By Rudy Severns, N6LF

Marconi, Ground Systems and Some History

What makes a vertical antenna cook? Here you can gain some insight as to what this popular antenna likes and dislikes.

Over the past 100 years, beginning with Marconi and continuing to this day, vertical antennas and their associated ground systems have received considerable attention. Many fine articles and technical papers have explained the finer points of vertical antenna operation. Sometimes we forget the information's origins—and sometimes the wisdom gets a little distorted. Occasionally it's worthwhile to revisit the earlier work and recognize how the old relates to present-day applications.

Research

A few years ago, I decided to get on 160 meters and wanted an effective antenna. I decided on a vertical of one form or another, but soon realized that I really didn't have a good understanding of how to get the best performance from a vertical. That led me to research the amateur and professional literature and discover a treasure trove of information.

Examining these early papers, I was struck by the depth of understanding and the quality of the work, both analytical and experimental. These papers represent a tremendous amount of effort—especially when you realize that up until a few years ago, all the computations were done manually with nothing more advanced than a pencil, a slide rule or a mechanical adding machine! Today, personal digital computers, equipped with a variety of software quickly manipulate the most complex expressions. With the software, it's easy for us to examine and manipulate mathematical expressions derived in earlier work and mine them for new understanding and insights. We now have antenna-modeling programs that are nothing short of magical, although their magic must be used with some caution. It's important to not only have a fundamentally solid understanding of antennas, but the modeling programs as well.[1]

[1]Notes appear on page 44.

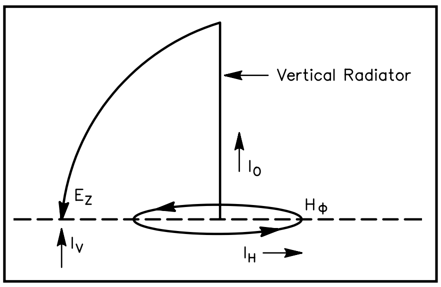

Figure 1—Fields and ground currents near the base of a vertical antenna.

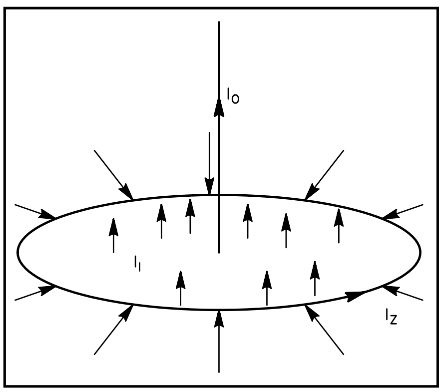

Figure 2—Definition of the current zone near the base of a vertical antenna. I_z represents the total current flowing through a zone at a given radius (r_1) by assuming the current is u niform to a depth of one skin depth (δ) as shown in Figure 13.

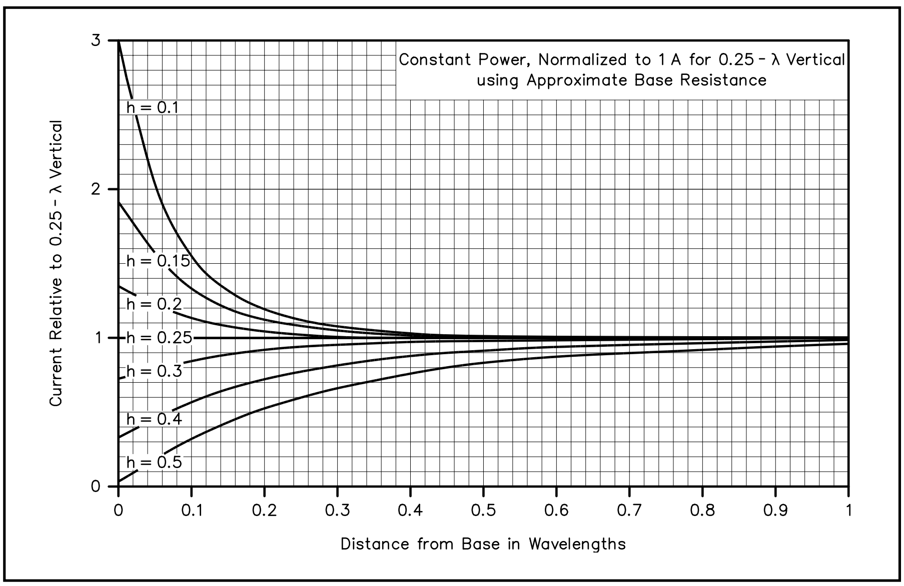

Figure 3—Plot of the current in amperes at the base of a vertical as a function of height and radius in wavelengths. The current in the base of the 0.25-λ antenna is assumed to be 1 A and the currents in the other antennas are adjusted to maintain the same input power.

