

Appendix A4

Rg and Ground Systems

A4.0 A closer look at ground systems

Chapter 5 provided a number of practical examples of ground systems. For the most part the performance of these systems was derived from NEC modeling with very little math. For many readers that's more than sufficient but some will want more information. To address this need a series of appendixes (A.tbd-A.tbd) have been created. This appendix describes how ground systems actually work.

A4.1 Feedpoint equivalent circuit

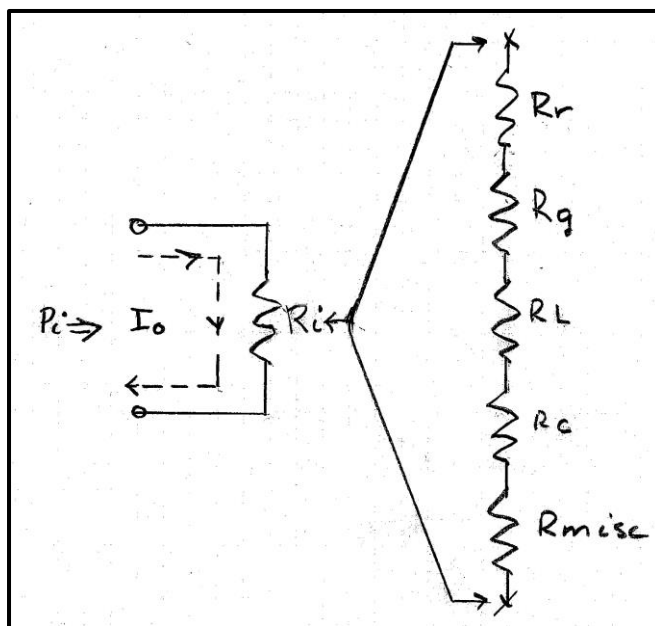


Figure A4.1 - Equivalent circuit for the resistive part of the feedpoint impedance.

Figure A4.1 shows an equivalent circuit used to represent the resistive part of an antenna's feedpoint impedance (R_i). I_o is the current at the feedpoint and the input power $P_i = I_o^2 R_i$.

- R_r is the radiation resistance representing the radiated power (P_r).
- R_g accounts for the power dissipated in the soil (P_g).
- R_L represents the tuning inductor loss (P_L).
- R_c represents the loss in the conductors (P_c).
- R_{misc} represents other losses such as insulator leakage, etc.

For this discussion our interest will be focused on R_g and it's relation to R_r . The other losses are important but have been addressed elsewhere.

R_r is very dependent on the specific details of the antenna: i.e. dimensions and loading. R_r can also be a function of soil electrical characteristics and ground system design. Although this effect is prominent at HF it's significantly less at LF/MF. A detailed discussion on this can be found in appendix TBD.

R_g depends on soil electrical characteristics, which vary with frequency, details of the ground system and the antenna associated with the ground system. If we modify the antenna, even without changing the ground system or soil, R_g will change. We have to remember that neither R_r nor R_g is a physical resistor, they are "accounting tools" we use to keep track of where the input power (P_i) is going. Because P_g depends on the electric and magnetic field intensities at the ground surface which change when the antenna is changed, R_g is dependent on the details of the antenna as well as the ground system itself.

A4.2 Definitions for P_r , P_g , R_r and R_g

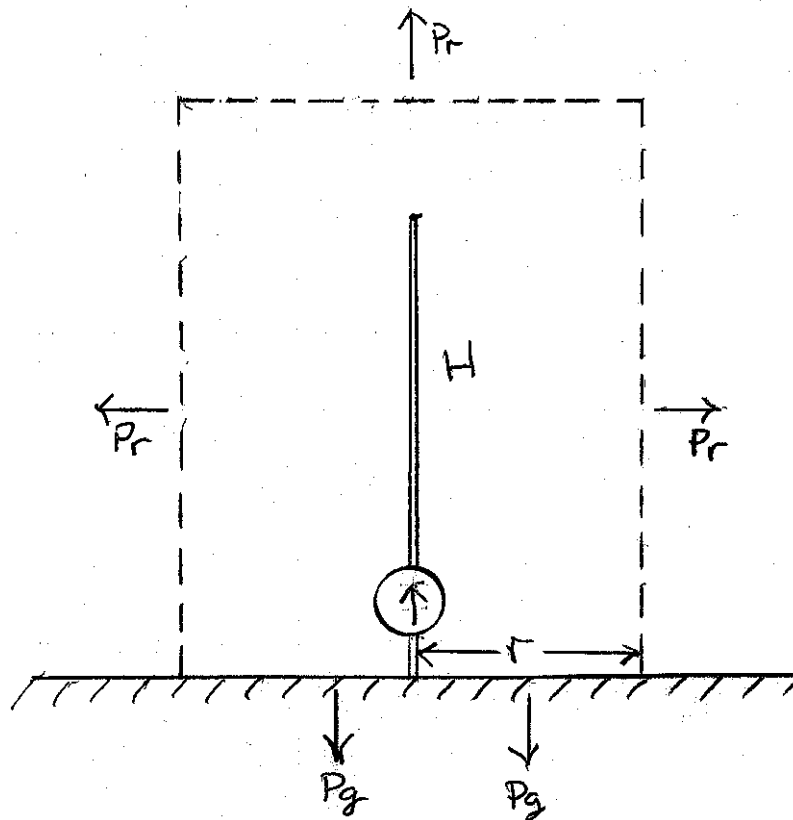


Figure A4.2 - P_r and P_g .

Figure A4.2 illustrates "Pr" and "Pg". The dashed line represents a hypothetical cylindrical surface enclosing a vertical antenna. The cylinder radius r is usually set $r=\lambda/2$ because that is approximately the outer boundary of the reactive near-field for verticals with a height of $\lambda/8$ - $\lambda/4$. A detailed discussion of the fields around an antenna and the math to calculate Pg and Pr can be found in appendix A.TBD. Pg is defined as the power radiated through the bottom of the cylinder (the ground surface) and dissipated in the soil. Pr is defined as the total power radiated through the other surfaces of the cylinder (top and sides)..

Rr and Rg are defined in terms of Pr and Pg:

$$Rr \equiv \frac{P_r}{I_o^2} \Omega \quad (A4.1) \quad Rg \equiv \frac{P_g}{I_o^2} \Omega \quad (A4.2).$$

A4.3 Efficiency

We can state efficiency η In general:

$$\eta = \frac{1}{1 + \frac{R_g}{R_r} + \frac{RL}{R_r} + \frac{R_c}{R_r} + \frac{R_{misc}}{R_r}} \quad (A4.3)$$

The purpose of the a ground system is to minimize the Rg/Rr term. It should be kept in mind that it's not necessary for Rg/Rr to be zero. When Rg/Rr becomes small compared to the sum of the other terms then that ground system is in a the region of diminishing returns. Before designing the ground system we need to maximize Rr as described in chapters 3 and 4, minimize RL as described in chapter 6 and also minimize conductor loss (Rc). When this has been done we can judge how extensive a ground system will be useful.

A4.4 Soil characteristics

For this discussion some soil electrical definitions will be helpful.

σ = soil conductivity in Siemens/meter [S/m], Siemen=Mho

ϵ_o = permittivity of a vacuum = 8.854×10^{-12} [Farads/m]

ϵ_r = relative permittivity or relative dielectric constant

$\epsilon = \epsilon_0 \epsilon_r$ = effective permittivity or dielectric constant [Farads/m]

μ_0 = permeability of free space = $4\pi \cdot 10^{-7}$ H/m

$\omega = 2\pi f$

We can combine σ and ϵ_r into the loss tangent (D).

$$D \equiv \tan \delta \equiv \frac{\sigma}{2\pi f \epsilon_0 \epsilon_r} = \frac{\sigma}{\omega \epsilon} \quad (\text{A4.4})$$

A4.5 Ground system geometries

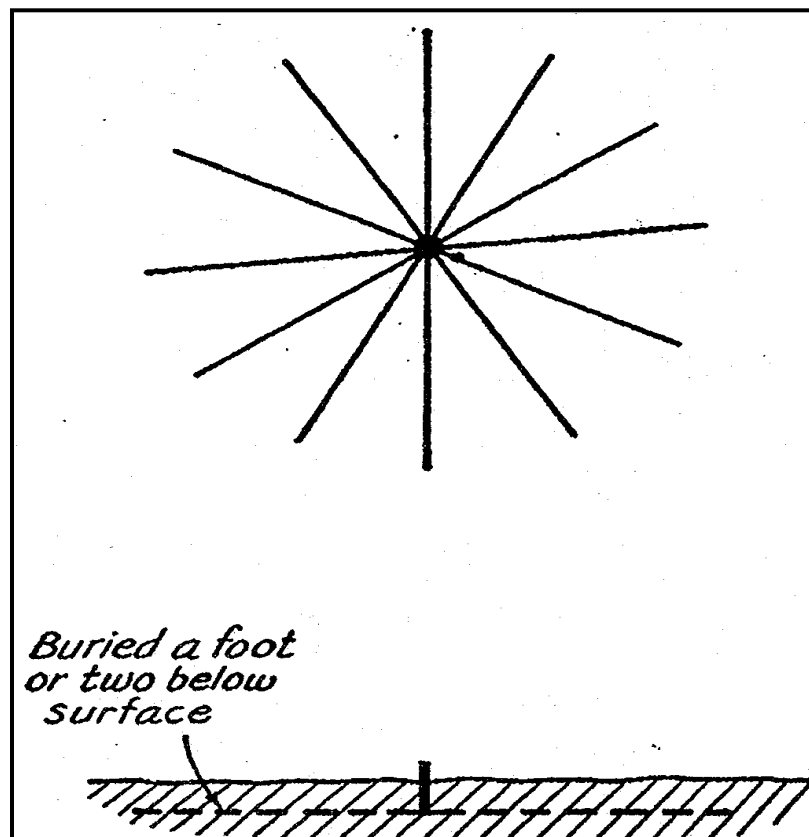


Figure A4.3 -Typical radial wire ground system.

