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Electrical parameters of soils in the frequency range from 1 kHz to 1 GHz, using lumped-circuit methods

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Abstract. For studying electrical properties of soil samples with various compositions and water contents, we applied a lumped-circuit approach. The extension of this method up to 1GHz was made possible by using a coaxial sample holder. The complex electrical parameters of soils, such as the relative permittivity $\hat{\varepsilon}$, conductivity $\hat{\sigma}$, and resistivity $\hat{\rho}$, were obtained by measuring the magnitude Z and phase φ of the sample impedance $\hat{Z}$. The experimental setup is described in our previous paper [*Levitskaya and Sternberg*, 2000]. The relative real permittivity ε' and imaginary permittivity (dielectric losses) ε'' for high-loss soils from Arizona decrease with frequency and increase with water content. Regression equations, derived for the relative permittivity ε' versus water content at a given frequency, can be used to determine the water content in soil from ε' data. The third-degree polynomial equations, which relate the relative permittivity to the volumetric soil moisture content, are different for various frequencies. The complex electrical resistivity components ρ' and ρ'' reveal a time-dependent polarization process at frequencies above 1 MHz, which shifts to higher frequencies with increasing water content. The propagation parameters, such as attenuation constant α, phase velocity V_p, and penetration depth P, which we calculated from the electrical parameters, also depend on soil wetness. Our comparison of the electrical and propagation parameters for different soils shows that the high-loss soil samples from Avra Valley, Arizona, have higher values of ε' and ε'', higher attenuation constant α, and lower penetration depth P than the low-loss soils from Brookhaven, New York. For example, at 500 MHz, a high-loss soil (Avra Valley) with volumetric moisture content of ~10 %, exhibits an attenuation of 43 dB/m, whereas for a low-loss soil (Brookhaven) with the same wetness the attenuation constant is only 4 dB/m. We also note that very dry, clean sand in a sheltered "sand box," which is a favorite medium for testing ground-penetrating radar (GPR), is usually not representative of natural conditions. Therefore, GPR data from such "sand box" experiments must be used with considerable caution because they yield unrealistically large penetration depths and unnatural target responses.

1. Introduction

In our previous paper [*Levitskaya and Sternberg*, 2000] we described in detail lumped-circuit methods for determining electrical properties of materials, which we extended to higher frequencies, up to 1 GHz. This extension to 1 GHz was made possible by using a coaxial sample holder for measuring the sample impedance $\hat{Z}$ with an impedance analyzer. From these measurements the lumped-circuit parameters (resistance R, conductance G, and capacitance C) were defined. The inductance L and resistance R_{ms} of the measuring system were taken into account. Then, using the sample sizes, the complex resistivity $\hat{\rho} = \rho' - j\rho''$, complex conductivity $\hat{\sigma} = \sigma' + j\sigma''$, and complex permittivity $\hat{\varepsilon} = \varepsilon' - j\varepsilon''$ were calculated. Throughout this paper the relative values of the dielectric permittivity are used. For example, the real relative permittivity is $\varepsilon'=\varepsilon/\varepsilon_0$, where $\varepsilon_0=8.854\times10^{-12}$ F/m is the permittivity of vacuum. The imaginary permittivity $\varepsilon''=\varepsilon'\tan\delta$ is also relative. Here $\tan\delta$ is the loss tangent (also called the dissipation factor). We assume that our soils are nonmagnetic; therefore the relative complex permeability $\hat{\mu} = \mu' - j\mu'' = 1.0 - j0.0$, where $\mu' = \mu / \mu_0$ and $\mu_0 = 1.257\times10^{-6}$ H/m.

The purpose of this paper is to show some experimental results, obtained by the lumped-circuit methods in the frequency range from 1 kHz to 1 GHz, for soils

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from different locations and with various volumetric water contents W_v. We have studied soils from Avra Valley, Arizona, and Brookhaven, New York. These soils have different compositions and different levels of energy losses. We consider the soil from Arizona as a high-loss soil and the soil from Brookhaven as relatively low loss because the loss factor ε'' of Arizona soils is larger by an order of magnitude in comparison with that of Brookhaven soils, with similar volumetric water content. Loss factor and attenuation plots will be shown in section 4.2.

Composition and water content primarily determine the electrical properties of soil. Therefore we acquired disturbed soil samples, which are satisfactory for our purpose. For soils from Avra Valley, precautions were taken to retain the natural moisture. This procedure is described in section 2. Soil samples from Avra Valley have natural volumetric water contents in a narrow range, typically below 14%. Therefore, in order to study the effect of water content on electrical properties of soils, some soil samples with a wider range of water content, up to full saturation, were prepared in the laboratory.

Studying the real dielectric permittivity of soils as a function of water content can be used to solve the inverse task of determining soil moisture from relative permittivity (ε') measurements. Some relationships of $\varepsilon' = F(W_v)$ at various frequencies are shown, and corresponding regression equations are obtained. Comparison of electrical and propagation parameters for soil samples of various compositions and moisture contents may also contribute to a variety of problems in exploration geophysics, such as environmental site characterization, geotechnical surveys, and water resource studies.

2. Sample Acquisition and Preparation

As described in our previous paper [*Sternberg and Levitskaya*, 1998], in order to retain the natural soil moisture the soil samples from Avra Valley were collected within a very short time after excavation (a few minutes). Excellent agreement was obtained between laboratory and field resistivity measurements. From this we conclude that although the samples have been disturbed, they are representative of the in situ electrical properties [*Sternberg and Levitskaya*, 1998; *Sternberg and Birken*, 1999]. Samples collected from Brookhaven were also disturbed, but the natural moisture was not retained. Therefore we prepared moist samples in the laboratory from previously oven-dried soil. Some moist soil samples from Avra Valley were also artificially prepared.