What follows is a short tour of some of the earlier work that explains some of the lore of verticals and where it came from. I put the math in an Appendix and generated graphs for the discussion. All the graphs were done using a spreadsheet. After reading this article, I recommend you explore for yourself using the equations in the Appendix. The integration of power for Figure 6 was done with *Maple*; *MathCad* or *Mathmatica* would also do fine. You can also do integration with a spreadsheet.[2]

George Brown

In the mid-1930s, radio broadcasting was coming of age and the Institute of Radio Engineers (IRE) proceedings had many papers on vertical antennas and associated ground systems. One of the more influential writers of the time was George H. Brown. A series of papers written by Brown and his colleagues[3,4,5,6,7,8,9,10] at RCA have proved over time to be the most influential. The 1937 IRE paper (see Note 9) has been repeatedly referred to in Amateur Radio publications and is the basis for many later articles.[11,12,13,14,15,16,17,18,19] (References 16 and 19 have extensive bibliographies for further study.) At the time, these papers were so influential that they became the basis for the FCC standards for broadcast antenna installations! The way we think about verticals today has, in large part, been shaped by this work.

George Brown received his PhD from the University of Wisconsin-Madison in 1933. The core of his dissertation[20] is an analysis of the fields and ground currents associated with a vertical antenna with an extensive buried-radial ground system. This became the basis for much of the work that followed. Brown's work contains a great deal of analysis in addition to experimental results.

Papers on broadcast verticals were not Brown's only contributions to antenna art. He is credited with inventing the groundplane antenna and wrote numerous other papers on antenna subjects. In later years, Brown was the director of the RCA Sarnoff laboratory. Although not a ham, George Brown contributed enormously to Amateur Radio.

A Closer Look at Verticals

A vertical antenna has two field components that induce currents in the ground around the antenna. Figure 1 shows (in a general way) the electric (E, V/m) and magnetic (H, A/m) field components in the region near the antenna. Because the soil near the antenna usually has a relatively high resistance, both of these field components can induce currents (I_V and I_H) in the ground surrounding the antenna resulting in losses. The worms may enjoy the heated ground, but the power dissipated there subtracts from the radiated power, weakening the signal. As indicated in Figure 1, the tangential component of the H field ($H\phi$) induces horizontal currents (I_H) flowing radially and the normal component of the E field (E_z) induces vertically flowing currents (I_v). Actually, things are a bit more complex than this, but we don't need to thrash that to understand conceptually what's going on. Introducing a system of ground wires, buried or elevated, modifies the current flowing in the ground and (hopefully) reduces loss.

Brown's work was primarily concerned with broadcast antennas in the 0.5 to 1.5 MHz range, although some of his experimental work was carried out at 3 MHz. To make the analysis tractable he made several assumptions:

- The ground system would consist of a large number of radials buried a short distance below the surface.
- The ground characteristics were predominately resistive, ie, dominated by conduction currents, so displacement currents could be ignored.
- Because of the extensive ground screen and its shallow depth, the E-field losses were assumed to be small.

For his work, these assumptions were good approximations, but they are not en-

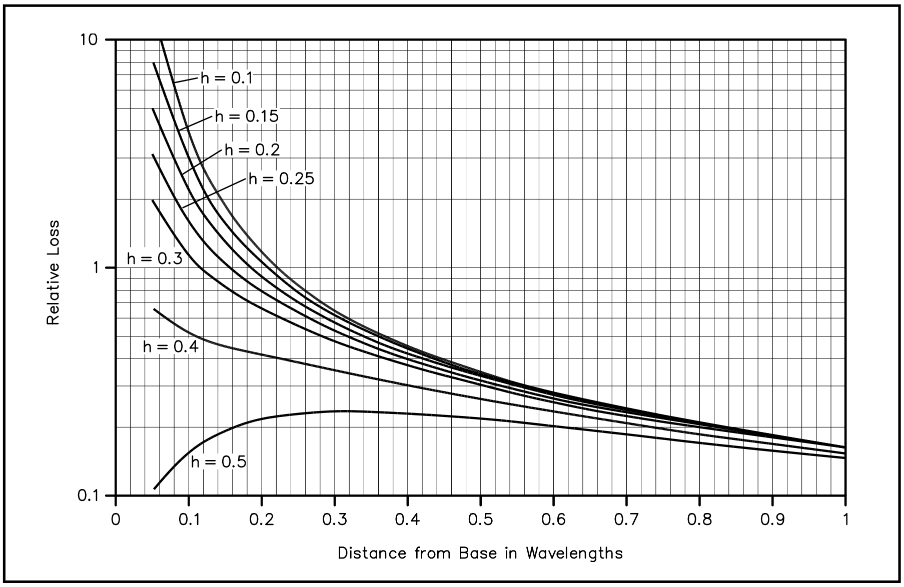

Figure 4—Relative ground loss for several different height verticals. The loss is normalized by allowing the expression which takes into account skin depth and ground conductivity to be equal to 1.

