

Dielectric Properties of Soils at UHF and Microwave Frequencies

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The complex dielectric constant of four soils, including a sand, a silt, and two clays, was measured over the frequency range from 0.1×10^9 Hz to 26×10^9 Hz. The water content of the soils was varied from 0.0 g H₂O/g soil to 0.15 g H₂O/g soil, and the temperature from 24°C to -20°C. The dielectric relaxation spectrum of water in soils was found to be displaced to lower frequencies than the dielectric relaxation spectrum of water in bulk. The results showed that the relation between volumetric water content and the complex dielectric constant is relatively independent of soil type. At temperatures above freezing the complex dielectric constant of water in soils, at the water contents investigated, decreases with temperature, a type of behavior normally found only in solids. Below the freezing point the phase composition of water in soils determines the temperature dependence of the complex dielectric constant.

Electromagnetic systems in the frequency range from 10^8 to 2×10^{10} Hz are extensively used in applications that interface with the earth. The return of an active radar and the image of a passive radiometer depend, among other things, on the complex permittivity of the ground. The skin depth of electromagnetic radiation in the ground can be computed from a knowledge of the dielectric properties. Likewise, the dispersion and velocity of propagation of electromagnetic pulses can be derived from the dielectric constants. The purpose of this study was to add to the library of dielectric data on soils and to determine the main parameters influencing the complex dielectric constant, such as temperature, water content, and soil type. To achieve this purpose a considerable number of data were required, and techniques adaptable to routine measurements were needed. Advances in high-frequency time domain techniques have made it possible to make dielectric measurements over the frequency range from 10^8 to 2×10^{10} Hz. This range was previously difficult to cover. There are several aspects of the dielectric behavior of water in soils that could not be resolved by the reconnaissance type data reported here, and further work is needed.

Throughout this paper the relative complex dielectric constant, the ratio of the complex dielectric permittivity to the dielectric permittivity of free space, is indicated by $K^*(\omega)$, where ω refers to the angular frequency. Here $K^*(\omega)$ is written as $K^*(\omega) = K'(\omega) - iK''(\omega)$, where $K'(\omega)$ is the dielectric constant and $K''(\omega)$ is the dielectric loss factor. Conductivity is indicated by the symbol σ and has units of mhos per meter. The relation between σ and $K''(\omega)$ is $K''(\omega) = \sigma/\epsilon_0\omega$, where ϵ_0 is the dielectric permittivity of free space, equal to 8.85×10^{-12} F/m. The loss tangent, indicated by $\tan \delta$, is given by $\tan \delta = K''(\omega)/K'(\omega)$.

The literature contains substantial information on the dielectric properties of soils to a frequency of 10^8 Hz. Very high dielectric constants ($>10^3$) have been measured at frequencies below 10^4 Hz [Smith-Rose, 1933; Scott *et al.*, 1967]. Investigations by Scott *et al.* [1964] and Hoekstra and O'Brien [1969] on soils and clay suspensions and by Schwann [1963] and Schwarz [1962] on biological media, where the same effects occur, have shown that interfacial polarizations in heterogeneous media cause the high dielectric constants. Several investigators observed that at low frequency the dielectric constant is approximately inversely proportional to

frequency [Smith-Rose, 1935; Scott *et al.*, 1967] and levels off at a frequency of about 10^7 Hz at values ranging from 5 to 30, depending on the density and water content of the soil.

In studying low-frequency relaxation, one problem has been the relatively high values of conductivity in soils. The conductivity of saturated soil varies from 10^{-1} mho/m in typical clay soils to 10^{-8} mho/m in sands [Parkhomenko, 1967]. The contribution of conductivity to the dielectric loss factor at frequencies up to 10^6 Hz often masks the contribution of relaxation effects. The relation between water content, conductivity, and dielectric constant at frequencies below 10^6 Hz is a strong function of soil type. The relation between water content and conductivity typically takes the form shown in Figure 1, where the conductivity first increases sharply with water content and then levels off [Smith-Rose, 1933; Chernyak, 1967].

At frequencies above 10^8 Hz, very few measurements on soils containing water have been reported, although a series of indirect measurements from which an approximate value of the complex dielectric constant could be inferred have been made [Davis *et al.*, 1966; Poe and Edgerton, 1971]. All these measurements were performed at selected fixed frequencies, so that it is difficult to derive a frequency dependence from these data. Von Hippel [1954] reports on a series of measurements on soils at various water contents up to frequencies of 10^{10} Hz. When the water content of his samples exceeded 10% by weight, a substantial decrease in the dielectric constant and an increase in $\tan \delta$ at frequencies between 10^8 and 10^{10} Hz were observed. This dispersion is no doubt due to the dielectric relaxation of water in soils.

An extensive series of measurements at 4.5×10^8 and 35×10^8 Hz was made by Campbell and Ulricks [1969] on dry mineral and rock samples. The difference between the mean values of the complex dielectric constant at the two frequencies was small, supporting their conclusion that dry materials have no measurable dispersion at microwave frequencies. The dielectric constant varied from 2.5 for low-density rock types to 9.5 for high-density basaltic rocks, and $\tan \delta$ varied from 0.009 to 0.07.

The Debye relaxation spectrum of water in bulk is relatively well known [Eisenberg and Kauzmann, 1969; Von Hippel, 1973]. Figure 2 shows the dielectric relaxation of water in bulk. The maximum value of the dielectric loss factor occurs at frequencies in excess of 8×10^9 Hz at temperatures above 0°C. There are, however, several reports in the

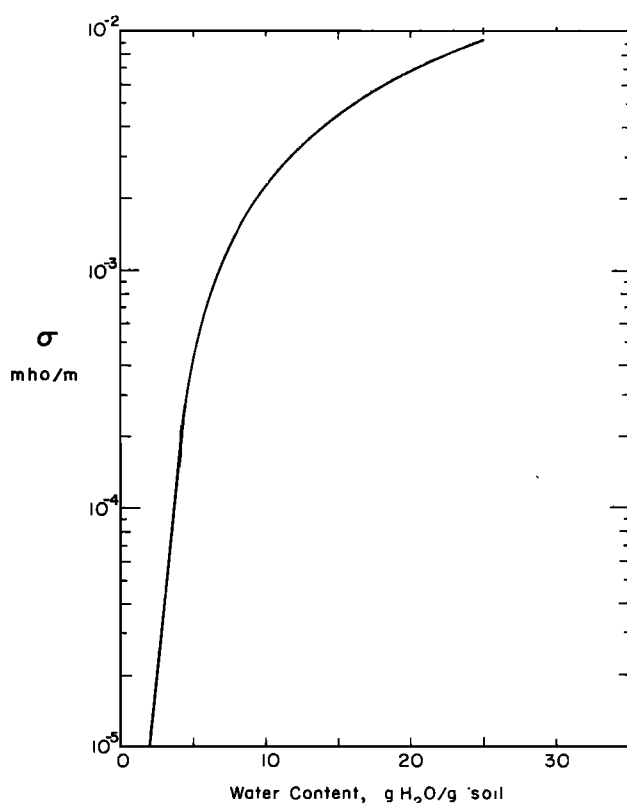


Fig. 1. The conductivity of a silty clay soil as a function of water content measured at 2×10^8 Hz [after Smith-Rose, 1933].

literature indicating a lower relaxation frequency for absorbed water [DeLoor, 1956; Harvey and Hoekstra, 1972; Hoekstra and Doyle, 1971].

