

Measurement Of Soil Electrical Parameters At HF

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Introduction

Modeling of antennas over real ground requires at least a reasonable guess for the values of the ground parameters: the soil conductivity (σ) and relative permittivity or dielectric constant (E_r). For horizontal polarization at heights of 1/4-wave or more, the numbers are not very critical but for vertical polarization and antennas close to ground level, where ground has a large effect, the soil parameters are very important. Unfortunately most amateurs have only the sketchiest idea of what their ground parameters really are.

Another problem with current modeling practice is the assumption that the soil parameters are constant over frequency, i.e. for a given soil, the values at 160 m are the same as the values at 20 m. That is not the case. Ground parameters at HF vary substantially with frequency.

This is not the first time this has been pointed out in an amateur publication. Bob Haviland, W4MB, brought this out in his 1996 Antenna Compendium 5 article^[1] which was later incorporated into the ARRL Antenna Book^[2]. The use of probes for ground measurements was mentioned but not pursued in detail.

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

Pete Gaddie, W6XX, and I have been building and testing a variety of ground probes and much of what follows is a discussion of 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.

The discussion will start with a review of some traditional soil parameter measurement techniques but most of the attention will be on the ground probe method. To make the discussion a bit easier to follow I have moved some of the math and probe calibration discussion to an appendix.

Soil parameter measurement schemes

There are many ways to measure ground parameters (see references). Each has advantages and limitations. The traditional method used by amateurs is the Wenner array (and variations like it)^[3, 4] which uses four probes in line as shown in figure 1 and is excited with line frequency AC. This approach gives a good estimate of the ground conductivity at 50-60 Hz and by varying the spacing of pairs of probes can be used to define the sub-soil layering characteristics. However it gives no information on ϵ_r .

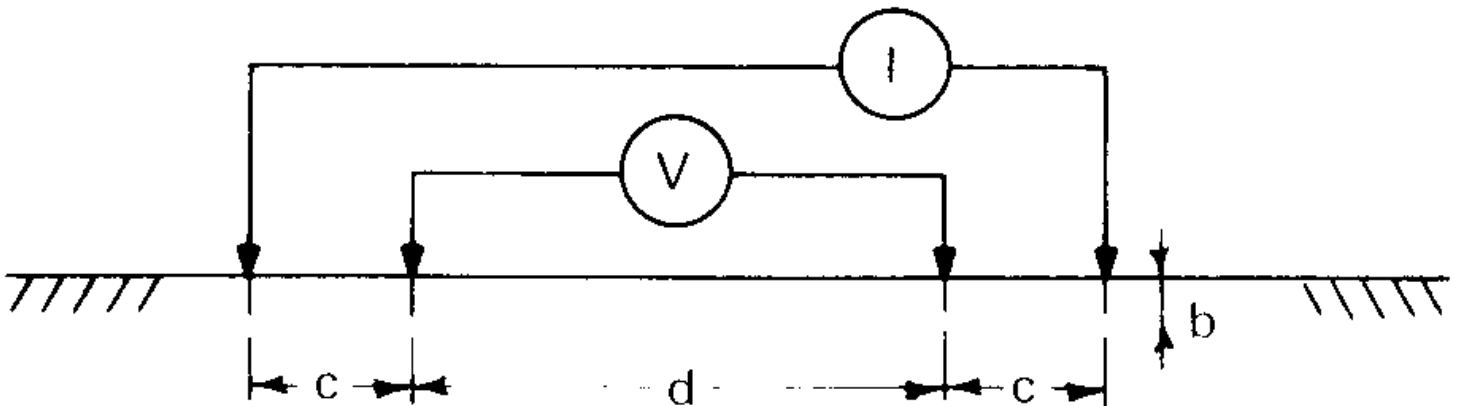


Figure 1, four ground probes using line frequency AC excitation.

A common misperception is that the soil conductivity does not vary with frequency until well into the HF region and that the Wenner measurements of conductivity are valid up through at least 40 m. This perception is due to a widely used graph shown in figure 2. The graph indicates that for most soils sigma does not begin to vary until you go above 10 MHz.

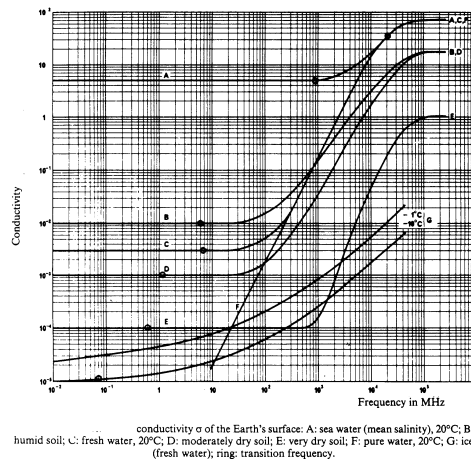


Figure 2, widely used graph of conductivity versus frequency for various soils.

The latest IEEE standard for soil parameter measurements^[5] makes the following statement regarding curves like this one (dispersion means "varies with frequency"):

"The curves of conductivity and relative permittivity in ITU-R Recommendation 527-3 [B1.8] exhibit no dispersion in the band 3-30 MHz, whereas measured values show significant dispersion in the band for which surface soils typically can show characteristics from lossy conductors to lossy dielectrics.....Therefore, the ITU values for the HF band are inconsistent with the results of complex variable theory and are in error."

This is an extraordinary statement for a profession standard and illustrates the problem with the conventional values for soils at HF. It is my feeling that the low frequency measurements can be valuable in detecting the stratified structure of soil and setting a low frequency limit on σ but the low frequency numbers do not apply at HF.

