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- "Some Thoughts on Vertical Ground Systems over Seawater" by Rudy Severns, N6LF

Chapter 3

# The Effects of Ground

The **Antenna Fundamentals** chapter dealt mainly with ideal antennas in free space, completely removed from the influence of ground. Real antennas however, are placed over ground and in some cases have components right on or even buried in the ground. The presence of ground can have a profound effect on the behavior of an antenna, including the feed point impedance, the efficiency and the radiation pattern. This chapter is devoted to describing the interactions between antennas and ground and ways to reduce ground losses close to the antenna. For the purposes of this chapter the terms "soil" or "earth" are considered equivalent to "ground". In some cases "ground" may actually be fresh water or seawater.

We will begin by examining the characteristics of typical soils and then proceed to interactions between grounds and antennas. The interaction discussion is divided between two areas around the antenna: the *reactive near field* and the *radiating far field*. The reactive near field only exists very close to the antenna itself, essentially within one wavelength. In this region the antenna acts as though it were a large lumped-constant R-L-C tuned circuit where energy is stored in the fields close to the antenna. Only a portion of this energy is radiated. The RF current in the antenna will induce currents in the ground which in turn will affect the currents in the antenna. These interactions can modify the feed point impedance of an antenna and, due to the currents flowing in the ground, add power losses. This loss represents power supplied to the antenna from the transmitter but not radiated so there is a net reduction in signal for a given power input to the antenna. For vertical antennas located on or near ground, this can be very significant.

In the radiating far field, the presence of ground profoundly influences the radiation pattern of an antenna. (The radiating near field can be neglected as a transition zone between the reactive near field and radiating far field.) The interaction differs depending on the antenna polarization with respect to the ground. For horizontally polarized antennas, the shape of the radiated pattern in elevation plane depends primarily on the antenna's height above ground. For vertically polarized antennas, both the shape and the strength of the radiated pattern in the elevation plane strongly depend on the nature of the ground itself, as well as the height of the antenna above ground.

The material in this chapter assumes a flat ground surface surrounding the antenna. An extensive discussion of how to account for non-flat ground is presented in the chapter **HF Antenna System Design**, including use of the *HFTA* terrain analysis software by Dean Straw, N6BV.

## 3.1 EFFECTS OF GROUND IN THE REACTIVE NEAR FIELD

Sections 3.1 and 3.2 of this chapter have been expanded and reworked by the original author, Rudy Severns, N6LF to accommodate the results of work done since the previous version.

### 3.1.1 ELECTRICAL CHARACTERISTICS OF GROUND

One way to investigate the characteristics of a given sample of soil would be to fabricate a simple parallel plate capacitor as shown in **Figure 3.1**. First we might measure the capacitance ($C_s$) and the shunt resistance ($R_s$) without any soil between the plates. We would expect to get a very high value for $R_s$ and some modest capacitance proportional to the plate areas and inversely proportional to the plate spacing. If we then fill the space between the plates with the soil we're interested in and repeat the $R_s$ and $C_s$ measurements, the chances are we will see a marked change in both: much lower $R_s$ and higher $C_s$. What this experiment tells us is that soil acts like a lossy capacitor. When an RF current flows in the soil there will be some loss associated with $R_s$. The trick is to keep the RF current out of the soil at least near the antenna.

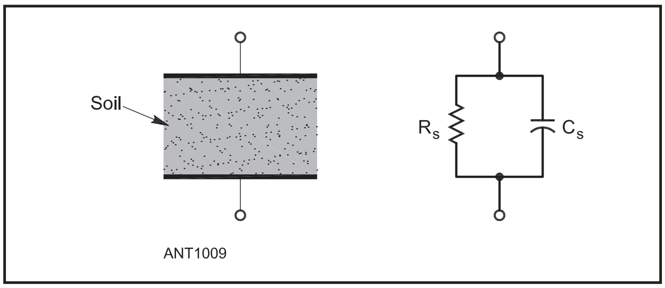



**Figure 3.1 — Equivalent circuit for soil characteristics.**

$R_s$ is inversely related to the soil conductivity ($\sigma$) and $C_s$ is directly related to the relative permittivity (dielectric constant) ($\varepsilon_{r\ or}$ Er as represented later in this chapter). We can infer values for $\sigma$ and $\varepsilon_r$ from measurements made on the capacitor with and without the soil between the plates. The unit for $\sigma$ is Siemens per meter (S/m). $\varepsilon_r$ is dimensionless. At HF both $\sigma$ and $\varepsilon_r$ are needed for the determination of ground losses or radiation patterns and are an important part of antenna modeling.

A century of measurements on different soils has shown that both $\sigma$ and $\varepsilon_r$ vary over a wide range depending on

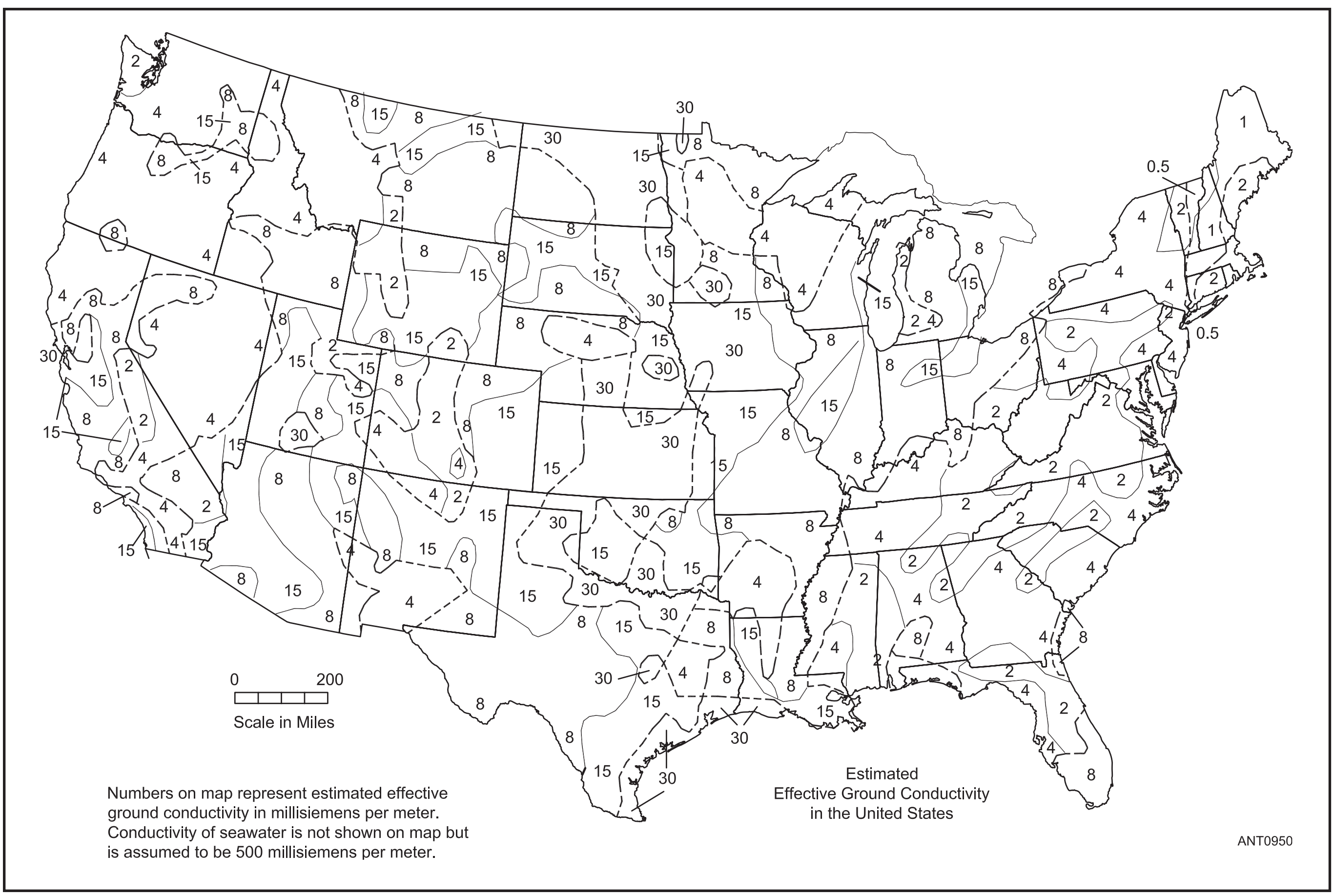



**Figure 3.2 — Estimated effective ground conductivity in the United States. FCC map prepared for the Broadcast Service, showing typical conductivity for continental USA. Values are for the band 500 to 1500 kHz. Values are for flat, open spaces and often will not hold for other types of commonly found terrain, such as seashores, river beds, etc.**

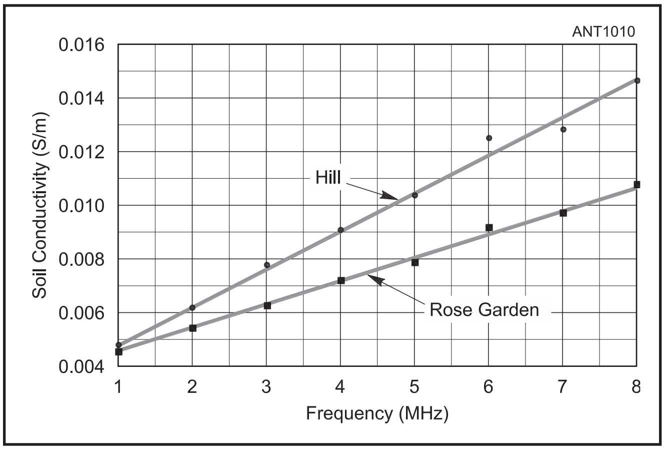



**Figure 3.3 — Typical soil conductivity variation with frequency.**

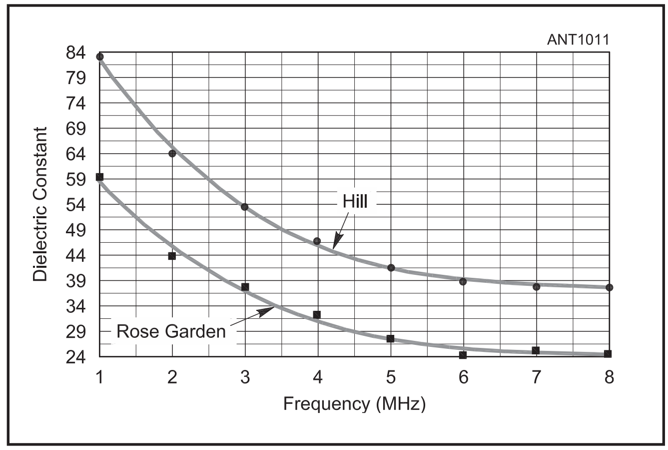



**Figure 3.4 — Typical soil permittivity variation with frequency.**

**Table 3.1**
**Conductivities and Dielectric Constants for Common Types of Earth**

| *Surface Type Constant* | *Dielectric (S/m)* | *Conductivity Quality* | *Relative* |
|---|---|---|---|
| Fresh water | 80 | 0.001 | |
| Salt water | 81 | 5.0 | |
| Pastoral, low hills, rich soil, typ Dallas, TX, to Lincoln, NE areas | 20 | 0.0303 | Very good |
| Pastoral, low hills, rich soil typ OH and IL | 14 | 0.01 | |
| Flat country, marshy, densely wooded, typ LA near Mississippi River | 12 | 0.0075 | |
| Pastoral, medium hills and forestation, typ MD, PA, NY, (exclusive of mountains and coastline) | 13 | 0.006 | |
| Pastoral, medium hills and forestation, heavy clay soil, typ central VA | 13 | 0.005 | Average |
| Rocky soil, steep hills, typ mountainous | 12-14 | 0.002 | Poor |
| Sandy, dry, flat, coastal | 10 | 0.002 | |
| Cities, industrial areas | 5 | 0.001 | Very Poor |
| Cities, heavy industrial areas, high buildings | 3 | 0.001 | Extremely poor |

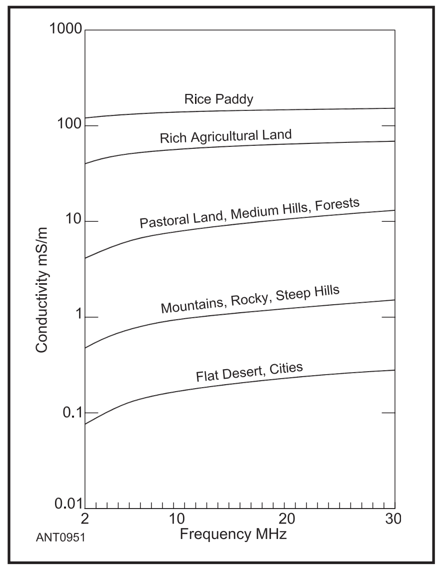



**Figure 3.5 — Ground conductivity variation with frequency for different types of soils.**

location, soil composition, stratification of the soil, soil moisture content and many other variables. **Table 3.1** lists typical characteristics for a variety of typical grounds.

Real soils seldom have these exact pairs of $\sigma$ and $\varepsilon_r$. For a given value of $\sigma$, $\varepsilon_r$ can vary widely. Both $\sigma$ and $\varepsilon_r$ tend to increase with soil moisture content so it is normal to have higher $\varepsilon_r$ when you have higher $\sigma$. However, it is also possible to have moderate values of $\sigma$ but quite high values for $\varepsilon_r$. Soils with clay particles often have high $\varepsilon_r$. For fresh water at 23° C, $\varepsilon_r = 78$, so you may wonder how soil can have an $\varepsilon_r$ higher than water. The higher values are the result of polarization effects that can occur in clay soils. It is quite possible to have $\varepsilon_r > 100$, at least at lower HF frequencies. In general, conductivity will increase with frequency and permittivity will decrease initially at lower HF but level out at higher frequencies.

Much of the data on soil conductivity stems from work at broadcast band frequencies. **Figure 3.2** is a graphic of typical ground conductivity for the United States. While useful for BC (AM broadcast) station planning this graphic is of limited use to amateurs because it averages the conductivity over large areas and the primary concern is ground wave propagation at BC frequencies. Amateurs are usually more concerned with the soil close to their antennas where the conductivity can vary dramatically from the large area average.

Soil characteristics vary not only with location and time of year but also with frequency. **Figures 3.3** and **3.4** show the variation of $\sigma$ and $\varepsilon_r$ with frequency at two locations at a typical amateur QTH (N6LF). See this chapter's section "Ground Parameters for Antenna Analysis" for methods of measuring ground parameters for antenna modeling and design.

George Hagn and his associates at SRI have made a very large number of ground characteristic measurements at many different places in the world.[1] **Figure 3.5** shows the results of some of this work.

### 3.1.2 SKIN DEPTH IN SOIL

It is very probable that the soil at a given location will be stratified (vary with depth) so it will be necessary to take some average value. The question is then "how deep do I have to go to make the average?" This question is best answered by determining the depth to which the fields or the RF currents penetrate the soil. This penetration depth is often expressed in terms of the "skin depth" where the skin depth ($\delta$) is the depth at which the current or the field has been attenuated to 1/e or 37% ($e \approx 2.71828$) of its value at the ground surface. Skin depth is also used in the calculation of ground loss.

Knowing $\sigma$ and $\varepsilon_r$, the skin depth in an arbitrary material can be determined from:

$$\delta = \left(\frac{\sqrt{2}}{\omega\sqrt{\mu\varepsilon}}\right)\left[\sqrt{1+\left(\frac{\sigma}{\omega\varepsilon}\right)^2}-1\right]^{-1/2} \quad (1)$$

where

$\delta$ = skin or penetration depth [meters]
$\omega = 2\pi f$, f = frequency [hertz]
$\sigma$ = conductivity [siemens/meter, S/m]
$\mu = \mu_r \mu_o$ = permeability
$\mu_o$ = permeability of vacuum = $4\pi 10^{-7}$ [henry/meter]
$\mu_r$ = relative permeability [dimensionless]
$\varepsilon = \varepsilon_r \varepsilon_o$ = permittivity [farad/meter]
$\varepsilon_o$ = permittivity of vacuum = $8.854 \times 10^{-12}$ [farad/meter]
$\varepsilon_r$ = relative permittivity [dimensionless]

A graph of Eq 1 for typical grounds is given in **Figure 3.6**.

Skin depth varies with frequency and soil characteristics. For example, at 1.8 MHz $\delta$ varies from about 16 cm in seawater to 15 m in poor soil. As we go up in frequency the skin depth decreases, roughly proportional to $1/\sqrt{f}$, until at some point it flattens out.

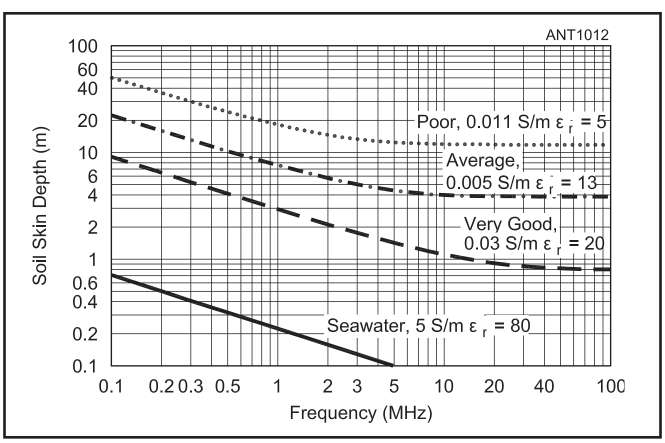



**Figure 3.6 — Examples of skin depth variation with frequency for different grounds.**

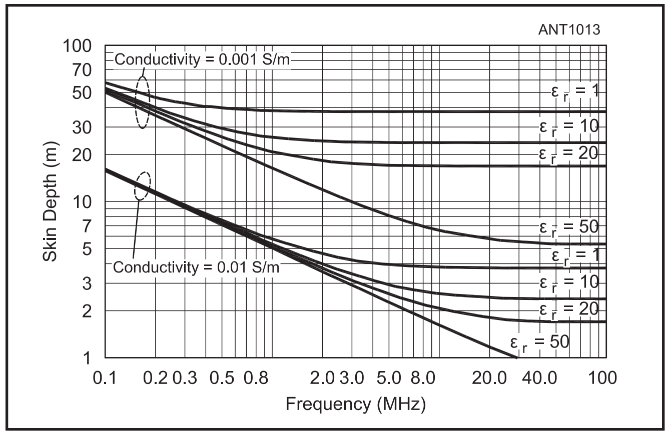



**Figure 3.7 — Examples of skin depth as a function of $\varepsilon_r$ for two different conductivities.**

The soil types in Figure 3.6 represent the typical values used in antenna modeling. An example of the effect of differing $\varepsilon_r$ for soils with $\sigma$ = 0.001 and 0.01 S/m is shown in **Figure 3.7**. In Figure 3.7, we can see several interesting things. At low frequencies (in the BC band) the values for $\delta$ converge and $\varepsilon_r$ makes little difference. This is one reason why soil characteristics from BC data seldom include the permittivity. At high frequencies the curves are flat with a value that depends on $\sigma$ and $\varepsilon_r$.

### 3.1.3 WAVELENGTH IN SOIL

Because soil is a complex medium where both $\sigma$ and $\varepsilon_r$ are significantly different from their values in free space, the wavelength in soil ($\lambda$) may differ greatly from the wavelength in free space ($\lambda_o$). This is important for antennas and radial systems close to or buried in the ground. In general the wavelength in soil will be considerably shorter than the free space wavelength and this must be taken into account for wire segmentation during modeling.

The wavelength in free space ($\lambda_o$) is:

$$\lambda_o = \frac{299.79}{f(\text{MHz})} \text{ in meters} \quad (2)$$

The wavelength in soil ($\lambda$) is:

$$\lambda = \frac{\lambda_o}{\left[\varepsilon_r^2 + \left(\frac{\sigma}{\omega\varepsilon_o}\right)^2\right]^{1/4}} \quad (3)$$

**Figure 3.8** gives examples of wavelength as a function of frequency for different soils, salt and fresh water and free space. It can be seen that the wavelength in soil is typically much smaller than in free space.

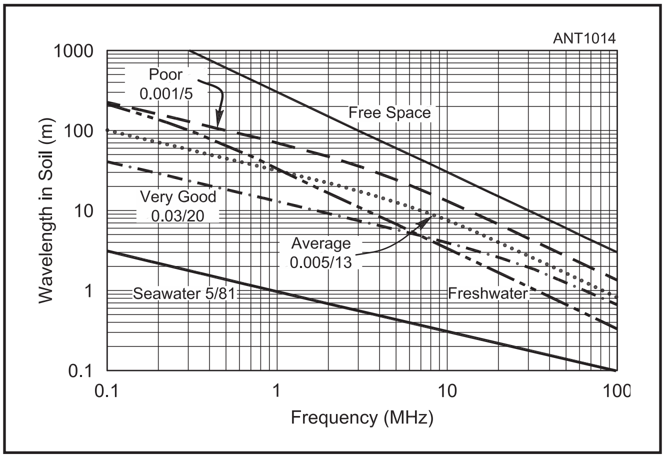



**Figure 3.8 — Wavelength in typical soils as a function of frequency.**

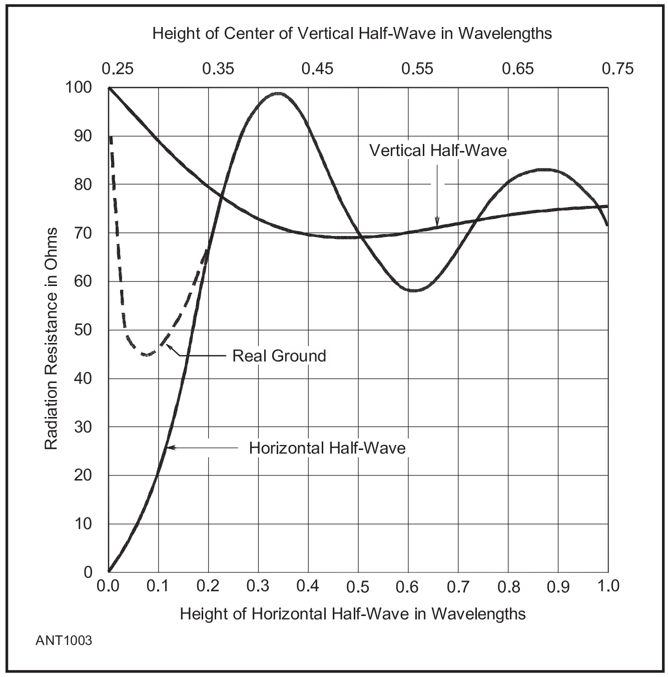



**Figure 3.9 — Variation of feed point resistance with height for vertical and horizontal antennas.**

### 3.1.4 FEED POINT IMPEDANCE VERSUS HEIGHT ABOVE GROUND

Radiation directly downward from the antenna will reflect vertically from the ground and, in passing the antenna on the upward journey, induce a current in it. The magnitude and phase of the current depends on the height of the antenna above the reflecting surface and the characteristics of the surface.[10] The total current in the antenna consists of two components: the amplitude of the first is determined by the excitation from the transmitter and the second component is induced in the antenna by the wave reflected from the ground. This second component of current, while considerably smaller than the first at most useful antenna heights, is by no means insignificant. At some heights, the two components will be in phase but at other heights the two components are out of phase. Changing the height of the antenna above ground will change the current amplitude at the feed point (we are assuming that the power input to the antenna is constant). A higher current at the same input power means that the effective resistance of the antenna is lower, and vice versa. In other words, the feed point resistance of the antenna is affected by the height of the antenna above ground because of mutual coupling between the antenna and the ground beneath it.

The electrical characteristics of the ground affect both the amplitude and the phase of reflected signals. For this reason, the electrical characteristics of the ground under the antenna will have some effect on the impedance of that antenna, the reflected wave having been influenced by the ground. Different impedance values may be encountered when an antenna is erected at identical heights but over soils with different characteristics.

**Figure 3.9** gives an example of the way the feed point impedance of horizontal and vertical half-wave antennas can vary with height above ground. The height of the vertical half-wave is the distance from the bottom of the antenna to ground. For horizontally polarized half-wave antennas, the differences between the effects of perfect ground and real earth are negligible if the antenna height is greater than 0.2 λ. At lower heights, the feed point resistance over perfect ground decreases rapidly as the antenna is brought closer to a theoretically perfect ground. However, over real earth, the resistance actually begins increasing again at heights below about 0.08 λ as indicated by the dashed line. The reason for the increasing resistance at very low heights is that the field of the antenna interacts more strongly with the ground increasing ground losses. This increase in loss is reflected in an increased value for the feed point resistance.