MEASUREMENT TECHNIQUES

The complex dielectric constant of soils was measured over the frequency range from 10^8 to 2.6×10^{10} Hz as a function of

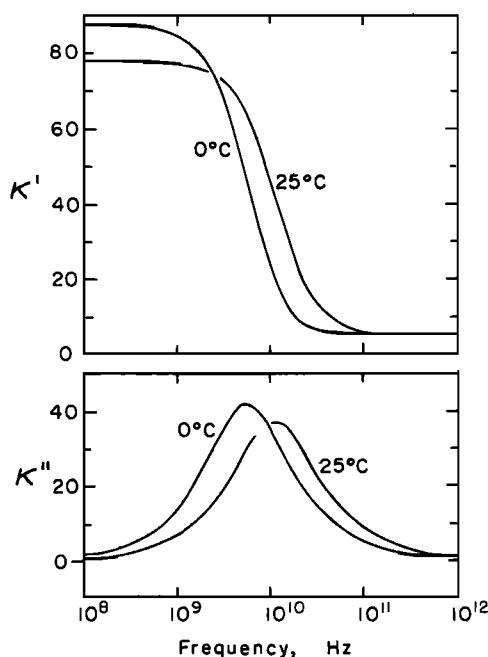


Fig. 2. The dielectric relaxation spectrum of water at two temperatures.

water content and temperature. Figure 3 shows the different methods used to obtain the complex dielectric constant.

The slotted line determinations were all made in wave guide transmission lines, and the samples were placed against a short circuit. The dimensions of the sample changed with the size of the wave guide. For example, in the G band (3.95×10^9 to 5.8×10^9 Hz) the dimensions of the rectangular wave guide were 4.755 by 2.215 cm, and the sample was made 1.67 cm thick; in the K band (18×10^9 to 26.5×10^9 Hz) the wave guide dimensions were 1.067 by 0.432 cm, and the sample was made 0.3 cm thick. The methods described by Westphall [1954] and Redheffer [1947] were used to measure the dielectric properties of the samples. Calculation of the complex dielectric constant requires measuring the change in the position of the minimum and the VSWR of a standing wave pattern resulting from placing a sample of certain thickness against a short in the wave guide. Determinations were made at one or two frequencies in each band. The method is not suitable for samples with dielectric constants in excess of 20, and for this reason the measurements were limited to water contents of 15% by weight.

In the time domain reflection technique (TDR), soil samples were packed in a coaxial line 20 cm long with an ID of 7 mm. The placing of the sample in the line requires great care, since variations in density will cause unwanted reflections.

The equipment is shown in Figure 4. A voltage ramp is propagated via a coaxial cable to the tunnel diode [Moffit, 1966]. This ramp then opens the tunnel diode, from which a very fast step voltage (rise time about 35×10^{-12} s) arises. Such a pulse remains unaltered as long as the propagation characteristics of the line stay the same, but any discontinuity in the line, such as a transition to a section with a different characteristic impedance, will give rise to a partial reflection and partial transmission of the pulse. The nature of the discontinuity will be indicated by the resulting pulse shapes, whereas its location will be shown by the time relationship between incident and reflected pulses.

For a coaxial line filled with a dielectric the characteristic impedance Z is given by [e.g., VonHippel, 1954]

$$Z = Z_0/K^*(\omega) \quad (1)$$

where Z_0 is the characteristic impedance of an air-filled line.

The voltage reflection coefficient ρ for a discontinuity in the line from impedance Z_0 to Z is given by

$$\rho = (Z - Z_0)/(Z + Z_0) \quad (2)$$

Combining (1) and (2) and solving for $K^*(\omega)$ yield

$$K^*(\omega) = (1 + \rho)^2/(1 - \rho)^2 \quad (3)$$

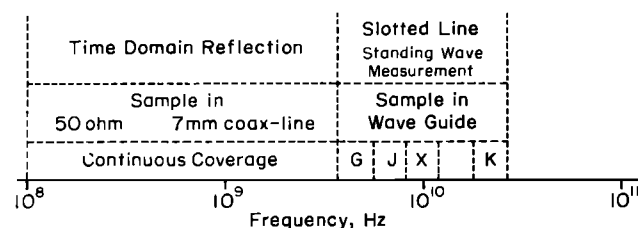


Fig. 3. Schematic representation of the methods used to measure the complex dielectric constant of soils. The capital letters indicate the common denominations of the wave guide bands.

The complex dielectric constant can thus be determined from the measurement of the reflection coefficient at a dielectric interface. For a dielectric sample, Z and ρ will be complex frequency-dependent quantities, and their frequency dependence will be shown in differences between the time domain pulse shapes of the incident and reflected signals.

The behavior of a dielectric in the frequency domain may be found by measuring the reflection of a suitable incident pulse off a sample and calculating the ratio of the Fourier transforms of the incident and reflected pulses. The basis of the transformation is that any pulse in the time domain $f(t)$ is related to a complex spectrum $F(\omega)$ in the frequency domain by the Fourier transform as follows:

$$F(\omega) = \int_{-\infty}^{+\infty} f(t) \exp(-i\omega t) dt \quad (4)$$

Thus $\rho(\omega)$, the complex reflection coefficient of an air-dielectric interface in the frequency domain, is related to the incident $f_i(t)$ and reflected $f_r(t)$ pulses in the time domain by

$$\begin{aligned} \rho(\omega) &= \frac{\int_{-\infty}^{\infty} f_r(t) \exp(-i\omega t) dt}{\int_{-\infty}^{\infty} f_i(t) \exp(-i\omega t) dt} \\ &= \int_{-\infty}^{\infty} \rho(t) \exp(-i\omega t) dt \end{aligned} \quad (5)$$

where $\rho(t)$ is the reflection coefficient in the time domain and $\rho(\omega)$ is defined for all frequencies contained in the incident pulse, where $F(\omega) \neq 0$.

Figure 5 shows typical traces of voltage step pulses reflected from air-sample interfaces and from a short circuit; the traces in Figure 5 are plots of $\rho(t)$ versus t . These traces were digitized at time intervals of 2×10^{-12} s. The modification introduced by Samulon [1951] of the Shannon sampling theorem has been shown to be a convenient method for Fourier-transforming step pulses. The relevant relation for the reflection coefficient $\rho(\omega)$ is [Loeb et al., 1971]

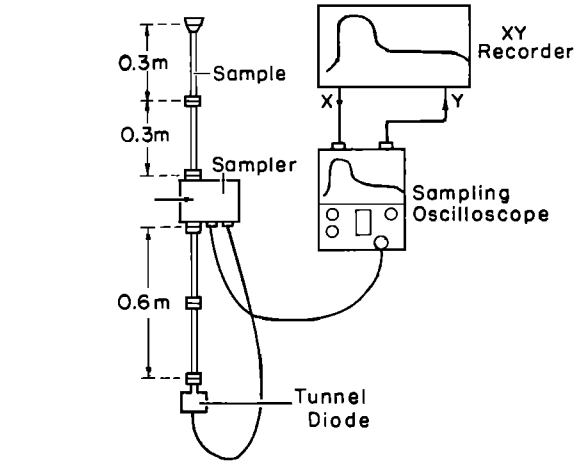


Fig. 4. Schematic diagram of experimental apparatus used in time domain measurements.

$$\begin{aligned} \rho(\omega) &= \frac{\omega T \exp(i\omega T/2)}{2 \sin(\omega T/2)} \\ &\cdot \sum_{n=-\infty}^{\infty} [\rho(nT) - \rho(nT - T)] \exp(-in\omega T) \end{aligned} \quad (6)$$

provided that $F_i(\omega) = 0$ for $\omega > (\pi/T)$, where T is the time interval between the digitized data samples and $\rho(nT)$ is the reflection coefficient at time nT . The inherent properties of the coaxial equipment used ensure that no frequency components above 250 GHz ($1/(4 \times 10^{-12})$) are present.