We have many choices for ground systems, from a simple ground stake to a complex web of wires which can be elevated above ground, lying on the ground surface or buried in the soil a short distance (usually 3"-12"). Figure A4.3 shows a typical radial wire ground system for a simple vertical. The radials can be above ground, on the surface or buried. In the case of an elevated system the radials may be long enough

to be resonant. While this is often practical on 160m, on the lower LF-MF bands it's usually not so non-resonant or "capacitive" systems are used. As shown in appendix A.tbd resonant, or near resonant elevated ground systems have special problems.

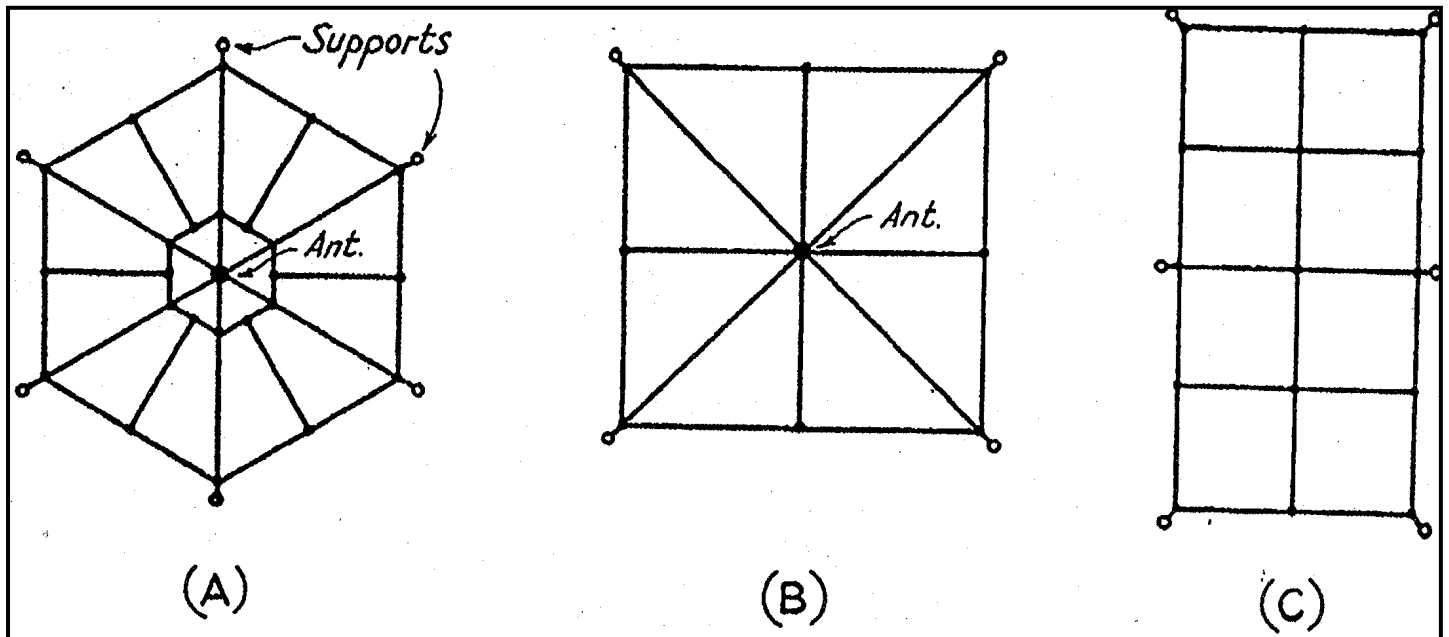


Figure A4.4 - Alternative wire ground systems.

Figure A4.4 shows some alternative wire ground systems. Very often these are elevated and, when non-resonant, referred to as "counterpoises". However, these systems can also be placed on the ground surface. In particular the rectangular wire grid shown in (C) is often placed under vertical loop transmitting antennas. It's widely assumed that a vertical loop transmitting antenna does not require a ground system and this is true, the ground system is not "required". What is often not appreciated however, is the substantial ground loss associated with loops placed close to ground. Adding a ground system like that shown in (C) can substantially improve the efficiency as will be shown in a later section.

A4.6 Models for ground systems

There are several different models we can use to explain how ground systems work. They vary from simple to mathematically complex and their explanatory power varies from limited to very detailed.

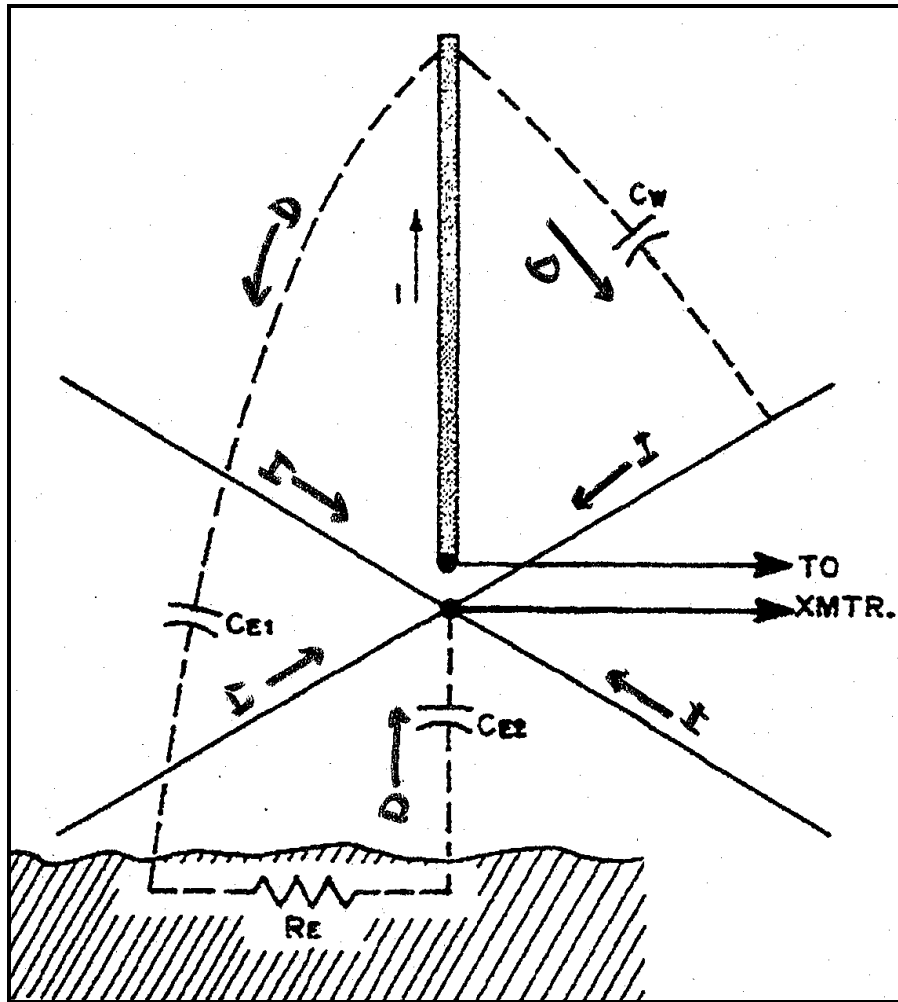


Figure A4.5 - Simple capacitive equivalent circuit model.

Figure A4.5 is the classic model seen in amateur literature for over 100 years. The figure shows the radials elevated but the basic argument is the same when the radials are buried. The idea is that the vertical is capacitively coupled to the both the radial system and the soil via the displacement currents (D) flowing in the capacitances. Some of D flows directly to the radials and then back along the radials to the vertical as conduction currents (I). However, some of D flows into the soil and then back into the radial system. Conduction currents flowing in the soil result in dissipation (i.e. R_c). This simple model has considerable explanatory power! We can see that more and/or longer radials increase the coupling to the radials and partially shield the soil, reducing the soil current and R_c . We can also see that the capacitance from the soil to the radials will be significantly reduced when the radials are elevated. In practice even a small elevation results in significantly less ground current.