As described by *Sternberg and Levitskaya* [1998], before measuring the electrical parameters the soil was sieved to a fraction <0.6 mm in order to remove any stones or clumps. The measuring cell containing the sample was weighed, and its thickness between the electrodes was measured with a micrometer. The sample thickness h was determined by subtracting the known electrode thickness from the mean value of cell thickness measured at five to six points around the disk electrodes. As described in our previous paper [*Levitskaya and Sternberg*, 2000], three Teflon clamps allow compression of the soil sample to approximately in situ conditions.

Subtracting the weight of the empty cell from the weight of the cell with the sample, we obtained the sample weight M with natural moisture. Knowing the sample's weight M (g) and geometrical volume V (cm^3), we can calculate the density of the measured sample ρ_s (g/cm^3):

$$\rho_S = \frac{M}{V}. \tag{1}$$

The density ρ_s may serve as a measure of sample compaction in the sample holder. Also, the dry bulk density ρ_b was calculated as a ratio of the sample's dry weight M_{dry} to its volume. Our natural samples from Avra Valley have values of dry bulk density ($\rho_b = 1.5 \pm 0.07$), which is close to the measured dry bulk density ($\rho_b = 1.6$) for undisturbed soil from the same location [*Sternberg*, 1993]. The data for dry bulk densities of our samples are shown in Table 1.

The electrical property measurements were performed on soils with natural moisture as well as on specially prepared samples with various water contents. When we studied a sample with natural moisture, it was dried out at $T \approx 105^0$C after performing the measurements in order to determine its moisture content. The specially prepared soil samples were dried in an oven with a temperature $T \approx 105^0$C until the weight became constant. Then, a desired amount of distilled water ($\rho \approx 10^4$ Ohm-m) was added to the sample. We used distilled water rather than salt solutions because the natural salts remained in the dried sample.

The soil water content in the sample was calculated in percent by two ways: by weight (gravimetric, W_g) and by volume (volumetric, W_v). The difference between sample weights in the wet and dry state divided by its dry weight gives the gravimetric water content [Hillel, 1982]:

Table 1. Dry Bulk Density ρ_b (g/cc) of Soil Samples

	Samples from Arizona		Samples from Brookhsven	
	Natural	Prepared	Natural	Prepared
n	52	50	4	10
Mean m	1 49	1 83	1.62	1.58
Standard deviation σ_s	0.073	0.12	0.049	0 057
Relative Standard deviation δ_s, %	4.91	6.67	3.03	3.63

$$W_g = \frac{M_{\text{wet}} - M_{\text{dry}}}{M_{\text{dry}}} 100\ \%. \qquad (2)$$

The water volume divided by the sample volume gives the volumetric water content:

$$W_v = \frac{M_{\text{wet}} - M_{\text{dry}}}{\gamma_w V} 100\ \%, \qquad (3)$$

where $\gamma_w = 1$ g/cm^3 is the water specific weight. In our further discussion, we will use the volumetric soil water content W_v. It is easy to see from (2) and (3) that W_v and W_g are related through the dry bulk density $\rho_b = M_{\text{dry}}/V$.

3. Electrical Properties Interpretation

Earth materials, particularly soils, are heterogeneous (e.g., soil particles, air, and water). Therefore the actual measured parameters characterize some equivalent homogeneous material. Moist soils may behave primarily as a conductor at low frequencies (below 100 kHz), while at high frequencies (above 100 MHz) the features of a dielectric prevail. In the range of frequencies f = 100 kHz to 100 MHz, in moist soils, the dielectric phenomena are complicated by conductivity [*Dukhin and Shilov*, 1974]. Such materials behave as both a conductor and a dielectric, and the measured real parts of $\hat{\sigma}$ and $\hat{\varepsilon}$ are affected by each other. In this case, σ' consists of two components, such as the ohmic conductivity σ_{ohmic}, which corresponds to the direct current field, and the displacement current "dielectric conductivity" σ_{diel}, which is frequency dependent. Consequently, the total loss factor $\varepsilon''_{\text{total}}$ includes all the energy losses, which arise from two different mechanisms, (1) conduction phenomena (ohmic losses) and (2) polarization processes (dielectric losses), as follows [*Alvarez*, 1973; *Dukhin and Shilov*, 1974; *Taherian et al.*, 1990]:

$$\varepsilon''_{\text{total}} = \varepsilon''_{\text{diel}} + \frac{\sigma'_{\text{ohmic}}}{\omega\varepsilon_0} = \frac{\sigma'_{\text{diel}} + \sigma'_{\text{ohmic}}}{\omega\varepsilon_0}. \qquad (4)$$

Similarly, the total loss tangent ($\tan\delta_{\text{total}} = \varepsilon''/\varepsilon'$) can also be expressed as consisting of two components, dielectric and conductive parts, as follows [*Bartnikas*, 1987]:

$$\tan\delta_{\text{total}} = \tan\delta_{\text{diel}} + \frac{\sigma'_{\text{ohmic}}}{\omega\varepsilon'\varepsilon_0}. \qquad (5)$$

Usually, for high-loss materials the experimental data represent the total values of conductivity and energy losses.

