Laboratory Evaluation of a Field-Portable Dielectric/Soil-Moisture Probe

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Abstract—There has been a need for a rapid method of collecting soil-moisture information, especially for verifying microwave remote sensing field experiments. In this investigation an evaluation of an L-band dielectric probe was conducted to examine its capabilities, calibration, and performance under laboratory conditions. Results indicated that the probe can estimate the real part of the dielectric constant over a wide range of values. The imaginary part of the dielectric constant was overestimated. Since the soil moisture estimate is made using only the real part of the dielectric constant, the probe should produce reliable estimates of soil moisture. Studies utilizing a variety of soils, ranging from a loamy sand to a clay loam, produced results which were not as variable as those predicted by the dielectric models.

I. INTRODUCTION

REMOTE SENSING investigations involving microwave measurements of soil moisture require ground observations for calibration and verification. Conventional methods of soil moisture measurements, i.e., gravimetric sampling, are tedious and costly, especially in large-area studies. There has been a need for a rapid and reliable method of soil moisture sampling [12].

Brundfeldt [3] has developed a field-portable soil-moisture probe that has the potential of providing the data needed in these studies. This instrument utilizes measurements of dielectric constant at a specific microwave frequency to estimate soil moisture.

The availability of such an instrument could be a great benefit to the remote sensing of soil-moisture research. The instrument allows the rapid collection and storage of data and immediate display of results. In addition, the instrument also stores the dielectric data. Direct observations of the dielectric data are valuable to the development of microwave emission and backscattering models. Normally, such data are not collected because suitable field instruments have not been available. In this investigation, an evaluation of an L-band probe (1.25 GHz) was conducted to examine its capabilities, calibration, and performance under laboratory conditions.

The objectives of this investigation were to evaluate how well this probe could estimate the dielectric constants and soil moisture. Reference standards of a variety of liquids were used to determine how well the dielectric constant could be estimated, and prepared soil samples were used to evaluate soil-moisture measurement capabilities.

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II. L-BAND DIELECTRIC PROBE SYSTEM

The microwave dielectric probe, as reported by [3], utilizes an open-ended coaxial cable. Various contact probe tips can be interchanged for different applications. A reflectometer is used to measure the amplitude and phase of the material at a particular frequency. The device used in this study operated at 1.25 GHz. Measurements are referenced to observations in air. The real (ϵ') and imaginary (ϵ'') components are computed using a capacitor model which involves two parameters that must be calibrated for the particular instrument and probe tip. These two parameters are a scale factor for the phase and the characteristic impedance of the system. The system must be calibrated to determine these parameters.

Data are processed via a Hewlett-Packard HP41 calculator with extended memory and an interface loop. Any number of samples can be used to compute the field average and standard deviation of ϵ' , ϵ'' , and the soil moisture that are stored in memory. Up to 75 field averages can be stored. These data can later be printed or transferred to another computer.

Soil-moisture computations are performed using regression equations developed by Ulaby *et al.* [14] (see also [7]). These equations require the user to input the percentages of sand and clay in the soil. Conversion to soil moisture can also be performed afterward if the soil parameters are not available, or if one wishes to use a more sophisticated model for estimating the soil moisture, such as those developed by Dobson *et al.* [6] and Wang and Schmugge [16].

III. EXPERIMENTAL PROCEDURE

Instrument Calibration

Brundfeldt [3] utilized a variety of liquids and ceramic blocks to calibrate the instrument. Three probe tips are supplied with the instruments that are recommended for the ranges of dielectric values in Table I. Soil dielectric constants are normally in the ranges described by Tips 2 and 3 [6].

Three dielectric blocks ($\epsilon' = 3, 6$, and 13) and liquids of known dielectric properties were used to evaluate calibration. One advantage of using liquids instead of solids or granular materials in the calibration is that the contact between the probe tip and material can be assumed to be perfect. Contact can be a problem with solid materials.

TABLE I
RANGES OF DIELECTRIC VALUES

Tip	ϵ'	ϵ''
1	8-80	5-50
2	3-30	2-20
3	1-15	0-10

TABLE II
REFERENCE LIQUID DIELECTRIC PROPERTIES AT 1.25 GHz

Liquid	Chemical formula	T(C)	ϵ'	ϵ''	Reference
Methanol	CH ₃ OH	20	28.2	12.5	[1], [13]
Butanol	CH ₃ CH ₂ CH ₂ CH ₂ OH	20	4.2	3.1	[13]
1-Propanol	CH ₃ H ₇ OH	20	6.3	6.1	[13]
Ethanol	C ₂ H ₅ OH	20	12.8	12.1	[13]
Octanol	CH ₃ (CH ₂) ₆ CH ₂ OH	20	3.2	0.5	[5]
i-Amyl Alcohol	(CH ₃) ₂ CHCH ₂ CH ₂ OH	20	3.2	2.1	[13]
Distilled Water	H ₂ O	20	79.7	5.4	[13]
Butanol	CH ₃ CH ₂ CH ₂ CH ₂ OH	22	4.7	3.9	[2]
Ethylene Glycol	HOCH ₂ CH ₂ OH	23	24.6	18.7	[4]
Methanol	CH ₃ OH	23	27.0	10.8	[4]
Distilled Water	H ₂ O	25	77.9	4.6	[9]