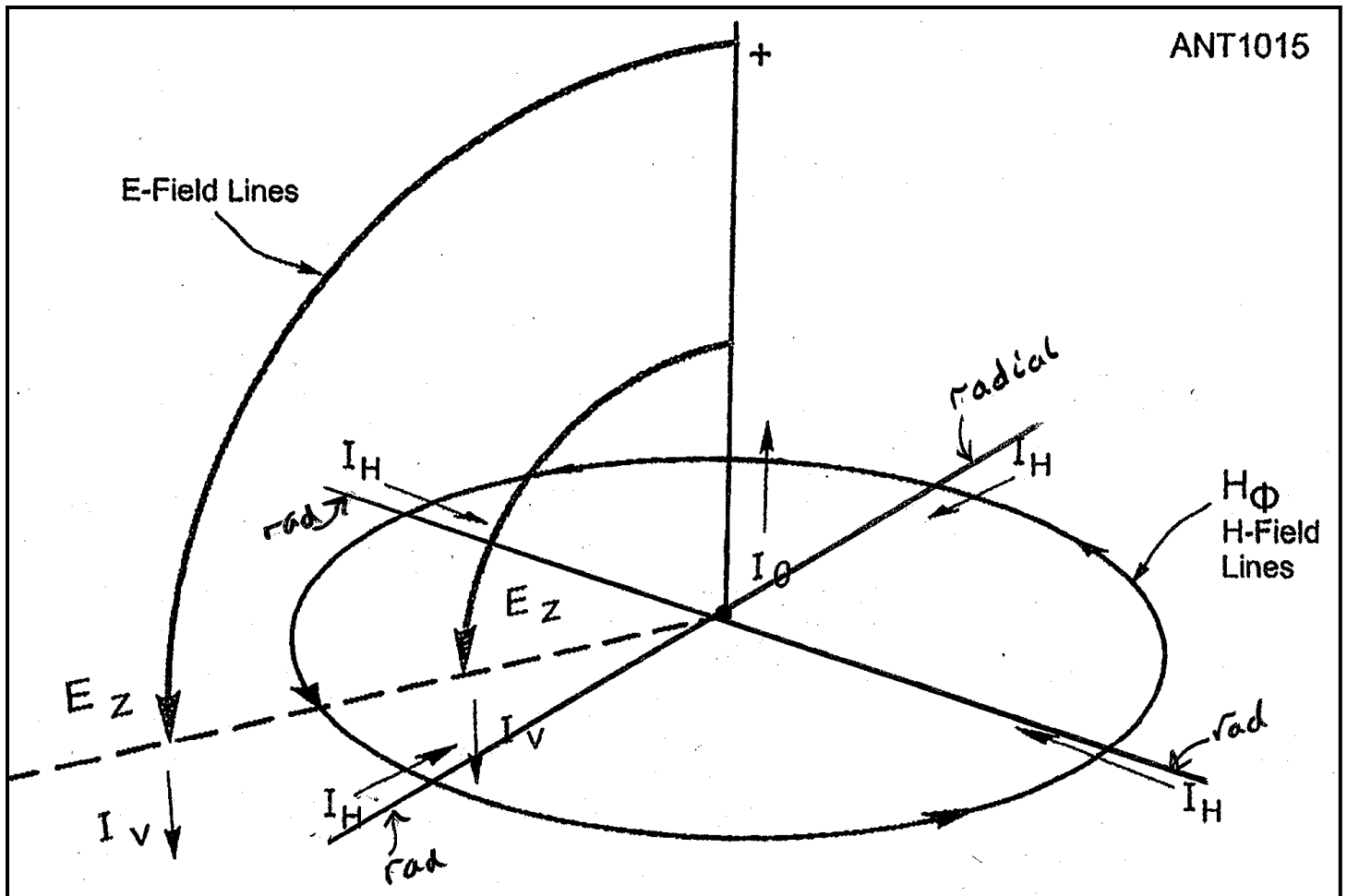


Figure A4.6 -Field model for a vertical and ground system.

However, this model is not very useful if we want to determine the specific details regarding the currents and associated ground loss. For that kind of information we can change to the model shown in figure A4.6. This model recognizes that the current in the vertical creates an electromagnetic field around the antenna. As indicated there will be both electric (E-field) and magnetic (H-field) components. The fields interact with the radial system and ground introducing loss. While this model can determine R_r and R_c accurately it's very complex mathematically. For those with graduate level mathematical skills and interests an extensive discussion can be found in appendix A.tbd.

Fortunately there is an intermediate model derived from optics. When an antenna is placed over soil some of the input power (P_i) is radiated and some is absorbed in the soil. One of the earliest quantitative analysis regarding ground loss and propagation of radio waves over lossy soil was done by Arnold Sommerfeld. About 1896^[37] he solved the general problem of the diffraction of electromagnetic waves (EM) in lossy media, i.e. reflection and refraction at an interface between two media, air and soil. Some

years later Sommerfeld used this insight to solve the general problem of waves interacting with and propagating over real lossy ground^[44, 45].

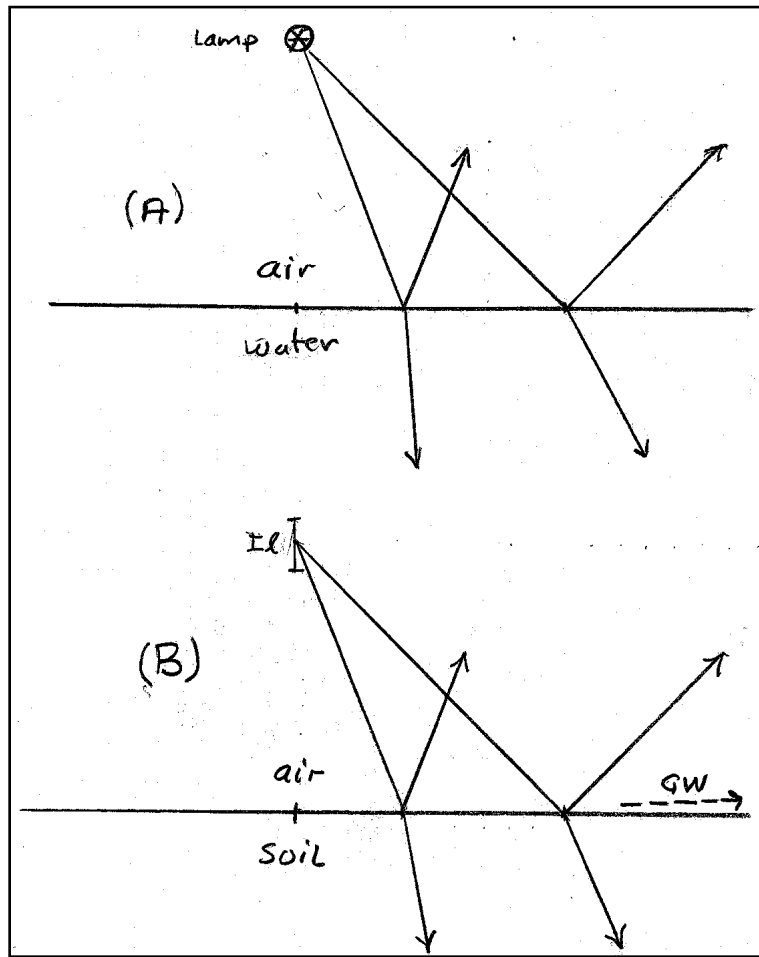


Figure A4.7 - A lamp over a pond (A) and a short vertical antenna over soil (B).

The "Sommerfeld Ground Model", is still widely used. His analysis was based on the diffraction theory which represents the physical processes.

We can understand his view with an analogy to a lamp placed over the surface of a pond as shown in figure A4.7(A). We know that if a light source (the lamp) is placed over the surface of a pond some of the light will be reflected from the surface but the rest will be refracted into the water and absorbed. Light is electromagnetic radiation. Radio waves are also electromagnetic radiation only much lower in frequency. As shown in figure A4.7(B), instead of a lamp over a pond, we could substitute a short vertical conductor carrying an RF current. This short conductor is an antenna. A portion of the radiation is reflected from the soil and the rest is refracted into the soil and dissipated. The lost radiation is the ground loss, P_g . In most recent editions of Antenna Book and other texts the reflection part of figure A4.7 is discussed at length in

the context of the formation of the far-field pattern. However, although common in professional papers, refraction into the soil is not seen very often in amateur literature.

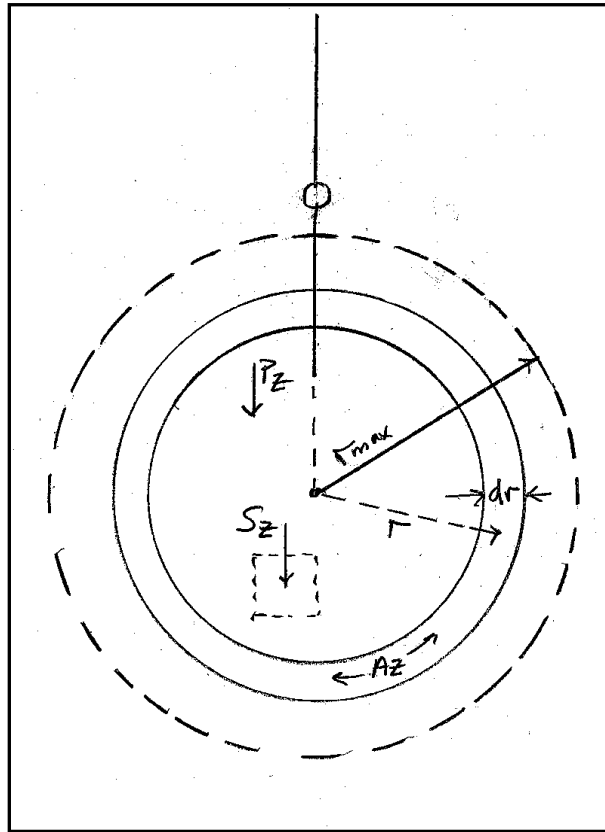


Figure A4.8 - A short vertical over ground.