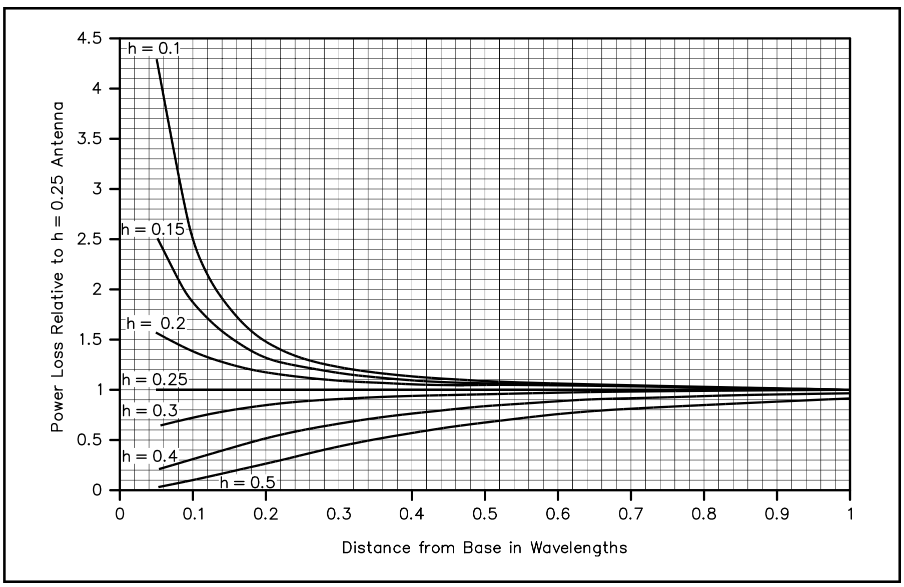

Figure 5—Ground loss at a given radius relative to a 0.25-λ vertical.

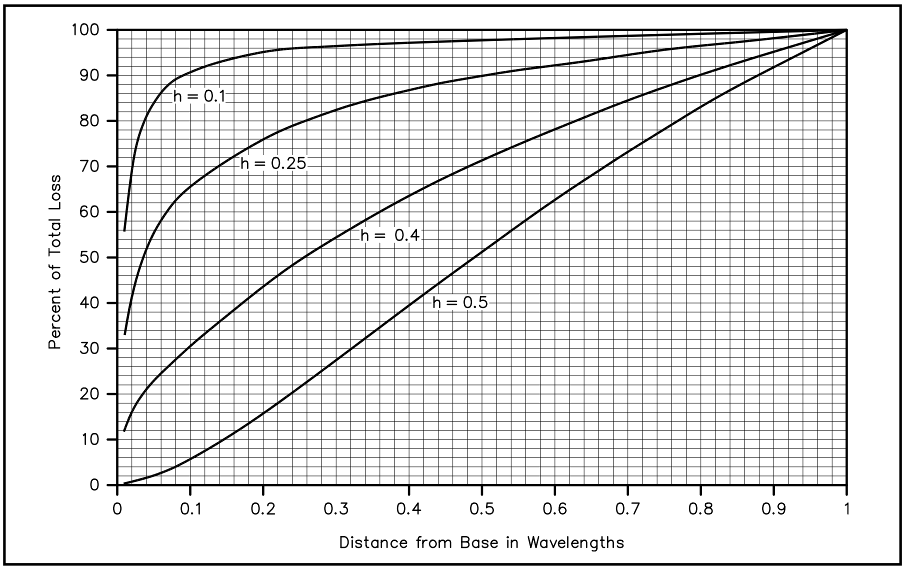

Figure 6—Percent of total ground loss within a given radius (in wavelengths) relative to the total loss at 1-l. This is a measure of the effectiveness of a ground system of a given radius.

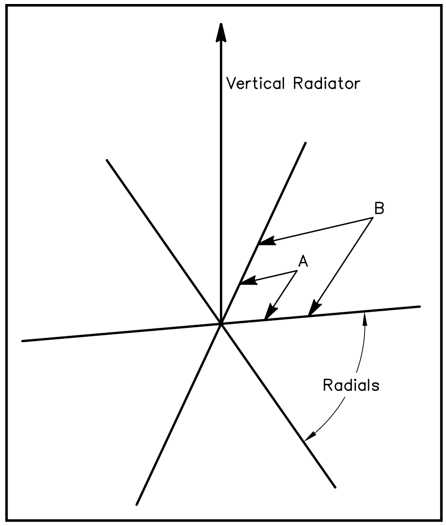

Figure 8—Current entering the ground between radial wires.

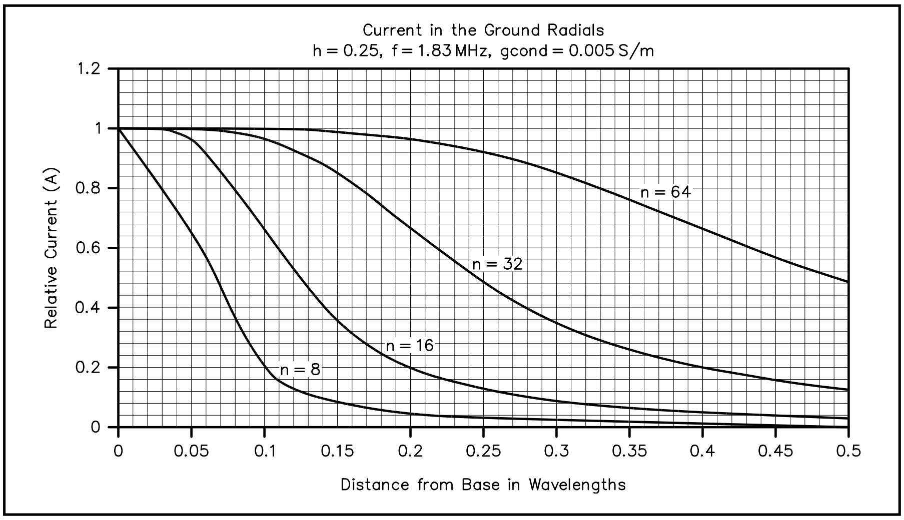

Figure 7—Total current in the radials (I_w) as a function of radius from the base of a 0.25-λ vertical operating at 1.83 MHz and with a ground conductivity of 0.005 S/m (average ground).

tirely valid for HF amateur verticals with small numbers of radials and certainly not valid for elevated radials. Nonetheless, his work is a very good place to start. At the end of the discussion we will look again at these assumptions.

