground-mounted quarter-wave vertical and a horizontal dipole at 30 ft. In tests, the CVD was always the superior antenna. Every DX station that was called by K8CH responded with one or two calls. What more could you ask for?

Later, the CVD loading wires were shortened for operation on 20 meters. Once again the results were very encouraging. Many contest QSOs were entered in the log using this antenna.

Finally, a late winter ice storm deposited about ¾-inch of radial ice on the antenna, loading wires and guys. The antenna would probably have survived had it not been for the sustained 45 mph winds that followed. The upper loading wires and their guy lines were not heavy enough to support the load and the antenna bent and broke. This combination of ice and wind is very unusual.

Project: All-Wire 30 Meter CVD

If you have a tree or other support that will support the upper end of a CVD at 32 ft above the ground, you might want to consider an all-wire version of the 30 meter CVD. The vertical is 24 ft long and it will have an SWR of less than 1.1:1 across the band. The four loading wires at top and bottom are each 5 ft, 2 inches long.

The configuration is shown in **Fig 21.68**. As with any vertical dipole, you'll need to use a balun between the feed line and the antenna.

Alternatively you can use two loading wires at the top and two at the bottom. In this case each of the loading wires is 8 ft, 7.5 inches long.

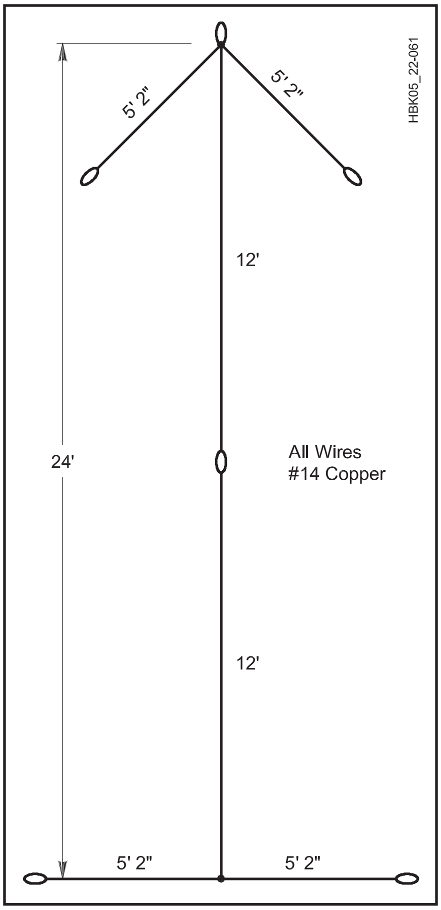


Fig 21.68 — The all-wire 30 meter CVD consists of a vertical dipole and loading wires. It can be made entirely with #14 AWG wire. Support lines have been omitted for simplicity. See text for details.

21.6 Yagi Antennas

Most antennas described earlier in this chapter have unity gain compared to a dipole, or just slightly more. For the purpose of obtaining gain and directivity it is convenient to use a Yagi-Uda *beam* antenna. The former is commonly called a *Yagi*. There are other forms of directive antennas, but the Yagi is by far the most popular used by amateurs. (For more information on phased arrays and other types of directive antennas, see the *ARRL Antenna Book*.)

Most operators prefer to erect these antennas for horizontal polarization, but they can be used as vertically polarized antennas merely by rotating the elements by 90°. In effect, the beam antenna is turned on its side for vertical polarization. The number of elements used will depend on the gain desired and the limits of the supporting structure. At HF, many amateurs obtain satisfactory results with only two elements in a beam antenna, while others have four or five elements operating on a single amateur band, called a *monoband beam*. On VHF and above, Yagis with many elements are common, particularly for simplex communication without repeaters. For fixed point-to-point communications, such as repeater links, Yagis with three or four elements are more common.

Regardless of the number of elements used, the height-above-ground considerations discussed earlier for dipole antennas remain valid with respect to the angle of radiation. This is demonstrated in **Fig 21.69** at A and B where a comparison of radiation characteristics is given for a 3-element Yagi at one-half and one wavelength above average ground. It can be seen that the higher antenna (Fig 21.69B) has a main lobe that is more favorable for DX work (roughly 15°) than the lobe of the lower antenna in Fig 21.69A (approximately 30°). The pattern at B shows that some useful high-angle radiation exists also, and the higher lobe is suitable for short-skip contacts when propagation conditions dictate the need.

The azimuth pattern for the same antenna is provided in **Fig 21.70**. (This is a free-space pattern, so the pattern is taken in the plane of the antenna. Remember that azimuth

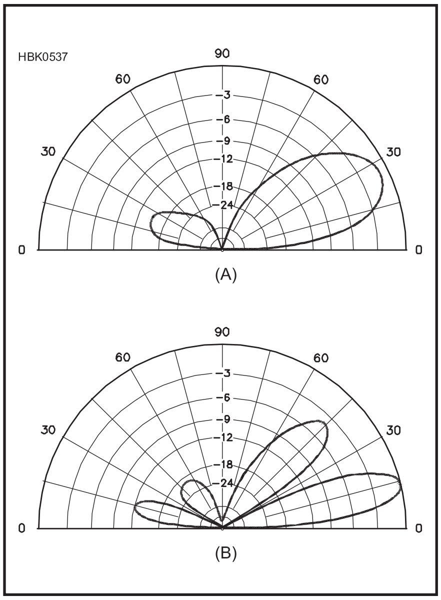


Fig 21.69 — Elevation-plane response of a 3-element Yagi placed ½ λ above perfect ground at A and the same antenna spaced 1 λ above ground at B.

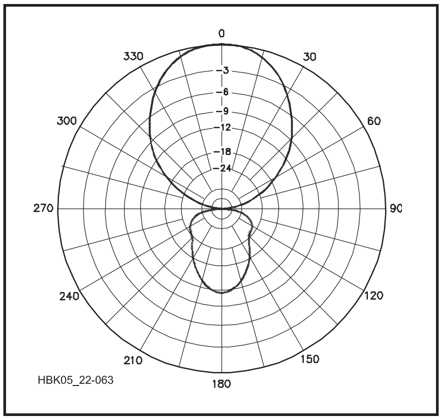


Fig 21.70 — Azimuthal pattern of a typical three-element Yagi in free space. The Yagi's boom is along the 0° to 180° axis.

patterns taken over a reflecting surface must also specify the elevation angle at which the pattern was measured or calculated.) Most of the power is concentrated in the main lobe at 0° azimuth. The lobe directly behind the main lobe at 180° is often called the *back lobe* or *rear lobe*. The front-to-back ratio (F/B) of this antenna is just less than 12 dB — the peak power difference, in decibels, between the main lobe at 0° and the rearward lobe at 180°. It is infrequent that two 3-element Yagis with different element spacing and tuning will yield the same lobe patterns. The patterns also change with frequency of operation. The pattern of Fig 21.70 is shown only for illustrative purposes.

21.6.1 Parasitic Excitation

In a Yagi antenna only one element (the *driven element*) is connected to the feed line. The additional elements are *coupled* to the driven element because they are so close. (Element-to-element spacing in a Yagi antenna is generally on the order of 1⁄10-1⁄8 wavelength.) This *mutual coupling* results in currents being induced in the non-driven elements from the radiated field of the driven element. These elements are called *parasitic elements* and the Yagi antenna is therefore a *parasitic array*. (An antenna in which multiple elements all receive power from the transmitter is called a *driven array*.) The currents induced in the parasitic elements also result in radiated fields, just as if the current were the result of power from a feed line. This is called *reradiation*. The combination of the field radiated by the driven element, the fields from the parasitic elements, and the physical spacing of the elements results in the fields having the proper phase relationship so as to focus the radiated energy in the desired direction and reject it in other directions.

The parasitic element is called a *director* when it reinforces radiation along a line pointing to it from the driven element, and a *reflector* in the opposite case. Whether the parasitic element is a director or reflector depends on the parasitic element tuning, which is usually adjusted by changing its length. The structure on which the elements are mounted is called the *boom* of the antenna.

21.6.2 Yagi Gain, Front-to-Back Ratio and SWR

The gain of a Yagi antenna with parasitic elements varies with the spacing and tuning of the elements. Element tuning is a function of length, diameter and *taper schedule* (the steps in length and diameter) if the element is constructed with telescoping tubing. For any given number of elements and the spacing between them, there is a tuning condition that will result in maximum gain. However, the maximum front-to-back ratio seldom, if ever, occurs at the same condition that gives maximum forward gain. The impedance of the driven element in a parasitic array, and thus the SWR, also varies with the tuning and spacing.

It is important to remember that all these parameters change as the operating frequency is varied. For example, if you operate both the CW and phone portions of the 20 meter band with a Yagi antenna, you probably will want an antenna that *spreads out* the performance over most of the band. Such designs typically must sacrifice a little gain in order to achieve good F/B and SWR performance across the band.

Gain and F/B performance generally improve with the number of elements. In Yagi antennas with more than three elements (a driven element and one director and reflector), the additional elements are added as directors, since little additional benefit is obtained from multiple reflectors. Wider spacing also improves gain and F/B up to a certain point, depending on a number of factors, beyond which performance begins to fall. Optimizing element spacing is a complex problem and no single spacing satisfies all design requirements. For the lower HF bands, the size of the antenna quickly becomes impractical for truly *optimal* designs, and compromise is necessary.

21.6.3 Two-Element Beams

A two-element beam is useful — especially where space or other considerations prevent the use of a three-element, or larger, beam. The general practice is to tune the parasitic element as a reflector and space it about 0.15 λ from the driven element, although some successful antennas have been built with 0. 1-λ spacing and director tuning.

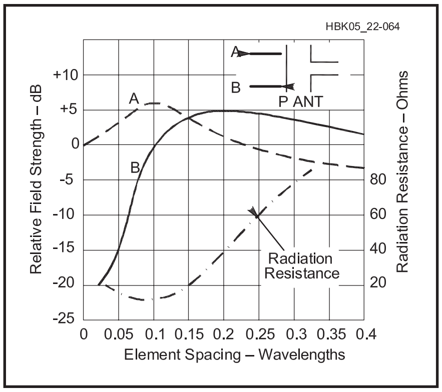


Fig 21.71 — Gain vs element spacing for a two-element Yagi, having one driven and one parasitic element. The reference point, 0 dB, is the field strength from a half-wave antenna alone.

Gain vs element spacing for a two-element antenna is given in **Fig 21.71** for the special case where the parasitic element is resonant. It is indicative of the performance to be expected under maximum-gain tuning conditions. Changing the tuning of the driven element in a Yagi or quad will not materially affect the gain or F/R. Thus, only the spacing and the tuning of the single parasitic element have any effect on the performance of a 2-element Yagi.

In Fig 21.71, the greatest gain is in the direction A (in which the parasitic element is acting as a director) at spacings of less than 0.14 λ, and in direction B (in which the parasitic element is a reflector) at greater spacings. The front-to-back ratio is the difference in decibels between curves A and B. The figure also shows variation in radiation resistance of the driven element.

These curves are for the special case of a self-resonant parasitic element, but are representative of how a two-element Yagi works. At most spacings the gain as a reflector can be increased by slight lengthening of the parasitic element; the gain as a director can be increased by shortening. This also improves the front-to-rear ratio.

Most two-element Yagi designs achieve a compromise F/R of about 10 dB, together with an acceptable SWR and gain across a frequency band with a percentage bandwidth less than about 4%.

21.6.4 Three-Element Beams

A theoretical investigation of the three-element case (director, driven element and reflector) has indicated a maximum gain of about 9.7 dBi (7.6 dBd). A number of experimental investigations have shown that the spacing between the driven element and reflector for maximum gain is in the region of 0.15 to 0.25 λ. With 0.2-λ reflector spacing, **Fig 21.72** shows that the gain variation with director spacing is not especially critical.

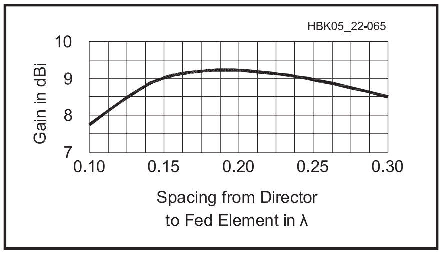


Fig 21.72 — General relationship of gain of three-element Yagi vs director spacing, the reflector being fixed at 0.2 λ. This antenna is tuned for maximum forward gain.

Also, the overall length of the array (boom length in the case of a rotatable antenna) can be anywhere between 0.35 and 0.45 λ with no appreciable difference in the maximum gain obtainable.

If maximum gain is desired, wide spacing of both elements is beneficial because adjustment of tuning or element length is less critical and the input resistance of the driven element is generally higher than with close spacing. A higher input resistance improves the efficiency of the antenna and makes a greater bandwidth possible. However, a total antenna length, director to reflector, of more than 0.3 λ at frequencies of the order of 14 MHz introduces difficulty from a construction standpoint. Lengths of 0.25 to 0.3 λ are therefore used frequently for this band, even though they are less than optimum from the viewpoint of maximum gain.

In general, Yagi antenna gain drops off less rapidly when the reflector length is increased beyond the optimum value than it does for a corresponding decrease below the optimum value. The opposite is true of a director. It is therefore advisable to err, if necessary, on the long side for a reflector and on the short side for a director. This also tends to make the antenna performance less dependent on the exact frequency at which it is operated. An increase above the design frequency has the same effect as increasing the length of both parasitic elements, while a decrease in frequency has the same effect as shortening both elements. By making the director slightly short and the reflector slightly long, there will be a greater spread between the upper and lower frequencies at which the gain starts to show a rapid decrease.

21.6.5 Construction of Yagi Antennas

Most beams and verticals are made from sections of aluminum tubing. Compromise beams have been fashioned from less-expensive materials such as electrical conduit (steel) or bamboo poles wrapped with conductive tape or aluminum foil. The steel conduit is heavy, is a poor conductor and is subject to rust. Similarly, bamboo with conducting material attached to it may deteriorate rapidly in the weather. Given the drawbacks of alternative materials, aluminum tubing (or rod for VHF and UHF Yagis) is far and away the best choice for antenna construction.

For reference, **Table 21.10** details the standard sizes of aluminum tubing, available in many metropolitan areas. Dealers may be found in the Yellow Pages under *Aluminum*. Tubing usually comes in 12-ft lengths, although 20-ft lengths are available in some sizes. Your aluminum dealer will probably also sell aluminum plate in various thicknesses needed for boom-to-mast and boom-to-element connections. Distributors of antenna towers and masts often sell aluminum tubing, as well.

Aluminum is rated according to its hardness. The most common material used in antenna construction is grade 6061-T6. This material is relatively strong and has good workability. In addition, it will bend without taking a *set*, an advantage in antenna applications where the pieces are constantly flexing in the wind. The softer grades (5051, 3003 and so on) will bend much more easily, while harder grades (7075 and so on) are more brittle.

Wall thickness is of primary concern when selecting tubing. It is of utmost importance that the tubing fits snugly where the element sections join. Sloppy joints will make a mechanically unstable antenna. The magic wall thickness is 0.058 inch. For example (from Table 21.10), 1-inch outside diameter (OD) tubing with a 0.058-inch wall has an inside diameter (ID) of 0.884 inch. The next smaller size of tubing, ⅞ inch, has an OD of 0.875 inch. The 0.009-inch difference provides just the right amount of clearance for a snug fit.

Fig 21.73 shows several methods of fastening antenna element sections together. The slot and hose clamp method shown at the upper left is probably the best for joints where adjustments are needed. Generally, one adjustable joint on each side of the element is sufficient to tune the antenna — usually the tips at each end of an element are made adjustable. Stainless steel hose clamps (beware — some "stainless steel" models do not have a stainless screw and will rust) are recommended for longest antenna life.

The remaining photos show possible fastening methods for joints that are not adjustable. At the upper right, machine screws and nuts hold the elements in place. At the lower left, sheet metal screws are used. At the lower right, rivets secure the tubing. If the antenna is to be assembled permanently, rivets are the best choice. Once in place, they are permanent. They will never work free, regardless of vibration or wind. If aluminum rivets with aluminum mandrels are employed, they will never rust. Also, being aluminum, there is no danger of corrosion from interaction between dissimilar metals. If the antenna is to be disassembled and moved periodically, either machine or sheet metal screws will work. If machine screws are used, however, take precautions to keep the nuts from vibrating free. Use of lock washers, lock nuts and flexible adhesive such as silicone bathtub sealant will keep the hardware in place. For portable or temporary use, such as Field Day, rivets may be held in place with electrical tape and removed when the operation is finished.

Use of a conductive grease at the element joints is essential for long life. Left untreated, the aluminum surfaces will oxidize in the weather, resulting in a poor connection. Some trade names for this conductive grease are Penetrox, Noalox and Dow Corning Molykote 41. Many electrical supply houses carry these products.

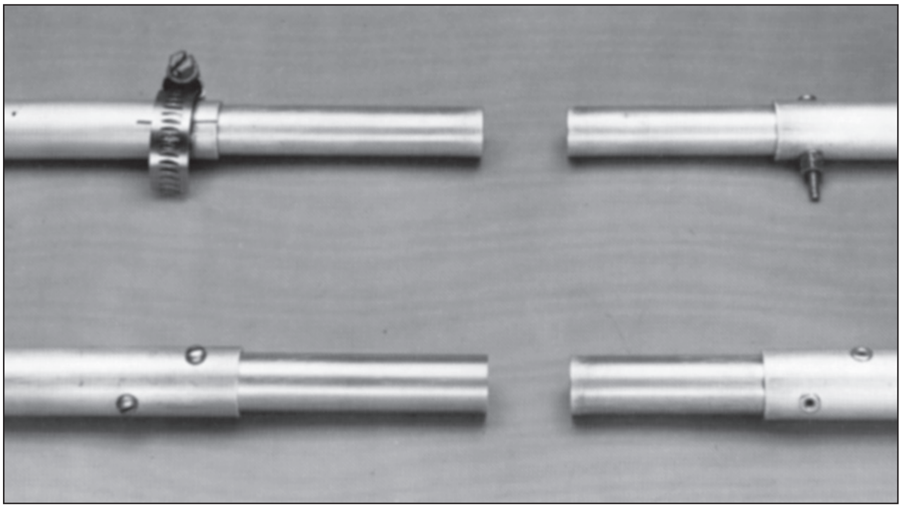


Fig 21.73 — Some methods of connecting telescoping tubing sections to build beam elements. See text for a discussion of each method.

Table 21.10
Standard Sizes of Aluminum Tubing

6061-T6 (61S-T6) Round Aluminum Tube in 12-ft Lengths

OD (in)	***Wall Thickness*** *(in)*	*stubs ga*	*ID (in)*	***Approx Weight (lb)*** *per ft*	*per length*
3/16	0.035	no. 20	0.117	0.019	0.228
	0.049	no. 18	0.089	0.025	0.330
¼	0.035	no. 20	0.180	0.027	0.324
	0.049	no. 18	0.152	0.036	0.432
	0.058	no. 17	0.134	0.041	0.492
5⁄16	0.035	no. 20	0.242	0.036	0.432
	0.049	no. 18	0.214	0.047	0.564
	0.058	no. 17	0.196	0.055	0.660
⅜	0.035	no. 20	0.305	0.043	0.516
	0.049	no. 18	0.277	0.060	0.720
	0.058	no. 17	0.259	0.068	0.816
	0.065	no. 16	0.245	0.074	0.888
7⁄16	0.035	no. 20	0.367	0.051	0.612
	0.049	no. 18	0.339	0.070	0.840
	0.065	no. 16	0.307	0.089	1.068
½	0.028	no. 22	0.444	0.049	0.588
	0.035	no. 20	0.430	0.059	0.708
	0.049	no. 18	0.402	0.082	0.948
	0.058	no. 17	0.384	0.095	1.040
	0.065	no. 16	0.370	0.107	1.284
⅝	0.028	no. 22	0.569	0.061	0.732
	0.035	no. 20	0.555	0.075	0.900
	0.049	no. 18	0.527	0.106	1.272
	0.058	no. 17	0.509	0.121	1.452
	0.065	no. 16	0.495	0.137	1.644
¾	0.035	no. 20	0.680	0.091	1.092
	0.049	no. 18	0.652	0.125	1.500
	0.058	no. 17	0.634	0.148	1.776
	0.065	no. 16	0.620	0.160	1.920
	0.083	no. 14	0.584	0.204	2.448
⅞	0.035	no. 20	0.805	0.108	1.308
	0.049	no. 18	0.777	0.151	1.810
	0.058	no. 17	0.759	0.175	2.100
	0.065	no. 16	0.745	0.199	2.399
1	0.035	no. 20	0.930	0.123	1.467
	0.049	no. 18	0.902	0.170	2.040
	0.058	no. 17	0.884	0.202	2.424
	0.065	no. 16	0.870	0.220	2.640
	0.083	no. 14	0.834	0.281	3.372
1⅛	0.035	no. 20	1.055	0.139	1.668
	0.058	no. 17	1.009	0.228	2.736
1¼	0.035	no. 20	1.180	0.155	1.860
	0.049	no. 18	1.152	0.210	2.520
	0.058	no. 17	1.134	0.256	3.072
	0.065	no. 16	1.120	0.284	3.408
	0.083	no. 14	1.084	0.357	4.284
1⅜	0.035	no. 20	1.305	0.173	2.076
	0.058	no. 17	1.259	0.282	3.384
1½	0.035	no. 20	1.430	0.180	2.160
	0.049	no. 18	1.402	0.260	3.120
	0.058	no. 17	1.384	0.309	3.708
	0.065	no. 16	1.370	0.344	4.128
	0.083	no. 14	1.334	0.434	5.208
	*0.125	⅛"	1.250	0.630	7.416
	*0.250	¼"	1.000	1.150	14.823
1⅝	0.035	no. 20	1.555	0.206	2.472
	0.058	no. 17	1.509	0.336	4.032
1¾	0.058	no. 17	1.634	0.363	4.356
	0.083	no. 14	1.584	0.510	6.120
1⅞	0.508	no. 17	1.759	0.389	4.668
2	0.049	no. 18	1.902	0.350	4.200
	0.065	no. 16	1.870	0.450	5.400
	0.083	no. 14	1.834	0.590	7.080
	*0.125	⅛"	1.750	0.870	9.960
	*0.250	¼"	1.500	1.620	19.920
2¼	0.049	no. 18	2.152	0.398	4.776
	0.065	no. 16	2.120	0.520	6.240
	0.083	no. 14	2.084	0.660	7.920
2½	0.065	no. 16	2.370	0.587	7.044
	0.083	no. 14	2.334	0.740	8.880
	*0.125	⅛"	2.250	1.100	12.720
	*0.250	¼"	2.000	2.080	25.440
3	0.065	no. 16	2.870	0.710	8.520
	*0.125	⅛"	2.700	1.330	15.600
	*0.250	¼"	2.500	2.540	31.200

*These sizes are extruded; all other sizes are drawn tubes.Shown here are standard sizes of aluminum tubing that are stocked by most aluminum suppliers or distributors in the United States and Canada.

DRIVEN ELEMENT

The ARRL recommends *plumbers delight* construction, in which all elements are mounted directly on, and grounded to, the boom. This puts the entire array at dc ground potential, affording better lightning protection. A gamma- or T-match section can be used for matching the feed line to the array.

An alternative method is to insulate the driven element from the boom, but use a *hairpin* or *beta match*, the center point of which is electrically neutral and can be attached directly to the boom, restoring the dc ground for the driven element.

Direct feed designs in which the feed point impedance of the driven element is close to 50 Ω, requiring no impedance matching structure, presents some issues. First, a current or choke balun should be used (see the **Transmission Lines** chapter) to prevent the outer surface of the feed line shield from interacting with the antenna directly or by picking up the radiated signal. Such interaction can degrade the antenna's radiation pattern, especially by compromising signal rejection to the side and rear. Second, the driven element must be insulated from the boom, requiring some additional mechanical complexity.

BOOM MATERIAL

The boom size for a rotatable Yagi or quad should be selected to provide stability to the entire system. The best diameter for the boom depends on several factors, but mostly the element weight, number of elements and overall length. Two-inch-diameter booms should not be made any longer than 24 ft unless additional support is given to reduce both vertical and horizontal bending forces. Suitable reinforcement for a long 2-inch boom can

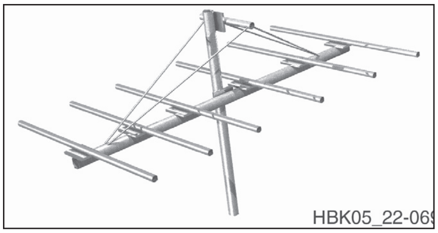


Fig 21.74 — A long boom needs both vertical and horizontal support. The crossbar mounted above the boom can support a double truss, which will help keep the antenna in position.

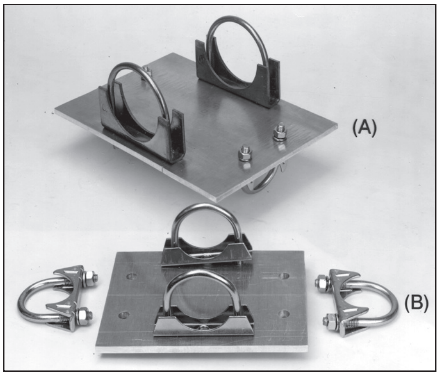


Fig 21.75 — The boom-to-element plate at A uses muffler-clamp-type U-bolts and saddles to secure the round tubing to the flat plate. The boom-to-mast plate at B is similar to the boom-to-element plate. The main difference is the size of materials used.

Table 21.11
10 Meter Optimized Yagi Designs

	Spacing Between Elements (in)	*Seg 1 Length (in)*	*Seg 2 Length (in)*	*Seg 3 Length (in)*	*Midband Gain F/R*
310-08					
Refl	0	24	18	66.750	7.2 dBi
DE	36	24	18	57.625	22.9 dB
Dir 1	54	24	18	53.125	
410-14					
Refl	0	24	18	64.875	8.4 dBi
DE	36	24	18	58.625	30.9 dB
Dir 1	36	24	18	57.000	
Dir 2	90	24	18	47.750	
510-24					
Refl	0	24	18	65.625	10.3 dBi
DE	36	24	18	58.000	25.9 dB
Dir 1	36	24	18	57.125	
Dir 2	99	24	18	55.000	
Dir 3	111	24	18	50.750	

Note: For all antennas, the tube diameters are: Seg 1=0.750 inch, Seg 2=0.625 inch, Seg 3=0.500 inch.

Table 21.12
12 Meter Optimized Yagi Designs

	Spacing Between Elements (in)	*Seg 1 Length (in)*	*Seg 2 Length (in)*	*Seg 3 Length (in)*	*Midband Gain F/R*
312-10					
Refl	0	36	18	69.000	7.5 dBi
DE	40	36	18	59.125	24.8 dB
Dir 1	74	36	18	54.000	
412-15					
Refl	0	36	18	66.875	8.5 dBi
DE	46	36	18	60.625	27.8 dB
Dir 1	46	36	18	58.625	
Dir 2	82	36	18	50.875	
512-20					
Refl	0	36	18	69.750	9.5 dBi
DE	46	36	18	61.750	24.9 dB
Dir 1	46	36	18	60.500	
Dir 2	48	36	18	55.500	
Dir 3	94	36	18	54.625	

Note: For all antennas, the tube diameters are: Seg 1 = 0.750 inch,Seg 2 = 0.625 inch, Seg 3 = 0.500 inch.

consist of a truss or a truss and lateral support, as shown in **Fig 21.74**.

A boom length of 24 ft is about the point where a three-inch diameter begins to be very worthwhile. This dimension provides a considerable amount of improvement in overall mechanical stability as well as increased clamping surface area for element hardware. The latter is extremely important to prevent rotation of elements around the boom if heavy icing is commonplace. Pinning an element to the boom with a large bolt helps in this regard. On smaller diameter booms, however, the elements sometimes work loose and tend to elongate the pinning holes in both the element and the boom. After some time the elements shift their positions slightly (sometimes from day to day) and give a ragged appearance to the system, even though this may not harm the electrical performance.

A 3-inch-diameter boom with a wall thickness of 0.065 inch is very satisfactory for antennas up to about a five-element, 20 meter array that is spaced on a 40-ft boom. A truss is recommended for any boom longer than 24 ft. One possible source for large boom material is irrigation tubing sold at farm supply houses.

PUTTING IT TOGETHER

Once you assemble the boom and elements, the next step is to fasten the elements to the boom securely and then fasten the boom to the mast or supporting structure using mounting plates as shown in **Fig 21.75**. Be sure to leave plenty of material on either side of the U-bolt holes on the element-to-boom mounting plates. The U-bolts selected should be a snug fit for the tubing. If possible, buy muffler-clamp U-bolts that come with saddles.

The *boom-to-mast* plate shown in Fig 21.75B is similar to the *boom-to-element* plate in 21.75A. The size of the plate and number of U-bolts used will depend on the size of the antenna. Generally, antennas for the bands up through 20 meters require only two U-bolts each for the mast and boom. Longer antennas for 15 and 20 meters (35-ft booms and up) and most 40 meter beams should have four U-bolts each for the boom and mast because of the torque that the long booms and elements exert as the antennas move in the wind. When tightening the U-bolts, be careful not to crush the tubing. Once the wall begins to collapse, the connection begins to weaken. Many aluminum suppliers sell ¼-inch or ⅜-inch thick plates just right for this application. Often they will shear pieces to the correct size on request. As with tubing, the relatively hard 6061-T6 grade is a good choice for mounting plates.

The antenna should be put together with good-quality hardware. Stainless steel is best for long life. Rust will attack plated steel hardware after a short while, making nuts difficult, if not impossible, to remove. If stainless muffler clamps are not available, the next best thing is to have them plated. If you can't get them plated, then at least paint them with a good zinc-chromate primer and a finish coat or two. Good-quality hardware is more expensive initially, but if you do it

Table 21.13
15 Meter Optimized Yagi Designs

	Spacing Between Elements (in)	*Seg 1 Length (in)*	*Seg 2 Length (in)*	*Seg 3 Length (in)*	*Seg 4 Length (in)*	*Midband Gain F/R*
315-12						
Refl	0	30	36	18	61.375	7.6 dBi
DE	48	30	36	18	49.625	25.5 dB
Dir 1	92	30	36	18	43.500	
415-18						
Refl	0	30	36	18	59.750	8.3 dBi
DE	56	30	36	18	50.875	31.2 dB
Dir 1	56	30	36	18	48.000	
Dir 2	98	30	36	18	36.625	
515-24						
Refl	0	30	36	18	62.000	9.4 dBi
DE	48	30	36	18	52.375	25.8 dB
Dir 1	48	30	36	18	47.875	
Dir 2	52	30	36	18	47.000	
Dir 3	134	30	36	18	41.000	

Note: For all antennas, the tube diameters (in inches) are: Seg 1 = 0.875, Seg 2 = 0.750, Seg 3 = 0.625, Seg 4 = 0.500.

Table 21.14
17 Meter Optimized Yagi Designs

	Spacing Between Elements (in)	*Seg 1 Length (in)*	*Seg 2 Length (in)*	*Seg 3 Length (in)*	*Seg 4 Length (in)*	*Seg 5 Length (in)*	*Midband Gain F/R*
317-14							
Refl	0	24	24	36	24	60.125	8.1 dBi
DE	65	24	24	36	24	52.625	24.3 dB
Dir 1	97	24	24	36	24	48.500	
417-20							
Refl	0	24	24	36	24	61.500	8.5 dBi
DE	48	24	24	36	24	54.250	27.7 dB
Dir 1	48	24	24	36	24	52.625	
Dir 2	138	24	24	36	24	40.500	

Note: For all antennas, tube diameters (inches) are: Seg 1=1.000, Seg 2=0.875, Seg 3=0.750, Seg 4=0.625, Seg 5=0.500.

Table 21.15
20 Meter Optimized Yagi Designs

	Spacing Between Elements (in.)	*Seg 1 Length (in.)*	*Seg 2 Length (in.)*	*Seg 3 Length (in.)*	*Seg 4 Length (in.)*	*Seg 5 Length (in.)*	*Seg 6 Length (in.)*	*Midband Gain F/R*
320-16								
Refl	0	48	24	20	42	20	69.625	7.3 dBi
DE	80	48	24	20	42	20	51.250	23.4 dB
Dir 1	106	48	24	20	42	20	42.625	
420-26								
Refl	0	48	24	20	42	20	65.625	8.6 dBi
DE	72	48	24	20	42	20	53.375	23.4 dB
Dir 1	60	48	24	20	42	20	51.750	
Dir 2	174	48	24	20	42	20	38.625	

Note: For all antennas, tube diameters (inches) are: Seg 1=1.000, Seg 2=0.875, Seg 3=0.750, Seg 4=0.625, Seg 5=0.500. Seg 6=0.375.

right the first time, you won't have to take the antenna down after a few years and replace the hardware. Also, when repairing or modifying an installation, nothing is more frustrating than fighting rusty hardware at the top of a tower. Stainless steel hardware can also develop surface defects called *galling* that can cause threads on nuts and bolts to seize. On hardware ¼-inch and larger, the use of an anti-seize compound is recommended.

Project: Family of Computer-Optimized HF Yagis

Yagi designers are now able to take advantage of powerful personal computers and software to optimize their designs for the parameters of gain, F/R and SWR across frequency bands. Dean Straw, N6BV, has designed a family of Yagis for HF bands. These can be found in **Tables 22.11**, **22.12**, **22.13, 22.14** and **22.15**, for the 10, 12, 15, 17 and 20 meter amateur bands, respectively.

For 12 through 20 meters, each design has been optimized for better than 20 dB F/R, and an SWR of less than 2:1 across the entire amateur frequency band. For the 10 meter band, the designs were optimized for the lower 800 kHz of the band, from 28.0 to 28.8 MHz. Each Yagi element is made of telescoping 6061-T6 aluminum tubing, with 0.058 inch thick walls. This type of element can be telescoped easily, using techniques shown in Fig 21.73. Measuring each element to an accuracy of ⅛ inch results in performance remarkably consistent with the computations, without any need for tweaking or fine-tuning when the Yagi is on the tower.

The dimensions shown are designed for specific telescoping aluminum elements, but the elements may be scaled to different sizes by using the information about tapering and scaling in *The ARRL Antenna Book*, although with a likelihood of deterioration in performance over the whole frequency band.

Each element is mounted above the boom with a heavy rectangular aluminum boom-to-element plate, by means of galvanized U-bolts with saddles, as shown in Fig 21.75. 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 mounting plate. The element mounting plate for all the 10 meter Yagis is a 0.250-inch thick flat aluminum plate, 4 inches wide by 4 inches long. For the 12 and 15 meter Yagis, a 0.375-inch thick flat aluminum plate, 5 inches wide by 6 inches long is used, and for the 17 and 20 meter Yagis, a 0.375-inch thick flat aluminum plate, 6 inches wide by 8 inches long is used. Where the plate is rectangular, the long dimension is in line with the element.

Each design table shows the dimensions for *one-half* of each element, mounted on one side of the boom. The other half of each element is the same, mounted on the other side of the boom. Use a tubing sleeve inside the center portion of the element so that the element is not crushed by the mounting U-bolts. Each telescoping section is inserted 3 inches into the next size of tubing. For example, in the 310-08 design for 10 meters (3 elements on an 8-ft boom), the reflector tip, made out of ½-inch OD tubing, sticks out 66.75 inches from the ⅝-inch OD tubing. For each 10 meter element, the overall length of each ⅝-inch OD piece of tubing is 21 inches, before insertion into the ¾-inch piece. Since the ¾-inch OD tubing is 24 inches long on each side of the boom, the center portion of each element is actually 48 inches of uncut ¾-inch OD tubing.

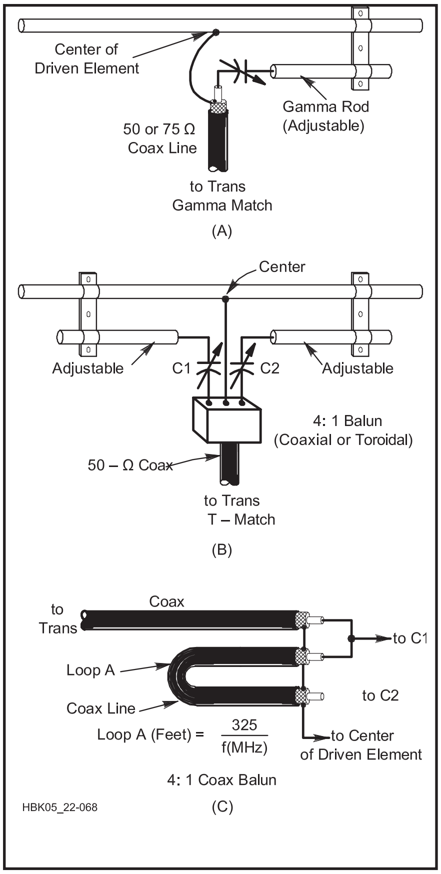


Fig 21.76 — Illustrations of gamma and T matching systems. At A, the gamma rod is adjusted along with the capacitor until the lowest SWR is obtained. A T match is shown at B. It is the same as two gamma-match rods.

The boom for all these antennas should be constructed with at least 2-inch-OD tubing, with 0.065-inch wall thickness. Because each boom has three inches of extra length at each end, the reflector is actually placed three inches from one end of the boom. For the 310-08 design, the driven element is placed 36 inches ahead of the reflector, and the director is placed 54 inches ahead of the driven element. The antenna is attached to the mast with the *boom-to-mast* mounting plate shown in Fig 21.74.

Each antenna is designed with a driven element length appropriate for a gamma or T matching network, as shown in **Fig 21.76**. The variable gamma or T capacitors can be housed in small plastic enclosures for weatherproofing; receiving-type variable capacitors with close plate spacing can be used at powers up to a few hundred watts. Maximum capacitance required is usually 140 pF at 14 MHz and proportionally less at the higher frequencies.

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.

TUNING ADJUSTMENTS

To tune the gamma match, adjust the gamma capacitor for best SWR, then adjust the position of the shorting strap or bar that connects the gamma rod to the driven element. Repeat this alternating sequence of adjustments until a satisfactory SWR is reached.

To tune the T-match, the position of the shorting straps and C1 and C2 are adjusted alternately for a best SWR. To maintain balance of the antenna, the position of the straps and capacitor settings should be the same for each side and adjusted together. A coaxial 4:1 balun transformer is shown at 21.76C. A toroidal balun can be used in place of the coax model shown. The toroidal version has a broader frequency range than the coaxial one. The T match is adjusted for 200 Ω and the balun steps this balanced value down to 50 Ω, unbalanced. Or the T match can be set for 300 Ω, and the balun used to step this down to 75 Ω unbalanced.

Dimensions for the gamma and T match rods will depend on the tubing size used, and the spacing of the parasitic elements of the beam. Capacitors C1 and C2 can be 140 pF for 14-MHz beams. Somewhat less capacitance will be needed at 21 and 28 MHz.

Preliminary matching adjustments can be done on the ground. The beam should be aligned vertically so that the reflector element is closest to and a few feet off the ground, with the beam pointing upward. The matching system is then adjusted for best SWR. When the antenna is raised to its operating height, only slight touch-up of the matching network may be required.

A *choke balun* (see the **Transmission Lines** chapter) should be used to isolate the coaxial feed line shield from the antenna. Secure the feed line to the boom of the antenna between the feed point and the supporting mast.