## 3.2 GROUND SYSTEMS FOR VERTICAL MONOPOLES

In this section we look at vertical monopoles which are shorter than λ/2 and require some sort of ground system in order to make up for the "missing" part of the antenna and, just as importantly, reduce the power dissipated in the near field. (For the purposes of this chapter, the term "vertical" should be understood to represent a vertical monopole antenna mounted on or near the ground.)

Because the losses in the soil near a vertical are a function of the electric and magnetic field intensities close to the antenna we will begin by looking at these fields. The next step will be to show what the actual soil losses are and how that loss is distributed in the soil near the base of the vertical. Finally we'll describe ground systems which can greatly reduce this loss.

### 3.2.1 FIELDS NEAR THE BASE OF A VERTICAL

In this section we will be examining the E and H fields at ground level within λ/2 of the base of typical verticals. (See the **Antenna Fundamentals** chapter for a discussion of E and H fields.) This may seem like an abstract exercise but it's important because it allows us to visualize what's happening in the soil around the base of a vertical, giving us both the amplitude and location of the ground currents and their associated losses. This information will guide us in the design and optimization of ground systems.

A vertical antenna has two field components that induce currents in the ground around the antenna: $E_z$ and $H_\Phi$. **Fig-ure 3.10** shows in a general way the electric-field component ($E_z$, in V/m) and magnetic-field component ($H_\Phi$, in A/m) in the region near a vertical. Both of these field components will induce currents ($I_V$ and $I_H$) in the soil. Because the soil near the antenna typically has relatively high resistance this results in power loss in the soil. Power dissipated in the ground is subtracted from the power supplied to the antenna weakening your signal.

As shown in Figure 3.10, the tangential component of the H-field ($H_\Phi$) induces horizontal currents ($I_H$) flowing radially in the soil. The normal component (perpendicular to the ground surface) of the E-field ($E_z$) induces vertically flowing currents ($I_v$) in the soil. These field-induced ground currents will decrease as we go deeper into the soil with the rate of decrease a function of the skin depth in the particular soil.

We can determine $E_z$ and $H_\Phi$ from either modeling (near-field calculations with *NEC*-based software, for example) or directly from equations. It turns out that the field intensities close to the base (<λ/2) of a vertical (within λ/2) over real ground are very close to the values for perfect ground. This allows us to use much simpler modeling or equations. The following graphs for field intensities assume perfect ground.

The base currents and the resistive part of the feed point impedance at the base of verticals with different heights (h) are given in **Table 3.2**. These are the values of current which result from an input power of 1.5 kW for an ideal vertical over perfect ground.

**Figure 3.11** shows the H-field intensity within λ/2 of the base of the vertical for four different vertical heights (h): 0.05 λ, 0.125 λ, 0.250 λ and 0.375 λ. **Figure 3.12** shows the E-field intensity for the same values of h. Both of these graphs make the same two points:

1) Field intensity increases rapidly as you approach the base, particularly within a radius <λ/8, and

2) The shorter the antenna, the higher the fields for the same power input.

**Table 3.2**
**Base Excitation Currents as a Function of Vertical Height (h) in Wavelengths**
The input power is 1500 W.

| *h* (λ) | $I_o$ (A) | $R_r$ (Ω) |
|---|---|---|
| 0.050 | 39.7 | 0.95 |
| 0.125 | 15.1 | 6.57 |
| 0.250 | 6.45 | 36.1 |
| 0.375 | 2.53 | 234 |

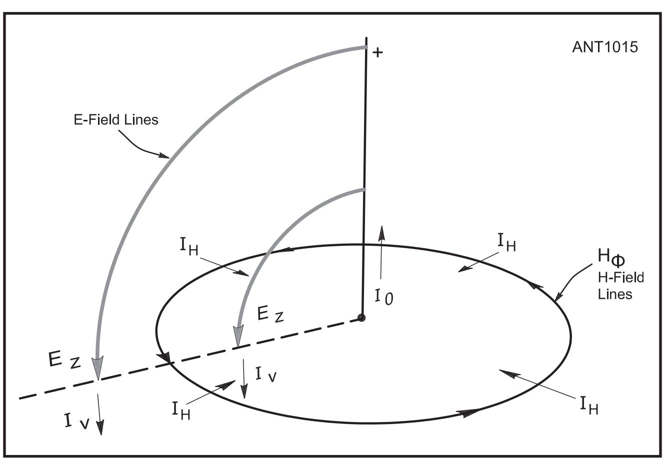



**Figure 3.10 — Examples of the fields and currents close to a vertical.**

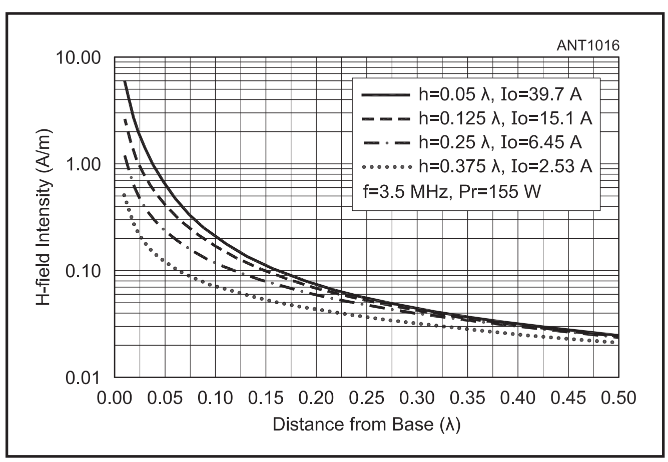



**Figure 3.11 — $H_\Phi$ intensity as a function of distance from the base in wavelengths. Data is for a vertical at 3.5 MHz.**

In the case of the E-field, the minimum field occurs for h = 0.25 λ and then increases again as h is increased beyond 0.25 λ. Ground losses are proportional to the square of the field intensity. In other words, if you double the intensity the power loss increases by 4 times! *This tells us that we must pay special attention to the ground system within λ/8 of the base and that short verticals require additional attention to the ground system.*

Another point which can be inferred from Figure 3.12 is the very high voltages which can be present on the antenna. The shorter the antenna and the higher the power level, the higher these voltages will be. Verticals taller than λ/4 can also have very high voltages near the base. This is a very real safety hazard! Touching a vertical while transmitting can lead to severe RF burns.

**Figures 3.13** and **3.14** show the field intensities for a λ/4 vertical at frequencies from 1.8 to 28 MHz. At a given distance in λ, both E and H fields increase with frequency but, as the dashed line in Figure 3.13 indicates, at a given fixed physical distance the H-field intensity is constant, independent of frequency. However, as the dashed line in Figure 3.14 shows, the E-field at a given physical distance is not constant but increases with frequency.

This behavior may seem a bit strange because it says that the field distributions do not scale linearly with frequency! Keep in mind that the base current at all frequencies was set to 6.45 A ($P_r$ = 1500 W, h = 0.250 λ). As the frequency was changed the height of the vertical was reduced from 135 feet at 1.8 MHz to 8.8 feet at 28 MHz. The high current point on a vertical (h ≤ λ/4) is at the base but the high voltage point is at the top. As we change frequency and alter h, the H-field is primarily influenced by the base current which does not change amplitude or location. However, the E-field is primarily influenced by the high voltage at the top of the vertical which is moving closer to ground as we go up in frequency. Normally we scale the dimensions of the ground system as we go up in frequency. If we elect to use λ/4 radials they will be approximately 34 feet on 40 meters, 17 feet on 20 meters, etc. The problem is that the fields are not scaling with frequency. At a given distance in λ the fields are higher as we go up in frequency. These observations tell us that for a given size (in λ) ground system *as we go up in frequency the ground loss will increase!*

As shown earlier, soil conductivity typically improves as we go up in frequency but that varies over a wide range and may not help as much as we would like. Better to be conservative and not count on the increase in σ unless you have actually measured your particular soil characteristics.

## 3.2.2 RADIATION EFFICIENCY AND POWER LOSSES IN THE SOIL

We can discuss the efficiency of an antenna by using an equivalent circuit model like that shown in **Figure 3.15** for the resistive part of the feed point impedance. We account for the radiated power ($P_r$) by assuming there is a resistor we call the *radiation resistance* ($R_r$) through which the antenna base current ($I_o$) flows. The radiated power ($P_r$) is then:

$$P_r = R_r I_o^2 \tag{4}$$

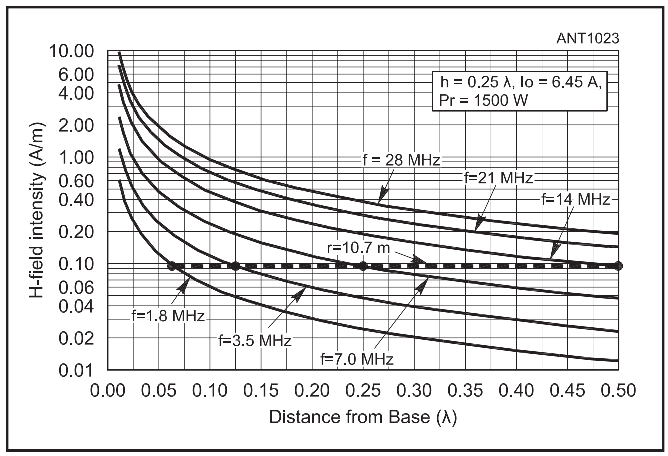



**Figure 3.13 — $H_\Phi$ intensity as a function of distance from the base in wavelengths. Data is for a λ/4 vertical.**

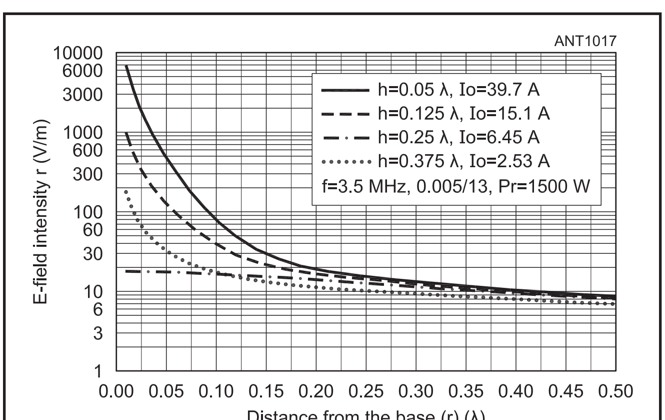



**Figure 3.12 — $E_z$ intensity as a function of distance from the base in wavelengths. Data is for a vertical at 3.5 MHz.**

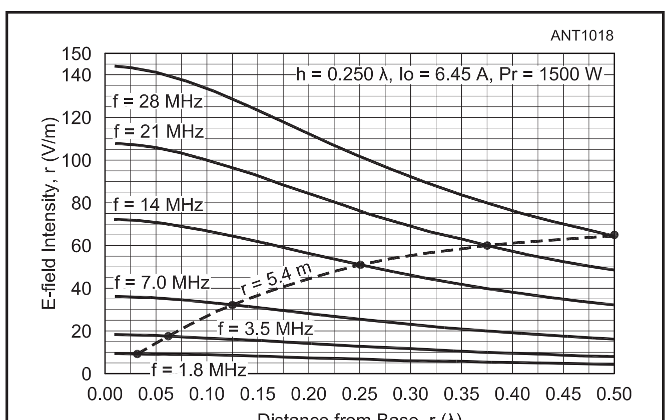



**Figure 3.14 — $E_z$ intensity as a function of distance from the base in wavelengths. Data is for a λ/4 vertical.**

Similarly, we can account for the power dissipated in the ground ($P_g$) by adding a loss resistance ($R_g$) in series with $R_r$. The ground loss is:

$$P_g = R_g I_o^2 \tag{5}$$

Additional losses due to conductors, loading coils, etc can also be simulated by adding more series loss resistances to the equivalent circuit but for this discussion we will ignore these additional losses although they can be significant in real antennas. The total input power ($P_T$) is simply the sum of $P_r$ and $P_g$

The efficiency ($\eta$) of a vertical can be expressed as:

$$\eta = \frac{P_r}{P_r + P_g} = \frac{P_r}{P_T} \tag{6}$$

This can be restated in terms of resistances as:

$$\eta = \frac{R_r}{R_r + R_g} = \frac{1}{1 + \frac{R_g}{R_r}} \tag{7}$$

In essence, efficiency is the ratio of the radiated power to the total input power. Another way of saying this is that efficiency depends on the ratio of ground loss resistance to radiation resistance. The smaller we make $R_g$ the more power will be radiated for a given input power. Reducing $R_g$ is the purpose of the ground system.

We can determine $P_g$ near the vertical from the E- and H-fields shown earlier. Given $P_g$ and $I_o$ we can calculate $R_g$ and from that the radiation efficiency. For this discussion we will omit the mathematical details but these can be found in the spreadsheet referenced earlier.

In the following discussion the radiated power is kept constant at 1.5 kW but the total input power may be much greater because it will include the power dissipated in the soil which can become very large for short antennas with limited ground systems. The ground losses shown in **Figures 3.16** and **3.17** are what you would see if the ground system were simply a long stake driven into the soil beneath the antenna.

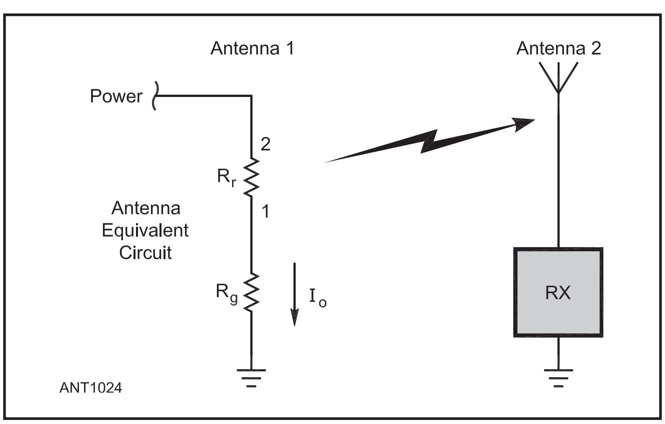



**Figure 3.15 — Equivalent circuit for a vertical in terms of $R_r$ and $R_g$.**

The size of these losses makes it clear why we need to add a radial ground system around the base of a vertical.

Figure 3.16 shows the total ground loss (including both E- and H-field losses) within a radius r (in λ) around the base of verticals with different heights at 3.5 MHz, over average ground ($\sigma$ = 0.005 S/m and $\varepsilon_r$ = 13). For all heights the loss is significant but becomes almost astronomical for very short antennas. For example, the loss associated with the 0.050 λ vertical (about 13 feet for 3.5 MHz) amounts to a signal loss of almost 14 dB; in other words, over 20 kW of power is lost in the ground in order to produce 1.5 kW of radiated power. The efficiency of each antenna (using the values for $R_r$ listed in Table 3.2) is listed in **Table 3.3**.

The efficiencies listed in Table 3.3 make it clear why some additional ground system beyond a simple ground stake is highly desirable in most installations. Keep in mind that these numbers are for one particular ground type (average). Poorer grounds will have even higher losses but better soils will have lower losses. Even a λ/4 vertical will have more

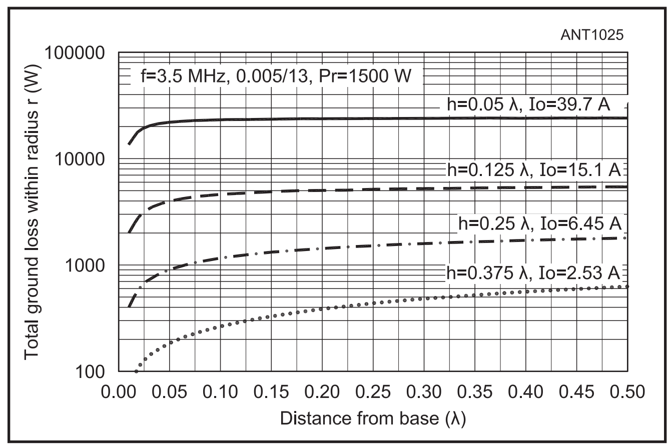



**Figure 3.16 — Total ground loss within a fixed radius around verticals of different heights at 3.5 MHz.**

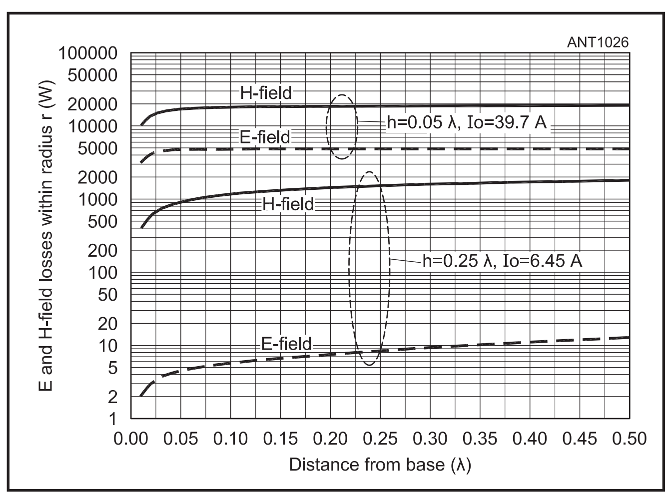



**Figure 3.17 — Comparison between E- and H-field losses for two antenna heights.**

**Table 3.3**
**Efficiency for Verticals of Different Heights with Ground System Consisting of Only a Ground Stake in Average Soil**

| *Height (h)* ($\lambda$) | *Efficiency* (%) | *Power Loss* (dB) |
|---|---|---|
| 0.050 | 4 | –13.8 |
| 0.125 | 21 | –6.7 |
| 0.250 | 46 | –3.4 |
| 0.375 | 71 | –1.5 |

## Saltwater Grounds

Saltwater is often cited or imagined to be the very best ground for an HF vertical antenna. While very good, the issues to be considered are discussed by Rudy Severns, N6LF, in the paper "Some Thoughts on Vertical Ground Systems over Seawater," included on this book's CD-ROM.

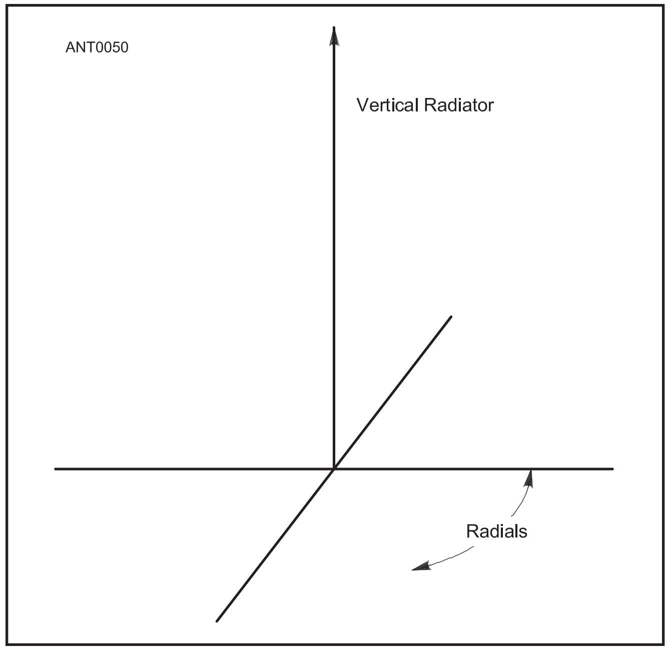


**Figure 3.18 — Example of a radial wire ground system.**

than 3 dB of signal loss for a given input power because over half the input power is dissipated in the soil. This shows us that *the shorter the vertical, the more critical the ground system is!*

Figure 3.16 also shows that most of the loss is occurring within $\lambda/8$ of the base which correlates with the field intensities shown in Figures 3.13 and 3.14. When designing radial ground systems this ground loss distribution is reflected in the need to increase the number of radials close to the base.

Figure 3.16 shows the total loss in the soil due to both E- and H-fields. However, the relative contribution of each field component to the total varies greatly with the height of the vertical. Figure 3.17 shows a comparison between the E and H losses for $h = \lambda/4$ and $h = 0.05\ \lambda$. For the $\lambda/4$ vertical the E-field losses are very small compared to the H-field losses but for the shorter vertical both the E- and H-field losses increase dramatically and the E-field loss is comparable to the H-field loss. In very short verticals the E-field losses can become larger than the H-field losses.

### 3.2.3 WIRE GROUND SYSTEMS

Figure 3.18 illustrates what we mean by a "radial" ground system. The ground system wires are connected together at the base of the antenna and arranged radially outward from the base. Why radial wires? Why not wires in circles or some other shape? As shown in Figure 3.10, the H-field lines have the form of circles around the base of the vertical. When the H-field passes over a conductor there will be a current induced in the conductor which flows at right angles to the H-field vector. In a wire ground system the optimum orientation for the wires is at right angles to the field (i.e. radially). If the wire were oriented parallel to the field (in a circle) there would be no current induced in the wire and the current would simply flow in the soil instead. In some cases where multiple verticals are present (i.e. in an array for example) it may not be practical to use only radial wires. Some form of coarse mesh may be needed.

#### Buried or Ground Surface Radial Systems

There are different ways to install wire ground systems: the wires may be buried in the soil a few inches or lying on the ground surface or elevated several feet above ground or even some combination of these. In addition, in elevated systems there may be interconnections between the radial wires to form what is called a "counterpoise". Another possibility is to use a coarse rectangular mesh, either on the ground surface or elevated. We will discuss all these options but for the moment we'll focus on radial systems either buried or lying on the ground surface.

If we know the values for E and H, $I_o$ and the soil electrical characteristics we can determine $P_g$. We can then determine $R_g$ directly from $P_g$:

$$R_g = \frac{P_g}{I_o^2} \tag{8}$$

$R_g$ is *not* a resistance unique to a particular ground system that you can measure with some kind of ohmmeter. It is simply the relation between a given excitation current ($I_o$) and the power dissipated in the soil ($P_g$) for a given vertical. $P_g$ in turn depends not only on the soil characteristics but on both $I_o$ *and* the details of the vertical itself, i.e. height, loading, etc. For this reason $R_g$ for a given ground system *will change* as we change the vertical even if the soil characteristics and the physical ground system itself are kept constant.

## Ideal Ground Screens

Initially we'll assume that the ground system is ideal: i.e. a high conductivity ground screen that covers the soil from the base out to some radius "r". This ideal ground screen will give us the minimum possible $R_g$ for ground system of a given radius. Later we'll look at $R_g$ for more practical wire ground systems with a limited number of radials to see how they compare. From the ideal ground screen information we will know what the ultimate limits are and can determine when adding more wire might result in only a small improvement. Surprisingly, it does not take a large number of radials to give a good approximation of an ideal ground screen.

**Figure 3.19** is an example of $R_g$ as a function of ground screen radius for several antenna heights at 3.5 MHz, over average ground. As we saw in Figure 3.16, near the base of the vertical the total ground loss is large but as we move outward from the base the *additional* ground loss becomes much smaller. This means that the values for $R_g$ fall quickly as r initially increases but as the radius of the screen gets larger, the rate of decrease in $R_g$ slows down.

If we take the values for $R_r$ from Table 3.2 and combine these with the values for $R_g$ in Figure 3.19 and use Eq 8, we can calculate the efficiency as shown in **Figure 3.20**. The efficiency is stated in dB so that this graph tells us directly how much our signal will improve as we expand the radius of the ground screen. For example, for h = 0.25 λ, expanding the screen radius from 0.01 λ to 0.125 λ increases the signal by 1.5 dB. If we further increase the radius to 0.250 λ we pick up another 0.6 dB and if we go to a screen radius of 0.375 λ the gain is an additional 0.4 dB. Clearly there is a substantial advantage to having a screen with a radius of at least λ/8 but as we increase the size, the incremental improvement gets smaller. In general for amateur applications expanding the ground screen radius beyond λ/4 is seldom worth the additional cost and effort at least on the lower bands (160 and 80 meters). But as pointed out earlier, we can make a case for larger ground systems (in terms of λ) at higher frequencies.

Figure 3.19 shows $R_g$ for one frequency and one ground characteristic. **Figures 3.21** and **3.22** show what happens to $R_g$ as we change frequency or ground characteristics for a given height (λ/4 in this example).