The use of TDR requires that the reflected pulse be known for all values of t , and this requirement places a major restriction on its use because the decay of any relaxation process must be monitored to completion. The measurement is made at the interface of air and dielectric, and the recording of the reflected pulse must be discontinued when the reflection from the end of the sample reaches the interface. Therefore the maximum time available for measurement is equal to the duration of the return trip of the wave in the sample-filled line. The minimum relaxation frequency measurable for a 20-cm-long sample with a dielectric constant of 9 is therefore

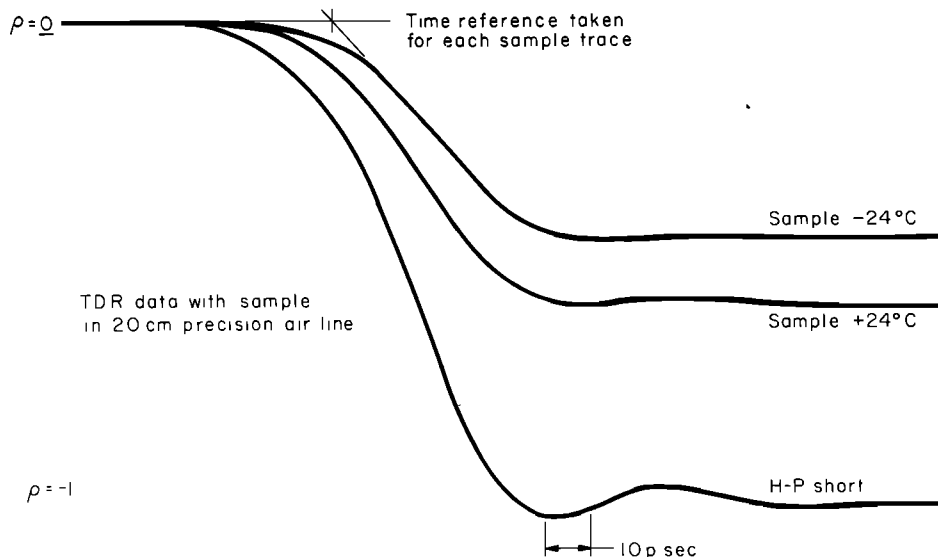


Fig. 5. Typical traces of voltage step pulses reflected from air-sample interfaces and from a short circuit.

TABLE 1. Relevant Data for the Soils Used in the Measurements

Soil	Classification Unified	Surface Area, m ² /g	Specific Gravity, g/cm ³	Liquid Limit, %	Plastic Limit, %	Grain Size Distribution, % Finer				
						$c = 0.5$	$c = 0.1$	$c = 0.05$	$c = 0.01$	$c = 0.002$
Manchester fine sand	SM	<1	2.71	...	...	100	18	5	0	0
Fairbanks silt	ML	40	2.74	25	Not plastic	100	95	80	26	13
Suffield silty clay	CL	140	2.69	35	20	100	98	95	58	33
Goodrich clay	CL	140	2.73	45	22	100	98	96	81	47

Here c stands for the particle size in mm.

about 10^6 Hz; this minimum assumes that equilibrium is reached after a time interval equal to 3 times the relaxation time. The results show that the dielectric relaxation of water in soils was higher than 10^6 Hz.

In theory, TDR methods can be extended to frequencies well beyond 2×10^9 Hz, because a step pulse with a rise time of 35×10^{-12} s contains sufficient energy in frequency components higher than 2×10^9 Hz. In practice, however, the occurrence of higher-order modes in coaxial lines sets an upper limit. Higher-order modes set in if the wavelength in the sample λ_s is less than $\lambda_c \leq \pi(b + a)$, where a and b are the inner and outer diameters of the coaxial line. To avoid errors caused by this effect, the TDR data were not extended beyond 2×10^9 Hz.

TDR measurements were thus made in the frequency range from 10^6 to 2×10^9 Hz. Equation 6 shows that $\rho(\omega)$ and by the use of (3) the complex dielectric constant can be computed for any frequency in this range. In practice the calculation was performed only at a selected number of frequencies, spaced so as to yield a well-defined description of the frequency dependence of $K^*(\omega)$.

By far the largest source of error in TDR dielectric measurement is in locating a time reference for the pulse. The methods developed by Loeb *et al.* [1971] were used in this work, and Figure 5 illustrates on one pulse shape how a time reference is obtained. This method was tested on standard samples of alcohols and found to yield data of $\pm 5\%$ in the ab-

solute magnitude of the complex relative dielectric constant and better than $\pm 3\%$ in the frequency of maximum dielectric loss.

A very high direct current conductivity may interfere with TDR measurements [VanGermert, 1971; VanGermert and Bordewyk, 1972], since the reflection coefficient of conductivity approaches that of a short circuit ($K^*(\omega) = \sigma/\epsilon_0\omega \rightarrow \infty$ as $\omega \rightarrow 0$). Since the soils used have conductivities of the order of 10^{-2} – 10^{-3} mho/m, conductivity will begin to contribute to the dielectric loss factor at frequencies below 5×10^6 Hz. The influence of conductivity can be observed from the reflected pulse shape. For example, the pulse shapes in Figure 5 are flat after a time interval of about 50 ps; in the presence of appreciable conductivity the pulse shape would show a continuous downward slope. The use of the time domain method and comparison of the results with other techniques have been reported by Loeb *et al.* [1971], Harvey and Hoekstra [1972], and Nicholson and Ross [1970].

In both the wave guide and coaxial line sample holders, coolant from a constant temperature bath was circulated through a jacket around the sample holder for temperature control.

RESULTS

The complex dielectric constants of four soils were measured at water contents of 0.0, 0.05, 0.10, and 0.15 g H₂O/g soil and over the temperature range from 24°C to

TABLE 2. Gravimetric and Volumetric Water Content and Dry Density of the Samples Used in the Experiment

Water Content, g H ₂ O/g soil	Dry Density, g/cm ³					Water Content, g H ₂ O/cm ³				
	K	X	J	G	TDR	K	X	J	G	TDR
<i>Manchester fine sand</i>										
0	...	...	...	...	1.40	...	...	...	...	0.0
5	...	1.3	1.53	1.57	...	...	0.06	0.08	0.07	...
10	...	1.3	1.50	1.64	1.52	...	0.13	0.15	0.15	0.14
15	1.45	1.48	1.50	...	...	0.22	0.22	0.23	...	...
<i>Fairbanks silt</i>										
0	1.40	...	...	...	1.40	0.0	...	...	...	0.0
5	1.48	1.46	1.65	1.63	1.63	0.07	0.07	0.08	0.08	0.08
10	1.48	1.47	1.65	1.76	1.64	0.13	0.15	0.17	0.18	0.18
15	1.48	1.57	1.67	1.69	1.64	0.20	0.23	0.25	0.25	0.25
<i>Suffield silty clay</i>										
0	...	...	...	...	1.3	...	...	...	...	0.0
5	1.35	1.37	1.53	1.49	...	0.07	0.07	0.08	0.07	...
10	...	1.49	1.50	1.58	1.48	...	0.15	0.15	0.16	0.13
15	1.60	1.53	1.50	1.62	1.57	0.25	0.23	0.23	0.24	0.25
<i>Goodrich clay</i>										
0	...	...	...	...	1.2	...	...	...	...	0.0
5	1.14	1.25	1.54	1.46	1.43	0.03	0.06	0.08	0.07	0.07
10	1.23	1.27	1.57	1.50	1.47	0.13	0.13	0.16	0.15	0.15
15	1.23	1.42	1.66	1.58	...	0.19	0.21	0.25	0.24	...