By way of an example we can shift the view point as shown in figure A4.8. S_z represents the intensity of the power flow in W/m^2 into the ground surface at a given point on the surface. For this part of the discussion we will let $P_g = P_z$, the total power flowing into the soil at the surface within a radius r . $A_z = 2\pi r dr$ is the area of ring at radius r with width dr . r_{max} is the maximum radius which for this example will be 1000' ($\approx \lambda/2$ at 475 kHz). $H = 40'$ with the bottom end 10' above ground. The frequency is 475 kHz.

With $P_i = 1W$ we can ask "what is the total power dissipated in the soil near the antenna, for radii (r) out to 1000'. Using techniques shown in Appendix A.tbd we can calculate and graph the intensity of the power flow (S_z) across the air-soil interface into the soil as shown in figure A4.9 for three different soils. We can take a further step and sum the power flow through the ring A_z as shown in figure A4.10. Finally we can sum S_z within a radius r_{max} to get the total power flowing into the soil as shown in figure A4.11.

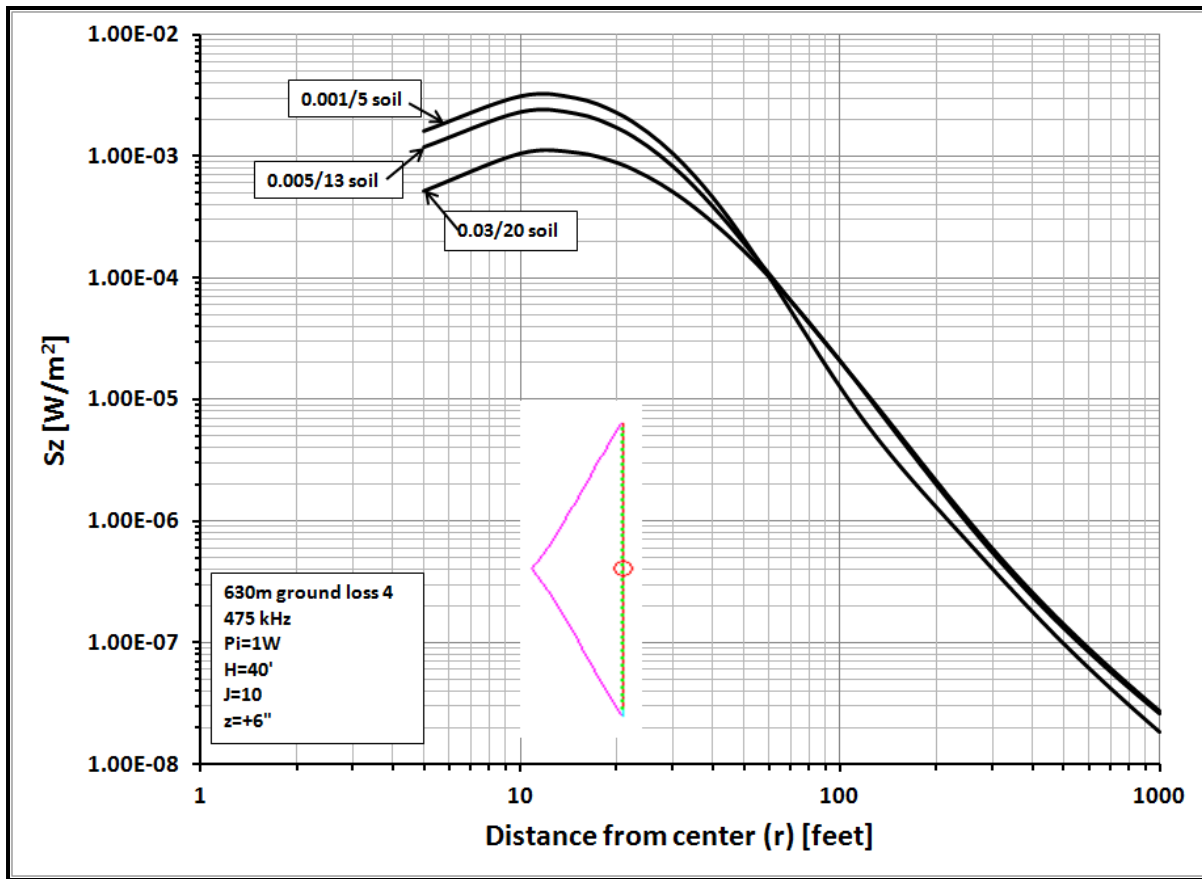


Figure A4.9 - Power density (S_z [W/m²]) near soil surface versus radius r .

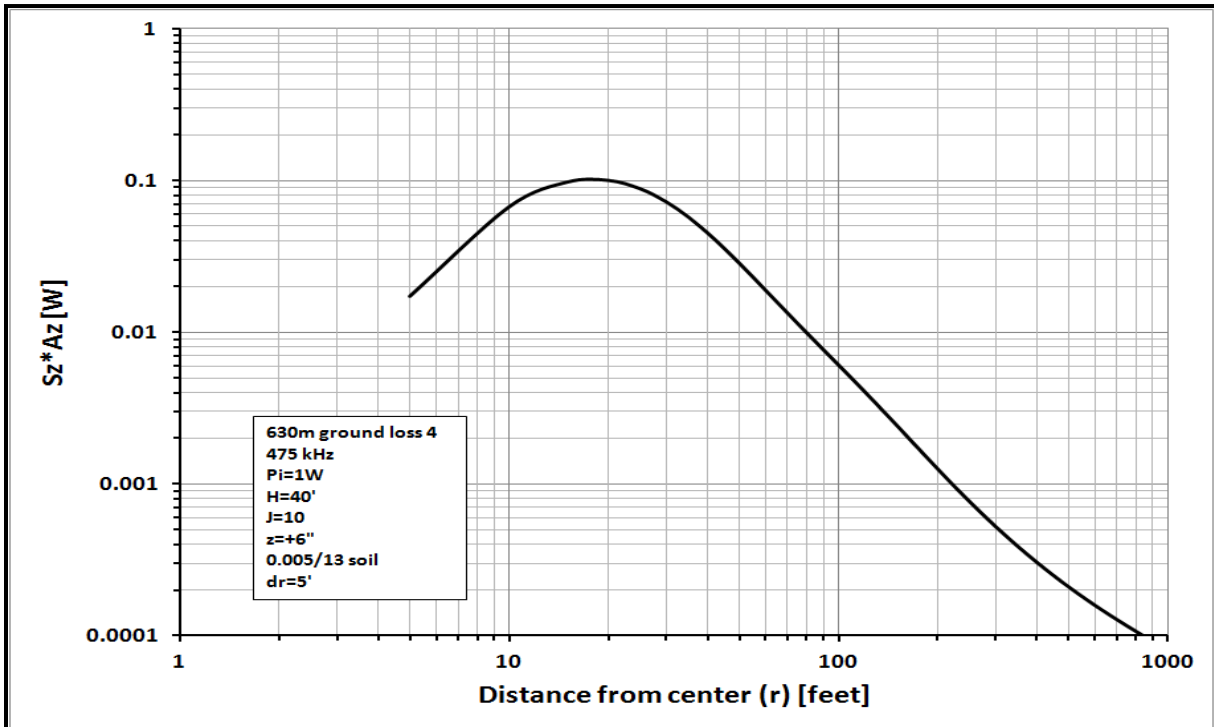


Figure A4.10 - Power dissipation in a ring ($dr=5'$) at a distance r .