21.7 Quad and Loop Antennas

One of the more effective DX antennas is the *quad*. It consists of two or more loops of wire, each supported by a bamboo or fiberglass cross-arm assembly. The loops are ¼-λ per side (one full wavelength overall). One loop is driven and the other serves as a parasitic element — usually a reflector. The design of the quad is similar to that of the Yagi, except that the elements are loops instead of dipoles. A two-element quad can achieve better F/R, gain and SWR across a band, at the expense of greater mechanical complexity compared to a two-element Yagi and very nearly the same performance as a three-element Yagi. A type of Yagi called the *quagi* has also been constructed with a quad element as the driven element. The larger quad driven element results in somewhat better SWR bandwidth, but gain and F/B are approximately the same as on regular Yagi antennas.

A variation of the quad is called the *delta loop*. The electrical properties of both antennas are the same. Both antennas are shown in **Fig 21.77**. They differ mainly in their physical properties, one being of plumber's delight construction, while the other uses insulating support members. One or more directors can be added to either antenna if additional gain and directivity are desired, though most operators use the two-element arrangement.

It is possible to interlace quads or deltas for two or more bands, but if this is done the lengths calculated using the formulas given in Fig 21.77 may have to be changed slightly to compensate for the proximity effect of the second antenna. Using a tuning capacitor as shown in the following project allows the antenna to be adjusted for peak performance without cumbersome adjustment of wire lengths.

If multiple arrays are used, each antenna should be tuned separately for maximum forward gain, or best front-to-rear ratio, as observed on a field-strength meter. The reflector stub on the quad should be adjusted for this condition. The resonance of the antenna can be found by checking the frequency at which the lowest SWR occurs. By lengthening or shortening it, the driven element length can be adjusted for resonance in the most-used portion of the band.

A gamma match can be used at the feed point of the driven element to match the impedance to that of coaxial cable. Because the loop's feed point impedance is *higher* than that of 50-Ω coaxial cable, a *synchronous transmission line transformer* or *Q-section* (see the **Transmission Lines** chapter) with an impedance intermediate to that of the loop and the coaxial cable can be used.

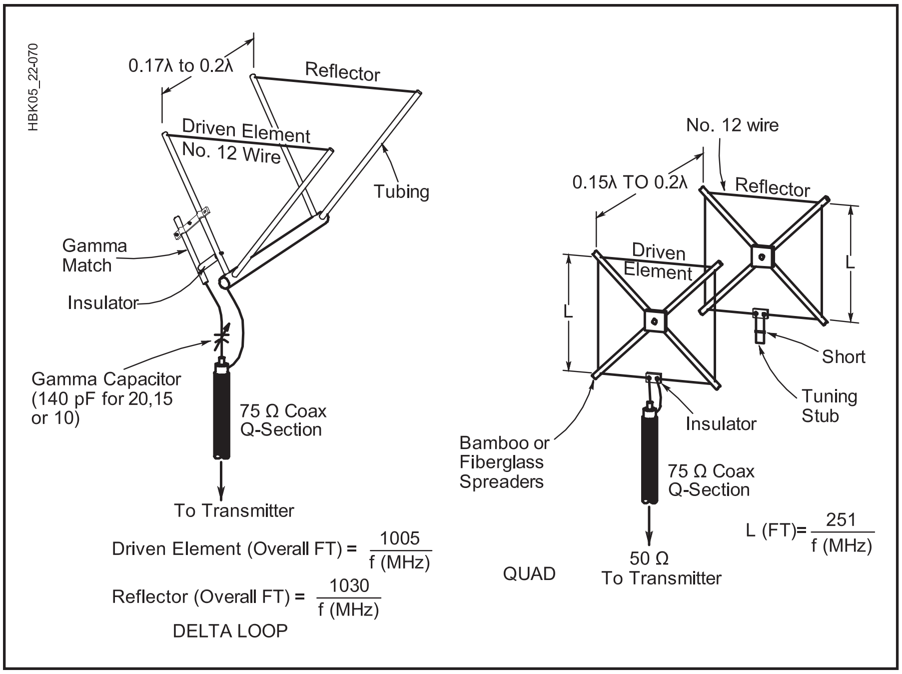


Fig 21.77 — Information on building a quad or a delta-loop antenna. The antennas are electrically similar, but the delta-loop uses plumber's delight construction. The λ/4 length of 75-Ω coax acts as a synchronous transmission-line transformer from approximate 100-Ω feed point impedance of quad to the 50-Ω feed line.

Project: Five-Band, Two-Element HF Quad

Two quad designs are described in this article, both nearly identical. One was constructed by KC6T from scratch, and the other was built by Al Doig, W6NBH, using modified commercial triband quad hardware. The principles of construction and adjustment are the same for both models, and the performance results are also essentially identical. One of the main advantages of this design is the ease of (relatively) independent performance adjustments for each of the five bands. These quads were described by William A. Stein, KC6T, in *QST* for April 1992. Both models use 8-ft-long, 2-inch diameter booms, and conventional X-shaped spreaders (with two sides of each quad loop parallel to the ground).

These designs can also be simplified to monoband quads by using the formulas in Fig 21.77 for loop dimensions and spacing. It is recommended to the antenna builder unfamiliar with quads that a monoband quad be attempted first in order to become acquainted with the techniques of building a quad. Once comfortable with constructing and erecting the quad, success with a multiband design is much easier to achieve.

THE FIVE-BAND QUAD AS A SYSTEM

Unless you are extraordinarily lucky, you should remember one general rule: Any quad must be adjusted for maximum performance after assembly. Simple quad designs can be tuned by pruning and restringing the elements to control front-to-rear ratio and SWR at the desired operating frequency. Since each element of this quad contains five concentric loops, this adjustment method could lead to a nervous breakdown!

Fig 21.78 shows that the reflectors and

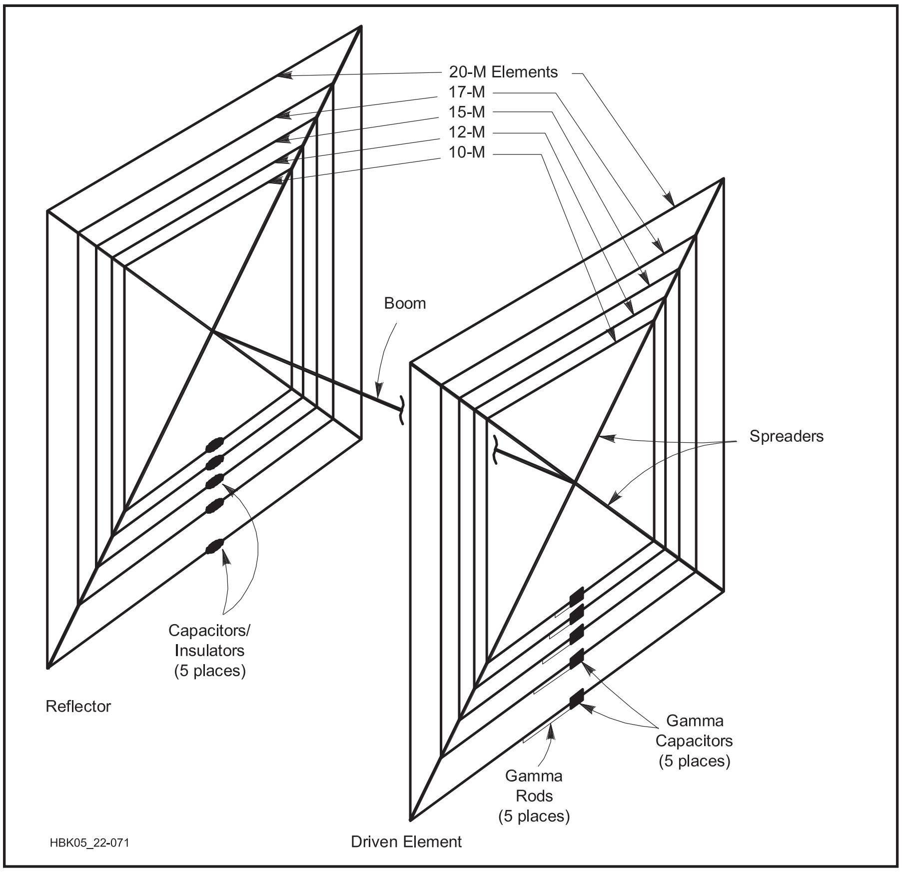


Fig 21.78 — Mechanical layout of the five-band quad. The boom is 8 ft long; see Table 21.16 for all other dimensions.

driven elements are each independently adjustable. After assembly, adjustment is simple, and although gamma-match components on the driven element and capacitors on the reflectors add to the antenna's parts count, physical construction is not difficult. The reflector elements are purposely cut slightly long (except for the 10 meter reflector), and electrically shortened by a tuning capacitor. The driven-element gamma matches set the lowest SWR at the desired operating frequency.

As with most multiband directive antennas, the designer can optimize any two of the following three attributes at the expense of the third: forward gain, front-to-rear ratio and bandwidth (where the SWR is less than 2:1). These three characteristics are related, and changing one changes the other two. The basic idea behind this quad design is to permit (without resorting to trimming loop lengths, spacing or other gross mechanical adjustments):

- The forward gain, bandwidth and front-to-rear ratio may be set by a simple adjustment after assembly. The adjustments can be made on a band-by-band basis, with little or no effect on previously made adjustments on the other bands.
- Setting the minimum SWR in any portion of each band, with no interaction with previously made front-to-back or SWR adjustments.

The first of the two antennas described, the KC6T model, uses aluminum spreaders with PVC insulators at the element attachment points. (The author elected not to use fiberglass spreaders because of their high cost.) The second antenna, the W6NBH model, provides dimensions and adjustment values for the same antenna, but using standard tri-band quad fiberglass spreaders and hardware. If you have a tri-band quad, you can easily adapt it to this design. When W6NBH built his antenna, he had to shorten the 20 meter reflector because the KC6T model uses a larger 20 meter reflector than W6NBH's fiberglass spreaders would allow. Performance is essentially identical for both models.

MECHANICAL CONSIDERATIONS

Even the best electrical design has no value if its mechanical construction is lacking. Here are some of the things that contribute to mechanical strength: The gamma-match capacitor KC6T used was a small, air-variable, chassis-mount capacitor mounted in a plastic box (see **Fig 21.79**). A male UHF connector was mounted to the box, along with a screw terminal for connection to the gamma rod. The terminal lug and wire are for later connection to the driven element. The box came from a local hobby shop, and the box lid was replaced with a piece of 1/32-inch ABS plastic, glued in place after the capacitor, connector and wiring had been installed. The capacitor can be adjusted with a screwdriver through an access hole. Small vent (drain) holes were drilled near corresponding corners of each end.

Enclose the gamma-match capacitor in such a manner that you can tape unwanted openings closed so that moisture can't be directly blown in during wind and rainstorms. Also, smaller boxes and sturdy mounts to the driven element ensure that you won't pick up gamma capacitor assemblies along with the leaves after a wind storm.

Plastic gamma-rod insulators/standoffs were made from 1/32-inch ABS, cut ½-inch wide with a hole at each end. Use a knife to cut from the hole to the side of each insulator so that one end can be slipped over the driven element and the other over the gamma rod. Use about four such insulators for each gamma rod, and mount the first insulator as close to the capacitor box as possible. Apply five-minute epoxy to the element and gamma rod at the insulator hole to keep the insulators from sliding. If you intend to experiment with gamma-rod length, perform this gluing operation after you have made the final gamma-rod adjustments.

ELEMENT INSULATORS

As shown in Fig 21.78, the quad uses insulators in the reflectors for each band to break the loop electrically, and to allow reflector adjustments. Similar insulators were used to

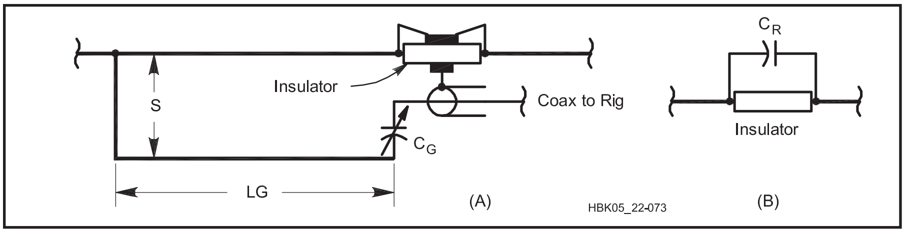


Fig 21.80 — Gamma-match construction details at A and reflector-tuning capacitor (CR) attachment schematic at B. The gamma matches consist of matching wires (one per band) with series capacitors (Cg). See Table 21.16 for lengths and component specifications.

Table 21.16
Element Lengths and Gamma-Match Specifications of the KC6T and W6NBH Five-Band Quads

KC6T Model

	Driven	*------Gamma Match-----*			*Reflector*	
Band (MHz)	*Element Length (in)*	*Length (in)*	*Spacing (in)*	C_g *(pF)*	*Length (in)*	C_R *(pF)*
14	851.2	33	2	125	902.4	68
18	665.6	24	2	110	705.6	47
21	568	24	1.5	90	604.8	43
24.9	483.2	29.75	1	56	514.4	33
28	421.6	26.5	1	52	448.8	(jumper)

W6NBH Model

	Driven	*-----Gamma Match------*			*Reflector*	
Band (MHz)	*Element Length (in)*	*Length (in)*	*Spacing (in)*	C_g *(pF)*	*Length (in)*	C_R *(pF)*
14	851.2	31	2	117	890.4	120
18	665.6	21	2	114	705.6	56
21	568	26	1.5	69	604.8	58
24.9	483.2	15	1	75.5	514.4	54
28	421.6	18	1	41	448.8	(jumper)

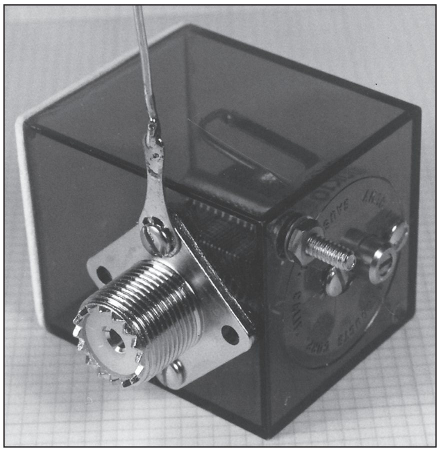


Fig 21.79 — Photo of one of the feed point gamma-match capacitors.

break up each driven element so that element impedance measurements could be made with a noise bridge. After the impedance measurements, the driven-element loops are closed again. The insulators are made from ¼ × 2 × ¾-inch phenolic stock. The holes are ½-inch apart. Two terminal lugs (shorted together at the center hole) are used in each driven element. They offer a convenient way to open the loops by removing one screw. **Fig 21.80** shows these insulators and the gamma-match construction schematically. **Table 21.16** lists the component values, element lengths and gamma-match dimensions.

ELEMENT-TO-SPREADER ATTACHMENT

Probably the most common problem with quad antennas is wire breakage at the element-to-spreader attachment points. There are a number of functional attachment methods; **Fig 21.81** shows one of them. The attachment method with both KC6T and W6NBH spreaders is the same, even though the spreader constructions differ. The KC6T model uses #14 AWG, 7-strand copper wire; W6NBH used #18 AWG, 7-strand wire. At the point of element attachment (see **Fig 21.82**), drill a hole through both walls of the spreader using a #44 (0.086-inch) drill. Feed a 24-inch-long piece of antenna wire through the hole and center it for use as an attachment wire.

After fabricating the spider/spreader assembly, lay the completed assembly on a flat surface and cut the element to be installed to the correct length, starting with the 10 meter element. Attach the element ends to the insulators to form a closed loop before attaching the elements to the spreaders. Center the insulator between the spreaders on what will become the bottom side of the quad loop, then carefully measure and mark the element-mounting-points with fingernail polish (or a similar substance). Do *not* depend on the at-rest position of the spreaders to guarantee that the mounting points will all be correct.

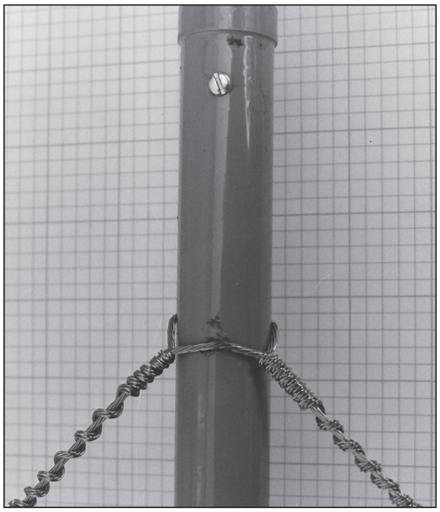
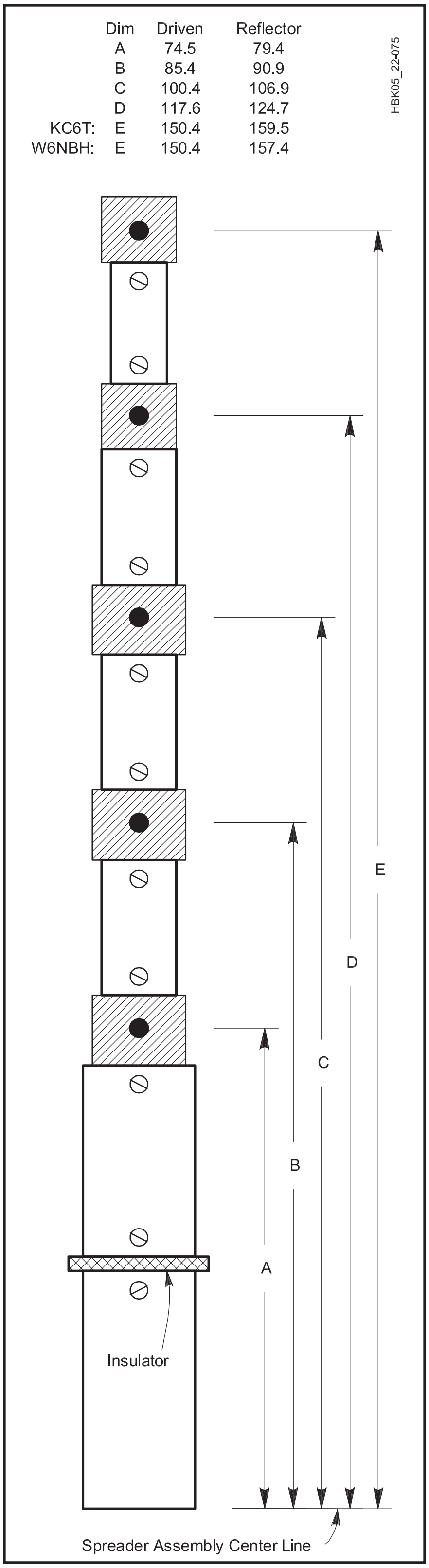


Fig 21.81 — Attaching quad wires to the spreaders must minimize stress on the wires for best reliability. This method (described in the text) cuts the chances of wind-induced wire breakage by distributing stress.



	Dim	Driven	Reflector
	A	74.5	79.4
	B	85.4	90.9
	C	100.4	106.9
	D	117.6	124.7
KC6T:	E	150.4	159.5
W6NBH:	E	150.4	157.4

Fig 21.82 — Spreader-drilling diagram and dimensions (in.) for the five-band quad. These dimensions apply to both spreader designs described in the text, except that most commercial spreaders are only a bit over 13 ft (156 inches) long. This requires compensation for the W6NBH model's shorter 20 meter reflector as described in the text.

Holding the mark at the centerline of the spreader, tightly loop the attachment wire around the element and then gradually space out the attachment-wire turns as shown. The attachment wire need not be soldered to the element. The graduated turn spacing minimizes the likelihood that the element wire will flex in the same place with each gust of wind, thus reducing fatigue-induced wire breakage.

FEEDING THE DRIVEN ELEMENTS

Each driven element is fed separately, but feeding five separate feed lines down the tower and into the shack would be costly and mechanically difficult. The ends of each of these coax lines also require support other than the tension (or lack of thereof) provided by the driven element at the feed point. It is best to use a remote coax switch on the boom approximately 1 ft from the driven-element spider-assembly attachment point.

If the gamma match is used, the cables connecting the gamma-match capacitors and the coax switch help support the driven elements and gamma capacitors. The support can be improved by taping the cables together in several places. A single coaxial feed line (and a control cable from the remote coax switch, if yours requires one) is the only required cabling from the antenna to the shack.

If the synchronous transmission line transformer is used, the ¼-wavelength of cable required is of convenient lengths that allow a remote antenna switch to be mounted on the antenna boom and the matching sections connected between the switch and driven elements. The drawback of the matching section technique is that it is not easily adjustable.

THE KC6T MODEL'S COMPOSITE SPREADERS

If you live in an area with little or no wind, spreaders made from wood or PVC are practical, but if you live where winds can reach 60 to 80 mi/h, strong, lightweight spreaders are a must. Spreaders constructed with electrical conductors (in this case, aluminum tubing) can cause a myriad of problems with unwanted resonances, and the problem gets worse as the number of bands increases.

To avoid these problems, this version uses composite spreaders made from machined PVC insulators at the element-attachment points. Aluminum tubing is inserted into (or over) the insulators 2 inches on each end. This spreader is designed to withstand 80 mi/h winds. The overall insulator length is designed to provide a 3-inch center insulator clear of the aluminum tubing. The aluminum tubing used for the 10 meter section (inside dimension "A" in Fig 21.82) is 1⅛-inch diameter × 0.058-inch wall. The next three sections are ¾-inch diameter × 0.035-inch wall, and the outer length is made from ½-inch diameter × 0.035-inch wall. The dimensions shown in Fig 21.82 are *attachment point* dimensions only.

Attach the insulators to the aluminum using #6 sheet metal screws. Mechanical strength is provided by Devcon no. S 220 Plastic Welder Glue (or equivalent) applied liberally as the aluminum and plastic parts are joined. Paint the PVC insulators before mounting the elements to them. Paint protects the PVC from the harmful effects of solar radiation. As you can see from Fig 21.82, an additional spreader insulator located about halfway up the 10 meter section (inside dimension "A") removes one of the structure's electrical resonances not eliminated by the attachment-point insulators. Because it mounts at a relatively high-stress point in the spreader, this insulator is fabricated from a length of heavy-wall fiberglass tubing.

Composite spreaders work as well as fiberglass spreaders, but require access to a well-equipped shop, including a lathe. The main objective of presenting the composite spreader is to show that fiberglass spreaders aren't a basic requirement — there are many other ways to construct usable spreaders. If you can lay your hands on a used multiband quad, even one that's damaged, you can probably obtain enough spreaders to reduce construction costs considerably.

GAMMA ROD

The gamma rod is made from a length of #12 AWG solid copper wire (W6NBH used #18 AWG, 7-strand wire). Dimensions and spacings are shown in Table 21.16. If you intend to experiment with gamma-rod lengths and capacitor settings, cut the gamma-rod lengths about 12 inches longer than the length listed in the table. Fabricate a sliding short by soldering two small alligator clips back-to-back such that they can be clipped to the rod and the antenna element and easily moved along the driven element. Note that gamma-rod spacing varies from one band to another. When you find a suitable shorting-clip position, mark the gamma rod, remove the clip, bend the gamma rod at the mark and solder the end to the element.

THE W6NBH MODEL

As previously mentioned, this model uses standard 13-ft fiberglass spreaders, which aren't quite long enough to support the larger 20 meter reflector specified for the KC6T model. The 20 meter W6NBH reflector loop is cut to the dimensions shown in Table 21.16, 12 inches shorter than that for the KC6T model. To tune the shorter reflector, a six-inch-long stub of antenna wire (conductors spaced two inches) hangs from the reflector insulator, and the reflector tuning capacitor mounts on another insulator at the end of this stub.

GAMMA-MATCH AND REFLECTOR-TUNING CAPACITOR

Use an air-variable capacitor of your choice for each gamma match. Approximately 300 V can appear across this capacitor (at 1500 W), so choose plate spacing appropriately. If you want to adjust the capacitor for best match and then replace it with a fixed capacitance, remember that several amperes of RF will flow through the capacitance. If you choose disc-ceramic capacitors, use a parallel combination of at least four l-kV units of equal value. Any temperature coefficient is acceptable. NP0 units are not required. Use similar components to tune the reflector elements.

ADJUSTMENTS

Well, here you are with about 605 ft of wire. Your antenna will weigh about 45 pounds (the W6NBH version is slightly lighter) and have about nine square ft of wind area. If you chose to, you can use the dimensions and capacitance values given, and performance should be excellent. If you adjust the antenna for minimum SWR at the band centers, it should cover all of the lower four bands and 28 to 29 MHz with SWRs under 2:1; front-to-back ratios are given in **Table 21.17**.

Instead of building the quad to the dimensions listed and hoping for the best, you can adjust your antenna to account for most of the electrical environment variables of your installation. The adjustments are conceptually simple: First adjust the reflector's electrical length for maximum front-to-rear ratio (if you desire good gain, and are willing to settle for a narrower than maximum SWR bandwidth), or accept some compromise in front-to-rear ratio that results in the widest SWR bandwidth. You can make this adjustment by placing an air-variable capacitor (about 100-pF maximum) across the open reflector loop ends, one band at a time, and adjusting the capacitor for the desired front-to-rear ratio. The means of doing this will be discussed later.

Table 21.17
Measured Front-to-Back Ratios

Band	*KC6T Model*	*W6NBH Model*
14	25 dB	16 dB
18	15 dB	10 dB
21	25 dB	>20 dB
24.9	20 dB	>20 dB
28	20 dB	>20 dB

During these reflector adjustments, the driven-element gamma-match capacitors may be set to any value and the gamma rods may be any convenient length (but the sliding-short alligator clips should be installed somewhere near the lengths specified in Table 21.16). After completing the front-to-rear adjustments, the gamma capacitors and rods are adjusted for minimum SWR at the desired frequency.

ADJUSTMENT SPECIFICS

Make a calibrated variable capacitor (with a hand-drawn scale and wire pointer). Calibrate the capacitor using your receiver, a known-value inductor and a grid-dip meter (plus a little calculation) or SWR analyzer.

Adjust each band by feeding it separately if the gamma match technique is used. If transmission line matching sections are used, they must all be connected to the remote switch when adjusting the antenna because each unused section acts as a short coaxial stub, adding reactance at the connection to the antenna.

To adjust front-to-back ratio, simply clip the (calibrated) air-variable capacitor across the open ends of the desired reflector loop. Connect the antenna to a portable receiver with an S meter. Point the back of the quad at a signal source, and slowly adjust the capacitor for a dip in the S-meter reading.

After completing the front-to-back adjustments, replace the variable capacitor with an appropriate fixed capacitor and seal the connections against the weather. Then move to the driven-element adjustments. Connect the coax through the SWR bridge to the 10 meter gamma-match capacitor box. Use an SWR bridge that requires only a watt or two (not more than 10 W) for full-scale deflection in the calibrate position on 10 meters. Using the minimum necessary power, measure the SWR. Go back to receive and adjust the capacitor until (after a number of transmit/receive cycles) you find the minimum SWR. If it is too high, lengthen or shorten the gamma rod by means of the sliding alligator-clip short and make the measurements again.

Stand away from the antenna when making transmitter-on measurements. The adjustments have minimal effect on the previously made front-to-rear settings, and may be made in any band order. After making all the adjustments and sealing the gamma capacitors, reconnect the coax harness to the remote coax switch.

Adjusting the SWR when using transmission-line matching sections requires first measuring the impedance of each loop at the feed point. To avoid standing next to the antenna while making the measurement, connect the test equipment to the antenna using a ½-λ piece of transmission line of any characteristic impedance. Cut a ¼-λ section of transmission line with an appropriate impedance a few percent longer than the exact value. Attach the matching section to the loop feed point. Measure the resulting impedance at the output of the matching section and trim its length to place the minimum SWR point at the desired frequency. Using this technique, it is not likely that an SWR of 1:1 can be obtained, but values below 1.5:1 should be attainable.

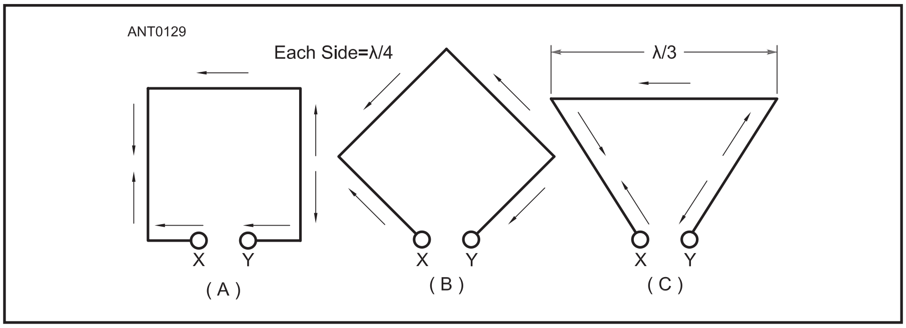


Fig 21.83 — At A and B, loops have sides ¼-λ long , and at C having sides 1/3-λ long for a total conductor length of 1 λ. The polarization depends on the orientation of the loop and on the position of the feed point (terminals X-Y) around the perimeter of the loop.

21.7.1 Loop Antennas

The loop antennas described in this section are continuous loops at least one wavelength in circumference and formed into open shapes with sides that are approximately equal, such as triangles, diamonds, squares, or circles. Smaller loops used for receiving purposes are discussed in the *ARRL Antenna Book*. Loops with ratios of side lengths greater than 2 or 3:1 begin to have special characteristics beyond the scope of this chapter.

A 1-λ loop can be thought of as two ½-λ dipoles with their ends connected together and pulled apart into an open shape as described above. The feed point of one dipole is replaced with a short circuit so that there is only one feed point on the antenna. As such, the current and voltage distribution around the loop is an extension of Fig 21.1. Three typical loop shapes and the current distributions on them are shown in **Fig 21.83**. Note that the current flow reverses at points ¼-λ to either side of the feed point. That means the current direction opposite the feed point is the same as at the feed point.

The maximum radiation strength of a 1-λ loop is perpendicular to the plane of the loop and minimum in the plane of the loop. If the loop is horizontal, the antenna radiates best straight up and straight down and poorly to the sides. The gain of a 1-λ loop in the direction of maximum radiation is approximately 1 dBd.

If the plane of the three loops shown in Fig 21.83 is vertical, the radiation is horizontally polarized because the fields radiated by the vertical components of current are symmetrical and opposing, so they cancel, leaving only the horizontally polarized fields that reinforce each other perpendicular to the loop plane. If the feed point of the antenna is moved to a vertical side or the antenna is rotated 90°, it is the horizontally polarized fields that will cancel, leaving a vertically polarized field, still maximum perpendicular to the plane of the loop. Feeding the loop at some other location, rotating the loop by some intermediate value, or constructing the loop in an asymmetrical shape will result in polarization somewhere between vertical and horizontal, but the maximum radiation will still occur perpendicular to the plane of the loop.

In contrast to straight-wire antennas, the electrical length of the circumference of a 1-λ loop is shorter than the actual length. For a loop made of bare #18 AWG wire and operating at a frequency of 14 MHz, so that the length-to-diameter ratio is very large, the loop will be close to resonance in free space when:

$$\text{Length (feet)} = \frac{1032}{\text{f (MHz)}} \qquad (7)$$

The radiation resistance of a resonant 1-λ loop is approximately 120 Ω under these conditions. Since the loop dimensions are larger than those of a ½-Ω dipole, the radiation efficiency is high and the SWR bandwidth of the antenna significantly larger than for the dipole.

The loop antenna is resonant on all frequencies at which it is an integral number of wavelengths in circumference; f_0, $2f_0$, $3f_0$, etc. That means an 80-meter 1-λ loop will also have a relatively low feed point impedance on 40, 30, 20, 15, 12, and 10 meters. As each side of the loop becomes longer electrically, the radiation pattern of the loop begins to develop nulls perpendicular to the plane of the loop and lobes that are closer to the plane of the loop. A horizontal diamond-shaped loop with legs more than a wavelength long is a *rhombic* antenna and can develop significant gain along the long axis of the antenna. (The diamond-shaped rhombic is the origin of the symbol of the ARRL and many other radio organizations.)

Project: Low-Band Quad and Delta Loops

(The following material is summarized from Chapter 10 of *ON4UN's Low-Band DXing, Fifth Edition*.) Dimensions for these designs assume an operating frequency of 3.75 MHz. The dimensions for the loops in this section may be scaled to frequencies in the 160, 60, 40 or 30 meter bands. The performance of the loops will vary with height above ground and ground conductivity.

SQUARE LOOP

Fig 21.84 shows the vertical-plane radiation patterns for a quad loop over very poor ground and over very good ground on the same dB scale for both horizontal and vertical polarization. Polarization of the loop depends on the location of the feed point as shown in the figure.

The vertically polarized quad loop can be considered as two shortened top-loaded vertical dipoles, spaced ¼-λ apart. Broadside radiation from the horizontal elements of the quad is very low because the currents in the horizontal legs are approximately equal but in opposite directions in each half of the leg. The radiation angle in the broadside direction will be essentially the same as for either of the vertical members.

The resulting radiation angle will depend on the quality of the ground up to several wavelengths away from the antenna, as is the case with all vertically polarized antennas. The quality of the ground is as important as it is for any other vertical antenna, meaning that vertically polarized loops close to the ground will not work well over poor soil. In a typical situation on 80 meters, a vertically-polarized quad loop will radiate an excellent low-angle signal (lobe peak at approximately 21°) when operated over average ground. Over poorer ground, the peak elevation angle would be closer to 30°. The horizontal directivity is rather poor and amounts to approximately 3.3 dB of side rejection at any elevation angle.

A horizontally polarized quad-loop antenna can be thought of as two stacked short dipoles with a peak elevation angle dependent on the height of the loop. The low horizontally polarized quad (top at 0.3 λ) radiates most of its energy right at or near zenith angle (straight up). At low wave angles (20° to 45°) the horizontally polarized loop shows more front-to-side ratio (5 to 10 dB) than the vertically polarized rectangular loop.

With a horizontally polarized quad loop the angle of peak radiation is very dependent

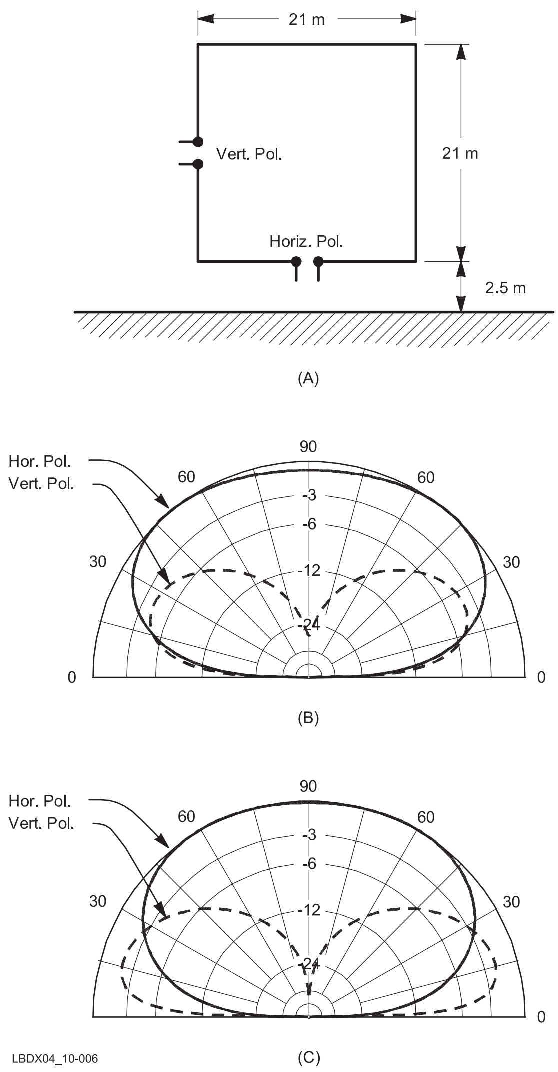


Fig 21.84 — Superimposed patterns for horizontally and vertically polarized square quad loops (shown at A) over very poor ground (B) and very good ground (C). In the vertical polarization mode the ground quality has a large effect on antenna performance as it does with all vertically-polarized antennas.

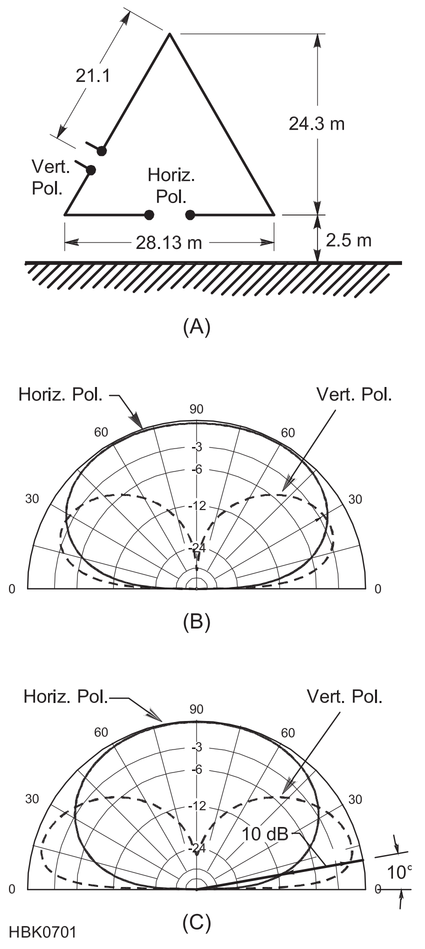


Fig 21.85 — Superimposed patterns for horizontally and vertically polarized delta quad loops (shown at A) over very poor ground (B) and very good ground (C). Over better ground, the vertically polarized loop performs much better at low radiation angles, while of both good and poor ground the vertically polarized loop gives good discrimination against high-angle local signals.

on the antenna height but not so much on the quality of the ground. At very low heights, the angle of peak radiation varies between 50° and 60° (but is rather constant all the way up to 90°). This is very good for NVIS and regional communication but not very good for DX. As far as gain is concerned, there is a 2.5-dB gain difference between very good and very poor ground, which is only half the difference found with the vertically polarized loop.

Comparing the gains of the horizontally and vertically polarized loops, Fig 21.84 shows that at very low antenna heights the gain is about 3 dB better for the horizontally polarized loop. But this gain exists at a high wave angle (50° to 90°) while the vertically polarized loop at very low heights radiates at 17° to 25°.

At heights from 3 to 6 meters for the bottom leg, feed point resistance for the horizontally polarized loop is approximately 100 to 120 Ω over average ground. For vertical polarization, feed point resistance varies from 200 to 170 Ω.

The quad loop feed point is symmetrical, whether you feed the quad in the middle of the vertical or the horizontal wire. At the feed point, use a common-mode choke balun (see the Transmission Lines chapter) as current flowing on the outside of the coaxial feed line could upset the radiation pattern.

DELTA LOOP

Fig 21.85 shows the configuration as well as the superimposed elevation patterns for vertically and horizontally polarized low-height equilateral triangle delta loops over two different types of ground (same dB scale). The model was constructed for a frequency of 3.75 MHz. The base is 2.5 meters above ground, which puts the apex at 26.8 meters. Over good ground, the vertically polarized delta loop shows nearly 3 dB front-to-side ratio at the peak radiation angle of 22°. With average ground the gain is 1.3 dBi.