As discussed in our previous papers [*Levitskaya and Sternberg*, 1996, 2000], in a polar or heterogeneous material, a time-dependent polarization may develop, such as dipole orientation or interfacial (Maxwell-Wagner) polarization, respectively. Both of these types of polarization result in a relaxation process, which can be described with a Debye equation of a semicircle for a dispersion with a single relaxation time τ [*Debye*, 1945], or with a Cole-Cole empirical formula for a broad distribution of relaxation times [*Cole and Cole*, 1941]. However, in materials with a conductive component the high conductivity may mask the dielectric relaxation [*Von Hippel*, 1959]. In general, it is possible, using (4), to extract the dielectric part $\varepsilon''_{\text{diel}}$ by subtracting the conduction, or ohmic, losses $\sigma'_{\text{ohmic}}/\omega\varepsilon_0$ from the total, measured, losses $\varepsilon''_{\text{total}}$. As a result, a Cole-Cole arc $\varepsilon''_{\text{diel}} = F(\varepsilon')$ can be obtained. We have found that the values of $\varepsilon''_{\text{diel}}$ are very sensitive to the accuracy of σ'_{ohmic}. A small error in the σ'_{ohmic} value may cause a large change in the frequency where the maximum $\varepsilon''_{\text{diel}}$ occurs. This leads to a large difference in the relaxation time τ, which is obtained from the resulting Cole-Cole arc.

In wet earth materials the polarization processes often show up in a frequency dependence of the resistivity. The Cole-Cole equation for the complex permittivity $\hat{\varepsilon}$ can also be applied to the complex resistivity ρ as follows [*Wait*, 1984]:

$$\hat{\rho} = \rho_\infty + \frac{\rho_0 - \rho_\infty}{1 + (j\omega\tau_0)^{1-\alpha}}, \qquad (6)$$

where ρ_0 is the static resistivity, ρ_∞ is the high-frequency limit of the given resistivity dispersion, τ_0 is the most probable relaxation time, and α is an empirical constant with values between 0 and 1 and is a measure of the distribution of the relaxation times. The τ_0 corresponds to the critical characteristic frequency f_{cr}, at which the maximum of ρ'' is attained, as follows:

$$2\pi f_{cr}\tau_0 = 1. \qquad (7)$$

Separation of real and imaginary parts of (6), analogous to ε' and ε'' [*Cole and Cole*, 1941; *Smyth*, 1955; *Böttcher and Bordewijk*, 1978], gives

$$\rho' = \rho_\infty + \frac{(\rho_0 - \rho_\infty)[1 + (\omega\tau_0)^{1-\alpha}\sin(\alpha\pi/2)]}{1 + 2(\omega\tau_0)^{1-\alpha}\sin(\alpha\pi/2) + (\omega\tau_0)^{2(1-\alpha)}} \qquad (8)$$

$$\rho'' = \frac{(\rho_0 - \rho_\infty)(\omega\tau_0)^{1-\alpha}\cos(\alpha\pi/2)}{1 + 2(\omega\tau_0)^{1-\alpha}\sin(\alpha\pi/2) + (\omega\tau_0)^{2(1-\alpha)}}, \qquad (9)$$

The complex resistivity data can also be represented as a Cole-Cole diagram, which is a circular arc with the center below the ρ' axis. Such a plot of ρ'' versus ρ' is often called an Argand diagram [*Böttcher and Bordewijk*, 1978; *Ruffet et al.*, 1991]. The diameter drawn through the center of the circle from the ρ_∞ point makes an angle $\alpha\pi/2$ with the ρ' axis. Measuring this angle, we can define the distribution parameter α. The most probable relaxation time τ_0 of the distribution can be calculated from the following relation [*Smyth*, 1955]:

$$\frac{v}{u} = (\omega\tau_0)^{1-\alpha}, \qquad (10)$$

where v is the distance on the Cole-Cole plot between ρ_0 and an experimental point at a particular radian frequency ω and u is the distance between ρ_∞ and the same point. Examples of complex resistivity dispersion and absorption as well as the Argand diagram will be shown in section 4.1 for moist soils from Arizona.

From the dielectric parameters we can define the complex wave-propagation constant $\gamma = \alpha + j\beta$ for the given material, where α is the attenuation constant, and β is the phase constant. The attenuation constant α (in dB/m) and phase constant β (in rad/m) are related to the dielectric parameters of a material as follows [Von Hippel, 1954]:

$$\alpha = 8.686\,\omega\sqrt{\frac{\varepsilon'\varepsilon_0\mu'\mu_0}{2}\left(\sqrt{1+\tan^2\delta} - 1\right)} \qquad (11)$$

$$\beta = \omega\sqrt{\frac{\varepsilon'\varepsilon_0\mu'\mu_0}{2}\left(\sqrt{1+\tan^2\delta} + 1\right)}. \qquad (12)$$

Phase velocity $V_p = \omega/\beta$ can be expressed as follows (in m/s):

$$V_p = \frac{1}{\sqrt{\frac{\varepsilon'\varepsilon_0\mu'\mu_0}{2}\left(\sqrt{1+\tan^2\delta} + 1\right)}}. \qquad (13)$$

An important propagation parameter, depth of wave penetration (or skin depth) $P = 1/\alpha$, can also be expressed through the relative permittivity ε' and loss tangent $\tan\delta$, as follows (in m):

$$P = \frac{1}{\omega\sqrt{\frac{\varepsilon'\varepsilon_0\mu'\mu_0}{2}\left(\sqrt{1+\tan^2\delta} - 1\right)}}. \qquad (14)$$

4. Experimental Results

4.1. Avra Valley, Arizona: High-Loss Soils

The soil from Avra Valley is relatively uniform and contains ~85% sand, 10% silt, and 5% clay (by weight) [*Sternberg et al.*, 1991]. The iron content is around 60-70 ppm by weight; therefore the magnetic permittivity μ can be considered equal to μ_0 [McGill, 1990]. We measured soil samples with natural moisture and samples prepared in the laboratory by adding various amounts of distilled water to oven-dried soil. Because many of the natural soil samples from Arizona had similar volume moisture contents, their dielectric permittivity values were also close. We used these data for evaluating the repeatability of our measurements. Table 2 shows the calculated values of the mean m and standard deviation σ_s for the relative permittivity ε' at 40 MHz for n = 30 soil samples with volumetric water content W_v of ~10%. We also defined the relative standard deviation δ_s, as the ratio of σ_s to m times 100%. As shown in Table 2, the error of a single measurement of ε' is 3.0 %, which is close to the scatter of water content in the samples (2.8 %).