Figure 3.21 is a graph of the changes in $R_g$ with frequency for several different screen radii. This graph is for a λ/4 vertical over average ground. What the figure shows us is that for a given antenna, screen radius (in wavelengths) and ground characteristic, $R_g$ can increase significantly as we go to higher frequencies. For example with r = λ/4, $R_g$ = 7 Ω at 3.5 MHz but at 28 MHz a λ/4 screen has an $R_g$ = 12 Ω. If we increased the screen radius at 28 MHz to 0.375 λ, $R_g$ drops back down to 5 Ω. Expanding the screen radius from λ/4 to 3λ/8 at 28 MHz means extending the radial lengths from 2.7 meters (8.8 feet ) to 4 meters (13.2 feet ) which is very practical. The message is: *as we go higher in frequency we should consider using a ground screen with a larger electrical radius (in terms of λ) and/or more radials.* Fortunately, as we go up in frequency the wavelength gets shorter so it's easier to add more and/or longer radials for a given total amount of wire.

From Figure 3.22 we see that with lower quality soils $R_g$

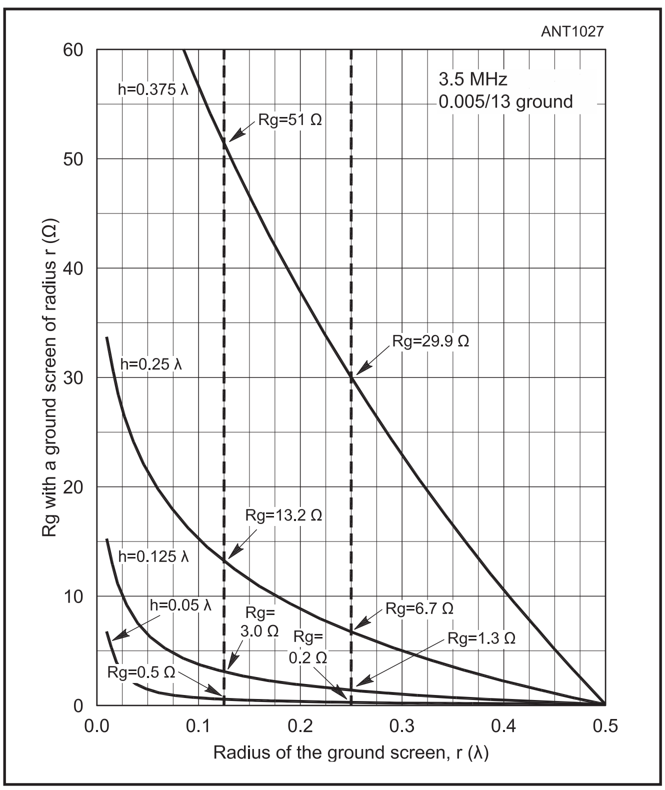



**Figure 3.19 — Variation in $R_g$ with ground screen radius. Normalized to include losses out to r = 0.5 λ.**

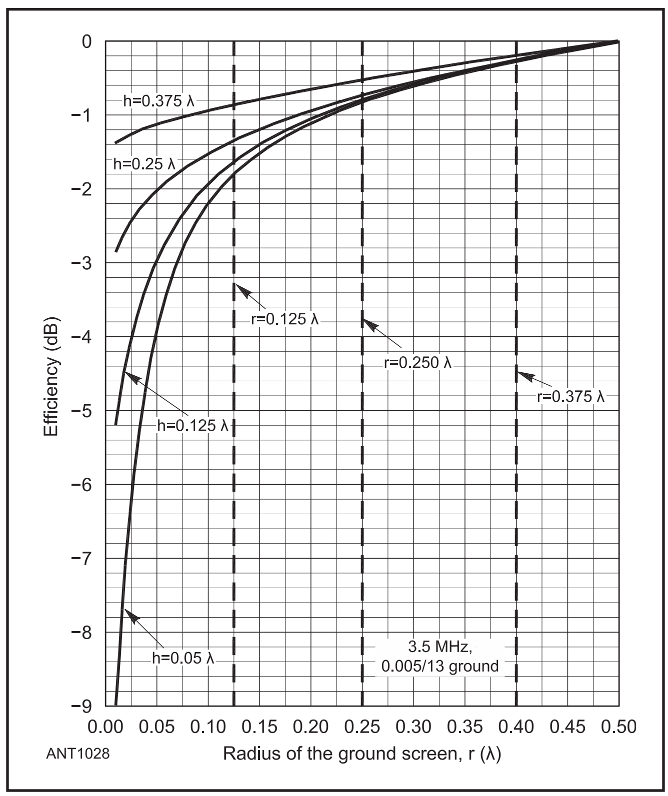



**Figure 3.20 — Efficiency in dB as a function of ground screen radius.**

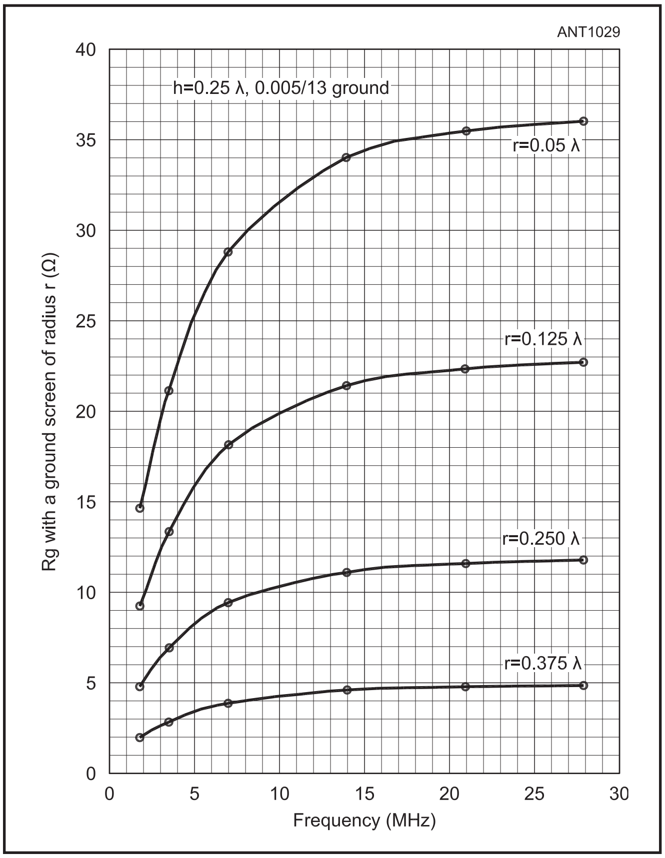



**Figure 3.21 — Variation in $R_g$ with frequency for h = λ/4 for several ground screen radii (in wavelengths) over average ground.**

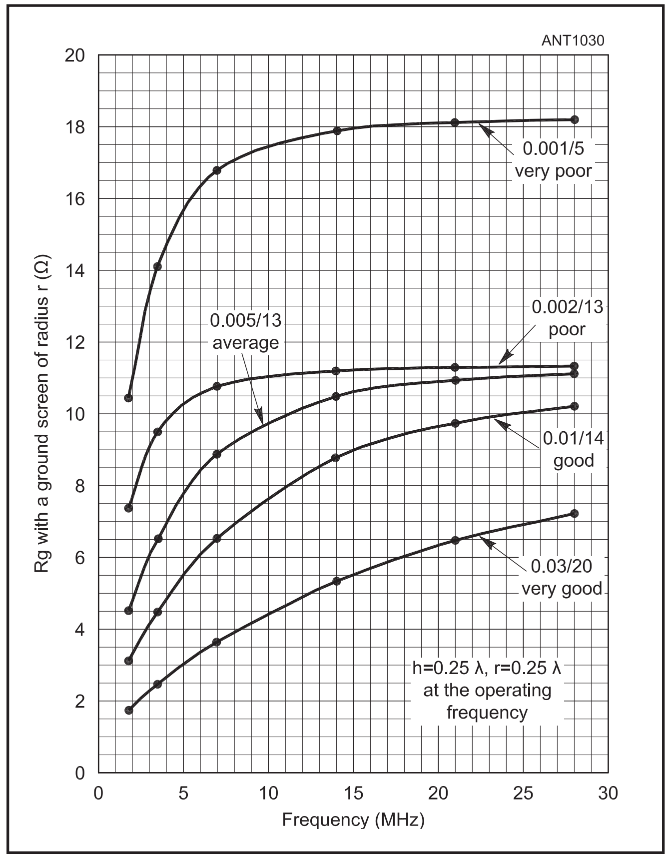



**Figure 3.22 — Variation in $R_g$ with frequency for h = r = λ/4 at the operating frequency.**

## Ground Radial System Design

Building an effective ground radial system is a study in compromises: space available, length of the radials, and available wire. The article "Maximum-Gain Radial Ground Systems for Vertical Antennas," by Al Christman, K3LC, shows you how to build the best radial system for the amount of wire you have available. It is available on the CD-ROM for this book.

is significantly higher and it becomes increasingly important to use a more extensive ground system to maintain efficiency.

### Real Wire Radial Systems

In practice, ground systems are usually made with wire in the form of a radial fan like that shown in Figure 3.18. How a particular ground system performs compared to an ideal ground screen can be determined using mathematical analysis or from *NEC* software modeling or from actual measurements on real antennas. All three routes give essentially the same answers but for this discussion we will use actual measurements on real antennas and also some *NEC* modeling results.

**Figure 3.23** shows the measured signal improvement as λ/4 (33 feet) radials lying on the ground surface were added to different 40 meter antennas: a λ/4 vertical, a λ/8 vertical

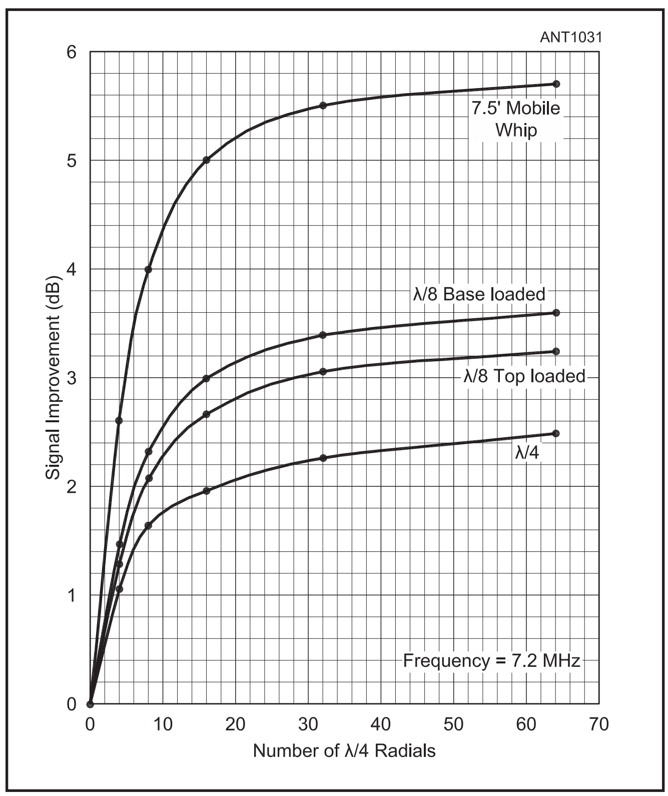



**Figure 3.23 — Signal improvement for typical 40-meter verticals as the radial number is increased from 0 to 64.**

with sufficient top-loading to resonate it, a λ/8 vertical resonated with an inductor at the base and a 7.5 foot 40 meter mobile whip.

The measurements began with only a single ground stake, no radials. Figure 3.23 shows the increase in signal strength (for a constant input power) for each antenna as the number of λ/4 radials was increased from 0 to 64. Initially, as radials were added, the signal improved rapidly but by the time there were 16 radials, the rate of increase in signal improvement turned a corner and started to decrease. Going from 32 to 64 radials the improvement was only a fraction of a dB (0.2 dB). What this tells us is that a radial fan with 32 or more radials is a good approximation of an ideal ground screen, at least for λ/4 radials. For short, loaded antennas over poor soils, 64 radials might be justified and should be considered. However, the standard broadcast ground system of 120, 0.4 λ radials would probably be a waste of copper for most amateur installations.

Another important thing we see in Figure 3.23 is that short loaded antennas benefit more from the same ground system. This is because (as shown earlier) the E- and H-field intensities are much higher close to the base of shorter antennas. Note also that in short antennas, moving the loading up the vertical, top-loading for example or placing the loading coil above the base, improves the signal for a given ground system.

The soil over which this experiment was conducted would be rated as very good ($\sigma$ = 0.015 S/m, $\varepsilon_r$ = 30). Over that soil the improvement going from 0 to 64 radials ranged from 2.5 to 5.7 dB. Over poor or even average soils the improvement would be substantially greater. Figure 3.23 also shows how important is to have at least a simple radial system. Sixteen radials is pretty much the practical minimum, especially over poor soils.

Measuring the signal strength for a given input power to the antenna, as radials are added to the ground system is a very direct way to gauge when adding more radials will give only a small improvement but for most amateurs that's not very practical. There is a simpler way to gauge when there are sufficient radials in the ground system. We can look at the feed point impedance which is a simple, direct measurement. An example of the variation of the resistive part ($R_{in}$) of the input impedance as radials are added to a ground system is given in **Figure 3.24**. The values are for the same antennas used in Figure 3.23. Note that for the 7.5 foot mobile whip, the series resistance of the loading coil has been subtracted from the measured feed point impedance.

If we assume that $R_{in} = R_r + R_g$ and that $R_r$ is constant as we add radials (a reasonable approximation), then the leveling out of the curves for radial numbers above 16 can be interpreted as meaning that the minimum $R_g$ for that radial length has been reached. Again, we see that 16 radials are pretty much the minimum but by the time we get to 32 radials the rate of change is quite small. Figures 3.23 and 3.24 tell the same tale.

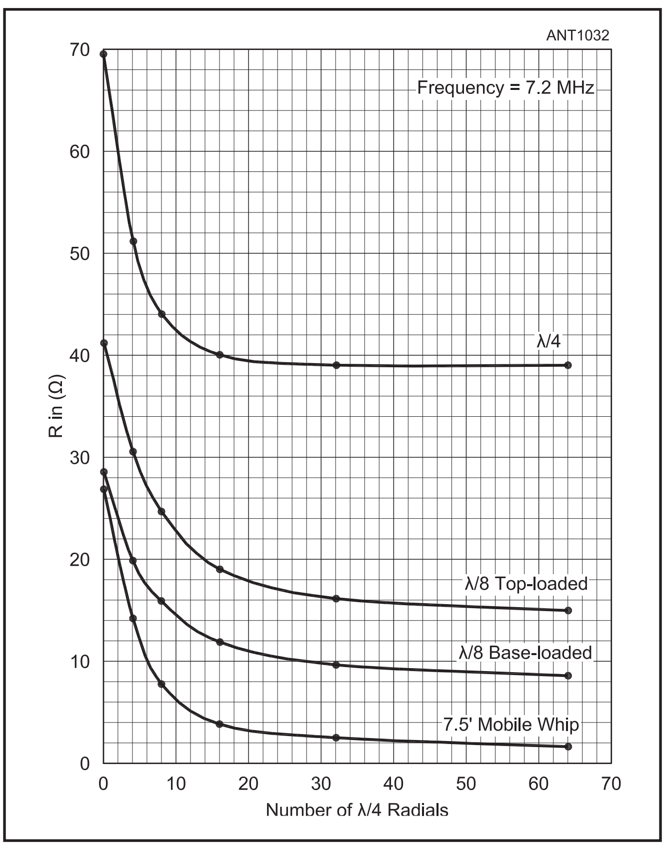



**Figure 3.24 — Variation in $R_g$ as a function of the number of λ/4 radials.**

## Optimizing Radial Lengths

In the real world the amount of wire available for a ground system may be limited. How should we use the available wire: a few long radials or a bunch of short ones?[2,3,4] We can use *NEC* modeling to address this question. **Figures 3.25** and **3.26** show the signal improvement as both the number and the length of the radials are changed. Both figures assume f = 1.8 MHz and average ground ($\sigma$ = 0.005 S/m, $\varepsilon_r$ = 13). Figure 3.25 is for h = λ/8 and Figure 3.26 is for h = λ/4. These figures illustrate a number of important points and provide a guide to the optimal use of a given total length of radial wire in the ground system. The 0 dB reference is four λ/8 radials. In both figures we see that when only a few radials are employed (<16) there is very little increase in signal when longer radials are used. In general, from both modeling and experiments, we can say that a few long radials make a poor ground system.[5] From the graphs we can see that longer radials become effective only as we increase the number of radials.

These graphs show how to optimize your signal for a given total length of radial wire. The dashed lines connect points which have the same total wire length in the ground system. For example, if we have a total of 2 λ of wire we could make four λ/2 radials or eight λ/4 radials or 16 λ/8 radials. From the graphs we can see that with a total of 2 λ of wire the best radial system would be 16 λ/8 radials. That would be an improvement of over 3 dB for the λ/8 vertical and 1 dB for the λ/4 vertical. Similarly, if 4 λ of wire is available then

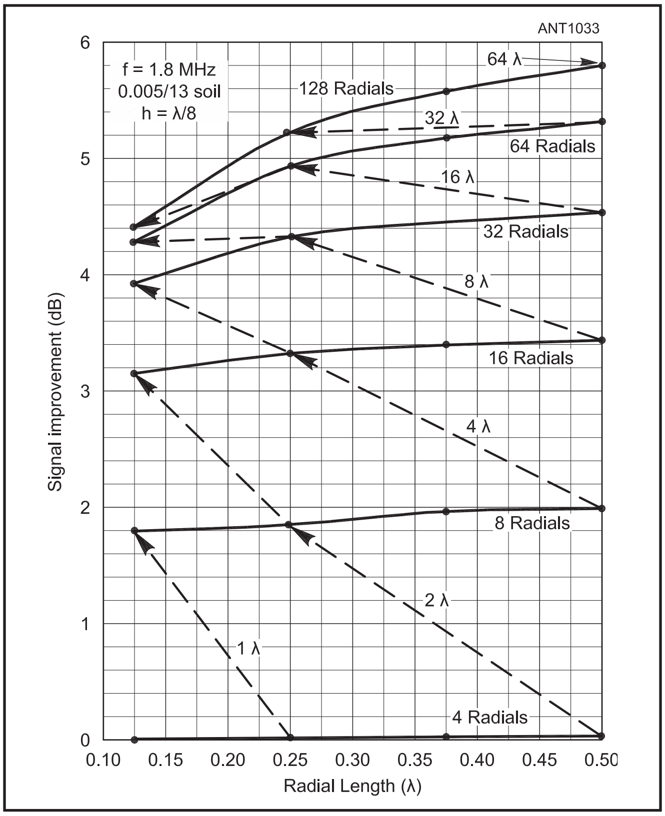



**Figure 3.25 — Comparison of radial lengths and number versus signal improvement for a given total amount of radial wire (in λ). In this example h = λ/8.**

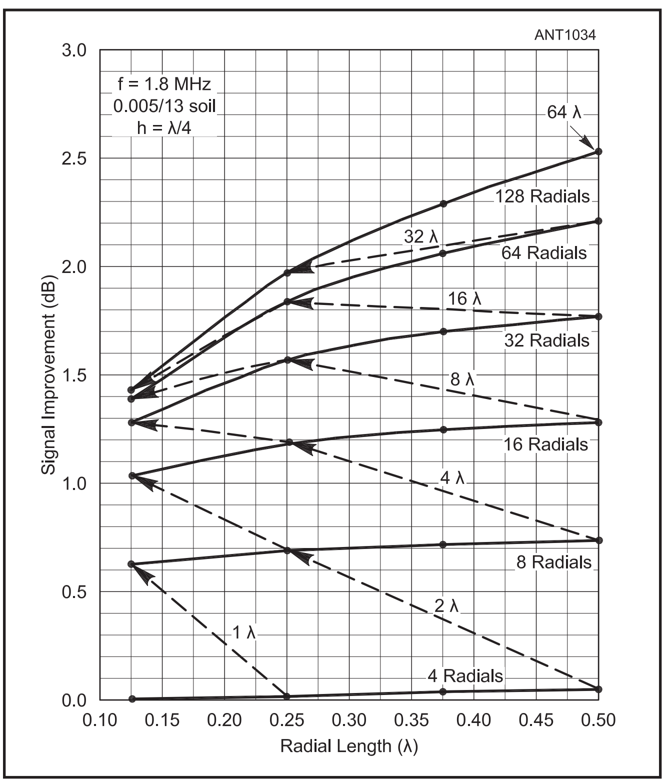



**Figure 3.26 — Comparison of radial lengths and number versus signal improvement for a given total amount of radial wire (in λ). In this example h = λ/4.**

the optimum use would be 32 λ/8 radials. When we go to 8 λ of wire, things change a bit. For the h = λ/8 antenna either 64 λ/8 or 32 λ/4 radials will work about the same. However, for the h = λ/4 antenna the best use of the wire would be 32 λ/4 radials. The reason that a large number of short radials are effective stems directly from the high field intensities close to the base of a vertical. The first priority is to reduce the losses close to the base. As more wire becomes available and the losses close to the base have been reduced then reducing the losses further out becomes useful.

A bit of long held conventional wisdom among amateurs is that "the length of the radials should be similar to the height of the vertical." Figures 3.25 and 3.26 give partial support to that belief. When 8 λ of wire is available, λ/8 radials will work fine for a λ/8 vertical but a smaller number of λ/4 radials work better for the λ/4 vertical. This stems from the much higher field intensities associated with the λ/8 vertical. In short antennas it's very important to use numerous radials close to the base. But in both cases, when sufficient wire is available, there comes a point where fewer but longer radials are a better choice.

### Radial Screens with Missing Sectors

In many installations a vertical may have to be located close to an obstacle such as a building or a driveway and it may not be possible to have a full 360° symmetrical radial field. The lack of radials in a subsector of the radial system will increase ground loss because there aren't any radials in that sector to keep the field out of the soil! In addition there will be pattern distortion. Depending on the size of the missing radial sector and the soil characteristics the signal reduction and pattern distortion can be several dB.[6] This is definitely undesirable but may be unavoidable in some situations. If the obstacle is a building, locating the antenna along one side will result in a 180° missing sector but if the antenna can be moved to a corner of the building the missing sector will only be 90° which will be a significant improvement over the 180° case. From the earlier discussion we know that the ground close to the base is the most critical. If possible, the antenna should be moved away from the structure and a fan of short radials inserted in the missing sector. Of course the building itself may have considerable effect on the antenna. It's generally a good idea to keep antennas as far as possible from structures. *If space is limited in all directions, it may be better to move the antenna away from the structure and accept short radials all the way around.*

## 3.2.4 ELEVATED GROUND SYSTEMS

Ground systems can elevated above ground and electrically isolated from ground. The most common system uses four or more λ/4 radial wires placed a few feet above ground. Another form of elevated system consists of a number of radial wires, which have lengths <λ/4, perhaps with a skirt wire connecting the outer ends of the radial wires as well as interconnecting wires between the radials closer to the base. It is also possible to use an elevated wire mesh. These last two options are often referred to as a "counterpoise" or "capacitive" ground system. A λ/4 vertical with several λ/4 radials (usually four radials) is called a "ground-plane" antenna. Ground plane antennas are discussed in the **Dipoles and Monopoles** chapter.

### Elevated Systems with Simple Radial Wires

In this section we discuss radial systems made from straight wires of the same length for single band use. Multiband and counterpoise systems are discussed in following sections.

For a number of years there has been much discussion regarding the relative merits of buried or ground surface radials versus elevated radials. Modeling using *NEC* software has consistently indicated that a few elevated radials should perform as well as a large number of radials on the ground. Modeling has also predicted that the signal would improve very quickly with height even for small elevations. To verify these modeling predictions a carefully controlled series of experiments were performed at 7.2 MHz directly comparing the signal from a vertical using either an on-the-ground system with many radials or an elevated system with only a few radials.[7]

The experiment began with the base of the vertical at ground level with four λ/4 radials lying on the ground surface. The signal strength at a remote point was recorded. This was used as the reference level (0 dB). The next step was to elevate the base of the antenna and the four radials in increments from zero to 48 inches. At each point the change in signal from the reference level was recorded. The second part of the experiment left all the radials on the ground surface but starting with four radials incrementally increased the number of radials. **Figure 3.27** shows the results of that experiment. The *NEC* modeling predictions agree well with the observed behavior:

1) Even a small elevation makes a considerable difference in signal and

2) The elevated system is equivalent to the ground system with 32 or more radials.

One additional point should be emphasized regarding this experimental work. For the 4-radial elevated system to work as well as the multiple radial ground based system, during the experiment it was found that very great care had to be taken to assure that the radial geometry was highly symmetric, the radial lengths identical and that the currents in the radials were all equal and in phase with the base current as discussed below.

### Safety Consideration with Elevated Radials

Before looking more closely at the assertion that four elevated radials are equivalent to many ground-based radials we need to consider a safety issue. Like a vertical located at ground level, elevated verticals will have high voltages on the vertical but in addition, elevated radial systems can have very high fields and voltages on and near the radial wires. **Figure 3.28** gives examples of the voltage from a radial wire to ground for 4, 12 and 32 λ/4 radial systems.