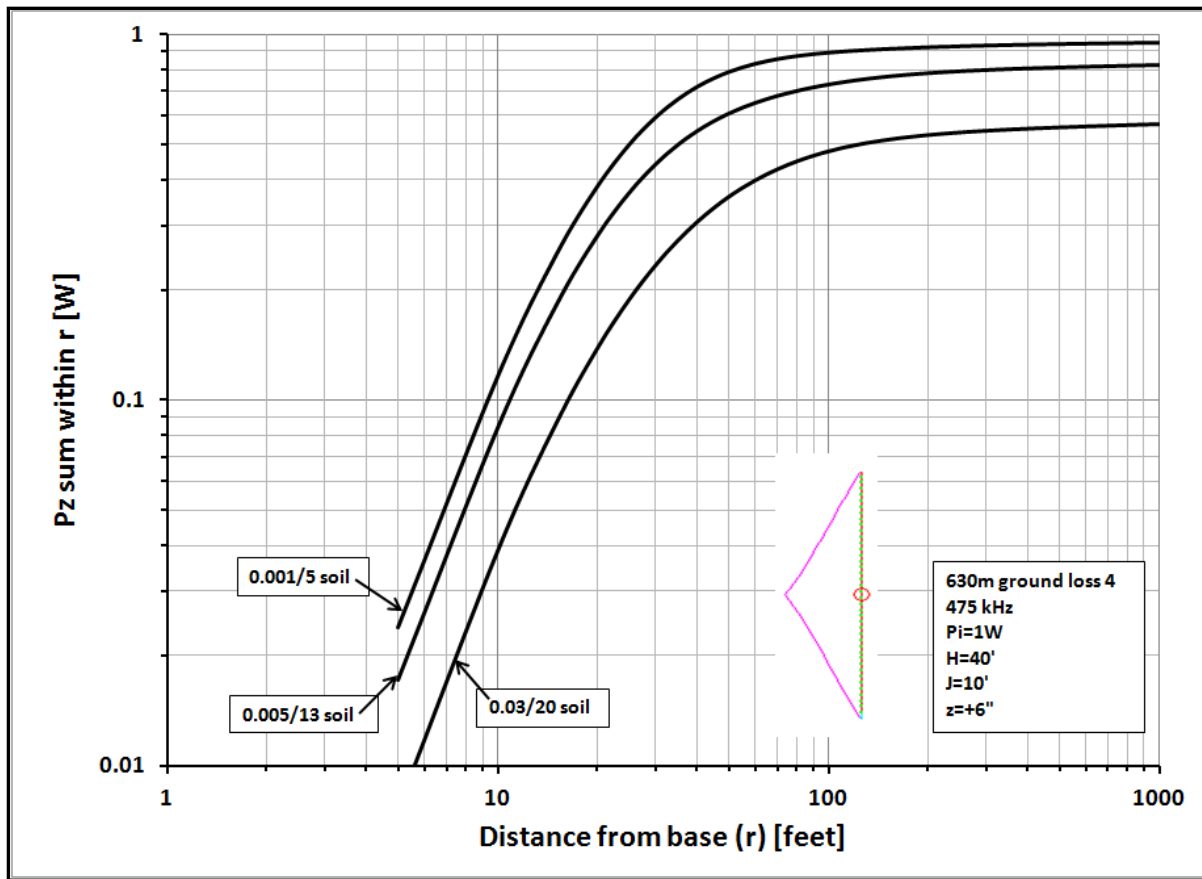


Figure A4.11 - Power flow (sum of S_z) into the soil within a given radius, 6" above the soil surface.

These graphs show several interesting things. First, most of the power is lost close to the base, within $50' \approx 0.025\lambda$ in this example. Concentration of power loss close to the base is typical of verticals and tells us that when installing a ground system we need to pay particular attention to the ground system near the base.

Table A4.1 - summary

soil=	ideal	0.001/5	0.005/13	0.03/20
R_i =	0.14Ω	2.736Ω	0.7483Ω	0.3258Ω
R_r =	0.14Ω	0.134Ω	0.1412Ω	0.1403Ω
R_g =	0Ω	2.601Ω	0.6433Ω	0.1855
X_c =	10160Ω	10160Ω	10160Ω	10160Ω
I_o =	2.673Arms	0.6046Arms	1.129Arms	1.752Arms
P_i =	1W	1W	1W	1W
P_r =	1W	0.049W	0.18W	0.43W
P_g =	0W	0.95W	0.82W	0.57W

Second, the loss is strong function of the soil characteristics. The dominant influence at MF is the conductivity but a HF ϵ_r becomes important. For this example, the effect of different soils, including perfect ground, on R_r and R_g is summarized in table A4.1.

Third, in this example $P_i=1W$ so we see that that for the poor soil almost 95% of the radiated power is absorbed in the soil! This indicates the need for a ground system.

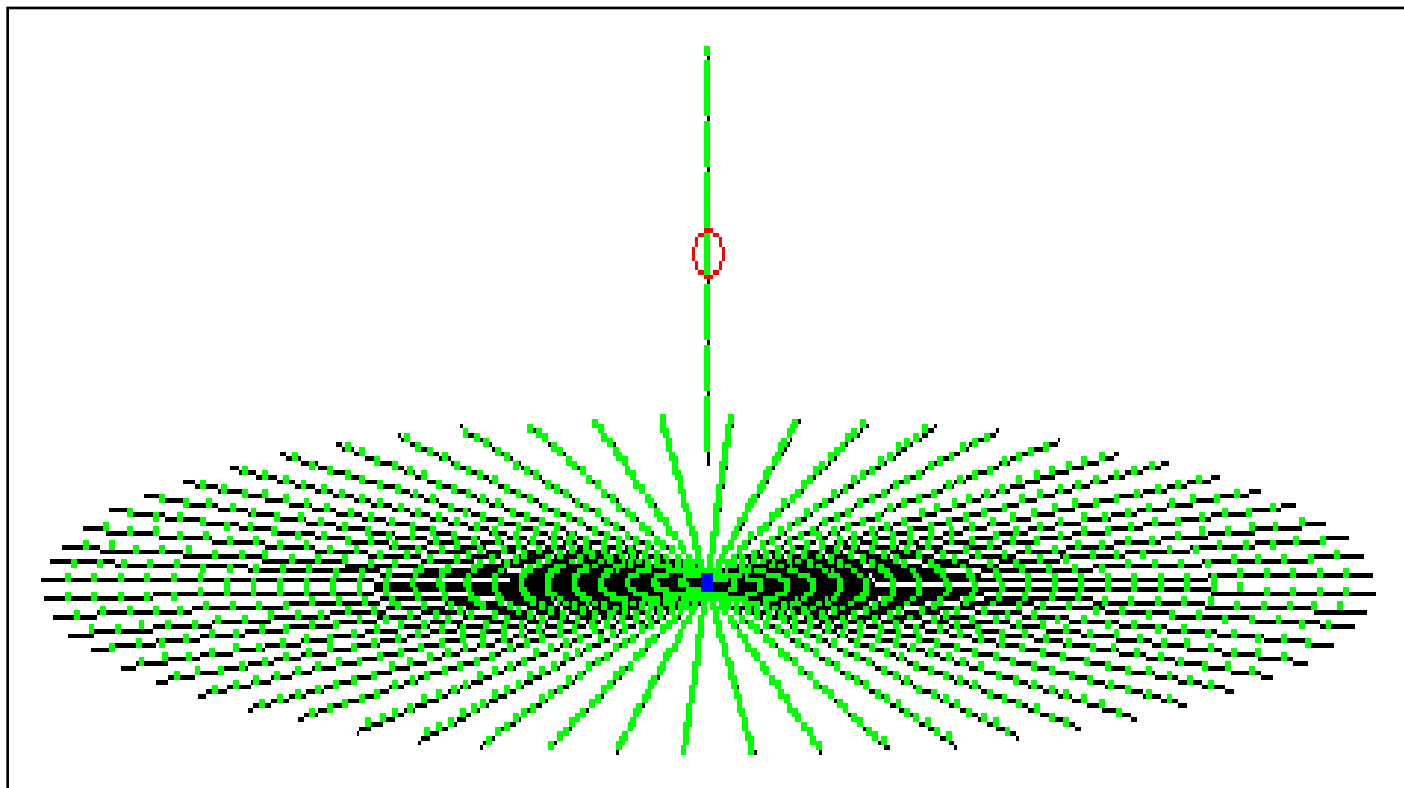


Figure A4.12 - Antenna with a buried radial ground system.

In the case of the lamp over the surface of a pond if we wanted to reduce the light lost into the water we could simply install a mirror on the surface under the lamp. The greater the mirror diameter the less light lost. We can do exactly the same thing with the antenna in figure A4.9 by placing a buried radial system under the antenna as shown in figure A4.12.

In this example there are 60 radials buried 1' in average soil (0.005/13). The radials are connected at the center but are not connected to the vertical conductor. The radial lengths are varied from 50' to 150' for the P_z calculations shown in figure 4.13.