Over very poor ground, the horizontally polarized delta loop is better than the vertically polarized loop for all wave angles above 35°. Below 35° the vertically polarized loop takes over, but quite marginally. The maximum gain of the vertically and the horizontally polarized loops differs by only 2 dB but the big difference is that for the horizontally polarized loop, the gain occurs at almost 90°, while for the vertically polarized loop it occurs at 25°. The vertically polarized antenna also gives good high-angle rejection (rejection of local signals), while the horizontally polarized loop will not.

Over very good ground, the performance at low angles is greatly improved for both polarizations. The vertically polarized loop is still better at any elevation angle under 30° than when horizontally polarized. At a 10°

radiation angle the difference is as high as 10 dB. This makes the vertically polarized delta over good ground far superior for DX operating.

Most practical delta loops show a feed point impedance between 50 and 100 Ω, depending on the exact geometry and coupling to other antennas. The antenna can be fed directly with a 50 or 70-Ω coaxial cable, or via a 70-Ω quarter-wave transformer (see the Transmission Lines chapter) if the feed point impedance is near 100 Ω. At the feed point, use a common-mode choke balun (see the Transmission Lines chapter) as current flowing on the outside of the coaxial feed line could upset the radiation pattern.

THE BOTTOM-CORNER-FED DELTA LOOP

Fig 21.86 shows the layout of the delta loop being fed at one of the two bottom corners. The antenna is slightly compressed from the previous section with a slightly lower apex and longer base than the loop described in the previous section. Because of the "incorrect" location of the feed point, cancellation of radiation from the base wire is incomplete, resulting in a significant horizontally polarized radiation component. The total field has a very uniform gain coverage (within 1 dB) from 25° to 90°. This may be a disadvantage for the rejection of high-angle signals when working DX at low angles.

Due to the "incorrect" feed-point location, the end-fire radiation (radiation in line with the loop) has become asymmetrical with a side null of nearly 12 dB at the peak radiation angle of 29°. The loop actually radiates its maximum signal about 18° off the broadside direction. This feed point configuration greatly affects the pattern of the loop so use bottom-corner-feed with care.

Project: **Two-Band Loop for 30 and 40 Meters**

The following antenna design is from a *QST* Hints and Kinks entry by James Brenner, NT4B, in the May 1989 issue. The version shown in **Fig 21.87** is fed at the apex of a delta loop but can be adapted to a square or quad loop shape.

The original design was derived from "The Mini X-Q Loop" in *All About Cubical Quad Antennas* by Bill Orr, W6SAI (now out of print) which is 1½ λ in circumference, with an open circuit opposite the feed point. That antenna has approximately 1 dB of additional gain over a 1-λ loop. Since 30 and 40 meters are close to the same 1:1½-λ ratio, one loop

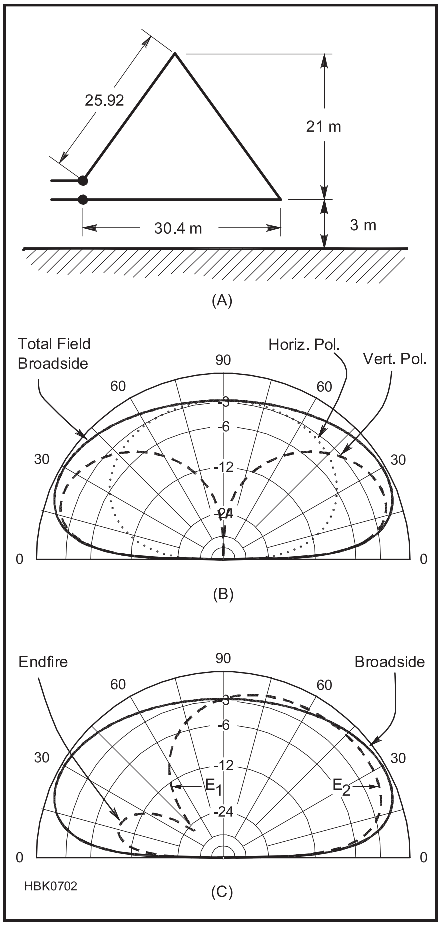


Fig 21.86 — Configuration and radiation patterns for the delta loop when fed in one of the bottom corners at a frequency of 3.75 MHz. Incomplete cancellation of radiation from the horizontal wire produces a strong high-angle horizontally polarized component. The antenna also shows horizontal directivity that varies strongly with vertical radiation angle.

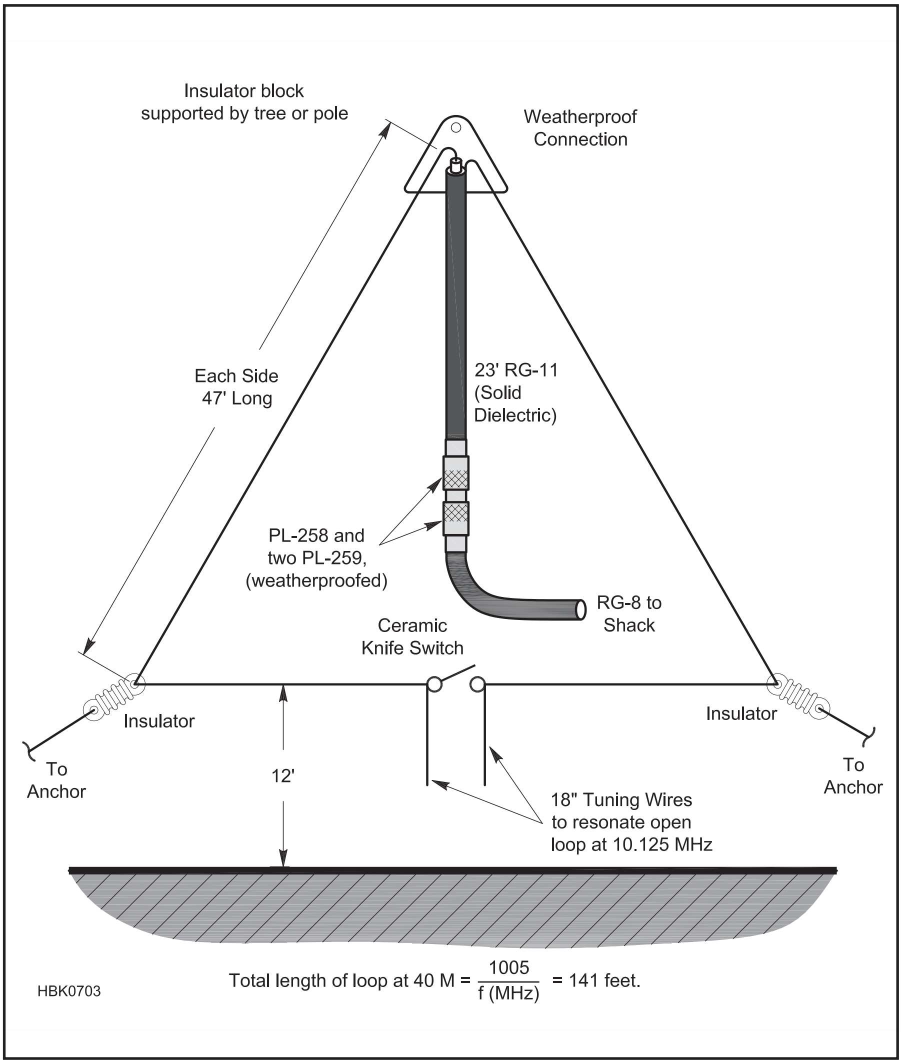


Fig 21.87 — NT4B's 30 and 40 meter loop is fed at the top via a quarter-wave 40 meter matching transformer made of 75-Ω coax. Note the 18-inch tuning wires used to lower the antenna's 30 meter resonance from 10.5 to 10.1 MHz. Adjust the length of these wires to set the 30 meter resonant frequency.

can be converted between 1 λ on 40 meters and 1½ λ on 30 meters with a switch.

A large, ceramic SPST knife switch is installed in the center of the delta loop's bottom leg as shown in Fig 21.87. With the switch open, the loop acts a 1½-λ loop at 10.5 MHz, so 18-inch wires were added to the loop on either side of the switch to lengthen the antenna and lower the resonant frequency to 10.1 MHz. Closing the switch shorts out the wires and the loop becomes a regular 1-λ continuous loop for 40 meters.

Note that there is fairly high voltage present at the switch when transmitting on 30 meters. If a relay is used, be sure the contact spacing is sufficient to avoid arcing or use additional pairs of contacts to increase the overall spacing.

The antenna is fed through a quarter-wave transformer (see the Transmission Lines chapter) of 75-Ω RG-11 coax, approximately 23 feet long. According to the author, when configured for 40 meters, the loop has a satisfactory SWR of less than 2:1 on 15 meters. In addition, the 30 meter configuration can be used successfully on 80 meters with the use of an antenna tuner.

Project: Skeleton Slot for 14-30 MHz

(The following material is adapted from the RSGB *Radio Communications Handbook, 11th Edition*.) The Skeleton Slot is a loop antenna that was first documented in an article by G2HCG in 1953. With the dimensions shown, it will operate on the HF bands from 14 to 28 MHz using a balanced feed line and antenna tuner. It is very easy to construct and has no traps or critical adjustments. The turning radius is 1.5 meters (5 feet) even though it is 14 meters (47 feet) tall. The antenna radiation pattern is bidirectional, perpendicular to the plane of the loop, and horizontally polarized with a gain of approximately 8 dBi on 14 MHz, increasing to 11 dBi on 28 MHz. The design can be scaled to the VHF bands, as well.

This version of the antenna uses wire for the vertical elements, resulting in a simplified and rugged construction as shown in **Fig 21.88**. The structure of the antenna is

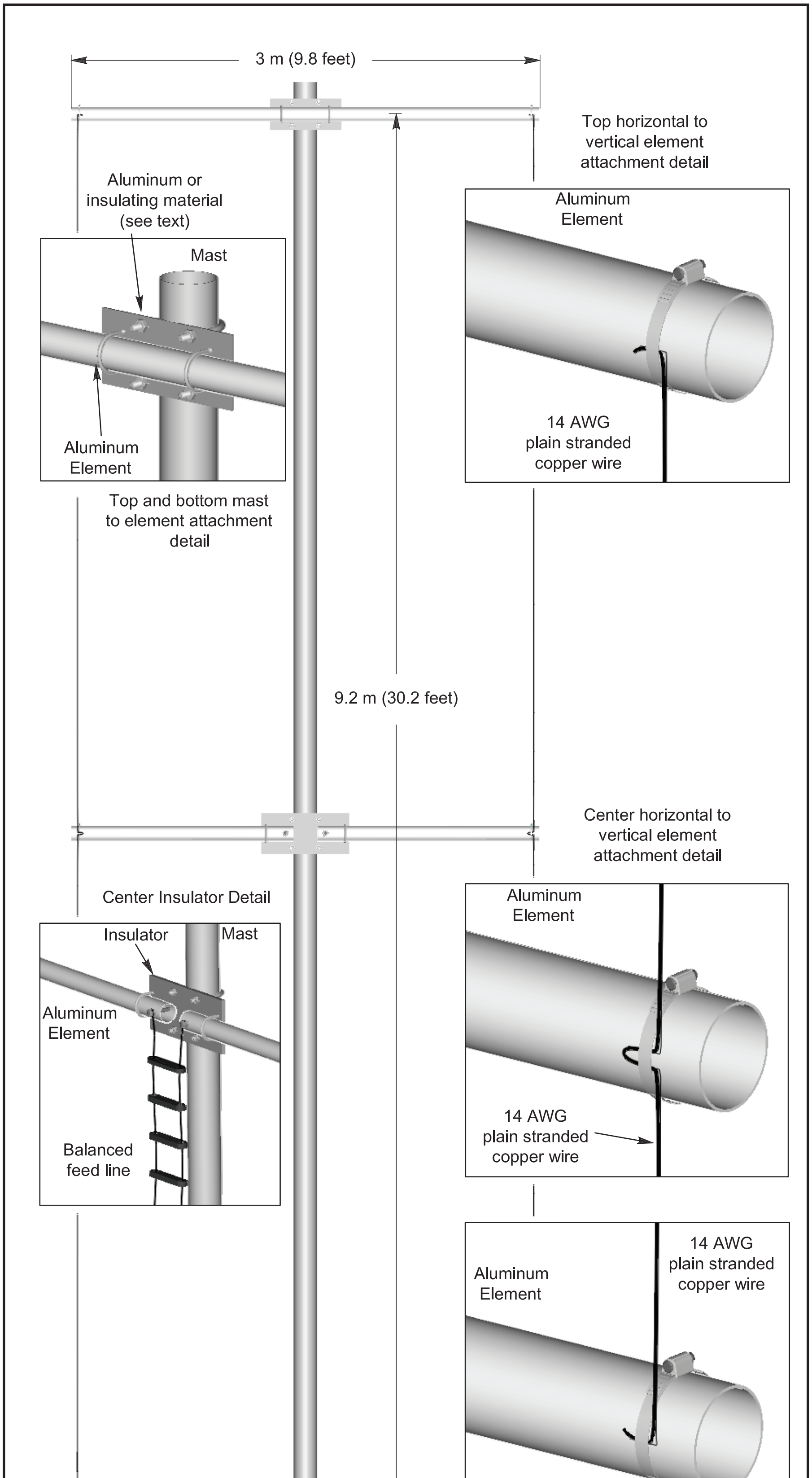


Fig 21.88 — The G3LDO multiband Skeleton Slot antenna for 15 to 28 MHz. The elements are attached to the mast and the whole mast is rotated. The wire elements are fixed to the horizontal elements with stainless steel hose clamps. The center insulator can be homebrewed from plastic sheet or a commercial unit may be used.

provided by three aluminum tube elements attached to a central mast at 15 foot intervals with the lowest element 15 feet above the ground. The mast is electrically connected to the supporting elements, just as Yagi elements are electrically connected to a supporting boom. The mast may be grounded without affecting antenna performance. A non-conductive mast may also be used or the elements insulated from a conductive mast without affecting the antenna performance.

The center element is fed in the center with connecting wires attached from the end of the center element to the upper and lower elements as shown in Fig 21.88. Stainless steel hose clamps are used to attach the wire and aluminum. Use an anti-oxidation compound such as Penetrox or Noalox to prevent corrosion from the contact between dissimilar metals.

The antenna requires a balanced feed line such as 450-Ω window line or 300-Ω twin-lead. The impedance and length of the feed line are not critical. Use standoffs to hold the feed line away from the mast and elements until clear of the antenna. Alternatively, a 9:1 impedance transformer at the feed point may be used with coaxial cable. A choke balun to decouple the coaxial feed line's outer surface from the antenna should also be used at the feed point. (See the Transmission Lines chapter.)

Project: Multiband Horizontal Loop Antenna

Along with the multiband, non-resonant dipole, many amateurs operate on HF with great success using a horizontal loop antenna. All that is required are at least three supports able to hold the corners of the antenna 20 or more feet above the ground (and even that is negotiable) and enough room for a loop of wire one wavelength or more in circumference at the lowest frequency of operation. (Smaller loops can be used with an impedance-matching unit.)

Start by calculating the total length of wire you need using Equation 7. You'll need one insulator for each support and lengths of rope that are at least twice the height to which the insulator will be raised. You can feed the antenna at one of the corner insulators or anywhere along the wire with a separate insulator. Examples of corner insulators are shown in **Fig 21.89**. Using floating insulators allows the wire to move as the antenna flexes. One of the insulators should be of the fixed type, or the antenna can be fed at one corner with the loop wires attached to a pair of insulators sharing a common support rope. This holds the antenna feed point in place.

If the loop is only going to be used on the band for which it is resonant, coaxial cable can be used as the feed line, since SWR will be low. A choke balun at the feed point is recommended. For multiband use, open-wire feed line should be used, with an impedance-matching unit in the shack. A feed point insulator for open-wire line is shown in **Fig 21.90**.

On its fundamental frequency, the antenna's maximum radiation will be straight up, making it most useful for regional communications at high elevation angles with the occasional DX contact. At higher frequencies, the loop will radiate more strongly at lower angles for better signal strengths at long distances.

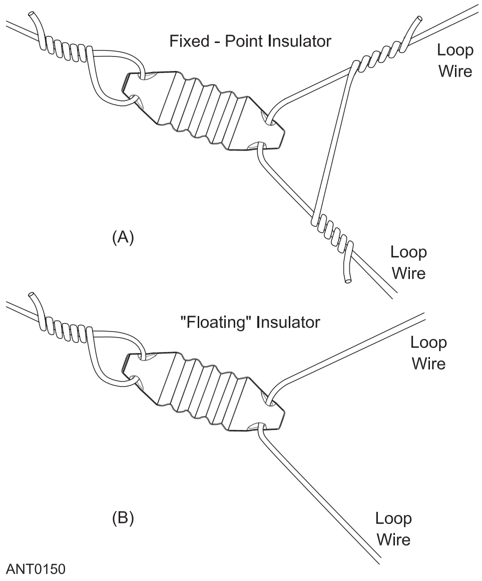


Fig 21.89 — Two methods of installing the insulators at the loop corners.

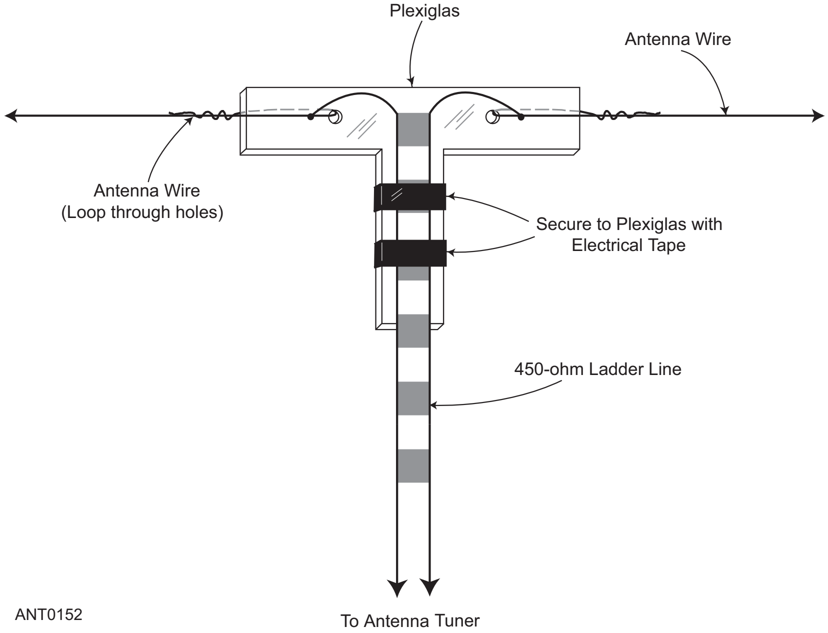


Fig 21.90 — One possible method of constructing a feed point insulator for use with open-wire line.

21.8 HF Mobile Antennas

HF mobile operation has been part of Amateur Radio since the 1930s. Once primarily an HF endeavor, the FM explosion of the 1970s seemed to displace HF mobiling in favor of local repeater and "mag-mount" VHF ground planes. HF mobiling is back, though, in a big way and with the excellent equipment and antennas available, here to stay. Material in this section was contributed and updated by Alan Applegate, K0BG.

High frequency (HF) mobile antennas come in every size and shape imaginable, from simple whips to elaborate, computer-controlled behemoths. Regardless of the type and construction, an HF mobile antenna should have a few important attributes.

1) Sturdiness: It should stay upright at highway speeds with a minimum of sway.

2) Mechanically stable: Sudden stops or sharp turns won't cause it to sway about, endangering others.

3) Flexibly mounted: Permits springing around branches and obstacles at low speeds.

4) Weatherproof: Withstands the effects of wind, rain, snow and ice at high speed.

5) Be tunable to different HF bands without stopping the vehicle if multiband operation is desired.

6) Can be mounted without altering the vehicle or its safety equipment.

7) Be easily removable when required.

8) Be as efficient as possible.

Of all the antenna choices available, the *whip* antenna has passed the test of time as providing all of these attributes in one way or another. The following sections discuss the different types of whips, how they are attached to and interact with the vehicle, and how they are connected to the transmitter.

21.8.1 Simple Whips

The simplest of antennas is a quarter-wave whip, but it's only practical on the upper HF bands due to the required length. For example, a 10 meter quarter-wavelength antenna is about 8 feet long. It doesn't require a loading coil, so its efficiency is close to 90%. The reason efficiency isn't 100% is because of resistive losses in the whip itself, stray capacitance losses in the mounting hardware and ground losses which we'll cover later. The end result is that the feed point impedance at the antenna's base is very close to 50 Ω and a good match to modern solid state transceivers.

WHIP RADIATION RESISTANCE

The power radiated by the antenna is equal to the radiation resistance times the square of the antenna current. The radiation resistance, R_r, of an electrically small antenna is given by:

$$R_r = 395 \times \left(\frac{h}{\lambda}\right)^2 \qquad (8)$$

where

h = radiator height in meters

λ = wavelength in meters = 300 / f in MHz

The efficiency of the antenna, η, equals the radiation resistance, R_r, divided by the resistive component of the feed point impedance, R_{fp}, which for actual antennas includes ground losses and losses in the antenna:

$$\eta = \frac{R_r}{R_{fp}} \times 100\% \qquad (9)$$

Since an electrically short antenna has a low radiation resistance, careful attention must be paid to minimizing losses in the antenna system that can greatly reduce the antenna's effectiveness.

21.8.2 Coil-Loaded Whips

As we move lower in frequency, the physical length has to increase, but there is a limit. In most localities, the maximum height at the tip of the antenna needs to be less than 13.5 feet. This generally limits an antenna to 10.5 feet (3.2 meters) for an average installation on a vehicle. In some areas even this is too long, while in others 16 feet isn't a problem. A 10.5-foot antenna is shorter than the resonant length for all HF bands except 10 and 12 meters and thus the feed point impedance will have some capacitive reactance. In order to keep within the 13.5 foot limit, we must add a loading coil to bring the antenna to resonance.

The capacitance in pF of an electrically small antenna is given approximately by:

$$C = \frac{55.78 \times h}{((\text{den1}) \times (\text{den2}))} \qquad (10)$$

where

(den1) = (ln (h/r) – 1)

(den2) = $(1 - (f \times h/75)^2)$

ln = natural logarithm

r = conductor radius in meters

f = frequency in MHz

Radiation resistance rises in a nonlinear fashion and the capacitance drops just as dramatically with increase in the ratio h/λ. **Fig 21.91** shows the relationship of capacitance to height for our 10.5 foot antenna. This can be used for estimating antenna capacitance for other heights. **Fig 21.92** shows that capacitance is not very sensitive to frequency for h/λ less than 0.075 which occurs at 8 MHz in this case. However, the sensitivity increases rapidly as frequency is lowered.

The required loading coil can take many forms, and it may be placed almost anywhere along the length of the radiating element. It cancels out the capacitive reactance (*–j*) by introducing an equal but opposite inductive reactance (*+j*). Some coils are mounted at the base of the mast — a *base-loaded* antenna — and some are mounted near the center (*center-loaded*) or the top (*top-loaded*).

As the coil is moved higher, the radiation resistance increases (a good thing), but the necessary coil reactance also increases as do resistive losses in the coil. Generally speaking, a center-loaded antenna requires twice the reactance of a base loaded antenna, thus the coil losses also double. Therefore, it becomes a balancing act to choose the optimal location and proper coil location requires a thorough understanding of the parameters involved.

Table 21.18 lists the characteristics of the 10.5 foot, base-loaded antenna with a coil Q of 200, a stray capacitance of 2 pF, a whip diameter of 0.003 meter, and the inductive reactance required to bring the antenna into resonance on 1.8 through 14 MHz. If we move the loading coil to the center, the requisite reactance doubles as do the coil resistive losses. The radiation resistance also increases, but only on that part of the antenna above the

Table 21.18
Characteristics of a 10.5-ft Whip Antenna

Freq (MHz)	*C (pF)*	*R_r (Ω)*	*Impedance (Ω)*	*Efficiency (%)*	*L (µH)*
1.8	30.1	0.146	13.72 –*j*2716	1.064	240
3.5	30.6	0.55	7.43 –*j*1375	7.4	62.5
7	32.8	2.2	7.04 –*j*644	31.2	14.6
10	36.5	4.5	6.5 –*j*408	69.2	6.49
14	46.5	8.8	10 –*j*232	88	2.64

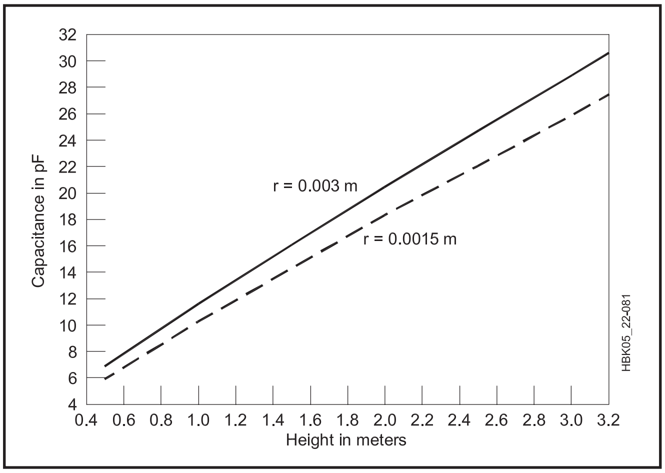


Fig 21.91 — Relationship at 3.5 MHz between vertical radiator length and capacitance. The two curves show that the capacitance is not very sensitive to radiator diameter.

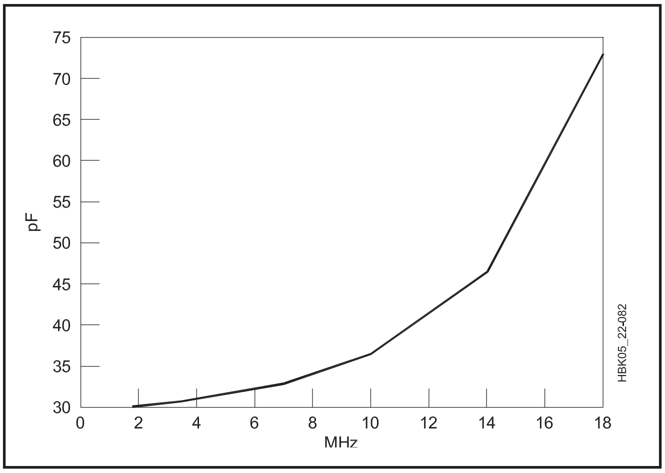


Fig 21.92 — Relationship between frequency and capacitance for a 3.2-meter vertical whip.

loading coil. Factor in the ground losses and the optimal position changes, but it is typically close to the center of the antenna.

It should be noted that stray capacitance mentioned above is primarily due to the mounting hardware. The total amount of stray capacitance may be much higher depending on where and how the antenna is mounted. The higher the stray capacitance, the less efficient the antenna will be.

Loading coil Q is especially important on the lower HF bands where coil losses can exceed ground losses. The factors involved include wire size, wire spacing, length-to-diameter ratio and the materials used in constructing the coil. All of the factors interact with one another, making coil design a compromise — especially when wind loading and weight become major considerations.

Antenna system Q is limited by the Q of the coil. The bandwidth between 2:1 SWR points of the system = 0.36 × f/Q. On 80 meters, the bandwidth of the 10.5 foot whip = 0.36 × 3.5/200 = 6.3 kHz. If we could double the Q of the coil, the efficiency would double and the bandwidth would be halved. The converse is also true. In the interest of efficiency, the highest possible Q should be used!

Another significant factor arises from high Q. Let's assume that we deliver 100 W on 80 meters to the 7.43 Ω at the antenna terminals. The current is 3.67 A and flows through the 1375-Ω reactance of the coil giving rise to 1375 × 3.67 = 5046 V_{RMS} (7137 V_{peak}) across the coil! This is a significant voltage and may cause arcing if the coil is wet or dirty.

With only 30.6 pF of antenna capacitance, the presence of significant stray capacitance at the antenna base shunts currents away from the antenna. RG-58 coax presents about 21 pF/foot. A 1.5-foot length of RG-58 would halve the radiation efficiency of our example antenna. For cases like the whip at 3.5 MHz, the matching network has to be right at the antenna!

In general, the larger the coil, the higher the Q. The more mass within the field of the coil (metal end caps for example) the lower the Q. Short, fat coils are better than long, skinny ones. Practical mechanical considerations for coils with reactances above 1000 Ω require the length-to-diameter ratio to increase, lowering Q.

21.8.3 Base vs Center vs Continuous Loading

There are a few important aspects to be kept in mind when selecting or building an HF mobile antenna. As the antenna becomes longer, less loading inductance is required and the coil Q can become higher, improving efficiency. Also, for longer antennas, the better the mounting location has to be in order to optimize efficiency. We'll cover mounting and efficiency later.

Placing the loading coil at the base results in the current distribution shown in **Fig 21.93A**. If we move the coil to the center, the current curve looks like the one in Fig 21.93B. The location of the optimal position between the two extremes depends on the ground losses, and to a lesser degree on loading coil Q and overall length. For example, if the ground losses were zero, the best position would be at the bottom. As the ground losses increase, the optimal position gets closer to the center. If the ground losses are high enough, the optimal position is in the top one-third of the antenna's length, but efficiency is very poor.

Center-loading increases the current in the lower half of the whip as shown in Fig 21.93B. Capacitance for the section above the coil can be calculated just as for the base-loaded antenna. This permits calculation of the loading inductance. The center-loaded antenna is often operated without any base matching in which case the resistive component can be assumed to be 50 Ω for purposes of calculating the current rating and selecting wire size for the inductor. The reduced size of the top section results in reduced capacitance which requires a much larger loading inductor.

Because of the high value of inductance required for center-loading, high-Q coils are very large. The large wind resistance necessitates a very sturdy mount for operation at highway speed. One manufacturer of this type of coil does not recommend their use in rain or inclement weather. The higher Q of these large coils results in a lower feed point impedance, necessitating the use of a base matching element in the form of either a tapped inductor or a shunt capacitor to match to 50 Ω. Another manufacturer places the coil above the center and uses a small extendable whip or wand for tuning.

To minimize wind resistance, the coil lengths are several times their diameters. These antenna coils are usually close wound with enameled wire. The coils are covered with a heat-shrink tubing sleeve. If used in heavy rain or snow for extended periods water may get under the sleeve and seriously detune and lower the Q of the coils. The lower Q of these coils means that the antennas usually do not require a base matching element as the feed point impedance seems to be enough to 50 Ω.

In recent years, continuously-loaded antennas as shown in **Fig 21.94** have become popular. Proponents often believe the coil radiates thus avoiding the position conundrum; this is a myth as the coil does not radiate. Because the coil's length to diameter ratio is so large, its Q is relatively low. They do have a few attributes which add to their popularity: Their input impedance is near

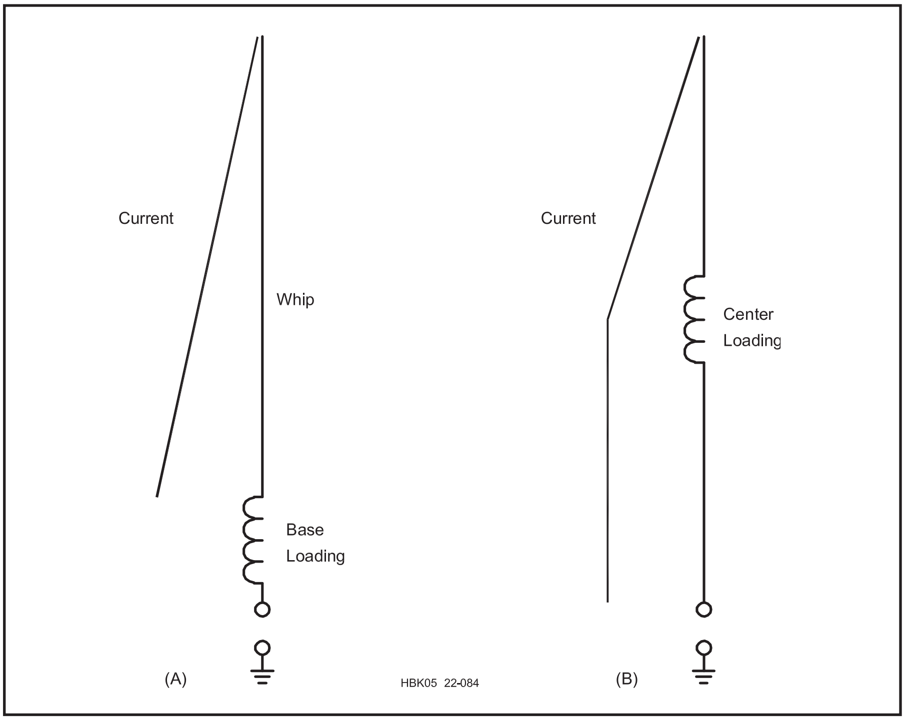


Fig 21.93 — Relative current distribution on a base-loaded antenna is shown at A and for a center-loaded antenna at B.

50 Ω in part because of their low-Q coils and they don't require matching once the length of the top whip or *stinger* is adjusted. They are light in weight (about a pound), short in length (typically 6 to 8 ft) and thus easy to mount. For temporary use, easy mounting may be more important than high efficiency. This type of antenna is most effective on 20 meters and higher frequency bands. **Table 21.19** compares different types of HF mobile antennas.

21.8.4 Remotely Controlled HF Mobile Antennas

Remotely controlled (motorized) HF mobile antennas are commonly referred to as *screwdriver antennas*. Don Johnson, W6AAQ (SK), is credited by many as the father of the screwdriver antenna. His design was not the first motorized antenna, but he certainly popularized it. There are now over 50 commercial versions available.

They're called screwdrivers because the first examples used a stripped-down rechargeable electric screwdriver assembly to adjust the resonant frequency of the antenna. The motor turns a threaded rod in and out of a nut attached to the bottom of the coil. This in turn moves the coil in and out of the lower mast section. Contacts at the top of the mast slide on the outside of the coil, thus adjusting the resonance point. Position sensors may be used to keep track of the location of the coil tap. Nowadays, calling them screwdrivers is a bit of a misnomer as the electric screwdriver motors have been replaced with much more reliable gear motors.

There are several remotely controlled HF mobile antennas that don't change length like true screwdrivers do. Both base and center loaded models are available (see **Fig 21.95**). Whether or not they're more efficient is dependent on the factors discussed in the previous section, rather than the method used to adjust the coil.

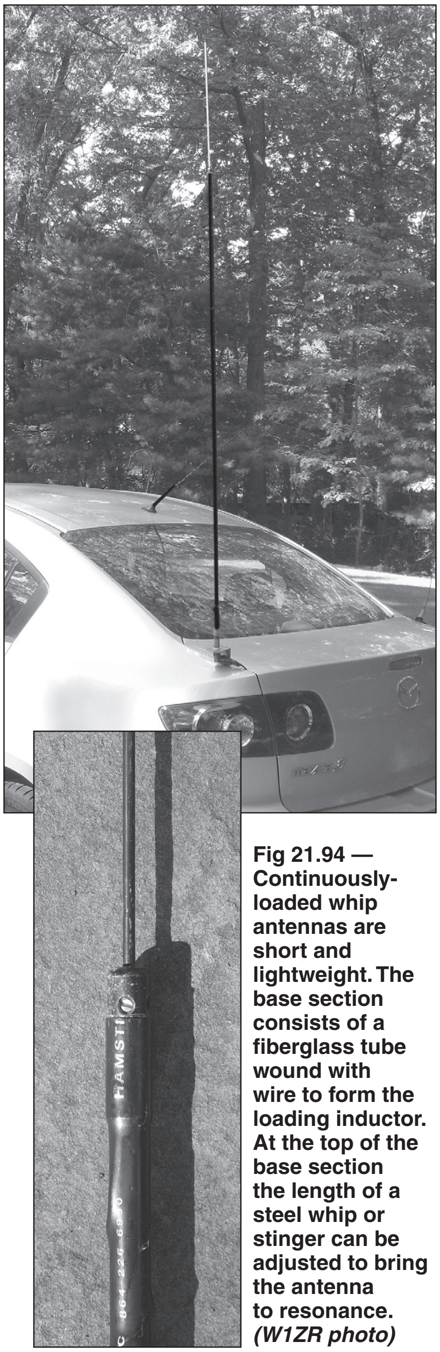


Fig 21.94 — Continuously-loaded whip antennas are short and lightweight. The base section consists of a fiberglass tube wound with wire to form the loading inductor. At the top of the base section the length of a steel whip or stinger can be adjusted to bring the antenna to resonance. *(W1ZR photo)*

RF CHOKES

The motors and position sensors of all remotely-controlled antennas operate above RF ground potential. The amount of RF present on the leads depends on several factors, especially where and how the antenna is mounted and its overall (electrical) length. Thus the RF current coupled onto the leads must be minimized with an RF choke before

Table 21.19
HF Mobile Antenna Comparison

Antenna Type	*Length*	*Frequency Coverage*	*Efficiency*	*Mounting Difficulty*	*Matching Required*
Simple Whip	< 11 ft	15 m & up	Excellent	Easy	No
Base-Loaded	9 to 10.6 ft	160 - 6 m	Fair to good	Average	Yes
Center-Loaded	9 to 10.5 ft	160 - 6 m	Good to excellent	Average	Yes
Top-Loaded	<9 ft	160 - 6 m	Fair	Average	No
Continuous Loading	< 7 feet	80 - 6 m	Poor to fair	Easy	No
Remote-tuned Small	< 7 feet	80 - 6 m	Poor to fair	Easy	No
Remote-tuned Large	9 to 10.5 ft	160 - 6 m	Excellent	Difficult	Yes

Designing a Base Loading System

This design procedure was contributed by Jack Kuecken, KE2QJ. To begin, estimate the capacitance, capacitive reactance and radiation resistance as shown at the beginning of this section. Then calculate the expected loss resistance of the loading coil required to resonate the antenna. There is generally additional resistance amounting to about half of the coil loss which must be added in. As a practical matter, it is usually not possible to achieve a coil Q in excess of 200 for such applications.

Using the radiation resistance plus 1.5 times the coil loss and the power rating desired for the antenna, one may select the wire size. For high efficiency coils, a current density of 1000 A/inch^2 is a good compromise. For the 3.67 A of the example we need a wire 0.068-inch diameter, which roughly corresponds to #14 AWG. Higher current densities can lead to a melted coil.

Design the coil with a pitch equal to twice the wire diameter and the coil diameter approximately equal to the coil length. These proportions lead to the highest Q in air core coils.

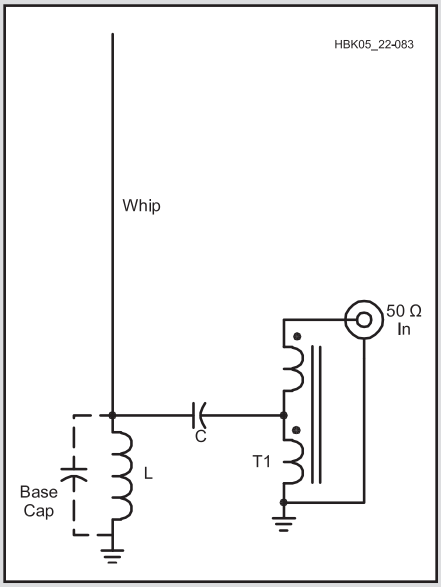


Fig 21.A3 — The base-matched mobile whip antenna

The circuit of **Fig 21.A3** will match essentially all practical HF antennas on a car or truck. The circuit actually matches the antenna to 12.5 Ω *and the transformer boosts it up to 50 Ω. Actual losses alter the required values of both the shunt inductor and the series capacitor. At a frequency of 3.5 MHz with an antenna impedance of 0.55* –*j*1375 Ω *and a base capacitance of 2 pF results in the values shown in* **Table 21.B.** Inductor and capacitor values are highly sensitive to coil Q. Furthermore, the inductor values are considerably below the 62.5 µH required to resonate the antenna.

