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LABORATORY MEASUREMENTS OF SOIL ELECTRIC PROPERTIES BETWEEN 0.1--ETC(U)
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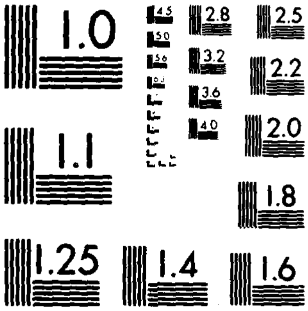

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US Army Corps of Engineers
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Laboratory measurements of soil electric properties between 0.1 and 5 GHz

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Cover: Schematic of equipment used for measuring soil electric properties.

CRREL Report 82-10

April 1982

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Allan J. Delaney and Steven A. Arcone

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Dielectric measurements have been performed on silt and sand samples from permafrost areas using Time Domain Reflectometry. The sample temperatures were varied from +25°C to -25°C, and volumetric water content was varied between oven-dry and 0.55 g H_2O/cm^3. The data were processed for frequencies between 0.1 and 5.0 GHz. The results show a constant K' and a low K'' for frequencies up to 1 GHz. A frequency dependence seen on the data above 2 GHz is probably the result of unfrozen, adsorbed water. At moisture levels near saturation at all temperatures, these soils have excellent propagation characteristics for ground-probing radar operating below 0.3 GHz. Massive ice should be easily detectable in permafrost within a few degrees of 0°C.

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PREFACE

This report was prepared by Allan J. Delaney, Physical Sciences Technician, and Dr. Steven A. Arcone, Research Geophysicist, of the Physical Sciences Branch, Research Division, U.S. Army Cold Regions Research and Engineering Laboratory. The study was funded under DA Project 4A161102AT24, Work Unit, *Dielectric Characteristics of Frozen Soil.* The report was technically reviewed by Dr. Kazuhiko Itagaki and Stephen Ackley of CRREL.

LABORATORY MEASUREMENTS OF SOIL ELECTRIC PROPERTIES BETWEEN 0.1 AND 5 GHz

Allan J. Delaney and Steven A. Arcone

INTRODUCTION

A geologic interpretation of a permafrost electromagnetic geophysical survey requires knowledge of the range of electrical properties as a function of temperature and moisture content for the material types encountered. Therefore, we have a continuing laboratory program at the U.S. Army Cold Regions Research and Engineering Laboratory to catalog dielectric properties of soil samples to complement our current electromagnetic exploration of permafrost in Alaska. The samples are obtained during our field studies and are used to help characterize our sites. The results apply to surface radar mapping, subsurface radar exploration, land-to-land communications engineering and electrical well logging in northern regions.

In this study we used Time Domain Reflectometry (TDR) to gather dielectric data on two soils from permafrost regions in the frequency range of 0.1 to 5.0 GHz. This range encompasses the many bandwidths available in subsurface radar systems. Hoekstra and Delaney (1974) measured the complex dielectric constant of Fairbanks silt and two clays over the frequency range of 0.1 to 10 GHz. This work showed a distinct frequency dispersion occurring between 1 and 3 GHz. Topp et al. (1980) used TDR to correlate dielectric properties with soil water content. Their measurements show that the real part of the dielectric permittivity at frequencies up to 1 GHz is constant for a wide range of soil moisture at room temperature. These results, as well as many others, have been reviewed and verified by Wang (1980).

This report presents dielectric properties as a function of temperature and volumetric water content. Measurements made on similar materials by Topp et al. (1980) and Wang (1980) were conducted only at room temperatures. The TDR technique allowed meaningful data to be compiled continuously at frequencies between 0.1 and 5 GHz.

Methods

In dielectric measurements the quantity sought is the complex relative dielectric permittivity $K^*(f)$, which is the ratio of the complex dielectric permittivity of the material to that of free space and is expressed as

$$K^*(f) = K' - jK''$$

where $j = \sqrt{-1}$. The quantity K' is the real part and is known as the dielectric constant when K' is much greater than K''. The imaginary part K'' is known as the dielectric loss factor under the same condition.

In TDR, $K^*(f)$ is calculated from Fourier transformation of the time-dependent quantities of incident and reflected pulses propagating along a standard coaxial transmission line. At any particular frequency the ratio of these field strength transformations is the reflection coefficient $\rho(f)$, which is determined by the change in transmission line impedance caused by the insertion of a test sample into the transmission line. In an air-filled line containing a sample at the end, $K^*(f)$ is related to $\rho(f)$ through the relation .

