Rr study appendix B

Soil characteristics at MF and HF

Introduction

The soil over which a vertical is installed has a profound effect on its performance and we need to understand the electrical characteristics of soil to design effective ground systems. This appendix describes the electrical properties of soils at both MF and HF and then discusses the effect of the soil characteristics on skin depth, wavelength in the soil, wave impedance and sky-wave radiation efficiency. All of these are helpful for understanding the design of ground systems and the interaction between the antenna and ground.

An equivalent circuit for soil

Figure B.1 shows an equivalent circuit for ground.

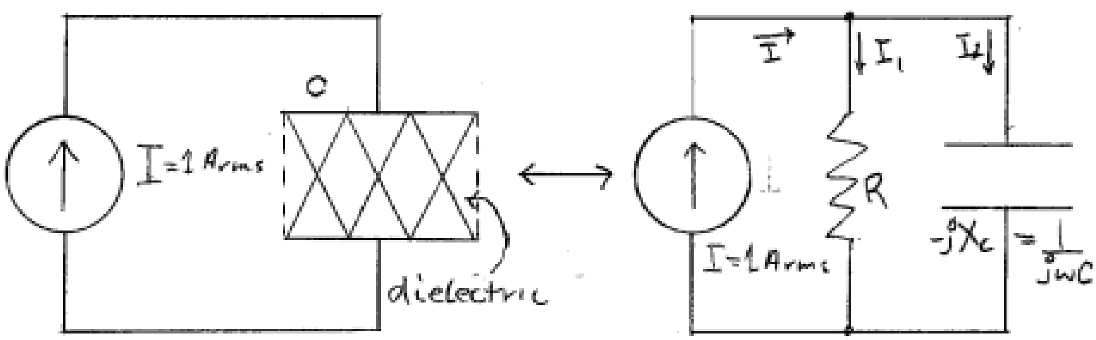

Figure B.1 - Equivalent circuit for ground.

The fields associated with a vertical will induce currents in the soil (I) which is a lossy dielectric material. Because soil is a dielectric we characterize it in terms of relative permittivity or relative dielectric constant, (ε_{er}) and conductivity (σ_e) but we have to be careful with our definitions. σ_e and ε_{er} are not the usual low frequency conductivity and relative dielectric constant we are accustomed to. σ_e is the "effective" conductivity and ε_{er} is the "effective" permittivity which takes into account the effects associated with both conduction and dielectric polarization in the soil[4]. At low frequencies where the soil characteristics are dominated by conduction losses, the conventional measurement of σ using low frequency AC is fine but not at HF where polarization effects are significant. σ_e and ε_{er} are the macroscopic quantities used in NEC modeling.

Table 1 gives some useful definitions. Commonly used pairs of values for σ_e and ε_{er} used in NEC modeling are given in table 2[4].

Table 1, some useful definitions

$\varepsilon_e = \varepsilon_o \varepsilon_{er}$ = effective permittivity or dielectric constant [Farads/m]
ε_o = permittivity of a vacuum = 8.854×10^{-12} [Farads/m]
ε_{er} = relative permittivity or relative dielectric constant, where: $\varepsilon_{er} = \frac{\varepsilon_e}{\varepsilon_o}$
σ_e = effective ground conductivity [Siemens/m]
$\omega = 2\pi f$, where f = frequency in Hertz
loss tangent or dissipation factor: T or D = $\tan\delta = \frac{\sigma_e}{\omega\varepsilon_e}$
good insulator, D << 1
good conductor, D >> 1
for a lossy dielectric D will be in the vicinity of 1

Table 2, σ_e and ε_{er} pairs for common types of soil

Soil type	σ_e [S/m]	ε_{er}	D @ 3.5 MHz
Fresh water	0.001	80	0.064
Salt water	5	81	317
Very good	.03	20	7.7
Average	0.005	13	1.98
Poor	.002	13	0.79
Very poor	0.001	5	1.03
Extremely poor	0.001	3	1.71

The E and H near-fields associated with a vertical will induce currents in the soil and these in turn create loss. The current and the associated loss will depend on the antenna, the ground system, the frequency and the soil characteristics. Referring to figure B.1, for a given current I, the current in R will be I_1:

$$I_1 = \left(\frac{-jXc}{R - jXc}\right) I = \left(\frac{Xc}{Xc + jR}\right) I$$

The power dissipation in R (P_d) for I=1Arms is expressed by:

$$P_d = R|I_1|^2 = \frac{RXc^2}{R^2 + Xc^2}$$

We can find the maximum value for P_d by taking the derivative with respect to R and setting it equal to zero. When we do that we find that the maximum value for Pd occurs for R=Xc, at which point the phase shift between the current and the voltage will be 45° (π/4 radians). R=Xc corresponds to a loss tangent of one (D=1).

In graphs of various parameters such as skin depth or **Rr**, a loss tangent equal to one often represents a critical turning point, especially as we transition from MF to HF.

The values in table 2 are only examples. It is possible to have much larger values of ε_{er} for a given σ_e in some soils. In general as the moisture content of the soil increases both σ_e and ε_{er} will increase. Examples of the effect of soil moisture content on σ_e and ε_{er} are given in figures B.2 through B.5.

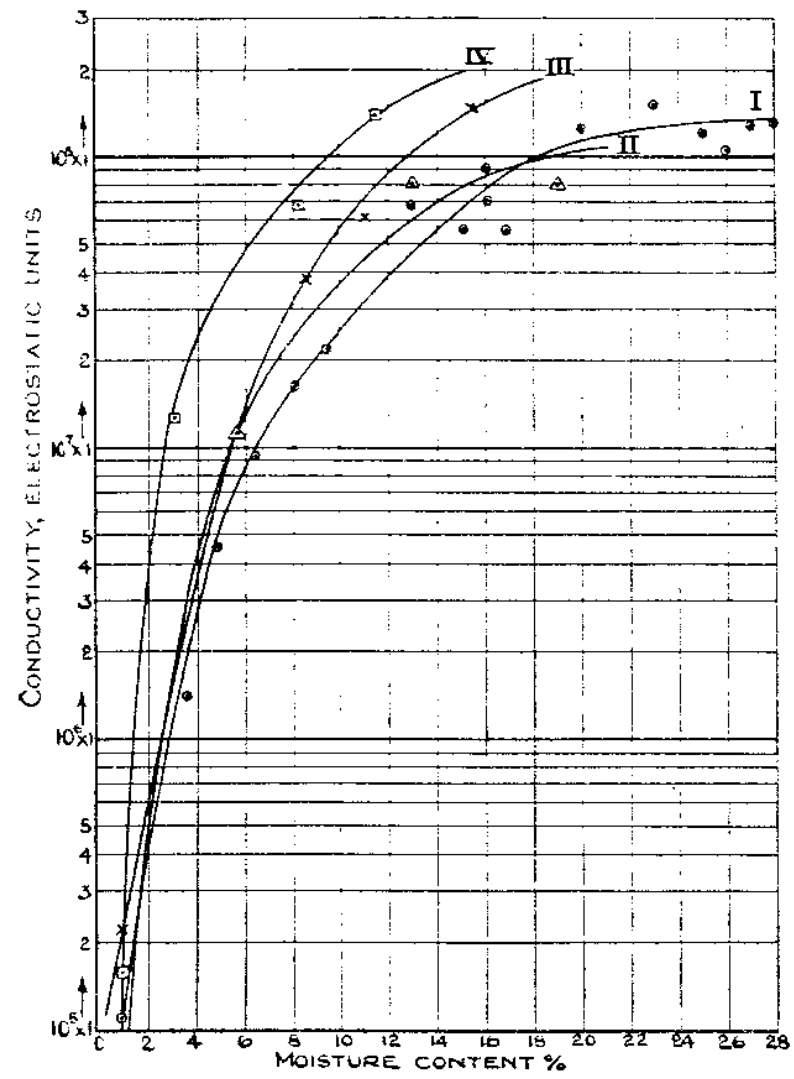

Figure B.2 - Examples of σ_e at 1.2 MHz at several different sites as a function of moisture content.

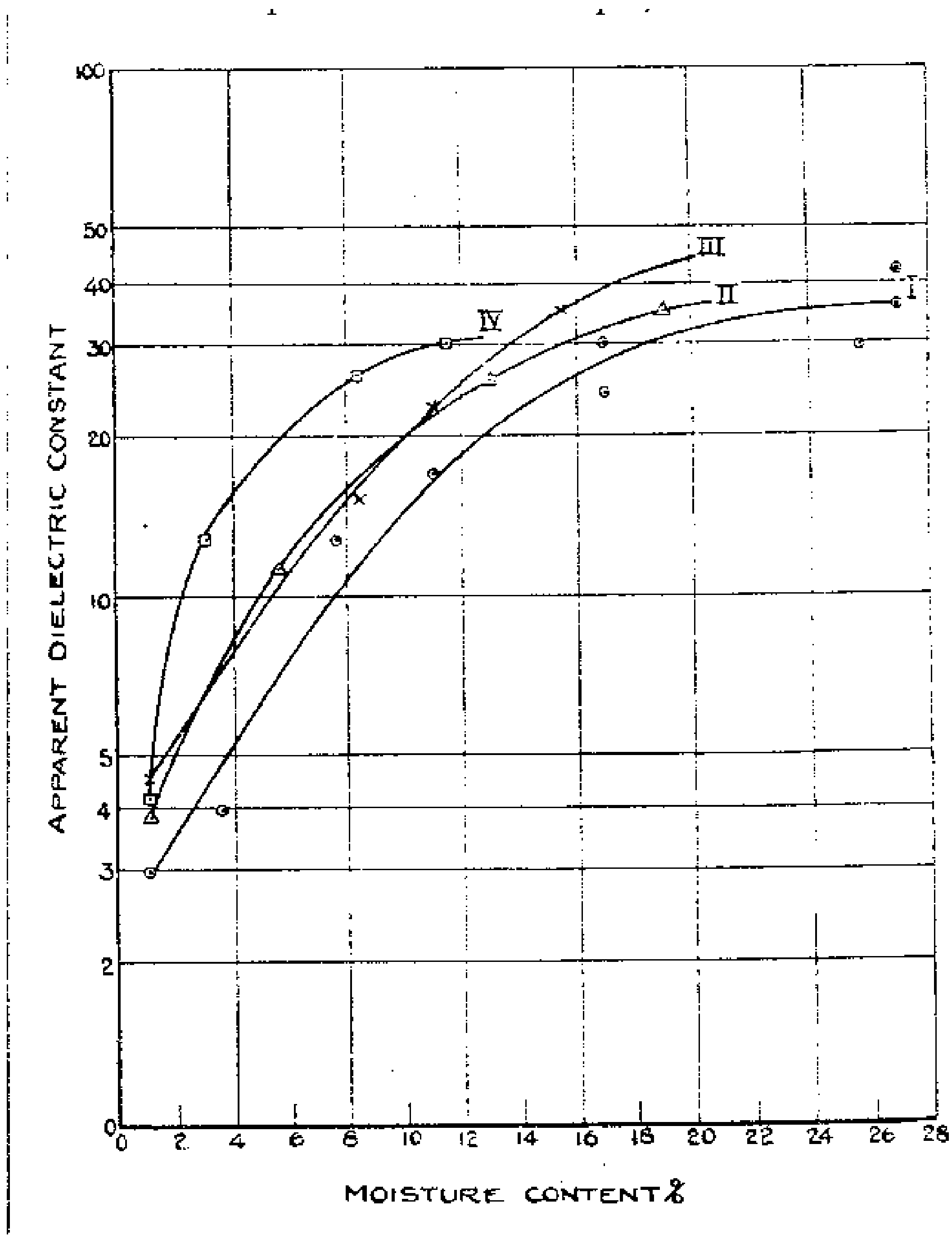

Figure B.3 - Examples of ε_{er} at 1.2 MHz at several different sites as a function of moisture content.