Figure 2 is a sketch of current flow in the antenna and the surrounding ground. I_z represents the total current flowing through a cylindrical zone at a given radius. I_1 represents the current returning to the antenna in addition to the base current. I_o is the current at the base of the antenna. Brown derived an equation (see the Appendix) that describes the ground current as a function of antenna height and distance from the base of the antenna. The heights I will be using in the following discussion are the effective *electrical* heights. For example, if you use some top loading on the vertical, the effective electrical height is greater than the physical height. For the following graphs, I have used simplified expressions that use the effective height. It is important to recognize that simply adding a top hat to a vertical of given physical height can reduce the ground losses. We will be able to see this from the effect of height on ground-current amplitudes. Simply moving a loading coil from the antenna's base further into the antenna reduces ground losses because it reduces ground-current amplitude.

Figure 3 is a graph of this current (I_2)for several effective heights. The currents have been adjusted for constant input power (about 37 W) at the base of the antenna, with 1 A into a 0.25-λ vertical as the reference. This graph clearly shows the high currents flowing in the ground near the base of a short antenna. Compared to a 0.25-λ vertical, the 0.1-λ vertical has three times the ground current; as you further shorten the antenna, the ground current increases rapidly. Keep in mind that the ground loss is proportional to the *square* of the current (I^2R), so the power loss in the immediate region of the base is *much* higher for the shorter antenna.

One way to visualize the relative losses is to calculate them. This is where a spreadsheet really helps. If you take the currents given in Figure 3, square them and divide by the circumference of a circle at a given distance from the base—taking into account the ground resistance and the current's depth of penetration—you know the power loss at a given radius. Figure 4 is a graph of the power loss as a function of the distance from the antenna base. This shows that the losses are high near the base, are greater for shorter antennas and taper off rapidly as distance from the base increases. Note also that for a 0.5-λ vertical, the maximum loss occurs about 0.3-λ away from the base! The ground system in this region may profit from some additional attention. You may ask "Who uses 0.5-λ verticals, especially on 80 or 160 meters?" What about 0.5-λ slopers hung from towers? Even though they are typically not connected directly to ground, they would benefit from a ground system under them. John Devoldere, ON4UN, makes this point in his book (see Note 19). For simplicity, in Figure 4, I have assumed that the depth of current penetration into the soil and the soil conductivity are normalized to 1. For the actual losses in real ground at amateur operating frequencies, the proper equations are in the Appendix if you would like to graph them for yourself. We can also generate a graph showing the loss relative to the 0.25-λ vertical as shown in Figure 5.

Now we can take the next step and integrate the total loss inside a given radius to get a feeling for how large we should make our ground systems. Figure 6 is a graph of the total loss within a given radius, relative to the total loss inside a 1-λ radius for *each* antenna height. I chose the 1-λ radius as the reference because it contains most of the near-field loss and also represents a practical maximum radial length for most installations (560 feet on 160 meters!). The absolute value of the total loss is, of course, higher for a short antenna when compared to a taller one. For the 0.1-λ-high antenna, if we have a good ground screen out to a distance of 0.1-λ, we'll eliminate over 90% of the ground loss! This is where the idea comes from that for short antennas we should concentrate our ground systems inside a short radius. A larger ground system will do no harm; in fact, it reduces the loss even more, but if we have a limited amount of wire, we are much better off to *use many short radials instead of a few long radials*. Note that this graph assumes a large number of radials (more than 100). If only a few radials are used, the effectiveness of the ground system is reduced, although for short antennas it is not necessary to use as large a number of radials.

We can see why this is so by using another of Brown's equations, the one for the current in the radials as a function of radial length and number of radials (see Appendix). Figure 7 is a graph of the current in the radials as you move away from the base of a 0.25-λ vertical with various numbers of radials. The vertical has a 1 A current in the base and (from Figure 3) the total current (I_z) is constant as you move farther out. What we see is the current in the radials (I_w) falling off. The fewer the radials, the more rapidly the current decreases with distance from the base. The total current is still 1 A, but the remainder (I_e) is flowing in the ground and inducing losses. If you use only a few radials it does no good to make them very long because the outer portions of the radials pick up very little current.

What's happening here? Figure 8 is a sketch of a radial system with current entering the ground at two points (A and B). Current reaching the ground at point B has to flow much farther in the soil than current at point A before reaching a radial. The farther from the radiator you go, the greater is the distance between each radial and its neighbor and the farther is the distance the current must flow in the soil. There comes