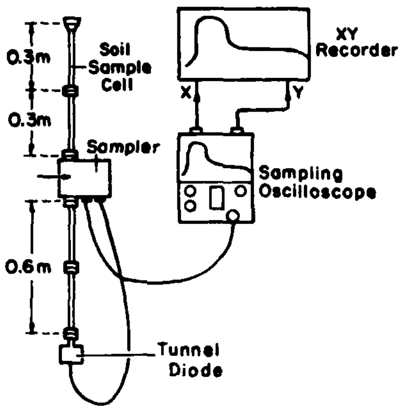

Figure 1. Schematic diagram of TDR equipment using a coaxial waveguide.

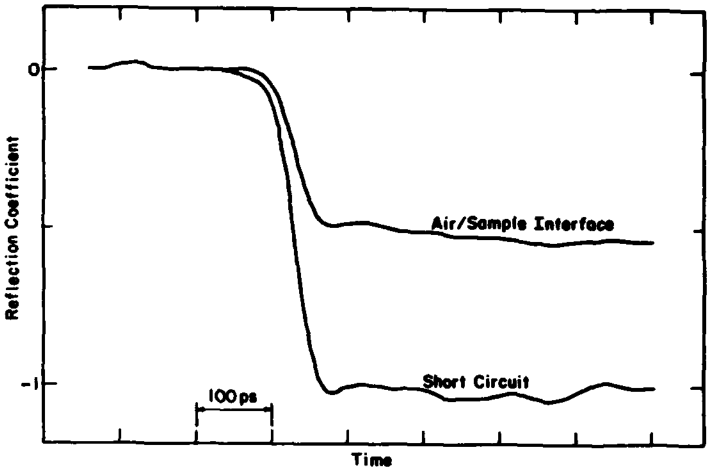

Figure 2. Typical TDR signals reflected from an air/sample interface and from a short circuit.

$$K^*(f) = \left[\frac{1-\rho(f)}{1+\rho(f)}\right]^2.$$

Obviously, then, $\rho(f)$ is a complex quantity, and great care must be taken to ensure that the relative time delay between incident and reflected waves is correctly determined to avoid errors in computing the reflection coefficients.

TDR techniques are described by Fellner-Feldegg (1972), Loeb et al. (1971) and Van Gemert (1972). A tunnel diode (Fig. 1) generates step waveforms with a very fast rise time in a coaxial waveguide. A sampling oscilloscope records the reflections from the sample interface and from a short circuit at the end of an air-filled line (Fig. 2). The latter reflection gives the incident waveform. The sampled reconstructions of the incident and reflected waves are Fourier-analyzed, using a modification of the Shannon sampling theorem (Samulon 1951) to give the incident and reflected amplitudes at discrete frequencies. The processed data are then converted to relative complex dielectric permittivities.

We used a Hewlett Packard Model 1815A sampler and an 1108A tunnel diode mount, which produced a rise time of less than 35 ps. Therefore, sufficient energy was contained in the pulse spectrum up to 4 GHz, above which the accuracy of the dielectric calculations became seriously impaired because of the difficulty in analyzing the waveforms. One set of incident and relected waveforms took less than one hour to record and analyze; single frequency measurements using slotted line techniques over the same frequency band take days. The main disadvantage of TDR is that only liquids or fine-grain soils can be placed in the coaxial sample holder. Solid samples could be accurately machined to the annulus dimensions, but we have yet to try this.

Preparation of soil samples

The volumetric moisture content of the field samples was measured to determine the range of moisture most appropriate for the laboratory measurements. The soils were oven-dried and then moistened with distilled water to typical soil moisture levels encountered in the field (0.17-0.55 g H_2O/cm^3). After thorough mixing, the sample was carefully compacted into the sample cell (transmission line annulus) to avoid variations in density, which would have caused unwanted reflections. The cell length was 20 cm, which was sufficient to keep reflections from the back of the sample from interfering with those from the front. The soil moisture was determined more accurately at the end of each test by oven-drying the entire sample and measuring the weight of the water loss.

