Measurement of Soil Electrical Parameters at HF

The author describes the technique he uses to measure soil conductivity and relative dielectric constant over a range of frequencies on the HF bands.

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Introduction

Modeling of antennas over real ground requires at least a reasonable guess of the values for the soil conductivity (σ) and relative permittivity (ε_r), also referred to as "relative dielectric constant." Unfortunately these numbers are usually not readily available. From broadcast (BC) work we have charts of ground conductivity covering large areas, but these numbers give only σ, not ε_r. In part, the absence of ε_r data is because, for sites where you would want to build a BC station, the soil characteristics are usually dominated by σ, and ε_r has only a second-order effect. This is often true at BC frequencies but is usually not the case in all but the most conductive soils at HF. In addition, the values for σ will be different between BC frequencies and HF. Another problem is that the BC ground conductivity charts cover much too large an area to take into account the details of local ground variation, which can deviate greatly from local averages.

It would appear that the best approach is to simply measure your local soil characteristics at the frequencies of interest. Unfortunately, this is much easier said than done. None of the known methods is anywhere near perfect, and many are difficult to implement. In fact there is a school of thought that the problem is impossible and we should not waste our time worrying about it. I don't share that view as a general proposition, but it is not without some justification, given the difficulties involved.

There are common situations where the values for the soil constants (which are anything but constant!) are really not very important for modeling purposes. For example, for horizontal polarization with antenna heights above 1/4-λ, the numbers are not very critical for determining feed-point impedances, near-field losses or the formation of the far-field radiation pattern. Another case would be for vertical antennas where one has the space, money and patience to lay down a large number of long radials. With this brute force approach, the near-field ground loss can be made arbitrarily small regardless of the soil, and you really don't care what the ground constants are, at least from a local loss point of view. The far-field pattern, however, is still just a guess without real data.

If your space and/or financial resources are more limited, then a modestly accurate estimate of your ground characteristics will allow you to design a ground system that minimizes the loss within the constraints of the space and resources you do have. There is also the situation that arises fairly often on 80 m. On that band a 1/2-λ is about 130 feet, which is not an exceptionally tall tower for amateur use. Horizontal gain antennas are certainly practical but they're not easy, being large and relatively expensive. The option is to go to a vertical array, which may be easier. Accurately predicting the performance of a possible vertical array in comparison to a competing horizontal array requires at least a reasonable guess for the ground characteristics on that band. The decision as to which way to go may depend, at least in part, on having a reasonable estimate of the ground characteristics.

Another problem with present ground modeling practice is the assumption that soil parameters, whatever they may be in a given location, are constant over frequency. For example, for a given soil, the assumption is that ground constant values at 160 m are the same as the values at 20 m. That's not the case. As pointed out by Bob Haviland, W4MB, and in many professional papers, ground parameters at HF vary substantially with frequency.[1,2]

There is a need for a practical method to estimate soil parameters at HF for amateurs. By practical, I mean a mechanically simple test apparatus and measurement equipment

[1]Notes appear on page 8.

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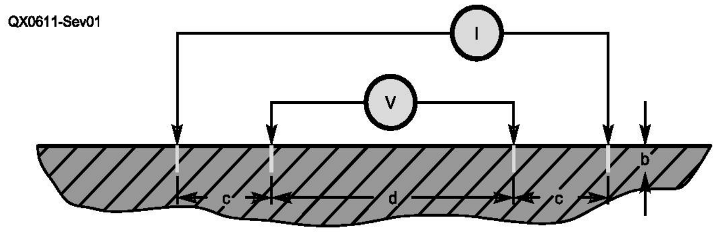

Figure 1 —This diagram shows the Wenner array, the traditional method used by amateurs to measure ground parameters.

no more advanced than an AEA or MFJ impedance analyzer. Fortunately, great accuracy is not required and it makes little difference in the modeling if the values are off by 25%. This article will discuss one particular approach, the use of ground probes, which at least approximate this ideal.

Soil Parameter Measurement

There are many ways to measure ground parameters. Each has advantages and limitations. None is the perfect answer. The traditional method used by amateurs is the Wenner array (or similar variations), which uses four probes in line as shown in Figure 1, excited with line-frequency ac.[3,4,5] This approach can give a good estimate of ground conductivity at 50 to 60 Hz, and by varying the spacing of pairs of probes, can be used to define sub-soil layering. It gives no information on ε_r, however. A measurement of this type provides only a lower bound on soil conductivity, which will be higher at HF.