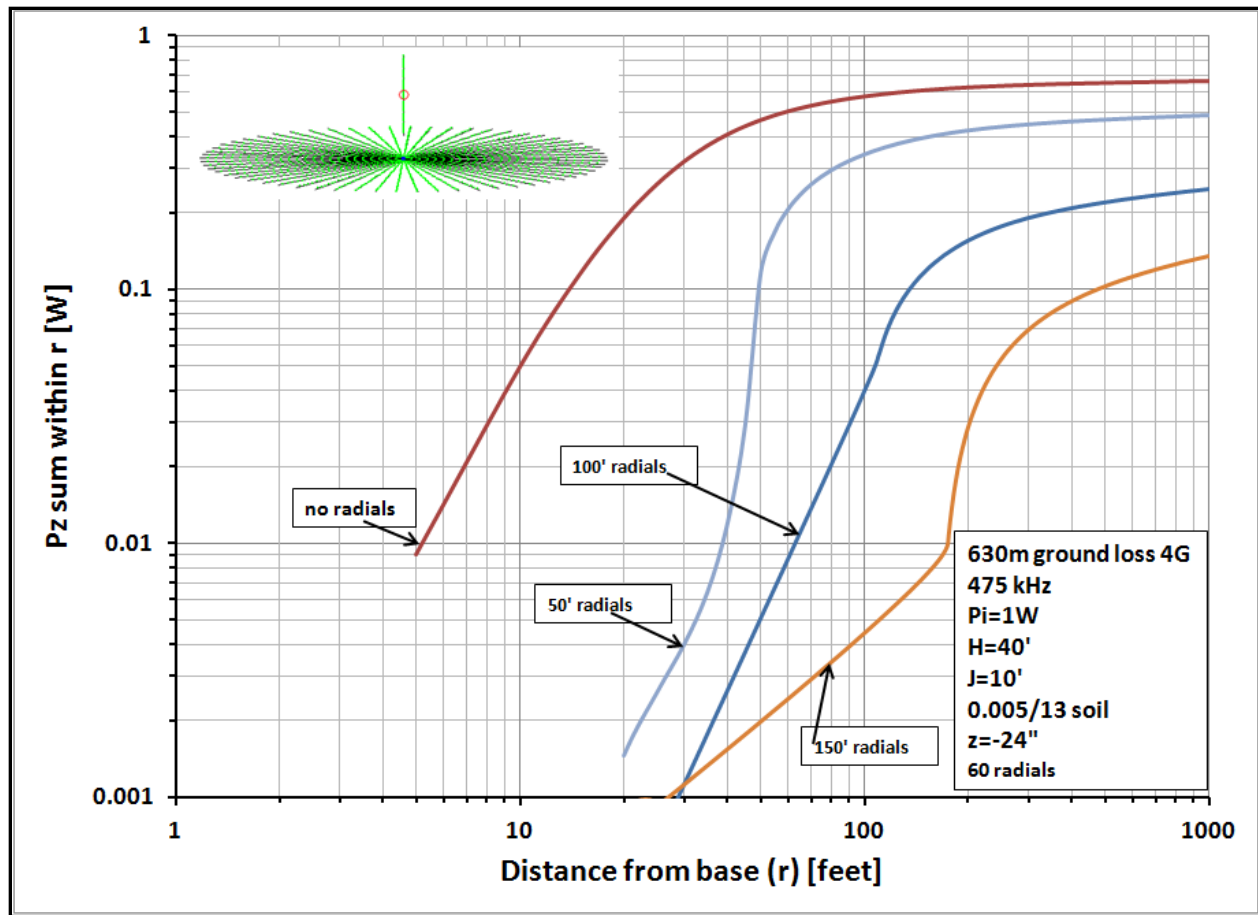


Figure A4.13 - P_z sum: 60 radials, 50', 100' and 150', $z=-24''$.

The radial system is not a perfect "mirror". Its effectiveness will depend on the number of radials and their length. More numerous and/or longer radials make for a better "mirror" and lower soil loss.

From the graph we can see how effective a radial ground system can be in reducing P_g in the soil under a vertical. As the radials are made longer the power absorbed under the ground system is drastically reduced, extending the radial lengths extends the radius of the "mirror". The number of radials is also important because the reflectivity of the ground system improves as the wires are brought closer together which is what happens when more numerous radials are used as illustrated in figure 4.14.

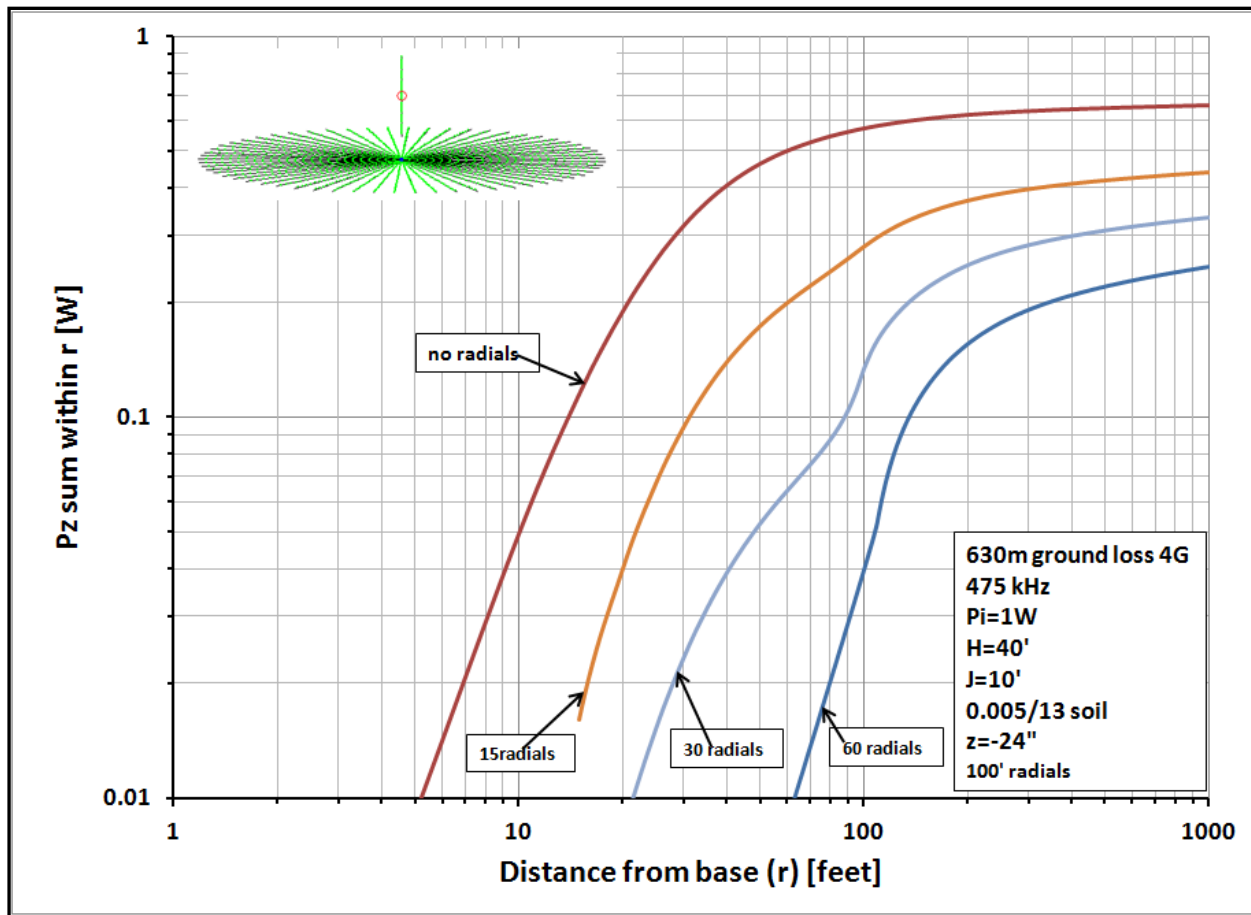


Figure 4.14 - The effect of radial number on P_z .

A4.7 P_g in a grounded vertical

The antenna example in figure A4.9 was useful for explaining P_g but the antenna itself is not very practical, at least at LF-MF. Let's now look at a much more typical 630m amateur antenna, the top-loaded vertical shown in figure 4.15 with two different ground system options: a single long ground stake and an extensive buried radial wire system. $H=50'$ and the 8-spoke hat has a radius of 15' and a skirt wire. The ground stake is 1" in diameter and extends into the soil 50'. The radial system has thirty 50' radials buried 1'. This exercise illustrates the shortcomings of a simple ground stake system.

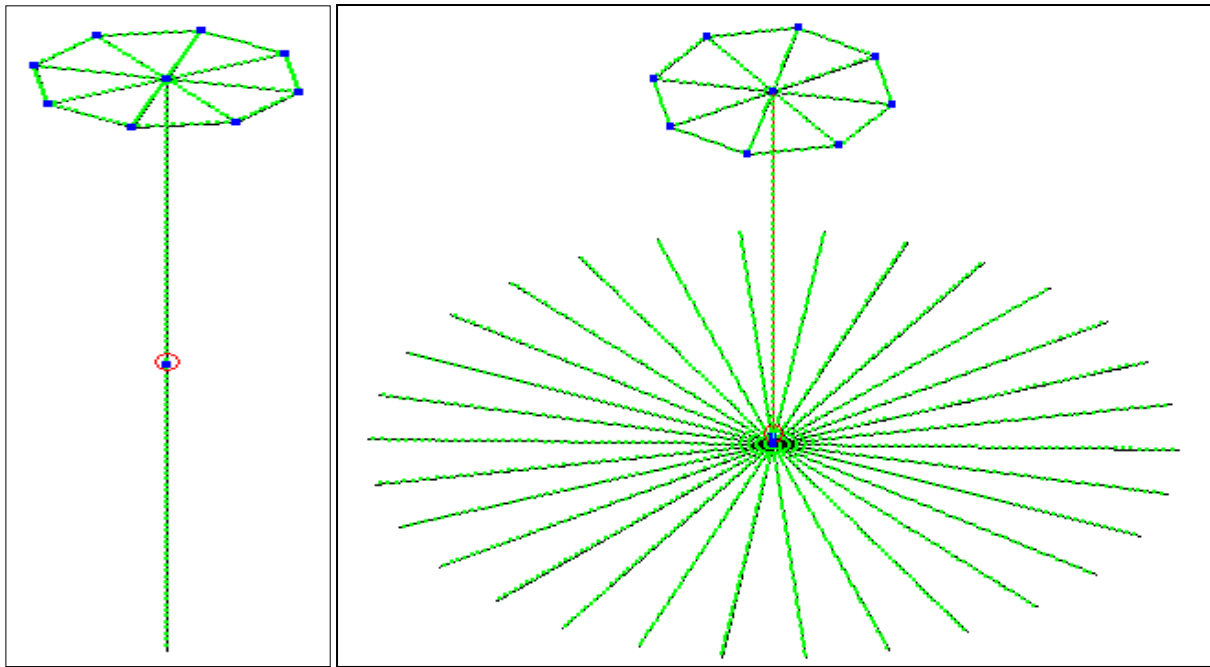


Figure 4.15 - 630m top-loaded vertical with two ground systems.

