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Chapter 2

Dipoles and Monopoles

Dipoles and monopoles are not only popular antennas, they are the basic elements from which most antennas used by amateurs are constructed, including beams. This chapter explores the basic characteristics of these antennas in support of the specific designs the reader will encounter later in the book. Material from previous editions is augmented by contributions from the dipole and vertical chapters of the 5th edition of *ON4UN's Low-Band DXing*.

2.1 DIPOLES

The *dipole* is a fundamental form of antenna — in its most common form it is approximately one-half wavelength (½ λ) long at the frequency of use. It is the unit from which many more complex forms of antennas are constructed. The name di- meaning *two*, and -pole meaning *electrical polarity*, relates to the opposite voltages applied to each half of the antenna so that it has two electrical halves as in **Figure 2.1**. A dipole is resonant when its electrical length is some multiple of ½ λ so that the current and voltage in the antenna are exactly 90° out of phase as shown in **Figure 2.2**.

2.1.1 EFFECTS OF CONDUCTOR DIAMETER

The physical length of a resonant ½-λ antenna will not be exactly equal to the half wavelength of a radio wave of that frequency in free space, but depends on the thickness of the conductor in relation to the wavelength as shown in **Figure 2.3**. **Table 2.1** gives resonant lengths for dipoles in free space, made of #12 AWG bare copper wire. If thinner wire is used, the resonant length will be a few percent longer, and vice versa.

An additional shortening effect occurs with wire antennas supported by insulators at the ends (and at the feed point) because of the capacitance added to the system by the loops of wire through the insulators. This shortening is called *end effect*.

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,

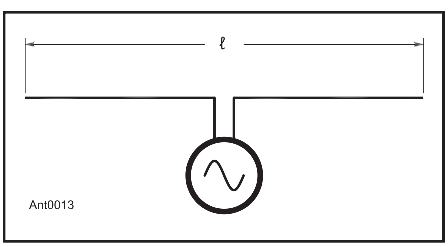

Figure 2.1 — The center-fed dipole antenna. It is assumed that the source of power is directly at the antenna feed point, with no intervening transmission line. Although λ/2 is the most common length for amateur dipoles, the length of a dipole antenna can be any fraction of a wavelength.

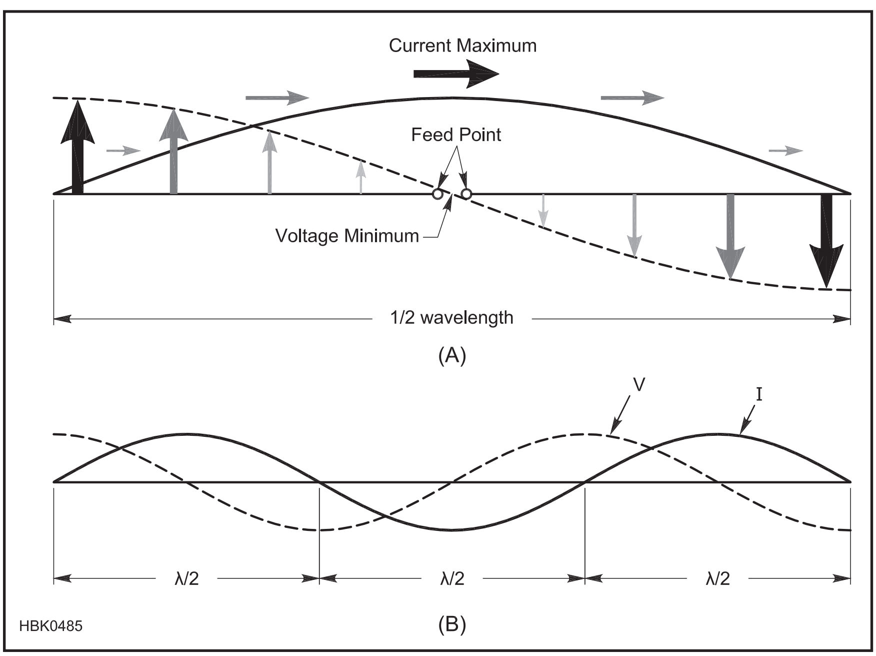

Figure 2.2 — The current and voltage distribution along a half-wave dipole (A) and for an antenna made from a series of half-wave dipoles (B).

Table 2.1
Resonant λ/2 Dipole Lengths in Free Space

Freq (MHz)	*½λ_{fs} (ft)*	*L (ft)*	*L (m)*
1.82	270.3	263.8	80.4
3.6	136.7	133.0	40.5
3.85	127.8	124.4	37.9
5.35	92.0	89.5	27.3
7.15	68.8	66.9	20.4
10.1	48.7	47.3	14.4
14.15	34.8	33.7	10.3
18.1	27.2	26.3	8.0
21.2	23.2	22.5	6.9
24.9	19.8	19.1	5.8
28.3	17.4	16.8	5.1
51	9.6	9.3	2.8

Dipole constructed from #12 AWG bare copper wire
½λ_{fs} is the free-space wavelength computed as 492/f(MHz)

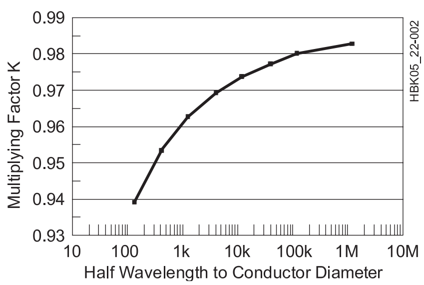

Figure 2.3 — Effect of antenna diameter on length for half-wavelength resonance in free-space, shown as a multiplying factor, K. The thicker the conductor relative to the wavelength, the shorter the physical length of the antenna at resonance. For antennas over ground, additional factors affect the antenna's electrical length.

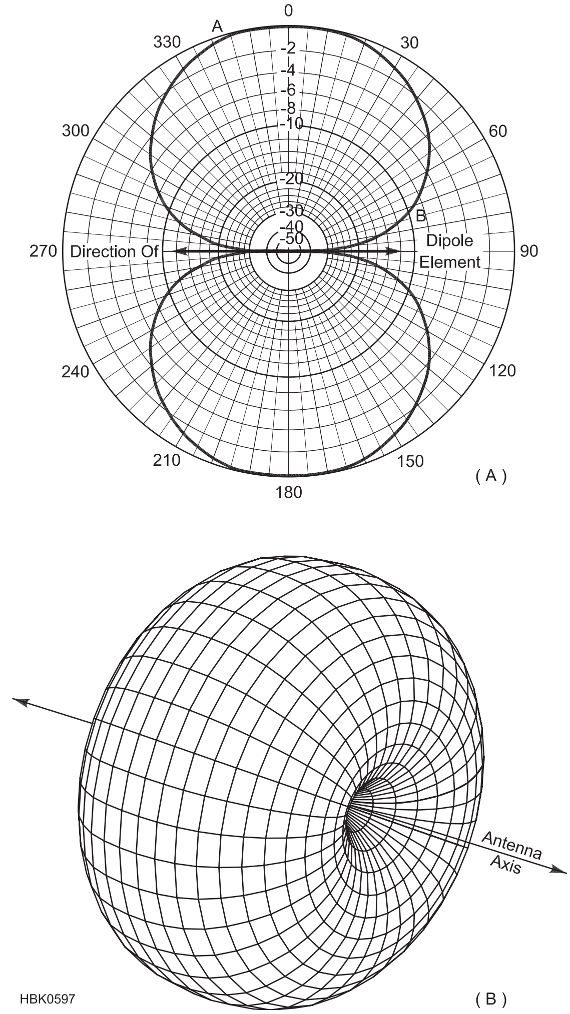

Figure 2.4 — Response of a dipole antenna in free space in the plane of the antenna with the antenna oriented along the 90° to 270° axis (A). The full three-dimensional pattern of the dipole is shown at (B). The pattern at A is a cross-section of the three-dimensional pattern taken directly through the axis of the antenna.

$$\text{Length (ft)} = \frac{492 \times 0.95}{f\,(\text{MHz})} = \frac{468}{f\,(\text{MHz})} \qquad \text{(Eq 1)}$$

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

For antennas at higher frequencies and/or higher above ground, use a numerator value closer to the free-space value, such as 485 to 490. Include additional wire for attaching 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 Figure 2.3.

$$\text{Length (ft)} = \frac{492 \times K}{f\,(\text{MHz})} \qquad \text{(Eq 2)}$$

$$\text{Length (in)} = \frac{5904 \times K}{f\,(\text{MHz})} \qquad \text{(Eq 3)}$$

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 Figure 2.3, K = 0.945 for this ratio. The length of the antenna, from Equation 2 is

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

or 9 feet 3⅜ inches. The answer is obtained directly in inches by substitution in Equation 3

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

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 effect of lowering the frequency at which the antenna element is resonant, as illustrated by the graph in Figure 2.1. 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 λ long electrically.

$$l / d = \frac{\lambda / 2}{d} = \frac{300}{2f \times d} \qquad \text{(Eq 4)}$$

where f is in MHz and d is in meters. For example, a ½-λ 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 Figure 2.3 an l/d ratio of 10,126 corresponds to K × 0.975, so the resonant length of that ½-wave dipole would be K × (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).

For single-wire HF antennas, the effects of ground and antenna construction make K impractical for determining antenna dimensions precisely. 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, but 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.

2.1.2 RADIATION PATTERNS AND EFFECTS OF GROUND

The radiation pattern of a dipole antenna in free space is strongest at right angles to the wire as shown in **Figure 2.4**, a free-space radiation pattern. The dipole in free space has a gain of 2.15 dBi.