This circuit has the advantage that the tuning elements are all at the base of the antenna. The whip radiator itself has minimal mass and wind resistance. In addition, the rig is protected by the fact that there is a dc ground on the radiator so any accidental discharge or electrical contact is kept out of the cable and rig. Variable tuning elements allow the antenna to be tuned to other frequencies.

Connect the antenna, L and C. Start with less inductor than required to resonate the antenna. Tune the capacitor to minimum SWR. Increase the inductance and tune for minimum SWR. When the values of L and C are right, the SWR will be 1:1.

Table 21.B
Values of L and C for the Circuit of Fig 21.A3 on 3.5 MHz

Coil Q	*L (µH)*	*C (pF)*	*System Efficiency (%)*
300	44	11.9	8.3
200	29.14	35	3.72
100	22.2	58.1	1.4

Fig 21.95 — The screwdriver-style remotely-controlled whip antenna. A small motor in the base mast moves a coil past contacts at the top of the metal base section. The top whip section is attached to the top of the coil. As the coil moves out of the mast, more inductance is connected in series between the base section and top section. Screwdriver antennas are popular because they offer multiband coverage. *(W1ZR photo)*

entering the vehicle. An inadequate choke may result in erratic controller operation and possible interference with transceiver operation.

The choke should have an impedance of at least two orders of magnitude greater than the impedance of the circuit. In other words, at least 5 kΩ, and perhaps two or three times that in some cases (stubby antennas and poor mounting schemes are examples). Mix 31 ferrite split beads are ideal for this application, but it takes eight turns to obtain a 5 kΩ choking impedance. Depending on the wire size and insulation, you'll need to use the ½- or ¾-inch ID cores. Snap-on ferrite beads are available from most Amateur Radio dealers. (More information on this type of RF choke may be found in the **RF Techniques** chapter.)

The choke shown in **Fig 21.96** consists of

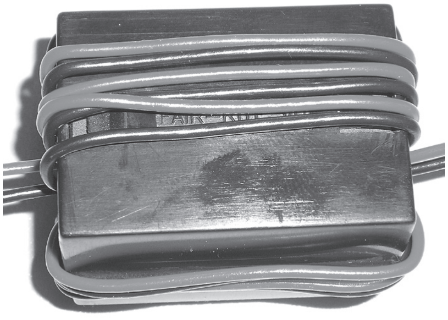


Fig 21.96 — RF choke for screwdriver antenna control and power leads.

13 turns of #18 AWG wire, wound on a ¾-inch ID mix 31 split bead. It has an impedance of approximately 10 kΩ at 10 MHz. When winding the chokes, try not to overlap or twist the wires as this reduces the effectiveness.

21.8.5 Ground Losses

High frequency mobile ground loss data first appeared in a 1953 issue of *QST*, in an article written by Jack Belrose, VE3BLW (now VE2CV). In the article, Belrose said that the current flowing at the base of the antenna must be returned to the base of the antenna by currents induced in the ground beneath the radiator (antenna). These currents must be collected by the car body and through the capacitance of the car body to the ground. Since the maximum dimension of car body is considerably less than a quarter wavelength on most HF bands, only a portion of these currents will be collected by the car frame itself, and the rest will be collected by ground currents flowing through the capacitance of the car to the ground. Since the ground is not lossless, quite a large loss resistance (R_g) is found.

From that article, the accepted ground loss figure for HF mobile applications varies between 12 Ω (for 80 meters) and 2 Ω (for 10 meters). However, these figures do not include stray capacitance from the mounting location and method. Stray capacitance has the same effect as ground losses: reduced efficiency. As a result, in the real world, ground losses can be double the accepted values, reducing an otherwise efficient antenna to mediocrity.

21.8.6 Antenna Mounting

Here is an important caveat to keep in mind: While the roof of a vehicle is a very good place to mount an antenna, more and more new vehicles are equipped with side curtain air bags. They typically are mounted along the edges of the headliner, including the rear seat area if there is one. The wiring to these devices is routed through any one (or more) of the roof pillars. Extra care is required when installing antennas in vehicles so equipped. If you are the least bit apprehensive about your installation, seek professional help from your dealer or a qualified installer.

Mobile antenna mounting hardware runs the gamut from mundane to extravagant. Choosing the correct hardware is based on need, as well as on personal preference. There are enough variables with respect to mounting HF mobile antennas on modern vehicles that one could easily fill this *Handbook* and not cover them all. It is almost easier to explain *what not* to do, than explain *what* to do. In any case, there are a few very important aspects that need to be covered. With concerns similar to those of the antenna, the antenna mount should:

- be permanently mounted;
- be strong enough to support the antenna;
- have as much metal mass under it as possible;
- be well-grounded to the chassis or body;
- not interfere with doors, trunks, or access panels and
- be removable with minimal damage to the vehicle.

There are many reasons to permanently install any mobile antenna. Aside from maximizing performance by minimizing ground and stray capacitance losses, there is also a safety issue. If you need to use a temporary mount, use the multiple-magnet mounts for their superior holding strength. An HF mobile antenna attached to a vehicle traveling at highway speed by a single-magnet mount is a tenuous situation at best.

The type of mount is dictated by several conditions. These include a decision whether or not to drill holes and the size, weight and length of the antenna. If you're into daily HF mobile operation, you've already drilled the necessary holes. If you're not, a trunk lip, angle bracket, or license plate mount, and a lightweight, continuously-loaded antenna may meet your needs.

Ground plane losses directly affect a mobile antenna's efficiency. From this standpoint, mounts positioned high on the vehicle are preferred over a trailer hitch, bumper or other low-position mounting locations.

The ground plane of a mobile vertical antenna begins where the coax shield connects. When the feed line shield couples to the vehicle body capacitively as in a magmount, or when the mass of the vehicle is far below the feed point (long stalks attached to trailer hitch mounts), ground losses escalate dramatically. Running a ground strap to the nearest connecting point to the vehicle body does not eliminate ground losses. Remember that the ground connection is also part of the antenna and it is the efficiency of the whole system that is important.

While it is difficult to mount an HF antenna without at least part of the mast being close to the body, the coil must be kept free and clear. If it isn't, tuning problems and reduced efficiency will result. In some cases, vans and SUVs for example, front-mounting may become necessary to avoid coil-to-body interaction.

One drawback to trunk lip and similar clip mounts is the stress imposed on them as the lids and doors are open and closed. In most cases, angle brackets that attach to the inner surfaces with screws are a better choice.

Sometimes, the only solution is a custom-made bracket like the one shown later in this chapter. Here too, the need dictates the requirements, and there is no standard to follow except for those attributes mentioned above. Keep in mind that removing permanently installed antenna mounts such as the ball mount shown in **Fig 21.97** will always leave some body damage, but temporary ones do, too. It is only the severity that is in question, and that's in the eyes of the beholder.

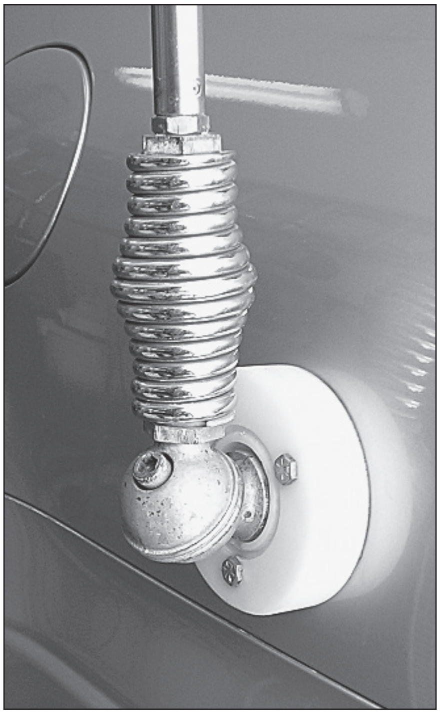


Fig 21.97 — A simple ball mount is sturdy but requires drilling holes in the vehicle body.

21.8.7 Mobile HF Antenna Matching

Modern solid-state transceivers are designed for loads close to 50 Ω impedance. Depending on the design of the antenna (primarily depending on coil position and Q), overall length and the ground losses present, the input impedance is usually closer to 25 Ω but may vary from 18 Ω to more than 50 Ω. Note that a vehicle is an inadequate ground plane for any HF mobile antenna. Typical ground loss varies from 20 Ω (160 meters) to 2 Ω (10 meters). Stray capacitance losses may further increase the apparent ground losses.

It's important to remember two important facts. First, as the coil is moved past the center of the antenna toward the top, the coil's resistive losses begin to dominate, and the input impedance gets closer to 50 Ω. Second, short stubby antennas require more inductance than longer ones, which increases resistive losses in the coil (low Q). While no matching is required in either case, efficiency suffers, and may actually drop below 1% on the lower bands. Another way to look at the situation is that an antenna with no matching required implies a low efficiency.

Ground loss, coil position, coil Q, mast size, whip size and a few other factors determine the feed point impedance, which averages about 25 Ω for a typical quality antenna and mount. This represents an input SWR of 2:1, so some form of impedance matching is required for the transceiver. There are three ways to accomplish the impedance transformation: capacitive, transmission-line transformer and inductive matching as shown in **Fig 21.98**. Each has its own unique attributes and drawbacks.

Transmission line transformers, in this case an unun in Fig 21.98A, do provide a dc ground for the antenna. They can be tapped or switched to match loads as low as a few ohms. Their broadband nature makes them ideal for HF mobile antenna matching. Since a remotely-controlled HF mobile antenna's input impedance varies over a wide range, transmission line transformers are best utilized for matching monoband antennas.

Inductive matching in Fig 21.98B borrows a little capacitance from the antenna (C_a) — the antenna is adjusted to a frequency slightly higher than the operating frequency, making the input impedance capacitive. This forms a high-pass L-network, which transforms the input impedance to the 50 Ω transmission line impedance. It is ideal for use with remotely-controlled antennas, as its reactance increases with frequency. By selecting the correct inductance, a compromise can be reached such that the impedance transformation will result in a low SWR from 160 through 10 meters. The approximate value is 1 µH, but may vary between 0.7 and 1.5 µH.

Adjusting the shunt coil can be done without transmitting by using an antenna analyzer and takes about 10 minutes. (Full instructions for properly adjusting a shunt coil may be found at **www.k0bg.com/coil.html**.) Because no further adjustment is necessary, shunt coil matching is ideal for remotely-controlled HF mobile antennas.

Capacitive matching in Fig 21.98C borrows a little inductance from the antenna (L_a) — the antenna is adjusted to a frequency slightly lower than the operating frequency, making the input impedance inductive. This forms a low-pass L-network, which transforms the input impedance to the 50 Ω transmission line impedance. While it works quite well, it has two drawbacks. First, capacitive matching presents a dc ground for the antenna, which tends to increase the static levels on receive. Second, the capacitance changes with frequency, so changing bands also requires a change in capacitance. This can be a nuisance with a remotely controlled antenna.

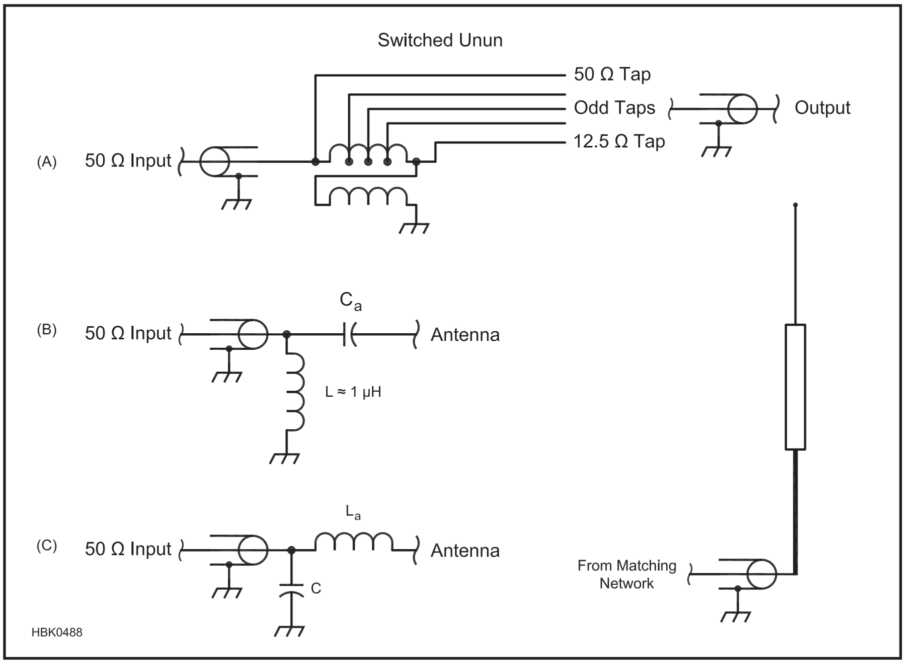


Fig 21.98 — A well-constructed and mounted HF mobile antenna will have an average input impedance around 25 Ω, requiring some matching to the feed line. The unun transmission line transformer (A) is a 4:1 configuration with taps added to match intermediate impedance values between 50 and 12.5 Ω. The high-pass L-network (B) uses some of the antenna's capacitive reactance as part of the network and the low-pass L-network (C) uses some of the antenna's inductive reactance as part of the network. Both (A) and (B) result in an antenna at dc ground, an important safety issue.

An important point should be made about dc grounding in addition to the static issue. If the antenna element should come in contact with a low-hanging high tension wire, or if lightning should strike it, dc grounding offers an additional level of protection for you and your transceiver.

21.8.8 Remotely-Tuned Antenna Controllers

There are three basic types of remote controllers: manual, position sensing and SWR sensing. Manual controllers consist of a DPDT center-off switch that changes the polarity of the current to the motor. Some

Fig 21.99 — A screwdriver antenna controller made to work with the IC-7000 transceiver.

commercial models include an interface with the radio that causes the radio to transmit a low-power carrier for tuning. Reading the SWR is left to the user. Some manual controllers incorporate a position readout to aid the operator in correctly positioning the antenna.

Position sensing controllers incorporate a magnet attached to the motor output shaft. The magnet opens and closes a reed switch. During set up, the antenna is set to one end of its range or the other. Then the resonant points are found (you have to do this yourself) and stored in multiple memory locations. As long as power remains applied to the controller, a simple button push will move the antenna to a specific preset point. Some controllers use band or frequency data from a port on the radio and reset the antenna to the nearest preset based on that information.

SWR-sensing controllers either read data from the radio or from a built-in SWR bridge. Depending on the make and model, a push of the radio's tuner button (or one on the controller) causes the radio to transmit at a reduced power setting. The controller then powers the antenna's tuning motor. When the preset SWR threshold is reached, the controller stops the transmission and shuts off the motor. **Fig 21.99** shows an example of a controller made to work with a specific transceiver.

Automatic controllers are far less distracting than manual ones. Most offer a parking function that collapses the coil of a screwdriver antenna into the mast (highest frequency position, lowest overall length). If you garage your vehicle, this is a welcome feature.

21.8.9 Efficiency

Length matters! All else being equal, a nine-foot antenna will be twice as efficient as a six-foot antenna, because radiation resistance relates directly to the square of the physical length. Further, longer antennas require less reactance to resonate, hence coil Q is higher, and resistive losses lower.

Mounting methodology matters! It is the mass under the antenna, not alongside, that counts. The higher the mounting, the less capacitive coupling there will be between the antenna and the surface of the vehicle and the lower ground losses will be.

Project: Mounts for Remotely-Tuned Antennas

Remotely tuned antennas have become very popular, but they all have one thing in common: they're difficult to mount. They require both a coaxial feed line and a dc power connection, and no one makes a universal mount for them. The short, stubby ones aren't any more difficult to mount than a small whip antenna, but the "full-sized" ones (8 ft and longer) require special consideration.

Fig 21.100 — The PA3VOS antenna mount easily supports a large screwdriver antenna and is offset to allow the hatch to open and close without removing the antenna.

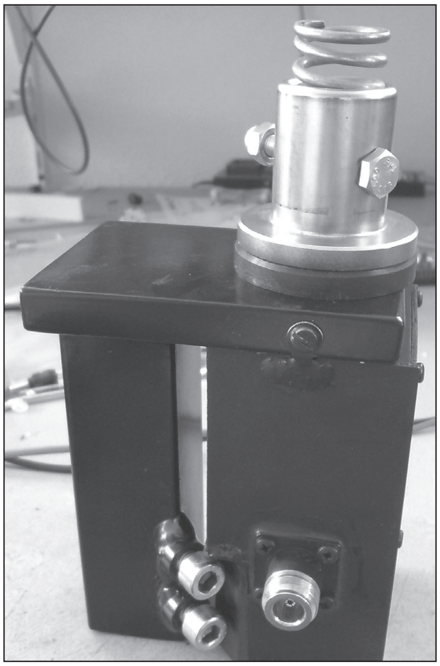


Fig 21.101 — A close-up of the PA3VOS mount.

These antennas are heavy (up to 18 pounds), so the mounting medium must be extra strong, and well anchored. As a result, many hams opt for a bumper or trailer hitch mount, even though the low mounting position reduces efficiency.

For some, efficiency is paramount which dictates mounting the antenna as high as possible. Doing either low or high mounting often requires custom fabrication. The accompanying photos illustrate the two different strategies that show Amateur Radio ingenuity at its finest.

Figs 21.100 and **21.101** depict the mobile installation of Fokko Vos, PA3VOS. Except for a Hi-Q heavy-duty quick-disconnect, the complete mount was custom engineered by Fokko. The mount bolts to a frame extension, which in turn is bolted to the undercarriage using existing bolts. Note that the rear hatch may be opened without the antenna being removed. Had the trailer hitch been used, this would not be the case.

Fig 21.102 depicts installation on a Ford F350-based motor home owned by Hal Wilson, KE5DKM. Hal designed the bracket, and had a local machine shop do the hard work. It is made of ¼-inch, high-strength aluminum, and the seams are welded. A powder-coat finish tops off the fabrication.

Shown here during installation, the bracket just fits into the right-side hood seam. The piece jutting out from the mount was to be used to further brace the mount. However, after all of the bolts were installed, additional bracing became unnecessary.

Fig 21.102 — The KE5DKM bracket mounts under the hood of a motor home.

Project: Retuning a CB Whip Antenna

The most efficient HF mobile antenna is a full-size quarter-wavelength whip. Wouldn't it be nice if we could use one on every band? Alas, we cannot, but we can use one easily on 10 and 12 meters since the overall length will

Determining the Radiation Efficiency of a Center Loaded Mobile Whip

We can measure the radiation efficiency by measuring ground wave field strength E (dB referenced to µV/m). For the average radio amateur, a field strength meter is not a part of his ham shack gear. We can predict performance using readily available antenna modeling software (one of the many available versions of *NEC*) provided we have a measure of actual losses.

There are a number of loss parameters we do not know. We do not know the Q factor for the center loading coil (R_L), and we do not know the ground-induced loss resistance (R_g). In fact we do not know with certainty the radiation resistance (R_r), since the antenna sees an image of itself in the ground. *NEC* only gives us the sum of the various resistances.

$$R_{as} = R_r + R_C + R_g + R_L$$

R_C, the only parameter not discussed above, is the conductor loss resistance.

We need to know R_r if we are going to compute radiation efficiency, since radiation efficiency is given by:

$$\eta = \frac{R_r}{R_{as}}$$

So what do we do? We can measure R_{as} using the SWR analyzer, by adjusting the tuning so the reactance at the base of the antenna is equal to zero. We can then use *NEC* to predict the base impedance (resistive component), by changing the Q factor of the inductor so that R_{as} predicted equals R_{as} measured. We can then predict the ground field strength (dBµV/m) at say 100 m for a transmitter power of 1 kW. We then reference this predicted field strength to that for an electrically small lossless vertical antenna (129.54 dBµV/m at 100 m for 1 kW transmitter power — which corresponds to the commonly quoted value of 300 mVm at 1 km). This gives us a pretty good estimate of the radiation efficiency of our mobile whip. *— Jack Belrose, VE2CV*

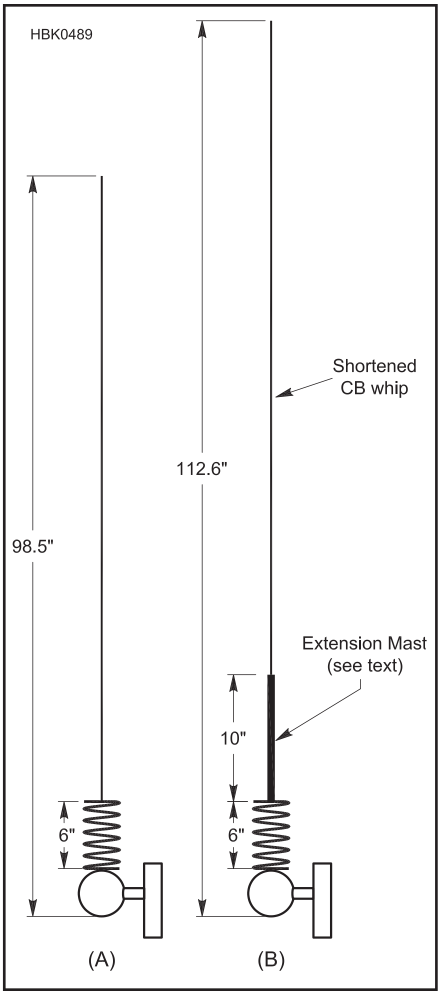


Fig 21.103 — CB whips are easily retuned for 10 meter (A) and 12 meter (B) mobile operation.

be less than 10 ft. If we start with a standard-length 102-inch whip and its base spring, we just need to shorten it a little for 10 meters, and lengthen it a little for 12 meters. Here's how to do it.

The formula for calculating the length of a ¼-λ antenna in feet is 234/f, where f is the frequency (MHz). Since the formula is for wire antennas, and the whip is larger in diameter, the resulting length will be slightly too long. This is a good thing because it is easier to remove a little length than it is to add some. This makes tuning easier.

Using the formula, we discover the needed length for 10 meters (28.5 MHz) is 98.5 inches. Thus, we need to remove 3.5 inches and account for the length of the base spring (about 6 inches), for a total of 9.5 inches to be removed. This is best accomplished by filing a notch on opposite sides of the tip of the whip, and snapping it in two. Protect your eyes when you do this, as shards and splinters can fly off the broken ends. If a fiberglass whip is being modified, clip the internal wire at the top of the remaining base section. Remove the plastic cap from the discarded top section and replace it over the new top of the antenna.

Depending on the mount used, the actual resonant frequency will be lower than 28.5 MHz as the mounts adds effective length. A standard CB antenna ball mount will easily support a whip. The finished antenna is shown in **Fig 21.103A.**

Once the antenna is mounted on the vehicle, simply trimming the overall length ½-inch at a time will eventually produce a low SWR at your desired frequency.

LENGTHENING FOR 12 METER OPERATION

Lengthening a CB whip for 12 meters requires a little more work. Thankfully, there's a easy solution if you have a CB radio or truck stop near you. Wilson and other vendors sell short masts designed for the CB market. They have the requisite ⅜ × 24 threads to accept a standard whip, and they come with a female-to-female coupler. The 10-inch model is ideal for our use, and costs under $10.

Using our formula 234/f, the overall length needs to be 112.6 inches for 24.93 MHz. Adding 6 inches for the spring, 10 inches. for the extension mast, and 102 inches. for the whip, gives us 118 inches. So we need to remove 5.4 inches from the whip. Then just trim off ½-inch at a time as above to resonate the antenna. The finished antenna is shown in Fig 21.103B.

FINISHING UP

There are two more things to consider. If a metal whip was modified, you'll need to replace the corona ball at the tip of the antenna. It helps reduce static from corona discharge. It's held on by a set screw and has little effect on tuning. Most CB shops sell them.

The other consideration is ground loss. Theoretically, a ¼-λ vertical will have an input impedance of 36 Ω. In a mobile installation, we have ground losses and stray capacitance losses in the mounting hardware. As a result, the real-world input impedance should be very close to 42 Ω, yielding a rather low SWR and good efficiency.

21.9 VHF/UHF Mobile Antennas

A common mistake is selecting a VHF/UHF mobile antenna based solely on its advertised gain with little consideration of the mounting method or its sturdiness.

Sturdiness is important given the unintended abuse to which mobile antennas are subjected. If you look closely at some antennas, you'll notice they have very small phasing coils, usually held together by small set screws. Smack one hard enough with a low-hanging limb, and your antenna will break. Do this to a simple quarter-wave whip and all you'll do is bend it. A little straightening and you're back on the air.

In urban areas, where higher angles of radiation are preferred, you're typically better off with a lower gain antenna such as a ¼-λ whip. If you're living in a suburban or rural area, gain antennas might have a slight edge. It all depends on the HAAT (height above average terrain) of the repeater being used with respect to the mobile station's HAAT. In mountainous areas you're better off with a unity gain antenna (¼-λ ground plane) as the repeaters are much higher in elevation.

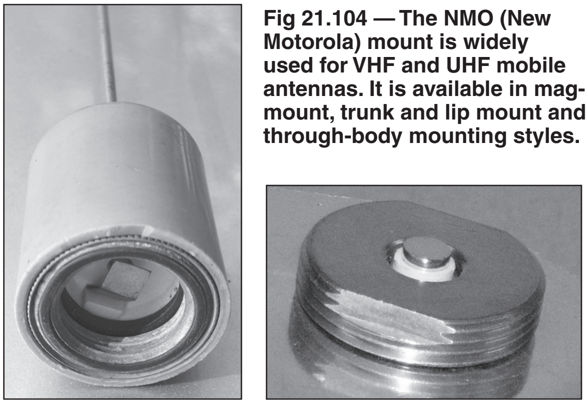


Fig 21.104 — The NMO (New Motorola) mount is widely used for VHF and UHF mobile antennas. It is available in mag-mount, trunk and lip mount and through-body mounting styles.

21.9.1 VHF/UHF Antenna Mounts

Without doubt, the best VHF/UHF mount ever devised is the NMO (New Motorola) shown in **Fig 21.104**. When properly installed in vehicle sheet metal, the mount will not leak even when the antenna is removed for car washing. SO-239 and ⅜-inch snap-in mounts often leak even with the antenna mounted.

Glass-mounted antennas are rather lossy, especially at lower VHF frequencies (2 meters). Many new vehicles use window glass with a metallic, anti-glare coating that interferes with capacitive coupling through the glass. These antennas also transfer mechanical abuse to the glass, risking breaking the glass the antenna is mounted on.

Setting the SWR of a VHF/UHF antenna is an important installation procedure, but not one to fret over afterwards. Unlike the HF bands, most VHF antennas will cover the whole band segment without the need to retune. That is to say, the SWR will be low across the FM portion of the respective bands. An in-line SWR meter is generally not required as the vertically-polarized antenna is not intended to be used in the weak-signal portion of the bands where horizontal polarization is the norm.

21.10 VHF/UHF Antennas

Improving an antenna system is one of the most productive moves open to the VHF enthusiast. It can increase transmitting range, improve reception, reduce interference problems and bring other practical benefits. The work itself is by no means the least attractive part of the job. Even with high-gain antennas, experimentation is greatly simplified at VHF and UHF because an array is a workable size, and much can be learned about the nature and adjustment of antennas. No large investment in test equipment is necessary.

Whether we buy or build our antennas, we soon find that there is no one *best* design for all purposes. Selecting the antenna best suited to our needs involves much more than scanning gain figures and prices in a manufacturer's catalog. The first step should be to establish priorities for the antenna system as a whole. Once the objectives have been sorted out in a general way, we face decisions on specific design features, such as polarization, length and type of transmission line, matching methods, and mechanical design.

21.10.1 Gain

As has been discussed previously, shaping the pattern of an antenna to concentrate radiated energy, or received signal pickup, in some directions at the expense of others is the only possible way to develop gain. Radiation patterns can be controlled in various ways. One is to use two or more driven elements, fed in phase. Such arrays provide gain without markedly sharpening the frequency response, compared to that of a single element. More gain per element, but with some sacrifice in frequency coverage, is obtained by placing parasitic elements into a Yagi array.

21.10.2 Radiation Pattern

Antenna radiation can be made omnidirectional, bidirectional, practically unidirectional, or anything between these conditions. A VHF net operator may find an omnidirectional system almost a necessity but it may be a poor choice otherwise. Noise pickup and other interference problems tend to be greater with omnidirectional antennas. Maximum gain and low radiation angle are usually prime interests of the weak-signal DX aspirant. A clean pattern, with lowest possible pickup and radiation off the sides and back, may be important in high-activity areas, where the noise level is high, or for challenging modes like EME (Earth-Moon-Earth).

21.10.3 Height Gain

In general, the higher a VHF antenna is installed, the better will be the results. If raising the antenna clears its view over nearby obstructions, it may make dramatic improvements in coverage. Within reason, greater height is almost always worth its cost, but height gain must be balanced against increased transmission line loss. Line losses can be considerable at VHF and above, and they increase with frequency. The best available line may be none too good, if the run is long in terms of wavelength. Consider line losses in any antenna planning.

21.10.4 Physical Size

A given antenna design for 432 MHz, say a 5-element Yagi on a 1-λ boom, will have the same gain as one for 144 MHz, but being only one-third the size it will intercept only one-ninth as much energy in receiving. Thus, to be equal in communication effectiveness, the 432-MHz array should be at least equal in physical size to the 144-MHz one, requiring roughly three times the number of elements. With all the extra difficulties involved in going higher in frequency, it is well to be on the big side in building an antenna for the UHF bands.

21.10.5 Polarization

Whether to position the antenna elements vertically or horizontally has been a question since early VHF operation. Originally, VHF communication was mostly vertically polarized, but horizontal gained favor when directional arrays became widely used. Tests of signal strength and range with different polarizations show little evidence on which to set up a uniform polarization policy. On long paths there is no consistent advantage, either way. Shorter paths tend to yield higher signal levels with horizontal in some kinds of terrain. Man-made noise, especially ignition interference, tends to be lower with horizontal polarization. Vertically polarized antennas, however, are markedly simpler to use in omnidirectional systems and in mobile work, resulting in a standardization on vertical polarization for mobile and repeater operation on FM and for digital communications. Horizontal polarization is the standard for weak signal VHF and UHF operation. (Circular polarization is preferred for satellite work as described below.) A loss in signal strength of 20 dB or more can be expected with cross-polarization so it is important to use antennas with the same polarization as the stations with which you expect to communicate.

21.10.6 Circular Polarization

Polarization is described as *horizontal* or *vertical*, but these terms have no meaning once the reference of the Earth's surface is lost. Many propagation factors can cause polarization change — reflection or refraction and passage through magnetic fields (Faraday rotation), for example. Polarization of VHF waves is often random, so an antenna capable of accepting any polarization is useful. Circular polarization, generated with helical antennas or with crossed elements fed 90° out of phase, will respond to any linear polarization.

The circularly polarized wave in effect threads its way through space, and it can be left- or right-hand polarized. These polarization senses are mutually exclusive, but either will respond to any plane (horizontal or vertical) polarization. A wave generated with right-hand polarization, when reflected from the moon, comes back with left-hand polarization, a fact to be borne in mind in setting up EME circuits. Stations communicating on direct paths should have the same polarization sense.

Both senses can be generated with crossed dipoles, with the aid of a switchable phasing harness. With helical arrays, both senses are provided with two antennas wound in opposite directions.

21.10.7 Transmission Lines

The most common type of transmission line at VHF through the low microwave bands is unbalanced coaxial cable. Small coax such as RG-58 or RG-59 should never be used in VHF work if the run is more than a few feet. Half-inch lines (RG-8 or RG-11) work fairly well at 50 MHz, and runs of 50 ft or less are acceptable at 144 MHz. Lines with foam rather than solid insulation have about 30% less loss. Low-loss cable is required for all but the shortest runs above 222 MHz and *waveguide* is used on microwave frequencies. (See the **Transmission Lines** chapter for a discussion of waveguides.)

Solid aluminum-jacketed *hardline* coaxial cable with large inner conductors and foam insulation are well worth the cost. Hardline can sometimes even be obtained for free from local Cable TV operators as *end runs* — pieces at the end of a roll. The most common CATV variety is ½-inch OD 75-Ω hardline. Hardline is considered *semi-rigid* in that it can be bent, but only with a large radius to avoid kinking and repeated bending should be avoided.

Waterproof commercial connectors for hardline are fairly expensive, but enterprising amateurs have *home-brewed* low-cost connectors. If they are properly waterproofed, connectors and hardline can last almost indefinitely. See *The ARRL Antenna Book* for details on connectors and techniques for working with hardline.

Properly-built open-wire line can operate with very low loss in VHF and even UHF installations. A line made of #12 AWG wire, spaced ¾-inch or less with Teflon spreaders, and running essentially straight from antenna to station, can be better than anything but the most expensive hardline at a fraction of the cost. Line loss under 2 dB per 100 feet at 432 MHz is readily obtained. This assumes the use of high-quality baluns to match into and out of the balanced line, with a short length of low-loss coax for the rotating section from the top of the tower to the antenna. Such an open-wire line could have a line loss under 1 dB at 144 MHz.

Effects of weather on transmission lines should not be ignored. A well-constructed open-wire line works well in nearly any weather, and it stands up well. TV-type twinlead is almost useless in heavy rain, wet snow or icing conditions. The best grades of coax and hardline are impervious to weather. They can be run underground, fastened to metal towers without insulation, or bent into almost any convenient position, with no adverse effects on performance. However, beware of bargain coax. Lost transmitter power can be made up to some extent by increasing power, but once lost in the transmission line a weak signal can never be recovered in the receiver.

21.10.8 Impedance Matching

Theory and practice in impedance matching are discussed in detail in the **Transmission Lines** chapter, and in theory, at least, are the same for frequencies above 50 MHz. Practice may be similar, but physical size can be a major modifying factor in choice of methods.

DELTA MATCH

Probably the first impedance match was made when the ends of an open line were fanned out and tapped onto a half-wave antenna at the points of most efficient power transfer, as in **Fig 21.105A**. Both the side length and the points of connection either side of the center of the element must be adjusted for minimum reflected power in the line, but the impedances need not be known. The delta makes no provision for tuning out reactance, so the length of the dipole is pruned for best SWR.

Once thought to be inferior for VHF applications because of its tendency to radiate if adjusted improperly, the delta has come back to favor now that we have good methods for measuring the effects of matching. It is very handy for phasing multiple-bay arrays with low-loss open lines, and its dimensions in this use are not particularly critical.

GAMMA MATCH

The gamma match is shown in Fig 21.105C and is covered in more detail in the preceding section on HF Yagi antennas and in the **Transmission Lines** chapter. The center of a half-wave dipole being electrically neutral, the outer conductor of the coax is connected to the element at this point, which may also be the junction with a metallic or non-conductive boom. The inner conductor is connected to the element at the matching point. Inductance of the connection to the element is canceled by means of C1. Both the point of contact with

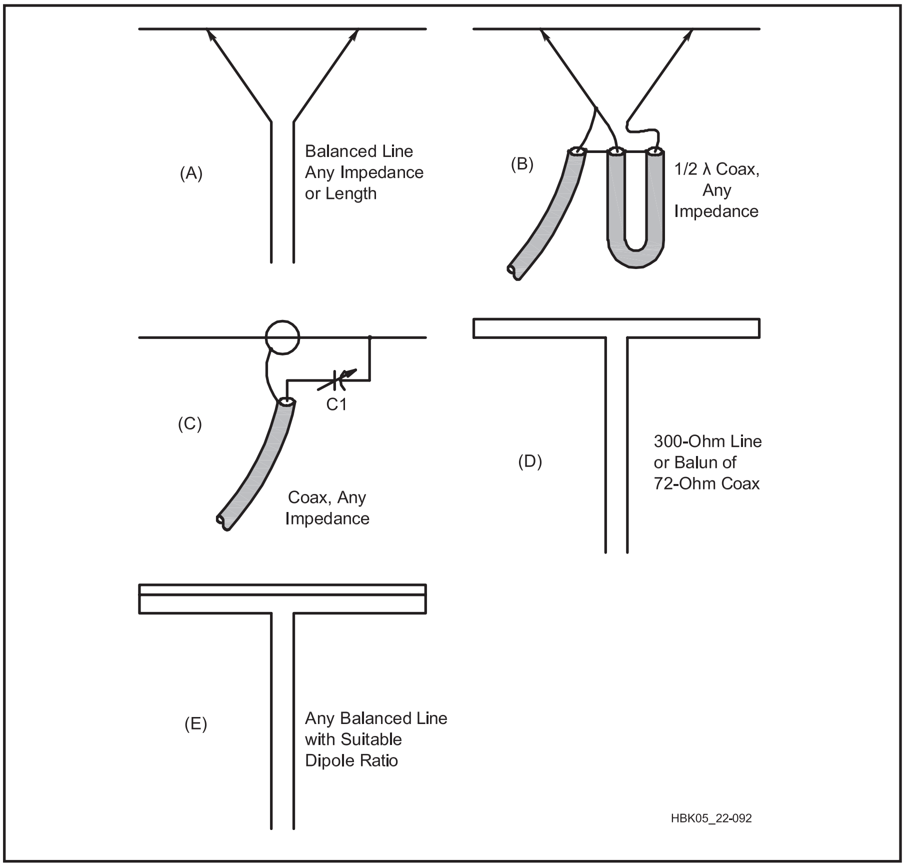


Fig 21.105 — Matching methods commonly used in VHF antennas. In the delta match, A and B, the line is fanned out to tap on the dipole at the points of best impedance match. The gamma match, C, is for direct connection of coax. C1 tunes out inductance in the arm. Folded dipole of uniform conductor size, D, steps up antenna impedance by a factor of four. Using a larger conductor in the unbroken portion of the folded dipole, E, gives higher orders of impedance transformation.

the element and the setting of the capacitor are adjusted for minimum SWR using an antenna analyzer or SWR bridge.

The capacitor C1 can be a variable unit during adjustment and then replaced with a suitable fixed unit when the required capacitance value is found. Maximum capacitance should be about 100 pF for 50 MHz and 35 to 50 pF for 144 MHz. The capacitor and arm can be combined with the arm connecting to the driven element by means of a sliding clamp, and the inner end of the arm sliding inside a sleeve connected to the inner conductor of the coax. It can be constructed from concentric pieces of tubing, insulated by plastic sleeving or shrink tubing. RF voltage across the capacitor is low, once the match is adjusted properly, so with a good dielectric, insulation presents no great problem. A clean, permanent, high-conductivity bond between arm and element is important, as the RF current is high at this point.

Because it is inherently somewhat unbalanced, the gamma match can sometimes introduce pattern distortion, particularly on long-boom, highly directive Yagi arrays. The T-match, essentially two gamma matches in series creating a balanced feed system, has become popular for this reason. (See the preceding discussion on T-matches in the HF Yagi section.) A coaxial balun like that shown in Fig 21.105B is used from the balanced T-match to the unbalanced coaxial line going to the transmitter. To maintain a symmetrical pattern, the feed line should be run along the antenna boom at the centerline of the elements to the mast. A choke balun is often used to minimize currents that might be induced on the outer surface of the feed line shield.