Note that the voltages vary from 250 $V_{RMS}$ to nearly 2000 $V_{RMS}$! These voltages are proportional to $\sqrt{P_{in}}$ so that if you drop the power from 1500 W to 100 W, a factor of 15:1, the voltages only drop by a factor of less than four. Even at 100 W, they are still very high! For safety reasons, elevated radial systems are usually placed well above head-height, 8 feet or more. This is done so that people or animals cannot accidentally run into the wires but also because the high voltages which are present on the radials, particularly at the ends, can cause severe RF burns. This hazard is typical of elevated ground systems.

Given the high potentials at the ends of the radials, high quality insulators should be used at the radial ends. In addition to the high voltages, the E-field intensities are also very high near the radial ends. This means there is a danger of corona discharge which can erode the wire or even damage a plastic

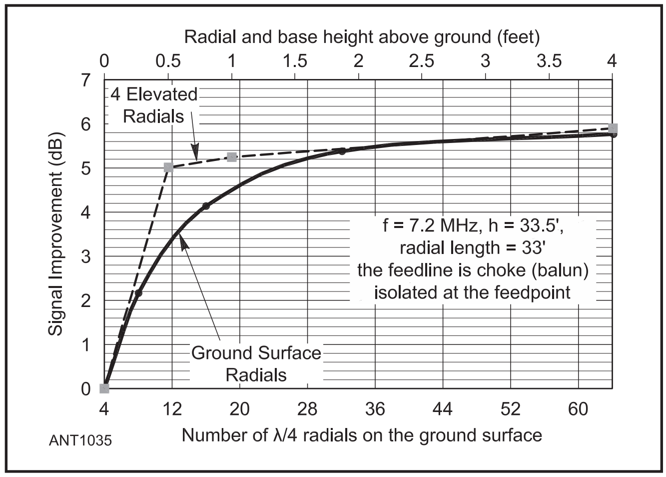



**Figure 3.27 — Comparison between four elevated λ/4 radials and λ/4 radials on the ground surface. Note that this graph has two different horizontal axes. The arrows associate the plots with the appropriate horizontal axis.**

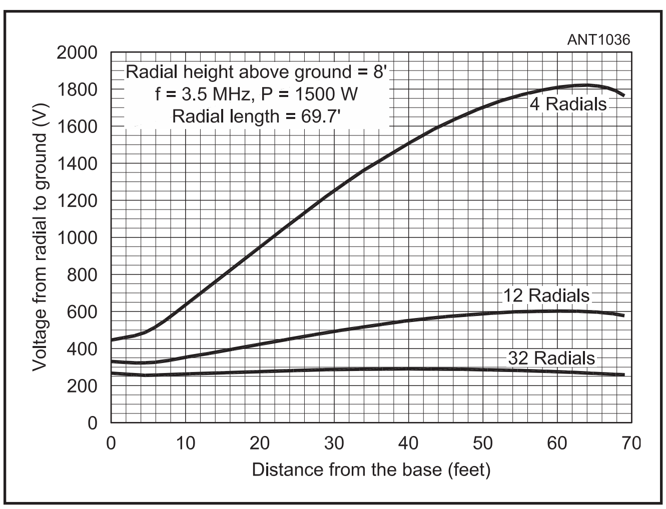



**Figure 3.28 — Examples of the voltage from an elevated radial wire to ground with different numbers of radials. The input power to the vertical is 1500 W, the operating frequency is 3.5 MHz and the radial system is elevated 8 feet above ground.**

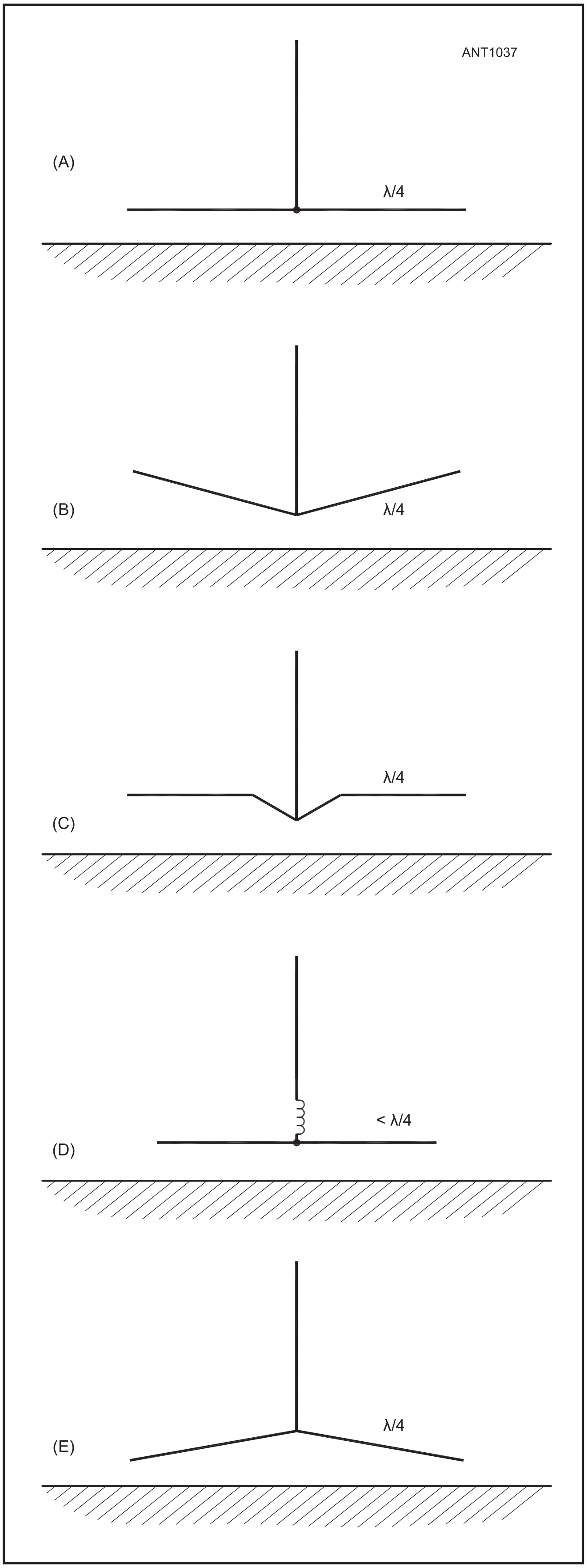


**Figure 3.29 — Alternate elevated ground system configurations.**

insulator. Where the radial wires are attached to the insulators, care should be taken that the wire ends do not form any sharp points which could be sites for corona discharge. Usually a ball of solder is used to cover the wire end. This problem will become more acute as the altitude of the station increases.

## Some Alternative Elevated Systems

It is not always practical to have the base of the antenna high above ground. For example, a 20 meter λ/4 vertical will only be about 17 feet long and made from small diameter aluminum tubing. Elevating this is not a great challenge. But a 160 meter λ/4 vertical will be about 130 feet high and probably made from tower sections or heavy tubing. It may not be possible to elevate the base of the larger antennas very high. As an alternative, the elevated radials can be arranged in several ways as shown in **Figure 3.29**. The simplest approach when the base is close to ground as shown in (B) is to just slope the radials out at an angle. While this approach can place the radial tips well above head height it still leaves a lot of the radial at low heights. Another approach (C) is to slope the initial portion of the radial upward at an angle of 45° until a height of 8 feet is reached and then to run the rest of the radial out at constant height. These are referred to as "gull wing" radials.[8]

Another problem that often arises (particularly on 80 and 160 meters) is that there may not be enough space for full λ/4 radials. That's OK because as shown in Figure 3.29D, shorter radials can be used and an inductor added at the base of the antenna to resonate it.[9] (Note, it is also possible to place individual inductors in each radial which may be helpful in balancing the current division between the radials.) Another alternative configuration is shown in Figure 3.29E. In this case the base is higher than the ends of the radials. This configuration is often used at 20 meters and above where the radials are self-supporting conductors. When the radials are anchored only at the base some droop to the outer end of the radials would be normal. In some cases the radials are deliberately sloped downward to increase the feed point impedance and provide a lower SWR. It should be pointed out that configurations (B) and (C), where the radials slope upward from the base, will have lower feed point impedances and somewhat reduced SWR bandwidths.[7]

This raises the question: how much is the antenna performance degraded by these alternate schemes? Again this can be addressed either with modeling or experimentally. The

**Table 3.4**
**Signal Comparison Between Different Elevated Radial Systems.**

| *Radial System Configuration* | *Relative Signal* |
|---|---|
| (A) Base and four radials elevated 4 ft | 0.00 dB |
| (B) Base at ground level, radial ends at 4 ft | –0.47 dB |
| (C) Base at ground level, gull-wing-radials, ends at 4 ft | –0.65 dB |
| (D) Base and radials at 4 ft, λ/8 radials with L = 2.2 µH | –0.36 dB |
| (E) Base at 4 ft and radial ends at 3 ft | +0.10 dB |

earlier experiment comparing elevated and ground surface radials on 40 meters was extended to compare the alternatives given in Figure 3.29. The results are listed in **Table 3.4**. All the alternatives were tested with four radials at 7.2 MHz. The base tuning inductor in option (D) had a Q of 350. The conventional system with all of the radials and the base elevated to the same height is used as the 0 dB reference. Except for (E), there is a small penalty associated with the alternate elevated radial configurations (on the order of –0.5 dB) which may be acceptable in many situations.

### Problems with Elevated Radials

The simplicity of elevated systems with only three or four radials is very attractive because, at least in principle, they can be just as effective as much more extensive ground based systems. However, as pointed out above with regard to the experimental work, elevated systems with small numbers of radials are very sensitive to the mechanical details of the radials: i.e. length, droop, asymmetry in the radial fan, nearby conductors and so forth. The input impedance, current division between radials, radiation pattern, resonant frequency and efficiency of the antenna are all sensitive to even small asymmetries. It has been demonstrated experimentally that radial geometry asymmetry[9] and irregularities in ground characteristics under the radial fan[10] will cause problems. The following discussion explores some of these problems.

Typically a vertical with an elevated ground system will be fabricated with the vertical and the radial lengths calculated from L = 234/f in MHz which is 5% shorter than a free-space λ/4. The common wisdom that 5% shortening should be used is derived from work done in the 1930s but is only an approximation. When the base impedance of an actual antenna is checked, the resonant frequency will often be substantially different from what was expected and dependent on the number of radials as well as their length.

*NEC* modeling can be used to explore what's happening. The modeling is done in two steps: first model the vertical radiator element over a perfect ground and adjust its length to resonate at the desired frequency (7.2 MHz in this example). This example uses a #12 AWG wire and to be resonant at 7.2 MHz, h = 32.22 feet which is about 5.5% shorter than free space. The next step in the modeling is to add various numbers of horizontal #12 AWG wire radials. Each of the radials has the same length as the vertical (L = 32.22 feet). **Figure 3.30** shows the resonant frequency as a function of the number of radials from 2 to 128.

The resonant frequency of the complete antenna with the radials approaches the desired 7.2 MHz but doesn't quite get there. Even when a large number of λ/4 radials are used, the radial fan is not the same as an infinite ideal ground. In general, elevated systems should start with radials and perhaps the vertical radiator, with a length corresponding to the free space value for λ/4 (L = 246/f in MHz) and then trim the radials to resonate the antenna at the desired frequency. There is another reason for starting with a vertical that is a bit taller. When the radials are trimmed to resonate the antenna, the length of the radials will be somewhat shorter than might be expected. This saves wire and reduces the footprint.

A very common problem in elevated systems is that the radials may not all be exactly the same length. Experimentally this has been shown to cause non-uniform current division between the radials which can have a serious effect on the performance of the antenna.[9] We can model an example to demonstrate how severe this effect can be. Start with a 40 meter λ/4 vertical with four radials as shown in **Figure 3.31**, where the base of the vertical and the radials are placed 8 feet above average ground ($\sigma$ = 0.005 S/m, $\varepsilon_r$ = 13). Radials 1 and 2 form a pair of opposing radials with a length = L. Radials 3 and 4 are a second opposing pair of radials with length = M. First we model the antenna with all the radials the same length (L = M) and then with radials that differ in length (L ≠ M). The initial length for the vertical and the radials was made 34.1 feet to resonate the antenna at 7.2 MHz.

The modeled feed point impedances (from 7.0 to

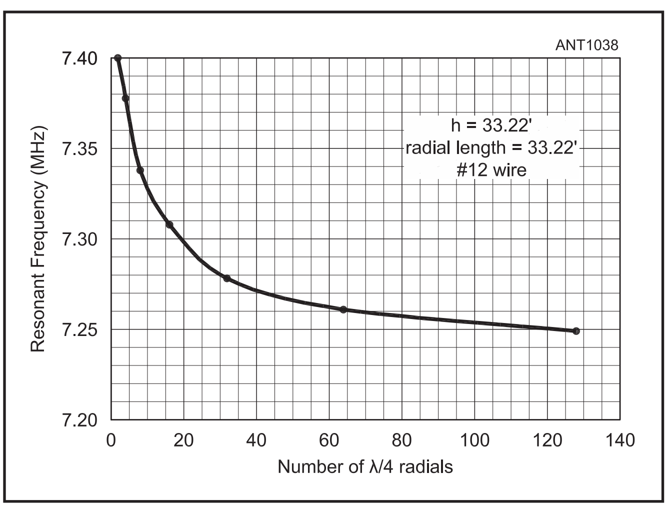



**Figure 3.30 — Resonant frequency of a λ/4 vertical for different numbers of elevated radials.**

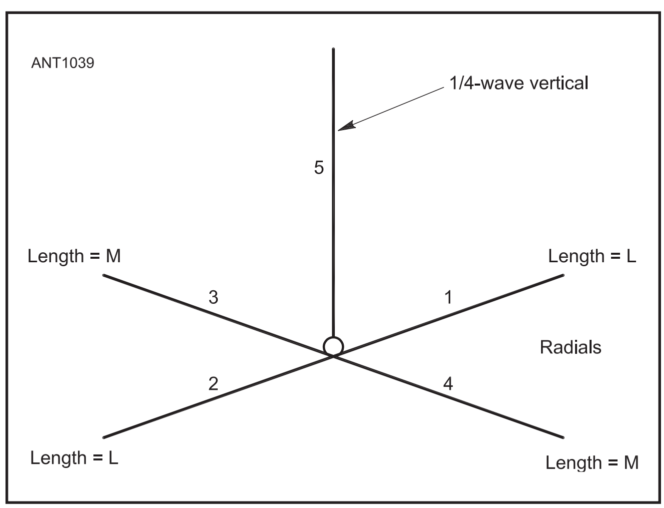



**Figure 3.31 — 40-meter λ/4 vertical with four radials. Vertical height is 34.1 feet. The radial lengths are varied.**

7.3 MHz) for three different radial length configurations are compared in **Figure 3.32** which is a graph of $R_{in}$ versus $X_{in}$ ($Z_{in} = R_{in} + jX_{in}$ = feed point impedance) as the frequency is varied from 7.0 to 7.3 MHz. The plot on the left is for the case where all the radials are identical (L = M = 34.1 feet). The looping plot on the right is for case where L = 35.6 feet and M = 33.1 feet, this represents a length error of ±2.9%. The middle plot is for L = 34.6 feet and M = 33.6 feet, which is a length error of ±1.4%. Clearly even small radial length asymmetry can have a dramatic effect on the feed point impedance and resonant frequency. The resonant frequency is the point at which $X_{in} = 0$.

But feed point impedance is not the only problem created by asymmetric radial lengths. **Figure 3.33** compares modeled radiation patterns between symmetric and asymmetric systems at 7.25 MHz. The amount of pattern distortion varies across the band from a fraction of a dB at 7.0 MHz to 3 dB at 7.25 MHz. Besides the distortion, the gain in all directions is smaller for the asymmetric case. Computing the average gains for the symmetric and asymmetric cases in Figure 3.33, there is about a 1.6 dB difference. What this tells us is that asymmetric radials can lead to significantly higher ground losses!

The pattern distortion and increased ground loss with asymmetric radials occurs because the radial currents with asymmetric radial lengths can be much different from the symmetric case. An example is given in **Figure 3.34**. The graph bars represent the current amplitudes at the base of the vertical and each of the radials immediately adjacent to the base of the vertical. The black bars are for symmetric radial lengths (L = M = 34.1 feet) and the red bars are for asymmetric radials (L = 35.1 feet and M = 33.1 feet). In the symmetric case each of the radials has a current of 0.25 A which sums to 1 A, the current at the base of the vertical. The radial currents are also in phase with the base current.

With asymmetric radials the picture is very different: the

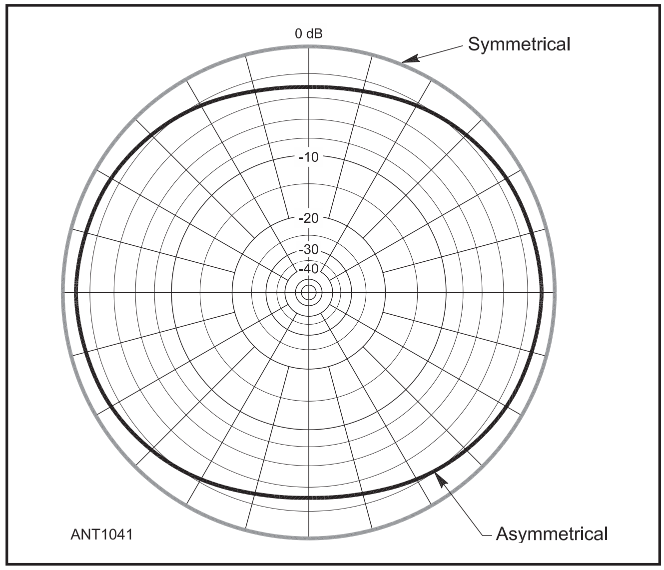



**Figure 3.33 — Azimuthal radiation pattern at an elevation angle of 22 degrees, comparing symmetric (L = M = 34.1 feet) and asymmetric (L = 35.1 feet, M = 33.1 feet) radials at 7.25 MHz.**

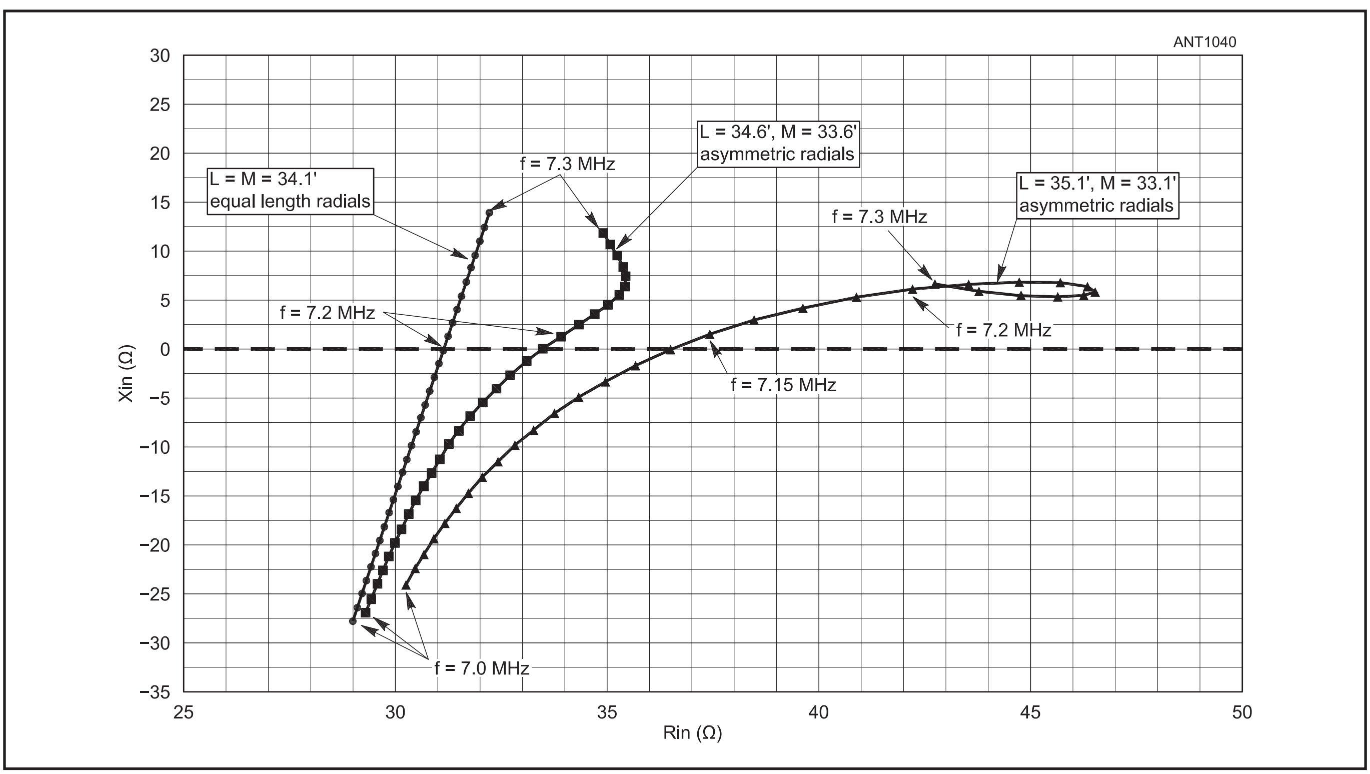



**Figure 3.32 — A comparison of the input impedances ($Z_{in} = R_{in} + jX_{in}$) from 7.0 to 7.3 MHz at the feed point of the vertical for symmetric and asymmetric radial lengths.**

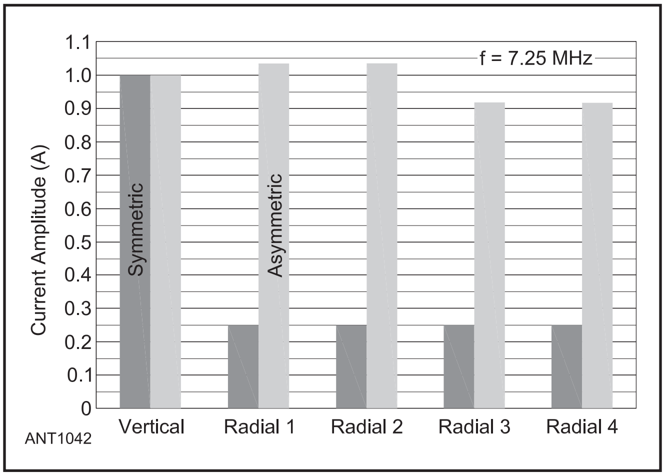



**Figure 3.34 — Comparison of radial current at the bases of the vertical and the radials with symmetric (L = M = 34.1 feet) and asymmetric (L = 35.1 feet and M = 33.1 feet) radial lengths. The radials are numbered as shown in Figure 3.31. The current shown is the magnitude.**

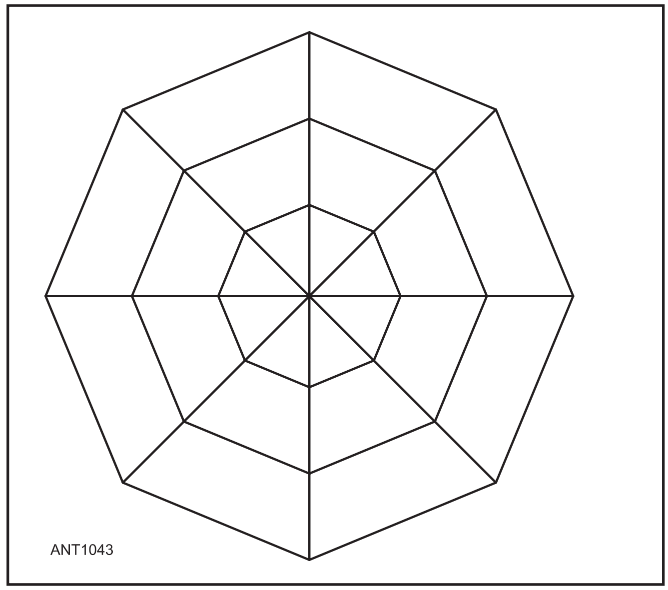



**Figure 3.35 — Example of a wire counterpoise ground system.**

current amplitudes are different between radial pairs 1 and 2 and 3 and 4 and the sum of the current amplitudes is *not* 1 A, it is much larger! This would seem to violate Kirchhoff's current law which requires the **vector** sum of the currents at a node to be zero. In this case the radial currents in the two pairs of radials are not in phase with each other or the vertical base current. The current in radials 1 and 2 is shifted by –62° from the base current and the current in radials 3 and 4 is shifted by +89°. The radial currents still sum *vectorially* to 1 A however. These large asymmetric currents go a long way towards explaining the increased loss and pattern distortion.