Dielectric measurements were made immediately after packing at room temperature (+25°C). The sample was then quickly frozen to about -25°C by immersing it in a refrigerated bath. This procedure prevented any heterogeneity from occuring from moisture migration during the slow freezing. The connecting transmission line was insulated to minimize thermal conduction along the waveguide from outside the bath. The sample temperature was determined with a

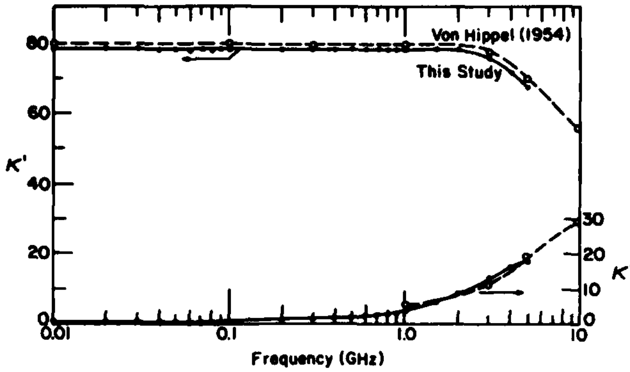

Figure 3. Dielectric constant and dielectric loss factor of distilled water at 23°C.

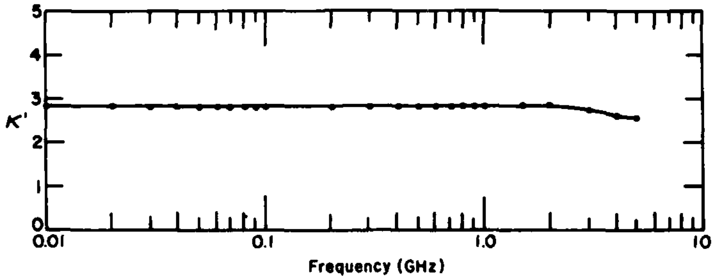

Figure 4. Dielectric constant of North Slope sand at 24°C.

copper/constantan short-time-constant thermocouple attached to the immersed sample. The thermocouple could not be placed within the sample since it would have caused unwanted reflections. The temperature was regulated by cycling a quartz heater in a constant refrigeration bath, resulting in ±0.1°C control. The sample temperature was allowed to stabilize for about an hour after any change in bath temperature.

We checked our dielectric measurement techniques frequently by performing measurements on well-documented substances. Figure 3 shows K′ and K″ for distilled water as a function of frequency at 23°C.

The accuracy of the TDR technique above 3-4 GHz is questionable (Van Gemert 1972) due to inaccuracies in determining the exact position in time of the pulse traces. The properties of the materials tested below about 0.05 GHz are affected by DC conductivity, but we only observed pulse decay for about 800 ps, during which the tails of the pulses became constant. A secondary relaxation due to conductivity effects would have occurred at about 10,000 ps. However, any rise in K″ below about 0.05 GHz due to DC conductivity is not observed in the data, as we assumed the pulse level to remain constant forever. Therefore, our data only show the dipolar contributions to K″.

Results and discussion

The relative complex dielectric permittivities of Fairbanks loess (Fairbanks silt) (Péwé 1958, 1975a, Sellmann 1967) and an eolian sand found on the North Slope that we call North Slope sand (Péwé 1975b, Carter 1981) were determined at several levels of moisture content and over a wide temperature range. Figure 4 shows K′ for air-dried North Slope sand as a function of frequency at 24°C. The quantity K″ was calculated to be less than 0.01 over this band, so it is not shown. K′ was constant to about 2 GHz, where a slight dip occurred, which may have been due to a very small amount of water present. However, no loss was calculated. Lowering the temperature did not affect K′. The data on air-dried Fairbanks silt (not presented here) are almost identical to these data, with K′ at about 2.9.

Figures 5 and 6 show K′ and K″ for Fairbanks silt and North Slope sand as a function of fre-