FOLDED DIPOLE

The impedance of a half-wave dipole feed point at its center is 72 Ω. If a single conductor of uniform size is folded to make a half-wave dipole, as shown in Fig 21.105D, the impedance is stepped up four times. Such a folded dipole can thus be fed directly with 300-Ω line with no appreciable mismatch. Coaxial feed line of 70 to 75 Ω impedance may then be used with a 4:1 impedance transformer. Higher impedance step-up can be obtained if the unbroken portion is made larger in cross-section than the fed portion, as in Fig 21.105E. The folded dipole is discussed further in the *ARRL Antenna Book*.

21.10.9 Baluns and Impedance Transformers

Conversion from balanced loads to unbalanced lines, or vice versa, can be performed with electrical circuits, or their equivalents made of coaxial line. A balun made from flexible coax is shown in **Fig 21.106A**. The looped portion is an electrical half-wave. This type of balun gives an impedance step-up of 4:1, 50 to 200 Ω, or 75 to 300 Ω typically. See the **RF Techniques** and **Transmission Lines** chapters for a detailed discussion of baluns and impedance transformers.

The physical length of the line section depends on the propagation factor of the line used, so it is best to check its resonant frequency, as shown at B. One end of the line is

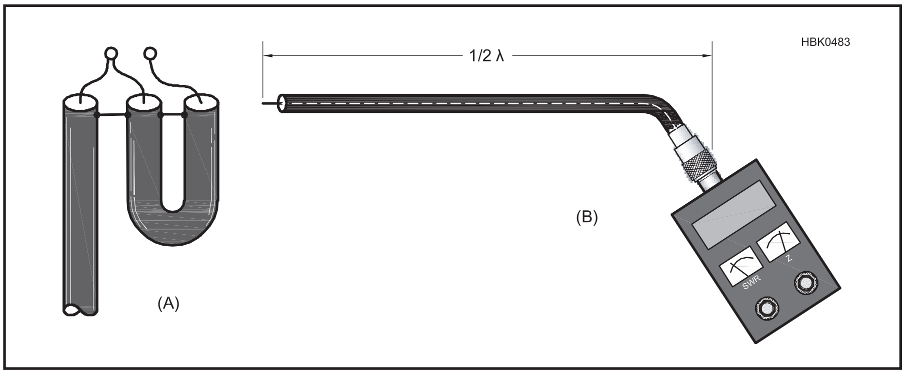


Fig 21.106 — Conversion from unbalanced coax to a balanced load can be done with a half-wave coaxial balun, A. The half-wave balun gives a 4:1 impedance step up. Electrical length of the looped section should be checked with an antenna analyzer with the far end of the line open, as in B. The lowest frequency at which the line impedance is a minimum is the frequency at which the line is ¼-λ long. Multiply that frequency by two to obtain the ½-λ frequency.

left open and an antenna analyzer used to find the lowest frequency at which the impedance at the other end of the line is a minimum, the frequency at which the section of line is ¼-λ long. Multiply the frequency by two to find the frequency at which the section is ½-λ long.

Coaxial baluns giving a 1:1 impedance transfer are shown in **Fig 21.107**. The coaxial sleeve, open at the top and connected to the outer conductor of the line at the lower end (Fig 21.107A) is the preferred type. A conductor of approximately the same size as the line is used with the outer conductor to form a quarter-wave stub, in Fig 21.107B. Another piece of coax, using only the outer conductor, will serve this purpose. Both baluns are intended to present a high impedance to any RF current that might otherwise tend to flow on the outer conductor of the coax. Choke baluns made of ferrite beads of the proper material type or mix may also be used. See the **RF Techniques** chapter for information about ferrite use at VHF and UHF.

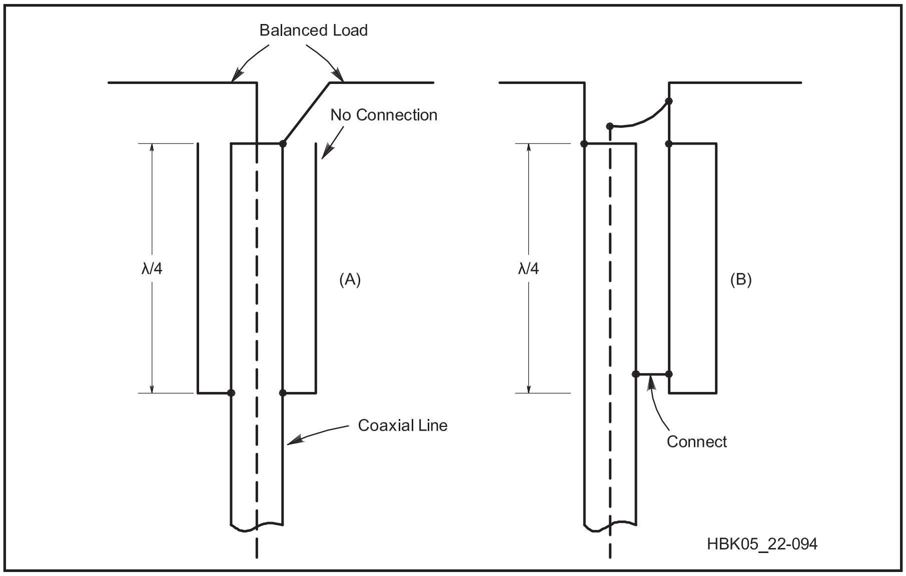


Fig 21.107 — The balun conversion function, with no impedance change, is accomplished with quarter-wave lines, open at the top and connected to the coax outer conductor at the bottom. The coaxial sleeve shown at A is preferred.

Project: Simple, Portable Ground-Plane Antenna

This utility antenna is built on a coaxial connector. UHF connectors work well, but you may prefer to use type N or BNC connectors. With only two radials, it is essentially two dimensional, which makes it easier to store when not in use.

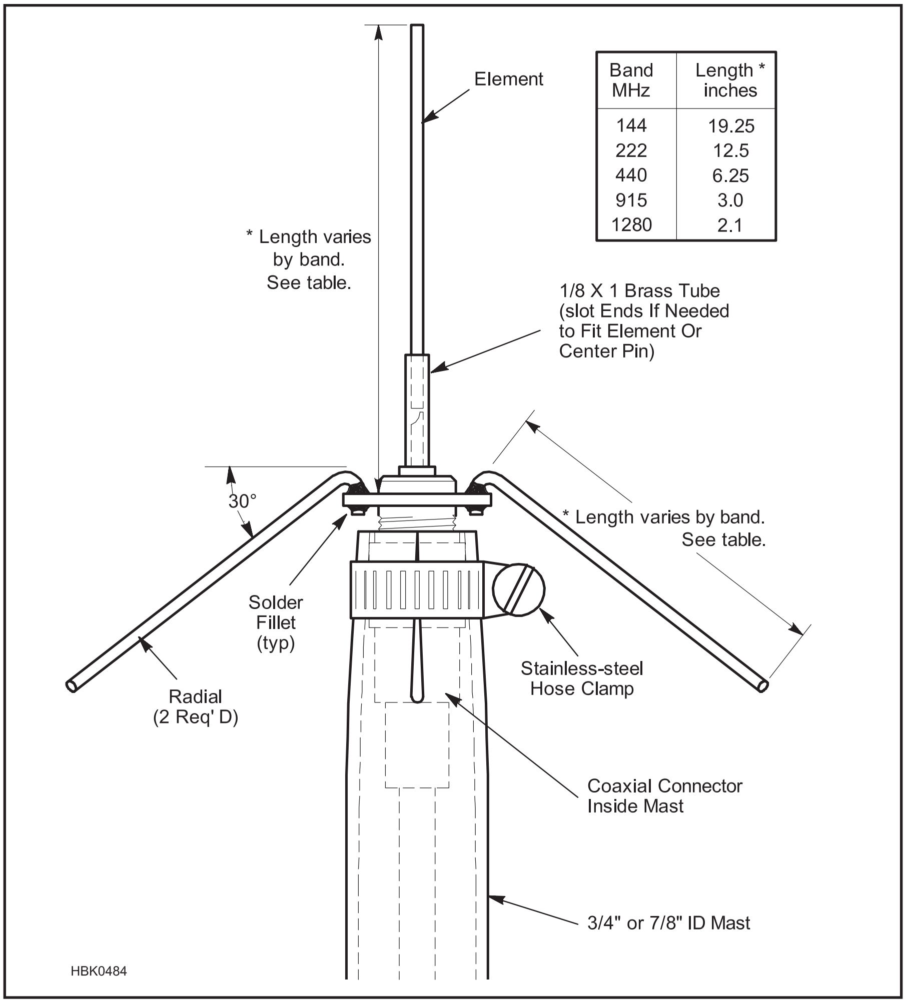
If the antenna is sheltered from weather, copper wire is sufficiently rigid for the radiating element and radials. Antennas exposed to the wind and weather can be made from brazing rod, which is available at welding supply stores. Alternatively, #12 or #14 AWG copper-clad steel wire could be used to construct this antenna.

The ground-plane antenna is shown in **Fig 21.108** and uses a female chassis-mount connector to support the element and two radials. To eliminate sharp ends, it's a good idea to bend the element and radial ends into a circle or to terminate them with a crimp terminal as in **Fig 21.109**. The crimp terminal approach is easier with stiff wire. Crimp and then solder the terminal to the wire. Make the overall length of the element and radials the same as shown in Fig 21.108, measuring to the outer tip of the loop or terminal.

Radials may be attached directly to the mounting holes of the coaxial connector. Bend a hook at one end of each radial for insertion through the connector. Solder the radials to the connector using a large soldering iron or propane torch.

Solder the element to the center pin of the connector. If the element does not fit inside the solder cup, use a short section of brass tubing as a coupler (a slotted ⅛-inch-ID tube will fit over an SO-239 or N-receptacle center pin).

If necessary, prune the antenna to raise the



Band MHz	Length * inches
144	19.25
222	12.5
440	6.25
915	3.0
1280	2.1

Fig 21.108 — A simple ground-plane antenna for the 144, 222 or 440-MHz bands. The feed line and connector are inside the mast, and a hose clamp squeezes the slotted mast end to tightly grip the plug body. Element and radial dimensions given in the drawing are good for the entire band.

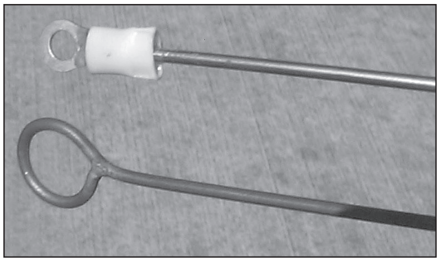


Fig 21.109 — Alternate methods for terminating element and radial tips on the simple ground-plane antenna. See text. *(Photo by K8CH)*

frequency of minimum SWR. Then adjust the radial droop angle for minimum SWR — this should not affect the frequency at which the minimum SWR occurs.

One mounting method for fixed-station antennas appears in Fig 21.108. The feed line and connector are inside the mast, and a hose clamp squeezes the slotted mast end to tightly grip the plug body. Once the antenna is mounted and tested, thoroughly seal the open side of the coaxial connector with silicone sealant, and weatherproof the connections with rust-preventative paint.

Project: Coaxial Dipole for VHF or UHF

(The following antenna was originally described in July 2009 *QST* by John Portune, W6NBC, and was also reprinted in *The ARRL Antenna Compendium Volume 8*.)

Here is a homebrew coaxial dipole built from a small stainless whip, a length of threaded table-lamp tubing and some ¾ inch copper and PVC fittings. The one shown is for 440 MHz but it can readily be scaled for 146 or 222 MHz.

For homebrew vertical VHF antennas, coaxial dipoles often play second fiddle to J-poles. That's because the center connection to coax is often difficult to fabricate in the home workshop. Yet both antennas have the same performance. They're both full sized, half wave vertical dipoles, and the coaxial is shorter.

MAKING A COAXIAL DIPOLE

If you start with a common half wave (λ/2) stainless whip and extend it all the way down through a λ/2 long support tubing, here made from a threaded table lamp tube, the lower part of the whip becomes the center conductor of a short length of rigid coax feeding the center of the antenna. Now connection to normal coax is easily made below the antenna. To form the rigid coax section, you'll need to insulate the center conductor (lower part of the stainless whip) from the lamp tubing with some ¼ inch inside diameter (ID) polyethylene tubing. Hardware stores normally carry it. This short length of rigid coax formed in this way isn't precisely 50 Ω characteristic impedance, but the difference is totally insignificant. The drawing in **Fig 21.110** shows the details.

Assembly Details

The bottom half (λ/4) of the radiating dipole is a coaxial sleeve made from ¾ inch copper pipe and a pipe cap. The coax feed runs up its center to the connector at the bottom

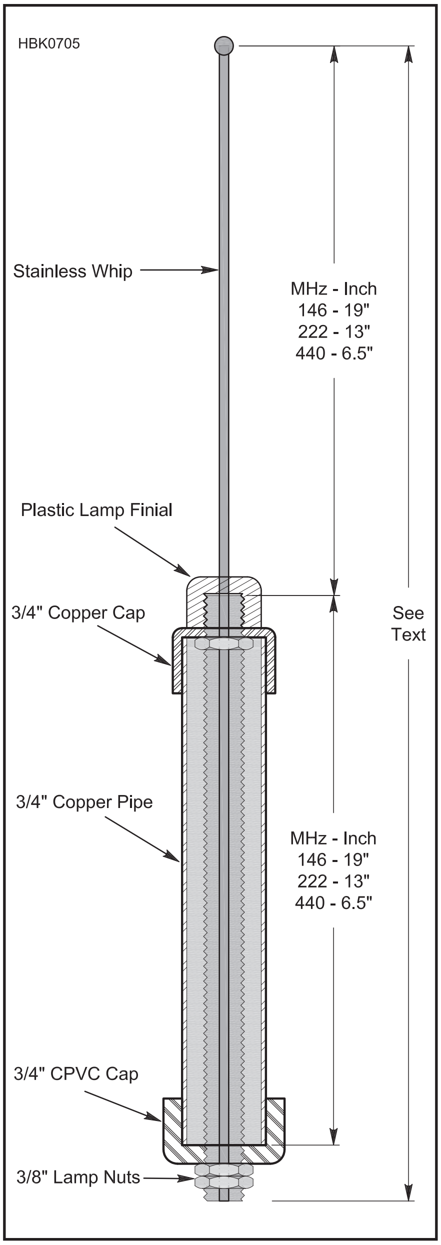
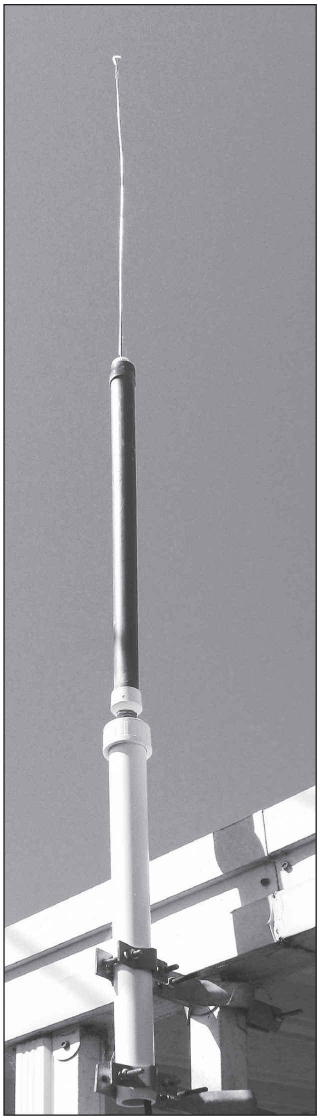


Fig 21.110 — Dimensioned drawing of coaxial dipole for three bands.



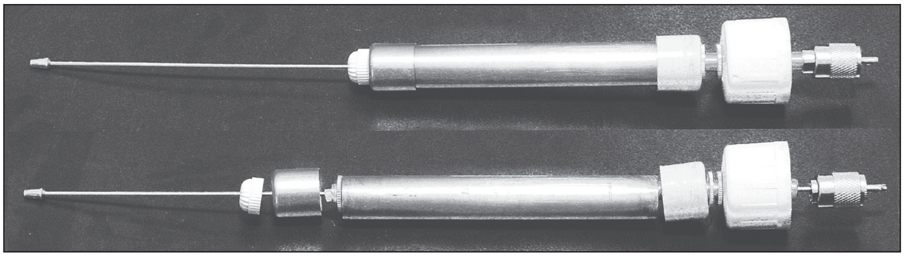


Fig 21.111 — Details of final assembly of coaxial dipole (A) and the finished product (B).

of the lamp tubing. Support and insulation of the bottom of the sleeve is provided by a ¾ inch CPVC plastic pipe cap. For those not familiar with CPVC fittings, they're made to mate with copper pipe and can handle high water temperatures. That's not true of common PVC fittings. Most hardware stores now carry CPVC. Drill a ⅜ inch hole in the center top of the copper and the CPVC caps for the lamp tubing to pass through.

The whole antenna is held together by two lamp tubing nuts and a plastic lamp finial, also readily available at hardware stores (see **Fig 21.111**). Note that a lamp tubing nut is also required inside the copper pipe cap. Drill a small hole in the middle of the lamp finial for the stainless whip. On the bottom of lamp tubing below the antenna install a 1¼ inch common PVC pipe cap, and secure it with two more lamp tubing nuts. This gives you a way to easily mount the antenna on top of any convenient length of 1¼ inch PVC pipe. Run the coax feed down through the PVC pipe.

Hooking it Up

A conventional PL-259 UHF type coax connector for RG-8 coax will actually screw onto the bottom of the lamp tubing. The threads are not a perfect fit, but will tighten satisfactorily. The stainless whip runs down all the way to the very tip of the PL-259 connector. Solder it in there. Before doing so, however, install all the pieces of the antenna onto the threaded lamp tubing.

Many hams may think that stainless steel won't solder. It definitely will with a hot iron and acid flux. Scrape the end of the whip and dip it in hydrochloric swimming pool acid. With a little action from the tip of the soldering iron the whip will tin perfectly well. Before soldering, however, grind two or three small side notches in the bottom end of the whip. A Dremel tool works well for this. The notches will help the solder securely lock the whip into the tip of the PL-259 connector. Neutralize any leftover acid with baking soda solution.

Perhaps surprising to some, it really isn't necessary to solder any other parts of the antenna. There is adequate mating surface at the joints for the RF to cross over efficiently. Do, however, seal all possible water access spots with common silicone sealant and or plastic electrical tape.

MAKE IT FOR THE BAND YOU LIKE

There isn't an exact length required for the lamp tubing or the stainless whip. These merely need to provide enough space for all the pieces of the antenna to go together. The author had a 48 inch whip on hand that he used uncut for the 146 MHz coaxial dipole and a similar 17 inch uncut whip for 440 MHz. He cut the lamp tubing to an appropriate length to fit the whips. What does matter, however, is the length of the whip above the top of the lamp tubing as well as the length of the coaxial sleeve. These need to be close to a $\lambda/4$ — for 440 MHz, 6-½ inches; for 222 MHz, 13 inches; and 19 inches for 146 MHz. These antennas are quite broad band and will cover the entire band in each case with these sizes. No cutting or pruning is necessary.

For ruggedness, or perhaps for stealth, you can install the whole antenna inside of 2 inch PVC water or ABS soil pipe and close the ends with end caps. The author lives in a mobile home park where antennas are not permitted, but the landlord thinks these coaxial dipoles (in ABS pipe) are vent pipes.

Try out one of these homebrew coaxial dipoles. You may find you prefer its smaller size, less obvious appearance and superior weatherproofing as compared to a J-pole.

21.11 VHF/UHF Yagis

Without doubt, the Yagi is king of home-station antennas these days. Today's best designs are computer optimized. For years amateurs as well as professionals designed Yagi arrays experimentally. Now we have powerful (and inexpensive) personal computers and sophisticated software for antenna modeling. These have brought us antennas with improved performance, with little or no element pruning required. A more complete discussion of Yagi design can be found earlier in this chapter and in the *ARRL Antenna Book*.

21.11.1 Stacking Yagis

Where suitable provision can be made for supporting them, two Yagis mounted one above the other and fed in-phase may be preferable to one long Yagi having the same theoretical or measured gain. The pair will require a much smaller turning space for the same gain, and their lower radiation angle can provide interesting results. On long ionospheric paths a stacked pair occasionally may show an apparent gain much greater than the 2 to 3 dB that can be measured locally as the gain from stacking.

Optimum spacing for Yagis with booms longer than 1 λ is one wavelength, but this may be too much for many builders of 50-MHz antennas to handle. Worthwhile results are possible with separations of as little as ½ λ (10 ft), but ⅝ λ (12 ft) is markedly better. At 50 MHz, the difference between 12 and 20-ft spacing may not be worth the added structural problems.

The closer spacings give lowered measured gain, but the antenna patterns are cleaner (less power in the high-angle elevation lobes) than with 1-λ spacing. Extra gain with wider spacings is usually the objective on 144 MHz and higher bands, where the structural problems are not quite as severe as on 50 MHz.

One method for feeding two 50-Ω antennas, as might be used in a stacked Yagi array, is shown in **Fig 21.112**. The transmission lines from each antenna, with a balun feeding each antenna (not shown in the drawing for simplicity), to the common feed point must be equal in length and an odd multiple of ¼-λ. This line acts as a quarter-wave (Q-section) impedance transformer, raises the feed impedance of each antenna to 100 Ω, and forces current to be equal in each driven element. When the feed lines are connected in parallel at the coaxial tee connector, the resulting impedance is close to 50 Ω.

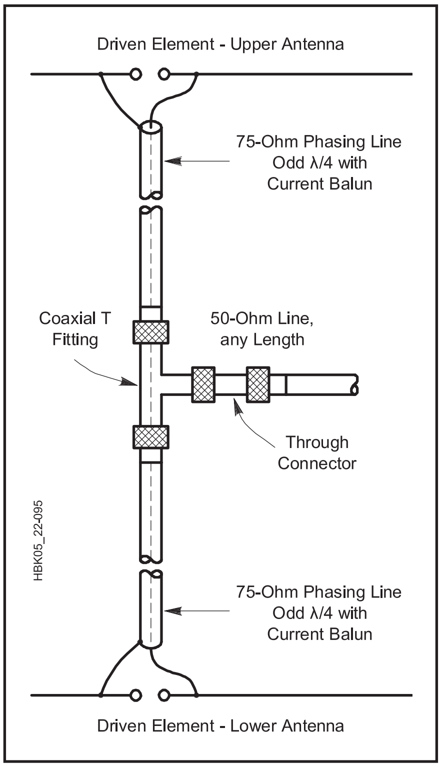


Fig 21.112 — A method for feeding a stacked Yagi array. Note that baluns at each antenna are not specifically shown. Good practice is to use choke baluns made up of ferrite beads slipped over the outside of the coax and taped to prevent movement. See the RF Techniques and Transmission Lines chapter for details.

Project: Three and Five-Element Yagis for 6 Meters

Boom length often proves to be the deciding factor when one selects a Yagi design. Dean Straw, N6BV, created the designs shown in **Table 21.20**. Straw generated the designs in the table for convenient boom lengths (6 and 12 ft). The 3-element design has about 8 dBi gain, and the 5-element version has about 10 dBi gain. Both antennas exhibit better than 22 dB front-to-rear ratio, and both cover 50 to 51 MHz with better than 1.6:1 SWR.

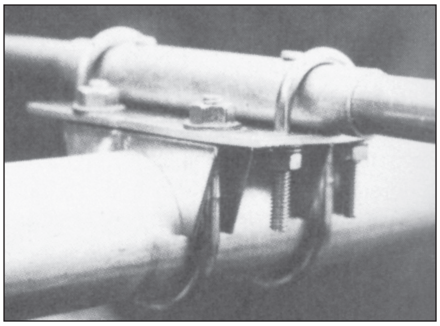


Fig 21.113 — The boom-to-element clamp. Galvanized U-bolts are used to hold the element to the plate, and 2-inch galvanized muffler clamps hold the plates to the boom.

Element lengths and spacings are given in the table. Elements can be mounted to the boom as shown in **Fig 21.113**. Two muffler clamps hold each aluminum plate to the boom, and two U bolts fasten each element to the plate, which is 0.25 inches thick and 4.4 inches square. Stainless steel is the best choice for hardware. However, galvanized hardware can be substituted. Automotive muffler clamps do not work well in this application, because they are not galvanized and quickly rust once exposed to the weather.

The driven element is mounted to the boom on a phenolic plate of similar dimension to the other mounting plates. A 12-inch piece of Plexiglas rod is inserted into the driven element halves. The Plexiglas allows the use of a single clamp on each side of the element and also seals the center of the elements against moisture. Self-tapping screws are used for electrical connection to the driven element.

Refer to **Fig 21.114** for driven element and hairpin match details. A bracket made from a piece of aluminum is used to mount

Table 21.20
Optimized 6 Meter Yagi Designs

	Spacing From Reflector (in.)	*Seg 1 Length (in.)*	*Seg 2 Length (in.)*	*Midband Gain F/R*
306-06				
Refl	0	36	22.500	8.1 dBi
DE	24	36	16.000	28.3 dB
Dir 1	42	36	15.500	
506-12				
OD		0.750	0.625	
Refl	0	36	23.625	10.0 dBi
DE	24	36	17.125	26.8 dB
Dir 1	36	36	19.375	
Dir 2	80	36	18.250	
Dir 3	138	36	15.375	

Note: For all antennas, telescoping tube diameters (in inches) are: Seg1=0.750, Seg2=0.625.

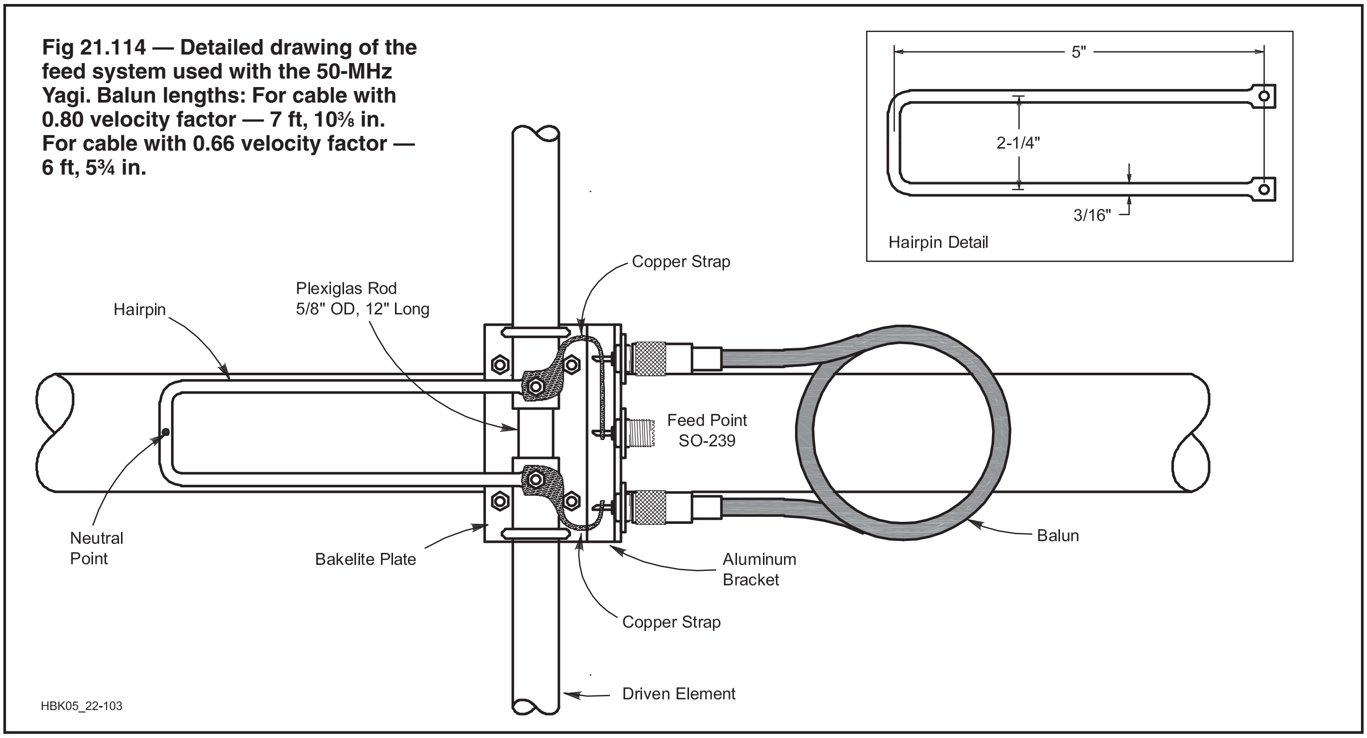


Fig 21.114 — Detailed drawing of the feed system used with the 50-MHz Yagi. Balun lengths: For cable with 0.80 velocity factor — 7 ft, 10⅜ in. For cable with 0.66 velocity factor — 6 ft, 5¾ in.

the three SO-239 connectors to the driven element plate. A 4:1 transmission-line balun connects the two element halves, transforming the 200-Ω resistance at the hairpin match to 50 Ω at the center connector. Note that the electrical length of the balun is λ/2, but the physical length will be shorter due to the velocity factor of the particular coaxial cable used. The hairpin is connected directly across the element halves. The exact center of the hairpin is electrically neutral and should be fastened to the boom. This has the advantage of placing the driven element at dc ground potential.

The hairpin match requires no adjustment as such. However, you may have to change the length of the driven element slightly to obtain the best match in your preferred portion of the band. Changing the driven-element length will not adversely affect antenna performance. *Do not adjust the lengths or spacings of the other elements — they are optimized already*. If you decide to use a gamma match, add three inches to each side of the driven element lengths given in the table for both antennas.

Project: Medium-Gain 2 Meter Yagi

This project was designed and built by L. B. Cebik, W4RNL (SK). Practical Yagis for 2 meters abound. What makes this one a bit different is the selection of materials. The elements, of course, are high-grade aluminum. However, the boom is PVC and there are only two #6 nut-bolt sets and two #8 sheet metal screws in the entire antenna. The remaining fasteners are all hitch-pin clips. The result is a very durable six-element Yagi that you can disassemble with fair ease for transport.

THE BASIC ANTENNA DESIGN

The 6-element Yagi presented here is a derivative of the *optimized wide-band antenna* (OWA) designs developed for HF use by NW3Z and WA3FET. **Fig 21.115** shows the general outline. The reflector and first director largely set the impedance. The next

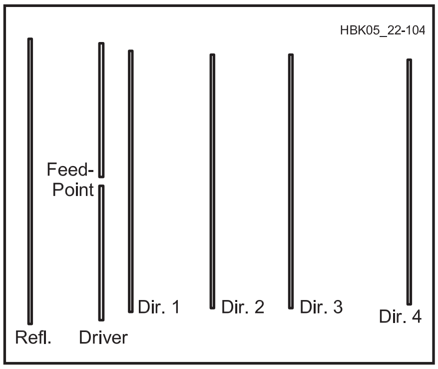


Fig 21.115 — The general outline of the 2 meter 6-element OWA Yagi. Dimensions are given in Table 21.21.

Table 21.21
2 Meter OWA Yagi Dimensions

Element	*Element Length (in)*	*Spacing from Reflector (in)*	*Element Diameter (in)*
Version described here:			
Refl.	40.52	——	0.1875
Driver	39.70	10.13	0.5
Alt. Driver	*39.96*	*10.13*	*0.1875*
Dir. 1	37.36	14.32	0.1875
Dir. 2	36.32	25.93	0.1875
Dir. 3	36.32	37.28	0.1875
Dir. 4	34.96	54.22	0.1875
Version using 1/8-inch diameter elements throughout:			
Refl.	40.80	——	0.125
Driver	40.10	10.20	0.125
Dir. 1	37.63	14.27	0.125
Dir. 2	36.56	25.95	0.125
Dir. 3	36.56	37.39	0.125
Dir. 4	35.20	54.44	0.125

Table 21.22
Parts List for the 2 Meter OWA Yagi

Qty	*Item*
17'	0.1875" (3/16") 6061-T6 aluminum rod (Source: Texas Towers)
3.5'	0.5" (½") 6063-T832 aluminum tubing (Source: Texas Towers)
7'	Schedule 40, ½" PVC pipe (Source: local hardware store)
3	Schedule 40, ½" PVC Tee connectors (Source: local hardware store)
2	Schedule 40, ½" PVC L connectors (Source: local hardware store)
—	Miscellaneous male/female threaded pipe diameter transition fittings (Source: local hardware store)
1	Support mast
10	Stainless steel hitch-pin clips (hairpin cotter pins), 3/16" to ¼" shaft range, 0.04" "wire" diameter (McMasters-Carr part number 9239A024, or local hardware store)
2	Stainless steel #6 nut/bolt/lock-washer sets, bolt length 1" (Source: local hardware store)
2	Stainless steel #8 sheet metal screws (Source: local hardware store)
1	BNC connector (Source: local electronics outlet)
2"	1/16" thick aluminum L-stock, 1" per side (Source: local hardware store)
1	VHF bead-balun choke (Source: Wireman, Inc.)

2 directors contribute to setting the operating bandwidth. The final director (Dir. 4) sets the gain. This account is over-simplified, since every element plays a role in every facet of Yagi performance. However, the notes give some idea of which elements are most sensitive in adjusting the performance figures.

Designed using *NEC-4*, the antenna uses 6 elements on a 56-inch boom. **Table 21.21** gives the specific dimensions for the version described in these notes. The parasitic elements are all 3/16-inch aluminum rods. For ease of construction, the driver is ½-inch aluminum tubing. Do not alter the element diameters without referring to a source, such as RSGB's *The VHF/UHF DX Book*, edited by Ian White, G3SEK, (Chapter 7), for information on how to recalculate element lengths.

The driver is the simplest element to readjust. Table 21.21 shows an alternative driver using 3/16-inch diameter material. Of all the elements, the driver is perhaps the only one for which you may extrapolate reasonable lengths for other diameters from the two lengths and diameters shown. However, the parasitic elements may require more work than merely substituting one diameter and length for another. The lower portion of the table shows the design adjusted for 1/8-inch elements throughout. Not all element lengths change by the same amount using any single formula.

The OWA design provides about 10.2 dBi of free-space gain with better than 20 dB front-to-back (or front-to-rear) ratio across the entire 2 meter band. Azimuth (or E-plane) patterns show solid performance across the entire band. This applies not only to forward gain but rejection from the rear.

One significant feature of the OWA design is its direct 50-Ω feed point impedance that requires no matching network. Of course, a choke balun to suppress any currents on the feed line is desirable, and a simple ferrite bead balun (see the **Transmission Lines** and **Station Accessories** chapters) works well in this application. The SWR, shown in **Fig 21.116**, is very flat across the band and never reaches 1.3:1. The SWR and the pattern consistency together create a very useful utility antenna for 2 meters, whether installed vertically or horizontally. The only remaining question is how to effectively build the beam in the average home shop.

THE BEAM MATERIALS

The boom is Schedule 40, ½-inch nominal PVC. Insulated booms are good for test antennas, since they do not require recalculating the element lengths due to the effects of a metal boom.

White PVC stands up for a decade of exposure in Tennessee, but apparently does not do as well in every part of the US. You may wish to use the gray electrical conduit version. If you use any other material for your boom, be sure that it is UV-protected. You'll find a parts list in **Table 21.22**. Sources for the parts are given in the table. However, you are encouraged to develop your own sources for antenna materials.

Fig 21.117 shows the element layout along the 56-inch boom. Centering the first element hole 1 inch from the rear end of the boom results in a succession of holes for the 3/16-inch pass-through parasitic elements. Only the driver requires special treatment. We shall use a 3/8-inch hole to carry a short length of fiberglass rod that will support the two sides of the driver element. Note that the antenna uses a BNC connector, mounted on a small plate that we shall meet along the way.

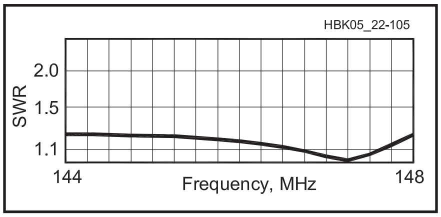


Fig 21.116 — SWR curve as modeled using *NEC-4* for the 2-m 6-element OWA Yagi.

The boom is actually a more complex structure than initially meets the eye. You need a support for the elements, and a means of connecting the boom to the mast. If you break the boom in the middle to install a Tee connector for the mast junction, you come very close to the 2nd director. **Fig 21.118** shows how to avoid the predicament.

Before drilling the boom, assemble it from common Schedule 40 ½-inch fittings and insert the lengths of PVC pipe. Fig 21.118 shows the dimensions for the center section of the boom assembly. However, PVC dimensions are always *nominal*, that is, meeting certain minimum size standards. So you may have to adjust the lengths of the linking pieces slightly to come up with a straight and true boom assembly.

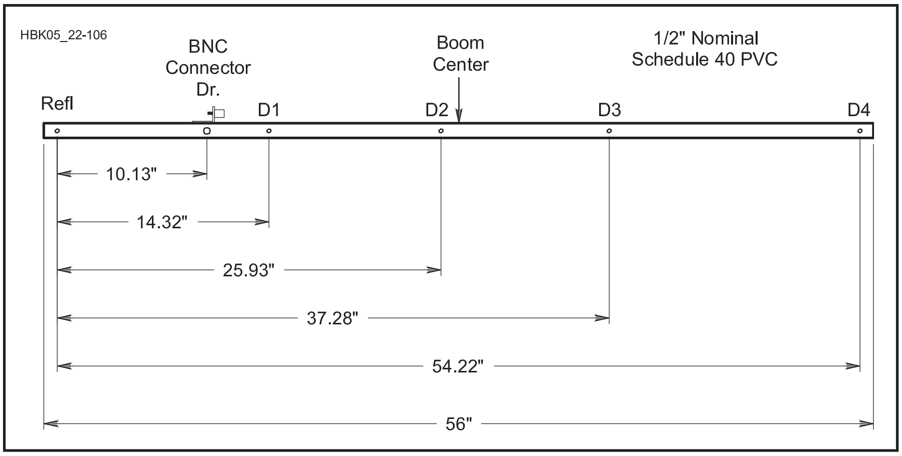


Fig 21.117 — Layout of elements along the PVC boom for the 2 meter 6-element OWA Yagi, showing placement of the BNC connector and the boom center.