The capital letters refer to the wave guide bands in Figure 3.

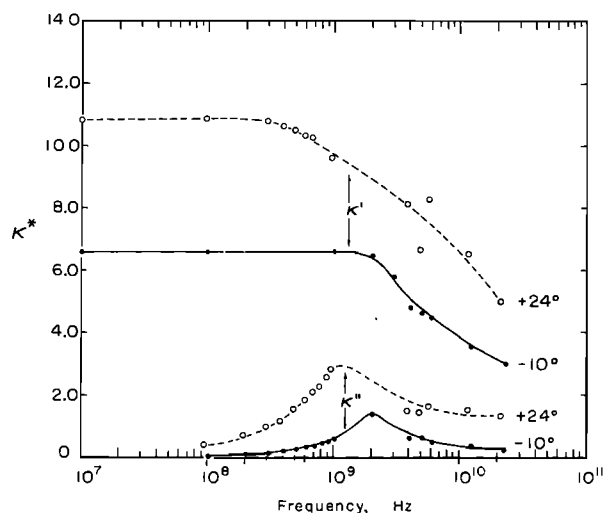


Fig. 6. The complex dielectric constant of Goodrich clay at a water content of 10% (g H₂O/g soil) as a function of frequency at two temperatures.

–20°C. Relevant data on the four soils are given in Table 1. Depending on the frequency of the measurement (Figure 3) the soils were packed in sample holders of different sizes and shapes. In the sample preparation the gravimetric water content was held constant from one frequency band to another, but often variations in dry density and therefore volumetric water content were unavoidable. In Table 2 the water content and density data of the samples used are given. From the substantial number of data some typical results have been selected to illustrate the dependence of the complex dielectric constant on the most important parameters.

Dependence of $K^*(\omega)$ on frequency. In Figure 6 the complex dielectric constant of a soil is given as a function of frequency at temperatures of 24°C and –10°C. The water content of these samples was 10% by weight. In Figure 7 the complex dielectric constant of the same soil is given as a function of frequency at two different water contents and at a temperature of 24°C. The results of both Figures 6 and 7 show a dielectric relaxation; the dielectric constant decreases with frequency, and the dielectric loss factor goes through a max-

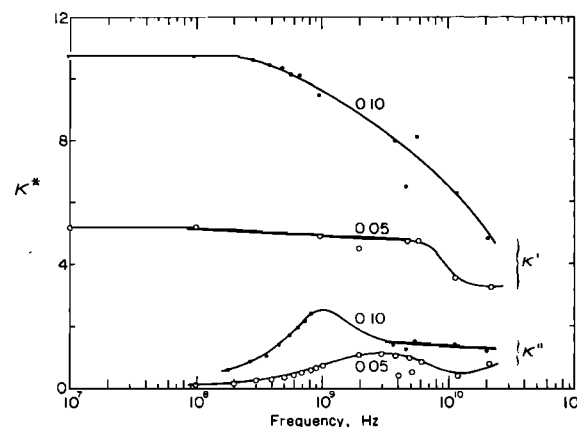


Fig. 7. The complex dielectric constant of Goodrich clay at 24°C as a function of frequency at two water contents (g H₂O/g soil).

imum. The relaxation observed can be attributed to the presence of water in soils, since interfacial and Maxwell-Wagner dispersions are unlikely to occur at these high frequencies [DeLoor, 1956].

In comparing the relaxation of water in bulk and soil water, it is observed that the frequency of maximum dielectric loss of the relaxation of water in soils is displaced to lower frequency and the relaxation occurs over a narrower frequency band in soils than in bulk water. The dielectric properties of a number of materials whose molecules have permanent dipole moments can be described by a modification of the Debye equation due to Cole and Cole [1941]:

$$K^*(\omega) = K_{\infty}' + \frac{K_s' - K_{\infty}'}{1 + (i\omega\tau)^{1-\alpha}} \quad (7)$$

where the subscripts ∞ and s refer to the values of K' at frequencies where $\omega\tau \gg 1$ and $\omega\tau \ll 1$, respectively; τ is the relaxation time; and α is a parameter indicating the distribution of relaxation times. For materials with a simple relaxation time (such as water), $\alpha = 0$, and (7) reduces to the form given by Debye [1929]. The effect of $\alpha > 0$ is to make the dispersion more broad band.

To describe the dielectric relaxations observed in Figures 6

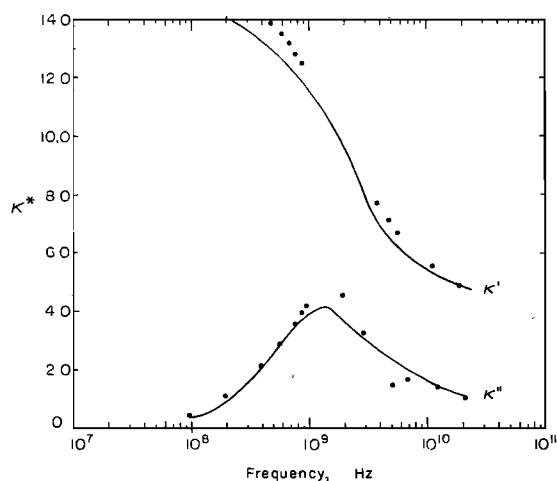


Fig. 8a.

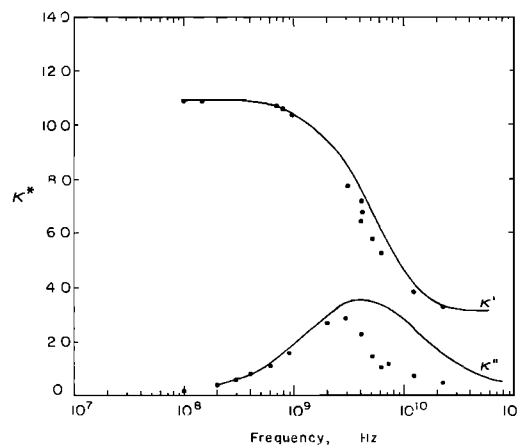


Fig. 8b.

Fig. 8. The complex dielectric constant of Suffield silty clay at a water content of 10% (g H₂O/g soil). The solid lines are curves generated by fitting two Debye type dispersions to the experimental points at (a) 24°C and (b) –10°C.