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 dipole is brought closer to ground, reflections from the ground combine with the direct radiation to create lobes at different angles as shown in **Figure 2.5**. In addition, the directivity of the dipole also changes with

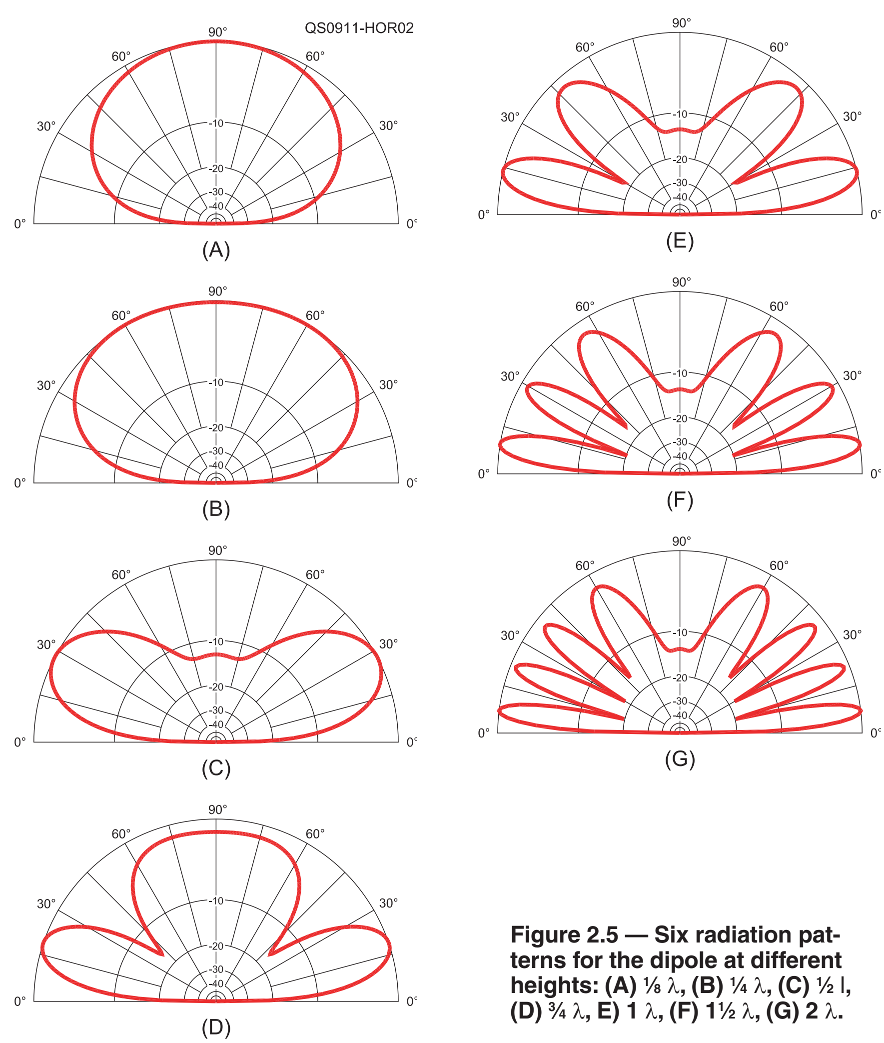

Figure 2.5 — Six radiation patterns for the dipole at different heights: (A) ⅛ λ, (B) ¼ λ, (C) ½ l, (D) ¾ λ, E) 1 λ, (F) 1½ λ, (G) 2 λ.

height. For example, **Figure 2.6** shows the dipole's three-dimensional pattern at a height of ½ λ. The deep null along the axis of the wire in Figure 2.6 is filled in with a substantial amount of radiation.

Figure 2.7 shows the radiation pattern for dipoles at different heights above ground and at four different elevation angles from 15° to 60°. You can see that for low heights (the H = ¼ λ figure) the dipole becomes almost omnidirectional at elevation angles of 60° and higher.

The type of ground under the dipole also affects the radiation pattern. **Figure 2.8** illustrates what happens over two different types of ground; very poor soil (desert) and saltwater. These two types of ground represent the extremes of what amateurs are likely to encounter and most installations will be somewhere in between these two examples.

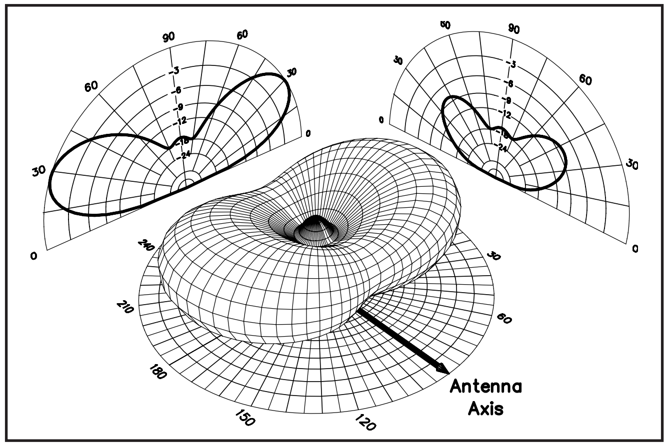

Figure 2.6 — Three-dimensional representation of the radiation patterns of a half-wave dipole, ½ λ above ground.

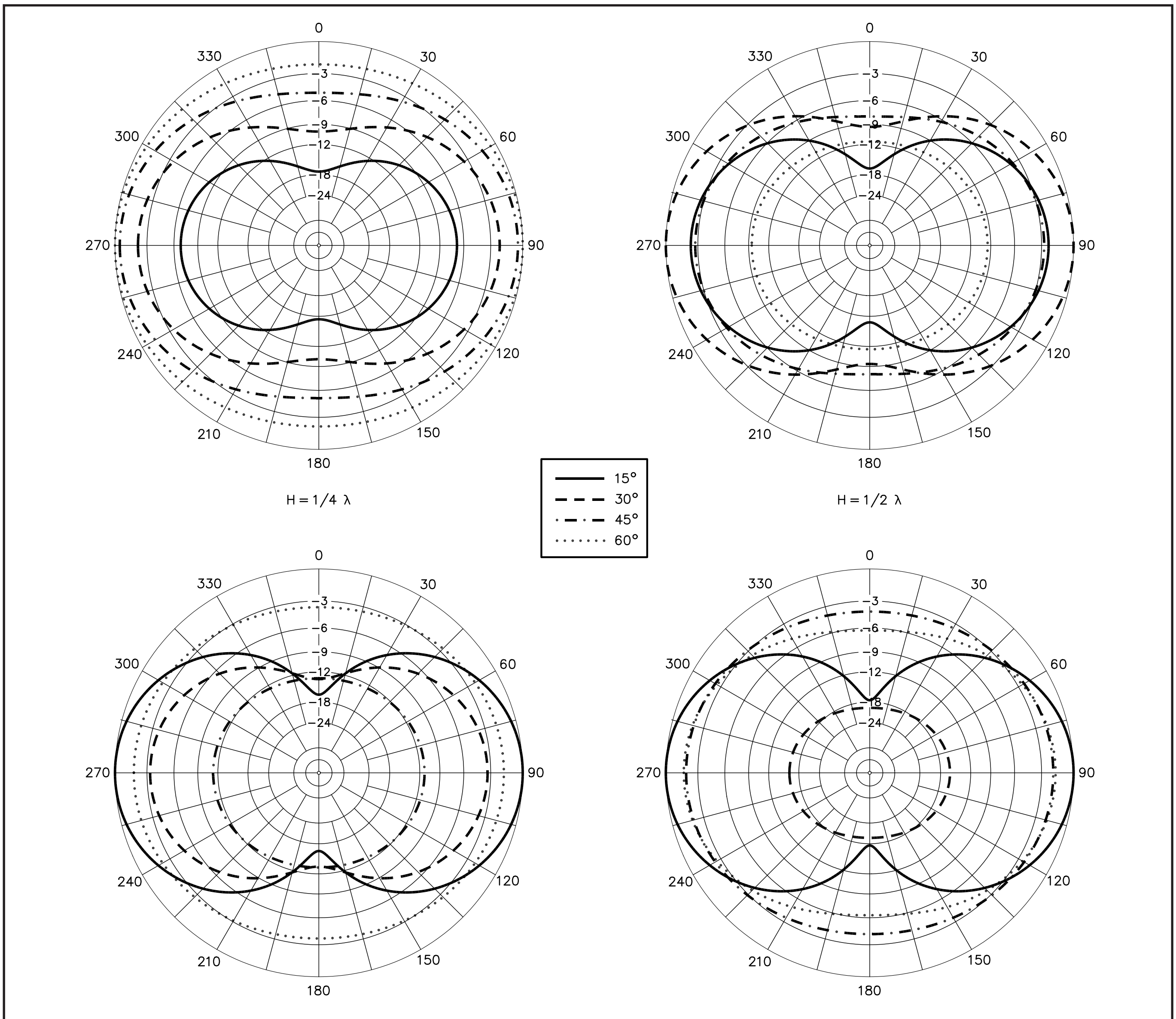

Figure 2.7 — Horizontal radiation pattern for ½-wave horizontal dipole at various heights above ground for wave angles of 15°, 30°, 45° and 60° (modeled over good ground).