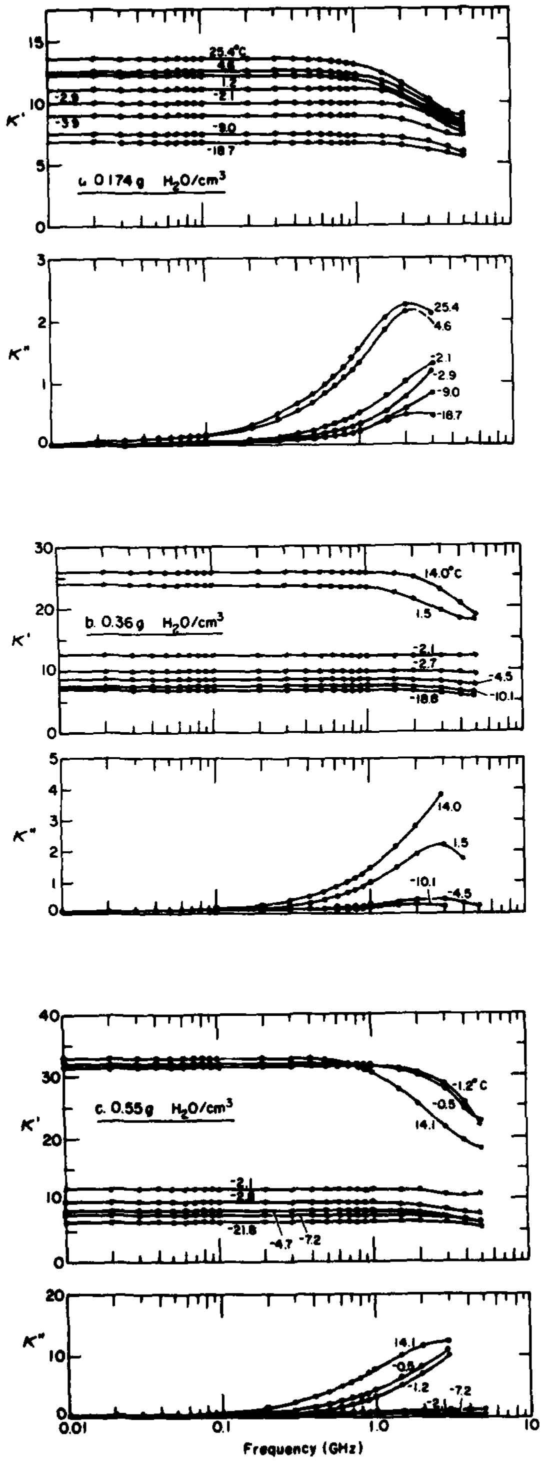

Figure 5. Dielectric constant and dielectric loss factor of Fairbanks silt as a function of frequency for several moisture contents and temperatures.

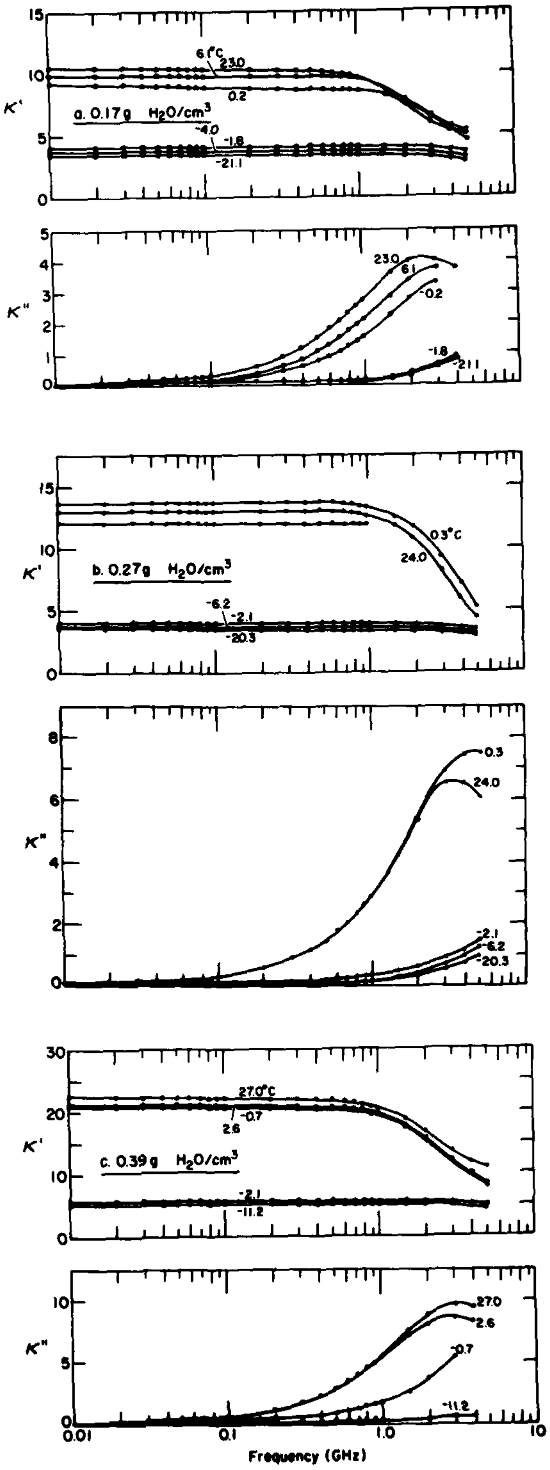

Figure 6. Dielectric constant and dielectric loss factor of North Slope sand as a function of frequency for several moisture contents and temperatures.