The graphs in figures B.2 and B.3 were taken from Smith-Rose[2], σ_e is in esu, to convert from esu to S/m multiply by 1.11×10^{-9}: 10^7 esu = 0.011 S/m.

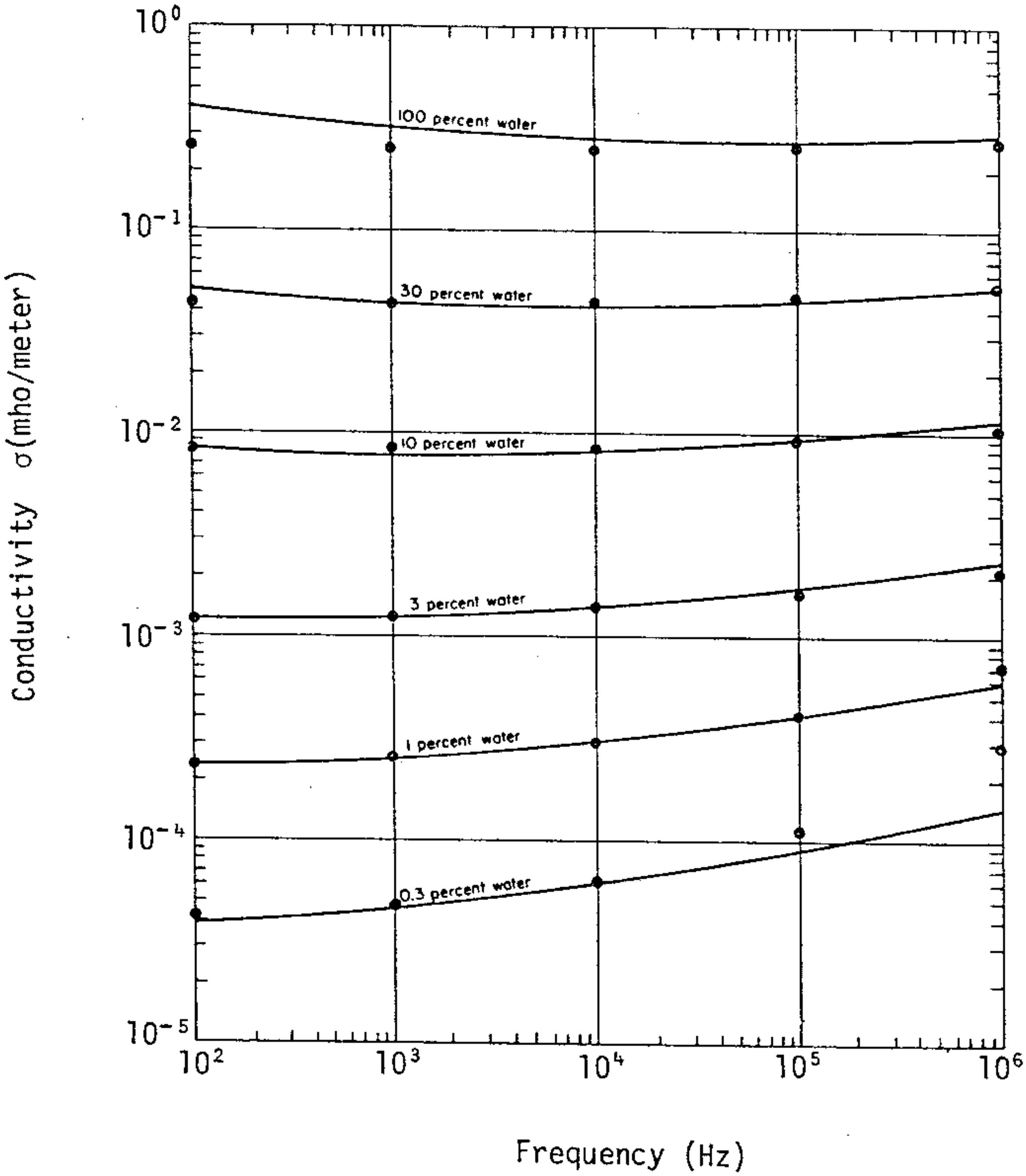

Figure B.4 - Examples of conductivity variation with moisture content and frequency.

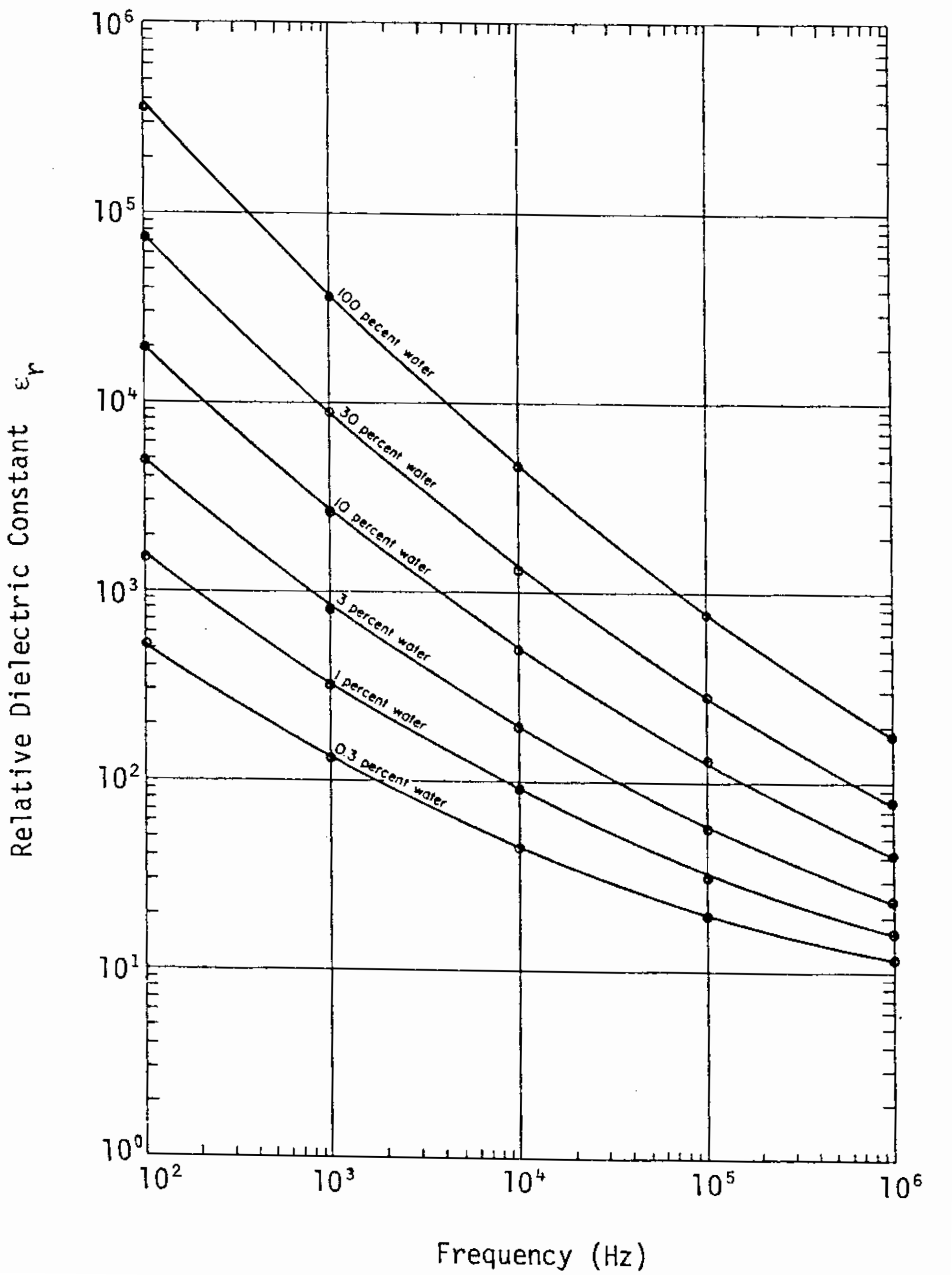

Figure B.5 - Examples of relative permeability variation with moisture content and frequency.

Figures B.4 and B.5 were taken from Longmire and Smith[5]. Note the large changes in both σ_e and ε_{er} with moisture content. σ_e and ε_{er} can change by 1 to 2 orders of magnitude! If you live in an area with a wet season followed by an extended dry season (the western US for example) you should expect large changes in your soil characteristics on a seasonal basis. It's best to design your ground system for the worst case. In addition to seasonal variations, most soils will be vary vertically (often stratified) and horizontally. In soils which have been disturbed for construction, agriculture or other reasons, the variations can be quite large over distances of only a few feet.

Those stations located in northern climates where freezing of the soil occurs may need to consider the often radical difference in soil characteristics between frozen and thawed states. Figures B.6 and B.7 illustrate the effect of temperature on σ_e and ε_{er}.