Another technique, frequently used in BC work, is to measure the rate of decrease of the E-field intensity as you go away from the antenna on a radial line. It is possible, by some judicious curve fitting to the measured data, to infer the average ground conductivity along the measured line. This is a reasonable approach at BC frequencies, where the soil characteristics are dominated by the conductivity. At HF, however, the soil is both resistive and capacitive. Typically, when trying this technique at HF, more than one pair of parameters (σ and ε_r) may generate curves that fit the data. This ambiguity is a problem. In addition, the measurements need to be made at some distance from the antenna where there are significant amplitude differences between measuring points and so do not give a very good idea of the ground characteristics within a $^1/_2$-λ of the base. Information on ground parameters close to the antenna is needed for ground system design, especially in the initial design stages for a new vertical.

A technique that would seem to fit our requirements is to insert a probe into the soil and measure its impedance.[6] In the simplest case the probe is basically just a capacitor, and the ground parameters are inferred from the change in impedance of this capacitor from when the probe is in air and to when it's in soil. This approach can yield a detailed characterization of the soil in the immediate area of the antenna and at distance also. A basic limitation of this procedure is that it is usually not possible to use a probe that reaches very far down into the soil. The result is characterization mainly of the top few feet of soil, which is usually substantially less than the skin depth. By making measurements at many spots over the area of interest the probe method can give a very good picture of the lateral variation of soil parameters. We know that the properties will also vary vertically (variations in moisture content, stratification, and so on) and we would like to know the variations down to a skin depth. It is possible to take a surface measurement, then dig down three feet or so in the same spot and reinsert the probe in the undisturbed soil at that level and make another measurement. This can be repeated until sufficient depth is achieved. That, however, defeats our goal of keeping the process simple, and is not practical for large-area surveys.

Is a fairly accurate characterization of only the top layer of soil of any real use? Certainly that's debatable but I think it is worth doing. There will be cases where the soil characteristics change slowly and the probe measurements are pretty close. It is also possible to have an entirely different strata a few feet down, with completely different characteristics. It probably is a good idea to dig one test hole as suggested above, to get a feeling for the local stratification and then do a survey with surface probes in the near area. In any case, I think probe measurements are a vast improvement over nothing but we should not be fooled into thinking the results are exact. Like everything in modeling, the information has to be used cautiously.

Monoprobe Technique

This method uses an impedance analyzer to measure the impedance of a single ground probe with a ground screen, as shown in Figure 2. The ground screen can be either square or circular, with a radius greater than the length of the longest probe. Rupar used a copper sheet for the ground screen.[7] I initially used a sheet of $^1/_8$-inch-thick aluminum, but a large metal sheet is awkward to work with and I found that a piece of ½ inch galvanized hardware cloth (as shown in Figure 3) worked just as well. Note the weights on the screen. The hardware cloth is flexible, and the weights are used to keep it in contact with the soil. This is an advantage if the ground is a little uneven in that the flexible screen may fit it better, minimizing any air gap between the screen and soil. More on this later. Anything will do for weights; bricks or rocks are fine. The flexibility of the hardware cloth means you can roll up the wire to make an easier package for

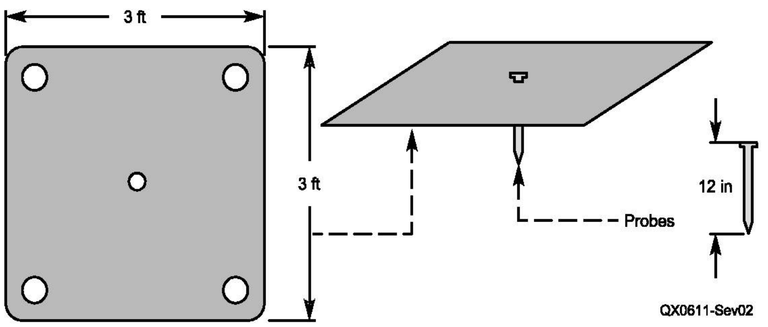

Figure 2 — This illustration shows the construction of the monoprobe. A three-foot square of half-inch hardware cloth forms the base. A hole cut in the center provides space for the probe to go through the screening without contacting the wire.