Table 2. Repeatability of the Volumetric Soil Moisture W_v and Relative Permittivity ε' (40 MHz) for a Set of n = 30 Samples

	W_v, %	ε'
Mean m	10.0	9.9
Standard deviation σ_s	0.28	0.30
Relative Standard deviation δ_s, %	2.8	3.0

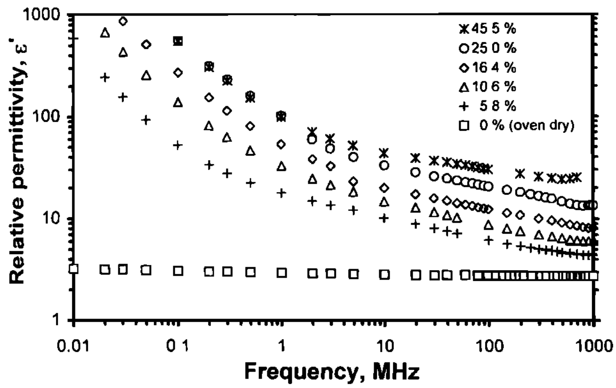

Figure 1. Relative permittivity ε' for soil samples from Avra Valley versus frequency with various moisture contents W_v.

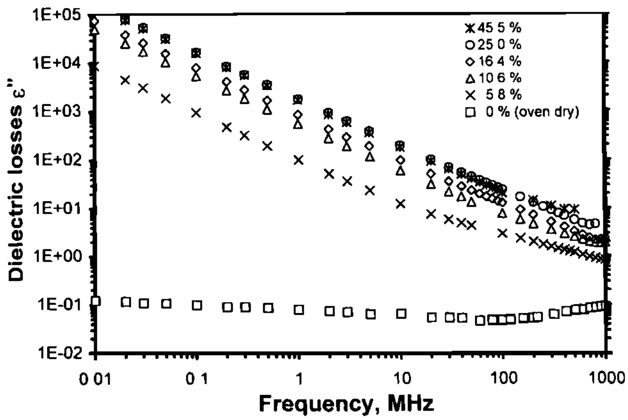

Figure 2. Real dielectric losses ε" for soil samples from Avra Valley versus frequency with various moisture contents W_v.

Figures 1 and 2 show relative complex permittivity data for wet soils from Avra Valley in a frequency range from 10 kHz to 1 GHz. The real relative permittivity ε' and the loss factor ε" decrease with increasing frequency. Data for an oven-dried sample are also shown for comparison. For dry soil, ε' and ε" values do not change appreciably with frequency. The relative permittivity data for moist soils are affected by the conductivity, which is rather high (0.004–0.1 S/m at low frequencies). Therefore we do not see any dielectric relaxation in our observed frequency range. For soils with high water content (above 25%) a saturation effect is observed for relative real permittivity ε' at frequencies below 1 MHz and for the relative imaginary permittivity ε" below 100 MHz. This saturation effect (i.e., no further dependence on moisture content) is apparently caused by dominance of the conduction effects in such wet soils.

The real conductivity σ' for moist soils from Avra Valley is shown in Figure 3 along with data for a dry sample. The real conductivity σ' for dry soil increases with frequency. For wet soils, σ' increases slightly with frequency up to approximately 10 MHz. At higher frequencies, σ' increases faster, especially when the water content is higher.

Figure 4 shows examples of resistivity data for two samples with volume moisture contents of W_v = 5.8 and 16.4%. The real resistivity ρ' decreases slightly with frequency up to between 1 and 10 MHz. In the frequency range f = 10-1000 MHz, ρ' reveals a dispersion, and the imaginary resistivity ρ" has a maximum. This indicates a relaxation process in the soil. The frequency at which the ρ" maximum occurs depends on the sample wetness. With higher water content in the sample, the relaxation shifts to higher frequencies. An Argand diagram for a sample with W_v = 5.8% is shown in Figure 5. The pa-

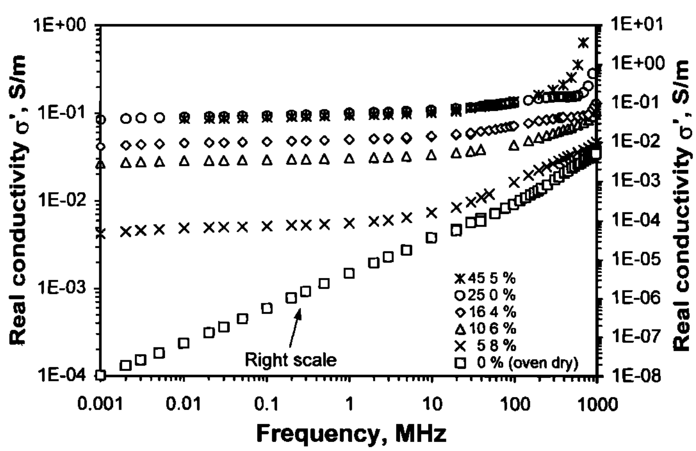

Figure 3. Real conductivity σ' for soil samples from Avra Valley versus frequency with various moisture contents W_v.