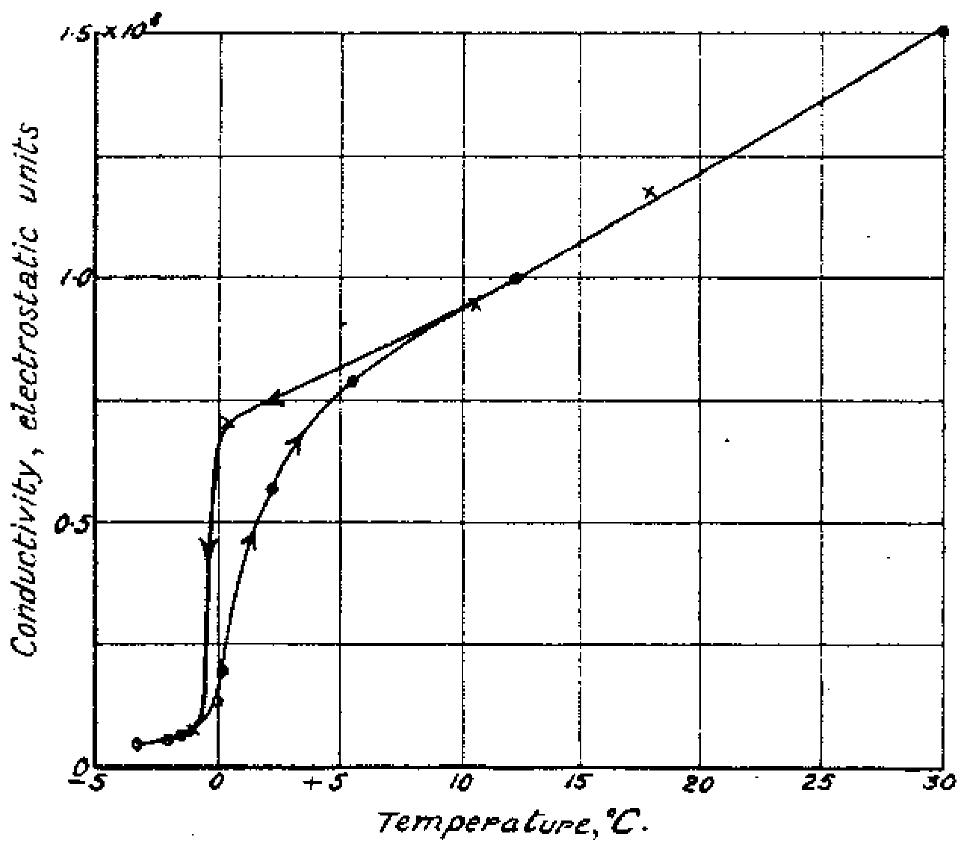

Figure B.6 - Conductivity Variation with temperature.

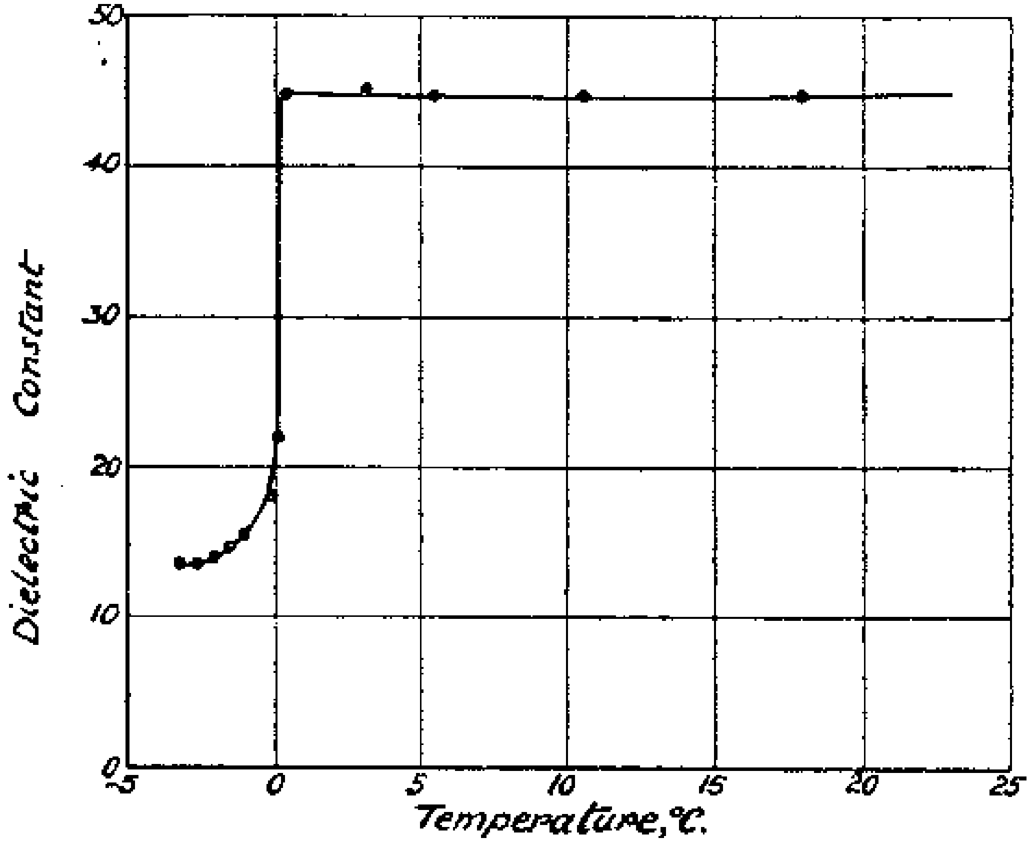

figure B.7 - Dielectric constant variation with temperature.

The graphs in figures B.6 and B.7 were taken from Smith-Rose[2], σ_e is in esu, to convert from esu to S/m multiply by 1.11×10^{-9}: 10^7 esu = 0.011 S/m.

There is an abrupt change in both σ_e and ε_{er} at the temperature (0˚ C) where the ground freezes. In most cases unless you live very far north, the depth of frozen soil will not be more than a foot or two. This might be a problem on 10m where the skin depth can be of that order but for at 160m the skin depth is much greater and all you might see is some detuning of the antenna.

Dispersion in soil characteristics

Variation of an electrical characteristic with frequency is termed "dispersion". Changes of soil electrical characteristics with frequency have been known since the early 1930's[2,3] but from the earliest days of radio amateurs have followed the lead of broadcast engineers in considering the conductivity of the soil to be the number one consideration. For convenience, conductivity is typically measured at a low frequency (50-60 Hz) using four probes[1]. While this technique is simple and useful at MF it's not appropriate at HF[7]. Below 1 MHz most soils are basically resistive and conductivity is the key characteristic, however, at HF most soils are both resistive and reactive and have electrical characteristics quite different from that seen at MF.

Figures B.8 and B.9 are examples of σ_e and ε_{er} for a typical soil over a frequency range from 100 Hz to 100 MHz. These graphs were generated using data excerpted from King and Smith[8]. Two important points are shown. First, σ_e varies little below 1 MHz. At those frequencies 60 Hz measurements for σ_e are useful but above 1 MHz σ_e rises significantly to values very different from the LF values.

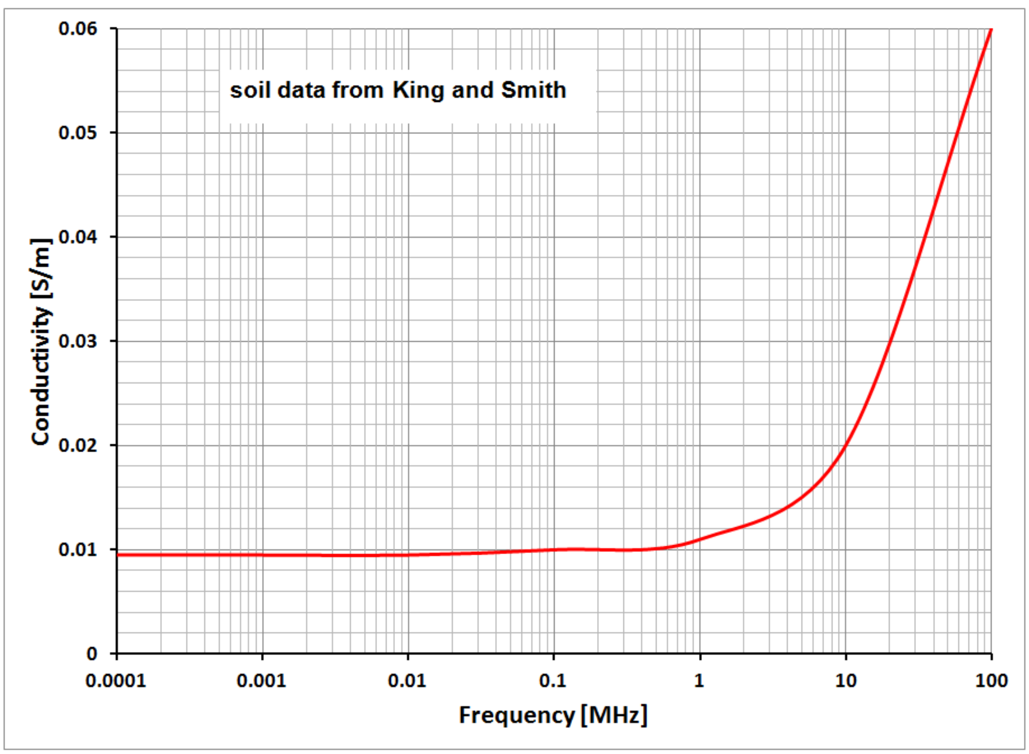

Figure B.8 - Example of soil conductivity variation with frequency.

The second point is that the behavior of ε_{er} is also very different above and below 1 MHz.

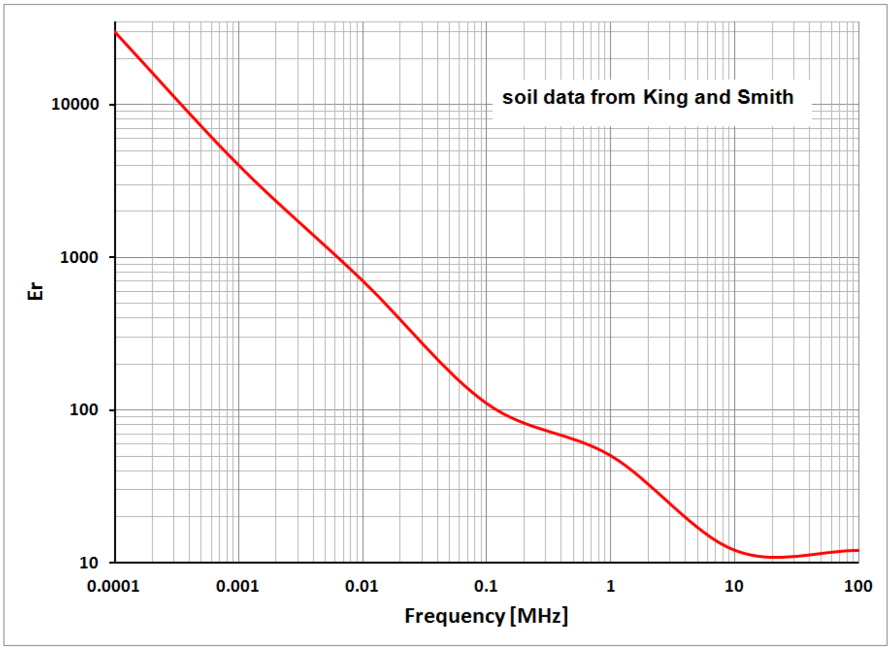

Figure B.9 - Example of soil permittivity variation with frequency.