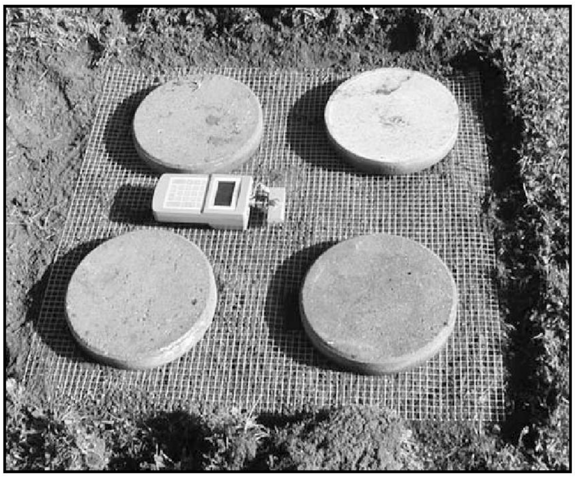

Figure 3 — This photo shows the monoprobe in use. Note the circular blocks used to hold the hardware cloth in contact with the ground, and the AEA impedance analyzer connected to the probe in the center.

carrying. The example in Figure 3 shows an AEA complex impedance analyzer being used. An MFJ-259B or other impedance analyzer will work just as well.

Figure 4 shows examples of typical probes (12 inches and 18 inches long). The crossbars in this example are phenolic, but any reasonable insulating material will work fine, even wood. The crossbar is there to help push the rod into the ground and pull it back out. The rod is inserted through a small hole (1 inch or so) in the screen and pushed down until the crossbar is pressed firmly onto the screen. The rods shown are brass but that's not essential. I just happened to have some $^{3}/_{8}$ inch brass rod stock on hand. For later experiments I found some inexpensive $^{7}/_{16}$ inch aluminum rod at a scrap yard. Anything from $^{1}/_{4}$ inch to $^{1}/_{2}$ inch should work fine. In fact, you can even use square rods if you wish. You can find suitable rod stock at most hardware stores. The larger diameters make for more sturdy probes, with a little more capacitance, but they may be harder to push into the ground. The presence of the thin insulating layer of oxide on aluminum rods has essentially no effect on the measurements.

Initially I threaded the top of the rod and the crossbar, then screwed them together, adding a nut on the top for a connection. You don't need to be so fancy. Later on I just drilled a tight fitting hole in the crossbar, drove the rod into it and added a cross 6-32 machine screw to hold it and to provide an electrical contact.

The impedance is measured between the top of the rod and the ground screen as shown in Figure 5. Note that I have used a lead from the top of the rod to the analyzer and a ground clip on the analyzer to connect to the screen. You could also mount a coaxial connector on the screen with a lead going to the top of the rod. The choice of which way to go affects the stray inductance and capacitance and is discussed in the appendix in the context of probe calibration.

OWL probes

The OWL (Open Wire Line) probes are simply two parallel rods and a crossbar without a ground screen, as shown in Figure 6.[6] The impedance is measured between the tops of the two rods. For a battery powered impedance analyzer like an MFJ, the measurement is floating (once you take your hands off the instrument!) and no balun is needed. If you want to use a more advanced analyzer, such as the Ten-Tec TAPR or N2PK vector network analyzers, with a cable, then a balun would be a good idea. I made up a test balun, which is included in the Figure 6 photo. I used a Fair-Rite FT240-43 ferrite core. This is standard core available from Amidon. The winding is a 3 foot length of RG-58 with BNC connectors at the ends. This length results in about 12 turns, and should give adequate isolation down to 1 MHz.

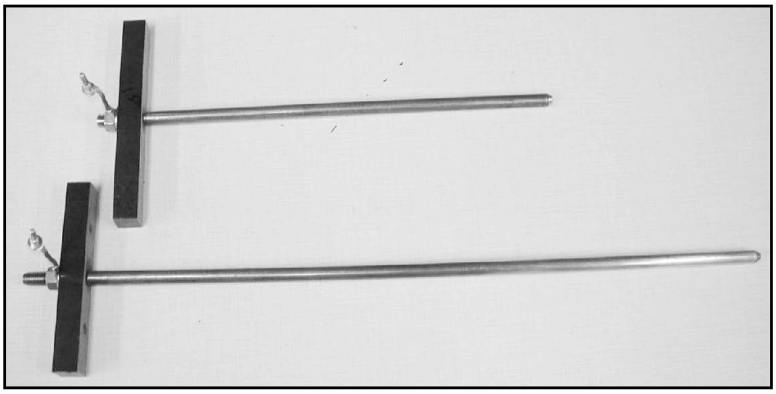

Figure 4 — Examples of 12-inch-long and 18-inch-long probes for use with the monoprobe technique.

Figure 5 — This photo shows the details of how the impedance analyzer is connected to the probe and ground screen.