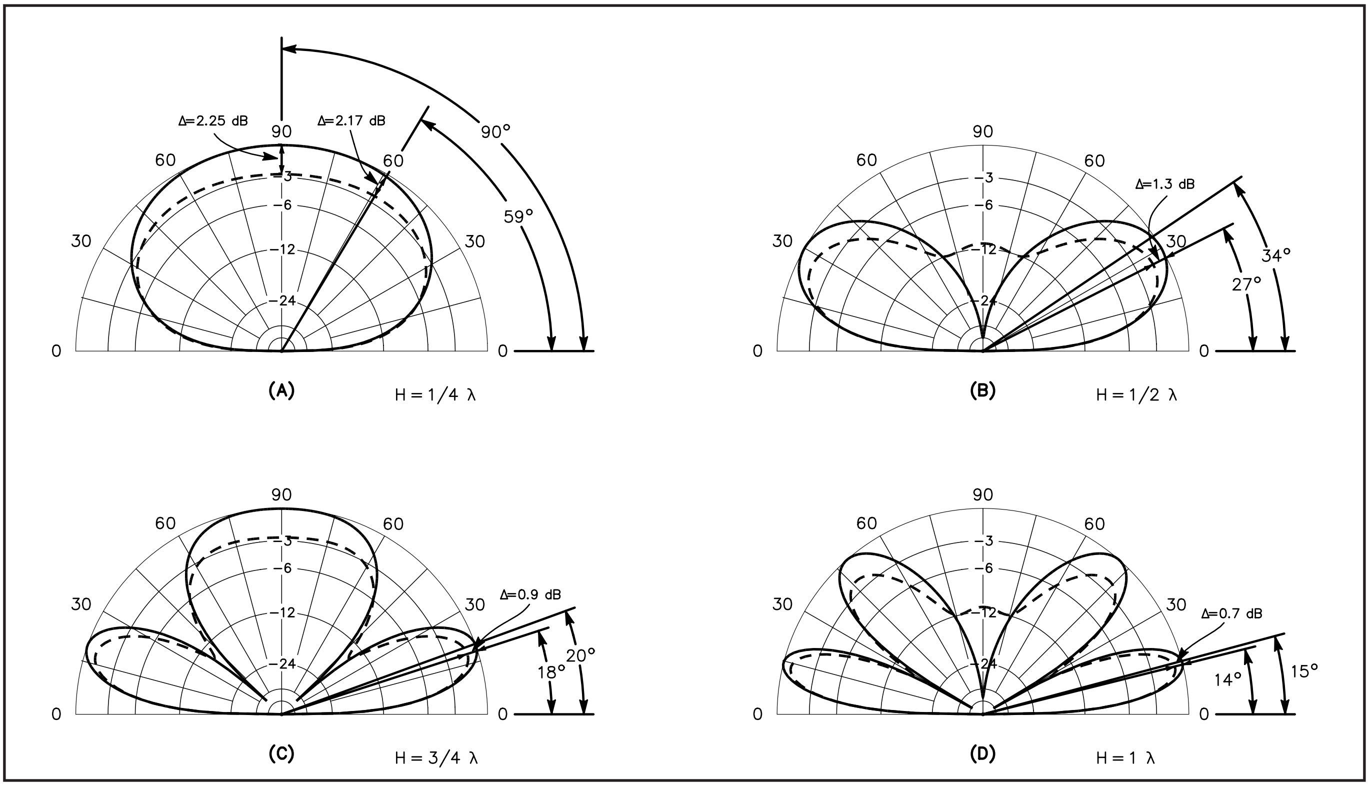

Figure 2.8 — Vertical radiation patterns over two types of ground: saltwater (solid line in each set of plots) and very poor ground (dashed line in each set of plots). The wave angles as well as the gain difference between saltwater and poor ground are given for four antenna heights.

Table 2.2
Variation in Dipole Performance with Height

Height in Wavelengths at 14.175 MHz (feet)	*Resonant Length in Feet (L x f)*	*Feed point Impedance in Ω (SWR)*	*Max Gain (dBi) at Angle (Degrees)*
⅛ (8.8)	33.0 (467.8)	31.5 (1.59)	8.3 @ 90
¼ (17.4)	32.9 (466.4)	81.7 (1.63)	6.5 @ 62
½ (34.7)	34.1 (483.4)	69.6 (1.39)	7.9 @ 28
¾ (52.0)	33.4 (473.4)	73.4 (1.47)	7.3 @ 18
1 (69.4)	33.9 (480.5)	71.9 (1.44)	7.7 @ 14
1½ (104.1)	33.8 (479.1)	72.0 (1.44)	7.8 @ 9
2 (138.8)	33.8 (479.1)	72.3 (1.45)	7.9 @ 7

Note: All gain values were calculated using *EZNEC*'s *MININEC* ground. These calculated gains and elevation angles are examples meant to illustrate the large effect that height above ground can have on antenna pattern. They are unlikely to be exactly correct for a real antenna in an actual installation.

For antennas over ground, the height above ground also affects the antenna's physical length as in the example of **Table 2.2** showing the resonant, half-wavelength length for a 20 meter dipole at various electrical heights. Nearby conducting surfaces and materials will also affect resonant length.

2.1.3 FEED POINT IMPEDANCE

A feed line is attached directly to the dipole, generally at the center with an insulator separating the antenna's conductor into two sections. Such a dipole is referred to as being *center-fed*. One conductor of the feed line is attached to each section. The point at which the feed line is attached is the dipole's *feed point*.

The dipole's feed point impedance is the ratio of voltage to current at the feed point. Referring back to Figure 2.2A, the feed point impedance of a half-wave dipole will be low at the center (where voltage is minimum and current is maximum) and high on each end (where voltage is maximum and current is minimum).

If a dipole is fed at the center and excited (supplied with power) at the third harmonic, the situation changes to that of Figure 2.2B. The dipole's physical length has not changed but its electrical length at the third harmonic has tripled — it is now three half-wavelengths long. If fed in the center, the same low impedance (low voltage/high current) is presented to the feed line. This situation occurs for all odd harmonics of the dipole's fundamental frequency because the center of the dipole is at a low impedance point and will present a reasonably low SWR to coaxial feed lines.

The situation is reversed if the dipole is excited at an even harmonic. Remove the right-most half-wavelength section in Figure 2.2B as the dipole is now electrically one full wavelength long. At the center of this antenna, voltage is high and current is low so the impedance is high and SWR will be high on any common feed line, coaxial or parallel-conductor. This is the situation at all even harmonics of the dipole's fundamental frequency and is sometimes referred to as *anti-resonance*.

At frequencies in between harmonics, the feed point impedance will take some intermediate value. When fed with parallel-conductor line and a wide-range impedance-matching unit, a dipole can be used on nearly any frequency, including non-resonant frequencies. (An example of such an antenna system is presented in the chapter **Single Band MF and HF Antennas**.)

A dipole can be fed anywhere along its length, although the impedance of the antenna will vary as the ratio of voltage and current change. 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 that occurs on several bands to that of coaxial cable.

Feed Point Impedance in Free-Space

In free space the theoretical impedance of a half-wavelength antenna made of an infinitely thin conductor is 73 + *j*42.5 Ω. This antenna exhibits both resistance and reactance. The positive sign in the + *j*42.5 Ω reactive term indicates that the antenna exhibits an inductive reactance at its feed point. The antenna is slightly long electrically, compared to the length necessary for exact resonance, where the reactance is zero.

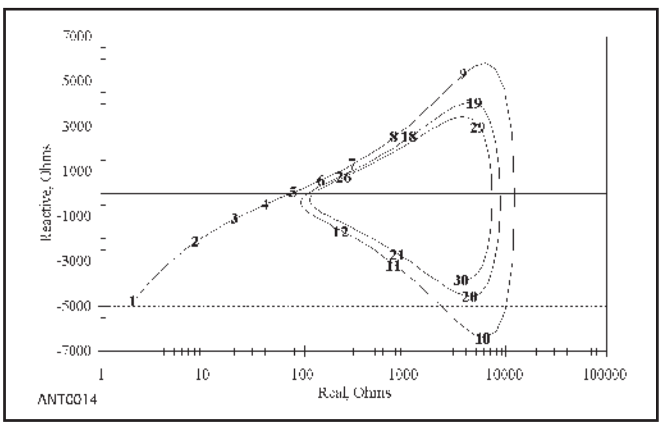

Figure 2.9 — Feed point impedance versus frequency for a theoretical 100-foot long dipole in free space, fed in the center and made of extremely thin 0.001-inch diameter wire. The y-axis is calibrated in positive (inductive) series reactance up from the zero line, and negative (capacitive) series reactance in the downward direction. The range of reactance goes from –6500 Ω to +6000 Ω. Note that the x-axis is logarithmic because of the wide range of the real, resistive component of the feed point impedance, from roughly 2 Ω to 10,000 Ω. The numbers placed along the curve show the frequency in MHz.

The feed point impedance of any antenna is affected by the wavelength-to-diameter ratio (λ/dia) of the conductors used. Theoreticians like to specify an "infinitely thin" antenna because it is easier to handle mathematically.

What happens if we keep the physical length of an antenna constant, but change the thickness of the wire used in its construction? Further, what happens if we vary the frequency from well below to well above the half-wave resonance and measure the feed point impedance? **Figure 2.9** graphs the impedance of a 100-foot long, center-fed dipole in free space, made with extremely thin wire — in this case, wire that is only 0.001 inch in diameter. There is nothing particularly significant about the choice here of 100 feet. This is simply a numerical example.

We could never actually build such a thin antenna (and neither could we install it in free space), but we can model how this antenna works using a very powerful piece of computer software called *NEC-4.1*. (See the **Antenna Modeling** chapter for details on antenna modeling.)

The frequency applied to the antenna in Figure 2.9 is varied from 1 to 30 MHz. The x-axis has a logarithmic scale because of the wide range of feed point resistance seen over the frequency range. The y-axis has a linear scale representing the reactive portion of the impedance. Inductive reactance is positive and capacitive reactance is negative on the y-axis. The bold figures centered on the spiraling line show the frequency in MHz.