Another commonly use technique is to measure the rate of decrease of the E-field intensity as you go away from the antenna on a radial line. In the broadcast field this is standard practice. It is possible, by curve fitting to the measured data, to infer the average ground parameters along the measured line. This is a reasonable approach at BC frequencies where the soil characteristics are dominated by resistance. But at HF the soil is both resistive and capacitive and more than one set of parameters (σ and E_r) may generate curves that fit the data. This ambiguity is a problem. In addition the measurements need to be made a some distance from the antenna and do not give a very good idea of the ground within a 1/2-wave 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 antenna.

Another well known technique^[6] is to insert a probe into the soil and measure it's impedance. In some cases 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 when it's in soil. This approach can yield a detailed characterization of the soil in the immediate area of the antenna. A limitation of this procedure is that it is usually not possible to use a probe which reaches very far down into the soil. The result is characterization mainly the top few feet of soil, which will usually be less than the skin depth for the particular soil. By making measurements at many spots over the area of interest the probe method can give a good picture of the lateral variation of soil parameters. But we know that the properties will also vary vertically (variations in moisture content, stratification, etc) and we would like to know the variations down to one 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, grossly increases the labor of what needs be a relatively simple process. It's probably not worth it!

With this limitation are the measurements worth doing? I think so. Certainly they are a vast improvement over nothing but we should not be fooled into thinking they are more than a guide. The rest of this discussion will focus on ground probes and data reduction.

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 3.

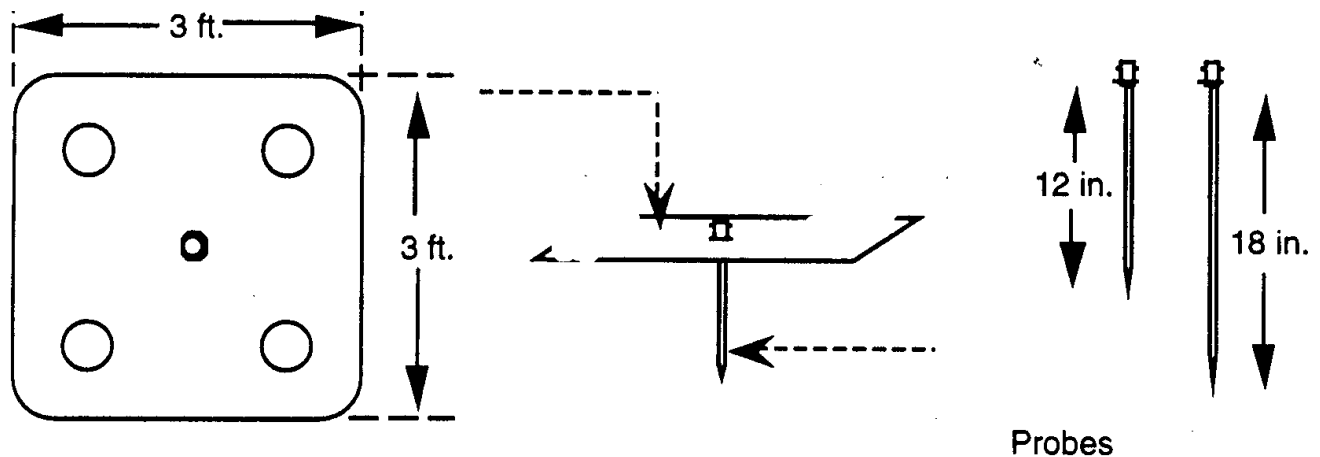


Figure 3, typical monopole ground probe. Figure taken from Rupar^[7].

The ground screen can be either square or circular with a radius greater than the length of the longest probe. Rupar^[7] used a copper sheet for the ground screen and I initially used a sheet of 1/8" aluminum. But a large metal sheet is awkward to work with and I found that a piece of 1/2' galvanized hardware cloth (as shown in figure 4) 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 to carry around. The example in figure 4 shows an AEA complex impedance analyzer. An MFJ-259B or other impedance analyzer in that class would work equally well.