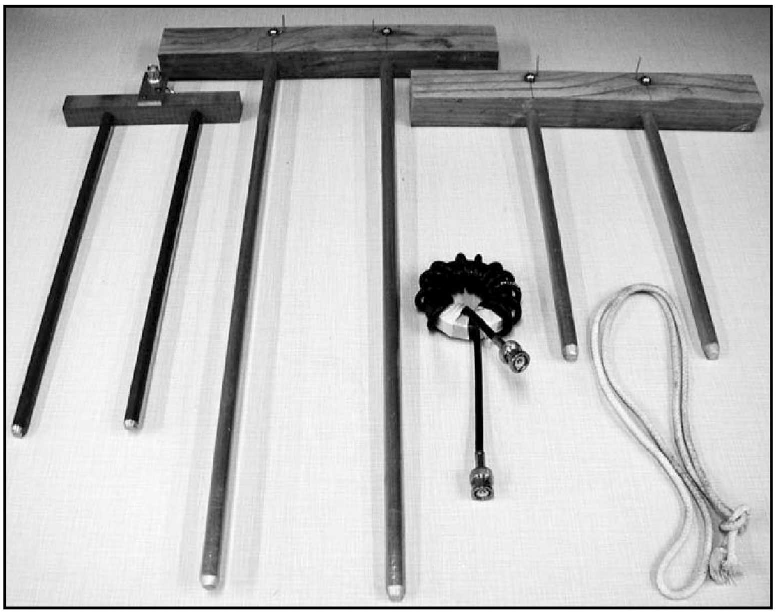

Figure 6 — Here are three open wire line (OWL) probes, along with a balun and a loop of rope used to pull the probes out of the ground after the measurements have been made.

The probes with 4 inch spacing use clip leads like those shown in Figure 5 but the 3 inch spacing probe (the probe on the left in Figure 6) has a BNC connector on the crossbar, to which the balun is connected. There is nothing magical about either arrangement.

Figure 6 also shows a vital piece of equipment: the cord! Before pushing a probe into the soil it's a really good idea to loop the cord around the crossbar. You will use it to pull the probe out of the ground. In hard soils, with the bar pressed against the ground, getting the probe out without the cord can be a chore. It also helps to put a handle on the cord.

I'd like to emphasize that the diameter, spacing and length of the probe rods is not critical. The only thing you must do is to measure or calculate the probe capacitance (as shown in the appendix) for your particular probe. Larger diameter rods and closer spacing result in lower measured impedances. With the AEA and MFJ analyzers, measurements of impedances above 200 Ω or so become less reliable and it is better to work with lower impedances. In soils with poor conductivity the measured impedance, with the same probe, will be higher than in more conductive soils, and it may be better to use closer rod spacing.

Choosing Between a Monoprobe or an OWL Probe

Both types of probes will work just fine, but each has advantages and disadvantages. The single probe is much easier to insert than a double probe. There is also the issue of keeping the rods parallel with the OWL. If the rod spacing varies between air and in the soil then the calibration of C_0 will be off. Given the modest accuracy required for ham applications this is usually not a problem. The OWL is much more compact to carry around because you don't need the large ground screen and weights to hold it down. That's a very practical advantage!

The monoprobe is influenced by a much larger volume of soil and provides an average over that volume whereas the OWL pretty much characterizes a small cylinder of soil. The monoprobe measurement is intrinsically unbalanced whereas the OWL may require a balun or other isolation for measurement with non-isolated instruments.

In the end, either will work. You just have to decide what suits you.

Taking and Reducing the Impedance Data

The procedure is very straightforward. You simply lay the screen on the ground if using a monoprobe, insert the probe into the soil and record the impedance reading on the analyzer at each frequency of interest. In the case of an OWL probe, you simply insert the probe into the ground up to the bar and make an impedance measurement. This should only take a few minutes and then you move on to the next points, recording the impedance measurements as you go. You can cover a lot of ground in an hour or so.

The next step is to convert the impedance readings to σ and ε_r using the equations given below. Putting these equations into a Microsoft *Excel* spreadsheet makes the whole process very painless.