quency for several volumetric moisture contents from -22° to 27°C. The materials have similar dispersive properties. The values of K′ at similar temperatures were different, mainly due to dissimilar moisture levels and, less importantly, to dissimilar proportions of adsorbed and free water. Both soils showed a steady value of K′ for each temperature at frequencies from 0.01 to 1.0 GHz. Figures 5c, 6a and 6b show some inconsistencies at temperatures above 0°C. The highest temperature run was taken before freezing, while the others were taken after freezing. Consequently, a water meniscus may have formed upon thawing, which would have layered the sample, causing these inconsistencies. This meniscus would also violate the assumption that the pulse reflection takes place at an interface that is normal to the line.

The quantity K′ began to decrease for both soils above 1 GHz, while a rise in K″ began at about 0.1 GHz. This occurred down to about -20°C in both materials because of small amounts of unfrozen, adsorbed water still remaining. (A hydrometer analysis of North Slope sand showed that 5% of the material was silt-size or smaller, which may account for the unfrozen, adsorbed water in the sand sample.) This frequency dependence is caused by a Debye-type relaxation, which occurs when water, wet materials and alcohols are placed in time-varying electric fields at these frequencies. The electric field polarizes the water by giving a net orientation to the water molecules, each of which is a permanent dipole. The time required for the polarization to reach equilibrium is referred to as the relaxation time, which is about 7 ps for free water and in the range of 20-150 ps for adsorbed water. This corresponds to a maximum dispersion centered at about 22 GHz for free water and about 1-8 GHz for adsorbed water. The frequency band over which this dispersion occurs will therefore vary with water content as these two effects take place.

Hoekstra and Doyle (1971) and Hoekstra and Delaney (1974) found a relaxation between 1 and 3 GHz in moist soils well below saturation. The relaxation frequencies shown in Figures 5 and 6 occurred at about 2 GHz and above, in agreement with the data of Topp et al. (1980) and Njoku and Kong (1977). Hoekstra and Delaney (1974) also suggested that two closely spaced relaxations may occur with water in clay-rich soils. Only one relaxation was observed in this study, but there may have been two that were too close to be resolved.

Figures 7 and 8 show the complex dielectric constants of Fairbanks silt and North Slope sand as a function of temperature for several soil

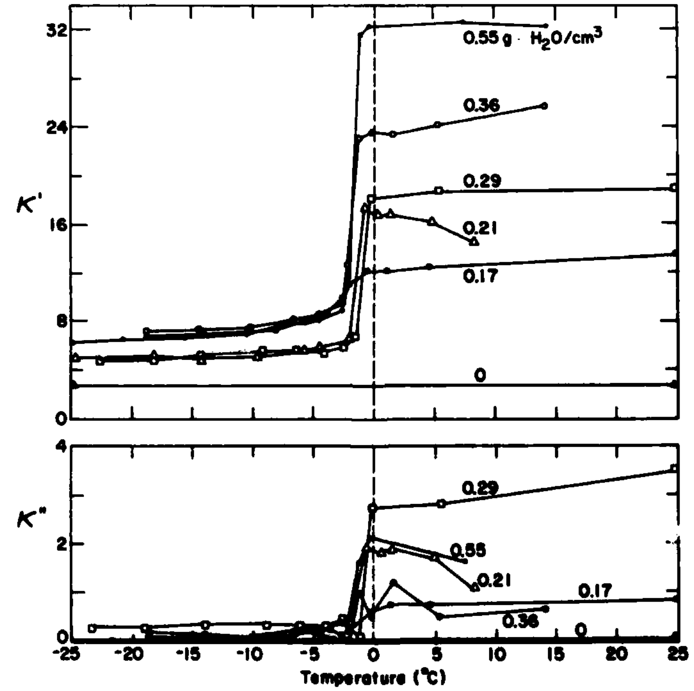

Figure 7. Dielectric constant and dielectric loss factor of Fairbanks silt as a function of temperature for five moisture contents at 0.5 GHz.