As indicated in figure 4.16, P_z represents the power radiated downward into the soil and P_x represents the power radiated from the ground rod.

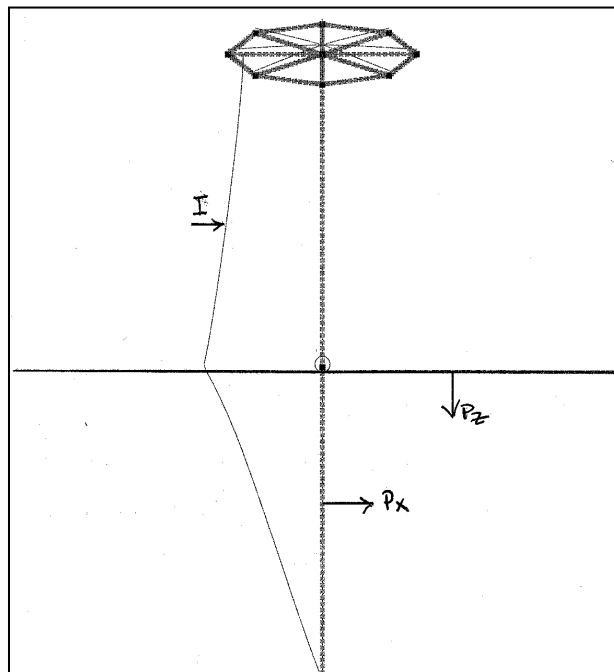


Figure 4.16 - Ground loss model using refraction.

When we do the calculation assuming $RL=0$ and $P_i=1W$, we get the following result: $P_r=0.03W$, $P_z=0.27W$ and $P_x=0.70W$. The efficiency is about 3% with 27% the power being refracted into the soil from the upper part of the antenna and 70% is radiated

from the lower half of the antenna directly into the soil! this picture also emphasizes that the ground rod is not just a auxiliary element, it is a radiating part of the antenna!

If we replace the ground rod with the radial system we find for $P_i=1W$, $P_r=0.24W$ and $P_g=0.76W$. The radial ground system increases the radiation efficiency from 3% to 24%! A larger ground system would further improve the efficiency.

At this point we've seen a general argument why we might want to use a ground system with a vertical. The practical details are more complicated and there are different kinds of ground systems, not just buried radial systems. More details are given in chapters 5 & 6.

4.8 Radial systems as reflectors

The concept that a wire ground system could be viewed as a mirror or reflector for EM waves has been carefully investigated from the very earliest days of Radio by many researchers^[37-43]. There are several variables: polarization of the EM wave, arrangement of the wires, the distance between the wires and the ground and the characteristics of the soil. Solving this problem for the general case requires some pretty advanced mathematics but fortunately the nature of the fields around a verticals usually allows us to use a simpler approximation.

We can understand the interaction of the field on this combination of soil and grating by using a transmission line analogy shown in figure A4.17.....

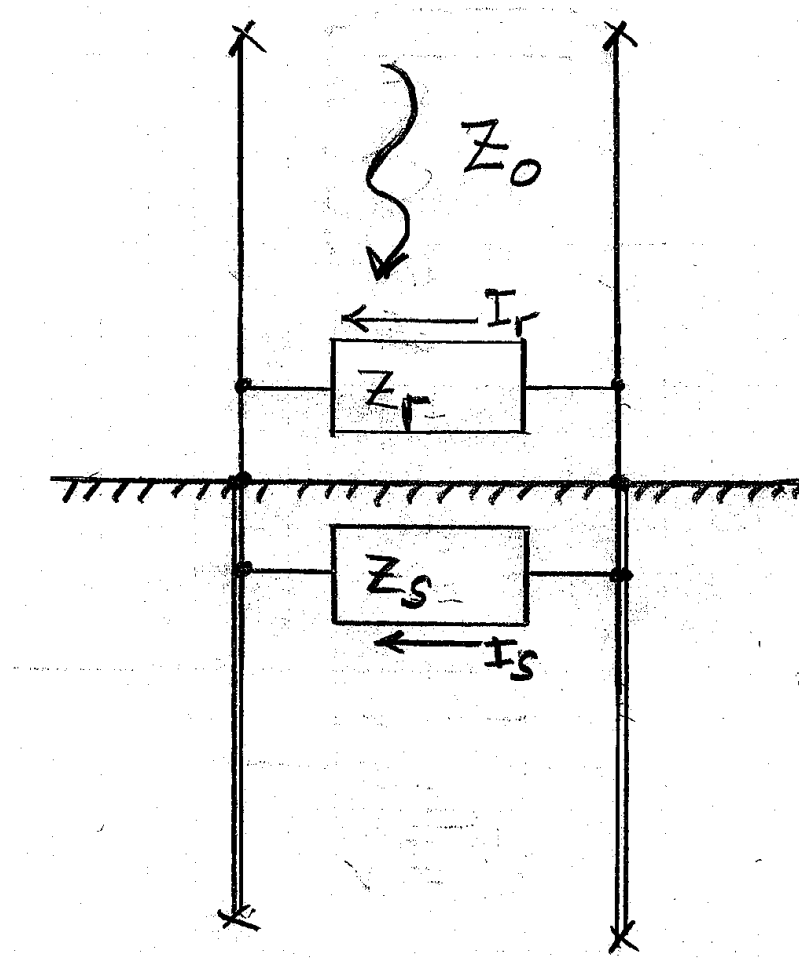


Figure 4.17 - Transmission line analogy.

A wave traveling in free space is equivalent to a wave traveling along a ideal transmission line with a characteristic impedance Z_0 . The space above ground is represented by a parallel wire transmission line with an impedance equal to free space, i.e.:

$$Z_0 = \sqrt{\frac{\mu_0}{\epsilon_0}} = \frac{E}{H} = 376.7\Omega \quad (\text{A4.5})$$

The grating can be viewed as an array of parallel two-wire transmission lines with a characteristic impedance Z_r :

$$Z_r = jX_r = j \left[f \mu_0 d' \ln \left(\frac{d'}{\pi d} \right) \right] \quad (\text{A4.6})$$

Where: d' = wire spacing and d =wire diameter in meters. Note that Z_r is an inductance with no dissipation. This is not strictly correct, ground system wires will have some loss but it's usually small. We also have to realize the equation (A4.6) is valid only for $d' < \lambda$ ^[tbd-Abbott]. Typically you have to keep $d' < 2.5 \text{ m}$ at 475 kHz.

When the ground system is arranged in a radial fan like that shown in figure A4.8 the spacing (d') between the radial wires will vary with the distance from the base (L') and the number of radials (N):

$$d' = 2L' \tan\left(\frac{\pi}{N}\right) \quad (\text{A4.7})$$

The soil can also be represented by a transmission line but we have to take into account the conductivity (σ) and relative permeability (ϵ_r) to determine the characteristic impedance Z_s :

$$Z_s = \frac{Z_o}{\sqrt{\epsilon_r}} \left(\frac{1}{\sqrt{1-jD}} \right) \quad (\text{A4.8})$$

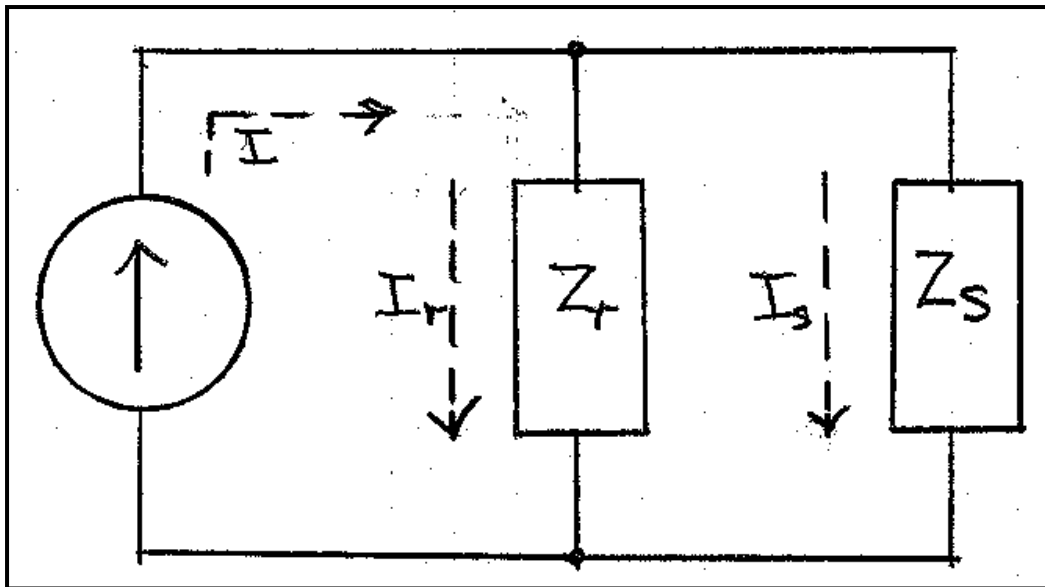


Figure A4.15 - Z_r - Z_s equivalent circuit.