The impedances can be in either of two formats: R + *j*X or magnitude (|Z|) and phase angle (θ). The equations for converting the measured impedances using R and X are:

$$\sigma = \frac{8.84}{C_0}\left[\frac{R}{R^2+X^2}\right] \quad \text{(Eq 1)}$$

$$\varepsilon_r = \frac{10^6}{2\pi f_{\mathrm{MHz}} C_0}\left[\frac{X}{R^2+X^2}\right] \quad \text{(Eq 2)}$$

If you prefer to work with |Z| and θ, the equations take the form:

$$\sigma = \frac{8.84}{C_0}\left[\frac{1}{|Z|\sqrt{1+\tan^2\theta}}\right] \quad \text{(Eq 3)}$$

$$\varepsilon_r = \frac{10^6}{2\pi f_{\mathrm{MHz}} C_0}\left[\frac{\tan\theta}{|Z|\sqrt{1+\tan^2\theta}}\right] \quad \text{(Eq 4)}$$

where C_0 = capacitance in pF of the probe in air. This can be either measured or calculated quite closely, as shown in the appendix. Frequency is in MHz and impedances are in ohms.

These equations assume the probe is simply a capacitor. If you make the probe longer at a given frequency, or push the measurement frequency up for a given probe length, there comes a point where the probe is no longer simply a capacitor, it becomes an antenna, buried in the soil. It can still be used but data reduction is more complex.

Some Actual Measurements

Now it's time to look at actual measurements taken on my property. Tables 1 and 2 show typical impedance measurements taken at two different locations, and their reduction to σ and ε_r. The data in Tables 1 and 2 is graphed in Figures 7 and 8.

Because of the relatively poor accuracy of the AEA analyzer, the graphs are a bit "lumpy."

Table 1

18 Inch Monoprobe, C_0 = 7.41 pF. On my antenna hill with an AEA-CIA analyzer.

Frequency (MHz)	*Resistance (Ω)*	*Reactance (Ω)*	*Conductivity, σ (S/m)*	*Relative Permittivity, ε_r*
1	129	–134	0.0044	83
2	83.3	–95.8	0.0062	64
3	66.3	–76.2	0.0078	53
4	56.7	–65.2	0.0091	47
5	51.5	–57.2	0.010	41
6	46.2	–47.8	0.012	39
7	40.2	–46.2	0.013	38
8	35.1	–40.4	0.015	38

Table 2

Four Inch × Nine Inch OWL, C_0 = 2.71 pF. In my backyard with AEA-CIA, no balun.

Frequency (MHz)	*Resistance (Ω)*	*Reactance (Ω)*	*Conductivity, σ (S/m)*	*Relative Permittivity, ε_r*
1	176	–137	0.0042	59
2	123	–119	0.0050	44
3	95.2	–98.5	0.0061	38
4	83.4	–86.3	0.0069	32
5	77.7	–75.0	0.0079	28
6	73.0	–63.4	0.0093	24
7	60.9	–60.9	0.0098	25
8	54.7	–52.8	0.011	25

In Figure 7 I have smoothed things out by inserting a linear trend line, which fits quite well. The lumpiness is typical using this class of instrument for measurement, but the lumps are still small enough not to matter. The data in Tables 1 and 2 is a bit sparse, but taking a large number of closely spaced data points and then smoothing with a trend line works even better.

You may notice that in Figure 3, the grass has been dug away so that the screen is in direct contact with the soil. I made measurements with and without the grass to see what the effect the grass would have. The results are shown in Figures 9 and 10.

As you can see from the graphs, the presence of the grass doesn't have much effect on the conductivity measurements, but does substantially affect the ε_r measurements. What the grass does is to insert a layer of air under the screen, which reduces the effective capacitance. That, in turn, reduces the value for ε_r. This is not a big issue but you should at least take a string trimmer and cut the grass as low as possible. If you are using an OWL probe then the effect of the grass is very small if the probe is pushed firmly down against the ground.

Another concern is the effect of using different probe lengths. The moisture in the very uppermost layer of soil responds rather quickly to weather conditions. When it rains, σ and ε_r go up and, when things dry out, σ and ε_r fall. This rate of variation with time and depth depends on the soil itself but for the most part the soil characteristics respond much more slowly at depths beyond 12 inches or so. This effect on measurements is illustrated in Figure 11. The soil at W6XX is quite sandy and the top layer dries out fairly rapidly. We can see this in the graph. σ is substantially lower in the upper layer which is being measured by the short probe. The longer probes reach down into soil that dries much more slowly, and as you can see the two longer probes give essentially the same data. A close look at the 24 inch probe data line illustrates a limitation mentioned earlier on probe length. As the probe is made longer the current distribution along the probe is no longer essentially constant. Instead of behaving like a simple capacitor (which Equations 1 and 2 assume) it is starting to act like an antenna. Notice how the 24 inch probe curve starts to bend over at the higher end. This can be corrected by using more complex equations for the data reduction, but for most users that may be more trouble than it's worth. The usable range is still above 40 m. Very high conductivity soils may require shorter probes.