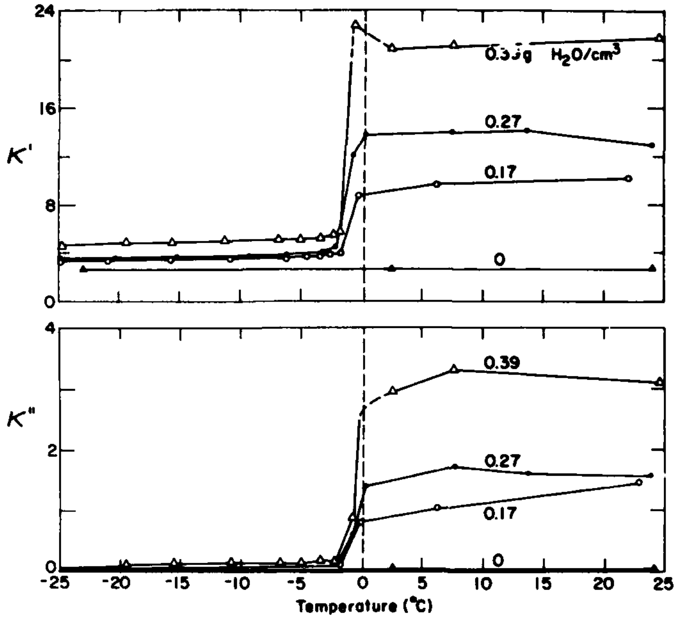

Figure 8. Dielectric constant and dielectric loss factor of North Slope sand as a function of temperature for three moisture contents at 0.5 GHz.

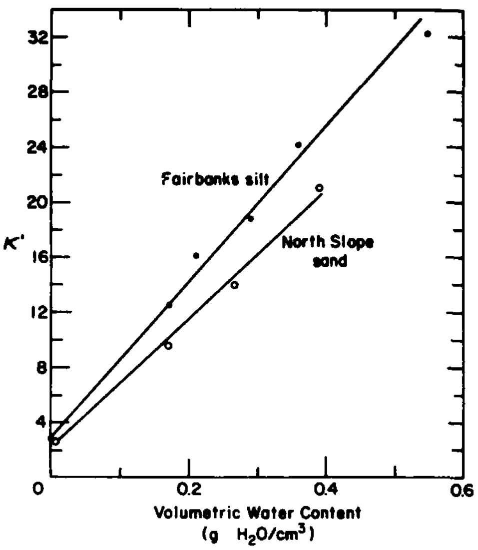

Figure 9. Dielectric constant as a function of volumetric water content for two soils at a frequency of 0.5 GHz and a temperature of 5°C.

moistures at 0.5 GHz. Note that below 0°C, K' of Fairbanks silt remained higher than K' for frozen moist sand due to the unfrozen, adsorbed water remaining in the silt. The abnormal behavior of K' for unfrozen Fairbanks silt (Fig. 7) with a higher moisture content may have resulted from the formation of a water meniscus, as discussed previously. As the data were recorded with increasing temperatures, the data points below 0°C would not be affected.

Figure 9 shows the dielectric constants of Fairbanks silt and North Slope sand as functions of volumetric water content at a frequency of 0.5 GHz, which is below the dispersion range shown in Figures 5 and 6. The dielectric constant is slightly dependent on material type, being higher for the fine-grain material, which is able to hold more water in the adsorbed state. We do not understand why the mixture with more adsorption gives higher values, but the data of Figures 5 and 6 (compare 0.36 and 0.39 water volumes, respectively) also verify this. These data show a very small dependence on material type, which is in good agreement with the experimental data of Wang (1980) and Topp et al. (1980).

CONCLUSIONS

The constant value of K' and the low K" (<0.2) for frequencies up to 0.3 GHz exhibited by the high-moisture-content silt and sand below -1°C are ideal for good propagation characteristics at VHF. In addition, the large K' values for high-ice-content silt demonstrate that massive ice (K' ≈ 3.0) should be easily detectable with VHF radar in this material if signal losses in the active layer are not too great. Arcone et al. (in press) have shown that massive ice in sandy soils can be easily distinguished. However, if a soil is dry or very cold (-20°C), distinguishing massive ice features based on variations in electrical properties will be much more difficult.

Preliminary measurements on organic soils by the authors show that K' may be extremely variable at temperatures above 0°C and that organic soils are different dielectrically than mineral soils. Our future work will explore this behavior.

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