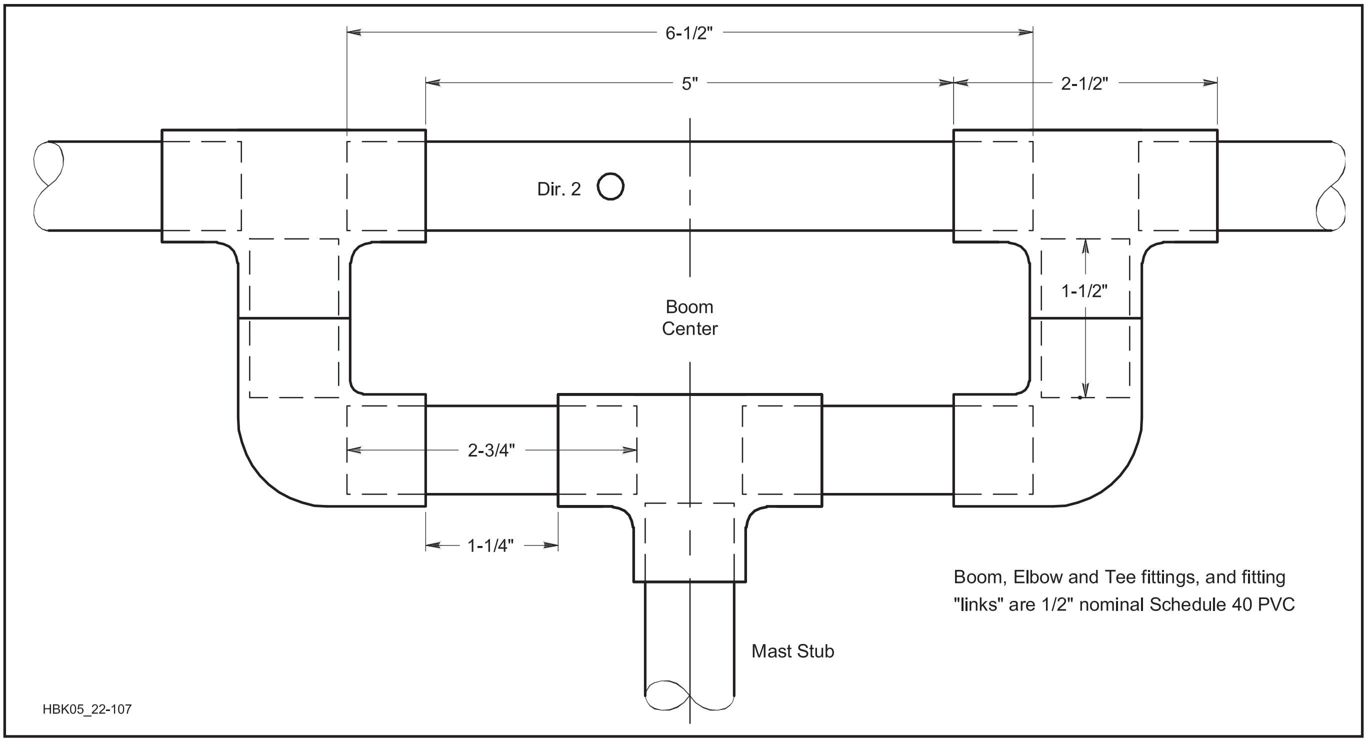


Fig 21.118 — Details of a parallel PVC pipe structure for the Yagi boom and mount.

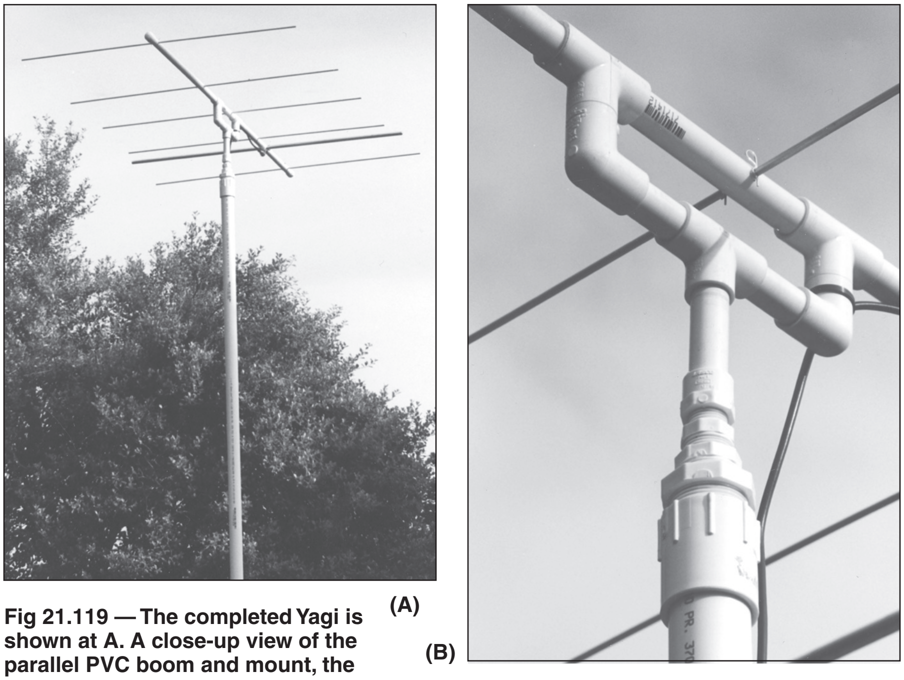

(A)
(B)

Fig 21.119 — The completed Yagi is shown at A. A close-up view of the parallel PVC boom and mount, the sequence of threaded fittings, and the hitch-pin clips used to secure parasitic elements is shown at B.

Use scrap lumber to help keep everything aligned while cementing the pieces together. A 1×4 and a 1×6 nailed together along the edges produce a very good platform with a right-angle. Start with the two upper Tees and the Ls below each one. Dry-fit scrap PVC into the openings except for the short link that joins the fitting. Cement these in place and align them using the dry-fit pieces as guides to keep everything parallel. Next, cement the two short (2¾-inch) links into the third Tee. Then, cement one link into its L, using the dry-fit tube in the upper Tee as an alignment guide.

Before proceeding further, carefully measure the required length of PVC for the boom section between Tees. How well you measure here will determine whether the boom will be straight or whether it will bow up or down. Now, cement both the L and the Tee at the same time, pressing the cemented sections into the 2-board jig to assure alignment.

The final step in the process is to add the 23-inch boom end pieces to the open ends of the upper Tees. For the brief period in which the PVC cement is wet, it is possible to misalign the tubing. Dry-fit end caps on the boom ends and do the cement work using the 2-board jig. By pressing the assembly into the right angle of the boards, you can assure that you have a very true boom. When you've put the PVC cement back onto its shelf, your boom should be ready to drill.

Consider the boom-to-mast connection. The lower Tee in Fig 21.118 receives a short length of ½-inch nominal Schedule 40 PVC. This material has an outside diameter of about ⅞-inch, not a useful size for joining to a mast. However, PVC fittings have a handy series of threaded couplers that allow you to screw-fit a series of ever-larger sizes until you reach a more useful size. As **Fig 21.119B** shows, enough of these fittings will finish off with a 1¼-inch threaded female side and a 1¼-inch cement-coupling side. To this fitting, cement a length of 1¼-inch tubing that slides over a length of common TV mast. For a tight fit, wrap the TV mast with several layers of electrical tape in two places — one near the upper end of the PVC pipe section and the other close to where the PVC pipe ends. You may then use stainless steel through-bolts or set-screws to prevent the PVC assembly from turning.

BOOM AND ELEMENTS

Before installing the elements, you need to drill the holes in the boom. The two-board jig comes in handy once more. The key goals in the drilling process are to: A) precisely position the holes; B) create holes that are a fairly tight fit for the rod elements; and C) keep the elements aligned in a flat plane. For this purpose, a drill press is almost a necessity for all but those with the truest eyes.

Use the jig and a couple of clamps to hold the boom assembly in place. Because the assembly has two parallel sections, laying it flat will present the drill press with the correct angle for drilling through the PVC in one stroke. Drill the holes at pre-marked positions, remembering that the driver hole is ⅜ inch while all the others are 3⁄16 inch. Clean the holes, but do not enlarge them in the process.

By now you should have the rod and tube stock in hand. For antenna elements, don't rely on questionable materials that are designed for other applications. Rather, obtain 6063-T832 tubing and 6061-T6 rods from mail order sources, such as Texas Towers, McMasters-Carr, and others. These materials are often not available at local hardware depots.

Cut the parasitic elements to length and smooth their ends with a fine file or sandpaper. Find the center of each element and carefully mark a position about 1⁄16 in. outside where the element will emerge from each side of the boom. You'll drill small holes in these locations. You may wish to very lightly file a flatted area where the hole is to go to prevent the drill bit from slipping as you start the hole.

Drill 1⁄16-inch holes at each marked location all the way through the rod. De-burr the exit ends so that the rod will pass through the boom hole. These holes are the locations for hitch-pin clips. **Fig 21.120** shows the outline of a typical hitch-pin clip, which is also called a hairpin cotter pin in some catalogs and stores. Obtain stainless steel pins whose bodies just fit tightly over the rod when installed. Initially, install 1 pin per parasitic element. Slide the element through the correct boom hole and install the second pin. Although the upper part of the drawing shows a bit of room between the boom and pin, this space is for clarity. Install the pins as close to each side of the boom as you can.

Pins designed for a 3⁄16-inch rod are small enough that they add nothing significant to the element, and antenna tests showed that they did not move the performance curve of the antenna. Yet, they have held securely through a series of shock tests given to the prototype. These pins — in various sizes — offer the home builder a handy fastener that is applicable to many types of portable or field antennas. Although you may wish to use better fasteners when making permanent metal-to-metal connections, for joining sections of Field Day and similar antennas, the hitch-pin clips perform the mechanical function, while clean tubing sections themselves provide adequate electrical contact for a limited period of use.

THE DRIVER AND FEED LINE CONNECTOR

The final construction step is perhaps the one requiring the most attention to detail, as shown in **Fig 21.121**. The driver and feed point assembly consists of a 4- to 6-inch length of ⅜-inch fiberglass or other non-conductive rod, two sections of the driver element made from ½-inch aluminum tubing, a BNC connector, a home-made mounting plate, two sets of stainless steel #6 nuts, bolts, and lock-washers, and two stainless steel #8 sheet metal screws. Consult both the upper and lower portions of the figure, since some detail has been omitted from each one to show other detail more clearly.

First, trial fit the driver tubing and the fiberglass rod, marking where the rod exits the boom. Now pre-drill 9⁄64-inch holes through the tubing and the fiberglass rod. Do not use larger hardware, since the resulting hole will weaken the rod, possibly to the breaking

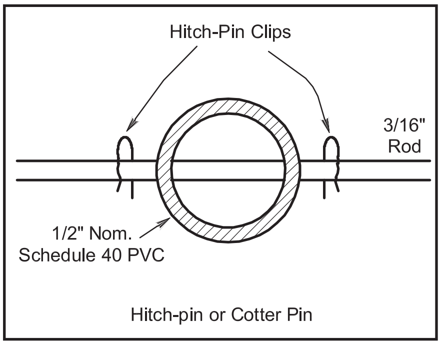


Fig 21.120 — The parasitic element mounting system, showing the placement of the hitch-pin clips and the shape of the clips.

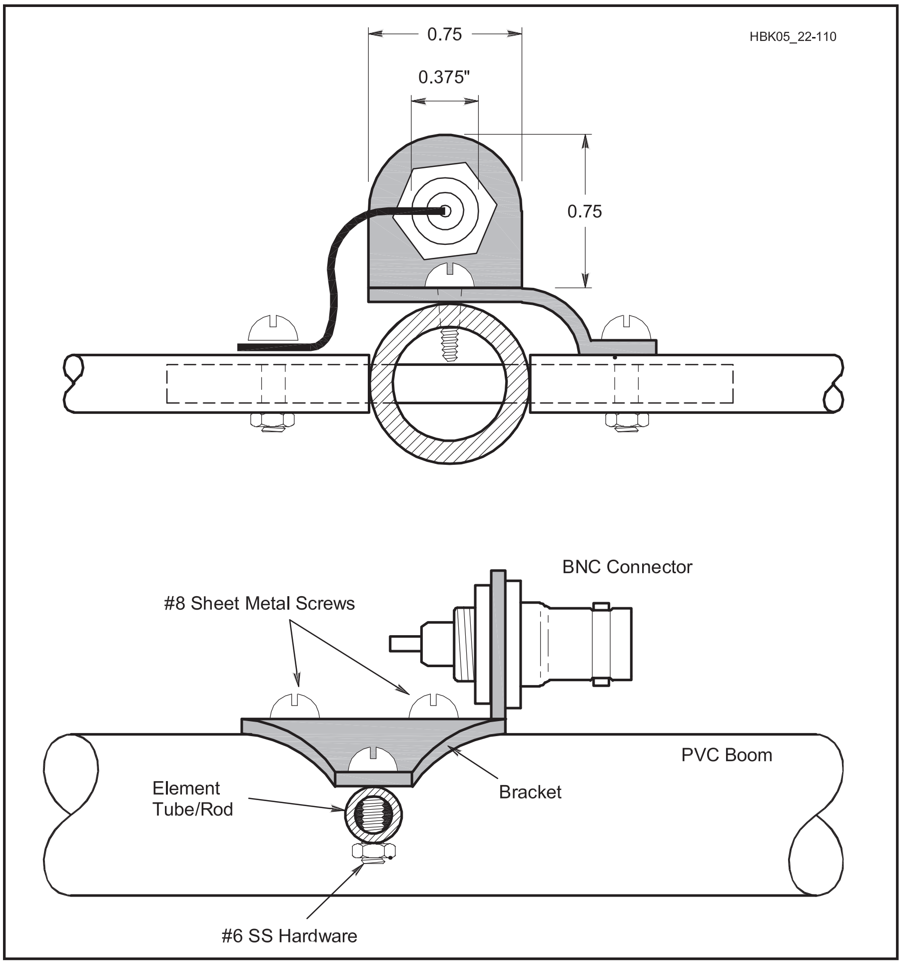


Fig 21.121 — Details of the feed point of the Yagi, showing the BNC connector, mounting plate, and connections to the ½-inch driver element halves placed over a central ⅜-inch fiberglass rod.

point. If you use an alternative plastic material, observe the same caution and be certain that the rod remains strong after drilling. Do not use wooden dowels for this application, since they do not have sufficient strength. Position the holes about ¼ to ⅜ inch from the tubing end where it presses against the boom. One hole will receive a solder lug and the other will connect to an extension of the BNC mounting plate.

Second, install the fiberglass rod through the boom. You can leave it loose, since the elements will press against the boom and hold it in place. Alternatively, you may glue it in place with a two-part epoxy. Slide the driver element tubes over the rod and test the holes for alignment by placing the #6 bolts in them.

Next, cut and shape the BNC mounting plate from 1⁄16-inch thick aluminum. The fitting is made from a scrap of L-stock 1 inch on a side. Before cutting the stock, drill the ⅜-inch hole needed for the BNC connector. Then cut the vertical portion. The horizontal portion requires a curved tab that reaches the bolt on one side of the boom. Use a bench vise to bend the tab in a curve and then flatten it for the bolt-hole. It takes several tries to get the shape and tab exact, so be patient. When the squared-edge piece finds its perfect shape, use a disk sander and round the vertical piece to follow the connector shape. Taper the tap edges to minimize excess material. The last step is to drill the mounting holes that receive the #8 sheet metal screws.

Mounting the assembly involves loosely attaching both the #6 and #8 hardware and alternately tightening up all pieces. Be certain that the side of the BNC connector that receives the coax points toward the mast. Next, mount the BNC connector. The shield side is already connected to one side of the driver. Mount the other side of the driver, placing a solder lug under the bolt head. Connect a short wire as directly as possible from the solder lug to the center pin of the BNC connector. After initial testing, you may coat all exposed connections with Plasti-Dip for weather protection.

TUNE-UP

Testing and tuning the antenna is a simple process if you build carefully. The only significant test that you can perform is to ensure that the SWR curve comes close to the one shown in Fig 21.116. If the SWR is high at 148 MHz but very low at 144 MHz, then you will need to shorten the driver ends by a small amount — no more than ⅛ inch per end at a time. Shaving the ends with a disk sander is most effective.

Using the antenna with vertical polarization will require good spacing from any support structure with metal vertical portions. One of the easiest ways to devise such a mounting is to create a PVC structure hat turns the entire boom by 90°. If you feel the need for added support, you can create can angular brace by placing 45° connectors in both the vertical and horizontal supports and running a length of PVC between them.

As an alternative, you can let the rear part of the boom be slightly long. To this end you can cement PVC fixtures — including the screw-thread series to enlarge the support pipe size. Create a smooth junction that you attach with a through-bolt instead of cement. By drilling one side of the connection with two sets of holes, 90° apart, you can change the antenna from horizontal polarization to vertical and back in short order.

The six-element OWA Yagi for 2 meters performs well. It serves as a good utility antenna with more gain and directivity than the usual three-element general-use Yagi. When vertically polarized, the added gain confirms the wisdom of using a longer boom and more elements. With a length under five feet, the antenna is still compact. The ability to disassemble the parts simplifies moving the antenna to various portable sites.

Project: **Cheap Yagis by WA5VJB**

If you're planning to build an EME array, don't use these antennas. But if you want to put together a VHF rover station with less than $500 in the antennas, read on as Kent Britain, WA5VJB, shows you how to put together a VHF/UHF Yagi with QRO performance at a QRP price. (This material is adapted from Kent's on-line paper "Controlled Impedance 'Cheap' Antennas" at **www.wa5vjb.com/references.html**.)

The simplified feed uses the structure of the antenna itself for impedance matching. So the design started with the feed and the elements were built around it. The antennas were designed with *YagiMax*, tweaked in *NEC*, and the driven elements experimentally determined on the antenna range.

Typically a high-gain antenna is designed in the computer, then you try to come up with a driven element matching arrangement for whatever feed point impedance the computer comes up with. In this design, compromises for the feed impedance, asymmetrical feed, simple measurements, wide bandwidth, the ability to grow with the same spacing, and trade-offs for a very clean pattern cost many dB of gain. But you can build these antennas for about $5!

Construction of the antennas is straightforward. The boom is ¾-inch square, or ½-inch by ¾-inch wood. To install an element, drill a hole through the boom and insert the element. A drop of cyanoacrylate "super glue," epoxy, or silicone adhesive is used to hold the elements in place. There is no boom-to-mast plate — drill holes in the boom and use a U-bolt to attach it to the mast!

The life of the antenna is determined by what you coat it with. The author had a 902-MHz version in the air varnished with polyurethane for two years with little deterioration.

The parasitic elements on prototypes have been made from silicon-bronze welding rod, aluminum rod, brass hobby tubing, and #10 or #12 AWG solid copper ground wire. So that you can solder to the driven element, use the welding rod, hobby tubing, or copper wire. The driven element is folded at one end with its ends inserted through the boom.

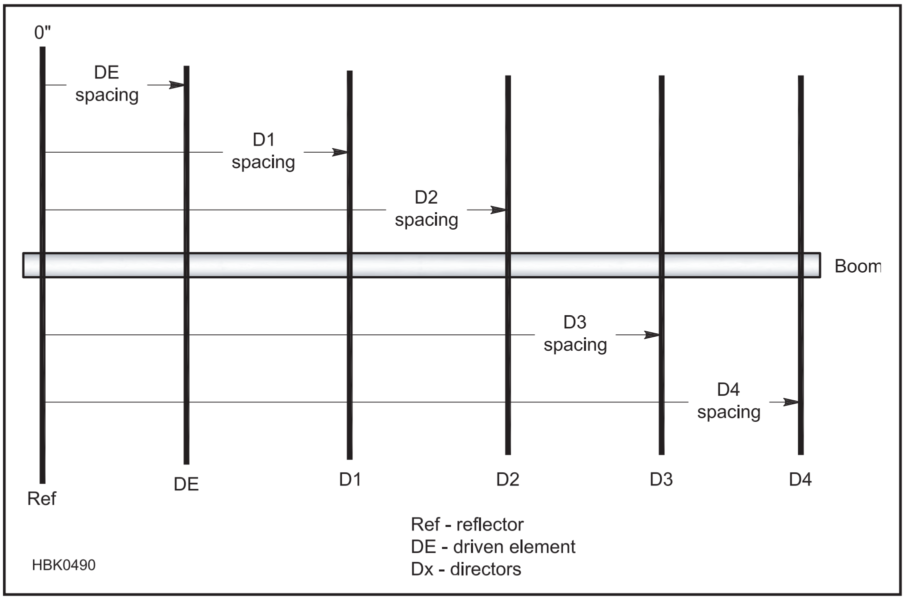


Fig 21.122 — Element spacing for the Cheap Yagis. Refer to Tables 21.23 to 21.30 for exact dimensions for the various bands.

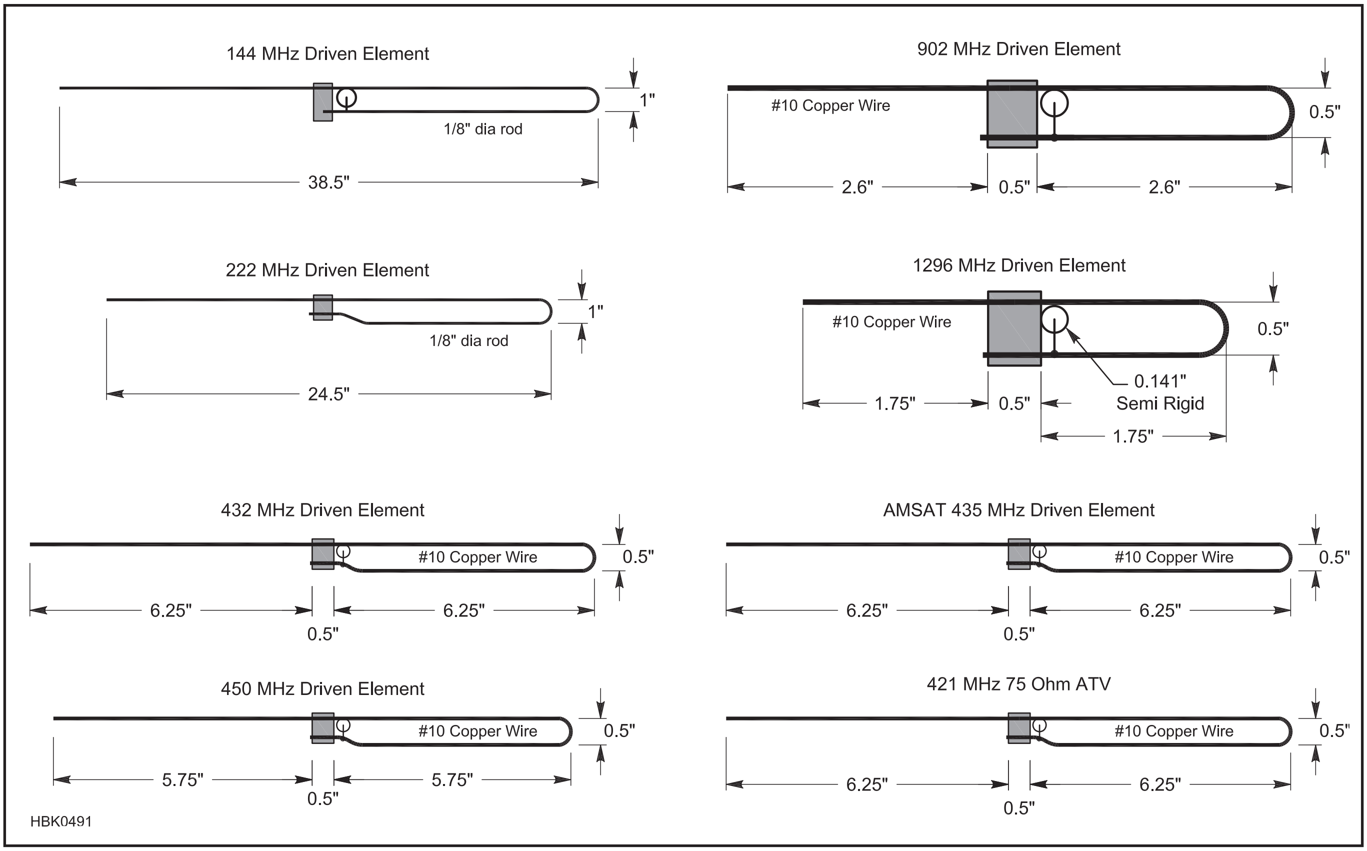


Fig 21.123 — Driven element dimensions for the Cheap Yagis. Attaching the coax shield to the center of the driven element is appropriate because that is the lowest impedance point of the element.

Fig 21.122 shows the basic plan for the antenna and labels the dimensions that are given in the table for each band. All table dimensions are given in inches.

Fig 21.123 shows how the driven element is constructed for each antenna. Trim the free end of the driven element to tune it for minimum SWR at the desired frequency. **Fig 21.124** shows how to attach coaxial cable to the feed point. Sliding a quarter-wave sleeve along the coax had little effect, so there's not much RF on the outside of the coax. You may use a ferrite bead choke balun if you like, but these antennas are designed for minimum expense!

Finally a bit of history on the design of these antennas. In 1993 at the Oklahoma City Central States VHF Society Conference, Arnie, CO2KK spoke on the difficulties building VHF antennas in non-industrialized nations. Just run down to the store and pick up some Delrin insulators and 0.141 inch Teflon coax? Arnie's tales were the motivation to use advanced technology to come up with something simple.

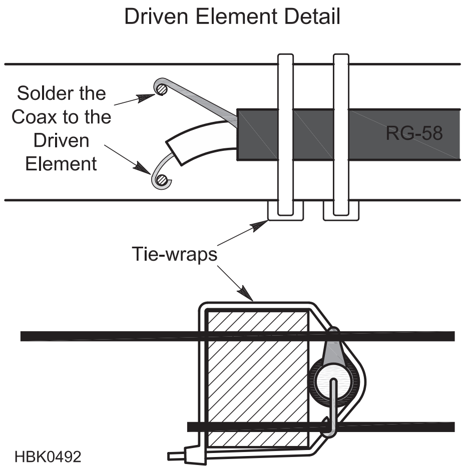


Fig 21.124 — Construction details and feed line attachment for the Cheap Yagi driven element.

144 MHz Yagi

While others have reported good luck with 16-element long-boom wood antennas, six elements was about the maximum for most rovers. The design is peaked at 144.2 MHz, but performance is still good at 146.5 MHz. All parasitic elements are made from 3/16-inch aluminum rod and the driven element is made from 1/8-inch rod. Lengths and spacings are given in **Table 21.23**.

222 MHz Yagi

This antenna is peaked at 222.1 MHz, but performance has barely changed at 223.5 MHz. You can drill the mounting holes to mount it with the elements horizontal or vertical. All parasitic elements are made from 3/16-inch aluminum rod and the driven element is made from 1/8-in. rod. Lengths and spacings are given in **Table 21.24**.

432 MHz Yagi

At this band the antenna is getting very practical and easy to build. All parasitic elements are made from 1/8-inch diameter rod and the driven element is made from #10 AWG solid copper wire. Lengths and spacings are given in **Table 21.25**.

435 MHz Yagi for AMSAT

KA9LNV provided help and motivation for these antennas. A high front-to-back ratio (F/B) was a major design consideration of all versions. The model predicts 30 dB F/B for the six-element and over 40 dB for the others. For gain, *NEC* predicts 11.2 dBi for the six-element, 12.6 dBi for the eight-element, and 13.5 dBi for the 10-element, and 13.8 dBi for the 11-element.

Using ¾-inch square wood for the boom makes it easy to build two antennas on the same boom for cross-polarization. Offset the two antennas 6½ inch along the boom and feed them in-phase for circular polarization, or just use one for portable operations. All parasitic elements are made from ⅛-inch diameter rod and the driven element is made from #10 AWG solid copper wire. Lengths and spacings are given in **Table 21.26**. The same element spacing is used for all four versions of the antenna.

450 MHz Yagi

For FM, this six-element Yagi is a good, cheap antenna to get a newcomer into a repeater or make a simplex-FM QSO during a contest. RadioShack ⅛ inch diameter aluminum ground wire (catalog #15-035) was used in the prototype for all the elements except the driven element, which is made from #10 AWG solid copper wire. Other ⅛-inch diameter material could be used. Lengths and spacings are given in **Table 21.27**.

902 MHz Yagi

This was the first antenna the author built using the antenna to control the driven element impedance. The 2.5-ft length has proven very practical. All parasitic elements are made from ⅛-inch-diameter rod and the driven element is made from #10 AWG solid copper wire. Lengths and spacings are given in **Table 21.28**.

1296 MHz Yagi

This antenna is the veteran of several "Grid-peditions" and has measured 13.5 dBi on the Central States VHF Society antenna range. Dimensions must be followed with great care. The driven element is small enough to allow 0.141-inch semi-rigid coax to be used. The prototype antennas use ⅛-inch silicon-bronze welding rod for the elements, but any ⅛-inch-diameter material can be used. The driven element is made from #10 AWG solid copper wire. Lengths and spacings are given in **Table 21.29**.

421.25 MHz 75-Ω Yagi for ATV

421 MHz vestigial sideband video is popular in North Texas for receiving the FM video input repeaters. These antennas are made for 421 MHz use and the driven element is designed for 75 Ω. RG-59 or an F adapter to RG-6 can be directly connected to a cable-TV converter or cable-ready TV on channel 57. All parasitic elements are made from ⅛-inch diameter rod and the driven element is made from #10 AWG solid copper wire. Lengths and spacings are given in **Table 21.30**. The same spacing is used for all versions.

Table 21.23
WA5VJB 144 MHz Yagi Dimensions

		Ref	*DE*	*D1*	*D2*	*D3*	*D4*
3-element	Length	41.0	—	37.0			
	Spacing	0	8.5	20.0			
4-element	Length	41.0	—	37.5	33.0		
	Spacing	0	8.5	19.25	40.5		
6-element	Length	40.5	—	37.5	36.5	36.5	32.75
	Spacing	0	7.5	16.5	34.0	52.0	70.0

Dimensions in inches.

Table 21.24
WA5VJB 222 MHz Yagi Dimensions

		Ref	*DE*	*D1*	*D2*	*D3*	*D4*
3-element	Length	26.0	—	23.75			
	Spacing	0	5.5	13.5			
4-element	Length	26.25	—	24.1	22.0		
	Spacing	0	5.0	11.75	23.5		
6-element	Length	26.25	—	24.1	23.5	23.5	21.0
	Spacing	0	5.0	10.75	22.0	33.75	45.5

Dimensions in inches.

Table 21.25
WA5VJB 432 MHz Yagi Dimensions

		Ref	*DE*	*D1*	*D2*	*D3*	*D4*	*D5*	*D6*	*D7*	*D8*	*D9*
6-element	Length	13.5	—	12.5	12.0	12.0	11.0					
	Spacing	0	2.5	5.5	11.25	17.5	24.0					
8-element	Length	13.5	—	12.5	12.0	12.0	12.0	12.0	11.25			
	Spacing	0	2.5	5.5	11.25	17.5	24.0	30.75	38.0			
11-element	Length	13.5	—	12.5	12.0	12.0	12.0	12.0	12.0	11.75	11.75	11.0
	Spacing	0	2.5	5.5	11.25	17.5	24.0	30.75	38.0	45.5	53.0	59.5

Dimensions in inches.

Table 21.26
WA5VJB 435 MHz Yagi Dimensions

		Ref	*DE*	*D1*	*D2*	*D3*	*D4*	*D5*	*D6*	*D7*	*D8*	*D9*
6-element	Length	13.4	—	12.4	12.0	12.0	11.0					
8-element	Length	13.4	—	12.4	12.0	12.0	12.0	12.0	11.1			
10-element	Length	13.4	—	12.4	12.0	12.0	12.0	12.0	11.75	11.75	11.1	
11-element	Length	13.4	—	12.4	12.0	12.0	12.0	12.0	11.75	11.75	11.75	11.1
	Spacing	0	2.5	5.5	11.25	17.5	24.0	30.5	37.75	45.0	52.0	59.5

Dimensions in inches.

Table 21.27
WA5VJB 450 MHz Yagi Dimensions

		Ref	*DE*	*D1*	*D2*	*D3*	*D4*
6-element	Length	13.0	—	12.1	11.75	11.75	10.75
	Spacing	0	2.5	5.5	11.0	18.0	28.5

Dimensions in inches.

Table 21.28
WA5VJB 902 MHz Yagi Dimensions

		Ref	*DE*	*D1*	*D2*	*D3*	*D4*	*D5*	*D6*	*D7*	*D8*
10-element	Length	6.2	—	5.6	5.5	5.5	5.4	5.3	5.2	5.1	5.1
	Spacing	0	2.4	3.9	5.8	9.0	12.4	17.4	22.4	27.6	33.0

Dimensions in inches.

Table 21.29
WA5VJB 1296 MHz Yagi Dimensions

		Ref	*DE*	*D1*	*D2*	*D3*	*D4*	*D5*	*D6*	*D7*	*D8*
10-element	Length	4.3	—	3.9	3.8	3.75	3.75	3.65	3.6	3.6	3.5
	Spacing	0	1.7	2.8	4.0	6.3	8.7	12.2	15.6	19.3	23.0

Dimensions in inches.

Table 21.30
WA5VJB 421.25 MHz 75-Ω Yagi Dimensions

		Ref	*DE*	*D1*	*D2*	*D3*	*D4*	*D5*	*D6*	*D7*	*D8*	*D9*
6-element	Length	14.0	—	12.5	12.25	12.25	11.0					
9-element	Length	14.0	—	12.5	12.25	12.25	12.0	12.0	11.25			
11-element	Length	14.0	—	12.5	12.25	12.25	12.0	12.0	12.0	11.75	11.75	11.5
	Spacing	0	3.0	6.5	12.25	17.75	24.5	30.5	36.0	43.0	50.25	57.25

Dimensions in inches.

21.12 Radio Direction Finding Antennas

Radio direction finding (RDF) is almost as old as radio communication. It gained prominence when the British Navy used it to track the movement of enemy ships in World War I. Since then, governments and the military have developed sophisticated and complex RDF systems. Fortunately, simple equipment, purchased or built at home, is quite effective in Amateur Radio RDF.

In European and Asian countries, direction-finding contests are foot races. The object is to be first to find four or five transmitters in a large wooded park. Young athletes have the best chance of capturing the prizes. This sport is known as *foxhunting* (after the British hill-and-dale horseback events) or *ARDF* (Amateur Radio direction finding).

In North America and England, most RDF contests involve mobiles — cars, trucks, and vans, even motorcycles. It may be possible to drive all the way to the transmitter, or there may be a short hike at the end, called a *sniff*. These competitions are also called foxhunting by some, while others use *bunny hunting, T-hunting* or the classic term *hidden transmitter hunting*.

In the 1950s, 3.5 and 28 MHz were the most popular bands for hidden transmitter hunts. Today, most competitive hunts worldwide are for 144-MHz FM signals, though other VHF bands are also used. Some international foxhunts include 3.5-MHz events.

Even without participating in RDF contests, you will find knowledge of the techniques useful. They simplify the search for a neighborhood source of power-line interference or TV cable leakage. RDF must be used to track down emergency radio beacons, which signal the location of pilots and boaters in distress. Amateur Radio enthusiasts skilled in transmitter hunting are in demand by agencies such as the Civil Air Patrol and the US Coast Guard Auxiliary for search and rescue support. RDF is an important part of the evidence-gathering process in interference cases.

The most basic RDF system consists of a directional antenna and a method of detecting and measuring the level of the radio signal, such as a receiver with signal strength indicator. RDF antennas range from a simple tuned loop of wire to an acre of antenna elements with an electronic beam-forming network. Other sophisticated techniques for RDF use the Doppler effect or measure the time of arrival difference of the signal at multiple antennas.

All of these methods have been used from 2 to 500 MHz and above. However, RDF practices vary greatly between the HF and VHF/UHF portions of the spectrum. For practical reasons, high gain beams, Dopplers and switched dual antennas find favor on VHF/UHF, while loops and phased arrays are the most popular choices on 6 meters and below. Signal propagation differences between HF and VHF also affect RDF practices. But many basic transmitter-hunting techniques, discussed later in this chapter, apply to all bands and all types of portable RDF equipment.

21.12.1 RDF Antennas for HF Bands

Below 50 MHz, gain antennas such as Yagis and quads are of limited value for RDF. The typical tribander installation yields only a general direction of the incoming signal, due to ground effects and the antenna's broad forward lobe. Long monoband beams at greater heights work better, but still cannot achieve the bearing accuracy and repeatability of simpler antennas designed specifically for RDF.

RDF LOOPS

An effective directional HF antenna can be as uncomplicated as a small loop of wire or tubing, tuned to resonance with a capacitor. When immersed in an electromagnetic field, the loop acts much the same as the secondary winding of a transformer. The voltage at the output is proportional to the amount of flux passing through it and the number of turns. If the loop is oriented such that the greatest amount of area is presented to the magnetic field, the induced voltage will be the highest. If it is rotated so that little or no area is cut by the field lines, the voltage induced in the loop is zero and a null occurs.

To achieve this transformer effect, the loop must be small compared with the signal wavelength. In a single-turn loop, the conductor should be less than 0.08-λ long. For example, a 28-MHz loop should be less than 34 inches in circumference, giving a diameter of approximately 10 inches. The loop may be smaller, but that will reduce its voltage output. Maximum output from a small loop antenna is in directions corresponding to the plane of the loop; these lobes are very broad. Sharp nulls, obtained at right angles to that plane, are more useful for RDF.

For a perfect bidirectional pattern, the loop must be balanced electrostatically with respect to ground. Otherwise, it will exhibit two modes of operation, the mode of a perfect loop and that of a non-directional vertical antenna of small dimensions. This dual-mode condition results in mild to severe inaccuracy, depending on the degree of imbalance, because the outputs of the two modes are not in phase.

The theoretical true loop pattern is illustrated in **Fig 21.125A**. When properly balanced, there are two nulls exactly 180° apart. When the unwanted antenna effect is appreciable and the loop is tuned to resonance, the loop may exhibit little directivity, as shown in Fig 21.125B. By detuning the loop to shift the phasing, you may obtain a useful pattern similar to Fig 21.125C. While not symmetrical, and not necessarily at right angles to the plane of the loop, this pattern does exhibit a pair of nulls.

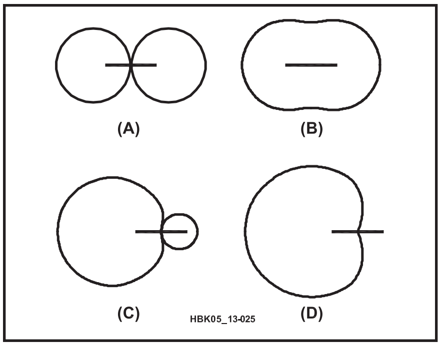


Fig 21.125 — Small loop field patterns with varying amounts of antenna effect — the undesired response of a loop acting merely as a mass of metal connected to the receiver antenna terminals. The horizontal lines show the plane of the loop turns.

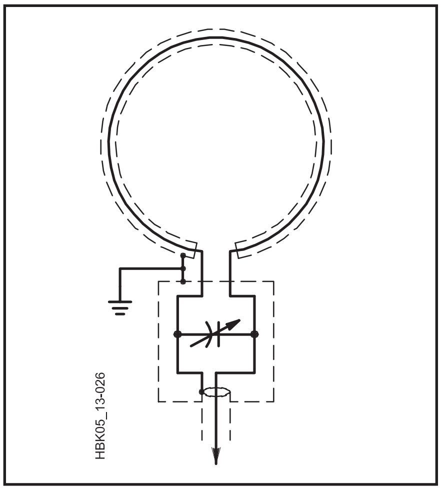


Fig 21.126 — Electrostatically-shielded loop for RDF. To prevent shielding of the loop from magnetic fields, leave the shield unconnected at one end.

By careful detuning and amplitude balancing, you can approach the unidirectional pattern of Fig 21.125D. Even though there may not be a complete null in the pattern, it resolves the 180° ambiguity of Fig 21.125A. Korean War-era military loop antennas, sometimes available on today's surplus market, use this controlled-antenna-effect principle.

An easy way to achieve good electrostatic balance is to shield the loop, as shown in **Fig 21.126**. The shield, represented by the dashed lines in the drawing, eliminates the antenna effect. The response of a well-constructed shielded loop is quite close to the ideal pattern of Fig 21.125A.