At 1 MHz, the antenna is very short electrically, with a resistive component of about 2 Ω and a series capacitive reactance about –5000 Ω. Close to 5 MHz, the line crosses the zero-reactance line, meaning that the antenna goes through half-wave resonance there. Between 9 and 10 MHz the antenna exhibits a peak inductive reactance of about 6000 Ω. It goes through full-wave resonance (again crossing the zero-reactance line) between 9.5 and 9.6 MHz. At about 10 MHz, the reactance peaks at about –6500 Ω. Around 14 MHz, the line again crosses the zero-reactance line, meaning that the antenna has now gone through 3/2-wave resonance.

Between 19 and 20 MHz, the antenna goes through 4/2-wave resonance, which is twice the full-wave resonance or four times the half-wave frequency. If you allow your mind's eye to trace out the curve for frequencies beyond 30 MHz, it eventually spirals down to a resistive component somewhere between 200 and 3000 Ω. Thus, we have another way of looking at an antenna—as a sort of transformer, one that transforms the free-space impedance into the impedance seen at its feed point.

Now look at **Figure 2.10**, which shows the same kind of spiral curve, but for a thicker-diameter wire, one that is 0.1 inch in diameter. This diameter is close to #10 AWG wire, a practical size we might actually use to build a real dipole. Note that the y-axis scale in Figure 2.10 is differ-

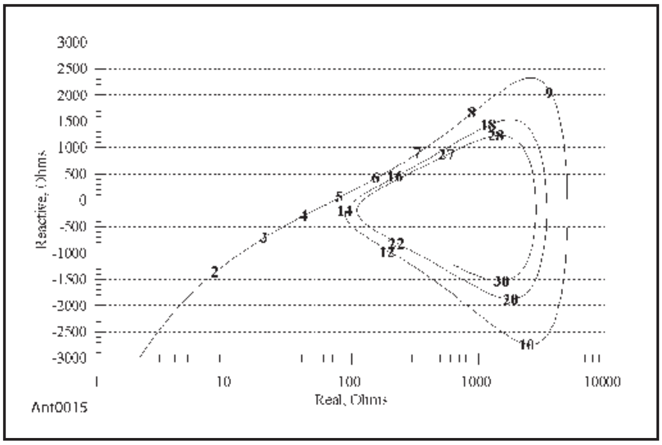

Figure 2.10 — Feed point impedance versus frequency for a theoretical 100-foot long dipole in free space, fed in the center and made of thin 0.1-inch (#10 AWG) diameter wire. Note that the range of change in reactance is less than that shown in Figure 2.9, ranging from –2700 Ω to +2300 Ω. At about 5000 Ω, the maximum resistance is also less than that in Figure 2.9 for the thinner wire, where it is about 10,000 Ω.

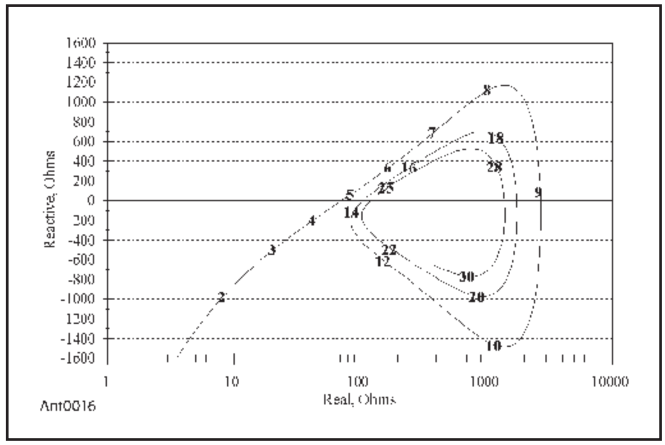

Figure 2.11 — Feed point impedance versus frequency for a theoretical 100-foot long dipole in free space, fed in the center and made of thick 1.0-inch diameter wire. Once again, the excursion in both reactance and resistance over the frequency range is less with this thick wire dipole than with thinner ones.

ent from that in Figure 2.9. The range is from –3000 Ω in Figure 2.10, while it was –7000 Ω in Figure 2.9. The reactance for the thicker antenna ranges from +2300 to –2700 Ω over the whole frequency range from 1 to 30 MHz. Compare this with the range of +5800 to –6400 Ω for the very thin wire in Figure 2.9.

Figure 2.11 shows the impedance for a 100-foot long dipole using really thick, 1.0-inch diameter wire. The reactance varies from +1000 to –1500 Ω, indicating once again that a larger diameter antenna exhibits less of an excursion in the reactive component with frequency. Note that at the half-wave resonance just below 5 MHz, the resistive component of the impedance is still about 70 Ω, just about what it is for a much thinner antenna. Unlike the reactance, the half-wave radiation resistance of an antenna doesn't radically change with wire diameter, although the maximum level of resistance at full-wave resonance is lower for thicker antennas.

Figure 2.12 shows the results for a very thick, 10-inch diameter wire. Here, the excursion in the reactive component is even less: about +400 to –600 Ω. Note that the full-wave resonant frequency is about 8 MHz for this extremely thick antenna, while thinner antennas have full-wave resonances closer to 9 MHz. Note also that the full-wave resistance for this extremely thick antenna is only about 1000 Ω, compared to the 10,000 Ω shown in Figure 2.9. All half-wave resonances shown in Figures 2.9 through 2.12 remain close to 5 MHz, regardless of the diameter of the antenna wire. Once again, the extremely thick, 10-inch diameter antenna has a resistive component at half-wave resonance close to 70 Ω. And once again, the change in reactance near this frequency is very much less for the extremely thick antenna than for thinner ones.

Now, we grant you that a 100-foot long antenna made with 10-inch diameter wire sounds a little odd! A length of 100 feet and a diameter of 10 inches represent a ratio of

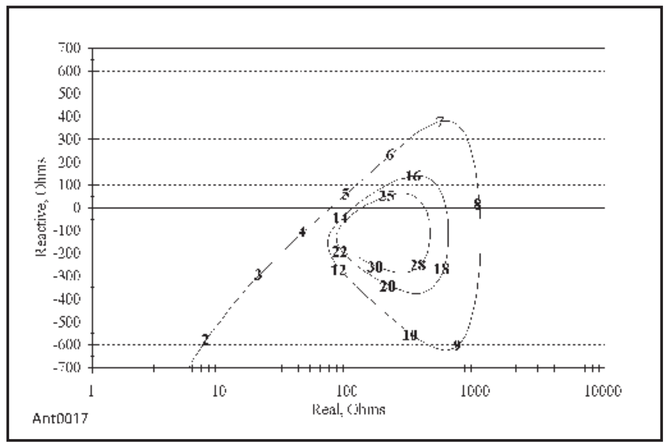

Figure 2.12 — Feed point impedance versus frequency for a theoretical 100-foot long dipole in free space, fed in the center and made of very thick 10.0-inch diameter wire. This ratio of length to diameter is about the same as a typical rod type of dipole element commonly used at 432 MHz. The maximum resistance is now about 1,000 Ω and the peak reactance range is from about –625 Ω to +380 Ω. This performance is also found in "cage" dipoles, where a number of paralleled wires are used to simulate a fat conductor.

120:1 in length to diameter. However, this is about the same length-to-diameter ratio as a 432 MHz half-wave dipole using 0.25-inch diameter elements, where the ratio is 109:1. In other words, the ratio of length-to-diameter for the 10-inch diameter, 100 foot long dipole is not that far removed from what might actually be used at UHF.

Another way of highlighting the changes in reactance and resistance is shown in **Figure 2.13**. This shows an expanded portion of the frequency range around the half-wave resonant frequency, from 4 to 6 MHz. In this region, the shape of each spiral curve is almost a straight line. The slope of the curve for the very thin antenna (0.001-inch diameter) is steeper than that for the thicker antennas (0.1 and 1.0-inch diameters). **Figure 2.14** illustrates another way of looking at the impedance data above and below the half-wave resonance. This is for a 100-foot dipole made of #14 AWG wire. Instead of showing the frequency for each impedance point, the wavelength is shown, making the graph more universal in application.

Just to show that there are lots of ways of looking at the same data, recall that Figure 2.8 graphs the constant "K" used to multiply the free-space half-wavelength as a function of the ratio between the half-wavelength and the conductor diameter. The curve approaches the value of 1.00 for an infinitely thin conductor, in other words an infinitely large ratio of half-wavelength to diameter.

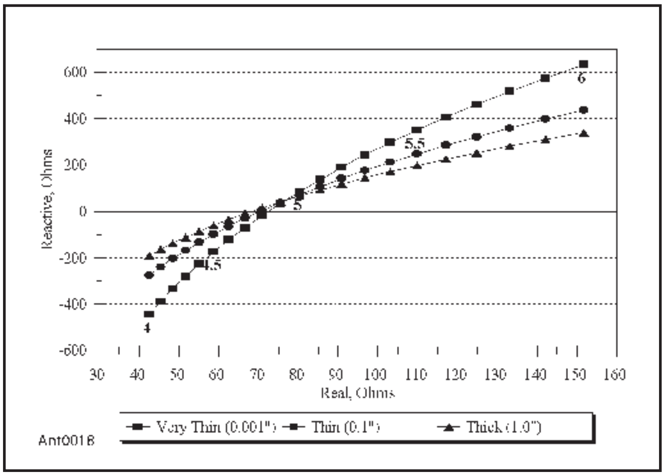

Figure 2.13 — Expansion of frequency range around half-wave resonant point of three center-fed dipoles of three different thicknesses. The frequency is shown along the curves in MHz. The slope of change in series reactance versus series resistance is steeper for the thinner antennas than for the thick 1.0-inch antenna, indicating that the Q of the thinner antennas is higher.