In this example at 100 Hz σ≈0.09 S/m and that value is relatively constant up to 1 MHz beyond which σ_e increases rapidly. ε_{er} behaves just the opposite, decreasing with frequency until about 10 MHz and then leveling out. The very large values for ε_{er} at low frequencies may come as a surprise and in the past it was thought that this was an artifact of the probe-soil interface but an explanation has been suggested by Longmire and Smith[5]:

> "The very large dielectric constant at lower frequencies, much larger than the value 80 for pure water, is puzzling if one thinks in terms of good dielectric materials. Soils typically contain a broad size spectrum of crystalline grains, with electrolytically conducting fissures between. One is reminded somewhat of the behavior of electrolytic capacitors."

It is generally accepted that the large values for ε_{er} are real and not an artifact of the measurement process.

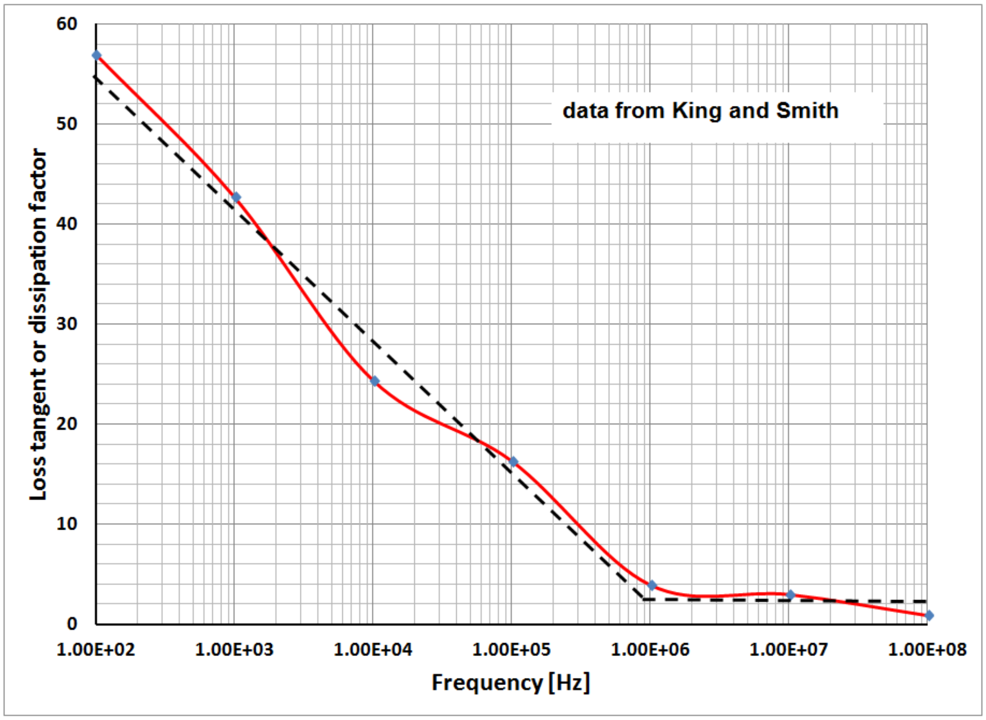

Figure B.10 - Graph of the loss tangent associated figures B.3 and B.4.

As shown in figure B.10 we can combine the data in figures B.8 and B.9 into a graph for the loss tangent: $D = \tan\delta = \frac{\sigma_e}{2\pi f \varepsilon_e}$. For most soils at HF $0.1<D<10$ but it is often close to 1 which, as shown earlier, is the worst case.

Figure B.10 shows something interesting happening as we transition from MF to HF. At HF D is usually not far from 1 but at MF D is usually much higher which implies the soil characteristics are dominated by the conductivity.

More detailed graphs for σ_e and ε_{er} in the HF region have been drawn from test measurements by Hagn[6]. Examples are shown in figures B.11 and B.12.

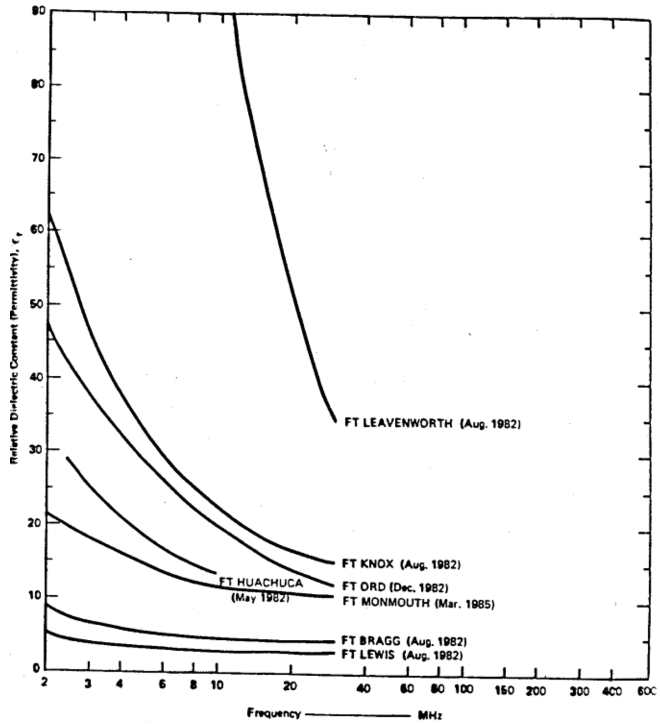

Figure B.11 - Graph from Hagn[6] for σ_e at different locations

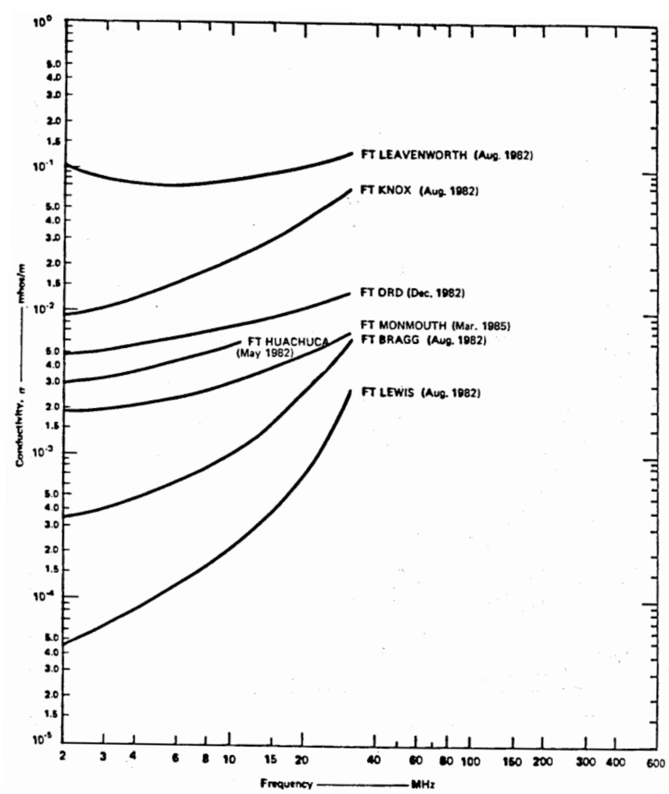

Figure B.12 - Graph from Hagn[6] for ε_{er} at different locations.

This kind of general information is interesting but not directly useful for a particular QTH. Figures B.13 and B.14 show results of localized soil measurements at two sites at the N6LF QTH.

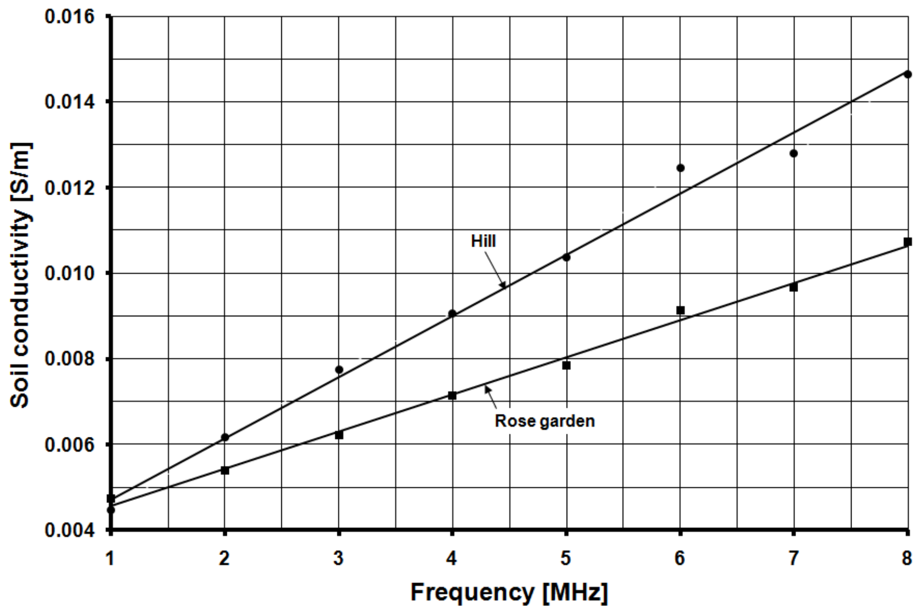

Figure B.13 - σ_e at two sites at N6LF's QTH.

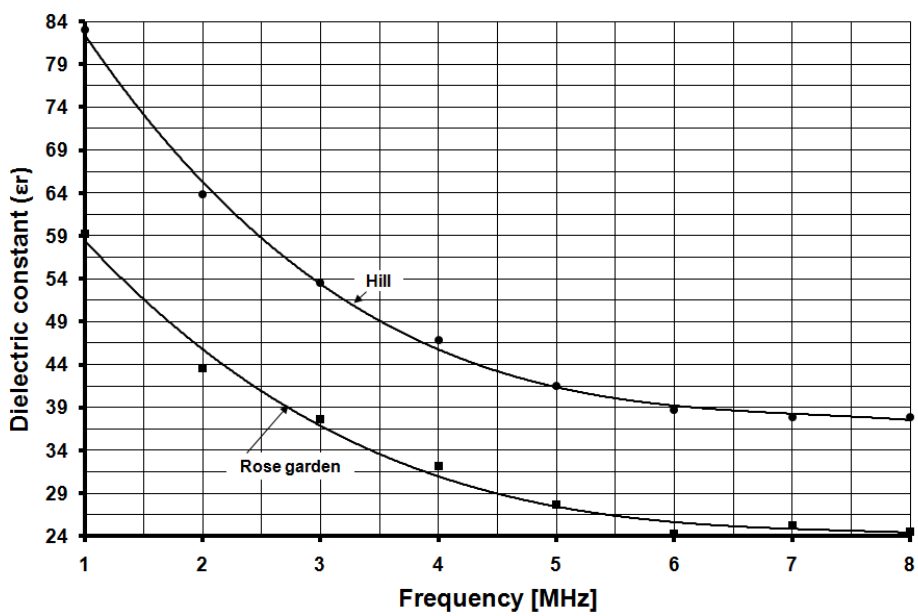

Figure B.14 - ε_{er} at two sites at N6LF's QTH.