For 160 through 30 meters, single-turn loops that are small enough for portability are usually unsatisfactory for RDF work. Multiturn loops are generally used instead. They are easier to resonate with practical capacitor values and give higher output voltages. This type of loop may also be shielded. If the total conductor length remains below 0.08 λ, the directional pattern is that of Fig 21.125A.

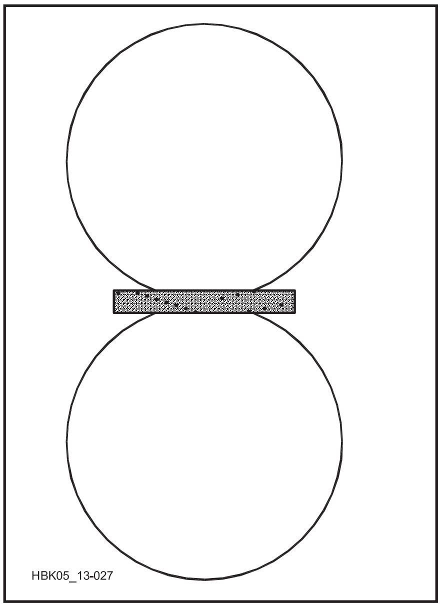


Fig 21.127 — Field pattern for a ferrite-rod antenna. The dark bar represents the rod on which the loop turns are wound.

FERRITE ROD ANTENNAS

Another way to get higher loop output is to increase the permeability of the medium in the vicinity of the loop. By winding a coil of wire around a form made of high-permeability material, such as ferrite rod, much greater flux is obtained in the coil without increasing the cross-sectional area.

Modern magnetic core materials make compact directional receiving antennas practical. Most portable AM broadcast receivers use this type of antenna, commonly called a *loopstick*. The loopstick is the most popular RDF antenna for portable/mobile work on 160 and 80 meters.

Like the shielded loop discussed earlier, the loopstick responds to the magnetic field of the incoming radio wave, and not to the electrical field. For a given size of loop, the output voltage increases with increasing flux density, which is obtained by choosing a ferrite core of high permeability and low loss at the frequency of interest. For increased output, the turns may be wound over two rods taped together. A practical loopstick antenna is described later in this chapter.

A loop on a ferrite core has maximum signal response in the plane of the turns, just as an air core loop. This means that maximum response of a loopstick is broadside to the axis of the rod, as shown in **Fig 21.127**. The loopstick may be shielded to eliminate the antenna effect; a U-shaped or C-shaped channel of aluminum or other form of "trough" is best. The shield must not be closed, and its length should equal or slightly exceed the length of the rod.

SENSE ANTENNAS

Because there are two nulls 180° apart in the directional pattern of a small loop or loopstick, there is ambiguity as to which null indicates the true direction of the target station. For example, if the line of bearing runs east and west from your position, you have no way of knowing from this single bearing whether the transmitter is east of you or west of you.

If bearings can be taken from two or more positions at suitable direction and distance from the transmitter, the ambiguity can be resolved and distance can be estimated by triangulation, as discussed later in this chapter. However, it is almost always desirable to be able to resolve the ambiguity immediately by having a unidirectional antenna pattern available.

You can modify a loop or loopstick antenna pattern to have a single null by adding a second antenna element. This element is called a *sense antenna*, because it senses the phase of the signal wavefront for comparison with the phase of the loop output signal. The sense element must be omnidirectional, such as a short vertical. When signals from the loop and the sense antenna are combined with 90° phase shift between the two, a heart-shaped (cardioid) pattern results, as shown in **Fig 21.128A**.

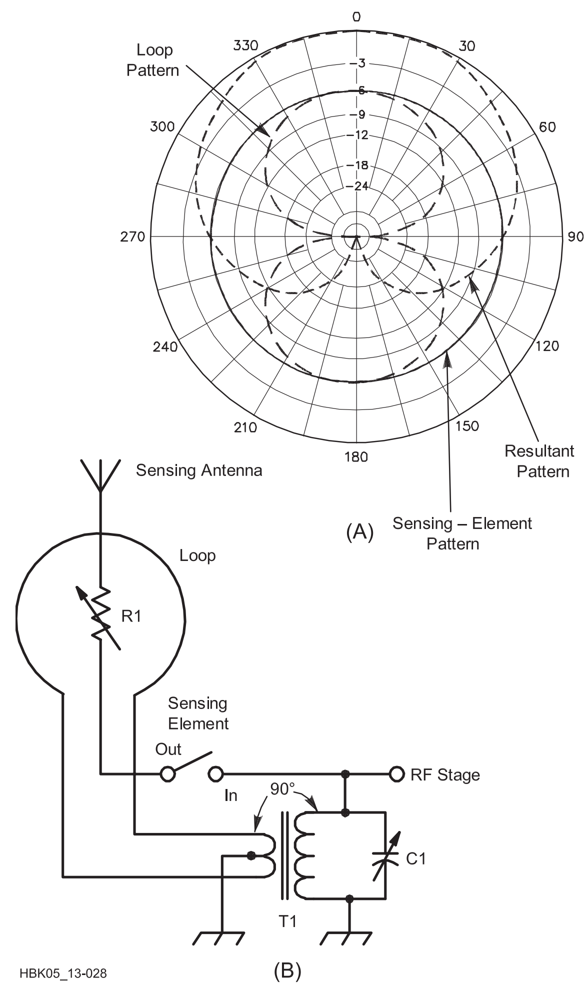


Fig 21.128 — At A, the directivity pattern of a loop antenna with sensing element. At B is a circuit for combining the signals from the two elements. Adjust C1 for resonance with T1 at the operating frequency.

Fig 21.128B shows a circuit for adding a sense antenna to a loop or loopstick. For the best null in the composite pattern, signals from the loop and sense antennas must be of equal amplitude. R1 adjusts the level of the signal from the sense antenna.

In a practical system, the cardioid pattern null is not as sharp as the bidirectional null of the loop alone. The usual procedure when transmitter hunting is to use the loop alone to obtain a precise line of bearing, then switch in the sense antenna and take another reading to resolve the ambiguity.

PHASED ARRAYS AND ADCOCK ANTENNAS

Two-element phased arrays are popular for amateur HF RDF base station installations. Many directional patterns are possible, depending on the spacing and phasing of the elements. A useful example is two ½-λ elements spaced ¼-λ apart and fed 90° out of phase. The resultant pattern is a cardioid, with a null off one end of the axis of the two antennas and a broad peak in the opposite direction. The directional frequency range of this antenna is limited to one band, because of the critical length of the phasing lines.

The best-known phased array for RDF is the Adcock, named after the man who invented it in 1919. It consists of two vertical elements fed 180° apart, mounted so the array may be rotated. Element spacing is not critical, and may be in the range from 0.1 to 0.75 λ. The two elements must be of identical lengths, but need not be self-resonant; shorter elements are commonly used. Because neither the element spacing nor length is critical in terms of wavelengths, an Adcock array may operate over more than one amateur band.

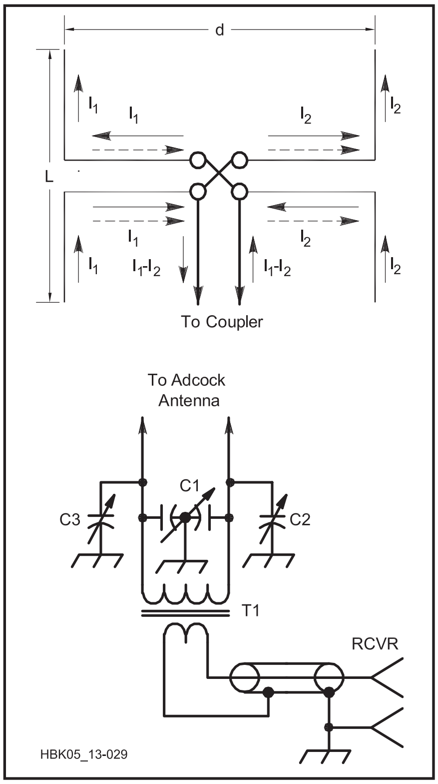


Fig 21.129 — A simple Adcock antenna and its coupler.

Fig 21.129 is a schematic of a typical Adcock configuration, called the H-Adcock because of its shape. Response to a vertically polarized wave is very similar to a conventional loop. The passing wave induces currents I1 and I2 into the vertical members. The output current in the transmission line is equal to their difference. Consequently, the directional pattern has two broad peaks and

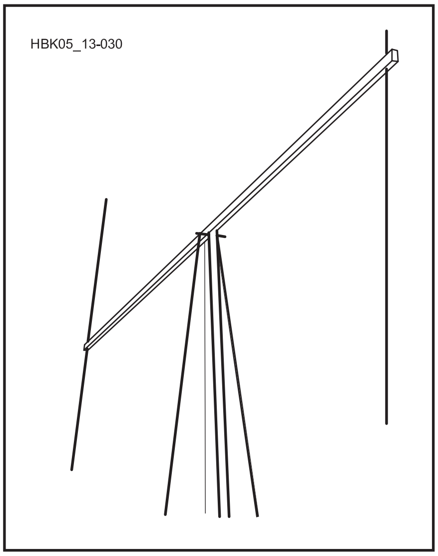


Fig 21.130 — An experimental Adcock antenna on a wooden frame.

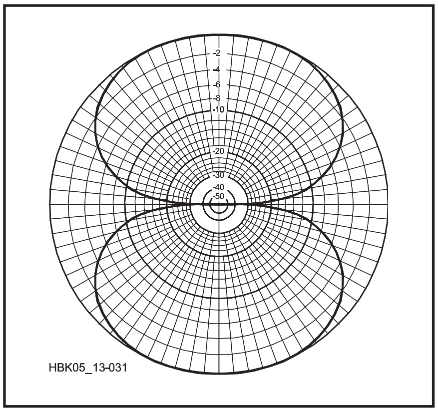


Fig 21.131 — The pattern of an Adcock array with element spacing of ½ wavelength. The elements are aligned with the vertical axis.

two sharp nulls, like the loop. The magnitude of the difference current is proportional to the spacing (d) and length (l) of the elements. You will get somewhat higher gain with larger dimensions. The Adcock of **Fig 21.130**, designed for 40 meters, has element lengths of 12 ft and spacing of 21 ft (approximately 0.15 λ).

Fig 21.131 shows the radiation pattern of the Adcock. The nulls are broadside to the axis of the array, becoming sharper with increased element spacing. When element spacing exceeds ¾ λ, however, the antenna begins to take on additional unwanted nulls off the ends of the array axis.

The Adcock is a vertically polarized antenna. The vertical elements do not respond to horizontally polarized waves, and the currents induced in the horizontal members by a horizontally polarized wave (dotted arrows in Fig 21.129) tend to balance out regardless of the orientation of the antenna.

Since the Adcock uses a balanced feed system, a coupler is required to match the unbalanced input of the receiver. T1 is an air-wound coil with a two-turn link wrapped around the middle. The combination is resonated with C1 to the operating frequency. C2 and C3 are null-clearing capacitors. Adjust them by placing a low-power signal source some distance from the antenna and exactly broadside to it. Adjust C2 and C3 until the deepest null is obtained.

While you can use a metal support for the mast and boom, wood is preferable because of its non-conducting properties. Similarly, a mast of thick-wall PVC pipe gives less distortion of the antenna pattern than a metallic mast. Place the coupler on the ground below the wiring harness junction on the boom and connect it with a short length of 300-Ω twin-lead-feed line.

LOOPS VS PHASED ARRAYS

Loops are much smaller than phased arrays for the same frequency, and are thus the obvious choice for portable/mobile HF RDF. For base stations in a triangulation network, where the 180° ambiguity is not a problem, Adcocks are preferred. In general, they give sharper nulls than loops, but this is in part a function of the care used in constructing and feeding the individual antennas, as well as of the spacing of the elements. The primary construction considerations are the shielding and balancing of the feed line against unwanted signal pickup and the balancing of the antenna for a symmetrical pattern. Users report that Adcocks are somewhat less sensitive to proximity effects, probably because their larger aperture offers some space diversity.

Skywave Considerations

Until now we have considered the directional characteristics of the RDF loop only in the two-dimensional azimuthal plane. In three-dimensional space, the response of a vertically oriented small loop is doughnut-shaped. The bidirectional null (analogous to a line through the doughnut hole) is in the line of bearing in the azimuthal plane and toward the horizon in the vertical plane. Therefore, maximum null depth is achieved only on signals arriving at 0° elevation angle.

Skywave signals usually arrive at nonzero wave angles. As the elevation angle increases, the null in a vertically oriented loop pattern becomes shallower. It is possible to tilt the loop to seek the null in elevation as well as azimuth. Some amateur RDF enthusiasts report success at estimating distance to the target by measurement of the elevation angle with a tilted loop and computations based on estimated height of the propagating ionospheric layer. This method seldom provides high accuracy with simple loops, however.

Most users prefer Adcocks to loops for skywave work, because the Adcock null is present at all elevation angles. Note, however, that an Adcock has a null in all directions from signals arriving from overhead. Thus for very high angles, such as under-250-mile skip on 80 and 40 meters, neither loops nor Adcocks will perform well.

ELECTRONIC ANTENNA ROTATION

State-of-the-art fixed RDF stations for government and military work use antenna arrays of stationary elements, rather than mechanically rotatable arrays. The best-known type is the *Wullenweber antenna*. It has a large number of elements arranged in a circle, usually outside of a circular reflecting screen. Depending on the installation, the circle may be anywhere from a few hundred feet to more than a quarter of a mile in diameter. Although the Wullenweber is not practical for most amateurs, some of the techniques it uses may be applied to amateur RDF.

The device, which permits rotating the antenna beam without moving the elements, has the classic name *radio goniometer*, or simply *goniometer*. Early goniometers were RF transformers with fixed coils connected to the array elements and a moving pickup coil connected to the receiver input. Both amplitude and phase of the signal coupled into the pickup winding are altered with coil rotation in a way that corresponded to actually rotating the array itself. With sufficient elements and a goniometer, accurate RDF measurements can be taken in all compass directions.

Beam Forming Networks

By properly sampling and combining signals from individual elements in a large array, an antenna beam is electronically rotated or steered. With an appropriate number and arrangement of elements in the system, it is possible to form almost any desired antenna pattern by summing the sampled signals in

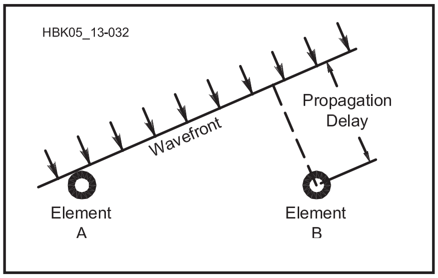


Fig 21.132 — One technique used in electronic beam forming. By delaying the signal from element A by an amount equal to the propagation delay, two signals are summed precisely in phase, even though the signal is not in the broadside direction.

appropriate amplitude and phase relationships. Delay networks and/or attenuation are added in line with selected elements before summation to create these relationships.

To understand electronic beam forming, first consider just two elements, shown as A and B in **Fig 21.132**. Also shown is the wavefront of a radio signal arriving from a distant transmitter. The wavefront strikes element A first, then travels somewhat farther before it strikes element B. Thus, there is an interval between the times that the wavefront reaches elements A and B.

We can measure the differences in arrival times by delaying the signal received at element A before summing it with that from element B. If two signals are combined directly, the amplitude of the sum will be maximum when the delay for element A exactly equals the propagation delay, giving an in-phase condition at the summation point. On the other hand, if one of the signals is inverted and the two are added, the signals will combine in a 180° out-of-phase relationship when the element A delay equals the propagation delay, creating a null. Either way, once the time delay is determined by the amount of delay required for a peak or null, we can convert it to distance. Then trigonometry calculations provide the direction from which the wave is arriving.

Altering the delay in small increments steers the peak (or null) of the antenna. The system is not frequency sensitive, other than the frequency range limitations of the array elements. Lumped-constant networks are suitable for delay elements if the system is used only for receiving. Delay lines at installations used for transmitting and receiving employ rolls of coaxial cable of various lengths, chosen for the time delay they provide at all frequencies, rather than as simple phasing lines designed for a single frequency.

Combining signals from additional elements narrows the broad beamwidth of the pattern from the two elements and suppress unwanted sidelobes. Electronically switching the delays and attenuations to the various elements causes the formed beam to rotate around the compass. The package of electronics that does this, including delay lines and electronically switched attenuators, is the beam-forming network.

21.12.2 Methods for VHF/UHF RDF

Three distinct methods of mobile RDF are commonly in use by amateurs on VHF/UHF bands: directional antennas, switched dual antennas and Dopplers. Each has advantages over the others in certain situations. Many RDF enthusiasts employ more than one method when transmitter hunting.

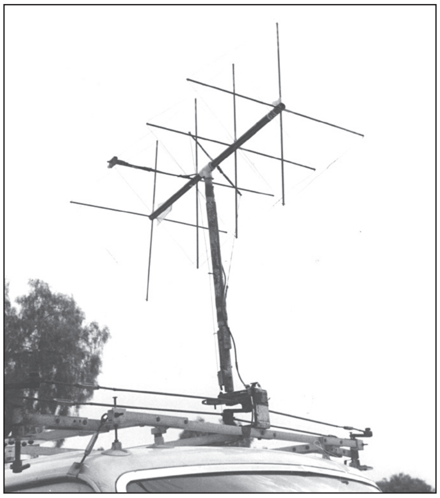


Fig 21.133 — The mobile RDF installation of WB6ADC features a thin wire quad for 144 MHz and a mechanical linkage that permits either the driver or front passenger to rotate the mast by hand.

Fig 21.134 — KØOV uses this mobile setup for RDF on several bands, with separate antennas for each band that mate with a common lower mast section, pointer and 360° indicator. Antenna shown is a heavy gauge wire quad for 2 meters.

DIRECTIONAL ANTENNAS

Ordinary mobile transceivers and handhelds work well for foxhunting on the popular VHF bands. If you have a lightweight beam and your receiver has an easy-to-read S-meter, you are nearly ready to start. All you need is an RF attenuator and some way to mount the setup in your vehicle.

Amateurs seldom use fractional wavelength loops for RDF above 60 MHz because they have bidirectional characteristics and low sensitivity, compared to other practical VHF antennas. Sense circuits for loops are difficult to implement at VHF, and signal reflections tend to fill in the nulls. Typically VHF loops are used only for close-in sniffing where their compactness and sharp nulls are assets, and low gain is of no consequence.

Phased Arrays

The small size and simplicity of two-element driven arrays make them a common choice of newcomers at VHF RDF. Antennas such as phased ground planes and ZL Specials have modest gain in one direction and a null in the opposite direction. The gain is helpful when the signal is weak, but the broad response peak makes it difficult to take a precise bearing.

As the signal gets stronger, it becomes possible to use the null for a sharper S-meter indication. However, combinations of direct and reflected signals (called *multipath*) will distort the null or perhaps obscure it completely. For best results with this type of antenna, always find clear locations from which to take bearings.

Parasitic Arrays

Parasitic arrays are the most common RDF antennas used by transmitter hunters in high competition areas such as Southern California. Antennas with significant gain are a necessity due to the weak signals often encountered on weekend-long T-hunts, where the transmitter may be over 200 miles distant. Typical 144-MHz installations feature Yagis or quads of three to six elements, sometimes more. Quads are typically home-built, using data from *The ARRL Antenna Book* and *Transmitter Hunting* (see Bibliography).

Two types of mechanical construction are popular for mobile VHF quads. The model of **Fig 21.133** uses thin gauge wire (solid or stranded), suspended on wood dowel or fiberglass rod spreaders. It is lightweight and easy to turn rapidly by hand while the vehicle moves. Many hunters prefer to use larger gauge solid wire (such as #10 AWG) on a PVC plastic pipe frame (**Fig 21.134**). This quad is more rugged and has somewhat wider frequency range, at the expense of increased weight and wind resistance. It can get mashed going under a willow, but it is easily reshaped and returned to service.

Yagis are a close second to quads in popularity. Commercial models work fine for VHF RDF, provided that the mast is attached at a good balance point. Lightweight and small-diameter elements are desirable for ease of turning at high speeds.

A well-designed mobile Yagi or quad installation includes a method of selecting wave polarization. Although vertical polarization is the norm for VHF-FM communications, horizontal polarization is allowed on many T-hunts. Results will be poor if a VHF RDF antenna is cross-polarized to the transmitting antenna, because multipath and scattered signals (which have indeterminate polarization) are enhanced, relative to the cross-polarized direct signal. The installation of Fig 21.133 features a slip joint at the boom-to-mast junction, with an actuating cord to rotate the boom, changing the polarization. Mechanical stops limit the boom rotation to 90°.

Parasitic Array Performance for RDF

The directional gain of a mobile beam (typically 8 dB or more) makes it unexcelled for both weak signal competitive hunts and for locating interference such as TV cable leakage. With an appropriate receiver, you can get bearings on any signal mode, including FM, SSB, CW, TV, pulses and noise. Because only the response peak is used, the null-fill problems and proximity effects of loops and phased arrays do not exist.

You can observe multiple directions of arrival while rotating the antenna, allowing you to make educated guesses as to which signal peaks are direct and which are from non-direct paths or scattering. Skilled operators can estimate distance to the transmitter from the rate of signal strength increase with distance traveled. The RDF beam is useful for transmitting, if necessary, but use care not to damage an attenuator in the coax line by transmitting through it.

The 3-dB beamwidth of typical mobile-mount VHF beams is on the order of 80°. This is a great improvement over 2-element driven arrays, but it is still not possible to get pinpoint bearing accuracy. You can achieve errors of less than 10° by carefully reading the S-meter. In practice, this is not a major hindrance to successful mobile RDF. Mobile users are not as concerned with precise bearings as fixed station operators, because mobile readings are used primarily to give the general direction of travel to "home in" on the signal. Mobile bearings are continuously updated from new, closer locations.

Amplitude-based RDF may be very difficult when signal level varies rapidly. The transmitter hider may be changing power, or the target antenna may be moving or near a well-traveled road or airport. The resultant rapid S-meter movement makes it hard to take accurate bearings with a quad. The process is slow because the antenna must be carefully rotated by hand to "eyeball average" the meter readings.

SWITCHED ANTENNA RDF UNITS

Three popular types of RDF systems are relatively insensitive to variations in signal level. Two of them use a pair of vertical dipole antennas, spaced ½ λ or less apart, and alternately switched at a rapid rate to the input of the receiver. In use, the indications of the two systems are similar, but the principles are different.

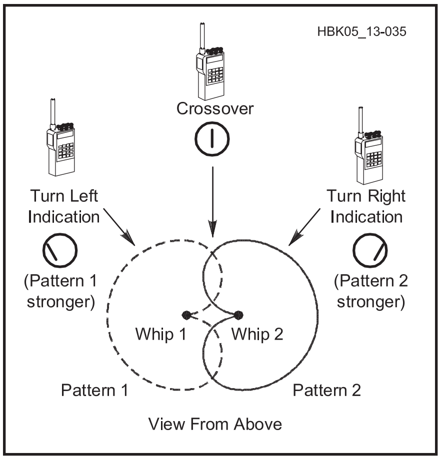


Fig 21.135 — In a switched pattern RDF set, the responses of two cardioid antenna patterns are summed to drive a zero center indicator.

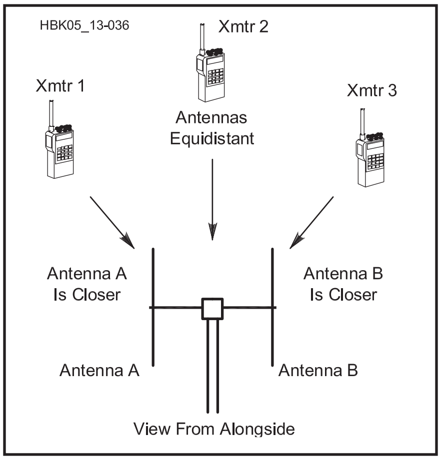


Fig 21.136 — A dual-antenna TDOA RDF system has a similar indicator to a switched pattern unit, but it obtains bearings by determining which of its antennas is closer to the transmitter.

Switched Pattern Systems

The switched pattern RDF set (**Fig 21.135**) alternately creates two cardioid antenna patterns with lobes to the left and the right. The patterns are generated in much the same way as in the phased arrays described above. PIN RF diodes select the alternating patterns. The combined antenna outputs go to a receiver with AM detection. Processing after the detector output determines the phase or amplitude difference between the patterns' responses to the signal.

Switched pattern RDF sets typically have a zero center meter as an indicator. The meter swings negative when the signal is coming from the user's left, and positive when the signal source is on the right. When the plane of the antenna is exactly perpendicular to the direction of the signal source, the meter reads zero.

The sharpness of the zero crossing indication makes possible more precise bearings than those obtainable with a quad or Yagi. Under ideal conditions with a well-built unit, null direction accuracy is within 1°. Meter deflection tells the user which way to turn to zero the meter. For example, a negative (left) reading requires turning the antenna left. This solves the 180° ambiguity caused by the two zero crossings in each complete rotation of the antenna system.

Because it requires AM detection of the switched pattern signal, this RDF system finds its greatest use in the 120-MHz aircraft band, where AM is the standard mode. Commercial manufacturers make portable RDF sets with switched pattern antennas and built-in receivers for field portable use. These sets can usually be adapted to the amateur 144-MHz band. Other designs are adaptable to any VHF receiver that covers the frequency of interest and has an AM detector built in or added.

Switched pattern units work well for RDF from small aircraft, for which the two vertical antennas are mounted in fixed positions on the outside of the fuselage or simply taped inside the windshield. The left-right indication tells the pilot which way to turn the aircraft to home in. Since street vehicles generally travel only on roads, fixed mounting of the antennas on them is undesirable. Mounting vehicular switched-pattern arrays on a rotatable mast is best.

Time-of-Arrival Systems

Another kind of switched antenna RDF set uses the difference in arrival times of the signal wavefront at the two antennas. This narrow-aperture Time-Difference-of-Arrival (TDOA) technology is used for many sophisticated military RDF systems. The rudimentary TDOA implementation of **Fig 21.136** is quite effective for amateur use. The signal from transmitter 1 reaches antenna A before antenna B. Conversely, the signal from transmitter 3 reaches antenna B before antenna A. When the plane of the antenna is perpendicular to the signal source (as transmitter 2 is in the figure), the signal arrives at both antennas simultaneously.

If the outputs of the antennas are alternately switched at an audio rate to the receiver input, the differences in the arrival times of a continuous signal produce phase changes that are detected by an FM discriminator. The resulting short pulses sound like a tone in the receiver output. The tone disappears when the antennas are equidistant from the signal source, giving an audible null.

The polarity of the pulses at the discriminator output is a function of which antenna is closer to the source. Therefore, the pulses can be processed and used to drive a left-right zero-center meter in a manner similar to the switched pattern units described above. Left-right LED indicators may replace the meter for economy and visibility at night.

RDF operations with a TDOA dual antenna RDF are done in the same manner as with a switched antenna RDF set. The main difference is the requirement for an FM receiver in the TDOA system and an AM receiver in the switched pattern case. No RF attenuator is needed for close-in work in the TDOA case.

Popular designs for practical do-it-yourself TDOA RDF sets include the Simple Seeker (described elsewhere in this chapter) and the W9DUU design (see article by Bohrer in the Bibliography). Articles with plans for the Handy Tracker, a simple TDOA set with a delay line to resolve the dual-null ambiguity instead of LEDs or a meter, are listed in the Bibliography.

Performance Comparison

Both types of dual antenna RDFs make good on-foot "sniffing" devices and are excellent performers when there are rapid amplitude variations in the incoming signal. They are the units of choice for airborne work. Compared to Yagis and quads, they give good directional performance over a much wider frequency range. Their indications are more precise than those of beams with broad forward lobes.

Dual-antenna RDF sets frequently give inaccurate bearings in multipath situations, because they cannot resolve signals of nearly equal levels from more than one direction. Because multipath signals are a combined pattern of peaks and nulls, they appear to change in amplitude and bearing as you move the RDF antenna along the bearing path or perpendicular to it, whereas a non-multipath signal will have constant strength and bearing.

The best way to overcome this problem is to take large numbers of bearings while moving toward the transmitter. Taking bearings while in motion averages out the effects of multipath, making the direct signal more readily discernible. Some TDOA RDF sets have a slow-response mode that aids the averaging process.

Switched antenna systems generally do not perform well when the incoming signal is horizontally polarized. In such cases, the bearings may be inaccurate or unreadable. TDOA units require a carrier type signal such as FM or CW; they usually cannot yield bearings on noise or pulse signals.

Unless an additional method is employed to measure signal strength, it is easy to "overshoot" the hidden transmitter location with a TDOA set. It is not uncommon to see a TDOA foxhunter walk over the top of a concealed transmitter and walk away, following the opposite 180° null, because there is no display of signal amplitude.

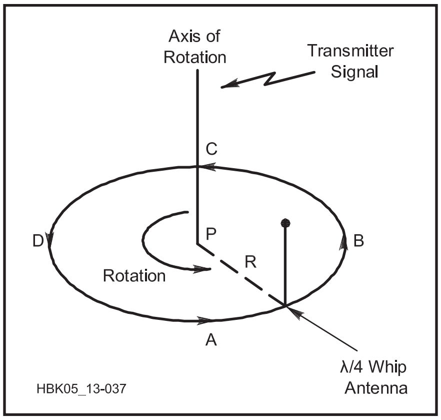


Fig 21.137 — A theoretical Doppler antenna circles around point P, continuously moving toward and away from the source at an audio rate.

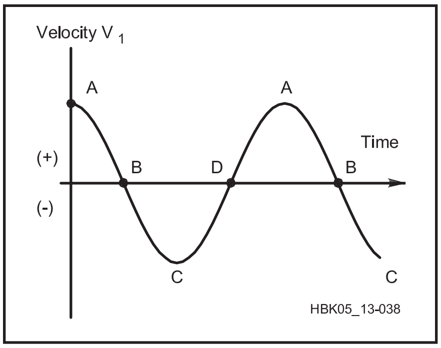


Fig 21.138 — Frequency shift versus time produced by the rotating antenna movement toward and away from the signal source.

DOPPLER RDF SETS

RDF sets using the Doppler principle are popular in many areas because of their ease of use. They have an indicator that instantaneously displays direction of the signal source relative to the vehicle heading, either on a circular ring of LEDs or a digital readout in degrees. A ring of four, eight or more antennas picks up the signal. Quarter-wavelength monopoles on a ground plane are popular for vehicle use, but half-wavelength vertical dipoles, where practical, perform better.

Radio signals received on a rapidly moving antenna experience a frequency shift due to the Doppler effect, a phenomenon well-known to anyone who has observed a moving car with its horn sounding. The horn's pitch appears higher than normal as the car approaches, and lower as the car recedes. Similarly, the received radio frequency increases as the antenna moves toward the transmitter and vice versa. An FM receiver will detect this frequency change.

Fig 21.137 shows a ¼-λ vertical antenna being moved on a circular track around point P, with constant angular velocity. As the antenna approaches the transmitter on its track, the received frequency is shifted higher. The highest instantaneous frequency occurs when the antenna is at point A, because tangential velocity toward the transmitter is maximum at that point. Conversely, the lowest frequency occurs when the antenna reaches point C, where velocity is maximum away from the transmitter.

Fig 21.138 shows a plot of the component of the tangential velocity that is in the direction of the transmitter as the antenna moves around the circle. Comparing Figs 21.137 and 21.138, notice that at B in Fig 21.138, the tangential velocity is crossing zero from the positive to the negative and the antenna is closest to the transmitter. The Doppler shift and resulting audio output from the receiver discriminator follow the same plot, so that a negative-slope zero-crossing detector, synchronized with the antenna rotation, senses the incoming direction of the signal.

The amount of frequency shift due to the Doppler effect is proportional to the RF frequency and the tangential antenna velocity. The velocity is a function of the radius of rotation and the angular velocity (rotation rate). The radius of rotation must be less than ¼ λ to avoid errors. To get a usable amount of FM deviation (comparable to typical voice modulation) with this radius, the antenna must rotate at approximately 30,000 RPM (500 Hz). This puts the Doppler tone in the audio range for easy processing.

Mechanically rotating a whip antenna at this rate is impractical, but a ring of whips, switched to the receiver in succession with RF PIN diodes, can simulate a rapidly rotating antenna. Doppler RDF sets must be used with receivers having FM detectors. The Dopple ScAnt and Roanoke Doppler (see Bibliography) are mobile Doppler RDF sets designed for inexpensive home construction.

Doppler Advantages and Disadvantages

Ring-antenna Doppler sets are the ultimate in simplicity of operation for mobile RDF. There are no moving parts and no manual antenna pointing. Rapid direction indications are displayed on very short signal bursts.

Many units lock in the displayed direction after the signal leaves the air. Power variations in the source signal cause no difficulties, as long as the signal remains above the RDF detection threshold. A Doppler antenna goes on top of any car quickly, with no holes to drill.

Many Local Interference Committee members choose Dopplers for tracking malicious interference, because they are inconspicuous (compared to beams) and effective at tracking the strong vertically polarized signals that repeater jammers usually emit.

A Doppler does not provide superior performance in all VHF RDF situations. If the signal is too weak for detection by the Doppler unit, the hunt advantage goes to teams with beams. Doppler installations are not suitable for on-foot sniffing. The limitations of other switched antenna RDFs also apply: (1) poor results with horizontally polarized signals, (2) no indication of distance, (3) carrier type signals only and (4) inadvisability of transmitting through the antenna.

Readout to the nearest degree is provided on some commercial Doppler units. This does not guarantee that level of accuracy, however. A well-designed four-monopole set is typically capable of ±5° accuracy on 2 meters, if the target signal is vertically polarized and there are no multipath effects.

The rapid antenna switching can introduce cross modulation products when the user is near strong off-channel RF sources. This self-generated interference can temporarily render the system unusable. While not a common problem with mobile Dopplers, it makes the Doppler a poor choice for use in remote RDF installations at fixed sites with high power VHF transmitters nearby.

MOBILE RDF SYSTEM INSTALLATION

Of these mobile VHF RDF systems, the Doppler type is clearly the simplest from a mechanical installation standpoint. A four-whip Doppler RDF array is easy to implement with magnetic mount antennas. Alternately, you can mount all the whips on a frame that attaches to the vehicle roof with suction cups. In either case, setup is rapid and requires no holes in the vehicle.

You can turn small VHF beams and dual-antenna arrays readily by extending the mast through a window. Installation on each model vehicle is different, but usually the mast can be held in place with some sort of cup in the arm rest and a plastic tie at the top of the window, as in **Fig 21.139**. This technique works best on cars with frames around the windows, which allow the door to be opened with the antenna in place. Check local vehicle codes, which limit how far your antenna may protrude beyond the line of the fenders. Larger antennas may have to be put on the passenger side of the vehicle, where greater overhang is generally permissible.

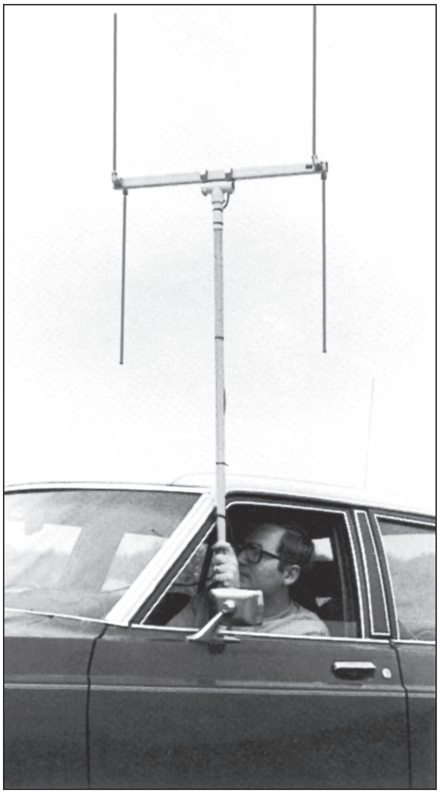


Fig 21.139 — A set of TDOA RDF antennas is light weight and mounts readily through a sedan window without excessive overhang.

Fig 21.140 — A window box allows the navigator to turn a mast mounted antenna with ease while remaining dry and warm. No holes in the vehicle are needed with a properly designed window box.

The window box (**Fig 21.140**) is an improvement over through-the-window mounts. It provides a solid, easy-turning mount for the mast. The plastic panel keeps out bad weather. You will need to custom-design the box for your vehicle model. Vehicle codes may limit the use of a window box to the passenger side.

For the ultimate in convenience and versatility, cast your fears aside, drill a hole through the center of the roof and install a waterproof bushing. A roof-hole mount permits the use of large antennas without overhang violations. The driver, front passenger and even a rear passenger can turn the mast when required. The installation in Fig 21.134 uses a roof-hole bushing made from mating threaded PVC pipe adapters and reducers. When it is not in use for RDF, a PVC pipe cap provides a watertight cover. There is a pointer and 360° indicator at the bottom of the mast for precise bearings.

21.12.3 Direction-Finding Techniques

The ability to locate a transmitter quickly with RDF techniques is a skill you will acquire only with practice. It is very important to become familiar with your equipment and its limitations. You must also understand how radio signals behave in different types of terrain at the frequency of the hunt. Experience is the best teacher, but reading and hearing the stories of others who are active in RDF will help you get started.

Verify proper performance of your portable RDF system before you attempt to track signals in unknown locations. Of primary concern is the accuracy and symmetry of the antenna pattern. For instance, a lopsided figure-8 pattern with a loop, Adcock, or TDOA set leads to large bearing errors. Nulls should be exactly 180° apart and exactly at right angles to the loop plane or the array boom. Similarly, if feed-line pickup causes an off-axis main lobe in your VHF RDF beam, your route to the target will be a spiral instead of a straight line.

Perform initial checkout with a low-powered test transmitter at a distance of a few hundred feet. Compare the RDF bearing indication with the visual path to the transmitter. Try to "find" the transmitter with the RDF equipment as if its position were not known. Be sure to check all nulls on antennas that have more than one.

If imbalance or off-axis response is found in the antennas, there are two options available. One is to correct it, insofar as possible. A second option is to accept it and use some kind of indicator or correction procedure to show the true directions of signals. Sometimes the end result of the calibration procedure is a compromise between these two options, as a perfect pattern may be difficult or impossible to attain.

The same calibration suggestions apply for fixed RDF installations, such as a base station HF Adcock or VHF beam. Of course it does no good to move it to an open field. Instead, calibrate the array in its intended operating position, using a portable or mobile transmitter. Because of nearby obstructions or reflecting objects, your antenna may not indicate the precise direction of the transmitter. Check for imbalance and systemic error by taking readings with the test emitter at locations in several different directions.

The test signal should be at a distance of 2 or 3 miles for these measurements, and should be in as clear an area as possible during transmissions. Avoid locations where power lines and other overhead wiring can conduct signal from the transmitter to the RDF site. Once antenna adjustments are optimized, make a table of bearing errors noted in all compass directions. Apply these error values as corrections when actual measurements are made.

PREPARING TO HUNT

Successfully tracking down a hidden transmitter involves detective work — examining all the clues, weighing the evidence and using good judgment. Before setting out to locate the source of a signal, note its general characteristics. Is the frequency constant, or does it drift? Is the signal continuous, and if not, how long are transmissions? Do transmissions occur at regular intervals, or are they sporadic? Irregular, intermittent signals are the most difficult to locate, requiring patience and quick action to get bearings when the transmitter comes on.