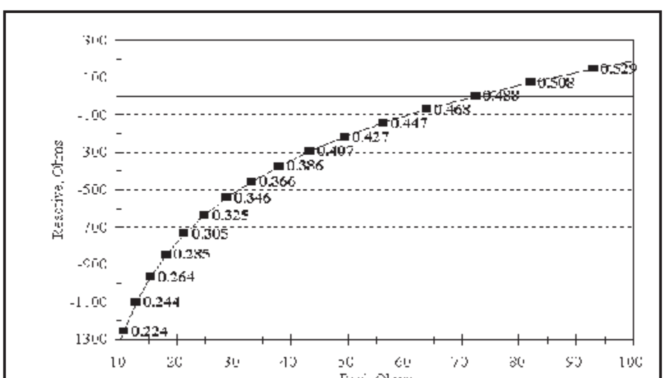

Figure 2.14 — Another way of looking at the data for a 100-foot, center-fed dipole made of #14 AWG wire in free space. The numbers along the curve represent the fractional wavelength, rather than frequency as shown in Figure 2.13. Note that this antenna goes through its half-wave resonance at about 0.488 λ, rather than exactly at a half-wave physical length.

The behavior of antennas with different λ/diameter ratios corresponds to the behavior of ordinary series-resonant circuits having different values of Q. When the Q of a circuit is low, the reactance is small and changes rather slowly as the applied frequency is varied on either side of resonance. If the Q is high, the converse is true. The response curve of the low-Q circuit is broad; that of the high-Q circuit sharp. So it is with antennas — the impedance of a thick antenna changes slowly over a comparatively wide band of frequencies, while a thin antenna has a faster change in impedance. Antenna Q is defined

$$Q = \frac{f_0 \Delta X}{2 R_0 \Delta f} \quad \text{(Eq 5)}$$

where f_0 is the center frequency, ΔX is the change in the reactance for a Δf change in frequency, and R_0 is the resistance at f_0. For the "Very Thin," 0.001-inch diameter dipole in Figure 2.9, a change of frequency from 5.0 to 5.5 MHz yields a reactance change from 86 to 351 Ω, with an R_0 of 95 Ω. The Q is thus 14.6. For the 1.0-inch-diameter "Thick" dipole in Figure 2.11, ΔX = 131 Ω and R_0 is still 95 Ω, making Q = 7.2 for the thicker antenna, roughly half that of the thinner antenna.

Let's recap. The dipole can be described as a transducer or as a sort of transformer to a range of free-space impedances. Now, we just compared the antenna to a series-tuned circuit. Near its half-wave resonant frequency, a center-fed λ/2 dipole exhibits much the same characteristics as a conventional series-resonant circuit. Exactly at resonance, the current at the input terminals is in phase with the applied voltage and the feed point impedance is purely resistive. If the frequency is below resonance, the phase of the current leads the voltage; that is, the reactance of the antenna is capacitive. When the frequency is above resonance, the opposite occurs; the current lags the applied voltage and the antenna exhibits inductive reactance. Just like a conventional series-tuned circuit, the antenna's reactance and resistance determines its Q.

Effect of Height Above Ground on Feed Point Impedance

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 **Figure 2.15** 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 around 75 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 λ 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.

Figure 2.15 also 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

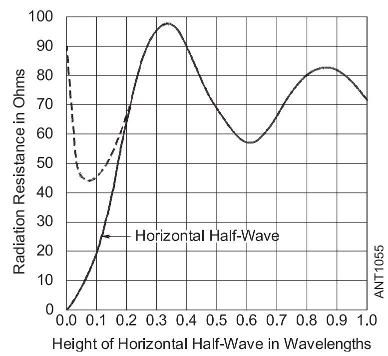

Figure 2.15 — Curves showing the radiation resistance of a horizontal half-wavelength dipole at various heights above ground. The broken-line portion of the curve for a horizontal dipole shows the resistance over *average* real earth, the solid line for perfectly conducting ground.

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 ground as the height drops below ¼ λ, seen as an increase in feed point impedance.

2.1.4 EFFECT OF FREQUENCY ON RADIATION PATTERN

Earlier, we saw how the feed point impedance of a fixed-length center-fed dipole in free space varies as the frequency is changed. What happens to the radiation pattern of such an antenna as the frequency is changed?

In general, the greater the length of a center-fed antenna, in terms of wavelength, the larger the number of lobes into which the pattern splits. A feature of all such patterns is the fact that the main lobe is always the one that makes the smallest angle with (is closest to) the antenna wire. Furthermore, this angle becomes smaller as the length of the antenna is increased.

Let's examine how the free-space radiation pattern changes for a 100-foot long wire made of #14 AWG wire as the frequency is varied. (Varying the frequency effectively changes the electrical length of a fixed-length wire.) **Figure 2.16** shows the E-plane pattern at the λ/2 resonant frequency of 4.8 MHz. This is a classical dipole pattern, with a gain in free space of 2.14 dBi referenced to an isotropic radiator.

Figure 2.17 shows the free-space E-plane pattern for the same antenna, but now at the full-wave (2 λ/2) resonant frequency of 9.55 MHz. Note how the pattern has been pinched in at the top and bottom of the figure. In other words, the two main lobes have become sharper at this frequency, making the gain 3.73 dBi, higher than at the λ/2 frequency.

Figure 2.18 shows the pattern at the 3 λ/2 frequency of 14.6 MHz. More lobes have developed compared to Figure 2.16. This means that the power has split up into more lobes and consequently the gain decreases a small amount, down to 3.44 dBi. This is still higher than the dipole at its λ/2 frequency, but lower than at its full-wave frequency. **Figure 2.19** shows the E-plane response at 19.45 MHz, the 4 λ/2, or 2 λ, resonant frequency. Now the pattern has reformed itself into only four lobes, and the gain has as a consequence risen to 3.96 dBi.

In **Figure 2.20** the response has become quite complex at the 5 λ/2 resonance point of 24.45 MHz, with ten lobes

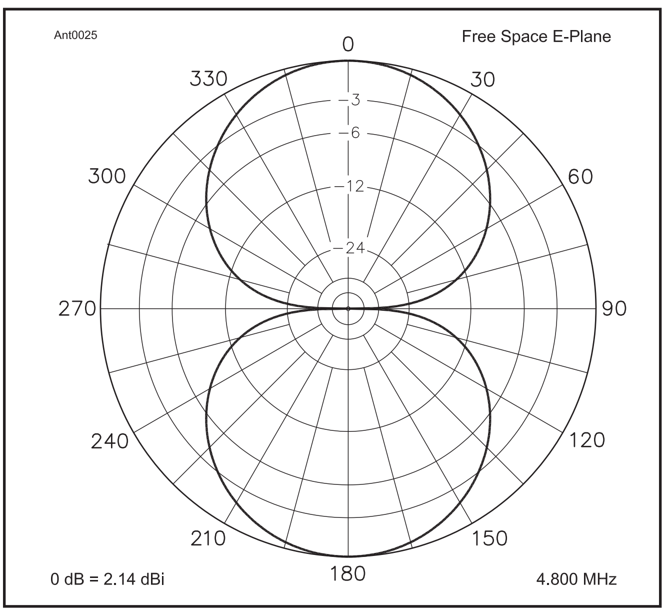

Figure 2.16 — Free-space E-Plane radiation pattern for a 100-foot dipole at its half-wave resonant frequency of 4.80 MHz. This antenna has 2.14 dBi of gain. The dipole is located on the line from 90° to 270°.

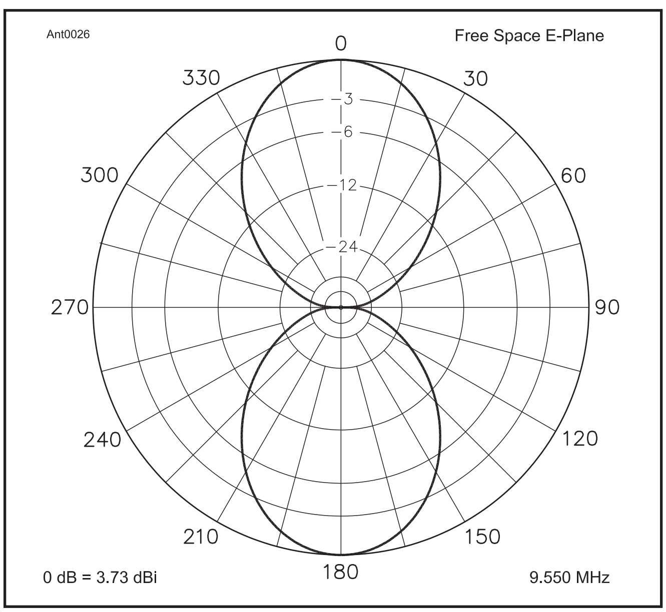

Figure 2.17 — Free-space E-Plane radiation pattern for a 100-foot dipole at its full-wave resonant frequency of 9.55 MHz. The gain has increased to 3.73 dBi, because the main lobes have been focused and sharpened compared to Figure 2.16.