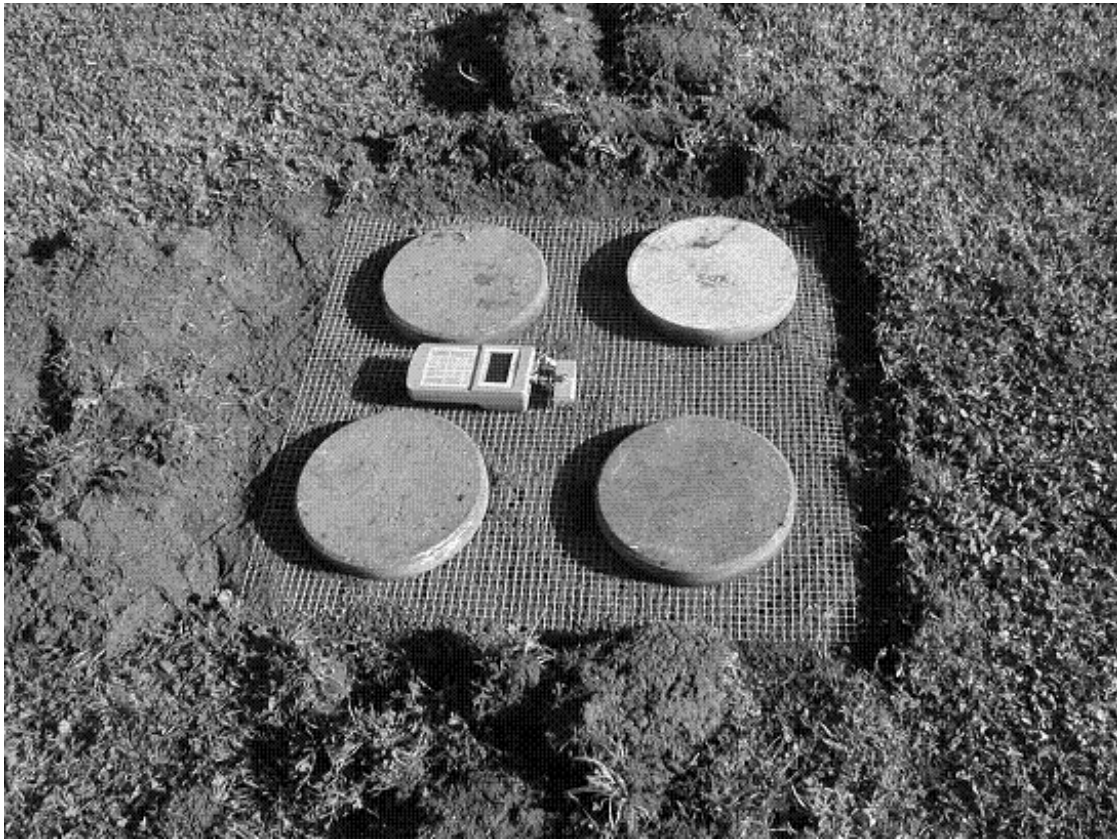


Figure 4, Monoprobe in action.

Figure 5 gives examples of typical 12" and 18" probes.

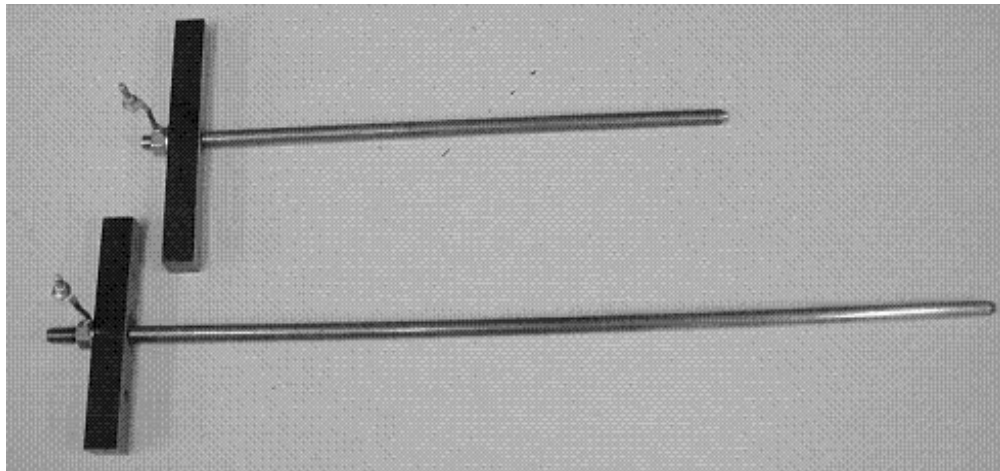


Figure 5, Typical ground probes.

The crossbars are phenolic but any reasonable insulating material will work fine, even varnished 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" or so) in the screen and pushed down until stopped by the crossbar. This will give a consistent depth to the rod. The rods

shown are brass but that's not essential. I just happened to have some 3/8" brass rod stock lying around. For the initial probes I threaded the top of the rod and the cross bar, and then screwed them together. I put 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 pin to hold it. For later experiments I found some inexpensive 7/16" aluminum rod at a scrap yard. You should be able find suitable rod stock at most hardware stores. The larger diameters make for more sturdy probes but they may be harder to push into the ground. In fact if your ground closely resembles concrete like mine does, you may want to make up a hole punching tool like that shown in figure 6.