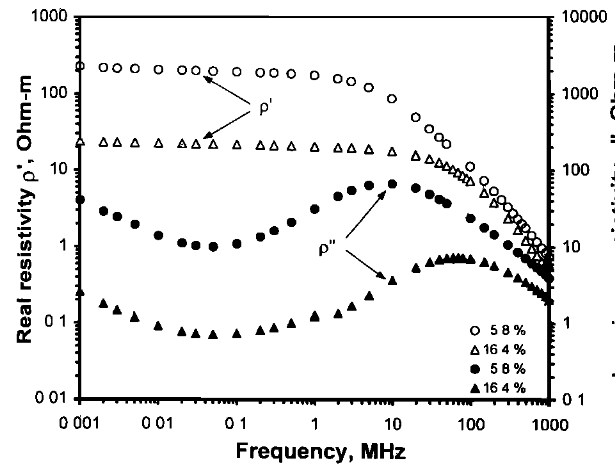

Figure 4. Complex resistivity (real ρ' and imaginary ρ'') versus frequency for two soil samples from Avra Valley with various moisture contents W_v.

rameters derived from the diagram are as follows: $\alpha = 0.194$ ($k = 1-\alpha = 0.8058$), $\rho_0 = 187$ Ohms, $\rho_\infty = 0$, and $\tau = 1.97 \times 10^{-8}$ s. The observed relaxation process most probably is caused by an interfacial (i.e., Maxwell-Wagner) polarization, which often occurs in inhomogeneous systems with a highly conductive component. Also, an orientational polarization of polar groups and molecules may take place in the same frequency range [*Debye*, 1945; *Von Hippel*, 1954; *Dukhin and Shilov*, 1974; *Levitskaya and Sternberg*, 1996].

As shown in Figure 1, the real dielectric permittivity ε' increases with the sample wetness. We received reasonable results up to 1 GHz for samples with volume moisture content less than or equal to 25 %. For samples with W_v > 25 % the frequency limit is lower. For a fully saturated sample, with W_v = 45.5 %, the data are accurate

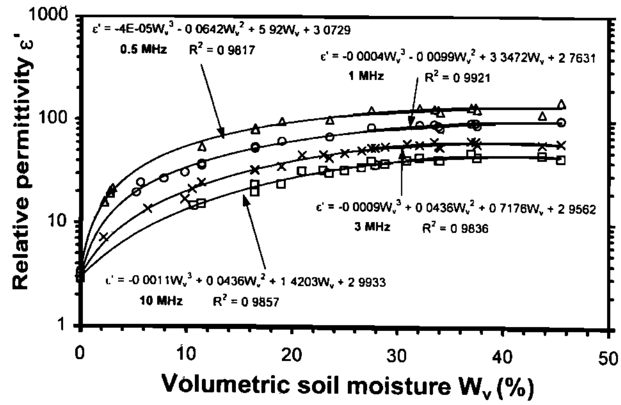

Figure 6. Relative permittivity ε' versus volumetric moisture content W_v for soil samples from Avra Valley at various low frequencies.

only to 700 MHz. The ε' relationship to volumetric moisture W_v at frequencies of 0.5, 1, 3, and 10 MHz is shown in Figure 6. Data for frequencies of 40, 100, and 500 MHz and 1 GHz are shown in Figure 7. The corresponding third-degree polynomial regression equations are displayed on the graphs. From these equations the amount of water content can be found, when the real dielectric permittivity is known. Analogous data have been described in the literature [*Hipp*, 1974; *Topp et al.*, 1980; *Jackson*, 1987; *Campbell*, 1990; *O'Connor and Dowding*, 1999]. Comparison of our data and published data shows that there is some difference in the shape of the plots $\varepsilon' = F(W_v)$, especially at high moisture contents. Our data are tending to saturation, while the published data show ε' continuously rising. This difference is more pronounced at lower frequencies (below 100 MHz, Figures 6 and 7). The saturation effect is also visible in Figures 1 and 2.

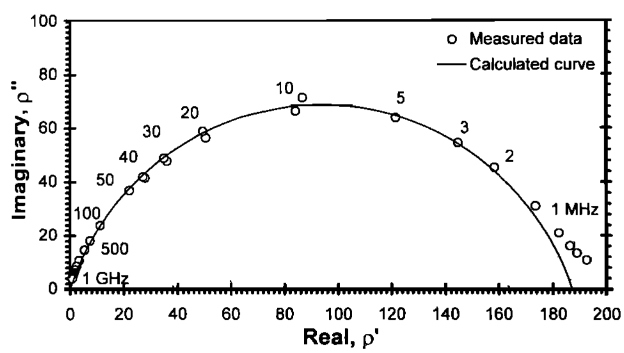

Figure 5. Argand diagram $\rho'' = F(\rho')$ for a soil sample from Avra Valley with W_v = 5.8%.

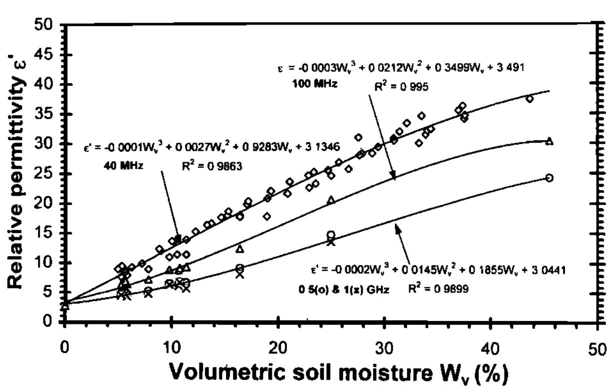

Figure 7. Relative permittivity ε' versus volumetric moisture content W_v for soil samples from Avra Valley at various high frequencies.