The loss tangent associated with the values in figures B.13 and B.14 is graphed in figure B.15.

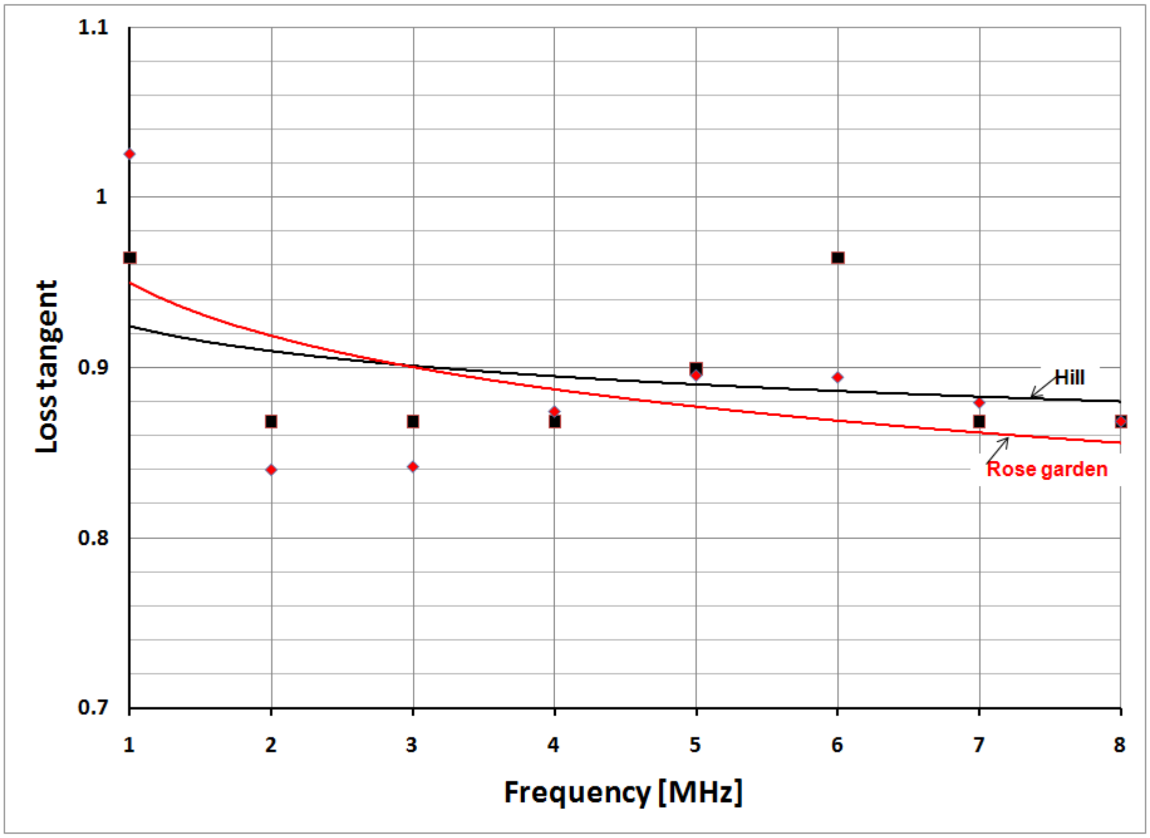

Figure B.15 - loss tangent (D) associated with figures B.13 and B.14.

The raw measurement data points are indicated by black squares (hill) and red diamonds (rose garden). Logarithmic trend lines are shown for the two locations. It's interesting that the loss tangent is quite similar for both sites and relatively stable over frequency. Note also that D is not too far from 1.

Now that we have a general idea of the characteristics of soils it's time to see how the variations effect such things as skin depth, wavelength in the soil, wave impedance and radiation efficiency.

Skin depth in soil

In many of the examples in this section and the following one on wavelength, I will not include the effect of dispersion. Instead I assume constant values for σ_e and ε_{er} over frequency. I do this for two reasons: first, it simplifies the discussion, making it much easier to follow and second, it shows that even if there were no dispersion in σ_e and ε_{er} the behavior at HF is still very different from that at MF. Dispersion is not the only root of the differences.

As radio waves penetrate into soil their amplitude is rapidly attenuated. The depth at which the amplitude of the wave is reduced to 1/e (≈0.37) of the value at the surface is called the "skin depth". Skin depth will depend on frequency and soil parameters. In general for the design of antenna ground systems we are interested in the soil characteristics down to one or two skin depths because this is the region in which the majority of the ground currents are flowing. Total ground losses are related to the skin depth.

The skin depth in a dielectric material is given by:

$$\delta = \left(\frac{\sqrt{2}}{\omega\sqrt{\mu\varepsilon_e}}\right)\left[\sqrt{1+\left(\frac{\sigma_e}{\omega\varepsilon_e}\right)^2}-1\right]^{-1/2} \qquad (1)$$

Where:

δ = skin or penetration depth

$\mu = \mu_r\mu_o$=permeability

μ_o= permeability of vacuum = $4\pi 10^{-7}$ [Henry/meter]

μ_r = relative permeability

For high conductivity materials like metals or sea water or soils at low frequencies where σ dominates we can simplify equation (1) to:

$$for\ \frac{\sigma_e}{\omega\varepsilon_e} \gg 1, \quad \delta \approx \frac{1}{\sqrt{\pi\sigma_e\mu f}} \qquad (2)$$

Equation (2) represents the low frequency approximation for equation (1). We can also derive the high frequency approximation for equation (1):

$$for\ \frac{\sigma_e}{\omega\varepsilon_e} \ll 1, \quad \delta \approx \frac{2}{\sigma}\sqrt{\frac{\varepsilon_e}{\mu}} \qquad (3)$$

These two asymptotes will intersect at the frequency where they're equal:

$$f_{crossover} = \frac{\sigma_e}{4\pi\varepsilon_e} = \frac{1}{2}\left(\frac{\sigma_e}{2\pi\varepsilon_e}\right) \qquad (4)$$

All of this can be summarized in a graph as shown in figure B.16 which is for σ_e = 0.005 S/m and ε_{er} = 13.

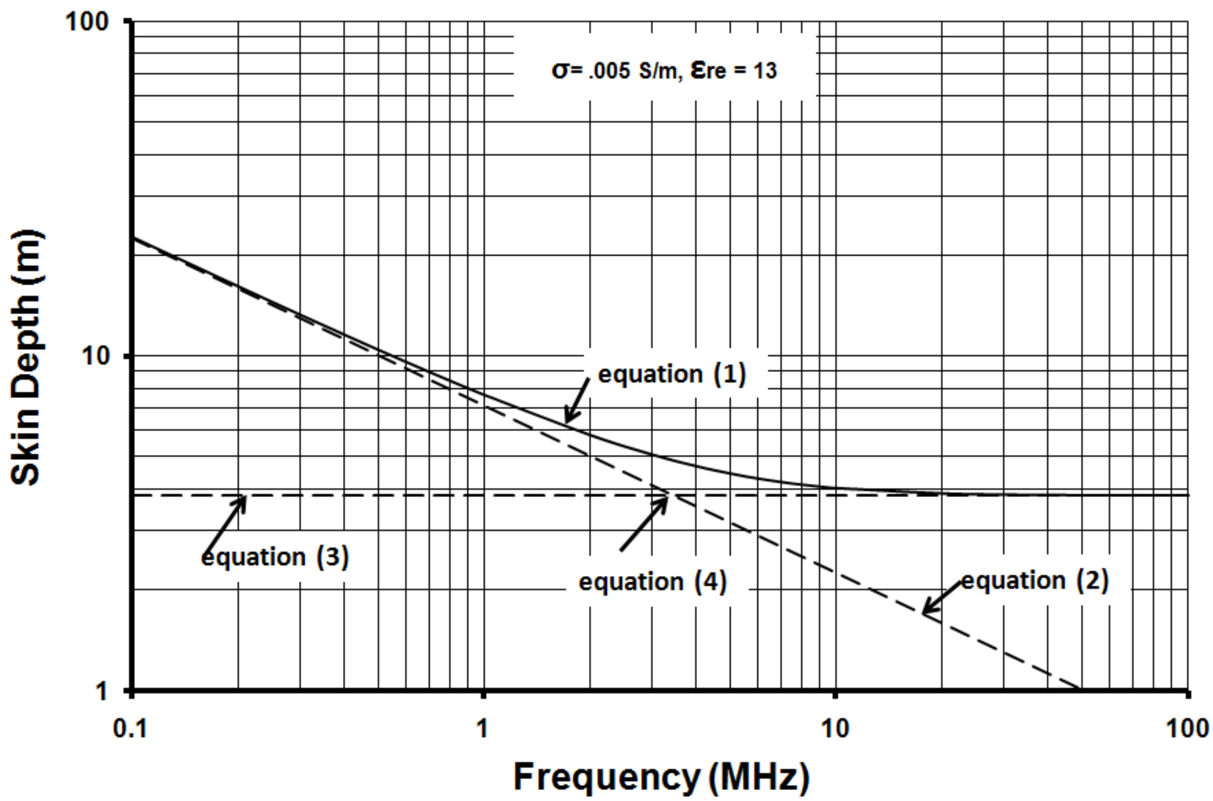

Figure B.16 - Relationships between the exact skin depth expression (equation 1) and the high frequency (equation 3) and low frequency (equation 2) approximations. The frequency of intersection of the asymptotes (equation 4) is also shown (≈3.4 MHz).

At low frequencies δ is dominated by σ_e but at HF both σ_e and ε_{er} play a role. We can explore this further by first holding ε_{er} constant and varying σ_e and then hold σ_e constant and vary ε_{er} as shown in figure B.17.