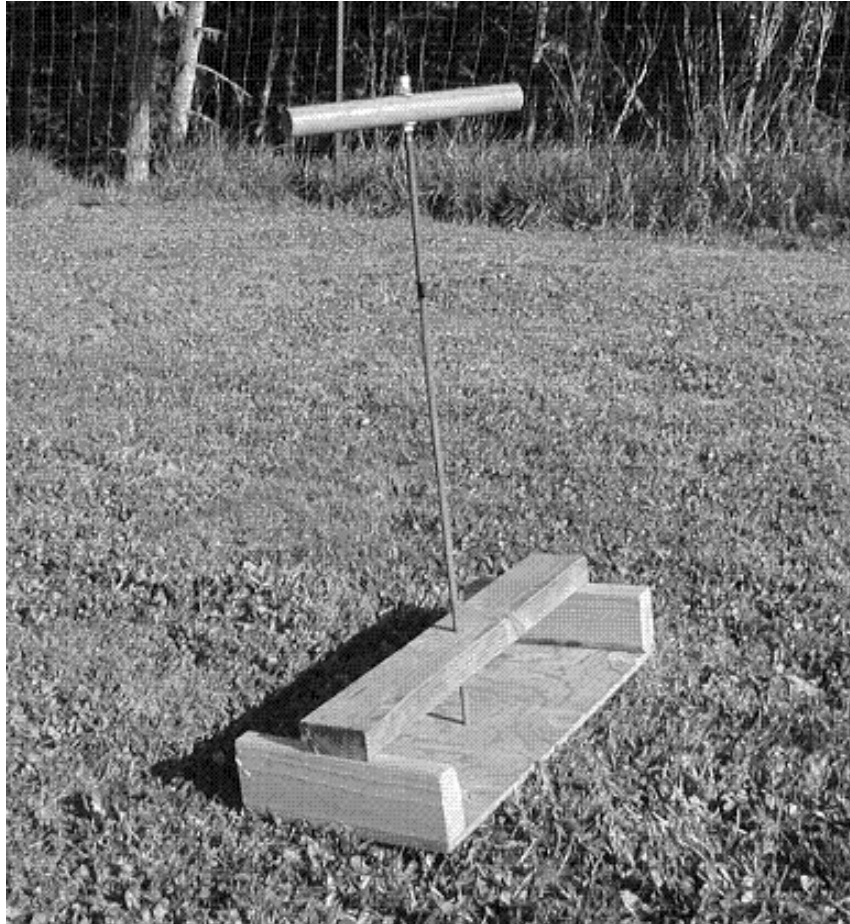


Figure 6, Ground hole puncher.

I took a 3/8" steel rod and put a handle on it as shown. The wooden jig is used to align the rod so it goes straight down into the soil. I stand with my feet on the jig and push down on the rod. While this may well be a bit of struggle initially, it makes pushing the probe in much easier.

The impedance is measured between the top of the rod and the ground screen as shown in figure 7.

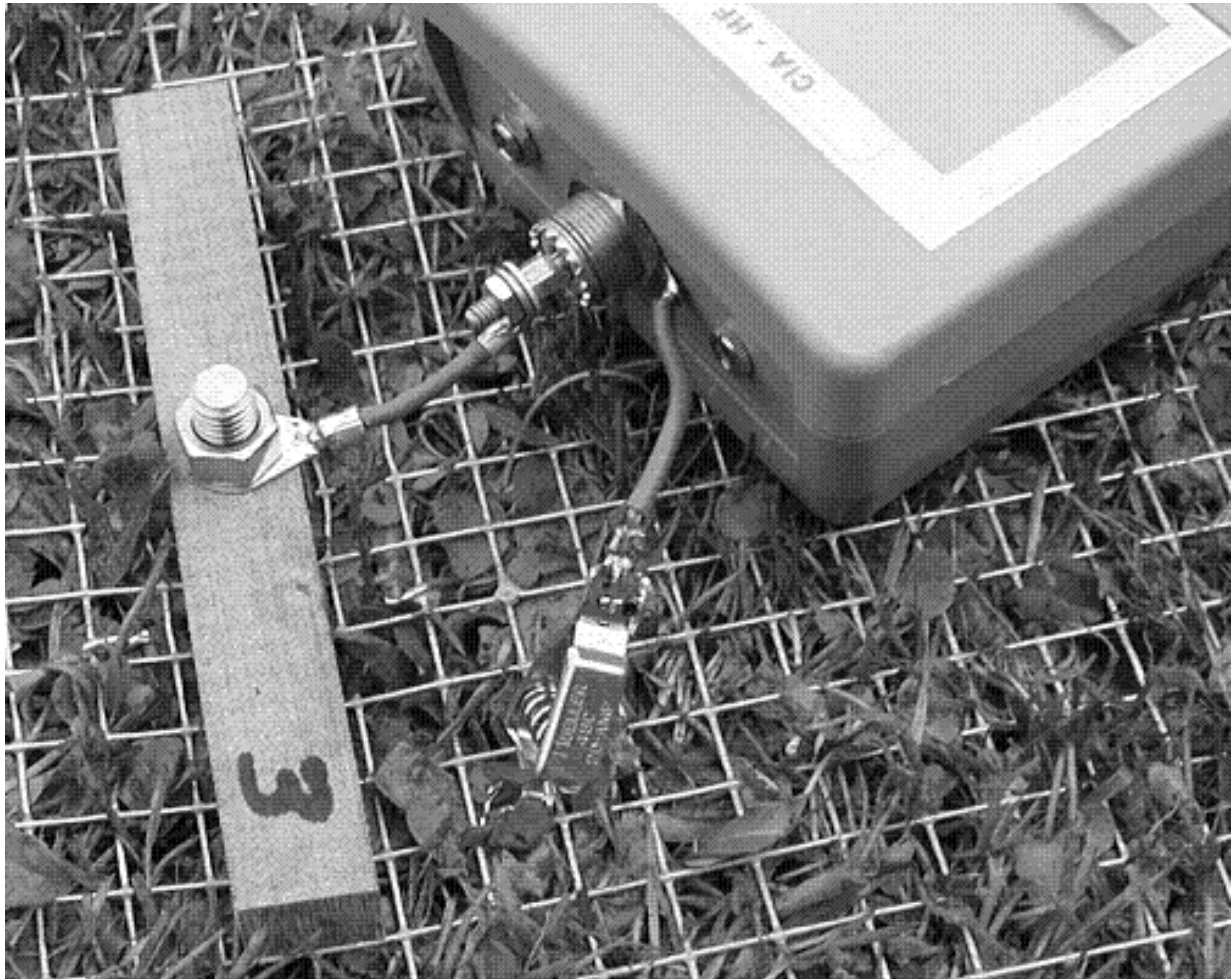


Figure 7, Example of measurement between ground screen and rod top.

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^[6] (Open Wire Line) probes are simply two parallel rods and a crossbar without a ground screen as shown in figure 8.