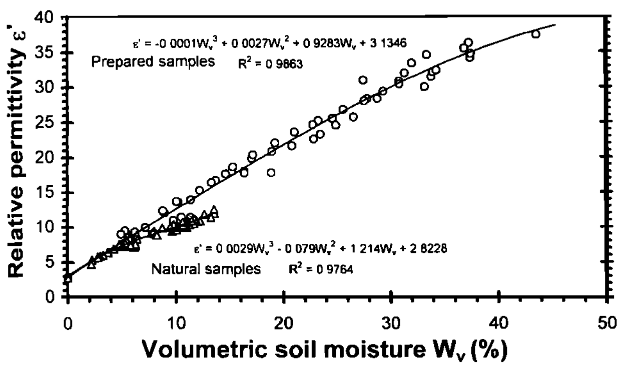

Figure 8. Relative permittivity ε' at a frequency of 40 MHz for two sets of soil samples from Avra Valley with different saturation history versus volumetric moisture content W_v.

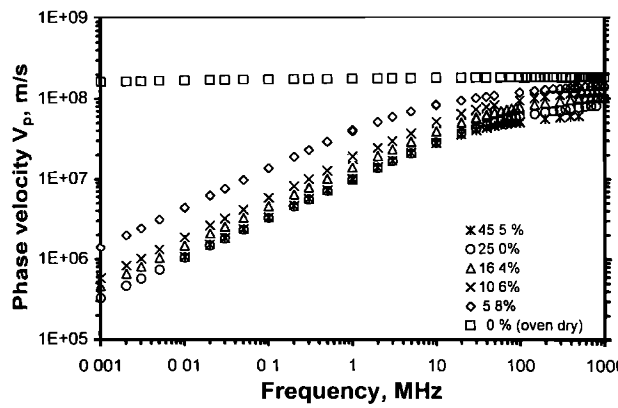

Figure 10. Phase velocity V_p versus frequency for soils from Avra Valley with various moisture contents W_v.

It must be stressed that the regression equations ε' = $F(W_v)$ are different for various frequencies; that is, the relative permittivity is a function of (at least) two variables. To define the soil moisture content from ε' measurements, the frequency must be given, and the corresponding equation must be used. At frequencies above 1 GHz, when the relative permittivity is virtually independent of frequency, a single equation for ε' = $F(W_v)$ may be derived. Some references show such high-frequency data [*Hoekstra and Delaney*, 1974; *Wang*, 1980; *Curtis*, 1994; *Peplinski et al.*, 1995; *Sarabandi and Li*, 1997].

In order to define the water amount in soil when the relative permittivity is known, we made the inverse graphs based on the same experimental data and found the regression equations for W_v versus ε', which are also third-degree polynomials. For example, such a relationship for high-frequency data (0.5-1 GHz) is the following:

$$W_v = 0.0048\varepsilon'^3 - 0.2053\varepsilon'^2 + 4.4813\varepsilon' - 10.971 \quad (15)$$

R^2 =0.9886,

where W_v is in percent. Analogous relationships were obtained by *Topp et al.* [1980].

Figure 8 shows relative permittivity data ε' at 40 MHz versus volumetric water content for two sets of samples, such as samples with natural moisture and samples prepared in the laboratory. Although the natural samples have a narrow range of moisture, they are seen to form a lower trend of ε' in comparison with the prepared samples. This difference appears to be related to different values of the dry bulk density ρ_b for these two sets. As seen in Table 1, the mean value of ρ_b = 1.83 for prepared soil samples is higher than for the natural samples, ρ_b = 1.49, from the same Arizona location. Perhaps the method of moist sample preparation in the laboratory (i.e., adding water to dry soil and stirring) could reduce

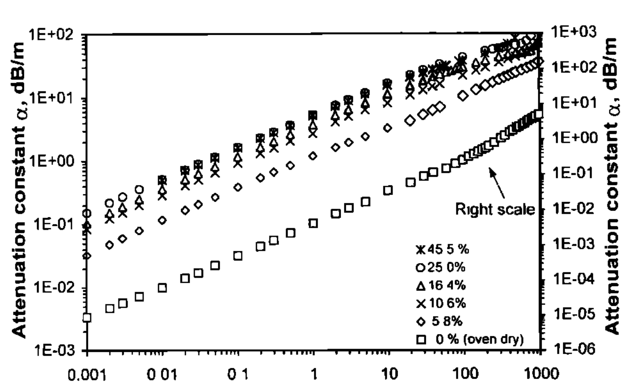

Figure 9. Attenuation constant α versus frequency for soils from Avra Valley with various moisture contents W_v.