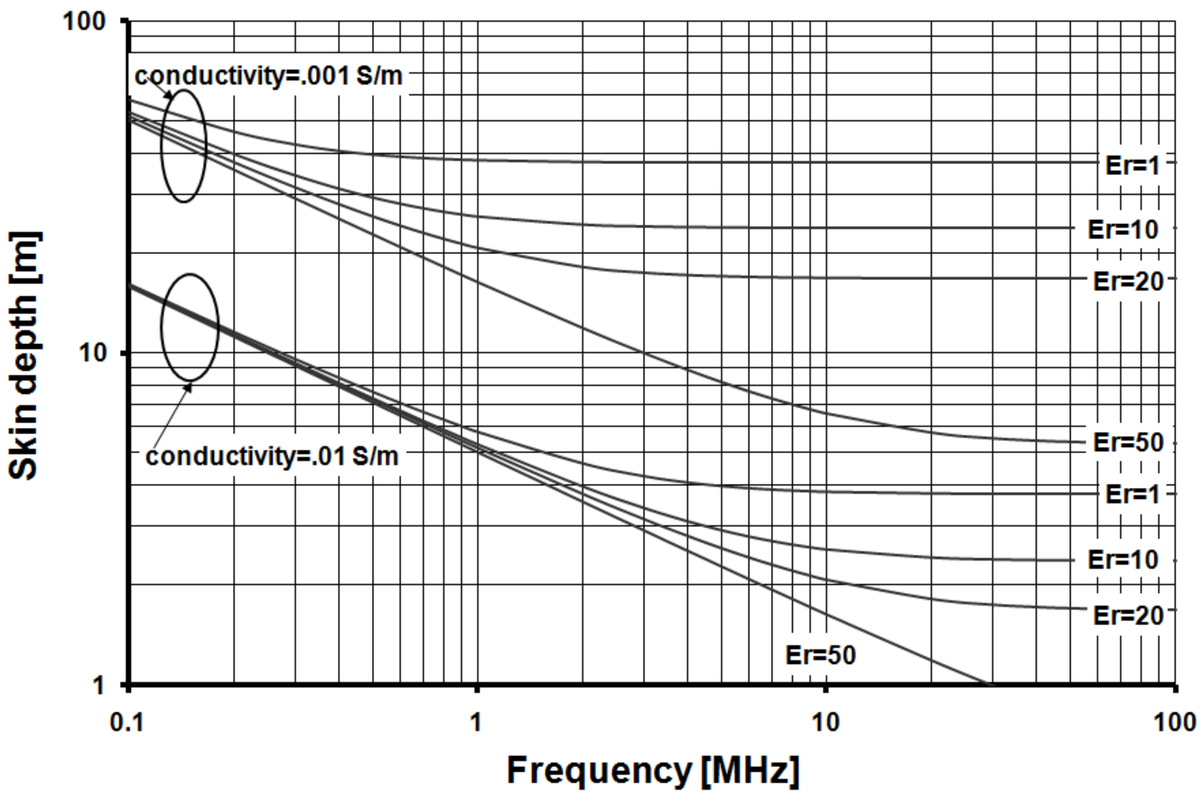

Figure B.17 - Examples of skin depth over frequency for different values of σ_e and ε_{er}.

The first thing that jumps out in figure B.17 is that at MF and below, ε_{er} doesn't matter much. δ is dominated by σ_e which is why BC engineers have typically not been concerned with permittivity.

Wavelength in soil

For reasonable accuracy using NEC modeling there are minimum and maximum limits on the length of the segments. Because the wavelength in soil is much shorter than in air the segments for those parts of the antenna which are within the soil must be shorter than they would be in air or free space.

In air or free space the wavelength (λ_o) is given by:

$$\lambda_o \approx \frac{300}{f_{MHz}} \quad [\text{m}] \qquad (5)$$

but the wavelength in soil (λ_s):

$$\lambda_s = \frac{\lambda_o}{\left[\varepsilon_{er}^2 + \left(\frac{\sigma_e}{\omega \varepsilon_o}\right)^2\right]^{1/4}} \quad [\text{m}] \quad (6)$$

Figure B.18 is a graph of equation (6) showing λ_s for fresh water, saltwater and several typical soils.

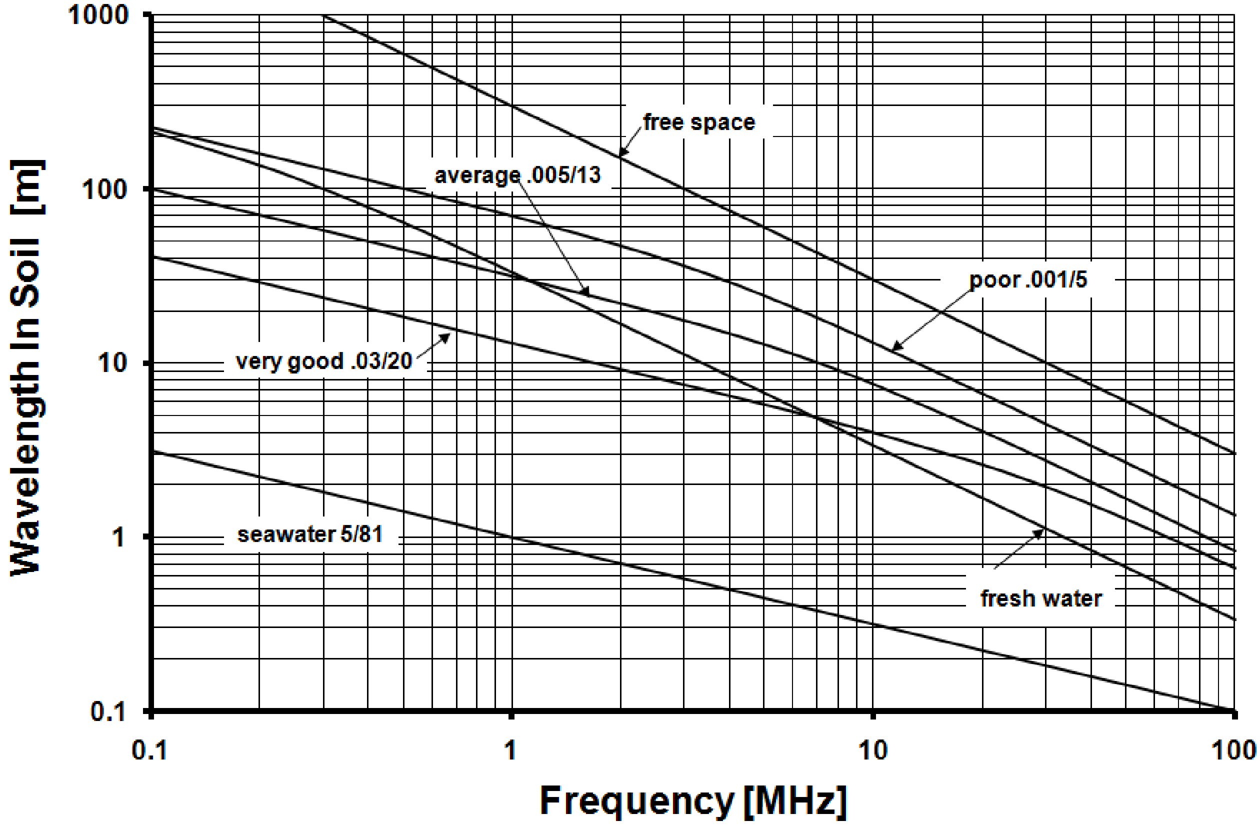

Figure B.18 - Wavelength [m] in freshwater, saltwater and several typical soils as a function of frequency.

While figure B.18 gives information for λ_s in a variety of soils, if we graph the ratio λ_s/λ_o we get a better picture of the differences between MF and HF as shown in figure B.19.

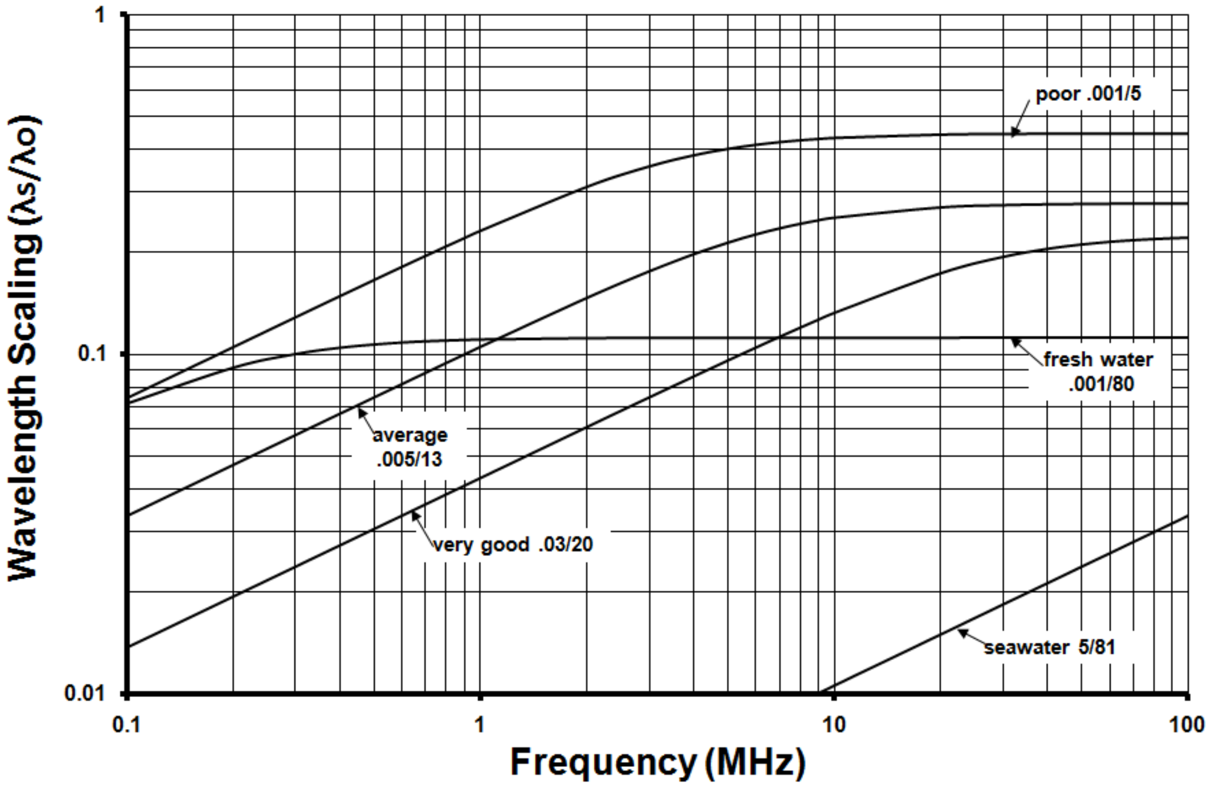

Figure B.19 - The ratio of the wavelength in soil to free space.

Figure B.19 gives us a good feeling for the differences between λ_o and λ_s both in magnitude and the variation with frequency. At MF and down, the reduction in λ_s is much greater than at higher frequencies and changes rapidly with frequency. We can explore the effects of σ_e versus ε_{er} by graphing λ_s/λ_o for a fixed σ_e and a range of values for ε_{er} as shown in figure B.20.