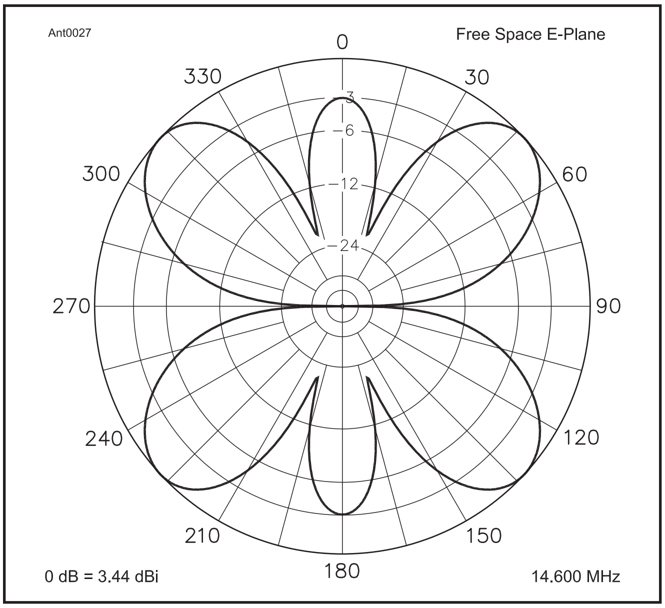

Figure 2.18 — Free-space E-Plane radiation pattern for a 100-foot dipole at its 3/2λ resonant frequency of 14.60 MHz. The pattern has broken up into six lobes, and thus the peak gain has dropped to 3.44 dBi.

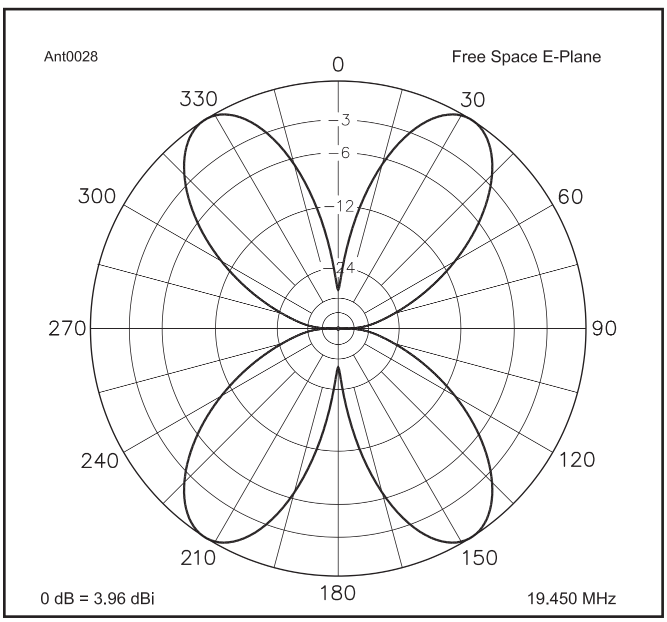

Figure 2.19 — Free-space E-Plane radiation pattern for a 100-foot dipole at twice its full-wave resonant frequency of 19.45 MHz. The pattern has been refocused into four lobes, with a peak gain of 3.96 dBi.

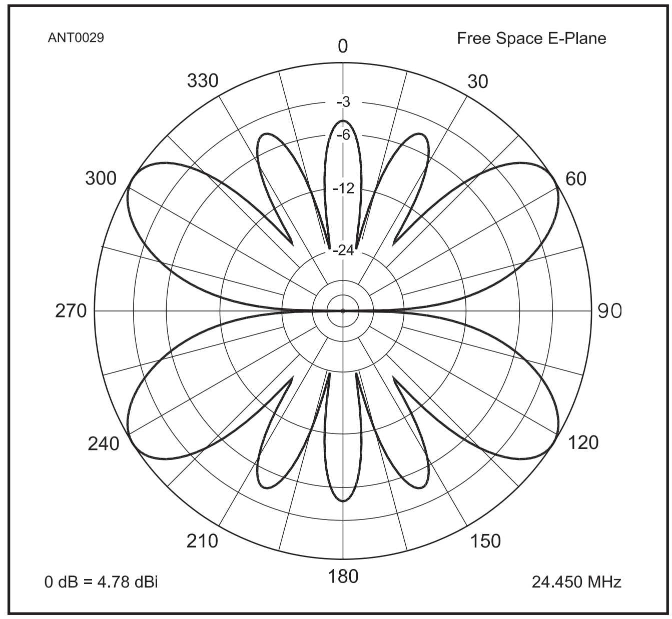

Figure 2.20 — Free-space E-Plane radiation pattern for a 100-foot dipole at its 5/2λ resonant frequency of 24.45 MHz. The pattern has broken down into ten lobes, with a peak gain of 4.78 dBi.

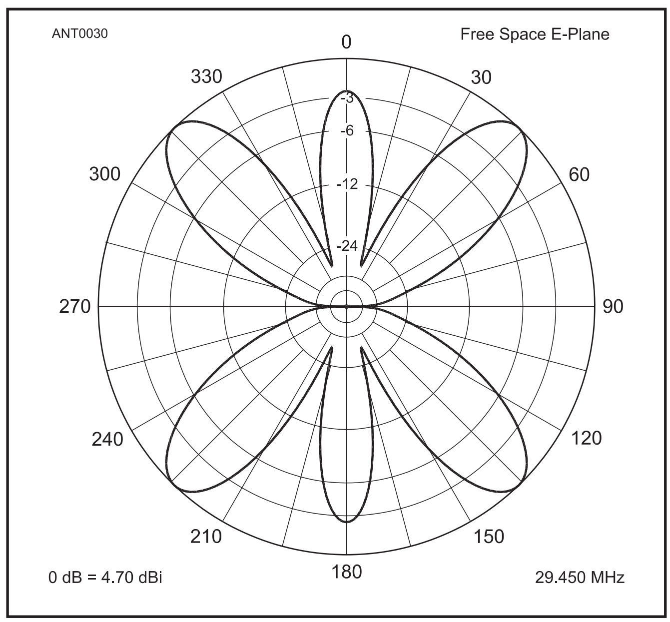

Figure 2.21 — Free-space E-Plane radiation pattern for a 100-foot dipole at three times its full-wave resonant frequency of 29.45 MHz. The pattern has returned to six lobes, with a peak gain of 4.70 dBi.

showing. Despite the presence all these lobes, the main lobes now show a gain of 4.78 dBi. Finally, **Figure 2.21** shows the pattern at the 3λ (6 λ/2) resonance at 29.45 MHz. Despite the fact that there are fewer lobes taking up power than at 24.45 MHz, the peak gain is slightly less at 29.45 MHz, at 4.70 dBi.

The pattern — and hence the gain — of a fixed-length antenna varies considerably as the frequency is changed. Of course, the pattern and gain change in the same fashion if the frequency is kept constant and the length of the wire is varied. In either case, the wavelength is changing. It is also evident that certain lengths reinforce the pattern to provide more peak gain. If an antenna is not rotated in azimuth when the frequency is changed, the peak gain may occur in a different direction than you might like. In other words, the main lobes change direction as the frequency is varied.

2.1.5 FOLDED DIPOLES

Figure 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 mutual coupling divides the antenna current between the upper and lower conductors, the ratio of voltage to current at the feed point (the feed point impedance) 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. If the diameter of the conductors are different, the ratio will not be an exact square of the number of conductors.

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 preferable because of its lower loss. 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.

2.1.6 VERTICAL DIPOLES

A half-wave dipole can also be oriented vertically over ground instead of horizontally, becoming a vertical dipole. The dipole's pattern becomes generally omnidirectional. In **Figure 2.23A** and B with the bottom of the vertical dipole very close (λ/80) to a saltwater ground plane the vertical dipole can have a gain of 6.1 dBi. Gain drops to about 0 dBi over good soil and lower over poorer soils. As with all vertical antennas, it is mainly the quality of the ground in the antenna's far field (several wavelengths from the antenna and beyond) that determines how good a low-angle radiator the vertical dipole will be as shown in Figure 2.23 and further discussed in the chapter **Effects of Ground**. Raising the λ/2 vertical higher above the ground introduces multiple lobes as shown in Figure 2.23C and D with the antenna's bottom tip λ/8 above ground.

The radiation resistance of the vertical dipole also depends on the height of its lower tip above ground as shown in **Figure 2.24**. The impedance of vertical and horizontal dipoles vary with height above ground for different reasons: The horizontal dipole receives reflected power from the ground affecting its mutual impedance. The vertical dipole, however, receives less reflected power from the ground and as it is lowered closer to ground, it is increasing its effective height and increasing its gain which has the effect of increasing its radiation resistance. As with the horizontal dipole, the radiation resistance varies above and below the free-space value of 73.5 Ω but not as much as for the horizontal dipole since its feed point is farther above ground. (Effective height of the dipole which is proportional to average current in the dipole divided by its physical length, increases as the antenna becomes lower because average current in the antenna increases. See Zavrel's referenced article on maximizing radiation resistance.)

In practice, it is not possible to obtain symmetrical currents in the upper and lower halves of the vertical dipole at HF due to the asymmetrical relationship of the two sections to ground. Further, the presence of the feed line introduces a third conductor for common-mode current that can influence the antenna's performance unless decoupled. Thus, the radiation patterns are unlikely to be very close to the ideal patterns shown here.