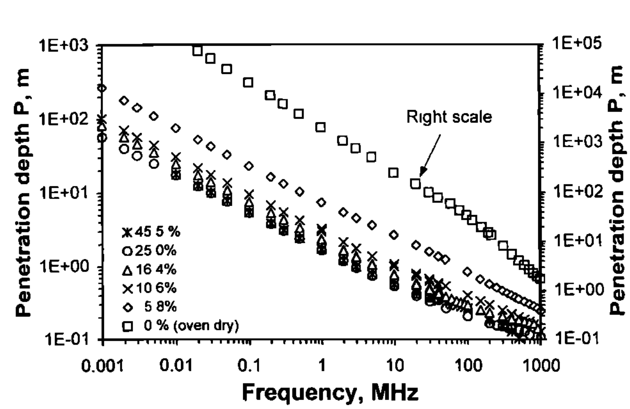

Figure 11. Penetration depth P versus frequency for soils from Avra Valley with various moisture contents W_v.

the soil cementation between grains, leading to a more compact structure, and thus increase its dry bulk density. From our study the relative permittivity increases with increasing dry bulk density for soils of similar composition. *Hipp* [1974] and *Curtis and Narayanan* [1998] found a similar effect of the dry bulk density on the electrical properties of soils.

The propagation parameters, such as the attenuation constant α, phase velocity V_p, and penetration depth P, for Avra Valley soils with various volume moisture contents are shown in Figures 9 - 11, respectively. The propagation parameters for an oven-dry sample are also shown for comparison. Samples with higher moisture content have a higher attenuation and a lower phase velocity, which are increasing with increasing frequency. The penetration depth decreases with moisture content and decreases with increasing frequency.

The Avra Valley soil samples are representative of soils throughout the southwestern U.S. basins. The high attenuation (Figure 9) and the shallow penetration depth (Figure 11) for these soils explain the very limited depth of investigation of ground-penetrating radar (GPR) surveys in this region [*Sternberg and McGill*, 1995]. These high-loss soils are also representative of conditions at many other sites around the world.

4.2. Brookhaven, New York: Low-Loss Soils

Brookhaven National Laboratory is located on Long Island, New York. The soil samples from this location consist of clean sand and are representative of low-loss soils.

In Figures 12-16 we show the electrical and propagation properties of a typical low-loss soil sample from

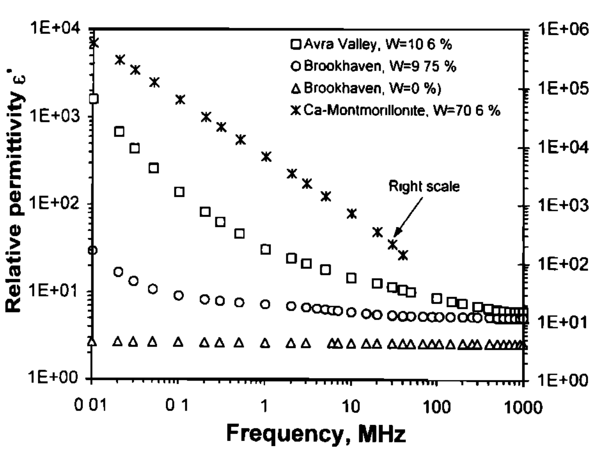

Figure 12. Relative permittivity ε′ versus frequency for soils from various locations but with similar moisture content W_v.

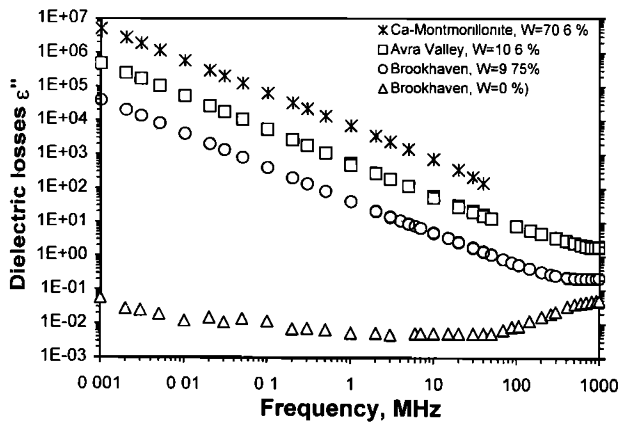

Figure 13. Dielectric losses ε″ versus frequency for soils from various locations but with similar moisture content W_v.

Brookhaven with W_v=9.75% in comparison with the data for a typical high-loss sample from Avra Valley with W_v=10.6%. The dry bulk density values for these soil samples are also close (ρ_b= 1.50 and 1.46, respectively). We have chosen to use a volumetric moisture content of ~10% since this is representative of soils at depths greater than a few centimeters but above the water table.

As seen in Figures 12 and 13, soils from Brookhaven, which do not contain clay, exhibit lower values of real dielectric permittivity ε′ and dielectric losses ε″ than the Avra Valley samples, which contain a similar amount of water but ~5 % clay. The soil samples from Brookhaven have a far lower attenuation factor α (Figure 13), higher phase velocity V_p (Figure15), and larger penetration depth P (Figure16) for any given frequency than the Avra Valley soils.

4.3. An Estimate of the Range of Soil Electrical Properties

In order to consider the complete range of electrical properties that may be encountered in the field, we have included in Figures 12-16 the experimental results for the following samples in addition to the typical high-loss and low-loss soils: (1) dry Brookhaven sample (W_v=0%). This condition is not typical in nature. Dry sand has, however, been frequently used in "sand box" experiments for GPR and other EM survey tests. Our results may provide a useful comparison of these artificial conditions with a natural setting. (2) wet Ca-Montmorillonite clay sample with water content W_v=70.6%. This sample is representative of a very high loss soil, which is not all that uncommon. For example, clay liners and clay caps often occur in environmental and engineering site investigations.