How can we tell if there is a problem in an existing radial fan? One way is to measure the current amplitudes in the individual radials close to the base of the vertical.[13] If the current amplitudes are significantly different between the radials *and/or* if the sum of the current amplitudes in the radials is greater than the base current then you have a problem. These measurements can be made with a RF ammeter. More accurate measurements which also show the phase can be made using current transformers and an oscilloscope (see the section "Practical Aspects of Phased Array Design" in the **Multielement Arrays** chapter) or a vector network analyzer (see the **Antenna and Transmission Line Measurements** chapter).[13]

The sensitivity to asymmetric radial lengths is reduced when a larger number of radials are employed. The primary effect of additional elevated radials (>4) is to reduce the sensitivity to radial asymmetry, nearby conductors, variations in ground conductivity or objects under the radial fan, and, as shown in Figure 3.28, more numerous radials reduce the potentials on the radials. More numerous radials also reduce the E-field intensity below the radial fan. *Whenever possible an elevated ground system should use 10 or more radials.* If you follow that rule you are very likely to get the performance you expect. With small numbers of elevated radials the results can be hit or miss.

Sometimes it's not possible to have a symmetric radial fan of λ/4 radials. This is often the case on 160 or 80 meters. Because each installation will be unique it is difficult to give general advice but certainly the first step should be to model the proposed antenna with different radial options to get a feeling for how well they might work. One option is to keep the radial fan symmetric with a radius smaller than λ/4. You can then resonate the vertical with an inductor as shown in Figure 3.29D, add some top-loading to the vertical, make the vertical taller, or some combination of all three. With short radials it may be helpful to add a skirt wire at the ends of the radials as shown in **Figure 3.35**. Adding a skirt wire to the radial system will reduce the size of the base loading inductance.

### Counterpoise Systems

In the early days of radio, operating wavelengths were in the hundreds or thousands of meters. Very often a ground system with λ/4 radials was not possible. Early on it was recognized that an elevated system of wires called a "counterpoise" or "capacitive ground" with dimensions much smaller than λ/4 could be very effective. Figure 3.35 shows a typical example that looks very much like a spider web. Rectangular counterpoises made with a coarse rectangular mesh were also very common. Amateurs have done some experimental work on counterpoise systems.[10] On 80 or 160 meters the normal λ/4 radial system may well be too large for many amateur locations so a counterpoise can be a practical option. However, it is recommended that the proposed installation be carefully modeled and optimized *before* construction to avoid surprises.

### Isolation of Elevated Ground Systems

In an elevated ground system it is good practice to isolate the feed line with a common mode choke (i.e. a current balun

— see the **Transmission Line System Techniques** chapter). Simply attaching a coaxial feed line to the antenna and running it back down to ground can increase ground loss and in some cases have a strong effect on the resonant frequency and behavior of the impedance across the band. The effects of not isolating the feed line vary from slight to severe depending on the details of each installation. Elevated systems with small numbers of radials are particularly sensitive. An additional problem with asymmetric radials is that they can greatly increase the voltage across the balun, leading to larger losses in the balun core.

### 3.2.5 DIFFERENCES BETWEEN RADIAL SYSTEMS

Ground systems using elevated radials, radials lying on the ground surface, or buried radials can all provide good performance but there are some differences with practical consequences which need to be recognized. As shown in **Figure 3.36**, the current distribution on a λ/4 radial is different for each of those arrangements.

When a radial is placed very close to the ground, the velocity of propagation along the radial is slower so that the radial is effectively electrically longer and the current maximum moves out onto the radial as shown in Figure 3.36B. This has two consequences: First, it can increase the ground loss and, second, it can affect the feed point impedance and resonant frequency of the vertical.[14,15] Note from the current distribution, that the ground surface radial behaves more like an elevated radial than a buried one. Ground surface radials can affect the resonant frequency of the antenna.

An example of this is given in **Figure 3.37**. The experiment from which the data in Figure 3.37 was obtained began with no radials and only a single ground stake. As radials were added, the resonant frequency of the antenna was measured. Initially the change in resonant frequency was quite rapid but by 32 radials the rate of change slowed and the resonant frequency stabilized. The additional ground loss when <8 radials are used can be significant, providing another reason for not using a few long radials.[14]

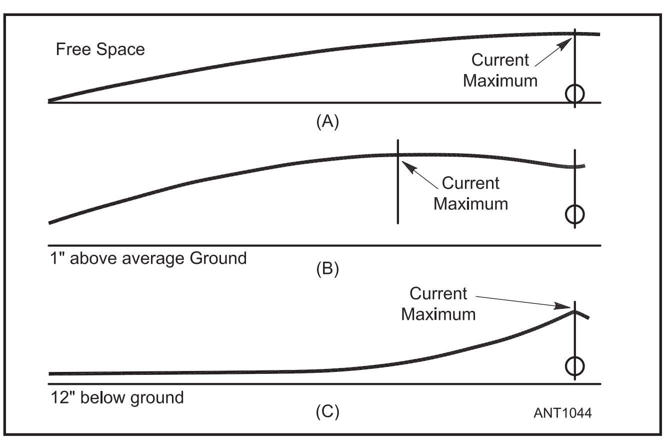



**Figure 3.36 — Examples of current distribution on radials in elevated, ground surface and buried systems.**

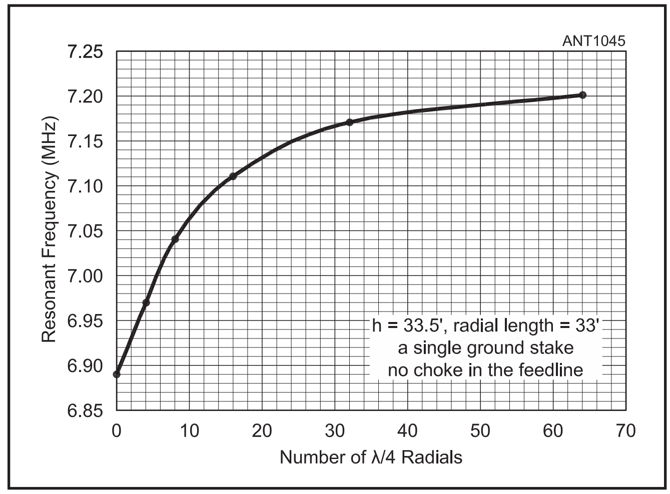



**Figure 3.37 — A typical example of the effect on resonant frequency as the number of ground surface radials is varied.**

For bare radials, well buried in the soil, the radial current distribution is exponential due to the damping effect of the soil conductivity (Figure 3.36C). In general, changing the radial number in buried systems does not greatly affect resonance except possibly in very low conductivity soils. The change in current distribution as a radial is taken from the surface into the soil is not abrupt. Radials just below the surface will behave much like radials right on the surface. The rate of change depends on the soil characteristics so don't be surprised if you see some shift in resonance as more radials are added with shallow burial.

#### Multiband Radial Systems

Multiband verticals are very popular which raises the question of what kind of ground system to use with them? In practice, the most common ground system, either on the ground or elevated, has four λ/4 radials *for each band*. For example if the vertical operates on 7, 14, 21 and 28 MHz there will be a total of 16 radials which is about 280 feet of radial wire. Multiband ground systems have been evaluated experimentally and shown to work very well.[15] Even though the most common system has only four radials on each band, coupling between the radials seems to minimize the elevated system problems discussed earlier. One alternative (for either

## Advice on Ground Systems

With so many configurations and options available, some advice on ground systems is in order: Buried, ground surface or elevated radial systems can all be very efficient. However, no matter which configuration is chosen, a few long radials are not likely to provide a satisfactory ground system. If you want an efficient ground system don't skimp on the radials! Try to use at least 20 or more radials on the ground and 10 or more in elevated systems.

on-the-ground or elevated systems) for a 40-10 meter vertical would be to use 30 or more 40 meter $\lambda/4$ radials without any of the shorter higher band radials. This also works well yielding an improvement of about 1 dB over the standard system. However, 30 radials on 40 meters total about 2100 feet of wire which is almost eight times the total wire in the standard system!

### Radial Wire Size and Material

If the recommended number of radials is used, the wire size used in a radial system usually has only a small effect on the electrical performance. For a given amount of copper it is much better to use many small diameter radials instead of a few large ones. The practical issues are more mechanical than electrical: i.e. is the wire sturdy enough for installation and will it survive burial in the soil or lying on the soil surface for extended periods? In the case of elevated radial systems, is the wire strong enough to be stretched between the supports and, in climates where icing is a problem, is it strong enough for the possible ice load? The wire can be either insulated or bare although in the case of buried radials insulated wire may resist corrosion longer. Wire sizes as small as #22 AWG may be acceptable if there are a large number of radials. Either copper or aluminum wire can be used. Steel wire is very strong and inexpensive but both copper and aluminum wire have much better conductivity. Generally speaking galvanized fence wire should be viewed as an emergency measure. Although aluminum wire is attractive because it's much cheaper than copper, it has much lower corrosion resistance and may not be suitable for buried installations in most soils. Aluminum has the additional problem that it is difficult to solder and usually requires mechanical connections which may not be reliable when exposed to the weather for long periods. Either solid or stranded wire can be used in ground systems although in buried systems solid wire may be more corrosion resistant. For elevated systems where severe ice loading is expected Copperweld or Alumaweld wire can be used. These are steel wires with a thick copper or aluminum cladding. This construction gives both good conductivity and great strength. However, any damage to the cladding will expose bare steel to the elements, resulting in corrosion.

Insulated copper wire will frequently be less expensive than bare wire and in addition, insulated wire of many different kinds is often available inexpensively from surplus sources. It is not necessary to strip the insulation from the wire to use it for radials except to connect it at the base of the antenna or to other radials. In an elevated system loading by the insulation will make the radials electrically 2-3% longer but add little loss. For buried radials the insulation may provide some corrosion protection.

## 3.3 THE EFFECT OF GROUND IN THE FAR FIELD

The properties of the ground in the far field of an antenna are very important, especially for a vertically polarized antenna. Even if the ground-radial system for a vertical has been optimized to reduce ground-return losses in the reactive near field to an insignificant level, the electrical properties of the ground may still diminish far-field performance to lower levels than "perfect-ground" analyses might lead you to expect. The key is that *ground reflections* from horizontally and vertically polarized waves behave very differently.

This section, from earlier editions, uses an alternate convention in which k and $\varepsilon_r$ refer to the same quantity and are interchangeable, as are $\sigma$ and G. Both are in common use in the technical literature.

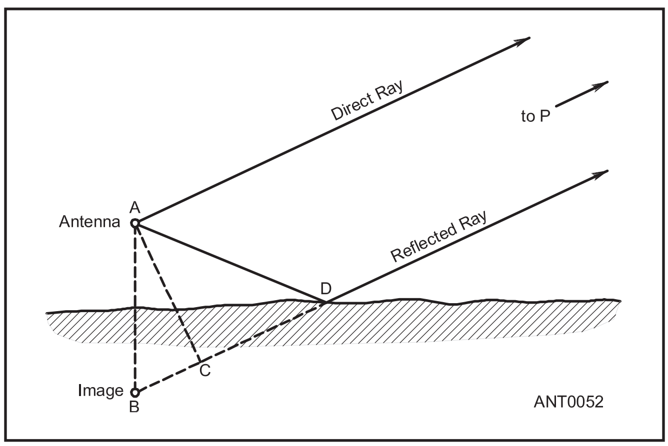



**Figure 3.38 — At any distant point, P, the field strength will be the vector sum of the direct ray and the reflected ray. The reflected ray travels farther than the direct ray by the distance BC, where the reflected ray is considered to originate at the image antenna.**

### 3.3.1 REFLECTIONS IN GENERAL

First, let us consider the case of flat ground. Over flat ground, either horizontally or vertically polarized downgoing waves launched from an antenna into the far field strike the surface and are reflected by a process very similar to that by which light waves are reflected from a mirror. As is the case with light waves, the angle of reflection is the same as the angle of incidence, so a wave striking the surface at an angle of, say, 15° is reflected upward from the surface at 15°.

The reflected waves combine with direct waves (those radiated at angles above the horizon) in various ways. Some of the factors that influence this combining process are the height of the antenna, its length, the electrical characteristics of the ground, and the polarization of the wave. At some elevation angles above the horizon the direct and reflected waves are exactly in phase — that is, the maximum field strengths of both waves are reached at the same time at the same point in space, and the directions of the fields are the same. In such a case, the resultant field strength for that angle is simply the sum of the direct and reflected fields. (This represents a theoretical increase in field strength of 6 dB over the free-space pattern at these angles.)

At other elevation angles the two waves are completely out of phase — that is, the field intensities are equal at the same instant and the directions are opposite. At such angles, the fields cancel each other. At still other angles, the resultant field will have intermediate values. Thus, the effect of the ground is to increase radiation intensity at some elevation angles and to decrease it at others. When you plot the results as an elevation pattern, you will see *lobes* and *nulls*, as described in the **Antenna Fundamentals** chapter.

The concept of an *image antenna* is often useful to show the effect of reflection. As **Figure 3.38** shows, the reflected ray has the same path length (AD equals BD) that it would if it originated at a virtual second antenna with the same characteristics as the real antenna, but situated below the ground just as far as the actual antenna is above it.

Now, if we look at the antenna and its image over perfect ground from a remote point on the surface of the ground, we will see that the currents in a horizontally polarized antenna and its image are flowing in opposite directions, or in other words, are 180° out of phase. But the currents in a vertically polarized antenna and its image are flowing in the *same* direction — they are *in* phase. This 180° phase difference between the vertically and horizontally polarized reflections off ground is what makes the combinations with direct waves behave so very differently.

### 3.3.2 FAR-FIELD GROUND REFLECTIONS AND THE VERTICAL ANTENNA

A vertical's azimuthal directivity is omnidirectional. A λ/2 vertical over ideal, perfectly conducting earth has the elevation-plane radiation pattern shown by the solid line in **Figure 3.39**. Over real earth, however, the pattern looks more like the shaded one in the same diagram. In this case, the low-angle radiation that might be hoped for because of perfect-ground performance is not realized in the real world.

Now look at **Figure 3.40A**, which compares the computed elevation-angle response for two half-wave dipoles at 14 MHz. One is oriented horizontally over ground at a height of λ/2 and the other is oriented vertically, with its center just over λ/2 high (so that the bottom end of the wire doesn't actually touch the ground). The ground is "average" in dielectric constant (13) and conductivity (0.005 S/m). At a 15° elevation angle, the horizontally polarized dipole has almost 7 dB more gain than its vertical brother. Contrast Figure 3.40A to the comparison in Figure 3.40B, where the peak gain of a vertically polarized half-wave dipole over seawater, which is virtually perfect for RF reflections, is quite comparable with

## Real-World Ground Surfaces

The material in this chapter deals with the effects of ground assuming that the ground surface around the antenna is flat. This is obviously not the case in the majority of actual installations! Accounting for the effects of non-flat ground is included in the chapter **HF Antenna System Design**, including an extensive discussion on the use of *HFTA* terrain analysis software by Dean Straw, N6BV.

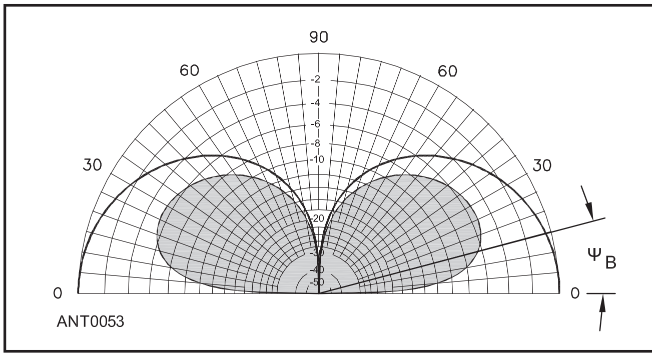



**Figure 3.39 — Vertical-plane radiation pattern for a ground-mounted half-wave vertical. The solid line is the pattern for perfect earth. The shaded pattern shows how the response is modified over average earth (k = 13, G = 0.005 S/m) at 14 MHz. ψ is the pseudo-Brewster angle (PBA), in this case 14.8°.**

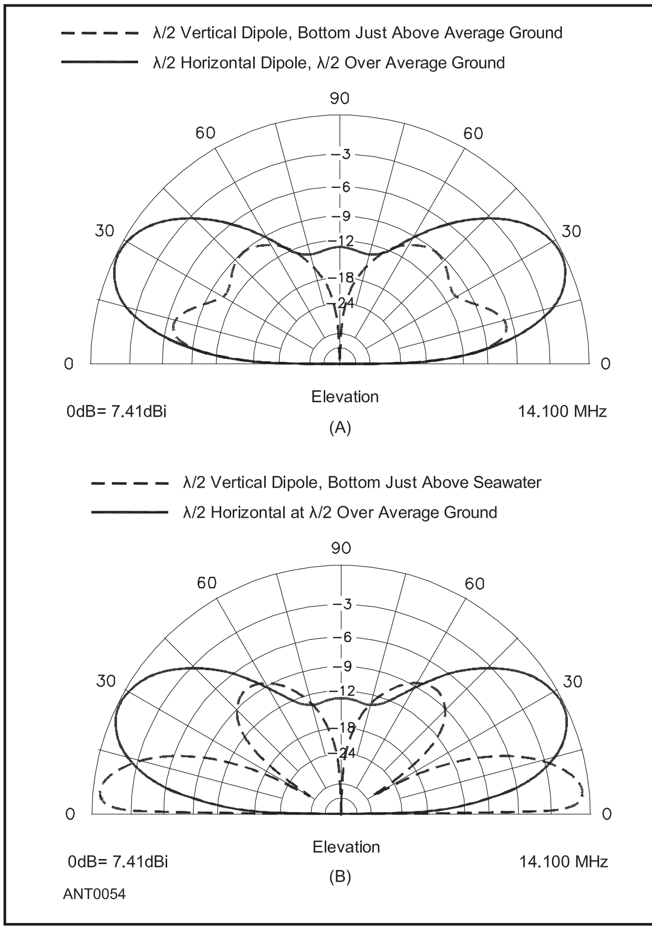



**Figure 3.40 — At A, comparison of horizontal and vertical λ/2 dipoles over average ground. Average ground has conductivity of 5 mS/m and dielectric constant of 13. Horizontal dipole is λ/2 high; vertical dipole's bottom wire is just above ground. Horizontal antenna is much less affected by far-field ground losses compared with its vertical counterpart. At B, comparison of 20 meter λ/2 vertical dipole whose bottom wire is just above seawater with λ/2-high horizontal dipole over average ground. Seawater is great for verticals!**

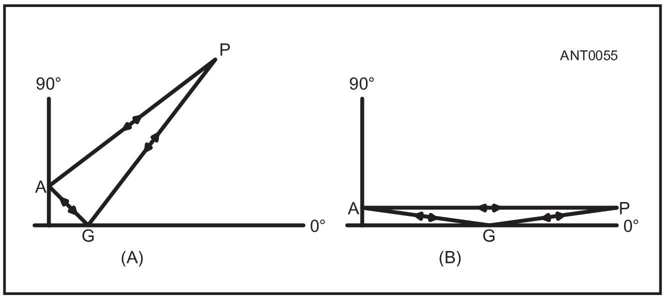



**Figure 3.41 — The direct wave and the reflected wave combine at point P to form the pattern (P is very far from the antenna). At A the two paths AP and AGP differ appreciably in length, while at B these two path lengths are nearly equal.**

the horizontal dipole's response at 15°, and exceeds the horizontally polarized antenna dramatically below 15° elevation.

To understand in a qualitative fashion why the desired low-angle radiation from a vertical is not delivered when the ground isn't "perfect," examine **Figure 3.41A**. Radiation from each antenna segment reaches a point P in space by two paths; one directly from the antenna, path AP, and the other by reflection from the earth, path AGP. (Note that P is so far away that the slight difference in angles is insignificant — for practical purposes the waves are parallel to each other at point P.)

If the earth were a perfectly conducting surface, there would be no phase shift of the vertically polarized wave upon reflection at point G. The two waves would add together with some phase difference because of the different path lengths. This difference in path lengths of the two waves is why the free-space radiation pattern differs from the pattern of the same antenna over ground.

Now consider a point P that is close to the horizon, as in Figure 3.41B. The path lengths AP and AGP are almost the same, so the magnitudes of the two waves add together, producing a maximum at zero angle of radiation. The arrows on the waves point both ways since the process works similarly for transmitting and receiving.

With real earth, however, the reflected wave from a vertically polarized antenna undergoes a change in both *amplitude* and *phase* in the reflection process. Indeed, at a low-enough elevation angle, the phase of the reflected wave will actually change by 180° and its magnitude will then subtract from that of the direct wave. At a zero takeoff angle, it will be almost equal in amplitude, but 180° out of phase with the direct wave.

Note that this is very similar to what happens with horizontally polarized reflected and direct waves at low elevation angles. Virtually complete cancellation will result in a deep null, inhibiting any radiation or reception at 0°. For real-world soils, the vertical loses the theoretical advantage it has at low elevation angles over a horizontal antenna, as Figure 3.40A so clearly shows.

The degree that a vertical works better than a horizontal antenna at low elevation angles is largely dependent on the characteristics of the ground around the vertical, as we'll next examine.

### 3.3.3 THE PSEUDO-BREWSTER ANGLE (PBA) AND THE VERTICAL ANTENNA

Much of the material presented here regarding pseudo-Brewster angle was prepared by Charles J. Michaels, W7XC (SK), and first appeared in July 1987 *QST*, with additional information in *The ARRL Antenna Compendium, Vol 3*.[12]

Most fishermen have noticed that when the sun is low, its light is reflected from the water's surface as glare, obscuring the underwater view. When the sun is high, however, the sunlight penetrates the water and it is possible to see objects below the surface of the water. The angle at which this transition takes place is known as the *Brewster angle*, named for the Scottish physicist, Sir David Brewster (1781-1868).

A similar situation exists in the case of vertically polarized antennas; the RF energy behaves as the sunlight in the optical system, and the earth under the antenna acts as the water. The *pseudo-Brewster angle* (PBA) is the angle at which the reflected wave is 90° out of phase with respect to the direct wave. "Pseudo" is used here because the RF effect is similar to the optical effect from which the term gets its name. Below this angle, the reflected wave is between 90° and 180° out of phase with the direct wave, so some degree of cancellation takes place. The largest amount of cancellation occurs near 0°, and steadily less cancellation occurs as the PBA is approached from below.

The factors that determine the PBA for a particular location *are not related to the antenna itself, but to the ground around it*. The first of these factors is earth conductivity, $\sigma$, which is a measure of the ability of the soil to conduct electricity. Conductivity, measured in siemens/meter is the inverse of resistivity. The second factor is the dielectric constant, $\varepsilon_r$, which is a unit-less quantity that corresponds to the capacitive effect of the earth. (See the section "Electrical Characteristics of Ground" earlier in this chapter for a discussion of both $\sigma$ and $\varepsilon$.) For both of these quantities, the higher the number, the better the ground (for vertical antenna

**Table 3.5**
**Pseudo-Brewster Angle Variation with Frequency, Dielectric Constant, and Conductivity**

| *Frequency (MHz)* | *Dielectric Constant* | *Conductivity (S/m)* | *PBA (degrees)* |
|---|---|---|---|
| 7 | 20 | 0.0303 | 6.4 |
| | 13 | 0.005 | 13.3 |
| | 13 | 0.002 | 15.0 |
| | 5 | 0.001 | 23.2 |
| | 3 | 0.001 | 27.8 |
| 14 | 20 | 0.0303 | 8.6 |
| | 13 | 0.005 | 14.8 |
| | 13 | 0.002 | 15.4 |
| | 5 | 0.001 | 23.8 |
| | 3 | 0.001 | 29.5 |
| 21 | 20 | 0.0303 | 10.0 |
| | 13 | 0.005 | 15.2 |
| | 13 | 0.002 | 15.4 |
| | 5 | 0.001 | 24.0 |
| | 3 | 0.001 | 29.8 |

purposes). The third factor determining the PBA for a given location is the frequency of operation. The PBA increases with increasing frequency, all other conditions being equal.

As the frequency is increased, the role of the dielectric constant in determining the PBA becomes more significant. **Table 3.5** shows how the PBA varies with changes in ground conductivity, dielectric constant and frequency. The table shows trends in PBA dependency on ground constants and frequency.