Comments on Ground Data

The conductivity graph (Figure 7) has an important feature: the ground "constants" are not constant at all with frequency. It is very typical in the HF region for σ to increase with

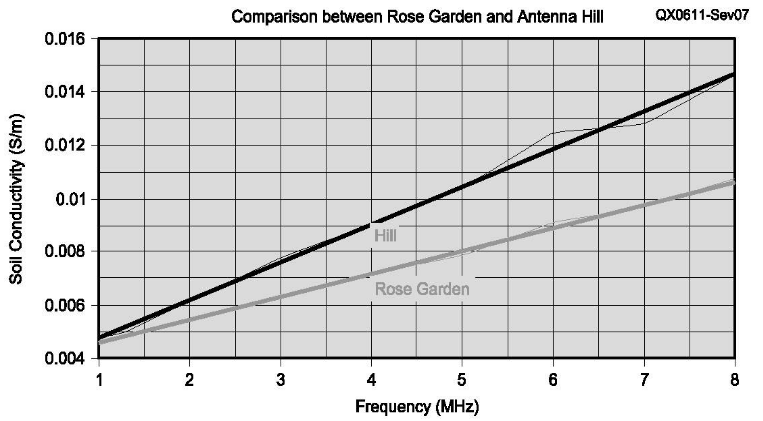

Figure 7 — This graph compares the conductivity I measured in two areas of my property.

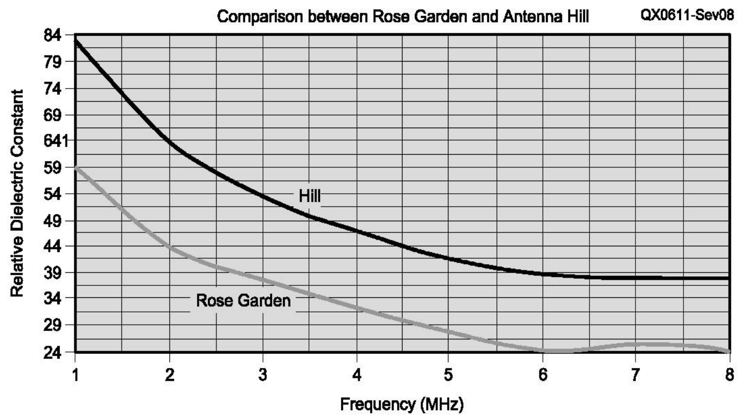

Figure 8 — The relative dielectric constant values on the antenna hill and in the rose garden, based on the measurements taken from 1 to 8 MHz.

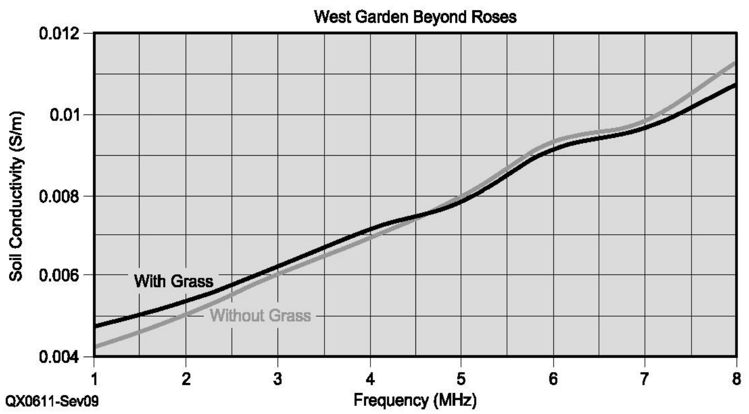

Figure 9 — I measured soil conductivity in an area of grass in my west garden, beyond the roses. Then I dug up a patch of grass and repeated the measurements to estimate the effects of grass.

frequency. In addition, as shown in Figure 8, ε_r is not constant either and tends to decrease as you go up in frequency to about 5 MHz, but then stabilize above that. The general shape and trends displayed in Figures 7 to 11 agree very well with those seen in the large body of professional work on ground parameter values.

At both sites in Figure 7, σ corresponds to what is generally called "average ground." Average ground is usually defined as σ = 0.005 S/m and ε_r = 13. In Figure 8, however, ε_r is much larger than 13, especially below 5 MHz. This is particularly characteristic of soils with a lot of clay particles. For many years there was a great deal of controversy over the large values of ε_r measured at low frequencies. The consensus is that it is very real. The following quote is from the King and Smith book, *Antennas In Matter*, which is considered a definitive work:[8]

"For some time, the high values of permittivity and the dispersion at these lower frequencies were thought to be artifacts of the measuring procedure; that is, it was thought that they were caused by electrochemical effects at the interface between the metallic electrodes and the sample of rock or soil. Measurements made using several different materials for the electrodes, however, indicate that there is a high permittivity associated with the geological material apart from any electrode effects."