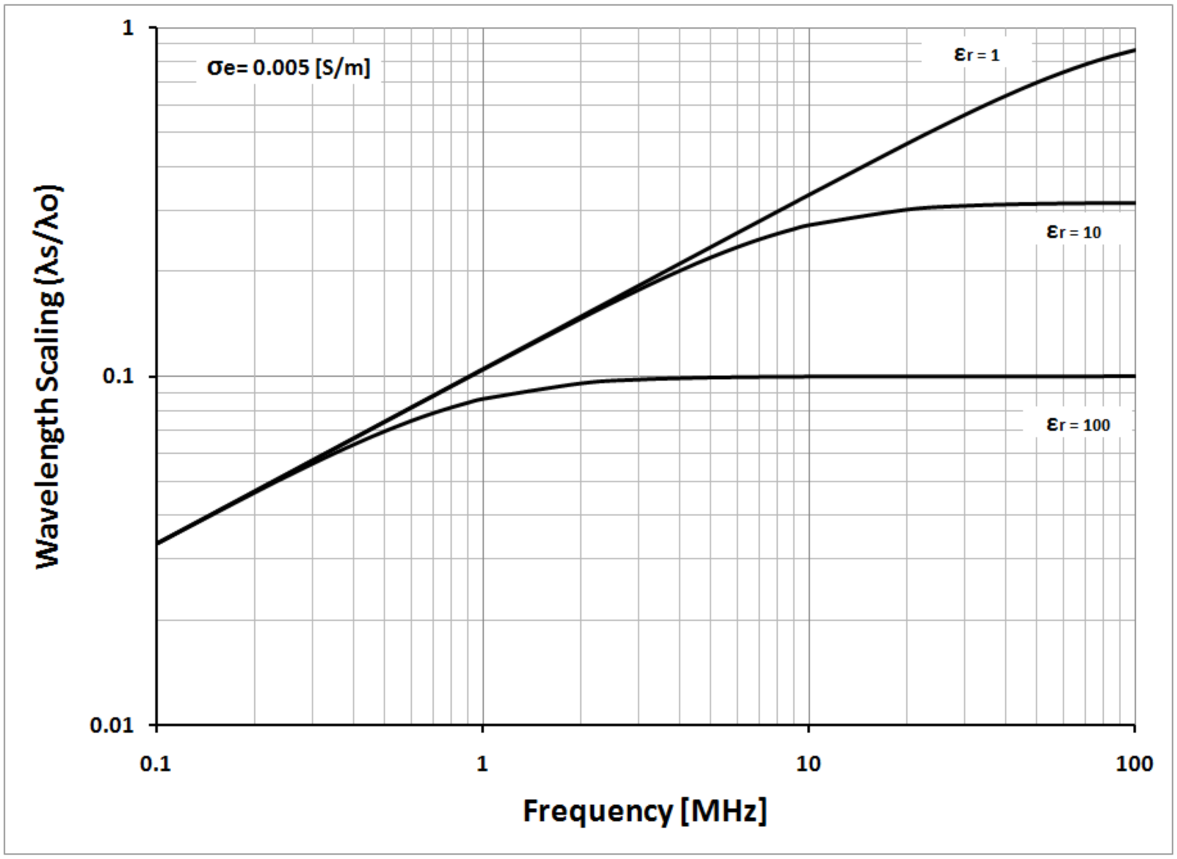

Figure B.20, Wavelength scaling for several values of ε_{er} and σ_e fixed at 0.005 [S/m].

As we saw with skin depth, the wavelength in soil is also dominated by σ_e at MF.

Radiation efficiency

Most NEC modeling software can calculate the average gain (Ga). Ga is a useful proxy for radiation efficiency in that it gives the proportion of the input power to the antenna which is actually radiated into space. Ga is the ratio of the radiated power (Pr) to the input power (Pin) in dB (Ga=10 Log [Pr/Pin]). All of the power dissipated in the earth, including the near-field losses and reflections in the far-field, are considered loss and subtracted from the input power. What is actually done is to integrate the power flow across a hemisphere with a very large radius centered on the antenna. The total power flowing through the surface of the hemisphere is Pr. I should emphasize that this is the power radiated towards the ionosphere, power in the ground-wave is considered a loss. For amateurs where sky-wave propagation is the norm at HF this makes sense. I modeled Ga as a function of σ_e with ε_{er} as a parameter using typical four radial ground-plane verticals at 3.65, 14.2 and 28.5 MHz. Figures B.21 through B.24 show Ga as a function of σ_e with ε_{er} as a parameter.

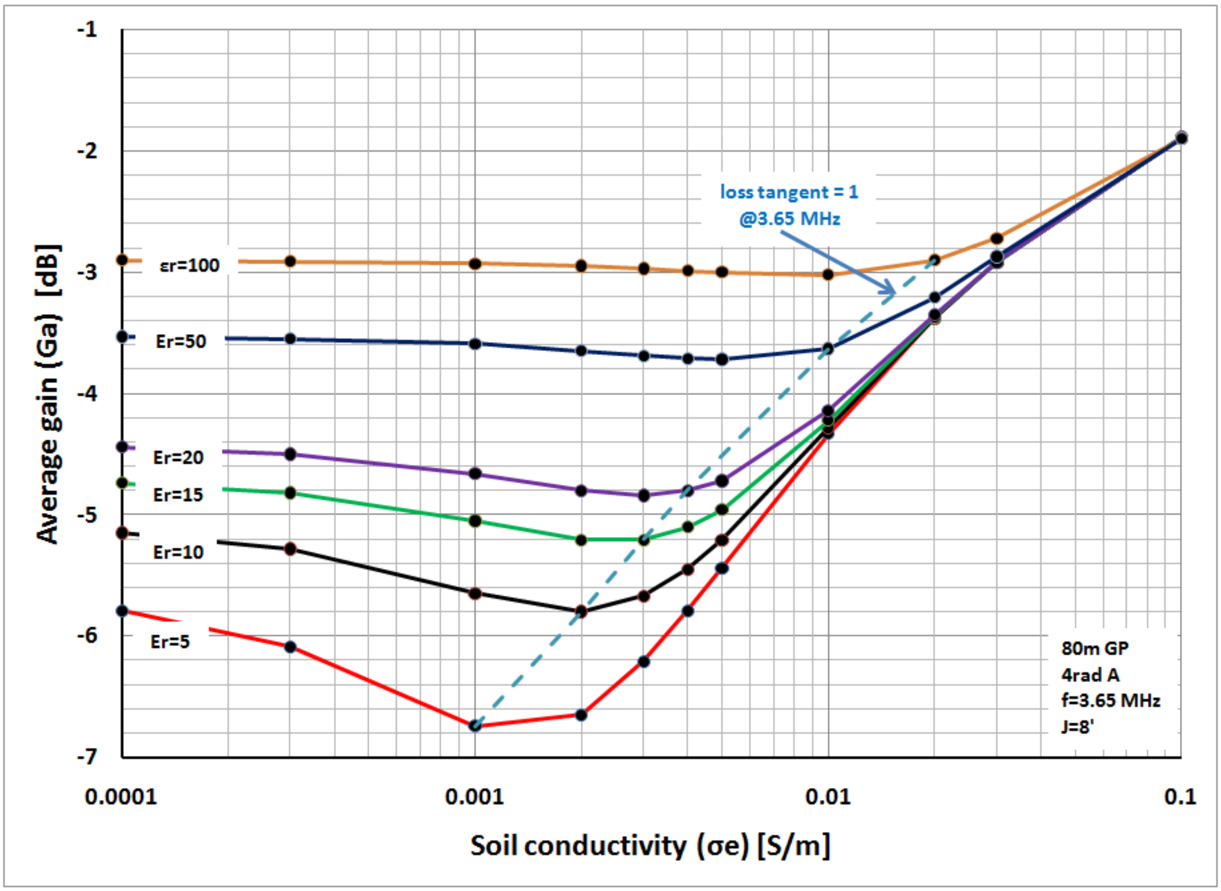

Figure B.21 - Average gain (Ga) for an 80m ground-plane vertical at 3.65 MHz with the base 8' above ground.

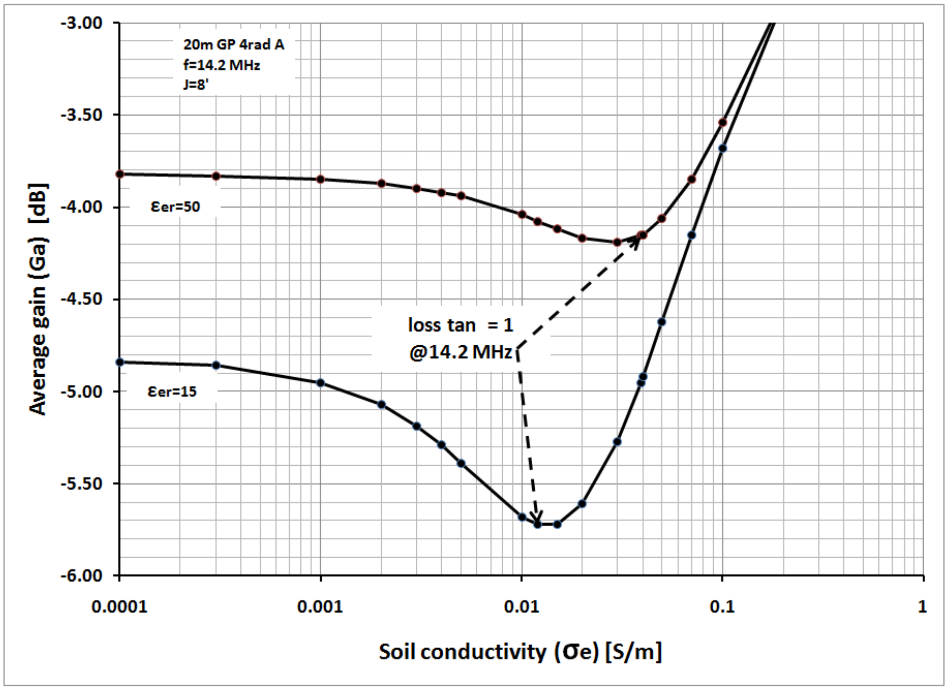

Figure B.22 - Average gain (Ga) for a 20m ground-plane vertical at 14.2 MHz with the base 8' above ground.

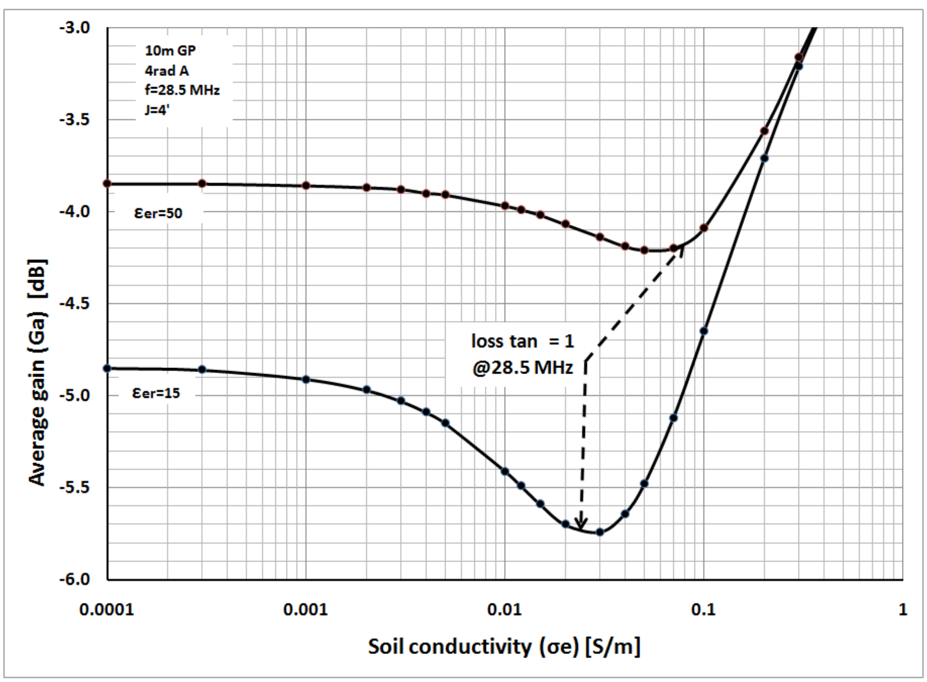

Figure B.23 - Average gain (Ga) for an 10m ground-plane vertical at 28.5 MHz with the base 4' above ground.