At angles below the PBA, the reflected vertically polarized wave subtracts from the direct wave, causing the radiation intensity to fall off rapidly. Similarly, above the PBA, the reflected wave adds to the direct wave, and the radiated pattern approaches the perfect-earth pattern. **Figure 3.42** shows the PBA, usually labeled $\psi_B$.

When plotting vertical-antenna radiation patterns over real earth, the reflected wave from an antenna segment is multiplied by a factor called the *vertical reflection coefficient*, and the product is then added vectorially to the direct wave to get the resultant. The reflection coefficient consists of an attenuation factor, A, and a phase angle, $\phi$, and is usually expressed as $A\angle\phi$. ($\phi$ is always a negative angle, because the earth acts as a lossy capacitor in this situation.) The following equation can be used to calculate the reflection coefficient for vertically polarized waves, for earth of given conductivity and dielectric constant at any frequency and elevation angle (also called the wave angle in many texts).

$$A_{Vert}\angle\phi = \frac{k'\sin\psi - \sqrt{k' - \cos^2\psi}}{k'\sin\psi + \sqrt{k' - \cos^2\psi}} \tag{9}$$

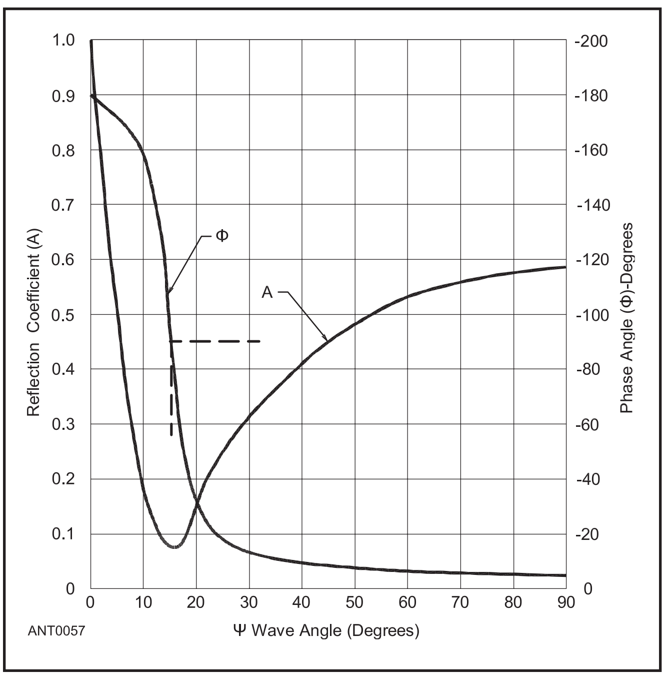



**Figure 3.42 — Reflection coefficient for vertically polarized waves. A and $\phi$ are magnitude and angle for wave angles $\psi$. This case is for average earth, (k = 13, G = 0.005 S/m), at 21 MHz.**

where

$A_{Vert}\angle\phi$ = vertical reflection coefficient

$\psi$ = elevation angle

$$k' = k - j\left|\frac{1.8\times10^4 \times G}{f}\right|$$

k = dielectric constant of earth (k for air = 1)

G = conductivity of earth in S/m

f = frequency in MHz

$j$ = complex operator ($\sqrt{-1}$)

(Reminder: k and $\varepsilon_r$ refer to the same quantity and are interchangeable, as are $\sigma$ and G. Both are in common use in the technical literature.)

Solving this equation for several points illustrates the effect of earth on vertically polarized signals at a particular location for a given frequency range. **Figure 3.42** shows the reflection coefficient as a function of elevation angle at 21 MHz over average earth (G = 0.005 S/m, and k = 13). Note that as the phase curve, $\psi$, passes through 90°, the attenuation curve (A) passes through a minimum at the same wave angle $\psi$. This is the PBA. At this angle, the reflected wave is not only at a phase angle of 90° with respect to the direct wave, but is so low in amplitude that it does not aid the direct wave by a significant amount. In the case illustrated in Figure 3.42 this elevation angle is about 15°.

### Variations in PBA with Earth Quality

From Eq 9, it is quite a task to search for either the 90° phase point or the attenuation curve minimum for a wide variety of earth conditions. Instead, the PBA can be calculated directly from the following equation.

$$\psi_B = \arcsin\sqrt{\frac{k-1+\sqrt{\left(x^2+k^2\right)^2(k-1)^2 + x^2\left[\left(x^2+k^2\right)^2 - 1\right]}}{\left(x^2+k^2\right)^2 - 1}} \tag{10}$$

where k, G and f are as defined for Eq 9, and

$$x = \frac{1.8\times10^4 \times G}{f}$$

**Figure 3.43** shows curves calculated using Eq 10 for several different earth conditions, at frequencies between 1.8 and 30 MHz. As expected, poorer earths yield higher PBAs. Unfortunately, at the higher frequencies (where low-angle radiation is most important for DX work), the PBAs are highest. The PBA is the same for both transmitting and receiving.

### Relating PBA to Location and Frequency

Table 3.2 presented earlier in this chapter lists the physical descriptions of various kinds of earth with their respective conductivities and dielectric constants, as mentioned earlier. Note that in general, the dielectric constants and conductivities are higher for better earths. This enables the labeling of the earth characteristics as extremely poor, very poor, poor,

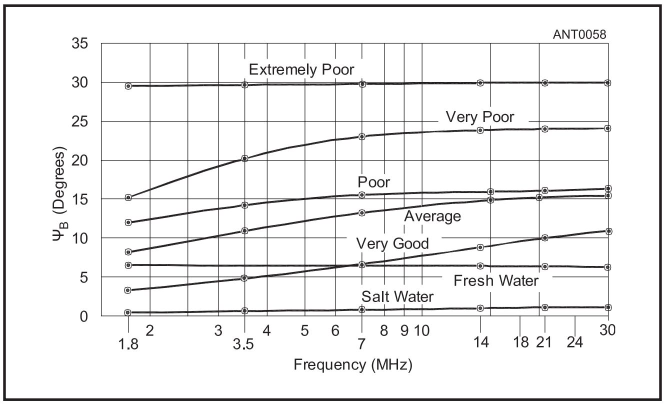



**Figure 3.43 — Pseudo-Brewster angle ($\psi$) for various qualities of earth over the 1.8 to 30-MHz frequency range. Note that the frequency scale is logarithmic. The constants used for each curve are given in Table 3.5.**

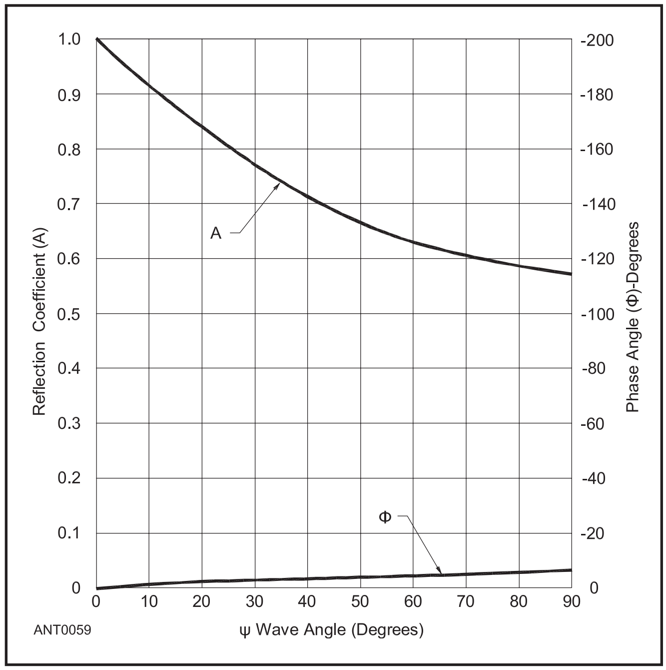



**Figure 3.44 — Reflection coefficient for horizontally polarized waves (magnitude A at angle $\phi$), at 21 MHz over average earth (k = 13, G = 0.005 S/m).**

average, very good, and so on, without the complications that would result from treating the two parameters independently.

Fresh water and salt water are special cases; in spite of high resistivity, the fresh-water PBA is 6.4°, and is nearly independent of frequency below 30 MHz. Salt water, because of its extremely high conductivity, has a PBA that never exceeds 1° in this frequency range. The extremely low conductivity listed for cities (the last case) in Table 3.5 results more from the clutter of surrounding buildings and other obstructions than any actual earth characteristic. The PBA at any location can be found for a given frequency from the curves in Figure 3.43. (The map presented earlier as Figure 3.2 shows approximate conductivity values for different areas in the continental United States.)

### 3.3.4 FLAT-GROUND REFLECTIONS AND HORIZONTALLY POLARIZED WAVES

The situation for horizontal antennas is different from that of verticals. **Figure 3.44** shows the reflection coefficient for horizontally polarized waves over average earth at 21 MHz. Note that in this case, the phase-angle departure from 0° never gets very large, and the attenuation factor that causes the most loss for high-angle signals approaches unity for low angles. Attenuation increases with progressively poorer earth types.

In calculating the broadside radiation pattern of a horizontal λ/2 dipole, the perfect-earth image current, equal to the true antenna current but 180° out of phase with it) is multiplied by the horizontal reflection coefficient given by Eq 11 below. The product is then added vectorially to the direct wave to get the resultant at that elevation angle. The reflection coefficient for horizontally polarized waves can be calculated using the following equation.

$$A_{Horiz}\angle\phi = \frac{\sqrt{k' - \cos^2\psi} - \sin\psi}{\sqrt{k' - \cos^2\psi} + \sin\psi} \qquad (11)$$

where

$A_{Horiz}\angle\phi$ = horizontal reflection coefficient
$\psi$ = elevation angle

$$k' = k - j\left|\frac{1.8 \times 10^4 \times G}{f}\right|$$

k = dielectric constant of earth
G = conductivity of earth in S/m
f = frequency in MHz
*j* = complex operator ($\sqrt{-1}$)

For a horizontal antenna near the earth, the resultant pattern is a modification of the free-space pattern of the antenna. **Figure 3.45** shows how this modification takes place for a horizontal λ/2 antenna over a perfectly conducting flat surface. The patterns at the left show the relative radiation when one views the antenna from the side; those at the right show the radiation pattern looking at the end of the antenna. Changing the height above ground from λ/4 to λ/2 makes a significant difference in the high-angle radiation, moving the main lobe down lower.

Note that for an antenna height of λ/2 (Figure 3.45, bottom), the out-of-phase reflection from a perfectly conducting surface creates a null in the pattern at the zenith (90° elevation angle). Over real earth, however, a *filling in* of this null occurs because of ground losses that prevent perfect reflection of high-angle radiation.

At a 0° elevation angle, horizontally polarized antennas also demonstrate a null, because out-of-phase reflection cancels the direct wave. As the elevation angle departs from 0°, however, there is a slight filling-in effect so that over other-than-perfect earth, radiation at lower angles is enhanced compared to a vertical. A horizontal antenna will often outperform a vertical for low-angle DX work, particularly over

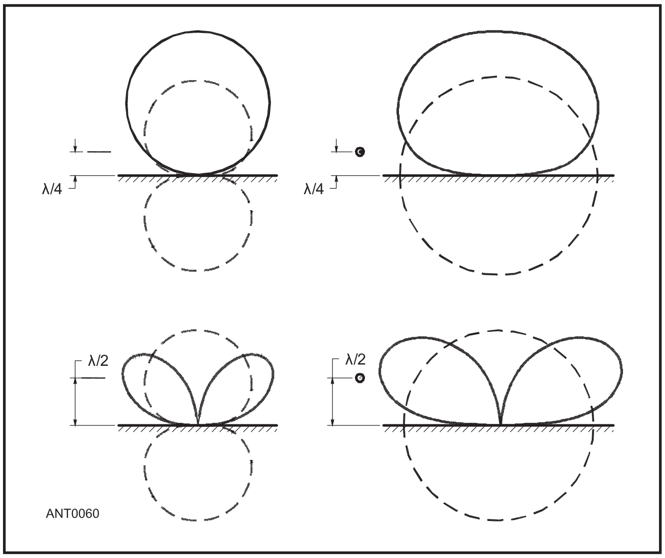



**Figure 3.45 — Effect of the ground on the radiation from a horizontal half-wave dipole antenna, for heights of one-fourth and one-half wavelength. Broken lines show what the pattern would be if there were no reflection from the ground (free space).**

lossy types of earth at the higher frequencies.

Reflection coefficients for vertically and horizontally polarized radiation differ considerably at most angles above ground, as can be seen by comparison of Figures 3.42 and 3.44. (Both sets of curves were plotted for the same ground constants and at the same frequency, so they may be compared directly.) This is because, as mentioned earlier, the image of a horizontally polarized antenna is out-of-phase with the antenna itself, and the image of a vertical antenna is in-phase with the actual radiator.

The result is that the phase shifts and reflection magnitudes vary greatly at different angles for horizontal and vertical polarization. The magnitude of the reflection coefficient for vertically polarized waves is greatest (near unity) at very low angles, and the phase angle is close to 180°. As mentioned earlier, this cancels nearly all radiation at very low angles. For the same range of angles, the magnitude of the reflection coefficient for horizontally polarized waves is also near unity, but the phase angle is near 0° for the specific conditions shown in Figures 3.42 and 3.44. This causes reinforcement of low-angle horizontally polarized waves. At some relatively high angle, the reflection coefficients for horizontally and vertically polarized waves are equal in magnitude and phase. At this angle (approximately 81° for the example case), the effect of ground reflection on vertically and horizontally polarized signals will be the same.

## 3.3.5 DIRECTIVE PATTERNS OVER REAL GROUND

As explained in the **Antenna Fundamentals** chapter, because antenna radiation patterns are three-dimensional, it is helpful in understanding their operation to use a form of representation showing the elevation-plane directional characteristic for different heights. It is possible to show selected elevation-plane patterns oriented in various directions with respect to the antenna axis. In the case of the horizontal half-wave dipole, a plane running in a direction along the axis and another broadside to the antenna will give a good deal of information.

The effect of reflection from the ground can be expressed as a separate *pattern factor*, given in decibels. For any given elevation angle, adding this factor algebraically to the value for that angle from the free-space pattern for that antenna gives the resultant radiation value at that angle. The limiting conditions are those represented by the direct ray and the reflected ray being exactly in-phase and exactly out-of-phase, when both (assuming there are no ground losses) have equal amplitudes. Thus, the resultant field strength at a distant point may be either 6 dB greater than the free-space pattern (twice the field strength), or zero, in the limiting cases.

### Horizontally Polarized Antennas

The way in which pattern factors vary with height for horizontal antennas over flat earth is shown graphically in the plots of **Figure 3.46**. The solid-line plots are based on perfectly conducting ground, while the shaded plots are based on typical real-earth conditions. These patterns apply to horizontal antennas of any length. While these graphs are, in fact, radiation patterns of horizontal single-wire antennas (dipoles) as viewed from the axis of the wire, it must be remembered that the plots merely represent pattern factors.

**Figure 3.47** shows vertical-plane radiation patterns in the directions off the ends of a horizontal half-wave dipole for various antenna heights. These patterns are scaled so they may be compared directly to those for the appropriate heights in Figure 3.46. Note that the perfect-earth patterns in Figures 3.46A and 3.46B are the same as those in the upper part of Figure 3.45. Note also that the perfect-earth patterns of Figures 3.47B and 3.46D are the same as those in the lower section of Figure 3.45. The reduction in field strength off the ends of the wire at the lower angles, as compared with the broadside field strength, is quite apparent. It is also clear from Figure 3.47 that, at some heights, the high-angle radiation off the ends is nearly as great as the broadside radiation, making the antenna essentially an omnidirectional radiator.

In vertical planes making some intermediate angle between 0° and 90° with the wire axis, the pattern will have a shape intermediate between the broadside and end-on patterns. By visualizing a smooth transition from the end-on pattern to the broadside pattern as the horizontal angle is varied from 0° to 90°, a fairly good mental picture of the actual solid pattern may be formed. An example is shown in **Figure 3.48**. At A, the elevation-plane pattern of a half-wave dipole at a height of λ/2 is shown through a plane 45° away from the favored direction of the antenna. At B and C, the pattern of the same antenna is shown at heights of 3λ/4 and 1λ (through the same 45° off-axis plane). These patterns are scaled so they may be compared directly with the broadside and end-on patterns for the same antenna

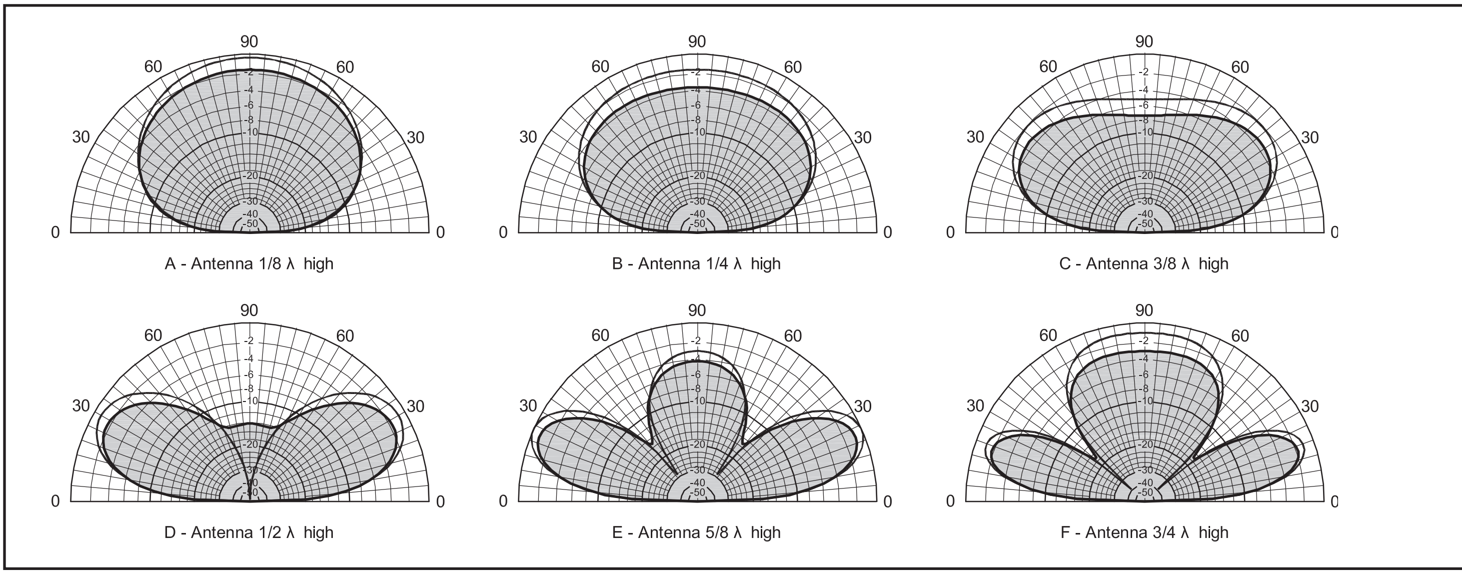



**Figure 3.46 — Reflection factors for horizontal dipole antennas at various heights above flat ground. The solid-line curves are the perfect-earth patterns (broadside to the antenna wire); the shaded curves represent the effects of average earth (k = 13, G = 0.005 S/m) at 14 MHz. Add 7 dB to values shown for absolute gain in dBd referenced to dipole in free space, or 9.15 dB for gain in dBi. For example, peak gain over perfect earth at ⅝ λ height is 7 dBd (or 9.15 dBi) at 25° elevation.**

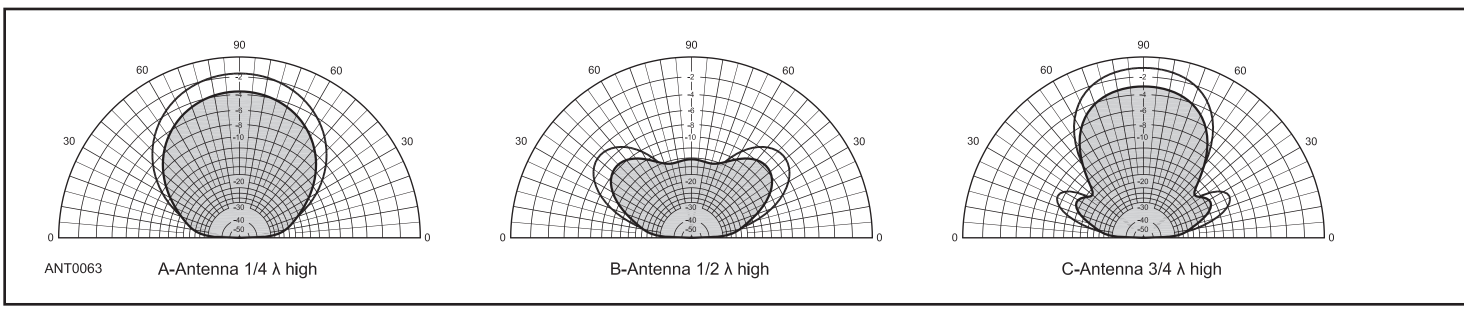



**Figure 3.47 — Vertical-plane radiation patterns of horizontal half-wave dipole antennas off the ends of the antenna wire. The solid-line curves are the flat, perfect-earth patterns, and the shaded curves represent the effects of average flat earth (k = 13, G = 0.005 S/m) at 14 MHz. The 0-dB reference in each plot corresponds to the peak of the main lobe in the favored direction of the antenna (the maximum gain). Add 7 dB to values shown for absolute gain in dBd referenced to dipole in free space, or 9.15 dB for gain in dBi.**

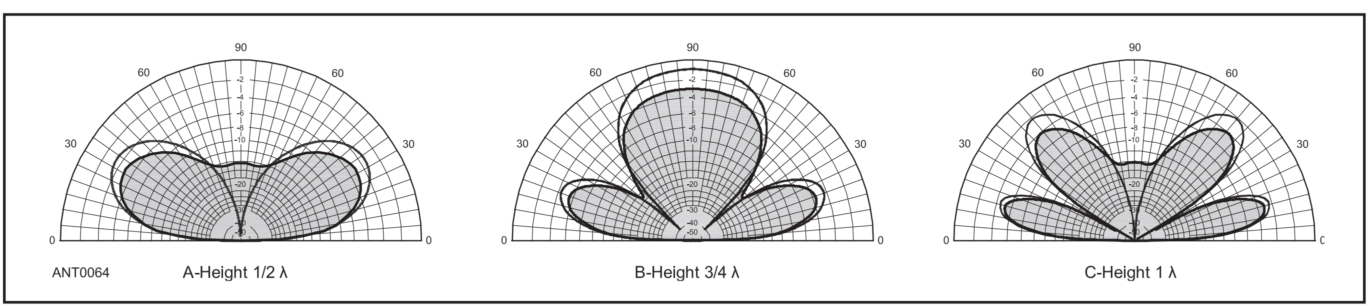
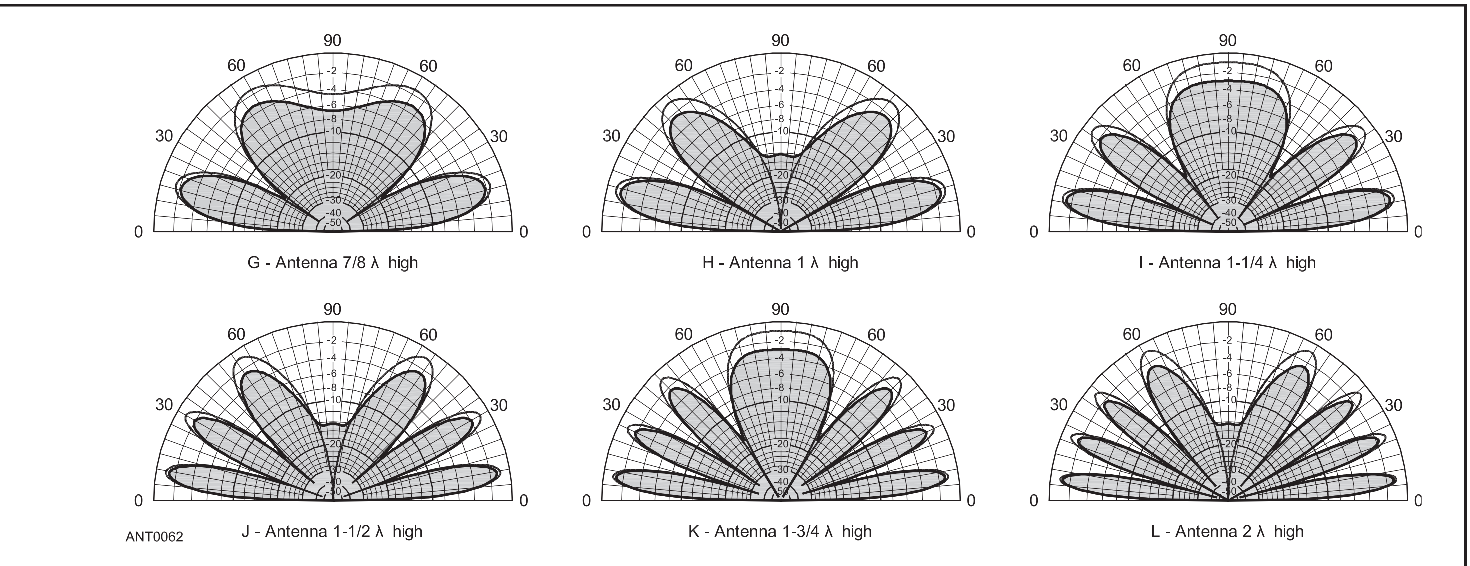
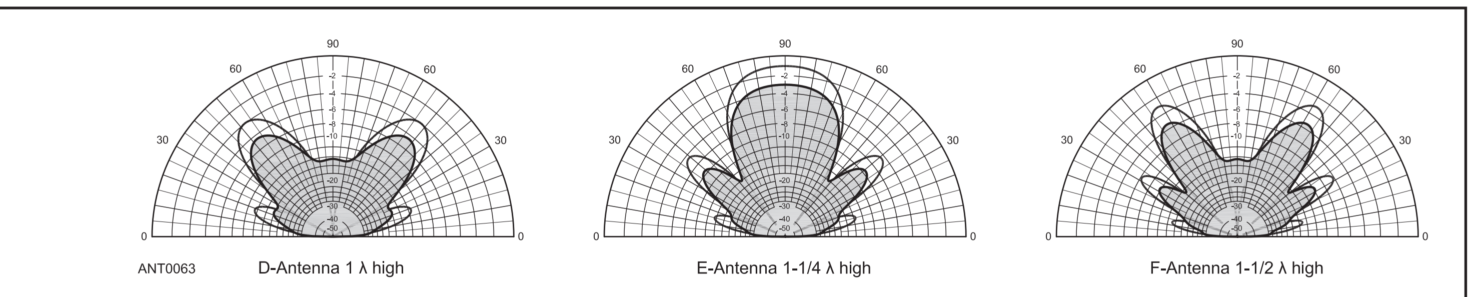



**Figure 3.48 — Vertical-plane radiation patterns of half-wave horizontal dipole antennas at 45° from the antenna wire over flat ground. The solid-line and shaded curves represent the same conditions as in Figures 3.46 and 3.47. These patterns are scaled so they may be compared directly with those of Figures 3.46 and 3.47.**




(at the appropriate heights) in Figures 3.47 and 3.48.