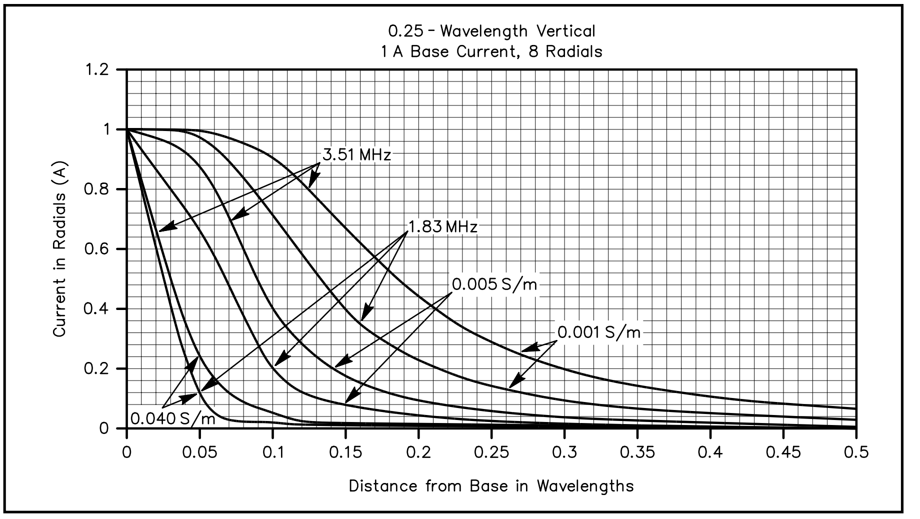

Figure 9—The effect of ground conductivity and frequency on the current in radial wires 1 A of base current and eight radials.

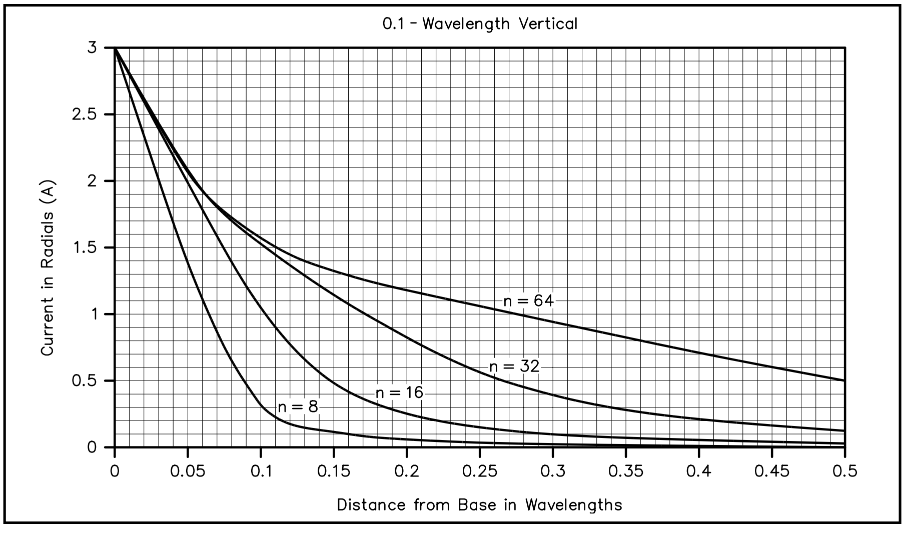

Figure 10—Radial-wire currents of a 0.1-λ vertical for several different numbers of radials (n).

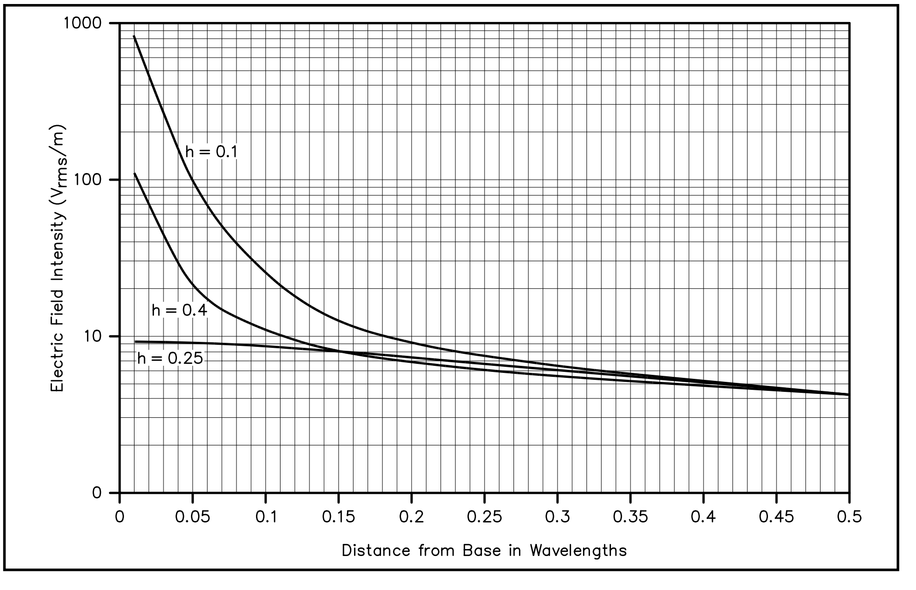

Figure 11—Electric-field intensity near the base of a vertical operating at 1.830 MHz with 1500 W input.

a point where the distance between the radials is so great that the radials are no longer effective. The more radials you use the closer together they will be (at a given radius) and the farther out will be the point at which the radial is no longer effective.

Now that we have Brown's equations in our spreadsheet we can explore further the effects of ground conductivity and frequency on radial number and length. In Brown's time this would have been very laborious, for us it is just a few mouse clicks! Figure 9 is a graph for a 0.25-λ vertical with eight radials, at 1.83 and 3.51 MHz for three different ground conductivities. Notice that as the ground improves (higher conductivity) the current in the radials falls more rapidly. This seems paradoxical: To get the full benefit of the radial system, you have to have more radials as the ground improves! Notice also that as frequency is increased, longer radials can be used effectively.