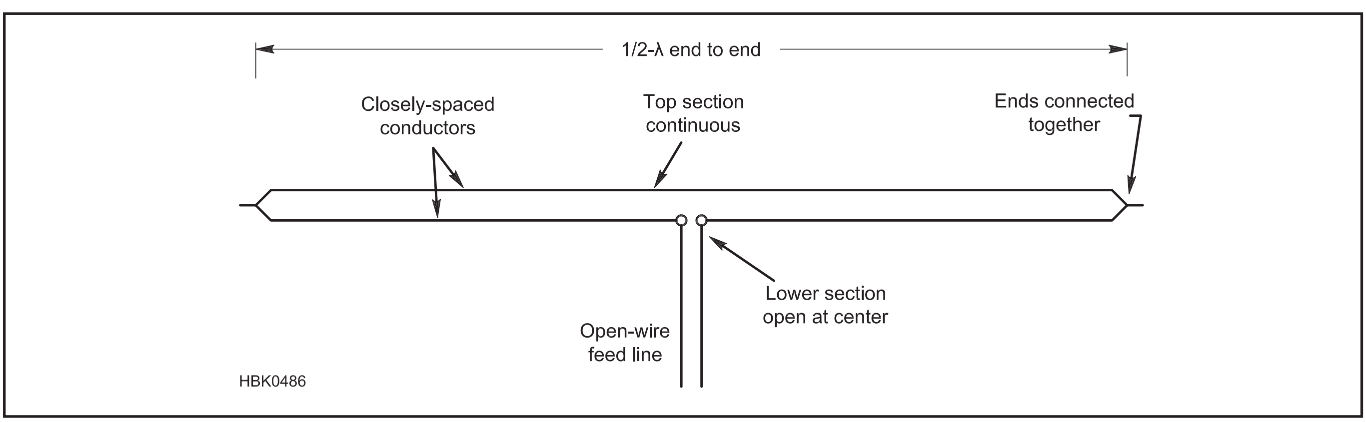

Figure 2.22 — The folded dipole is most often constructed from open-wire transmission line with the ends connected together. The close proximity of the two conductors and the resulting coupling act as an impedance transformer to raise the feed point impedance over that of a single-wire dipole by the square of the number of conductors used.

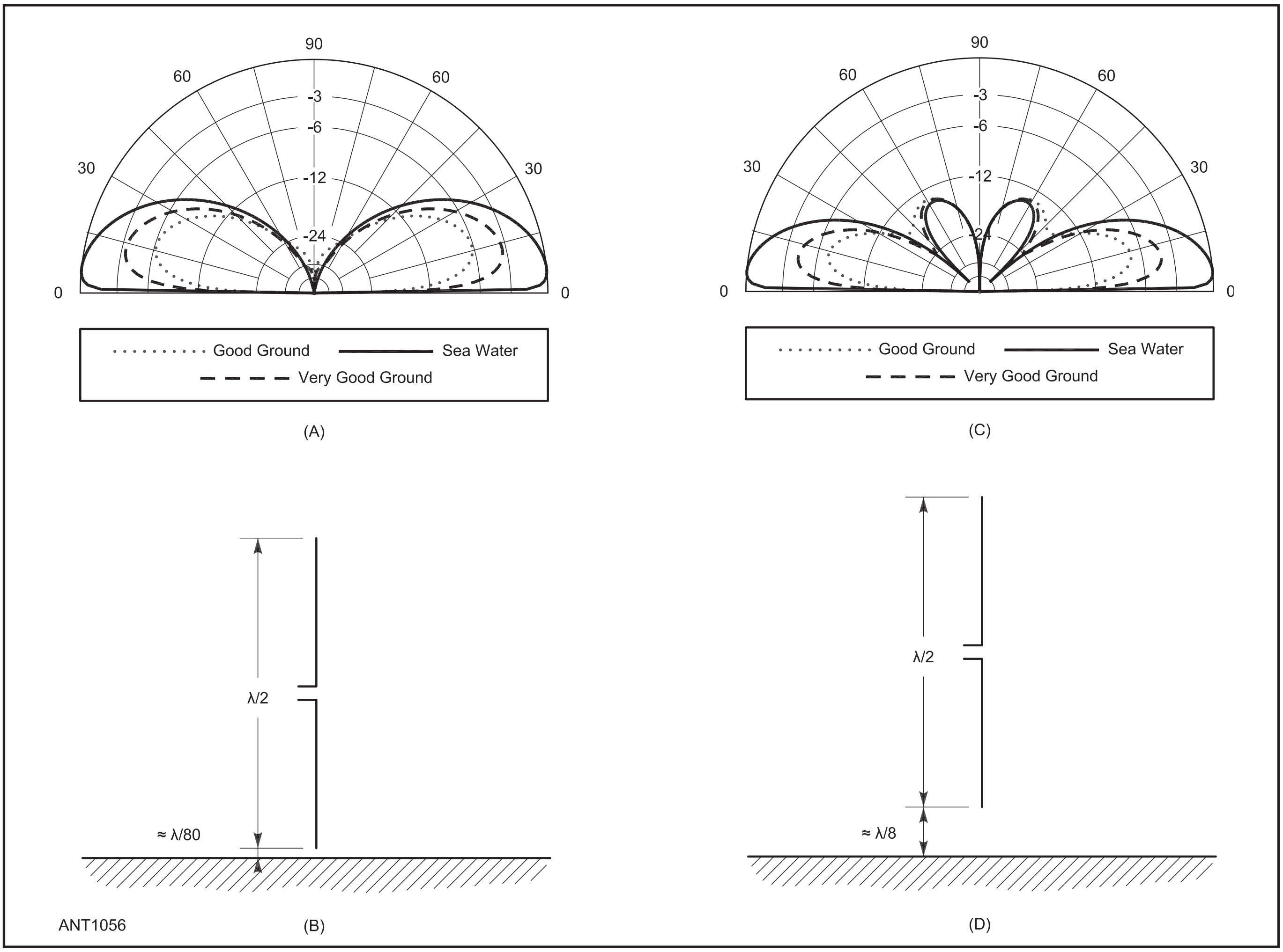

Figure 2.23 — At A and B, vertical radiation patterns over various grounds for a vertical half-wave center-fed dipole with the bottom tip just clearing the ground. The gain is as high as 6.1 dBi over ground and the feed point impedance is 100 Ω. At C and D, the vertical radiation patterns of the half-wave vertical dipole with the bottom tip ⅛ λ off the ground. Note the appearance of lobes in the radiation pattern at high elevation angles.

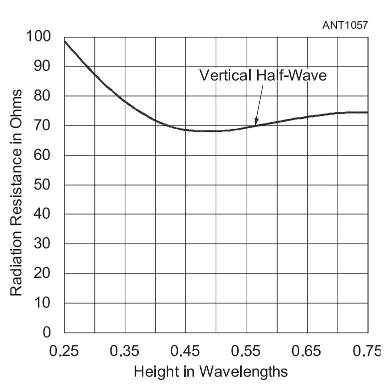

Figure 2.24 — The radiation resistance of a vertical half-wave dipole for various feed point heights above ground.

2.2 MONOPOLES

Another simple form of antenna derived from a dipole is called a *monopole*. The name suggests that this is one half of a dipole, and so it is. The monopole is always used in conjunction with a ground plane, which acts as a sort of electrical mirror. See **Figure 2.25**, where a λ/2 dipole and a λ/4 monopole are compared. The image antenna for the monopole is the dotted line beneath the ground plane. The image forms the missing second half of the antenna, transforming a monopole into the functional equivalent of a dipole.

Monopoles are usually mounted vertically with respect to the surface of the ground. As such, they are called *vertical monopoles*, or simply *verticals*. A practical vertical is supplied power by feeding the radiator against a ground system, usually made up of a series of paralleled wires radiating from and laid out in a circular pattern around the base of the antenna. These wires are called *radials* since they extend radially from the base of the antenna.

The term *ground plane* is also used to describe a vertical antenna employing a vertical radiating element (usually λ/4 long) and a *counterpoise* system, another name for the ground plane that supplies the missing half of the antenna. The counterpoise for a ground-plane antenna usually consists of four λ/4-long radials elevated well above the ground. See **Figure 2.26**.

The chapter **Effects of Ground** devotes much attention to the requirements for an efficient grounding system for vertical monopole antennas. The chapter **Single Band MF and HF Antennas** gives more information on practical ground-plane verticals at HF. Ground-plane antennas at higher frequencies are discussed in the chapter **VHF and UHF Antenna Systems** and **Mobile VHF and UHF Antennas**.

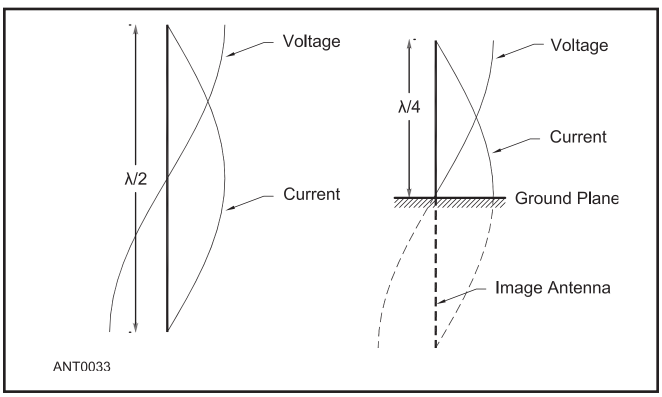

Figure 2.25 — The λ/2 dipole antenna and its λ/4 ground-plane counterpart. The "missing" quarter wavelength is supplied as an image in "perfect" (that is, high-conductivity) ground.

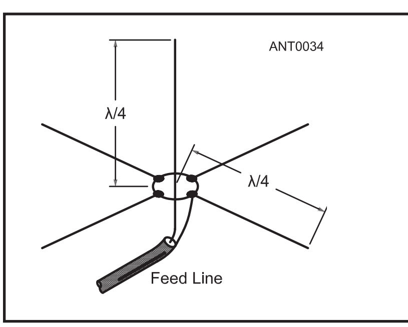

Figure 2.26 — The ground-plane antenna. Power is applied between the base of the vertical radiator and the center of the four ground plane wires.