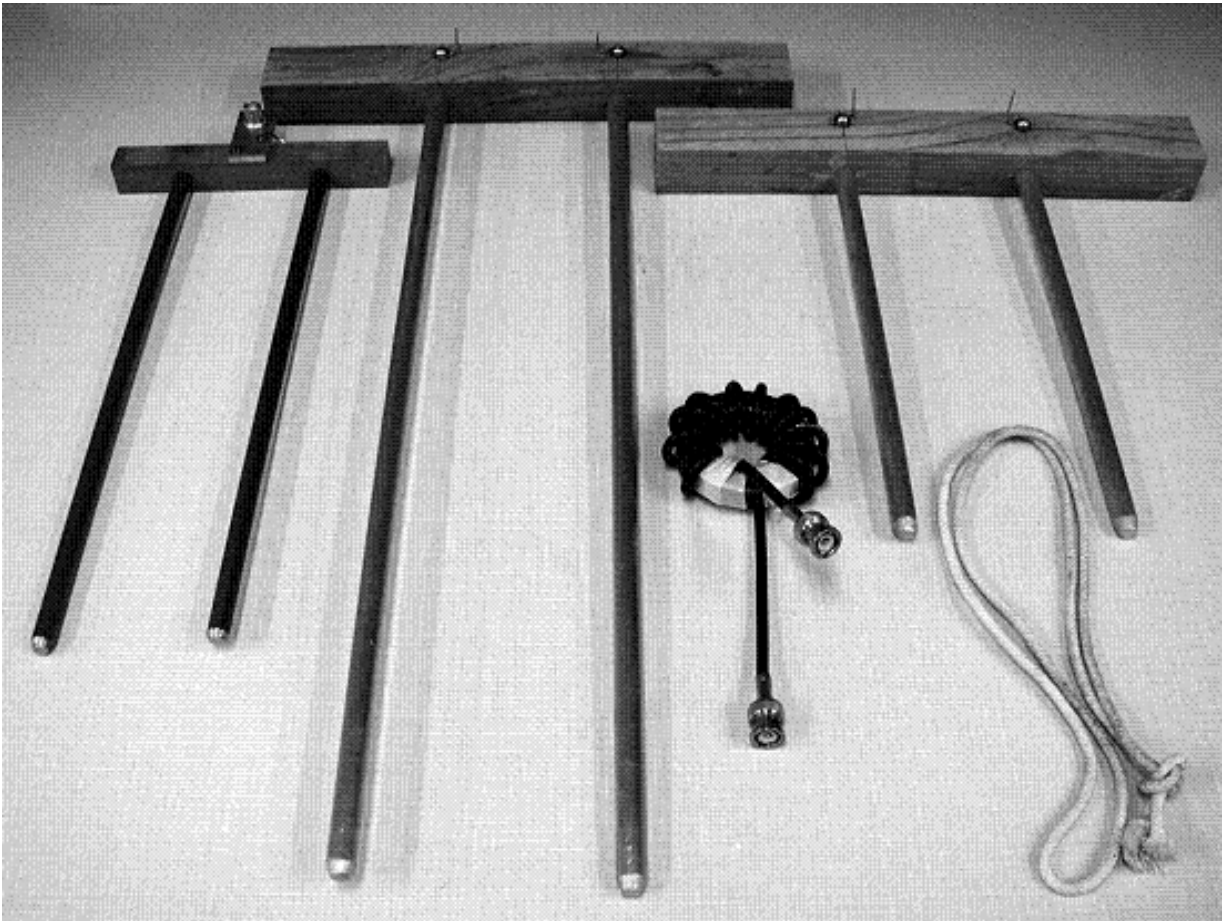


Figure 8, Typical OWL probes, 4" spacing by 9" and 18" long, using 7/16" aluminum rods and 3" x 12" with 3/8" brass rods.

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 N2PK vector network analyzer, with a cable then a balun would be a good idea. I made up a test balun which is included in figure 8. I used a Fair-Rite FT240-43 ferrite core. This is standard core available from Amidon. The winding is a 3' length of RG58 with BNC connectors at the ends. Makes about 12 turns and should give adequate isolation down to 1 MHz.

The probes with 4" spacing use clip leads like that shown in figure 7 but the 3" spacing probe (probe on the left in figure 8) has a BNC connector on the crossbar to which the balun is connected. There is nothing magical about either arrangement.

Figure 8 also includes 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 getting the probe out without the cord can be a real 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 have to do is to measure or calculate the probe capacitance (as shown in appendix) for your particular probe.

Choosing between a monoprobe or an OWL

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_o will be off. Given the modest accuracy required for ham applications this is usually not a big 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 measures a much larger volume of soil and provides an average over the volume whereas the OWL pretty much characterizes just 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. You then use the following equations to convert the impedance readings to σ and E_r . Putting these equations into an Excel spreadsheet makes the whole process very painless.

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

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

$$E_r = \frac{10^6}{2\pi f_{MHz} C_o} \left[\frac{X}{R^2 + X^2} \right] \quad (2)$$

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

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

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

Where: C_o = 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.

Tables 1 and 2 show typical impedance measurements taken at two different locations on my property and their reduction to σ and E_r .

Table 1, 18" monoprobe, $C_o = 7.41$ pF. On my antenna hill with an AEA-CIA analyzer

Frequency MHz	R Ohms	X Ohms	conductivity (S/m)	E_r
1	129	-134	.0044	83
2	83.3	-95.8	.0062	64
3	66.3	-76.2	.0078	53
4	56.7	-65.2	.0091	47
5	51.5	-57.2	.010	41
6	46.2	-47.8	.012	39
7	40.2	-46.2	.013	38
8	35.1	-40.4	.015	38

Table 2, 4" x 9" OWL, $C_o = 2.71$ pF. In my back yard with AEA-CIA, no balun.