What about the change in radial current for shorter or longer antennas? That's easy. We just multiply the current values in Figure 3 times the values in Figure 7. Figure 10 is an example for a 0.1–λ vertical. Again we see the advantages of using lots of relatively short radials with a short vertical.

Electric Fields Near the Base

Another consideration is the intensity of the electric field (E) in the region around the base of the antenna. Figure 12 is a graph of E near the base of several verticals of different heights with an input power of 1500 W at 1.830 MHz. Notice how high the field is for the 0.1-λ antenna: about 100 times the value for the 0.25-λ vertical. This is an important consideration for any conductors or structures close to the base of the antenna. Large potentials can be induced into them. These fields can even ignite tall grass! Notice also that as the antenna height exceeds 0.25-λ, the field intensity again increases. The old-fashioned 0.25-λ vertical has many advantages.

A Word of Caution

George Brown's work has proven to be very useful and has been the basis for many articles in amateur publications. However, we have to keep in mind the assumptions Brown made (listed earlier) and remember that his concern was for *broadcast* applications. One assumption he made is that the ground characteristic is primarily resistive. This is a good approximation for most grounds at 160 and even 80 meters, but at higher frequencies, the ground behaves as though there is *capacitance in parallel with the resistance*: ie, there will be displacement as well as conduction currents.

For frequencies above 4 MHz, Brown's equations still give us a good qualitative feeling for what's going on and the overall guidance they offer is still valid. But Brown was careful to point out that you shouldn't rely on the absolute numbers. The need to consider displacement currents can be illustrated by looking at curves for skin depth in soil as a function of frequency and ground characteristics (the generating equations are in the Appendix). Figure 12 is representative of skin depths for typical soils. The graph is an extension of one given in *QST* by Charlie Michaels, W7XC (see Note 18). The dashed lines represent skin depth when conductivity only is considered. The solid lines represent skin depths using the com-

Appendix

Definitions

I_o = current in the base of the antenna or at the current loop in the case of the 1/2λ antenna

I_z = zone current at radius $r_1 = I_w + I_e$

I_e = total current in the earth at radius r_1

I_w = total current in radial wires at radius r_1

f = frequency in Hertz

f_{MHz} = frequency in MHz

E = electric field intensity

h = height of antenna in wavelengths

r_1 = distance from base in wavelengths

s = soil conductivity in Siemens/meter [S/m]

n = number of wires in the radial system

r_2 = radius of radial wires in cm

Zone Currents

$$\frac{|I_Z|}{|I_o|} \equiv I_n = \frac{1}{\sin 2\pi h}\sqrt{\left[\sin 2\pi p - \sin 2\pi r_1 \cos 2\pi h\right]^2 + \left[\cos 2\pi p - \cos 2\pi r_1 \cos 2\pi h\right]^2}$$

$$p \equiv \sqrt{r_1^2 + h^2}$$

(Equation 1)

Current Distribution in Radial Wires

$$\frac{I_e}{I_w} = j\left(\frac{3.6\sigma\pi^4 r_1^2}{f_{MHz}\, n^2}\right)\left[\log\left(\frac{3\times10^4\, \pi r_1}{f_{MHz}\, n r_2}\right) - 0.5\right] = j\left|\frac{I_e}{I_w}\right|$$

$$\left|\frac{I_w}{I_z}\right| = \frac{1}{\sqrt{1+\left|\frac{I_e}{I_w}\right|^2}}$$

$$\left|\frac{I_e}{I_z}\right| = \frac{1}{\sqrt{1+\left|\frac{I_w}{I_e}\right|^2}}$$

(Equation 2)

Electric Field Intensity

$$|E| = \left(\frac{2 f_{MHz} I_o}{\sin 2\pi h}\right)\sqrt{\left(\frac{\cos 2\pi \sin 2\pi r}{r_1} - \frac{\sin 2\pi p}{p}\right)^2 + \left(\frac{\cos 2\pi h \cos 2\pi r_1}{r_1} - \frac{\cos 2\pi p}{p}\right)^2}\left[\frac{V}{m}\right]$$

(Equation 3)

plete equation for skin depth in a general medium. What has been added is the *permittivity of the soil*, which is related to capacitance. For seawater, the conductivity dominates at any frequency below 2 meters. For very good soil, we see that conductivity still dominates over the HF range, but for average or poor soils, the expression for skin depth considering only conductivity gives a depth that is progressively much too large, especially for poor soils. This alters the ground-current distributions from those predicted by Brown; the actual losses may be higher.

If we look at most amateur literature concerning ground characteristics, we see that the emphasis is on measuring ground resistance and the effect of ground resistance on losses, with little said about the permittivity. This is a direct reflection of Brown's work and his concern with broadcast frequencies. We have been following his lead for the last 60 years. In reality, for most soils at HF, we need to take into account the permittivity of ground. Unfortunately, measuring the complex impedance of soil is considerably more difficult than measuring just soil conductivity. W7XC's article partially corrected this and was incorporated in later editions of the *ARRL Antenna Book*, but we still have some work to do.