TABLE 3. Numerical Values of the Parameters Used for Fitting the Modified Debye Equation to the Dielectric Data on Suffield Silty Clay

	Relaxation 1	Relaxation 2
<i>At 24°C</i>		
Frequency of maximum $K''(\omega)$, Hz	1.5×10^9	2×10^{10}
K_{∞}'	14.6	7.0
K_{∞}''	7.0	3.0
α	0	0.5
<i>At -10°C</i>		
Frequency of maximum $K''(\omega)$, Hz	3×10^9	8×10^9
K_{∞}'	11.0	6.0
K_{∞}''	6.0	3.0
α	0.0	0.0

Water content of 0.10 g H₂O/g clay for the Suffield silty clay in both cases.

and 7 by (7) requires the assumption of two separate closely spaced relaxations. In Figure 8 the solid lines represent the curves given by the relation

$$K^*(\omega) = K_{1s}' + \frac{K_{1s}' - K_{1\infty}'}{(1 + i\omega\tau_1)^{1-\alpha_1}} + K_{2s}' + \frac{K_{2s}' - K_{2\infty}'}{(1 + i\omega\tau_2)^{1-\alpha_2}} \quad (8)$$

where the subscripts 1 and 2 refer to the two separate relaxations. The parameters used for the two dispersions in (8) are given in Table 3. The characteristic frequency of the second dispersion corresponds roughly to that of bulk water, but it has a distribution of relaxation times. The first dispersion at 24°C has a characteristic frequency of 1.5×10^9 Hz and a single relaxation time.

Similar values for the relaxation parameters were found to fit the data on the other soils. When the soil is frozen, it becomes more difficult to fit two Debye type relaxations to the data. However, there seems to be little doubt that the relaxation occurs over a narrower band of frequency than can be described by one relaxation. The accuracy of the data makes it impossible at the moment to determine the temperature dependence of the characteristic frequency of the relaxation. The relaxation of water in the sand soils and that in the clay soils were, within the accuracy of the experimental techniques, identical. This finding is not consistent with the notion that adsorbed water is the cause of the shift in the frequency

of relaxation, since the amounts of adsorbed water in sand and clay type soils differ greatly.

Dependence of $K^*(\omega)$ on temperature. The temperature dependence of the complex dielectric constant is given in Figure 9 at an X band frequency of 10×10^9 Hz. The temperature data were obtained during a warming cycle. The samples were first quickly frozen at a temperature of about -20°C to prevent water migration and supercooling. Subsequently, the temperature was raised to make the measurements. The temperature data at X band are typical of similar data at other frequencies.

When soils are frozen, their four components are minerals, ice, air, and unfrozen water. Since minerals, ice, and air have a dielectric loss at microwave frequencies less than 0.05 [Campbell and Ulricks, 1969; Cummings, 1952], a dielectric loss of frozen soils in excess of 0.07 can be attributed to the presence of unfrozen water. Several investigators [e.g., Anderson and Morgenstern, 1973] have found that the amount of unfrozen water depends mainly on the temperature below freezing and the surface area of the soil, whereas other factors such as external pressure, salt content, and mineral type have a secondary effect. Also, the amount of unfrozen water for a certain soil at a certain temperature was found to be independent of total water content. The dielectric measurements are in agreement with the findings on unfrozen water. The results on Fairbanks silt at three different water contents (Figure 9a) show that the dielectric loss in the frozen state is, within the experimental error, identical for all three water contents. In the clay sample (Figure 9b) the dielectric loss becomes identical for all three samples at -10°C; evidently, at higher temperatures the amount of unfrozen water in the samples at 10% and 15% exceeds the amount at 5%. Because adding water increases the total density of the soil, the dielectric constant increases with increased water content.

Microwave dielectric measurements on unfrozen water down to temperatures of -120°C were previously made on the clay mineral montmorillonite [Hoekstra and Doyle, 1971]. Because of its large surface area (800 m²/g) this mineral is better suited for low-temperature studies of unfrozen water than natural soils. The results on montmorillonite showed a measurable dielectric loss due to unfrozen water down to a temperature of -80°C. Other evidence [Anderson and Tice, 1971] supports the concept that unfrozen water is present in soils to temperatures well below -30°C, but the small quantities in natural soils made detection by routine techniques difficult.

The unfrozen water content of the four soils used was

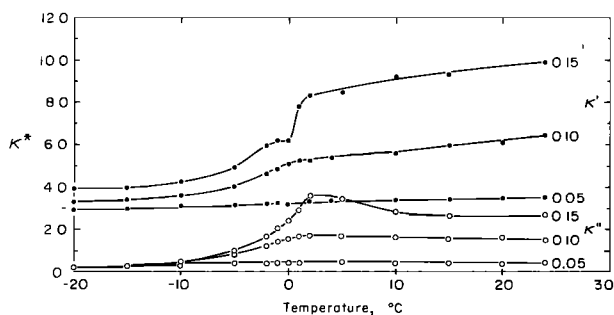


Fig. 9a.

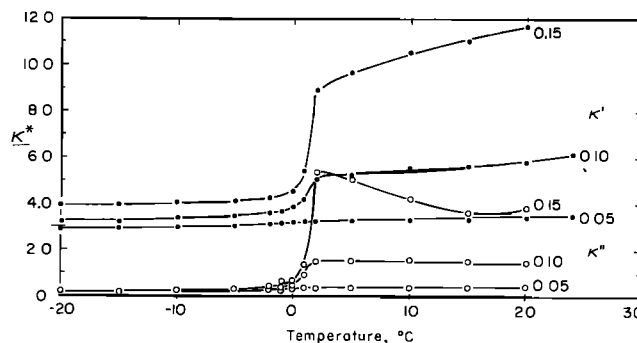


Fig. 9b.

Fig. 9. The complex dielectric constant at 10×10^9 Hz as a function of temperature at three water contents (g H₂O/g soil) for (a) Goodrich clay and (b) Fairbanks silt.

measured by *Anderson et al.* [1973]. In Figure 10 the unfrozen water content is plotted versus the relative dielectric loss normalized to 1 g of soil at 10×10^9 Hz. The experimental points are composed of data on four soils at different temperatures below freezing. There appears to be a linear relation between unfrozen water content and the dielectric loss factor independent of temperature over the range from 0°C to -10°C .

The slope of the line in Figure 10 is frequency dependent because of the relaxation of the unfrozen water. A maximum dielectric loss for unfrozen water occurs at frequencies between 10^9 and 4×10^9 Hz (Figure 6).

At temperatures above 0°C the relative dielectric constants in Figure 9 can be seen to decrease for both soil types at all three water contents. In bulk liquids the dielectric constant invariably increases with decreasing temperature, $dK'/dT < 0$ [Smyth, 1955]. A positive value of dK'/dT at temperatures above freezing appears to be a characteristic of adsorbed

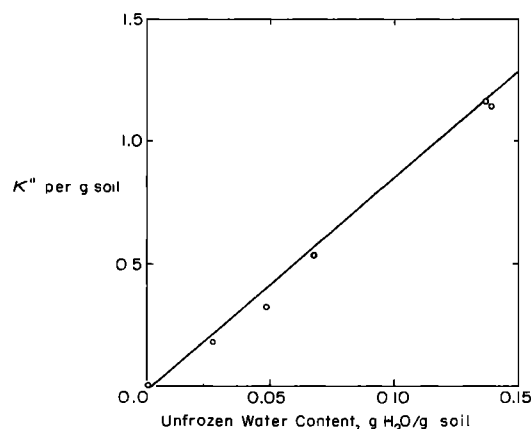


Fig. 10. The dielectric loss factor of frozen soils normalized to 1 g of soil at 10×10^9 Hz as a function of unfrozen water content.