Summary

How should we use the numbers we get? First, I try to take my readings at the end of the driest part of the year. Because both σ and ε_r are strong functions of soil moisture content, measuring near the end of the dry season will give you a conservative estimate. One exception I make is for my 80 and 160 m antennas, which I normally only use during the winter, which is definitely the wet season in Oregon. I use the winter ground parameters for these bands. Second, I average the readings found at different places over the site.

These are the values I use when designing a new antenna. Am I kidding myself? Well, perhaps, but I find it hard to believe that I am worse off than if I simply guessed and took the traditional value for mountains of σ = 0.001 S/m and ε_r = 5, which would appear to apply in my location even though these values are much lower than what I measure at my QTH.

I think that ground probe measurements are worth doing and I use them, but with care. Of course we would like even better methods, and in fact a number of workers are trying to find better ways.

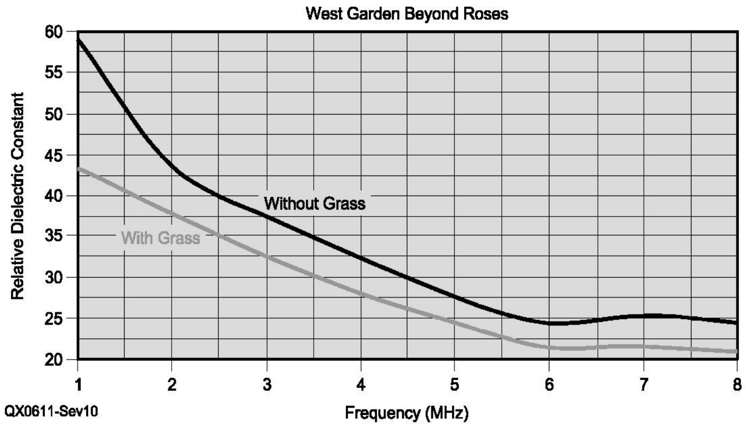

Figure 10 — This graph compares the relative dielectric constant as measured with and without grass.

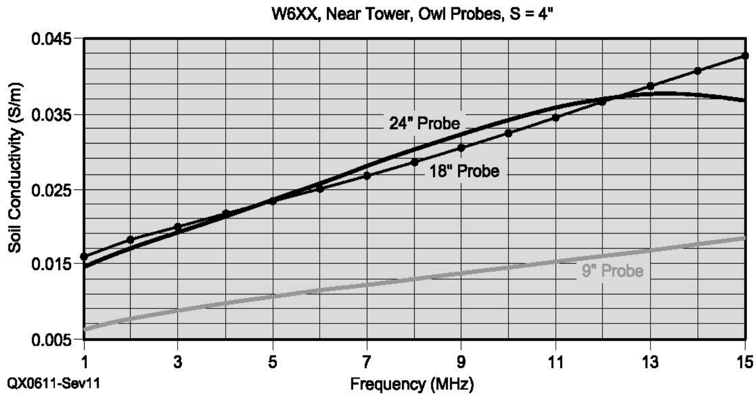

Figure 11 — This graph shows the data collected by Pete Gaddie, W6XX, near his tower, using three different-length OWL probes.

Acknowledgement

Pete Gaddie, W6XX, and I have been building and testing a variety of ground probes and much of what is in this article comes from our results. I would like to acknowledge the great assistance Pete has given me in supplying technical papers, extended discussion on technical details, measurement advice and a great deal of parameter measurement on his own. Thanks, Pete.

Notes

[1]R.P. Haviland, W4MB, "Ground Parameters for Antenna Analysis," *ARRL Antenna Compendium 5*, 1996, pp 96-100.

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[4]*IEEE Guide for Measuring Earth Resistivity, Ground Impedance and Earth Surface Potentials of a Ground System*, IEEE Std 81-1983, Mar 11, 1993.

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[9]I. L. McNally, K6WX, "Notes on Ground Systems," *ham radio*, May 1980, pp 27-29.

[10]Glenn S. Smith, "Measurement of the Electrical Constitutive Parameters of Materials Using Antennas, Part 2," *IEEE Transactions on Antennas and Propagation*, Vol AP-35, No. 8, Aug 1997, pp 962-967.