Brown also assumed that the E-field losses were small. (In his 1935 paper and his thesis, he does compute the electric-field intensity, but then points out that these ground losses are small when a shallow, dense, buried radial system is used with a 0.25-λ vertical. For systems with many buried radials, this is a good approximation. However, when there are only a few radials, or when the radials are elevated above ground, the E-field loss may not be small at all. The importance of E-field losses to amateurs has been pointed out by Clay Whiffen, KF4IX, and Ben Zieg, K4OQK.[21] They showed the increased loss possible when the top of a vertical (where there is a very high electric field) is placed close to a tree. We also know that the outer ends of elevated radials have very high potentials and can induce E-field losses in the ground, grass, shrubs and sod beneath the radial system.

When we compare buried radials with elevated radials we find that the current distribution is very different between the two types of radial systems (see Note 14). Making buried radials longer may not help much if only a few radials are used, but it doesn't hurt. Buried radial systems with a radius greater than 0.5λ can be very effective if enough radials are used. However, as Burke and Miller[22] have shown, making *elevated* radials longer than 0.3λ can lead to greatly increased loss when only a few radials are used. Larger numbers of elevated radials do reduce this loss and allow larger elevated ground systems to be effective. It is important that we *do not directly equate* buried and elevated ground systems on the basis of Brown's work. They are different animals, both of which certainly have their place.

A Final Word

I hope you will find this information useful. If you really want a thorough understanding of the topic, you should graph these equations yourself and read the listed references.[22] The *QST*, *ham radio* and *CQ* articles are quite easy to follow; even Brown's papers are no great chore to read. Some modeling with *NEC* or *MININEC* software will give you even more insight. Particularly on

Skin-Depth Equations

The exact expression for penetration or skin depth in a general material is given by:

$$\delta = \left(\frac{\sqrt{2}}{\omega\sqrt{\mu\varepsilon}}\right)\left[\sqrt{1+\left(\frac{\sigma}{\omega\varepsilon}\right)^2}-1\right]^{-1/2} \quad \text{(Equation 4)}$$

where:
δ = skin depth in meters
$\omega = 2\pi f$
$\mu = \mu_o\mu_r$
$\mu_o = 4\pi 10^{-7}$ Henry/meter
μ_r = relative permeability
$\varepsilon = \varepsilon_o\varepsilon_r$
$\varepsilon_o = 8.85\times10^{-12}$ Farads/meter
ε_r = relative permittivity

For most soils, $\mu_r \approx 1$ (unless you set up shop in an open-pit iron mine!). For good conductors:

$$\frac{\sigma}{\omega\varepsilon} >> 1 \quad \text{(Equation 5)}$$

Which allows the equation for δ to be simplified to:

$$\delta = \frac{1}{\sqrt{\pi\sigma\mu f}} \text{ m} \quad \text{(Equation 6)}$$

where:
f is in Hertz

Ground loss

Ground loss for a ring of soil (dr) at a given radius (r_1) from the base can be calculated with the aid of figure 13. If we assume that the average current is uniform to one skin depth (δ), the loss in the ring will be:

$$\frac{dP}{dr} = \frac{I_e^2}{2\pi\delta\sigma r} = \frac{f_{MHz} I_e^2}{600\pi\delta\sigma r_1} = \left(\frac{f_{MHz}}{300\delta\sigma}\right)\left(\frac{I_e^2}{2\pi r_1}\right)\left[\frac{W}{m}\right] \quad \text{(Equation 7)}$$

where:

δ and r are in meters and r_1 is in wavelengths (λ).

$$\lambda = \frac{300}{f_{MHz}}\,[\text{m}] \quad \text{(Equation 8)}$$

The graph in Figure 4 assumes that

$$\frac{f_{MHz}}{300\delta\sigma} = 1 \quad \text{(Equation 9)}$$

and that r_1 is in wavelengths.

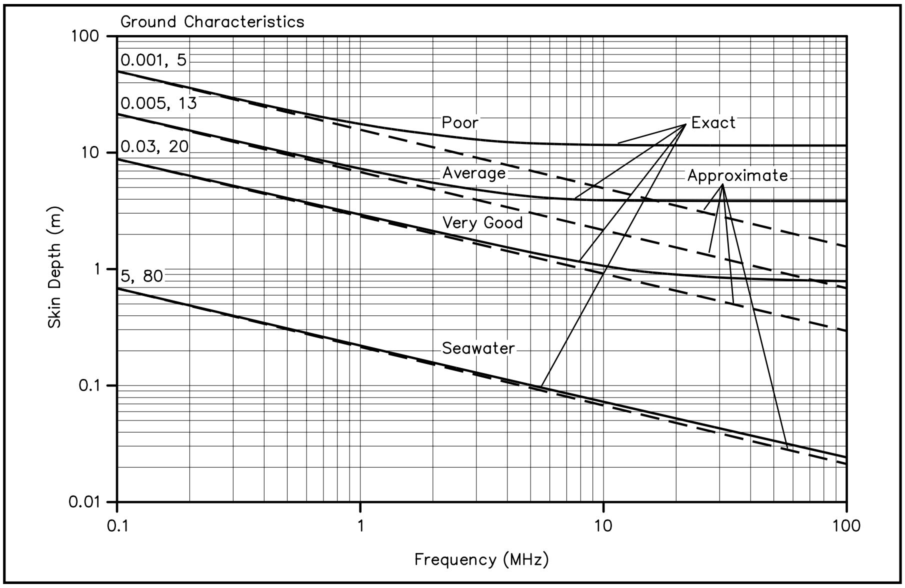

Figure 12—Skin depth in soil of various characteristics as a function of frequency.