The curves presented in **Figure 3.49** are useful for determining heights of horizontal antennas that give either maximum or minimum reinforcement at any desired wave angle. For instance, if you want to place an antenna at a height so that it will have a null at 30°, the antenna should be placed where a broken line crosses the 30° line on the horizontal scale. There are two heights (up to 2 λ) that will yield this null angle: 1 λ and 2 λ.

As a second example, you may want to have the ground reflection give maximum reinforcement of the direct ray from a horizontal antenna at a 20° elevation angle. The antenna height should be 0.75 λ. The same height will give a null at 42° and a second lobe at 90°.

Figure 3.49 is also useful for visualizing the vertical

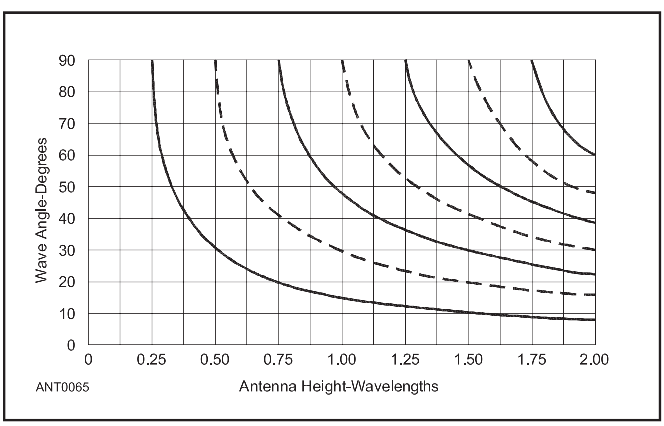



**Figure 3.49 — Angles at which nulls and maxima (factor = 6 dB) in the ground-reflection factor appear for antenna heights up to two wavelengths over flat ground. The solid lines are maxima, dashed lines nulls, for all horizontal antennas. See text for examples. Values may also be determined from the trigonometric relationship θ = arc sin (A/4h), where θ is the wave angle and h is the antenna height in wavelengths. For the first maximum, A has a value of 1; for the first null A has a value of 2, for the second maximum 3, for the second null 4, and so on.**

pattern of a horizontal antenna. For example, if an antenna is erected at 1.25 λ, it will have major lobes (solid-line crossings) at 12° and 37°, as well as at 90° (the zenith). The nulls in this pattern (dashed-line crossings) will appear at 24° and 53°.

The Y-axis in Figure 3.49 plots the wave angle versus the height in wavelength above flat ground on the X-axis. Figure 3.49 doesn't show the elevation angles required for actual communications to various target geographic locations of interest. The **Radio Wave Propagation** chapter and the CD-ROM in the back of this book give details about the range of angles required for target locations around the world. It is very useful to overlay plots of these angles together with the elevation pattern for horizontally polarized antennas at various heights above flat ground. This will be demonstrated in detail later in the **HF Antenna System Design** chapter.

### Vertically Polarized Antennas

In the case of a vertical λ/2 dipole or a ground-plane antenna, the horizontal directional pattern is simply a circle at any elevation angle (although the actual field strength will vary, at the different elevation angles, with the height above ground). Hence, one vertical pattern is sufficient to give complete information (for a given antenna height) about the antenna in any direction with respect to the wire. A series of such patterns for various heights is given in **Figure 3.50**. Rotating the plane pattern about the zenith axis of the graph forms the three-dimensional radiation pattern in each case.

The solid-line curves represent the radiation patterns of the λ/2 vertical dipole at different feed point heights over perfectly conducting ground. The shaded curves in Figure 3.50 show the patterns produced by the same antennas at the same heights over average ground (G = 0.005 S/m, k = 13) at 14 MHz. The PBA in this case is 14.8°.

In short, far-field losses for vertically polarized antennas are highly dependent on the conductivity and dielectric constant of the earth around the antenna, extending far beyond the ends of any radials used to complete the ground return for the near field. Putting more radials out around the antenna may well decrease ground-return losses in the reactive near field for a vertical monopole, but will not increase radiation at low elevation launch angles in the far field, unless the radials can extend perhaps 100 wavelengths in all directions! Aside from moving to the fabled "salt water swamp on a high hill," there is very little that someone can do to change the character of the ground that affects the far-field pattern of a real vertical. Classical texts on verticals often show elevation patterns computed over an "infinitely wide, infinitely conducting ground plane." Real ground, with finite conductivity and less than perfect dielectric constant, can severely curtail the low-angle radiation at which verticals are supposed to excel.

While real verticals over real ground are not a sure-fire method to achieve low-angle radiation, cost versus performance and ease of installation are still attributes that can highly recommend verticals to knowledgeable builders. Practical installations for 160 and 80 meters rarely allow amateurs to put up horizontal antenna high enough to radiate effectively at low elevation angles. After all, a half-wave on 1.8 MHz is 273 feet high, and even at such a lofty height the peak radiation for a horizontal antenna would be at a 30° elevation angle, which is higher than desired for long-distance communication. A simple ground-mounted vertical with a reasonable radial field will almost always give much better results in this case.

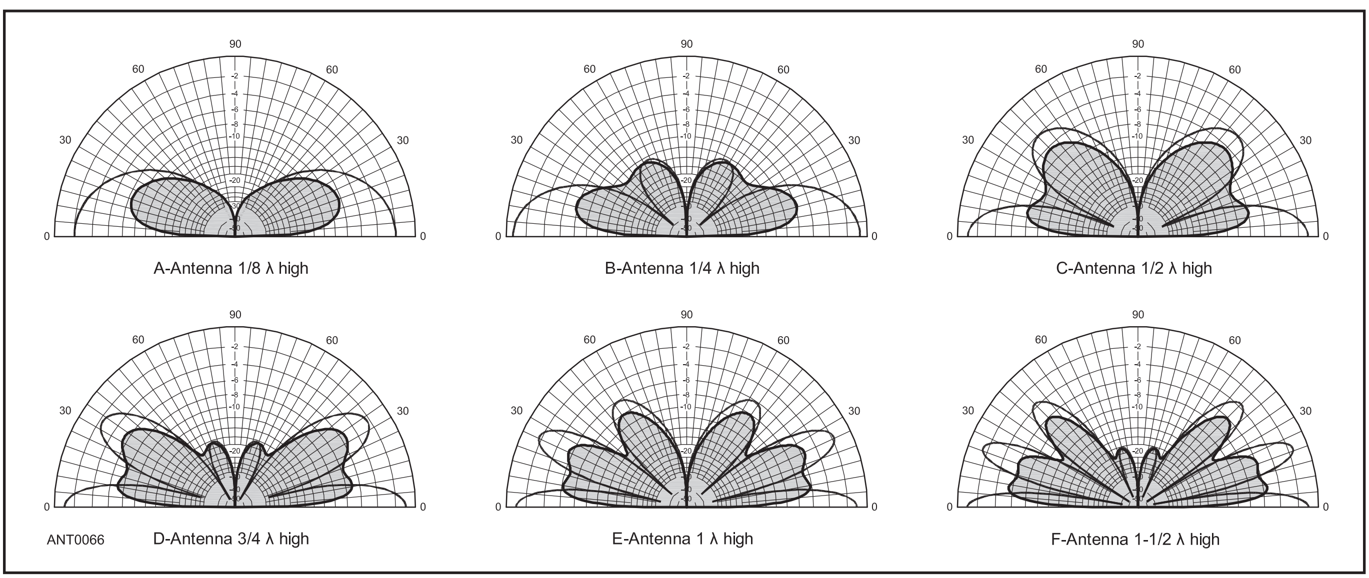



**Figure 3.50 — Vertical-plane radiation patterns of a ground-plane antenna above flat ground. The height is that of the ground plane, which consists of four radials in a horizontal plane. Solid lines are perfect-earth patterns; shaded curves show the effects of real earth. The patterns are scaled — that is, they may be directly compared to the solid-line ones for comparison of losses at any wave angle. These patterns were calculated for average ground (k = 13, G = 0.005 S/m) at 14 MHz. The PBA for these conditions is 14.8°. Add 6 dB to values shown for absolute gain in dBd over dipole in free space.**

# 3.4 GROUND PARAMETERS FOR ANTENNA ANALYSIS

*The first part of this section is taken from an article in The ARRL Antenna Compendium, Vol 5 by R. P. Haviland, W4MB. The sections on direct and indirect soil measurements have been updated by R. Severns, N6LF.*

In the past, amateurs paid very little attention to the characteristics of the earth (ground) associated with their antennas. There are two reasons for this. First, these characteristics are not easy to measure — even with the best equipment, care is needed. Second, most hams have to put up with what they have! Further, the ground is not a dominant factor for horizontally polarized antennas such as a tri-band Yagi at 40 feet or higher, or a 2 meter vertical at roof height. For vertically polarized antennas, however, the soil characteristics are very important for the design of ground systems, predictions of efficiency, and elevation radiation patterns. Ground data is useful for antennas mounted at low heights generally, and for such specialized ones as Beverage receiving antennas. The performance of such antennas changes significantly as the ground changes.

### 3.4.1 IMPORTANCE OF GROUND CONDITIONS

To see why ground conditions can be important, we can look at some values for ground wave attenuation with distance. At 10 MHz, *CCIR Recommendation 368* (see Bibliography), gives the distance at which the signal is calculated to drop 10 dB below its free-space level as:

| *Conductivity (mS/meter)* | *Distance for 10 dB Drop (km)* |
|---|---|
| 5000 | 100 |
| 30 | 15 |
| 3 | 0.3 |

The high-conductivity condition is for seawater. Inter-island work in the Caribbean on 40 and 80 meters is easy, whereas 40 meter ground-wave contact is difficult for much of the USA, because of much lower ground conductivity. On the other hand, the Beverage works because of poor ground conductivity.

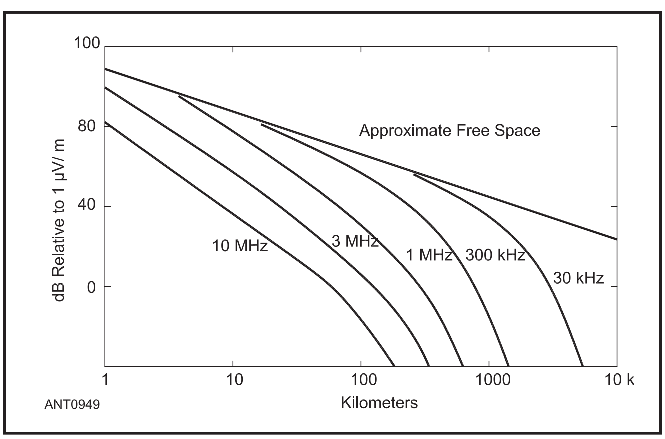



**Figure 3.51 — Variation of field strength with distance. Typical field strengths for several frequencies are shown. This is from CCIR data for fairly poor soil, with dielectric constant of 4 and conductivity of 3 mS/m. The curves for good soil are closer to the free-space line, and those for sea water are much closer to the free-space line.**

**Figure 3.51** shows a typical set of expected propagation curves for vertically polarized signals over a range of frequencies. This data is also from *CCIR Recommendation 368* for relatively poor ground, with a dielectric constant of 4 and a conductivity of 3 mS/m (one milliSiemens/meter is 0.001 mho/meter). The same data is available in the *Radio Propagation Handbook*. There are equivalent FCC curves, found in the book *Reference Data for Radio Engineers*, but only the ones near 160 meters are useful. In Florida the author has difficulty hearing stations across town on ground wave, an indication of the poor soil conditions — reflected sky-wave signals are often stronger.

### 3.4.2 SECURING GROUND DATA

There are two basic ways to approach this matter of ground data. One is to use generic ground data typical to the area. The second is to make direct measurements, which, with the introduction of moderately priced vector network analyzers (VNA), has become much easier. Some effort is still required however! For most amateurs the easiest approach a combination of these — make some simple measurements using the low frequency conductivity procedure outlined below and then combine this with the generic data to make a better estimate. For 220 meter and 630 meters the LF conductivity is adequate. For 160 meters and higher in frequency a more sophisticated measurement yielding both conductivity and permittivity can be helpful if an impedance measuring instrument is available. The simple approach of only measuring the LF conductivity may not be highly accurate for HF antennas but will still be much better than simply inserting some arbitrary preset values into an analysis program. Having a good set of values to plug into an analysis can be of great help in evaluating the true worth of a new antenna project, especially if the antenna is horizontally polarized.

#### Generic Data

In connection with its licensing procedure for broadcast stations, the FCC has published generic data for the entire country. This map was presented earlier as Figure 3.2, showing the "estimated effective ground conductivity in the United States." A range of 30:1 is shown, from 1 to 30 mS/m. An equivalent chart for Canada has been prepared, originally by DOT, now DOC.

Of course, some judgment is needed when trying to use this data for your location. Broadcast stations are likely to be in open areas, so the data should not be assumed to apply to the center of a city. And a low site near the sea is likely to have better conductivity than the generic chart for, say, the coast of Oregon. Other than such factors, this chart gives a good first value and a useful cross-check if some other method is used.

Still another FCC-induced data source is the license application of your local broadcast station. This includes calculated and measured coverage data. This may include specific ground data, or comparison of the coverage curves with the CCIR or FCC data to give the estimated ground conductivity. Another set of curves for ground conditions are those prepared by SRI (see References). These give the conductivity and dielectric constant versus frequency for typical terrain conditions. These are reproduced as **Figures 3.52** and

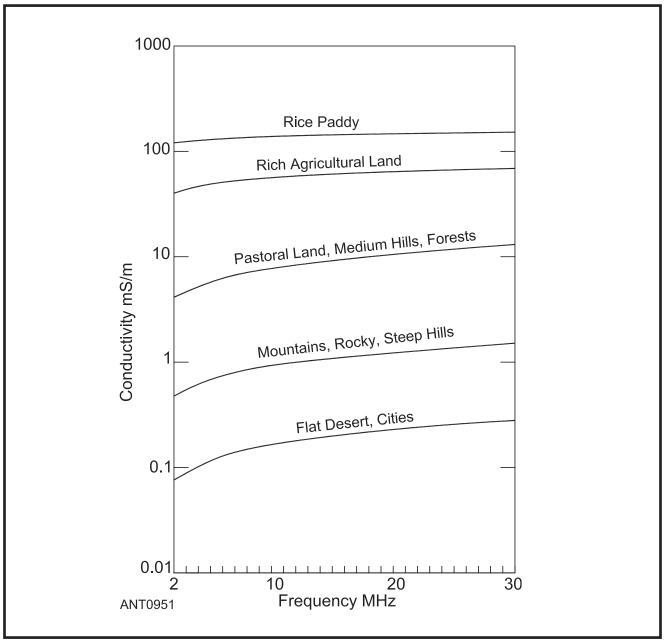



**Figure 3.52 — Typical terrain conductivities versus frequency for 5 types of soils. This was measured by SRI. Units are mS/m. Conductivity of seawater is usually taken as 5000 mS/m. Conductivity of fresh water depends on the impurities present, and may be very low. To extrapolate conductivity values (for 500 to 1500 kHz) shown in Figure 3.2 for a particular geographic area to a different frequency, move from the conductivity at the left edge of this figure to the desired frequency. For example, in rocky New Hampshire, with a conductivity of 1 mS/m at BC frequencies, the effective conductivity at 14 MHz would be approximately 4 mS/m.**

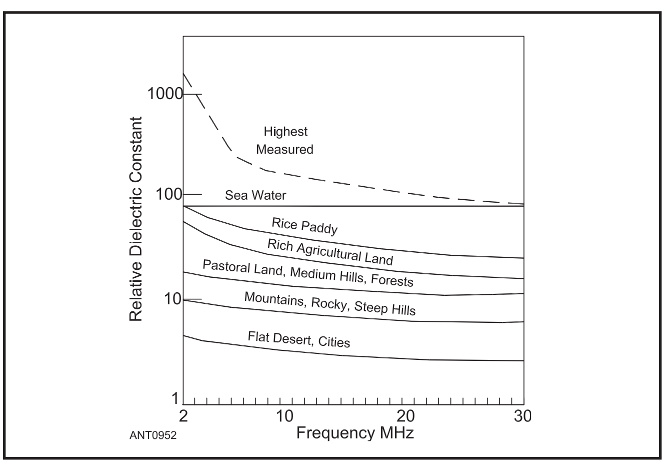



**Figure 3.53 — Typical terrain relative dielectric constant for the 5 soil types of Figure 3.52, plus sea water. The dashed curve shows the highest measured values reported, and usually indicates mineralization.**

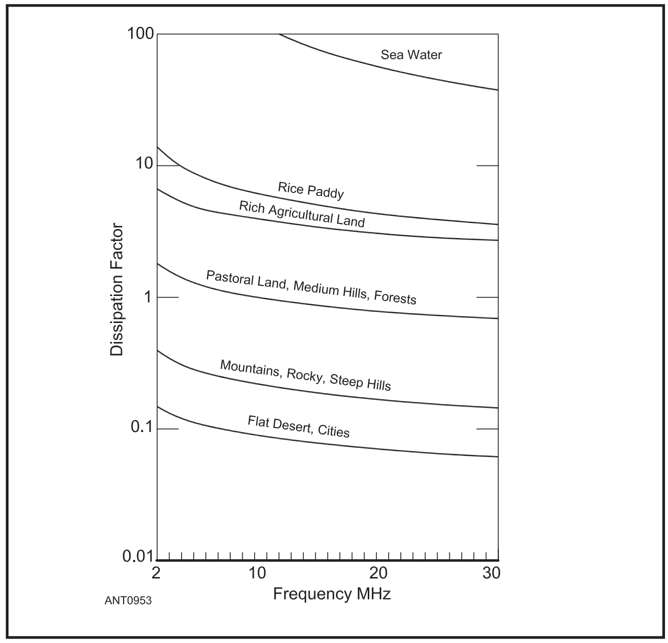



**Figure 3.54 — Typical values of dissipation factor. The soil behaves as a leaky dielectric. These curves showing the dimensionless dissipation factor versus frequency for various types of soils and for sea water. The dissipation factor is inversely related to soil conductivity. Among other things, a high dissipation factor indicates that a signal penetrating the soil or water will decrease in strength rapidly with depth.**

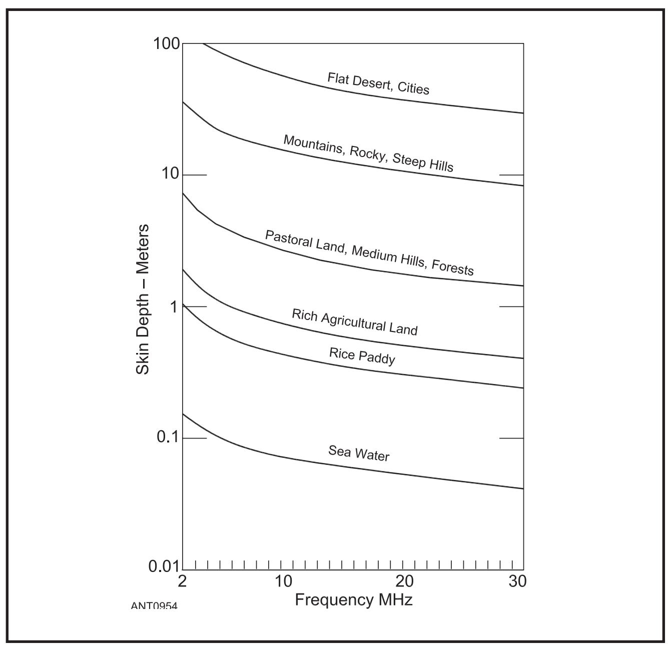



**Figure 3.55 — Typical values of skin depth. The skin depth is the depth at which a signal will have decreased to 1/e of its value at the surface (to about 30%). The effective height above ground is essentially the same as the physical height for sea water, but may be much greater for the desert. For practical antennas, this may increase low-angle radiation, but at the same time will increase ground losses.**

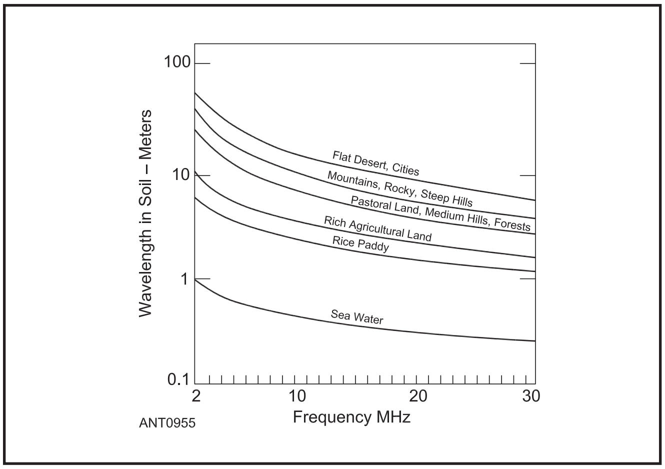



**Figure 3.56 — Typical values of wavelength in soil. Because of its dielectric constant, the wavelength in soils and water will be shorter than that for a wave traveling in air. This can be important, since in a Method of Moment the accuracy is affected by the number of analysis segments per wavelength. Depending on the program being used, adjust the number of segments for antennas wholly or partly in the earth, for ground rods, and for antennas very close to earth.**

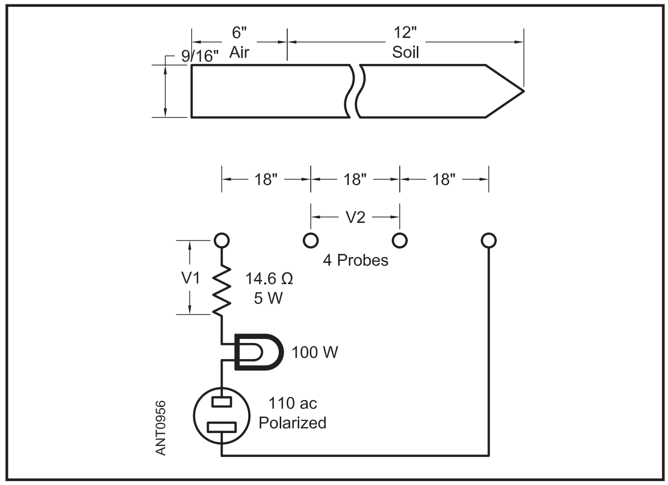



**Figure 3.57 — Low-frequency conductivity measurement system. A 60-Hz measuring system devised by W2FNQ and used by W2FMI. The basic system is widely used in geophysics. Use care to be certain that the plug connection is correct. A better system would use a lower voltage and an isolation transformer. Measure the value of $V_2$ with no power applied — there may be stray ground currents present, especially if there is a power station or an electric railway close.**

**3.53**. By inspecting your own site, you may select the curve most appropriate to your terrain. The curves are based on measurements at a number of sites across the USA, and are averages of the measured values.