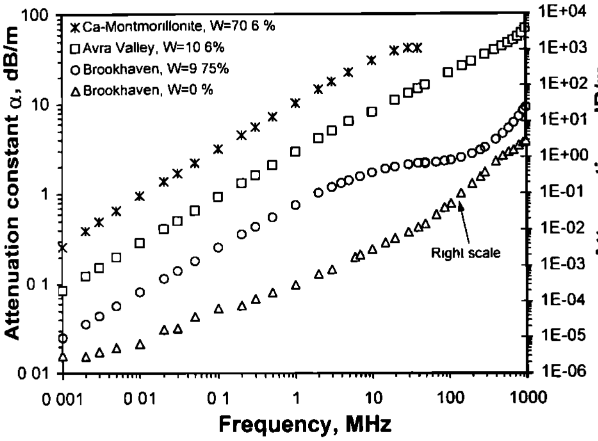

Figure 14. Attenuation constant α versus frequency for soils from various locations but with similar moisture content W_v.

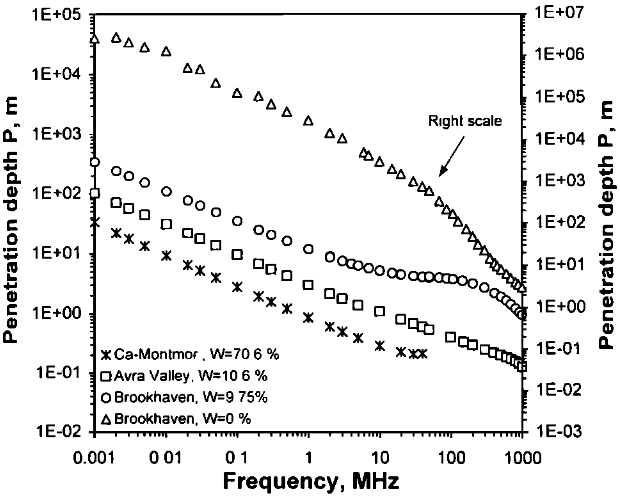

Figure 16. Penetration depth P versus frequency for soils from various locations but with similar moisture content W_v.

Data for the four samples displayed in Figures 12-16 give a good idea of the range of electrical properties (including attenuation and depth of penetration) that may be encountered in GPR and other electromagnetic (EM) surveys over soils.

5. Conclusions

Experimental results presented in this paper show that it is possible to extend the application of the lumped-circuit methods up to 1 GHz for measuring electrical properties of soils with various volumetric moisture contents (<25 %). Moderate relative permittivities, up to $\varepsilon' \leq 15$ at 1 GHz, can be measured. This was achieved by using a coaxial sample holder for measuring the sample impedance with an impedance analyzer. The experimental procedures are described in detail in our previous paper [*Levitskaya and Sternberg*, 2000].

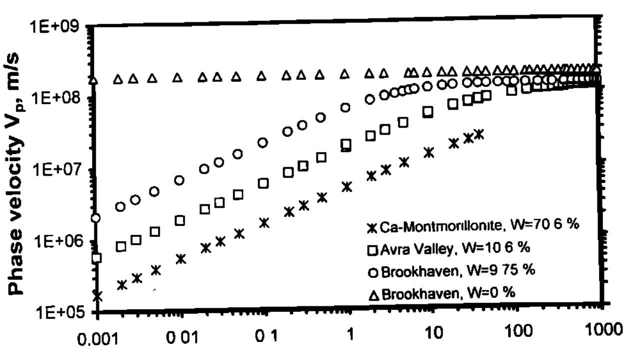

Figure 15. Phase velocity V_p versus frequency for soils from various locations but with similar moisture content W_v.

The complex relative permittivity parameters, ε' and ε'', for high-loss soils from Arizona decrease with frequency and increase with moisture content. In addition, we found that the dry bulk density affects the dielectric permittivity of soils. This is especially true for soils of the same composition. Soils with similar dry bulk densities but with different composition (from Arizona and Brookhaven) show different values of complex relative permittivity.

The complex relative permittivity data do not reveal any relaxation, which may be masked by transport phenomena in these conductive soils. In the resistivity plot we observed a time-dependent polarization above 1 MHz, which shifted to higher frequencies, when water content in the soil increased. We interpret this as a Maxwell-Wagner effect.

Regression equations are displayed for the relative permittivity as a function of volumetric soil moisture, which are third-degree polynomials and may be of practical use for the inverse task of defining the water content in soil from ε' data. For a given composition and dry bulk density the relative permittivity is a function not only of moisture content but also of frequency. To define the soil moisture content from ε' measurements, the frequency must be known, and the corresponding equation must be used. Only when the frequency is above 1 GHz, where the relative permittivity is virtually independent of frequency, may a single equation for $\varepsilon' = F(W_v)$ be derived. For high frequencies (0.5-1 GHz) a regression equation is given as an example for an inverse relationship, W_v versus ε', which is also a third-degree polynomial. Our comparison shows that high-loss soils have higher relative permittivity ε', which decreases with frequency more rapidly than ε' for low-loss soils. The values of dielectric losses ε'' are also higher for high-loss soil samples. The results in this paper also show the range of propagation parameters that can occur in soils. The possible range in natural soils having approximately the same volumetric moisture content is shown by the following examples: (1) the Avra Valley samples are representative of high-loss (sandy silt with clay) soils with W_v = 10.6% and have an attenuation factor of 43 dB/m and a depth of penetration of 0.2 m at 500 MHz. (2) The Brookhaven samples are representative of low-loss (pure sandy) soils with W_v = 9.75% and have an attenuation factor of only 4 dB/m and a depth of penetration of 2.0 m at 500 MHz.

The dry Brookhaven sand samples are representative only of artificial situations, such as "sand box" experiments in sheltered areas. Although such experiments may be useful for testing equipment, the results from experiments in a dry "sand box," in general, should not be extrapolated to natural conditions.

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