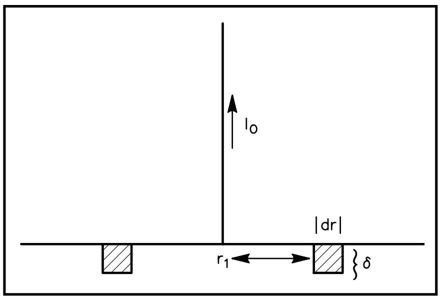

Figure 13—Calculation of ground loss in a small ring of soil at a given radius.

the lower bands, verticals can be very effective, but you have to understand what you are about to get good results.

Acknowledgement

The equations used here have been taken directly from Brown's 1935 (see Note 4) and 1937 (see Note 9) papers. All I have done is to restate them in a form handy for spreadsheet manipulations and to repeat some of his observations and conclusions.

Notes

[1]See also L. B. Cebik, W4RNL, "*NEC-4.1: Limitations of Importance to Hams*," *QEX*, May/Jun 1998, pp 3-16 and John Rockway and James Logan, N6BRF, "Wire Modeling Limitations of *NEC* and *MININEC* for *Windows*," *QEX*, May/Jun 1998, pp 17-21.

[2]Byron Gottfried, *Spreadsheet Tools For Engineers*, McGraw-Hill Basic Engineering Series Tools, 2000, see Chapter 9. A compressed *Excel* file (*SEVERNS.ZIP*) is available from **http://www.arrl.org/files/qst-binaries/**.

[3]G. H. Brown and Ronold King, "High-Frequency Models in Antenna Investigations," *IRE Proceedings*, Vol 22, No. 4, Apr 1934, pp 457-480.

[4]George H. Brown, "The Phase and Magnitude of Earth Currents Near Radio Transmitting Antennas," *IRE Proceedings*, Vol 23, No. 2, Feb 1935, pp 168-182.

[5]H. E. Gihring and G. H. Brown, "General Considerations of Tower Antennas for Broadcast Use," *IRE Proceedings*, Vol 23, No. 4, Apr 1935, pp 311-356.

[6]G. H. Brown, "A Critical Study of The Characteristics of Broadcast Antennas as Affected by Antenna Current Distribution," *IRE Proceedings*, Vol 24, No. 1, Jan 1936, pp 48-81.

[7]G. H. Brown, "Directional Antennas," *IRE Proceedings*, Vol 25, No. 1, Part 1, Jan 1937, pp 78-145.

[8]G. H. Brown and John G. Leitch, "The Fading Characteristics of the Top-Loaded WCAU Antenna," *IRE Proceedings*, Vol 25, No. 5, May 1937, pp 583-611.

[9]G. H. Brown, R. F. Lewis and J. Epstein, "Ground Systems as a Factor in Antenna Efficiency," *IRE Proceedings*, Vol 25, No. 6, Jun 1937, pp 753-787.

[10]G. H. Brown, "A Consideration of the Radio-Frequency Voltages Encountered by the Insulating Material of a Broadcast Tower Antenna," *IRE Proceedings*, Vol 27, No. 9, Sep 1939, pp 566-578.

[11]F. R. Abbott, "Design of Optimum Buried-Conductor RF Ground Systems," *IRE Proceedings*, Vol 30, No. 7, Jul 1952, pp 846-852.

[12]R. E. Leo, W7LR, "Vertical Antenna Ground Systems," *ham radio magazine*, May 1974, pp 30-35.

[13]John O. Stanley, K4ERO/HC1, "Optimum Ground Systems for Vertical Antennas," *QST*, Dec 1976, pp 13-15.

[14]Jerry Sevick, W2FMI, "Short Ground-Radial Systems for Short Verticals," *QST*, Apr 1978, pp 30-33.

[15]Archibald C. Doty, K8CFU (now W7ACD), John A. Frey, W3ESU, and Harry J. Mills, K4HU, "Efficient Ground Systems for Vertical Antennas" *QST*, Feb 1983, pp 20-25.

[16]Archibald C. Doty, K8CFU, "Improving Vertical Antenna Efficiency," *CQ*, Apr 1984, pp 24-31.

[17]Brian Edward, N2MF, "Radial Systems for Ground-Mounted Vertical Antennas," *QST*, Jun 1985, pp 28-30.

[18]C. J. Michaels, W7XC, "Some Reflections On Vertical Antennas," *QST*, Jul 1987, pp 15-19.

[19]John Devoldere, ON4UN, *Low-Band DXing*, (Newington: ARRL, 3rd ed), 1999, Chapter 9.

[20]G. H. Brown, "A Theoretical and Experimental Investigation of The Resistance of Radio Transmitting Antennas," PhD thesis, University of Wisconsin-Madison, June 29, 1933

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[22]G. J. Burke and E. K. Miller, "Numerical Modeling of Monopoles On Radial-Wire Ground Screens," *IEEE Antennas and Propagation Society International Symposium Proceedings*, Jun 1989, pp 244-247

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