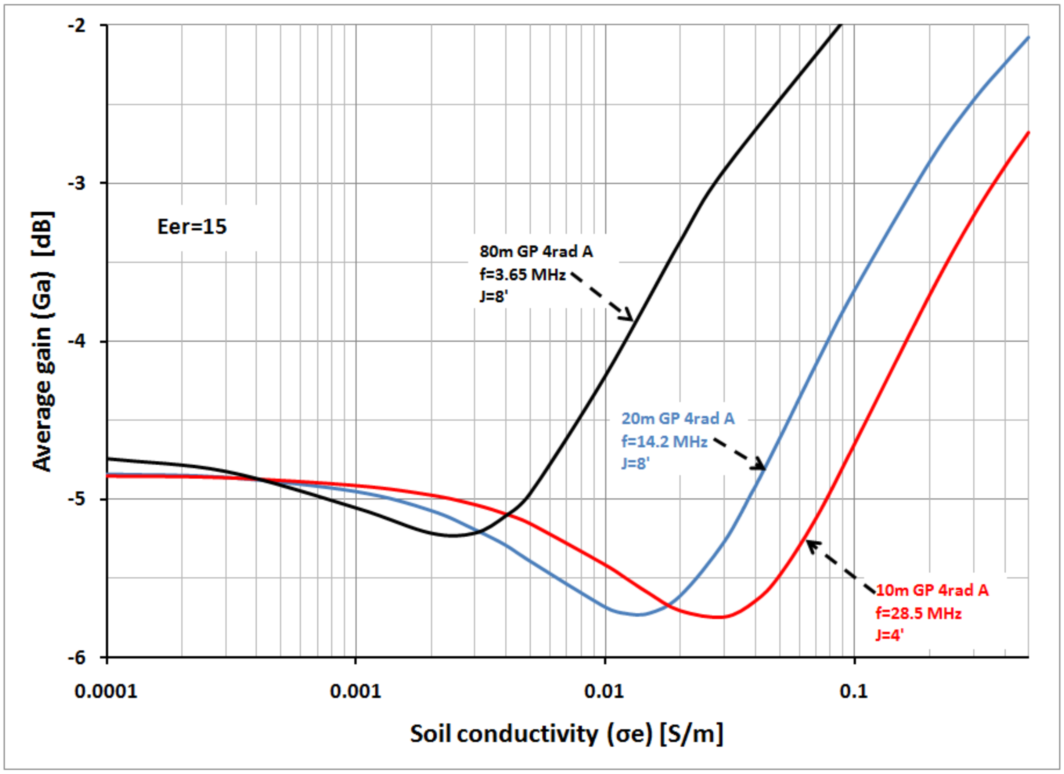

Figure B.24 - Comparison of Ga between the verticals in figures B21-b.23 with ε_{er} = 15.

On the right hand side of each graph we see Ga is essentially independent of ε_{er}. If we increase σ_e, Ga increases just as we would expect from conventional LF-MF thinking. However, on the left side of the graphs, for smaller values of σ_e, Ga is independent of σ_e and governed by the value for ε_{er}. In the mid-range between these two regions there is a minimum! As we reduce σ_e to values below the minimum, Ga increases even though the ground conductivity is less.

Note that the minimums are all close to D=1. It would appear that the worst loss case will be for soils with D ≈1. Actually this should not come as a surprise. Remember the discussion associated with figure B.1 where the maximum power loss point for was for R/Xc=1. R/Xc is equivalent to $D=\sigma/\omega\varepsilon_e$. For D>1, the dielectric is basically resistive and for D<1 it's capacitive. This is consistent with what we have seen earlier for wavelength and skin depth.

Impedance of soil

When we design mesh ground systems we need the concept of "soil or ground" impedance. The impedance of a material (Z) is defined as the ratio of the E field to the H-field (E/H). Note, Z is real in free space but typically complex in a dielectric.

In free space:

$$Z_o = \sqrt{\frac{\mu_o}{\varepsilon_o}} \approx 376.8 \approx 120\pi \, [\Omega] \quad (7)$$

In a lossy dielectric the impedance (Z_g for soil):

$$Z_g = \sqrt{\frac{j\mu_o\omega}{\sigma_e + j\omega\epsilon_e}} \quad (8)$$

In the case of free space E and H are in phase but when Z_g is complex E and H will not be in phase.

Equation (8) is messy but we can rearrange it a bit and use the definition for $D = \frac{\sigma_e}{\omega\varepsilon_e}$ to simplify things:

$$Z_g = \frac{Z_o}{\sqrt{\varepsilon_{er}}}\left[\frac{1}{\sqrt{1-jD}}\right] \quad (9)$$

For our purposes it's more convenient to express Z_g in the series impedance form:

$$Z_g = R_g + jX_g \quad (10)$$

Where:

$$R_g = |Z_g| cos\left[\frac{tan^{-1}(D)}{2}\right] \quad (11)$$

$$X_g = |Z_g| sin\left[\frac{tan^{-1}(D)}{2}\right] \quad (12)$$

$$\left|Z_g\right| = \frac{Z_o}{\sqrt{\varepsilon_{er}}}\left[\frac{1}{(1+D^2)^{1/4}}\right] \quad (13)$$

We can graph Z_g to see how it behaves over frequency as shown in figure B.25.

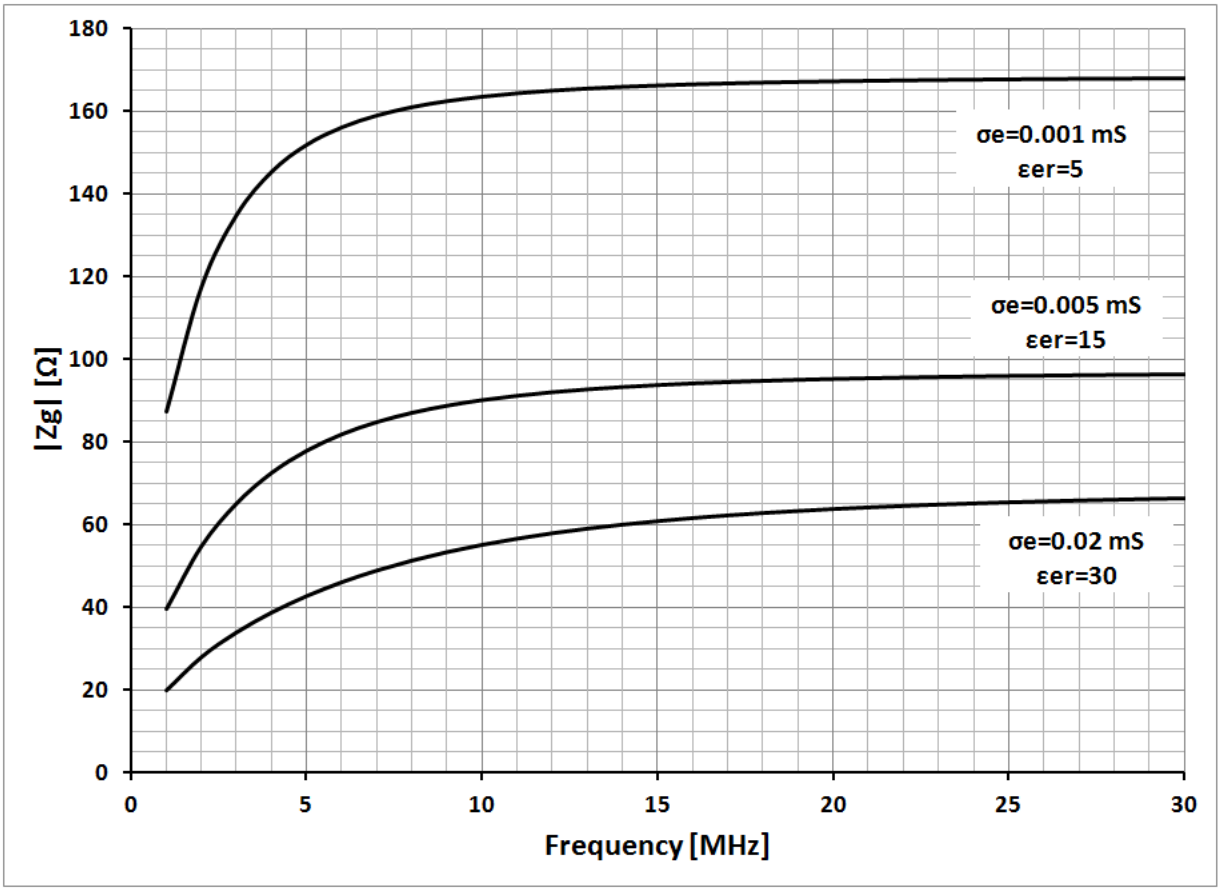

Figure B.25 - The magnitude of Z_g.

Once again we see differences when transitioning from MF to HF.

References

[1] The ARRL Antenna Book, 22nd edition, 2011, see page 3-31

[2] R. L. Smith-Rose, "Electrical Measurements on Soil With Alternating Currents", IEE proceedings, Vol. 75, July-Dec 1934, pp. 221-237

[3] R. H. Barfield, "Some Measurements of the Electrical Constants of the Ground at Short Wavelengths by the Wave-Tilt Method", IEE proceedings, Vol. 75, July-Dec 1934, pp. 214-220

[4] King and Smith, Antennas in Matter, MIT press 1981, page 399,

section 6.8

[5] Longmire and Smith, A Universal Impedance For Soils, Defense Nuclear Agency report DNA 3788T, July-September 1975

[6] George Hagn, Ground Constants at High Frequencies (HF), paper presented at the 3rd Annual Meeting of the Applied Computational Electromagnetics Society (ACES), 24-26 March 1987

[7] Rudy Severns, N6LF, Measurement of Soil Electrical Parameters at HF, QEX magazine, Nov/Dec 2006, pp. 3-9