Frequency MHz	R Ohms	X Ohms	conductivity (S/m)	Er
1	176	-137	.0042	59
2	123	-119	.0050	44
3	95.2	-98.5	.0061	38
4	83.4	-86.3	.0069	32
5	77.7	-75.0	.0079	28
6	73.0	-63.4	.0093	24
7	60.9	-60.9	.0098	25
8	54.7	-52.8	.011	25

The data in tables 1 and 2 is graphed in figures 9 and 10.

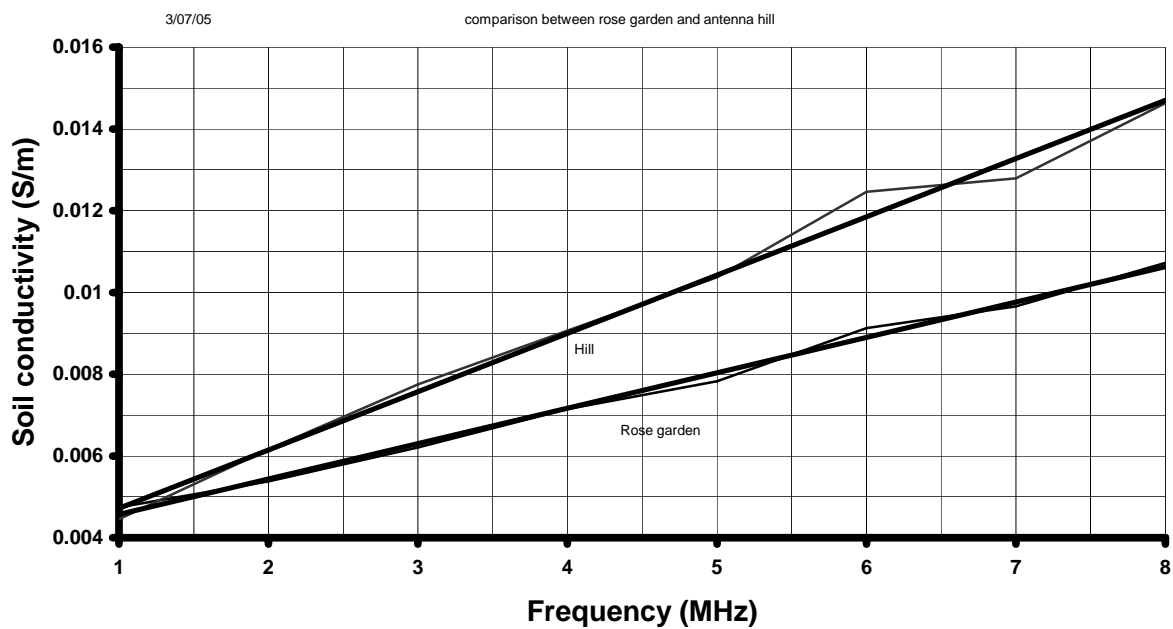


Figure 9, Comparison of conductivity between two sites.

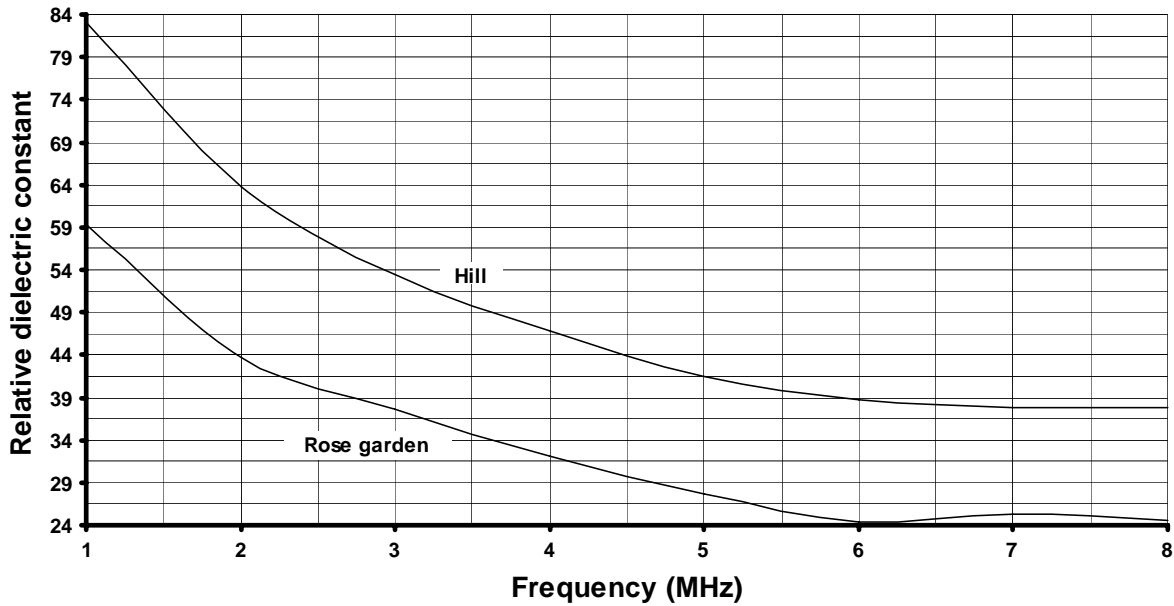


Figure 10, Comparison of Er between two sites.