Refraction, Reflections and the Night Effect

You will get best accuracy in tracking ground wave signals when the propagation path is over homogeneous terrain. If there is a land/water boundary in the path, the different conductivities of the two media can cause bending (refraction) of the wave front, as in **Fig 21.141A**. Even the most sophisticated RDF equipment will not indicate the correct bearing in this situation, as the equipment can only show the direction from which the signal is arriving. RDFers have observed this phenomenon on both HF and VHF bands.

Signal reflections also cause misleading bearings. This effect becomes more pronounced as frequency increases. T-hunt hiders regularly achieve strong signal bounces from distant mountain ranges on the 144-MHz band.

Tall buildings also reflect VHF/UHF signals, making mid-city RDF difficult. Hunting on the 440-MHz and higher amateur bands is even more arduous because of the plethora of reflecting objects.

In areas of signal reflection and multipath, some RDF gear may indicate that the signal is coming from an intermediate point, as in Fig 21.141B. High gain VHF/UHF RDF beams will show direct and reflected signals as separate S-meter peaks, leaving it to the operator to determine which is which. Null-based RDF antennas, such as phased arrays and loops, have the most difficulty with multi-path, because the multiple signals tend to make the nulls very shallow or fill them in entirely, resulting in no bearing indication at all.

If the direct path to the transmitter is masked by intervening terrain, a signal reflection from a higher mountain, building, water tower, or the like may be much stronger than the direct signal. In extreme cases, triangulation from several locations will appear to "confirm" that the transmitter is at the location of the reflecting object. The direct signal may not be detectable until you arrive at the reflecting point or another high location.

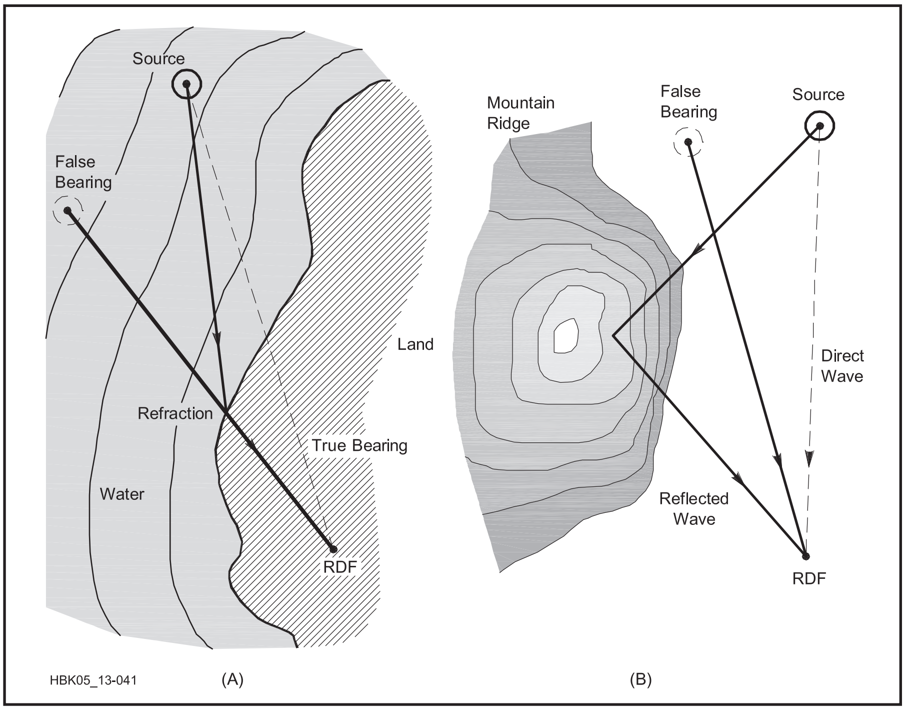


Fig 21.141 — RDF errors caused by refraction (A) and reflection (B). The reading at A is false because the signal actually arrives from a direction that is different from that to the source. At B, a direct signal from the source combines with a reflected signal from the mountain ridge. The RDF set may average the signals as shown, or indicate two lines of bearing.

Objects near the observer such as concrete/steel buildings, power lines and chain-link fences will distort the incoming wavefront and give bearing errors. Even a dense grove of trees can sometimes have an adverse effect. It is always best to take readings in locations that are as open and clear as possible, and to take bearings from numerous positions for confirmation. Testing of RDF gear should also be done in clear locations.

Locating local signal sources on frequencies below 10 MHz is much easier during daylight hours, particularly with loop antennas. In the daytime, D-layer absorption minimizes skywave propagation on these frequencies. When the D layer disappears after sundown, you may hear the signal by a combination of ground wave and high-angle skywave, making it difficult or impossible to obtain a bearing. RDFers call this phenomenon the *night effect*.

While some mobile T-hunters prefer to go it alone, most have more success by teaming up and assigning tasks. The driver concentrates on handling the vehicle, while the assistant (called the "navigator" by some teams) turns the beam, reads the meters and calls out bearings. The assistant is also responsible for maps and plotting, unless there is a third team member for that task.

MAPS AND BEARING-MEASUREMENTS

Possessing accurate maps and knowing how to use them is very important for successful RDF. Even in difficult situations where precise bearings cannot be obtained, a town or city map will help in plotting points where signal levels are high and low. For example, power line noise tends to propagate along the power line and radiates as it does so. Instead of a single source, the noise appears to come from a multitude of sources. This renders many ordinary RDF techniques ineffective. Mapping locations where signal amplitudes are highest will help pinpoint the source.

Several types of area-wide maps are suitable for navigation and triangulation. Street and highway maps work well for mobile work. Large detailed maps are preferable to thick map books. Contour maps are ideal for open country. Aeronautical charts are also suitable. Good sources of maps include auto clubs, stores catering to camping/hunting enthusiasts and city/county engineering departments.

A *heading* is a reading in degrees relative to some external reference, such as your house

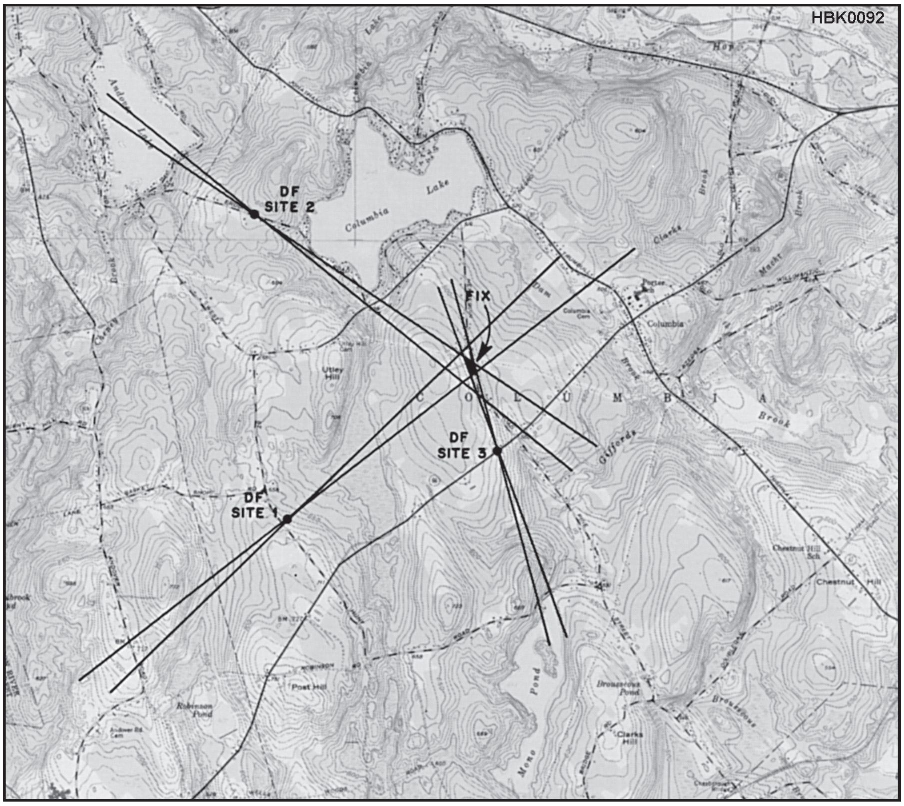
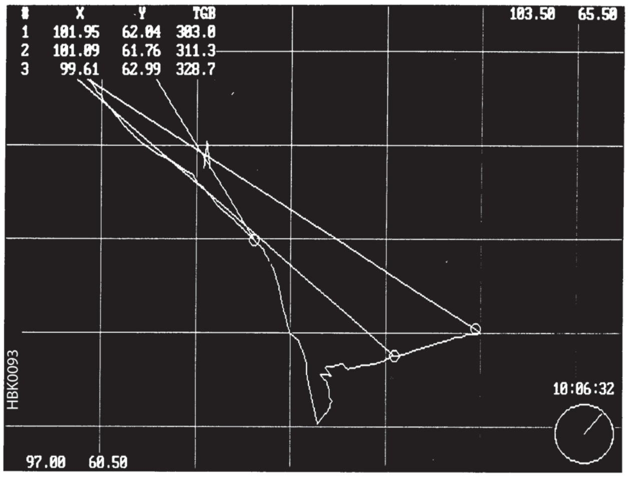


Fig 21.142 — Bearing sectors from three RDF positions drawn on a map for triangulation. In this case, bearings are from loop antennas, which have 180° ambiguity.



```
#     X      Y     TGB                          103.50   65.50
1  101.95  62.04  303.0
2  101.09  61.76  311.3
3   99.61  62.99  328.7

                                                 10:06:32

  97.00   60.50
```

Fig 21.143 — Screen plot from a computerized RDF system showing three T-hunt bearings (straight lines radiating from small circles) and the vehicle path (jagged trace). The grid squares correspond to areas of standard topographic maps.

or vehicle; a *bearing* is the target signal's direction relative to your position. Plotting a bearing on a hidden transmitter from your vehicle requires that you know the vehicle location, transmitter heading with respect to the vehicle and vehicle heading with respect to true north.

First, determine your location, using landmarks or a navigation device such as a GPS receiver. Next, using your RDF equipment, determine the bearing to the hidden transmitter (0 to 359.9°) with respect to the vehicle. Zero degrees heading corresponds to signals coming from directly in front of the vehicle, signals from the right indicate 90°, and so on.

Finally, determine your vehicle's true heading, that is, its heading relative to true north. Compass needles point to magnetic north and yield magnetic headings. Translating a magnetic heading into a true heading requires adding a correction factor, called *magnetic declination*, which is a positive or negative factor that depends on your location. (*Declination* is the term as denoted on land USGS topographic maps. *Deviation* and *Variation* are terms used on nautical and aviation charts, respectively.)

Declination for your area is given on US Geological Survey (USGS) maps, though it undergoes long-term changes. Add the declination to your magnetic heading to get a true heading.

As an example, assume that the transmitted signal arrives at 30° with respect to the vehicle heading, that the compass indicates that the vehicle's heading is 15°, and the magnetic declination is +15°. Add these values to get a true transmitter bearing (that is, a bearing with respect to true north) of 60°.

Because of the large mass of surrounding metal, it is very difficult to calibrate an in-car compass for high accuracy at all vehicle headings. It is better to use a remotely mounted flux-gate compass sensor, properly corrected, to get vehicle headings, or to stop and use a hand compass to measure the vehicle heading from the outside. If you T-hunt with a mobile VHF beam or quad, you can use your manual compass to sight along the antenna boom for a magnetic bearing, then add the declination for true bearing to the fox.

Triangulation Techniques

If you can obtain accurate bearings from two locations separated by a suitable distance, the technique of *triangulation* will give the expected location of the transmitter. The intersection of the lines of bearing from each location provides a *fix*. Triangulation accuracy is greatest when stations are located such that their bearings intersect at right angles. Accuracy is poor when the angle between bearings approaches 0° or 180°.

There is always uncertainty in the fixes obtained by triangulation due to equipment limitations, propagation effects and measurement errors. Obtaining bearings from three or more locations reduces the uncertainty. A good way to show the probable area of the transmitter on the triangulation map is to draw bearings as a narrow sector instead of as a single line. Sector width represents the amount of bearing uncertainty. **Fig 21.142** shows a portion of a map marked in this manner. Note how the bearing from Site 3 has narrowed down the probable area of the transmitter position.

Computerized Transmitter Hunting

A portable computer is an excellent tool for streamlining the RDF process. Some T-hunters use one to optimize VHF beam bearings, generating a two-dimensional plot of signal strength versus azimuth. Others have automated the bearing-taking process by using a computer to capture signal headings from a Doppler RDF set, vehicle heading from a flux-gate compass, and vehicle location from a GPS receiver (**Fig 21.143**). The computer program can compute averaged headings from a Doppler set to reduce multipath effects.

Provided with perfect position and bearing information, computer triangulation could determine the transmitter location within the limits of its computational accuracy. Two bearings would exactly locate a fox. Of course, there are always uncertainties and inaccuracies in bearing and position data. If these uncertainties can be determined, the program can compute the uncertainty of the triangulated bearings. A "smart" computer program can evaluate bearings, triangulate the bearings of multiple hunters, discard those that appear erroneous, determine which locations have particularly great or small multipath problems and even "grade" the performance of RDF stations.

By adding packet radio connections to a group of computerized base and mobile RDF stations, the processed bearing data from each can be shared. Each station in the network can display the triangulated bearings of all. This requires a common map coordinate set among all stations. The USGS Universal Transverse Mercator (UTM) grid, consisting of 1×1-km grid squares, is a good choice.

The computer is an excellent RDF tool, but it is no substitute for a skilled "navigator." You will probably discover that using a computer on a high-speed T-hunt requires a full-time operator in the vehicle to make full use of its capabilities.

SKYWAVE BEARINGS AND TRIANGULATION

Many factors make it difficult to obtain accuracy in skywave RDF work. Because of Faraday rotation during propagation, skywave signals are received with random polarization. Sometimes the vertical component is stronger, and at other times the horizontal. During periods when the vertical component is weak, the signal may appear to fade on an Adcock RDF system. At these times, determining an accurate signal null direction becomes very difficult.

For a variety of reasons, HF bearing accuracy to within 1 or 2° is the exception rather than the rule. Errors of 3 to 5° are common. An error of 3° at a thousand miles represents a distance of 52 miles. Even with every precaution taken in measurement, do not expect cross-country HF triangulation to pinpoint a signal beyond a county, a corner of a state or a large metropolitan area. The best you can expect is to be able to determine where a mobile RDF group should begin making a local search.

Triangulation mapping with skywave signals is more complex than with ground or direct waves because the expected paths are great-circle routes. Commonly available world maps are not suitable, because the triangulation lines on them must be curved, rather than straight. In general, for flat maps, the larger the area encompassed, and the greater the error that straight-line triangulation procedures will give.

A highway map is suitable for regional triangulation work if it uses some form of conical projection, such as the Lambert conformal conic system. This maintains the accuracy of angular representation, but the distance scale is not constant over the entire map.

One alternative for worldwide areas is the azimuthal-equidistant projection, better known as a great-circle map. True bearings for great-circle paths are shown as straight lines from the center to all points on the Earth. Maps centered on three or more different RDF sites may be compared to gain an idea of the general geographic area for an unknown source.

For worldwide triangulation, the best projection is the *gnomonic*, on which all great circle paths are represented by straight lines and angular measurements with respect to meridians are true. Gnomonic charts are custom maps prepared especially for government and military agencies.

Skywave signals do not always follow the great-circle path in traveling from a transmitter to a receiver. For example, if the signal is refracted in a tilted layer of the ionosphere, it could arrive from a direction that is several degrees away from the true great-circle bearing.

Another cause of signals arriving off the great-circle path is termed *sidescatter*. It is possible that, at a given time, the ionosphere does not support great-circle propagation of the signal from the transmitter to the receiver because the frequency is above the MUF for that path. However, at the same time, propagation may be supported from both ends of the path to some mutually accessible point off the great-circle path. The signal from the source may propagate to that point on the Earth's surface and hop in a sideways direction to continue to the receiver.

For example, signals from Central Europe have propagated to New England by hopping from an area in the Atlantic Ocean off the northwest coast of Africa, whereas the great-circle path puts the reflection point off the southern coast of Greenland. Readings in error by as much as 50° or more may result from sidescatter. The effect of propagation disturbances may be that the bearing seems to wander somewhat over a few minutes of time, or it may be weak and fluttery. At other times, however, there may be no telltale signs to indicate that the readings are erroneous.

CLOSING IN

On a mobile foxhunt, the objective is usually to proceed to the hidden T with minimum time and mileage. Therefore, do not go far out of your way to get off-course bearings just to triangulate. It is usually better to take the shortest route along your initial line of bearing and "home in" on the signal. With a little experience, you will be able to gauge your distance from the fox by noting the amount of attenuation needed to keep the S-meter on scale.

As you approach the transmitter, the signal will become very strong. To keep the S-meter on scale, you will need to add an RF attenuator in the transmission line from the antenna to the receiver. Simple resistive attenuators are discussed in another chapter.

In the final phases of the hunt, you will probably have to leave your mobile and continue the hunt on foot. Even with an attenuator in the line, in the presence of a strong RF field, some energy will be coupled directly into the receiver circuitry. When this happens, the S-meter reading changes only slightly or perhaps not at all as the RDF antenna rotates, no matter how much attenuation you add. The cure is to shield the receiving equipment. Something as simple as wrapping the receiver in foil or placing it in a bread pan or cake pan, covered with a piece of copper or aluminum screening securely fastened at several points, may reduce direct pickup enough for you to get bearings.

Alternatively, you can replace the receiver with a field-strength meter as you close in, or use a heterodyne-type active attenuator. Plans for these devices are at the end of this chapter.

The Body Fade

A crude way to find the direction of a VHF signal with just a hand-held transceiver is the body fade technique, so named because the blockage of your body causes the signal to fade. Hold your HT close to your chest and turn all the way around slowly. Your body is providing a shield that gives the hand-held a cardioid sensitivity pattern, with a sharp decrease in sensitivity to the rear. This null indicates that the source is behind you (**Fig 21.144**).

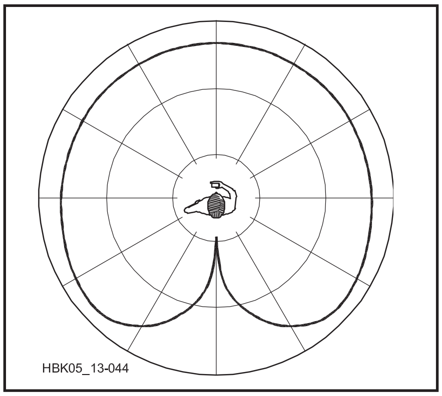


Fig 21.144 — When performing the body fade maneuver, a hand-held transceiver exhibits this directional pattern.

If the signal is so strong that you can't find the null, try tuning 5 or 10 kHz off frequency to put the signal into the skirts of the IF passband. If your hand-held is dual-band (144/440 MHz) and you are hunting on 144 MHz, try tuning to the much weaker third harmonic of the signal in the 440-MHz band.

The body fade null, which is rather shallow to begin with, can be obscured by reflections, multipath, nearby objects, etc. Step well away from your vehicle before trying to get a bearing. Avoid large buildings, chain-link fences, metal signs and the like. If you do not get a good null, move to a clearer location and try again.

Air Attenuators

In microwave parlance, a signal that is too low in frequency to be propagated in a waveguide (that is, below the *cutoff frequency*) is attenuated at a predictable logarithmic rate. In other words, the farther inside the waveguide, the weaker the signal gets. Devices that use this principle to reduce signal strength are commonly known as *air attenuators*. Plans for a practical model for insertion in a coax line are in *Transmitter Hunting* (see Bibliography).

With this principle, you can reduce the level of strong signals into your hand-held transceiver, making it possible to use the body fade technique at very close range. Glen Rickerd, KC6TNF, documented this technique for *QST*. Start with a pasteboard mailing tube that has sufficient inside diameter to accommodate your hand-held. Cover the outside of the tube completely with aluminum foil. You can seal the bottom end with foil, too, but it probably will not matter if the tube is long enough. For durability and to prevent accidental shorts, wrap the foil in packing tape. You will also need a short, stout cord attached to the hand-held. The wrist strap may work for this, if long enough.

Fig 21.145 — The air attenuator for a VHF hand-held in use. Suspend the radio by the wrist strap or a string inside the tube.

To use this air attenuation scheme for body fade bearings, hold the tube vertically against your chest and lower the hand-held into it until the signal begins to weaken (**Fig 21.145**). Holding the receiver in place, turn around slowly and listen for a sudden decrease in signal strength. If the null is poor, vary the depth of the receiver in the tube and try again. You do not need to watch the S-meter, which will likely be out of sight in the tube. Instead, use noise level to estimate signal strength.

For extremely strong signals, remove the "rubber duck" antenna or extend the wrist strap with a shoelace to get greater depth of suspension in the tube. The depth that works for one person may not work for another. Experiment with known signals to determine what works best for you.

Several RDF projects may be found on the *Handbook CD*.

21.13 Glossary

Antenna — An electrical conductor or array of conductors that radiates signal energy (transmitting) or collects signal energy (receiving).

Antenna tuner — A device containing variable reactances (and perhaps a balun) used to convert an antenna or feed line impedance to 50 Ω. (also called Transmatch, impedance-matching unit)

Apex angle — The included angle between the legs of an inverted-V antenna.

Azimuth (azimuthal) pattern — A radiation pattern in a plane oriented parallel to the Earth's surface or at a specified angle to the Earth's surface.

Balanced line — A symmetrical two-conductor feed line (also called open-wire line, ladder line, window line, twin-lead).

Balun — A device that transfers energy between a balanced and unbalanced system. A balun may or may not change the impedance ratio between the systems.

Base loading — Adding a coil to the base of a ground-plane antenna to increase its electrical length.

Beamwidth — The width in degrees of the major lobe of a directive antenna between the two angles at which the relative radiated power is equal to one-half its value (–3 dB) at the peak of the lobe.

Capacitance hat — A conducting structure with a large surface area that is added to an antenna to add capacitive reactance at that point on the antenna.

Center loading — Adding a coil near the center of a ground-plane antenna to increase its electrical length.

Coaxial cable (coax) — A coaxial transmission line with a center conductor surrounded by a layer of insulation and then a tubular shield conductor and covered by an insulating jacket. (see also — unbalanced line)

Delta loop — A full-wavelength loop shaped like a triangle or delta.

Delta match — Center-feed technique used with antenna elements that are not split at the center in which the transmission is spread apart and connected to the element symmetrically, forming a triangle or delta.

Dipole — An antenna, usually one-half wavelength long, divided into two parts at a feed point.

Directivity — The property of an antenna that concentrates the radiated energy to form one or more major lobes.

Director — An antenna element in a parasitic array that causes radiated energy from the driven element to be focused along the line from the driven element to the director.

Driven array — An array of antenna elements which are all driven or excited by means of a transmission line.

Driven element — An antenna element excited by means of a transmission line.

E-plane — The plane in which the electric field of an electromagnetic wave is maximum.

Efficiency — The ratio of useful output power to input power.

Elements — The conductive parts of an antenna system that determine the antenna's characteristics.

Elevation pattern — A radiation pattern in a plane perpendicular to the Earth's surface.

End effect — The effect of capacitance at the end of an antenna element that acts to electrically lengthen the element.

Feed line — see transmission line

Front-to-back ratio — The ratio in dB of the radiation from an antenna in a favored direction to that in the opposite direction.

Front-to-rear ratio — The ratio in dB of the radiation from an antenna is a favored direction to an average of the radiation in the opposite direction across some specified angle.

Front-to-side ratio — The ratio in dB of the radiation from an antenna in a favored direction to that at right angles to the favored direction.

Gain — The increase in radiated power in the desired direction of the major lobe.

Gamma match — A matching system used with driven antenna elements in which a conductor is placed near the element and connected to the feed line with an adjustable capacitor at the end closest to the center and connected to the element at the other.

Ground plane — A system of conductors configured to act as a reflecting surface to an antenna element and connected to one side of the transmission line.

H-plane — The plane in which the magnetic field of an electromagnetic wave is maximum.

***Hairpin match* —** A U-shaped conductor that is connected to the two inner ends of a split antenna element for the purpose of creating a match to a feed line.

Impedance — The ratio of voltage to current in a feed line or along an antenna.

Inverted-V — A dipole antenna supported at its mid-point with halves angled down toward the ground.

Isotropic — An imaginary antenna that radiates and receives equally well in all directions.

Ladder line — see balanced line.

Line loss — The power lost in a transmission line, specified in dB per unit of length.

Load — The electrical system or component to which power is delivered.

Lobe — A region in an antenna's radiation pattern between two nulls.

Matching — The process by which power at one impedance is transferred to a system at a different impedance.

Monopole — An antenna with a single-element that functions in concert with a ground-plane.

Null — A point of minimum radiation in an antenna's radiation pattern.

Open-wire line — see balanced line.

Parasitic array — A set of elements that form a radiation pattern through coupling and re-radiation of energy from one or more driven elements.

Polarization — The orientation of the electromagnetic field, usually referring to the orientation of the E field.

Q section — A quarter-wavelength section of transmission line used for impedance-matching purposes.

Quad — A directive antenna based on the Yagi with elements that consist of one-wavelength loops.

Radiation pattern — The characteristics of an antenna's distribution of energy in a single plane. (see also elevation pattern and azimuth pattern)

Radiation resistance — A resistance that represents the work done by the current in an antenna to radiate power.

Reflector — An antenna element in a parasitic array that causes radiated energy from the driven element to be focused along the line from the driven element away from the reflector.

Sense Antenna— An antenna added to a bidirectional array or loop that samples the incoming signal's phase for comparison to that of the main receiving antenna.

Stacking — Arranging two or more directive antennas such that their radiation pattern characteristics reinforce each other.

SWR — Standing-wave ratio. A measure of the match between a transmission line and a load such as an antenna.

T-match — A symmetrical version of the gamma match for a balanced antenna system.

Top loading — Addition of a reactance, usually capacitive, at the top of a ground-plane antenna so as to increase its electrical length.

Transmatch — see antenna tuner

Trap — A parallel LC-circuit used as an electrical switch to isolate sections of an antenna

Twin-lead — see balanced line.

Unipole — see monopole.

Yagi — A parasitic array consisting of a driven element and one or more director and reflectors.

Zepp — A half-wavelength antenna fed at one end by means of open-wire feed line.

21.14 References and Bibliography

J. S. Belrose, "Short Antennas for Mobile Operation," *QST*, Sep 1953, pp 30-35.

G. H. Brown, "The Phase and Magnitude of Earth Currents Near Radio Transmitting Antennas," *Proc IRE*, Feb 1935.

G. H. Brown, R. F. Lewis and J. Epstein, "Ground Systems as a Factor in Antenna Efficiency," *Proc IRE*, Jun 1937, pp 753-787.

G. H. Brown and O. M. Woodward, Jr, "Experimentally Determined Impedance Characteristics of Cylindrical Antennas," *Proc IRE*, April 1945.

C. L. Buchanen, W3DZZ, "The Multimatch Antenna System," *QST*, Mar 1955, p 22.

A. Christman, "Elevated Vertical Antenna Systems," *QST*, Aug 1988, pp 35-42.

R. B. Dome, "Increased Radiating Efficiency for Short Antennas," *QST*, Sep 1934, pp 9-12.

A. C. Doty, Jr, J. A. Frey and H. J. Mills, "Characteristics of the Counterpoise and Elevated Ground Screen," Professional Program, Session 9, Southcon '83 (IEEE), Atlanta, GA, Jan 1983.

A. C. Doty, Jr, J. A. Frey and H. J. Mills, "Efficient Ground Systems for Vertical Antennas," *QST*, Feb 1983, pp 20-25.

A. C. Doty, Jr, technical paper presentation, "Capacitive Bottom Loading and Other Aspects of Vertical Antennas," Technical Symposium, Radio Club of America, New York City, Nov 20, 1987.

A. C. Doty, Jr, J. A. Frey and H. J. Mills, "Vertical Antennas: New Design and Construction Data," *The ARRL Antenna Compendium, Volume 2* (Newington: ARRL, 1989), pp 2-9.

R. Fosberg, "Some Notes on Ground Systems for 160 Meters," *QST*, Apr 1965, pp 65-67.

G. Grammer, "More on the Directivity of Horizontal Antennas; Harmonic Operation — Effects of Tilting," *QST*, Mar 1937, pp 38-40, 92, 94, 98.

H. E. Green, "Design Data for Short and Medium Length Yagi-Uda Arrays," *Trans IE Australia*, Vol EE-2, No. 1, Mar 1966.

H. J. Mills, technical paper presentation, "Impedance Transformation Provided by Folded Monopole Antennas," Technical Symposium, Radio Club of America, New York City, Nov 20, 1987.

B. Myers, "The W2PV Four-Element Yagi," *QST*, Oct 1986, pp 15-19.

L. Richard, "Parallel Dipoles of 300-Ohm Ribbon," *QST*, Mar 1957.

J. H. Richmond, "Monopole Antenna on Circular Disc," *IEEE Trans on Antennas and Propagation*, Vol. AP-32, No. 12, Dec 1984.

W. Schulz, "Designing a Vertical Antenna," *QST*, Sep 1978, pp 19- 21.

J. Sevick, "The Ground-Image Vertical Antenna," *QST*, Jul 1971, pp 16-17, 22.

J. Sevick, "The W2FMI 20-Meter Vertical Beam," *QST*, Jun 1972, pp 14-18.

J. Sevick, "The W2FMI Ground-Mounted Short Vertical," *QST*, Mar 1973, pp 13-18, 41.

J. Sevick, "A High Performance 20-, 40- and 80-Meter Vertical System," *QST*, Dec 1973.

J. Sevick, "Short Ground-Radial Systems for Short Verticals," *QST*, Apr 1978, pp 30-33.

C. E. Smith and E. M. Johnson, "Performance of Short Antennas," *Proc IRE*, Oct 1947.

J. Stanley, "Optimum Ground Systems for Vertical Antennas," *QST*, Dec 1976, pp 13-15.

R. E. Stephens, "Admittance Matching the Ground-Plane Antenna to Coaxial Transmission Line," Technical Correspondence, *QST*, Apr 1973, pp 55-57.

D. Sumner, "Cushcraft 32-19 'Boomer' and 324-QK Stacking Kit," Product Review, *QST*, Nov 1980, pp 48-49.

B Sykes, "Skeleton Slot Aerials," *RSGB* Bulletin, Jan 1953.

W. van B. Roberts, "Input Impedance of a Folded Dipole," *RCA Review*, Jun 1947.

E. M. Williams, "Radiating Characteristics of Short-Wave Loop Aerials," *Proc IRE*, Oct 1940.

TEXTBOOKS ON ANTENNAS

C. A. Balanis, *Antenna Theory, Analysis and Design* (New York: Harper & Row, 1982).

D. S. Bond, *Radio Direction Finders*, 1st ed. (New York: McGraw-Hill Book Co).

W. N. Caron, *Antenna Impedance Matching* (Newington: ARRL, 1989).

L. B. Cebik, *ARRL Antenna Modeling Course* (Newington: ARRL, 2002).

K. Davies, *Ionospheric Radio Propagation* — National Bureau of Standards Monograph 80 2(Washington, DC: U.S. Government Printing Office, Apr 1, 1965).

R. S. Elliott, *Antenna Theory and Design* (Englewood Cliffs, NJ: Prentice Hall, 1981).

A. E. Harper, *Rhombic Antenna Design* (New York: D. Van Nostrand Co, Inc, 1941).

K. Henney, *Principles of Radio* (New York: John Wiley and Sons, 1938), p 462.

C. Hutchinson and R. D. Straw, *Simple and Fun Antennas for Hams* (Newington: ARRL, 2002).

H. Jasik, *Antenna Engineering Handbook*, 1st ed. (New York: McGraw-Hill, 1961).

W. C. Johnson, *Transmission Lines and Networks*, 1st ed. (New York: McGraw-Hill Book Co, 1950).

Johnson and Jasik, *Antenna Engineering Handbook*, 2nd ed. (New York: McGraw-Hill).

R. C. Johnson, *Antenna Engineering Handbook*, 3rd ed. (New York: McGraw-Hill, 1993).

E. C. Jordan and K. G. Balmain, *Electromagnetic Waves and Radiating Systems*, 2nd ed. (Englewood Cliffs, NJ: Prentice-Hall, Inc, 1968).

R. Keen, *Wireless Direction Finding*, 3rd ed. (London: Wireless World).

R. W. P. King, *Theory of Linear Antennas* (Cambridge, MA: Harvard Univ. Press, 1956).

R. W. P. King, H. R. Mimno and A. H. Wing, *Transmission Lines, Antennas and Waveguides* (New York: Dover Publications, Inc, 1965).

King, Mack and Sandler, *Arrays of Cylindrical Dipoles* (London: Cambridge Univ Press, 1968).

M. G. Knitter, ed., *Loop Antennas — Design and Theory* (Cambridge, WI: National Radio Club, 1983).

M. G. Knitter, ed., *Beverage and Long Wire Antennas* — Design and Theory (Cambridge, WI: National Radio Club, 1983).

J. D. Kraus, *Electromagnetics* (New York: McGraw-Hill Book Co).

J. D. Kraus, *Antennas*, 2nd ed. (New York: McGraw-Hill Book Co, 1988).

E. A. Laport, *Radio Antenna Engineering* (New York: McGraw-Hill Book Co, 1952).

J. L. Lawson, *Yagi-Antenna Design*, 1st ed. (Newington: ARRL, 1986).

P. H. Lee, *The Amateur Radio Vertical Antenna Handbook*, 2nd ed. (Port Washington, NY: Cowen Publishing Co., 1984).

D. B. Leeson, *Physical Design of Yagi Antennas* (Newington: ARRL, 1992).

A. W. Lowe, *Reflector Antennas* (New York: IEEE Press, 1978).

M. W. Maxwell, *Reflections — Transmission Lines and Antennas* (Newington: ARRL, 1990).

M. W. Maxwell, *Reflections II — Transmission Lines and Antennas* (Sacramento: Worldradio Books, 2001).

G. M. Miller, *Modern Electronic Communication* (Englewood Cliffs, NJ: Prentice Hall, 1983).

V. A. Misek, *The Beverage Antenna Handbook* (Hudson, NH: V. A. Misek, 1977).

T. Moreno, *Microwave Transmission Design Data* (New York: McGraw-Hill, 1948).

L. A. Moxon, *HF Antennas for All Locations* (Potters Bar, Herts: Radio Society of Great Britain, 1982).

Ramo and Whinnery, *Fields and Waves in Modern Radio* (New York: John Wiley & Sons).

V. H. Rumsey, *Frequency Independent Antennas* (New York: Academic Press, 1966).

P. N. Saveskie, *Radio Propagation Handbook* (Blue Ridge Summit, PA: Tab Books, Inc, 1980).

S. A. Schelkunoff, *Advanced Antenna Theory* (New York: John Wiley & Sons, Inc, 1952).

S. A. Schelkunoff and H. T. Friis, *Antennas Theory and Practice* (New York: John Wiley & Sons, Inc, 1952).

J. Sevick, *Transmission Line Transformers* (Atlanta: Noble Publishing, 1996).

H. H. Skilling, *Electric Transmission Lines* (New York: McGraw-Hill Book Co, Inc, 1951).

M. Slurzburg and W. Osterheld, *Electrical Essentials of Radio* (New York: McGraw-Hill Book Co, Inc, 1944).

G. Southworth, *Principles and Applications of Waveguide Transmission* (New York: D. Van Nostrand Co, 1950).

R. D. Straw, Ed., *The ARRL Antenna Book*, 21st ed. (Newington: ARRL, 2007).

F. E. Terman, *Radio Engineers' Handbook*, 1st ed. (New York, London: McGraw-Hill Book Co, 1943).

F. E. Terman, *Radio Engineering*, 3rd ed. (New York: McGraw-Hill, 1947).

S. Uda and Y. Mushiake, *Yagi-Uda Antenna* (Sendai, Japan: Sasaki Publishing Co, 1954). [Published in English — Ed.]

P. P. Viezbicke, "*Yagi Antenna Design*," NBS Technical Note 688 (US Dept of Commerce/National Bureau of Standards, Boulder, CO), Dec 1976.

G. B. Welch, *Wave Propagation and Antennas* (New York: D. Van Nostrand Co, 1958).

The GIANT Book of Amateur Radio Antennas (Blue Ridge Summit, PA: Tab Books, 1979).

IEEE Standard Dictionary of Electrical and Electronics Terms, 3rd ed. (New York: IEEE, 1984).

Radio Broadcast Ground Systems, available from Smith Electronics, Inc, 8200 Snowville Rd, Cleveland, OH 44141.

Radio Communication Handbook, 5th ed. (London: RSGB, 1976).

RDF BIBLIOGRAPHY

Bohrer, "Foxhunt Radio Direction Finder," *73 Amateur Radio*, Jul 1990, p 9.

Bonaguide, "HF DF — A Technique for Volunteer Monitoring," *QST*, Mar 1984, p 34.

DeMaw, "Maverick Trackdown," *QST*, Jul 1980, p 22.

Dorbuck, "Radio Direction Finding Techniques," *QST*, Aug 1975, p 30.

Eenhoorn, "An Active Attenuator for Transmitter Hunting," *QST*, Nov 1992, p 28.

Flanagan and Calabrese, "An Automated Mobile Radio Direction Finding System," *QST*, Dec 1993, p 51.

Geiser, "A Simple Seeker Direction Finder," *ARRL Antenna Compendium, Volume 3*, p 126.

Gilette, "A Fox-Hunting DF Twin'Tenna," *QST*, Oct 1998, pp 41-44.

Johnson and Jasik, *Antenna Engineering Handbook*, Second Edition, New York: McGraw-Hill.

Kossor, "A Doppler Radio-Direction Finder," *QST*, Part 1: May 1999, pp 35-40; Part 2: June 1999, pp 37-40.

McCoy, "A Linear Field-Strength Meter," *QST*, Jan 1973, p 18.

Moell and Curlee, *Transmitter Hunting: Radio Direction Finding Simplified*, Blue Ridge Summit, PA: TAB/McGraw-Hill. (This book, available from ARRL, includes plans for the Roanoke Doppler RDF unit and in-line air attenuator, plus VHF quads and other RDF antennas.)

Moell, "Transmitter Hunting — Tracking Down the Fun," *QST*, Apr 1993, p 48 and May 1993, p 58.

Moell, "Build the Handy Tracker," *73 Magazine*, Sep 1989, p 58 and Nov 1989, p 52.

O'Dell, "Simple Antenna and S-Meter Modification for 2-Meter FM Direction Finding," *QST*, Mar 1981, p 43.

O'Dell, "Knock-It-Down and Lock-It-Out Boxes for DF," *QST*, Apr 1981, p 41.

Ostapchuk, "Fox Hunting is Practical and Fun!" *QST*, Oct 1998, pp 68-69.

Rickerd, "A Cheap Way to Hunt Transmitters," *QST*, Jan 1994, p 65.

The "Searcher" (SDF-1) Direction Finder, Rainbow Kits.

RDF RESOURCES

Homing In
www.homingin.com — Web site by KØOV on direction finding techniques and activities

Amateur Radio Direction Finding (IARU Region II)
www.ardf-r2.org/en — ARDF activities and organizations in IARU Region II

Radio Direction Finding
en.wikipedia.org/wiki/Direction_finding — a general site on RDF with links to related subjects

DX Zone RDF Links
www.dxzone.com/catalog/Operating_Modes/Radio_Direction_Finding — a page of links to RDF articles and Web sites