**Figures 3.54** through **3.56** are data derived from these measurements. Figure 3.54 gives the ground-dissipation factor. Sea water has low loss (a high dissipation factor), while soil in the desert or in the city is very lossy, with a low dissipation factor. Figure 3.55 gives the skin depth, the distance for the signal to decease to 63% of its value at the surface. Penetration is low in high-conductivity areas and deep in low-conductivity soil. Finally, Figure 3.56 shows the wavelength in the earth. For example, at 10 meters (30 MHz), the wavelength in sea water is less than 0.3 meters. Even in the desert, the wavelength has been reduced to about 6 meters at this frequency. This is one reason why buried antennas have peculiar properties. Lacking other data, it is suggested that the values of Figure 3.52 and 3.53 be used in computer antenna modeling programs.

### Measuring Ground Conditions

M.C. Waltz, W2FNQ (SK) developed a simple technique to measure low-frequency earth conductivity, which has been used by Jerry Sevick, W2FMI (SK). The test setup is drawn in **Figure 3.57**, and uses a very old technique of 4-terminal resistivity measurements. For probes of 9⁄16-inch diameter (a standard grounding rod size), spaced 18 inches and penetrating 12 inches into the earth, the conductivity is:

$$G = 21\ V_1/V_2 \text{ mS/m} \qquad (12)$$

The voltages are conveniently measured by a digital voltmeter, to an accuracy of about 2%. In soil suitable for farming, the probes can be copper or aluminum. The strength of iron or Copperweld may be needed in hard soils. A piece of 2 × 6 inch or 4 × 4 inch lumber with guide holes drilled through it will help maintain proper spacing and vertical alignment of the probes, greatly speeding up the measurement process. Use care when measuring — there is a potential shock hazard! An isolating transformer with a 24 V secondary should be used instead of 120 V directly to reduce the danger. Ground conditions vary quite widely over even small areas. It is best to make a number of measurements around the area of the antenna, and average the measured values.

While this measurement gives only the low-frequency conductivity, it can be used to select curves in Figure 3.52 to give an estimate of the conductivity for the common ham bands. Assume that the 60 Hz value is valid at 2 MHz, and find the correct value on the left axis. Move parallel to the curves on the figure to develop the estimated curve for other soil conditions. This will give a value for conductivity which is a bit low but still very helpful.

A small additional refinement is possible. If the dielectric constant from Figure 3.53 is plotted against the conductivity from Figure 3.52 for a given frequency, a scatter plot develops, showing a trend to higher dielectric constant as conductivity increases which is mostly due to variations in moisture content. As the moisture content increases both conductivity and relative dielectric constant increase. At 14 MHz, the relation is:

$$k = \sqrt{1000 / G} \qquad (13)$$

where k is the dielectric constant and G is the measured conductivity. Using these values in *MININEC* or *NEC* calculations should give better estimates than countrywide average values.

## Direct Measurement of Ground Properties

For really good values, both the conductivity and dielectric constant should be measured at the operating frequency. This is particularly important at HF. This can be done using conducting probes inserted into the soil. Two examples of amateur-made monopole probes are shown in **Figure 3.58.**

The material for the probes can be aluminum, brass or even steel, the choice makes little difference in the measurement. The probes are inserted into the soil through a hole in a conducting sheet which can be a 36 × 36 inch galvanized mesh like that shown in **Figure 3.59**. The impedance, $Z = R + jX$, is then measured between the probe and the mesh as shown in **Figure 3.60**.

Another type of probe is the open-wire-line (OWL) technique described in George Hagn's article and Severn's *QEX* article from Nov/Dec 2006. (See the Reference section.) This was the technique used to secure the data for Figures 3.52 through 3.56. Examples of homemade OWL probes are shown in **Figure 3.61**.

Included in the photo is a simple coaxial common mode choke used to isolate the balanced probe terminals from an unbalanced measuring instrument. The short length of clothesline is placed around the horizontal wood shaft before inserting the probe into the soil, making it much easier to extract the probe when measurements are complete.

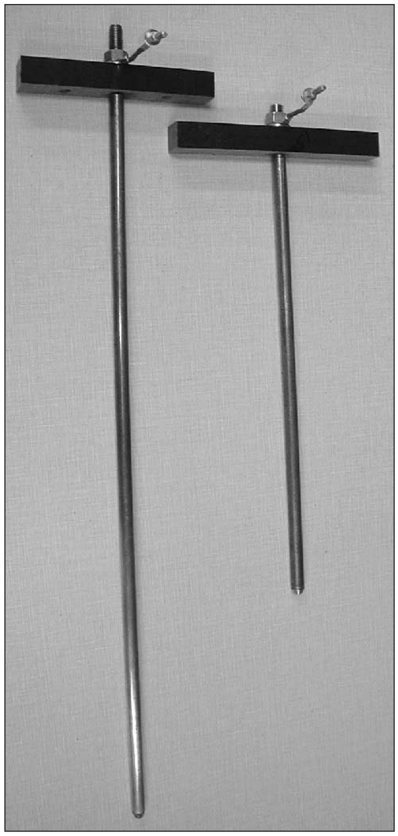


**Figure 3.58 —Typical monopole probes, 12-inch and 19-inch examples.**

In practice both of these types of probes will be very short in terms of wavelength even taking into account the effect of the soil. The probes are essentially just capacitors. The impedance of the probe plus ground screen or between the two probes in the OWL is first measured in air and again when the probes are inserted in the soil. The soil electrical characteristics are derived from the changes in the two measurements. In air the probe impedances will be very high because there is very little resistive loss, so it is only necessary to measure the capacitance ($C_o$) not the full complex impedance. This can be done with a digital capacitance meter or, if that's not available, use the predetermined $C_o$ value for a specific probe.

For example:

1) monopole probe — $\frac{3}{8} \times 19$ inch rod, 36 × 36 inch ground sheet, $C_o$=7.4 pF

2) OWL probe — $\frac{3}{8} \times 12$ inch rod, spaced 3 inches, $C_o$ = 4 pF

It is also possible to compute the capacitance from the dimensions with sufficient accuracy. It should be kept in mind that we are not trying to make 1% measurements. Even at a single location the soil constants will vary widely with season and at different places around the site. Knowing σ and Er within 20% is a vast improvement over a random guess, but you don't need much better than that! When using the measured values for σ and Er in a model it is normal for the values to vary as much as ±25%, reflecting seasonal variations and measurement errors on the predicted performance.

Once you have a measurement for $Z = R + jX$ and know $C_o$ and the frequency ($f_{MHZ}$), σ and Er can be calculated from:

**Figure 3.59 — Ground probe inserted through the mesh sheet.**

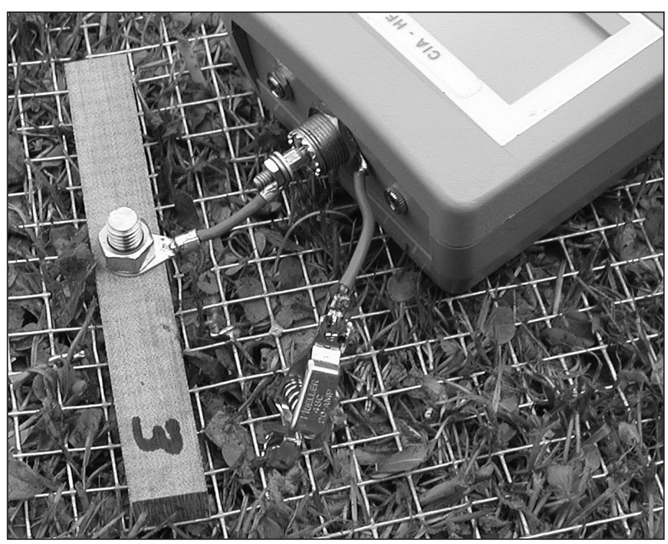


**Figure 3.60 — Ground probe impedance measurement.**

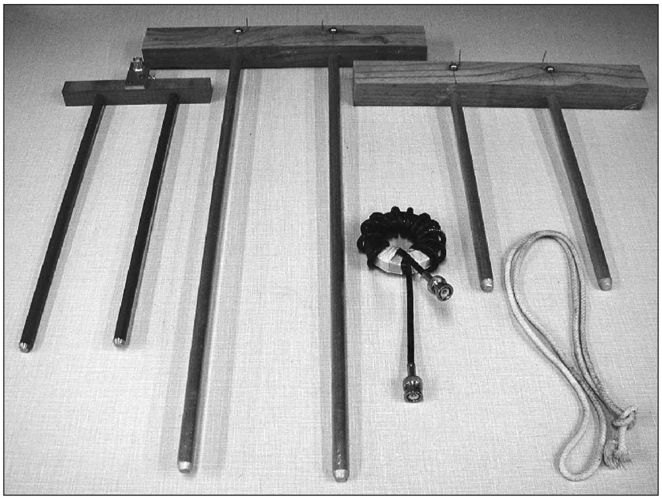


**Figure 3.61 — Examples of OWL probes.**

$$\sigma = \frac{8.84}{C_o}\left[\frac{R}{R^2+X^2}\right]$$

$$Er = \frac{10^6}{2\pi f_{MHZ} C_o}\left[\frac{X}{R^2+X^2}\right]$$

### Indirect Measurement

*The following material is a condensed version of the article "Determination of Soil Electrical Characteristics Using a Low Dipole" by R. Severns, N6LF, which is included on this book's CD-ROM as supplemental material.*

The direct measurements discussed in the previous section are effective for determining reasonable values for soil characteristics but the probe technique characterizes the soil in only a relatively small volume at one point in the site. You can get a more general characterization by repeating the measurements at several points spread over the site. This works, but there is another way to get average values over a large area. The terminal impedance and resonant frequency of an antenna will vary with both the height above ground and the electrical characteristics of the soil, it is possible to measure the feed point impedance of a low dipole and, from modeling of the antenna, determine the effective or average characteristics of the soil under the antenna.

The first question is "what height (z) should we use." Using a dipole with its length adjusted to maintain resonance at 3.7 MHz as the height and ground characteristics are varied, **Figure 3.62** illustrates how the feed point resistance, R, varies with height for a range of ground parameter pairs.

From Figure 3.62 it would appear that any height from 1 foot to 10 feet should give good resolution for determining the appropriate values of σ and Er. It should be noted that it is not necessary for the dipole to be resonant but if the dipole is close to resonance the values for R and X will be within the range of 10 to a few hundred ohms. That range is compatible with typical moderately priced impedance measurement instruments.

Erecting the test dipole can be greatly simplified if standard electric fence wire and insulating hardware are used.

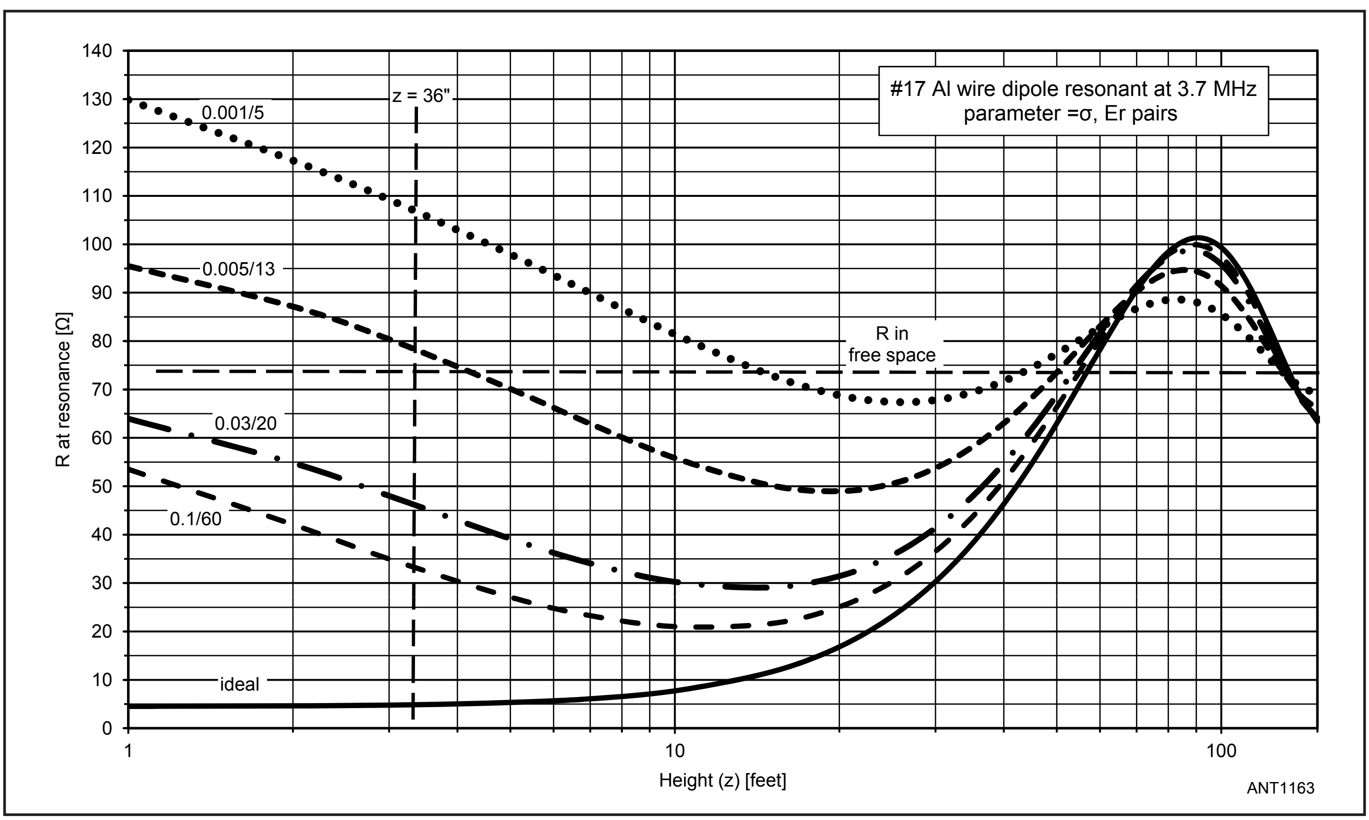



**Figure 3.62 — Variation of feed point resistance, R, with height.**

Figure 3.63 — Center connector and feed point support. Note use of a common mode choke at the feed point to isolate the feed line shield.

Figure 3.64 — Test antenna supported with fiberglass wands.

**Figures 3.63** and **3.64** are photos of a typical test antenna using standard electric fence hardware widely available in hardware and farm stores. #17 AWG aluminum electric fence wire is suspended at 36 inches from 5-foot fiberglass wands driven ≈1 foot deep, with yellow plastic wire clips which slide up/down the wands for height adjustment. The wands were spaced 10 to 20 feet apart and the wire anchored at the ends to steel fence posts 6 to 10 feet away from the ends of the wire. Multiple support points and significant wire tension can keep the droop to less than 0.25 inch. High quality insulators and non-conducting Dacron line were used at the wire ends. Figure 3.63 shows the Budwig center connecter and the common mode choke or choke balun at the feed point as described in the **Transmission Line System Techniques** chapter.

As an example of the procedure we'll assume a horizontal center-fed dipole made with #17 AWG aluminum wire at a convenient working height above ground (z) of 36 inches and the availability of antenna modeling software capable of properly calculating the effect of real ground, *NEC-4* for example.

After tuning to resonance at 3.5 MHz the length (L) is 131.11 feet. The measured feed point impedance (Z) at 3.5 MHz is $80.26 + j0\ \Omega$. With this information, we determine the values for soil conductivity ($\sigma$ [S/m]) and relative dielectric constant (Er) at 3.5 MHz. The first step is to create a *NEC-4* model with #17 Al wire, L = 131.11 feet and z = 36 inches. Since we do not know the values for $\sigma$ or Er we'll have to run the model repeatedly with a range of possible values for $\sigma$ and Er. If we're too far off in our choice of values the process will show us and point the way to go! In this case the trial values will be $0.001 < \sigma < 0.01$ [S/m] and $1 < \text{Er} < 50$ which covers a wide range of typical soils. Running the model repeatedly we can determine Z for a matrix of $\sigma$ and Er values. A spreadsheet is a good way to keep track as shown in **Table 3.6**.

A quick scan of the table shows that for Er > 20 and $\sigma$ = 0.009 there are no resonances (ie, Xi transitions from + to –) so we don't need to graph all the values. Using the spreadsheet we can graph a more restricted data as set shown in **Figure 3.65**, a graph of R versus X for the feed point impedance ($Z = R + jX$) with constant $\sigma$ and Er contours. The solid lines are constant values of $\sigma$ and the dashed lines constant values of Er.

The measured value of Z for the antenna at 3.5 MHz is $80.26 + j0\ \Omega$. A dot with a label has been placed at that value on the graph. What we see is that our matrix of values has bracketed this value. The $\sigma$ = 0.005 S/m line passes right through Z. We can also see that Z lies between Er = 10 and Er = 15 lines, with a bias towards Er = 15. Interpolation gives a value for Er ≈ 13. At this point we could repeat the process for multiple values of Er around Er = 13 to refine the answer further but from a practical point of view we're close enough! $\sigma$ = 0.005 S/m and Er = 13, which is average soil.

**Table 3.6**
**Calculated Values for R and X (in Ω)**

| *sigma (σ)=* | *0.001* | | *0.002* | | *0.003* | | *0.004* | | *0.005* | |
|---|---|---|---|---|---|---|---|---|---|---|
| *Er* | *Ri* | *Xi* | *Ri* | *Xi* | *Ri* | *Xi* | *Ri* | *Xi* | *Ri* | *Xi* |
| 1 | 130.09 | 19.13 | 101.36 | 26.50 | 87.12 | 21.85 | 78.76 | 16.71 | 73.05 | 11.68 |
| 5 | 111.22 | 6.37 | 100.86 | 14.26 | 90.05 | 14.03 | 82.13 | 11.41 | 76.23 | 7.80 |
| 10 | 104.72 | 2.61 | 98.61 | 5.33 | 91.25 | 6.14 | 84.60 | 5.07 | 79.06 | 2.86 |
| 15 | 102.87 | –2.21 | 97.34 | –0.71 | 91.51 | 0.05 | 85.88 | –0.54 | 80.89 | –1.84 |
| 20 | 101.52 | –7.01 | 96.45 | –5.80 | 91.38 | –5.29 | 86.51 | –5.45 | 82.05 | –6.16 |
| 30 | 98.60 | –16.00 | 94.56 | –14.75 | 90.58 | –13.97 | 86.74 | –13.62 | 83.09 | –13.65 |
| 40 | 95.71 | –23.00 | 92.50 | –21.72 | 89.30 | –20.79 | 86.17 | –20.18 | 83.14 | –19.86 |
| 50 | 93.00 | –28.50 | 90.40 | –27.27 | 87.77 | –26.30 | 85.17 | –25.60 | 82.62 | –25.14 |

| *sigma (σ )=* | *0.006* | | *0.007* | | *0.008* | | *0.009* | | *0.01* | |
|---|---|---|---|---|---|---|---|---|---|---|
| *Er* | *Ri* | *Xi* | *Ri* | *Xi* | *Ri* | *Xi* | *Ri* | *Xi* | *Ri* | *Xi* |
| 1 | 68.88 | 7.27 | 65.65 | 3.47 | 63.06 | 0.18 | 60.90 | –2.72 | 59.06 | –5.29 |
| 5 | 71.75 | 4.30 | 68.23 | 1.11 | 65.36 | –1.76 | 62.97 | –4.35 | 60.94 | –6.69 |
| 10 | 74.57 | 0.39 | 70.90 | –2.06 | 67.84 | –4.39 | 65.27 | –6.58 | 63.06 | –8.62 |
| 15 | 76.62 | –3.51 | 72.99 | –5.32 | 69.89 | –7.15 | 67.22 | –8.94 | 64.90 | –10.69 |
| 20 | 78.07 | –7.24 | 74.58 | –8.53 | 71.52 | –9.93 | 68.84 | –11.36 | 66.47 | –12.85 |
| 30 | 79.71 | –13.99 | 76.60 | –14.56 | 73.77 | –15.30 | 71.20 | –16.21 | 68.88 | –17.21 |
| 40 | 80.26 | –19.79 | 77.54 | –19.96 | 75.00 | –20.33 | 72.63 | –20.84 | 70.45 | –21.44 |
| 50 | 80.15 | –24.88 | 77.78 | –24.81 | 75.52 | –24.88 | 73.39 | –25.09 | 71.38 | –25.39 |

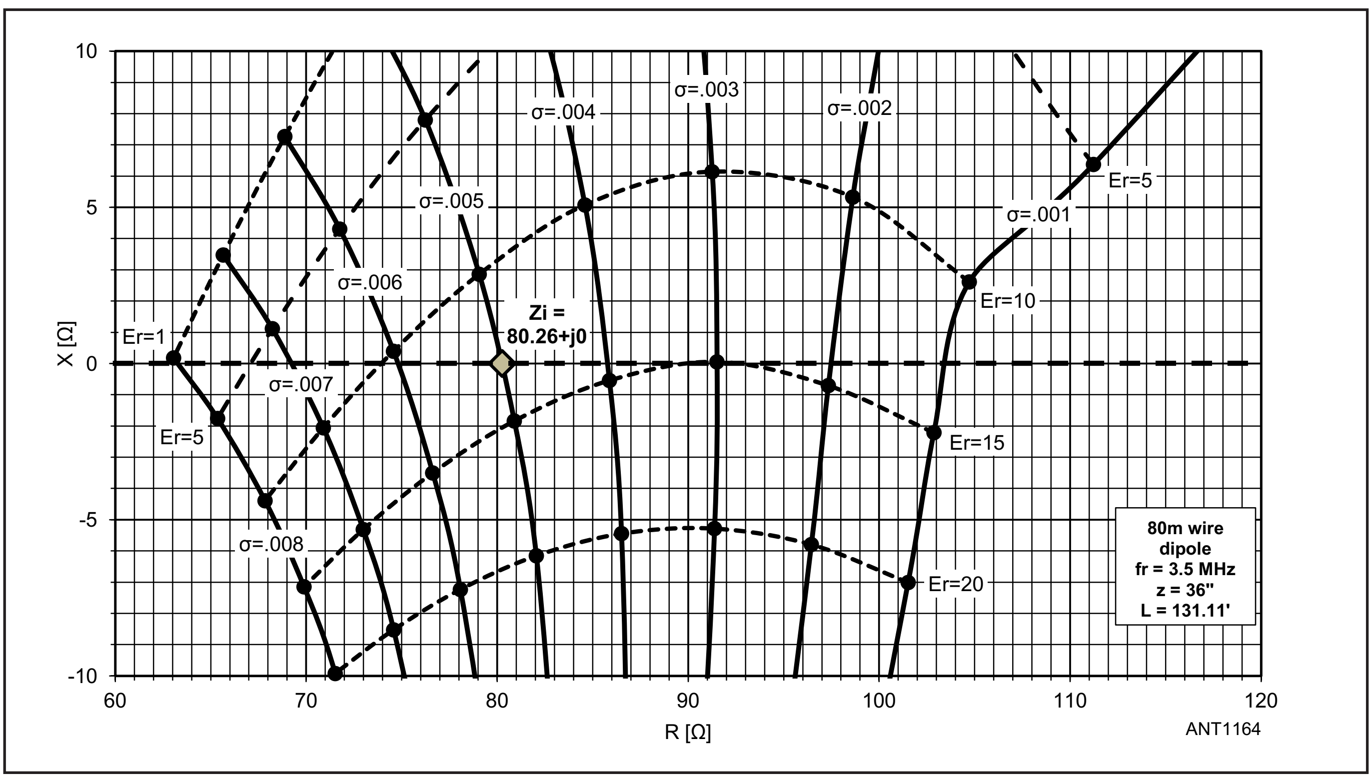



**Figure 3.65 — Graph of Z = R + *j*X for a range of σ and Er values at 3.5 MHz.**

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