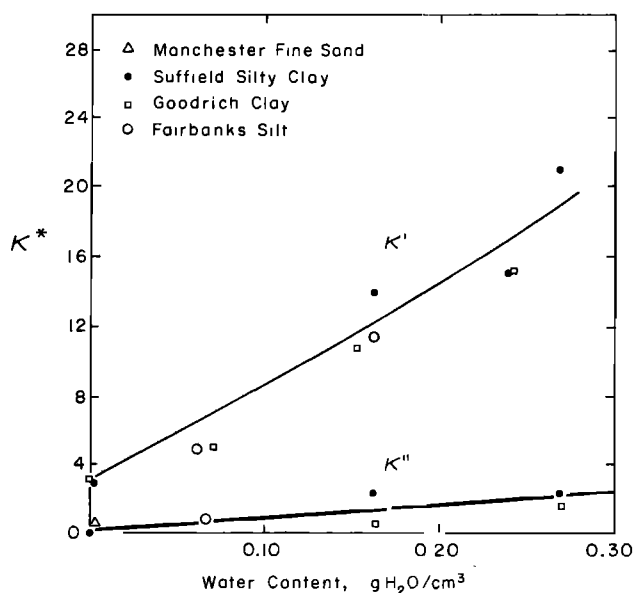


Fig. 11a. 5×10^9 Hz.

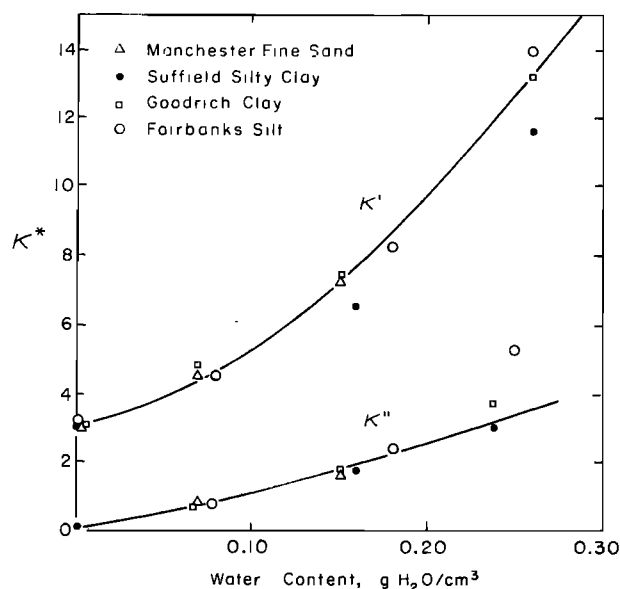


Fig. 11b. 4×10^9 Hz.

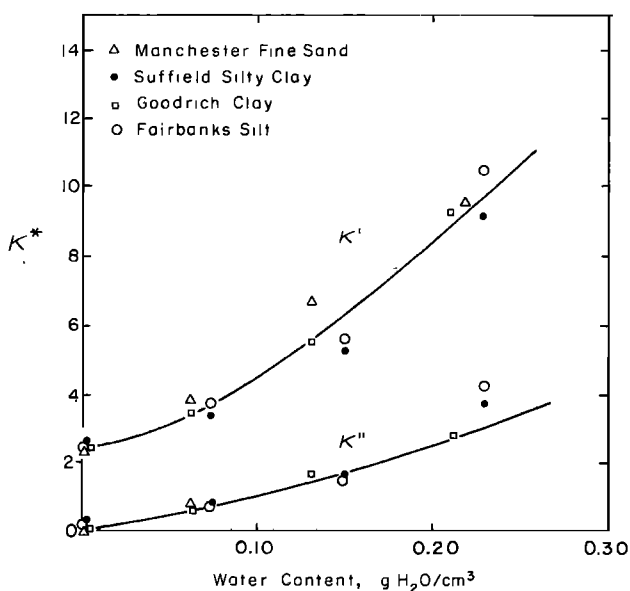


Fig. 11c. 10×10^9 Hz.

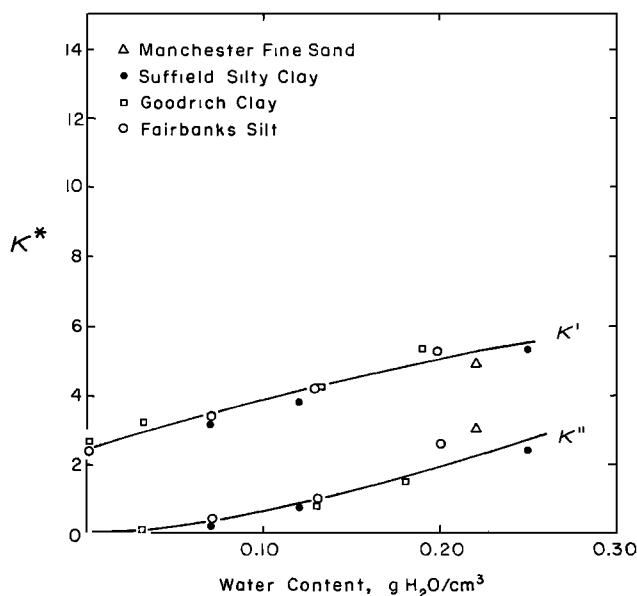


Fig. 11d. 26×10^9 Hz.

Fig. 11. The complex dielectric constant of soils as a function of volumetric water content at 10°C .

TABLE 4. $K^*(\omega)$ From Slope of $\frac{dK^*(\omega)}{dW}$

Frequency, Hz	$K''(\omega)$	$K'(\omega)$
5×10^8	7	56
4×10^9	13.4	33
6×10^9	14.4	33
12×10^9	14.5	26.5
26×10^9	10.0	10.0

W is water content in g/cm^3 .

water. VonEbert and Langhammer [1960] found $dK'/dT > 0$ for water adsorbed on γ alumina oxide, as did Harvey and Hoekstra [1972] for water adsorbed on the protein lysozyme.

Dependence of $K^*(\omega)$ on water content. When a relation is being established between the water content and the complex dielectric constant, volumetric rather than gravimetric water contents are used, since it is the number of dipole moments per unit volume that will determine the contribution of water to dielectric polarization. In Figure 11 the complex dielectric constants are plotted versus the volumetric water content at 10°C for all four soils at different frequencies.

The data points of all four soils fall within a relatively narrow band, indicating that the main parameter determining $K^*(\omega)$ at constant temperature is the volumetric water content. Other factors such as dry density and mineral type are probably the cause of the scatter observed.

The ratio $\Delta K^*/\Delta W$, the slope of the solid lines in Figure 11, represents the apparent complex dielectric constant of water in soils. The slope is somewhat a function of water content,

but in Table 4 the values of $K^*(\omega)$ derived from a mean value of the slopes are given. The relaxation of water in soils that was evident in Figures 6 and 7 is also clearly present in the data of Table 4. In dielectric relaxation the values of $K'(\omega)$ and $K''(\omega)$ are related by (7). The maximum value of $K'(\omega)$ in a Debye type relaxation cannot exceed $0.5(K_s' - K_\infty')$ and is less whenever $\alpha > 0$. The data are in agreement with this physical law.