Because of the relatively poor accuracy of the AEA analyzer, the graphs are a bit lumpy. In figure 8 I have simply 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 4, 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 of the grass was. The results are shown in figures 11 and 12.

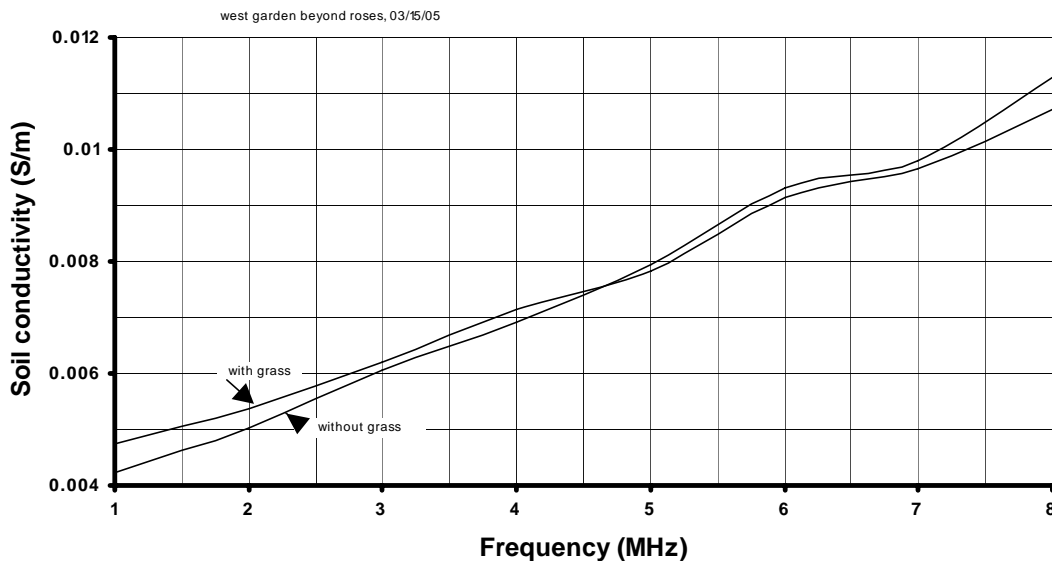


Figure 11, soil conductivity with and without grass cover using an 18" monoprobe.

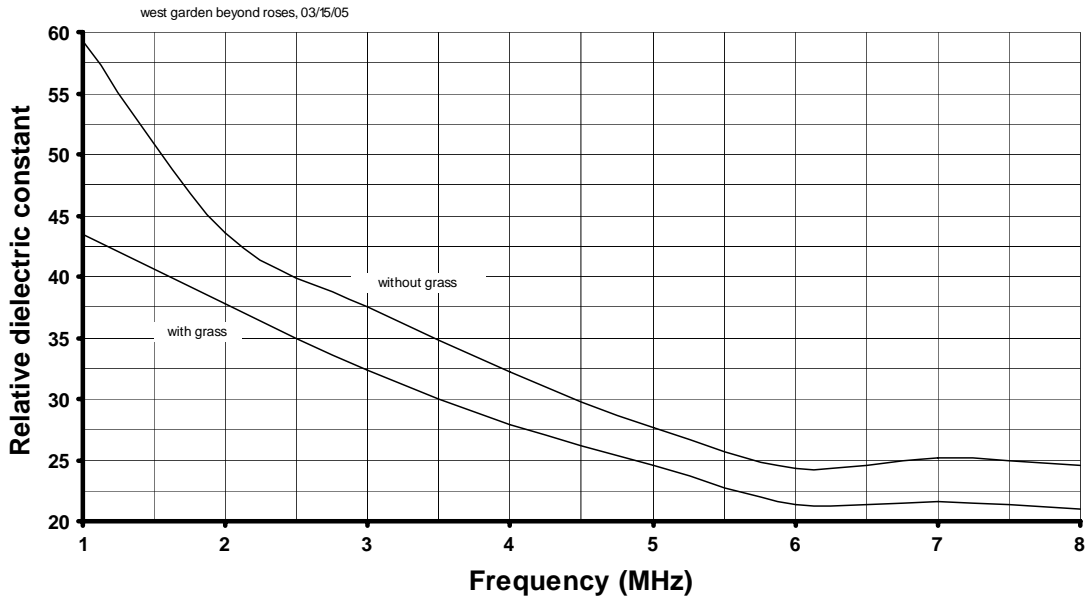


Figure 12, soil Er with and without grass cover using an 18" monoprobe.

As can be seen from the graphs, the presence of the grass doesn't have a lot of effect on the conductivity measurements but does substantially affect the Er measurements. What the grass does is to insert a layer air under the screen which reduces the effective capacitance which in turn reduces the value for Er. 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 Er go up and then when things dry out, σ and Er 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" or so. This effect on measurements is illustrated in figure 13. 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 which dries much more slowly and as you can see the two longer probes give essentially the same data. A close look at the 24" probe data line illustrates a limitation in ground probe measurements. 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" probe curve starts to bend over at the higher end. This can be corrected for by using more complex equations for the data reduction but for most users that may be more trouble

than its worth. The usable range is still above 40 m. Very high conductivity soils may require shorter probes but that's ok because the skin depth in such soils is very much reduced. A separate article on skin depths and wavelengths in soil will be added to this web page in due course.