2.2.1 CHARACTERISTICS OF A λ/4 MONOPOLE

The free-space directional characteristics of a λ/4 monopole with its ground plane are very similar to that of a λ/2 antenna in free space. The directivity (*D*) and, thus, gain for the λ/4 monopole over a perfect, infinite ground plane is double that of the λ/2 dipole in free-space (assuming no losses) because there is no radiation in the hemisphere below the ground plane. Real monopoles over finite ground planes have less gain.

Like a λ/2 antenna, the λ/4 monopole has an omnidirectional radiation pattern in the plane perpendicular to the monopole.

The current in a λ/4 monopole varies practically sinusoidally (as is the case with a λ/2 dipole), and is highest at the ground-plane connection. The voltage is highest at the open (top) end and minimum at the ground plane. The feed point resistance close to λ/4 resonance of a vertical monopole over a perfect ground plane is one-half that for a λ/2 dipole at its λ/2 resonance. This is because half of the radiation resistance of a full-size λ/2 dipole has been replaced by an electrical image that does not actually exist and so cannot radiate power.

The word "height" applied to a vertical monopole antenna whose base is on or near the ground has the same meaning as length when applied to λ/2 dipole antennas. Some texts refer to heights in electrical degrees, referenced to a free-space wavelength of 360°, or height may be expressed in terms of the free-space wavelength.

Figure 2.27, which shows the feed point impedance

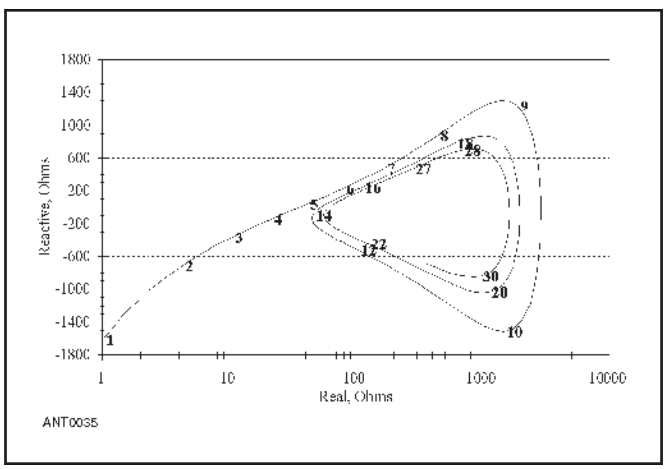

Figure 2.27 — Feed point impedance versus frequency for a theoretical 50-foot-high grounded vertical monopole made of #14 AWG wire. The numbers along the curve show the frequency in MHz. This was computed using "perfect" ground. Real ground losses will add to the feed point impedance shown in an actual antenna system.

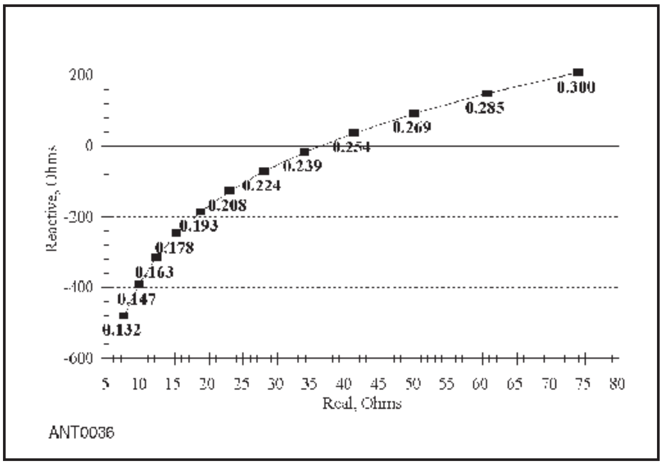

Figure 2.28 — Feed point impedance for the same antennas as in Figure 2.25, but calibrated in wavelength rather than frequency over the range from 0.132 to 0.300 λ, above and below the quarter-wave resonance.

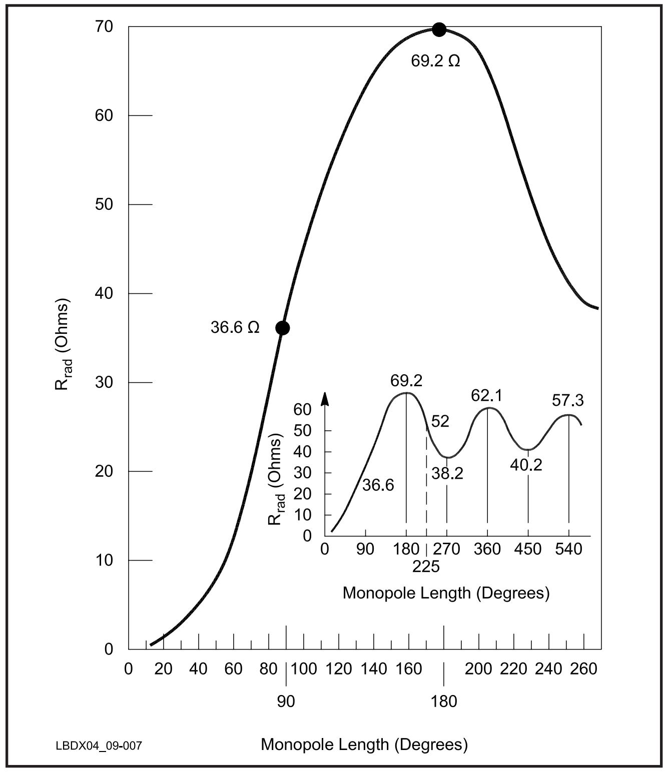

Figure 2.29 — Radiation resistances (at the current maximum) of monopoles with sinusoidal current distribution. The chart can be used for dipoles up to λ/2 in length, corresponding to the λ/4 monopole, but all values must be doubled.

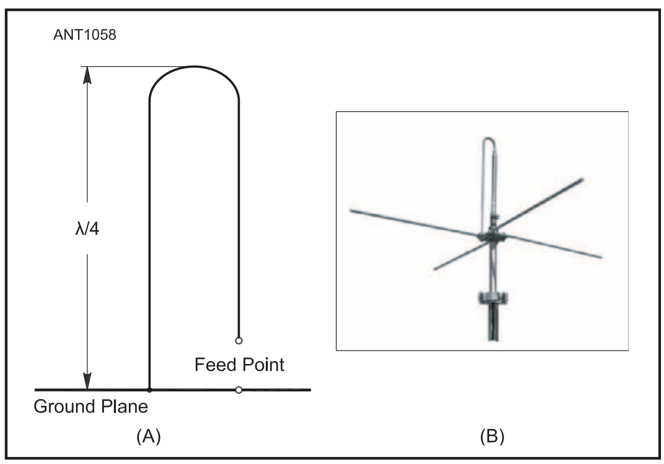

Figure 2.30 — The folded monopole antenna (A) can be nderstood similarly to the folded dipole with the ground-plane or counterpoise supplying the "missing half" of the antenna with an electrical image. An example of a commercial folded monopole is depicted in (B).

of a vertical antenna made of #14 AWG wire, 50 feet long, located over perfect ground. Impedance is shown over the whole HF range from 1 to 30 MHz. Again, there is nothing special about the choice of 50 feet for the length of the vertical radiator; it is simply a convenient length for evaluation.

Figure 2.28 shows an expanded portion of the frequency range above and below the λ/4 resonance, but now calibrated in terms of wavelength. Note that this particular antenna goes through λ/4 resonance at a length of 0.244 λ, not at exactly 0.25 λ. The exact length for resonance varies with the diameter of the wire used, just as it does for the λ/2 dipole at its λ/2 resonance. The range shown in Figure 2.28 is from 0.132 λ to 0.300 λ, corresponding to a frequency range of 2.0 to 5.9 MHz.

The variation of a monopole's radiation resistance with electrical length or height is shown in **Figure 2.29** from 0° to 270°. Note that for the λ/4 monopole (a length of 90°) the radiation resistance is 36.6 Ω, one-half the radiation resistance of a λ/2 dipole. The radiation resistance is measured at the current maximum, which for monopoles longer than λ/4 will be located above the base of the antenna and have a different value than that at the base. (See the referenced articles by Zavrel for a more complete discussion of radiation resistance and feed point impedance.)

The reactive portion of the feed point impedance is highly dependent on the length/dia ratio of the conductor, as was discussed previously for a horizontal center-fed dipole. The impedance curve in Figures 2.25 and 2.26 is based on a #14 AWG conductor having a length/dia ratio of about 800 to 1. As usual, thicker antennas can be expected to show less reactance at a given height, and thinner antennas will show more.

The efficiency of a real vertical antenna over real earth often suffers dramatically compared with that of a λ/2 antenna. Without a fairly elaborate grounding system, the efficiency is not likely to exceed 50%, and it may be much less, particularly at monopole heights below λ/4. In addition, the gain of a monopole at angles close to the ground plane is highly dependent on the conductivity of the ground-plane. Both effects are discussed extensively in the chapter **Effects of Ground**.

2.2.2 FOLDED MONOPOLES

A folded monopole, shown in **Figure 2.30**, can be understood similarly to the folded dipole and the same increase in feed point impedance is achieved. Again, the ground-plane or counterpoise supplies the "missing half" of the antenna with an electrical image. The point opposite the feed point is electrically neutral in the λ/4 folded monopole and so is connected to the ground plane as in Figure 2.30A. An example of a commercial folded monopole is depicted in Figure 2.30B.

The increased feed point impedance of the folded monopole is often misunderstood as reducing ground losses due to the lower current at the feed point. This is incorrect because the radiation resistance and ground losses of both single and multiple-conductor monopoles is the same when correctly normalized to the feed point and so there is no difference when calculating radiation efficiency. For equivalent amounts of power, the same amount of current will flow in the ground system, regardless of the impedance transformation created by folding the conductor.

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