Many attempts have been made to relate the complex dielectric constant of heterogeneous mixtures to the complex dielectric constant of the constituents. A critical review of mixture equations has been given by DeLoor [1956]. In general the mixture equations require as input parameters the dielectric properties of the constituents and some knowledge of the disposition and shapes of the constituents. In soils, where one often deals with a random arrangement of granules, an empirical form factor can be used instead of factors based on spheres or cylinders. At present the equations do not take boundary layer effects into account. Because the dielectric relaxation associated with water in soils differs significantly from that of water in bulk, it is difficult to use mixture equations to any advantage. The temperature dependence, the frequency dependence, and the values of the dielectric constant of water in soils differ from those of water in bulk. The evidence to date is that the relations between water content and $K^*(\omega)$ shown in Figure 11 are valid over a large range of soil types.

DISCUSSION

Two phenomena in the dielectric behavior of soils at UHF and microwave frequencies require much further study.

1. Two closely spaced relaxations appear to be associated with water in soils. The dominant relaxation has a frequency of maximum loss between 1×10^9 and 4×10^9 Hz. Since this relaxation occurs in sand as well as clay soils, it cannot be directly due to adsorption effects. Also, shifts in relaxation time due to mixing polar and nonpolar constituents always cause shifts toward higher relaxation frequencies [DeLoor, 1956].

2. A positive value of dK'/dT is characteristic of solids. One possible explanation may be a model proposed by Anderson [1968] in which the first few water layers on the surface are disordered, whereas cluster formations take place in the water further removed from the surface. Perhaps such cluster formations also form in sand soils. The dielectric relaxation time could be associated with the lifetime of a cluster. Much detailed experimental and theoretical work is required to resolve some of these mechanisms.

Some important conclusions about the use of UHF and microwave devices in remote sensing of the environment can be drawn from the results. The presence of water in most earth materials causes high attenuation of microwave radiation. In Figure 12 the attenuation in decibels per meter for plane wave propagation is given as a function of water content for several frequencies. The data used to compute the attenuation are the values of the complex dielectric constants given in Figure 11. Since the dielectric behavior as a function of water content was similar for the four soils used, the attenuation as a function of water content should be valid for a large range of soil types. In general, one can conclude that where liquid water is present, passive or active microwave devices will yield information for perhaps the first 5 cm of the ground. Because of the presence of unfrozen water, permafrost can also have a high attenuation for microwave radiation. Microwave radiation will penetrate deeper in

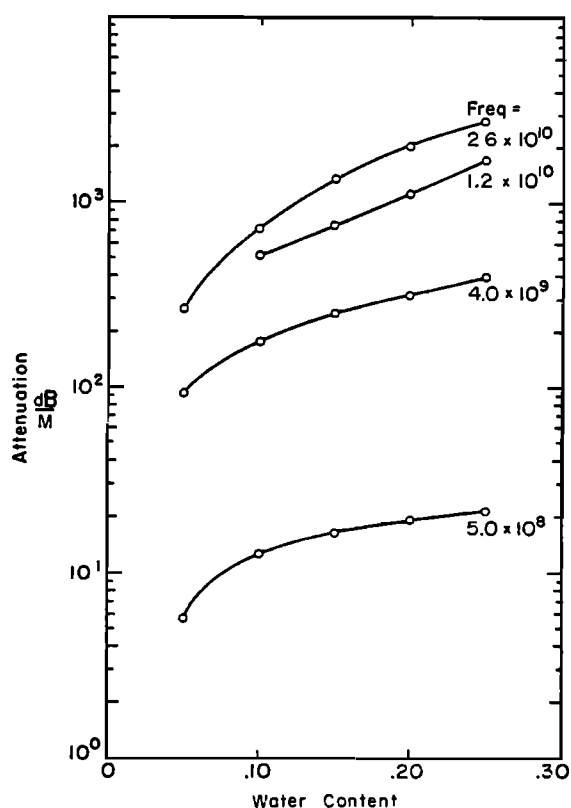


Fig. 12. The attenuation in soils for plane electromagnetic wave propagation as a function of volumetric water content ($\text{g H}_2\text{O}/\text{cm}^3$) at several frequencies.

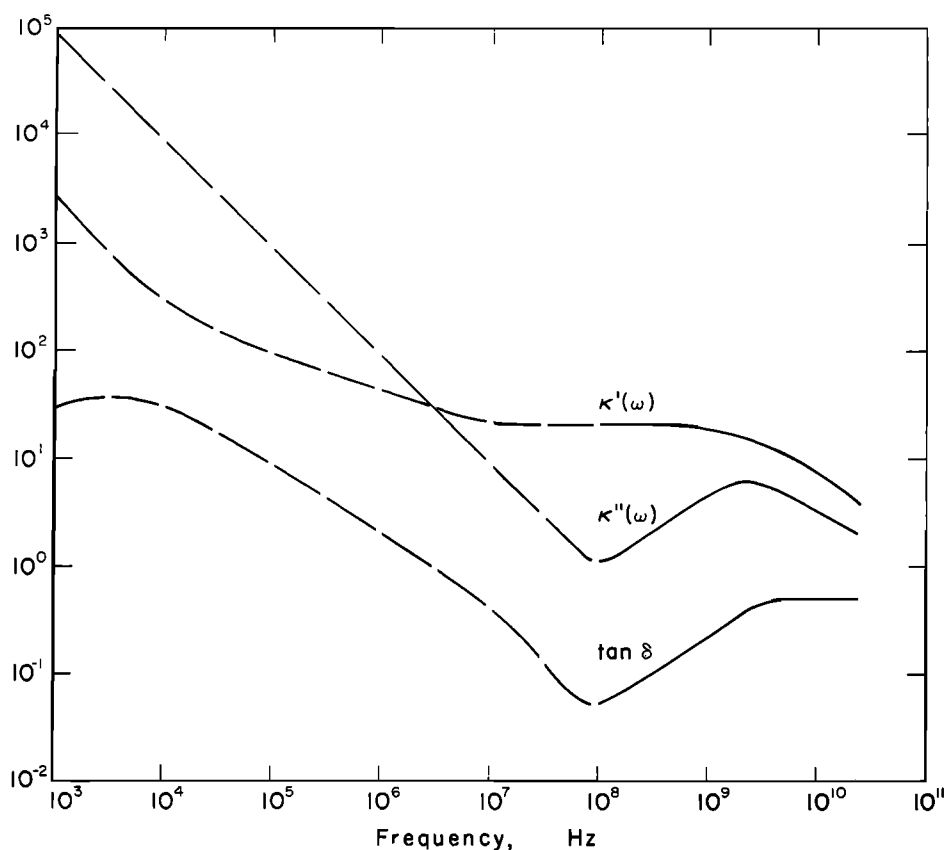


Fig. 13. The complex dielectric constant and the loss tangent of a silty clay soil at a water content of 15% (g H_2O /g soil). The solid curves are measurements from this study. The dashed curves are from data on comparable soil by Smith-Rose [1933]. The conductivity of the soil was 5×10^{-8} mho/m at 2×10^8 Hz.

places where there is no liquid water, such as cold glaciers [Gudmandsen, 1971] and perhaps some desert areas. Water also appears to be absent on the surfaces of the moon and Mars, and microwave devices may yield information on these planets to a depth of several meters [Campbell and Ulricks, 1969].