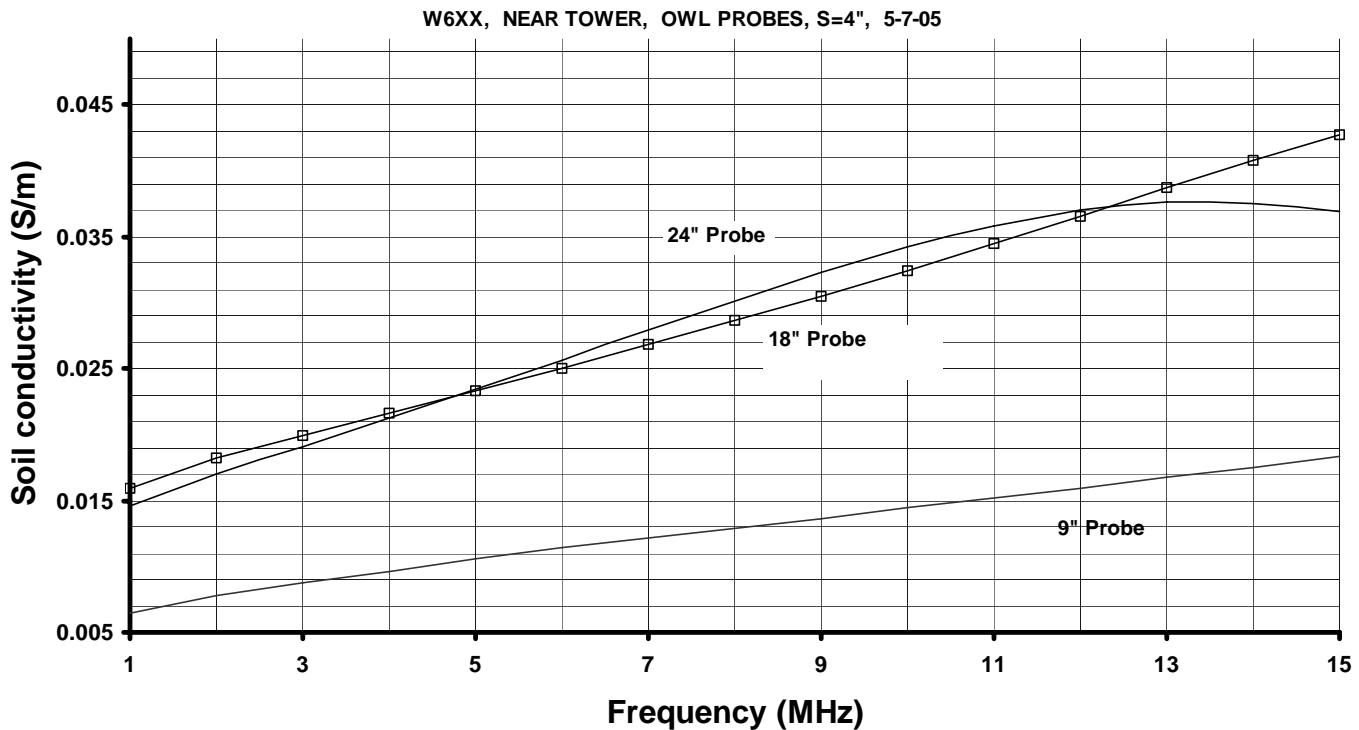


Figure 13, Effect of different probe lengths on conductivity data.

Comments on ground data

The conductivity graph (figure 9) 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 frequency. In addition, as shown in figure 10, E_r is not constant either and tends to decrease as you go up in frequency to about 5 MHz but then stabilize above that. While these characteristics have been known to professionals for many years they often come as a surprise to amateurs.

The general shape and trends displayed in figures 9-13 agree very well with those seen in the large body of professional work on ground parameter values.

At both sites in figure 9, σ corresponds to what is generally called "average ground".

Average ground is usually defined as $\sigma = .005$ S/m and $E_r = 13$. In figure 10 however, E_r is much larger than 13, especially below 5 MHz. This is particularly characteristic of soils with a lot 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 now is that it is very real. The following quote is from the King and Smith, *Antennas In Matter*^[8], which is considered a definitive work:

"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. Second, I average the readings found at different places over the site. 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.

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 $\sigma = .001$ S/m and $\epsilon_r = 5$ which would appear to apply in my location.

I think that ground probe measurements are worth doing and I use them but with care.

References

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Appendix - Co determination

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

$$C_o = \frac{3.677}{\log_{10} \left\{ \frac{D}{d} \left(1 + \sqrt{1 - \frac{1}{(D/d)^2}} \right) \right\}} \text{ pF/ft}$$

Where: D = center-to-center distance between rods and d = diameter of the rods. Dimension units for D and d must be the same but can be anything.

For an 18.5" OWL probe with D = 4" and d = 0.44", this gives Co = 4.51 pF. Of course there will also be a small additional capacitance due to end effect. A later measurement

gave $C_o = 4.83 \text{ pF}$ 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_o 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.



Figure A1, L/C meter

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 which is the sum of C_o and the part of the probe which sticks out of the ground and is connected 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 which is identical in all respects to the actual probe except that the portion of the rod or rods which 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 E_r and causes a small error. In practice C_p will be roughly the same magnitude as C_o . But when the probe is inserted into soil C_o is multiplied by E_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 E_r I don't think it buys much.

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, etc. I zero the meter by holding it with one stick and pushing the zero button with the another do that effect of my body is minimized.

Even with this simple and inexpensive instrument I believe I get quite accurate values for C_o . I confirmed the measurements using an HP 3577A vector network analyzer.

I found the following values:

probe type	rod diameter	spacing	length	ground screen	C_o
monoprobe	0.375"	-	18"	3' x 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

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.