As indicated in figure A4.14 We can join the three transmission lines (air, wire grid and soil) which gives us the equivalent circuit shown in figure A4.15. Keep in mind this is an analogy, I represents the incoming wave, I_r represents the portion of the wave

diverted into the ground system and I_s represents the portion of the wave absorbed in the soil.

If Z_r is small compared to Z_s then very little energy will be delivered to Z_s and lost. What we want is $Z_r \ll Z_s$ so the majority of the current flows in the ground system and not the soil. The wave energy goes into inductive storage in Z_r and is reradiated, i.e. reflected. We can use this model along with some spreadsheet calculations to obtain guidance on wire spacing, wire size and radial numbers in ground systems. Most soils are capacitive so X_s is usually negative.

For calculations it helps to restate Z_s as:

$$Z_s = R_s + jX_s \quad (\text{A4.9})$$

Where:

$$R_s = |Z_s| \cos \theta, \quad X_s = -|Z_s| \sin \theta, \quad \theta = \frac{\tan^{-1}(D)}{2}$$

$$D \equiv \frac{\sigma}{\omega \epsilon}, \quad |Z_s| = \frac{Z_o}{\sqrt{\epsilon_r}} \left[\frac{1}{(1+D^2)^{1/4}} \right]$$

The power loss in the soil is proportional to:

$$P_g \propto \left| \frac{I_s}{I} \right|^2 \quad (\text{A4.10})$$

The smaller this ratio the better!

From figure A4.15:

$$\left| \frac{I_s}{I} \right| = \frac{|Z_r|}{|Z_r + Z_s|} = \frac{X_r}{\sqrt{R_s^2 + (X_r + X_s)^2}} \quad (\text{A4.11})$$

By plugging these equations into a spreadsheet we can create some informative graphs.

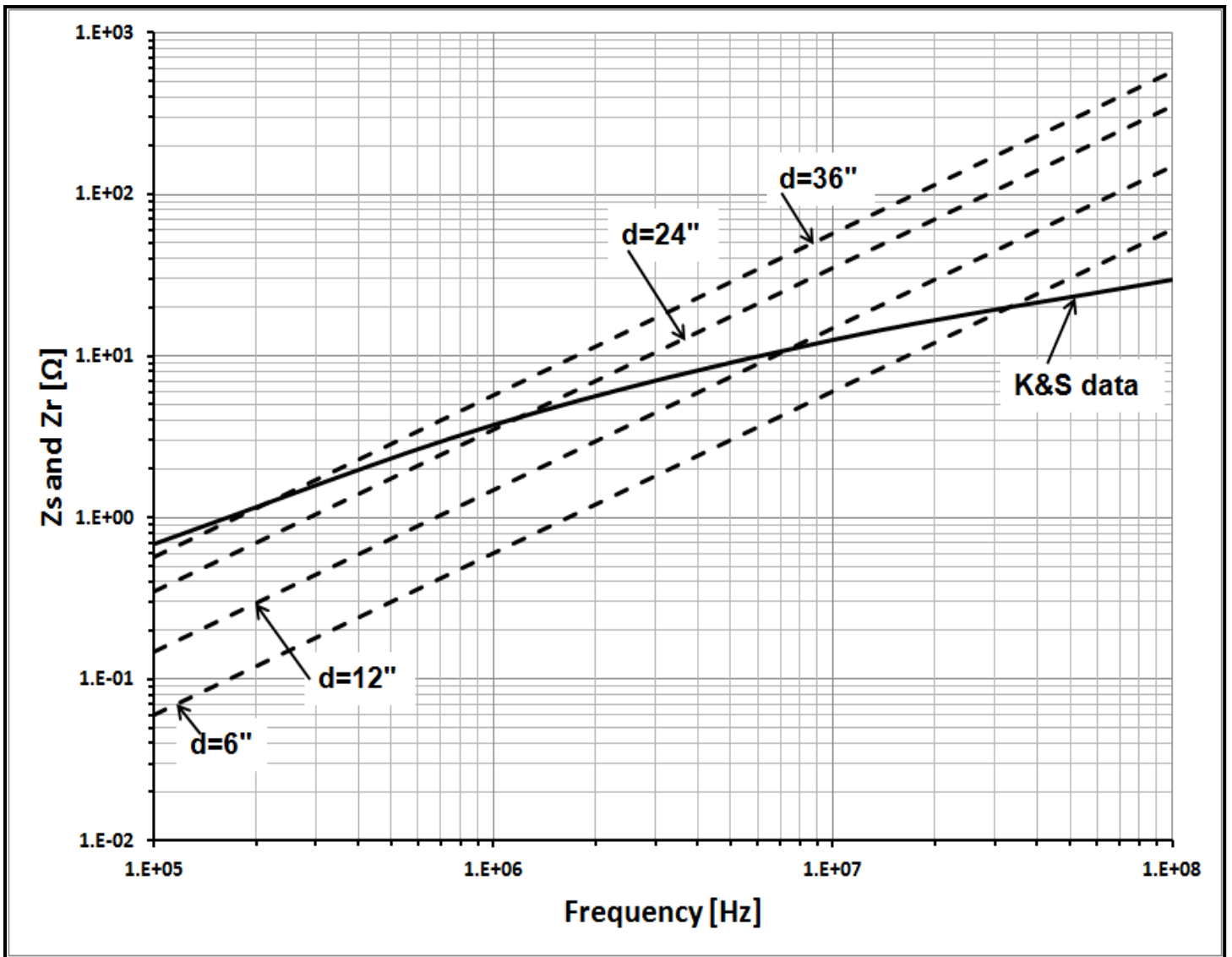


Figure A4.16 -

The solid line in figure A4.16 represents the value of Z_s for a typical soil as a function of frequency (100 kHz- 100 MHz). The data from which Z_s was calculated was taken from King and Smith^[tbd]. This particular data set is for moderate conductivity soil ($\sigma \approx 0.01$ S/m and $\epsilon_r \approx 60$ @ 475 kHz). An extensive discussion on soil electrical characteristic variations with frequency (dispersion) can be found in appendix TBD. The dashed lines in figure A4.16 represent Z_r for different spacing's ($d' = 6''$ -36'').

4.8 Radial ground systems

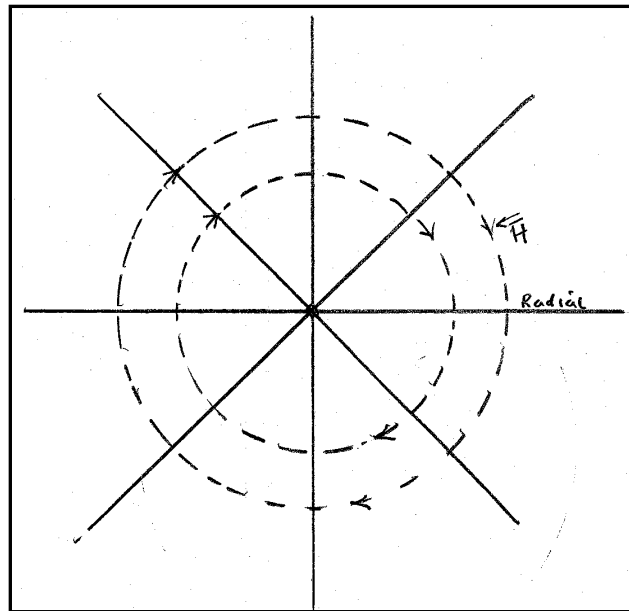


Figure 4.16 - Radial system for a vertical along with H-field lines.

Figure 4.16 is a view looking down on a vertical with a radial system. The solid lines represent the wire radials and the dashed lines indicate the magnetic field lines. Note, the field lines are perpendicular to the radial wires which is optimum. The optimum orientation of the wires combined with the simplicity of installing radial wires is why verticals typically use this configuration for a ground system. The disadvantage of this configuration is that as we go away from the base the spacing between the radial wires increases which increases Z_r reducing the proportion of current in the radials and increasing the soil current and associated losses. The way around this is to use more radials. Details on Z_r , Z_s and current division are given in chapter 9.

4.9 Mesh ground systems

Yet to be done!.....