Finally, it is instructive to sketch the dielectric behavior of a typical surface soil over a large frequency range from audio to microwave frequencies. This has been done in Figure 13. The high-frequency data are those from this study at a water content of 15% by weight on Suffield silty clay. The low-frequency data are based on data from Smith-Rose [1933, 1935] on a comparable soil, which had a conductivity of 5×10^{-8} mho/m. The complex dielectric constant of soils can be seen to change by several orders of magnitude with frequency. The part of the curves below 10^8 Hz will depend much on soil type.

REFERENCES

- Anderson, D. M., Undercooling, freezing point depression, and ice nucleation of soil water, *Is. J. Chem.*, 6, 349, 1968.
- Anderson, D. M., and N. R. Morgenstern, Physics, chemistry, and mechanics of frozen ground, in *Permafrost: Proceedings of an International Conference*, pp. 257-288, National Academy of Sciences, National Research Center, Washington, D. C., 1973.
- Anderson, D. M., and A. R. Tice, Low-temperature phases of interfacial water in clay-water systems, *Soil Sci. Soc. Amer. Proc.*, 35, 47, 1971.
- Anderson, D. M., A. R. Tice, and H. L. McKim, The unfrozen water in frozen soils, in *Permafrost: Proceedings of an International Conference*, pp. 289-294, National Academy of Sciences, National Research Center, Washington, D. C., 1973.
- Campbell, M. J., and J. Ulricks, Electrical properties of rocks and their significance for lunar radar observations, *J. Geophys. Res.*, 74, 5867, 1969.
- Cole, K. S., and R. H. Cole, Dispersion and absorption in dielectrics, 1, Alternating current characteristics, *J. Chem. Phys.*, 9, 341, 1941.
- Chernyak, C. Y., *Dielectric Methods for Investigating Moist Soils*, translated from Russian, pp. 18-24, Israel Program for Scientific Translations, Jerusalem, 1967.
- Cummings, W. A., The dielectric properties of ice and snow at 3.2 cm, *J. Appl. Phys.*, 23, 768, 1952.
- Davis, B. R., J. R. Lundien, and A. N. Williamson, Feasibility study of the use of radar to detect surface and ground water, *Tech. Rep. 3-727*, pp. 24-49, U.S. Army Eng. Waterways Exp. Sta., Vicksburg, Miss., 1966.
- Debye, P., *Polar Molecules*, chap. 5, pp. 77-108, Dover, New York, 1929.
- DeLoor, G. P., *Dielectric Properties of Heterogeneous Mixtures*, Ph.D. thesis, Univ. of Leiden, Leiden, Netherlands, 1956.
- Eisenberg, D., and W. Kauzmann, *The Structure and Properties of Water*, pp. 206-212, Oxford University Press, New York, 1969.
- Gudmandsen, P., Electromagnetic probing of ice, in *Electromagnetic Probing in Geophysics*, edited by J. R. Wait, pp. 321-348, Golem Press, Boulder, Colo., 1971.
- Harvey, S., and P. Hoekstra, Dielectric relaxation spectra of water adsorbed on lysozyme, *J. Phys. Chem.*, 76, 2987, 1972.
- Hoekstra, P., and W. Doyle, Dielectric relaxation of surface adsorbed water, *J. Colloid Interface Sci.*, 36, 513, 1971.
- Hoekstra, P., and H. W. O'Brien, The dielectric properties of clay suspensions in the frequency range from 50 Hz to 20 KHz, *Res. Rep. 266*, pp. 1-16, U.S. Army Cold Reg. Res. and Eng. Lab., Hanover, N. H., 1969.
- Loeb, H. W., G. M. Young, P. A. Quickenden, and A. Suggett, New methods for measurement of complex permittivity up to 13 GHz and their application to the study of dielectric relaxation of polar liquids including aqueous solutions, *Ber. Bunsenges. Phys. Chem.*, 75, 1155, 1971.
- Mofitt, L. R., Time domain reflectometry—Theory and applications,

- Appl. Note 75*, pp. 3–8, Hewlett-Packard, Colorado Springs, Colo., 1966.
- Nicholson, A. M., and G. F. Ross, Measurement of the intrinsic properties of materials by time-domain techniques, *IEEE Trans. Instrum. Meas.*, **19**, 377, 1970.
- Parkhomenko, E. I., *Electrical Properties of Rock*, translated from Russian by B. V. Keller, pp. 44–48, Plenum Press, New York, 1967.
- Poe, G., and A. T. Edgerton, Determination of soil moisture content with airborne microwave radiometry, *Sum. Rep. 4006R-2*, pp. 1–53, Aerojet ElectroSystems Co., Azusa, Calif., 1971.
- Redheffer, R. M., The Measurements of dielectric constant, in *Technique of Microwave Measurements*, vol. 2, edited by C. G. Montgomery, pp. 561–591, McGraw-Hill, New York, 1947.
- Samulon, H. A., Spectrum analysis of transient response curves, *Proc. IEEE*, **39**, 175, 1951.
- Schwann, H. P., Determination of biological impedances, in *Physical Techniques in Biological Research*, vol. 6, chap. 6, pp. 323–406, Academic, New York, 1963.
- Schwarz, G., A theory for the low frequency dielectric dispersion of colloidal particles in electrolyte solutions, *J. Phys. Chem.*, **66**, 2626, 1962.
- Scott, J. H., R. D. Carroll, and D. R. J. Cunningham, Dielectric constant and electrical conductivity of moist rock from laboratory measurements, *Spec. Proj. 12, Tech. Lett.*, U.S. Geol. Surv., Washington, D. C., 1964.
- Scott, J. H., R. D. Carroll, and D. R. J. Cunningham, Dielectric constant and electrical conductivity of moist rock from laboratory measurements, *J. Geophys. Res.*, **72**, 5101, 1967.
- Smith-Rose, R. L., The electrical properties of soils for alternating currents at radio frequencies, *Proc. Royal Soc. London*, **140**, 359, 1933.
- Smith-Rose, R. L., The electrical properties of soil at frequencies up to 100 MHz; with a note on the resistivity of ground in the United Kingdom, *Proc. Phys. Soc. London*, **47**, 923, 1935.
- Smyth, C. P., *Dielectric Behavior and Structure*, pp. 75–201, McGraw-Hill, New York, 1955.
- VanGemert, M. J. C., Dielectric measurements with time domain reflectometry when large conductivities are involved, *J. Phys. Chem.*, **75**, 1323, 1971.
- VanGemert, M. J. C., and P. Bordewyk, Calculation of the asymptotic behavior of the TDR step response related to the asymptotic behavior of dielectrics in the frequency domain, *Appl. Sci. Res.*, **27**, 156, 1972.
- VonEbert, G., and G. Langhammer, Das dielektrische Verhalten an γ -Aluminamoxyd Sorbierten Wassermolekeln, *Kolloid Z.*, **174**, 5, 1960.
- VonHippel, A. R. (Ed.), *Dielectric Materials and Applications*, p. 314, MIT Press, Cambridge, Mass., 1954.
- VonHippel, A. R., Molecular mechanisms of conduction and polarization in water vapor, liquid water and ice, *Tech. Rep. 12 (New Ser.)*, Lab. of Insul. Res., Mass. Inst. of Technol., Cambridge, Mass., 1973.
- Westphall, W. B., Permittivity, distributed circuits, in *Dielectric Materials and Applications*, edited by A. VonHippel, pp. 63–87, MIT Press, Cambridge, Mass., 1954.

(Received October 5, 1973;
revised January 7, 1974.)