[11]R. L. Smith-Rose, "Electrical Measurements on Soil With Alternating Currents," *Proceedings of the IEE*, Vol. 75, Jul-Dec, 1934, pp 221-237.

[12]Kenneth P. Spies and James R. Wait, "Determining Electrical Ground Constants From the Mutual Impedance of Small Coplanar Loops," *IEEE Transactions on Antennas and Propagation*, Jul 1972, pp 501-502.

[13]F. E. Terman, *Radio Engineer's Handbook*, McGraw Hill, 1943, New York, NY, Equation 140, p 118.

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Appendix — Determining C_0

The value for C_0, which appears in both of the equations for σ and ε_r, is the capacitance of the probe in air. It has to be determined before the impedance data can be reduced to σ and ε_r. There are two ways to go about finding C_0: direct measurement and calculation. For the OWL probes C_0 can be determined very closely from the following equation taken from Terman:[13]

$$C_0 = \frac{3.677}{\log_{10}\left\{\frac{D}{d}\left[1+\sqrt{1-\frac{1}{\left(D/d\right)^2}}\right]\right\}}\ \frac{\text{pF}}{\text{ft}} \qquad \text{(Eq A1)}$$

where:

D = center-to-center distance between rods
d = diameter of the rods.

Dimension units for D and d must be the same but can be anything.

For an 18.5-inch OWL probe with D = 4 inches and d = 0.44 inches, this gives C_0 = 4.51 pF. Of course there will also be a small additional capacitance due to end effect. A later measurement gave C_0 = 4.83 pF, which indicates that the end effect adds about 10% to the calculated capacitance. Unfortunately, there isn't a similar simple expression for the monoprobe.

Measuring C_0 poses a problem because it is so small, typically less than 10 pF. I use an inexpensive L/C meter made by Almost All Digital Electronics, model L/C meter IIB, shown in Figure A1.

This meter operates at about 1 MHz. By being very careful to zero the instrument just before a measurement and taking great care not to change the layout between zeroing and measuring, I have found that this instrument does measure small values of capacitance very well. In the case of the OWL probes I always measured a value which was just a little bit higher than calculated, which is what you would expect taking end effect into account.

A direct measurement of a probe will give a capacitance that is the sum of C_0 and the part of the probe that sticks out of the ground and is connected to the impedance analyzer. This is a parasitic capacitance (C_p), which has to be subtracted from the total measurement. I determined C_p by building a dummy probe that is identical in all respects to the actual probe except that the portion of the rod or rods that would normally be in the soil is cut off. The mechanical layout for the part sticking out of the ground is carefully replicated and a direct measurement of C_p made. This is then subtracted from the total capacitance measurement for the probe. In principle C_p is in parallel with the impedance you want to measure to determine σ and ε_r and causes a small error. In practice, C_p will be roughly the same magnitude as C_0. When the probe is inserted into soil, however, C_0 is multiplied by ε_r and the effective capacitance is much larger than C_p. You can modify the equations to take C_p into account but except for soils with very low ε_r I don't think it matters much.

Figure A1 — I used this Almost All Digital Electronics L/C meter to measure the capacitance of the probes in air. By measuring the total capacitance of the probe and leads, and then measuring the parasitic capacitance, C_p, of the part of the probe above ground along with the connecting leads, I am able to calculate the capacitance of the probe alone, C_0.

Again, it is important to realize how small the measured capacitances are. You have to keep your body and any other conductors well away from the probe and the L/C meter. I place the probe and meter on top of a large plastic garbage can, well away from benches and other objects. I zero the meter by holding it with one stick and pushing the zero button with another, so the effect of my body is minimized.

Even with this simple and inexpensive instrument I believe I get quite accurate values for C_0. I confirmed the measurements using an HP 3577A vector network analyzer. Table A1 shows the parameters for my measurements.

C_p is in shunt with the measured impedance and might cause some error. You can, of course, modify the equations to remove this effect when C_p is known but I found that for most soils the values for the measured impedances were much lower than the shunt impedance presented by C_p and adding a correction factor was unnecessary.

Table A1

Measurement Parameters

Probe Type	*Rod Diameter (Inches)*	*Spacing (Inches)*	*Length (Inches)*	*Ground Screen (feet)*	C_o
Monoprobe	0.375	—	18	3 × 3	7.41 pF
OWL	0.44	4	18.5	—	4.83 pF
OWL	0.44	4	9.5	—	2.7 pF
OWL	0.44	3	12	—	3.4 pF