Published literature revealed that alcohols covered a wide range of dielectric values (Table II). Typically, the magnitude of the real part of the dielectric constant is a function of the length of the hydrocarbon chain. Experimental procedures, temperatures, and frequencies reported vary greatly, and the dielectric properties are sensitive to all of these. None of the published data were measured at exactly 1.25 GHz, the operating frequency of the probe used here. Therefore, it was necessary to interpolate. Several potential data sets had to be eliminated because there were not sufficient measurements to define the frequency versus ϵ' , ϵ'' curves at 1.25 GHz (i.e., [15]). The data set used in the current study is listed in Table II.

Measurements were made in a laboratory with a nominal air temperature of 23°C using all three probe tips. Samples were cooled or heated depending on the temperature of the published data and were stirred prior to measurement.

Laboratory analysis utilized a range of surface soil textures. A batch of soil was oven-dried at 100°C for 24 hr. A known weight of soil was then mixed with a specified weight of water to achieve a gravimetric moisture content. The soil was used to fill a sealable plastic container of known volume. Although an attempt was made to maintain a specific bulk density, this was not always pos-

sible. The sample was then sealed and allowed to equilibrate for 48 hr.

Dielectric measurements were obtained after at least 48 hr. The soil samples were weighted and oven-dried to determine the volumetric soil moisture and bulk density.

Standard soil-analysis procedures were used to measure soil particle-size distribution and specific surface. These results are listed in Table III for the soils studied. The montmorillonite and kaolinite listed in Table III were used for verification of the specific surface measurements and illustrate the range that can exist in this parameter for a clay.

IV. RESULTS AND DISCUSSION

A. Instrument Calibration

Observed and reference dielectric data are plotted in Fig. 1. It is apparent that the instrument reproduces the reference ϵ' values quite well within the suggested dielectric range presented in a previous section. Tip 1 yields good results through the entire ϵ' range. Tip 2 appears to be slightly biased above $\epsilon' = 30$. Tip 3 yields good results up to $\epsilon' = 30$; however, unlike Tip 2, it deviates significantly above this point. Since values of ϵ' for a soil would rarely exceed 30, Tip 3 is the most useful.

The ϵ'' results shown in Fig. 1(b) are not as good as those for ϵ' . The probe overestimates throughout the observed range. Overall, Tip 3 yields values closest to the reference measurements, while Tip 2 yields the poorest results. The bias appears to be deterministic and could be corrected by modifying the results using a linear equation. However, soil-moisture prediction is based solely on ϵ' ; hence, using the built-in equation, the error in estimating ϵ'' will not affect the soil-moisture estimate.

B. Soil Moisture

Data were collected using all three probe tips; however, based on the results described in the calibration experiments, only Tip 3 data will be presented. Probe usage as a soil-moisture instrument was evaluated by comparing the measured ϵ' and soil-moisture values with the probe soil-moisture equation [14]. This equation is a best-fit nonlinear regression based on laboratory measurements [14] at 1.4 GHz for a limited number of soils. Fig. 2 shows the data and predicted relationship for three soil textures.

The model predicts the same range of response as that observed up to about 0.3 soil moisture. However, the data do not show a texture dependence. Beyond this value there are unexplained variations. From Fig. 2 it was concluded that a single relationship exists between soil moisture and the probe-measured ϵ' regardless of soil texture.

There have been extensive investigations of the relationship between soil moisture and the dielectric constant that have shown that soil properties do have an effect on

Fig. 1. Comparison of measured and reference dielectric constants of liquids: (a) Real component (e'), and (b) imaginary component (e'').

TABLE III
SOIL PROPERTIES

Description	Depth	Texture			Surface area (m^2/gm)	Classification based on texture	Bulk density range (gm/cm^3)
		Sand	Silt	Clay			
Elinsboro sandy loam (East Farm)	Surface	71	25	4	13	Loamy sand	1.47 - 1.59
Woodstown sandy loam (North Farm)	Surface	67	27	6	17	Loamy sand	1.41 - 1.67
Christiana silt loam	5-15 cm	19	62	19	23	Silt loam	1.19 - 1.29
Christiana silt loam	60-70 cm	38	30	32	45	Clay loam	1.33 - 1.49
Montmorillonite (Bentonite)	-	0	0	100	718	Clay	-
Kaolinite	-	0	0	100	49	Clay	-

the relationship. Therefore, it is necessary to resolve these observations with previous studies by considering the dielectric mixing models.

It has been recognized for some time [6], [10], [12], [16] that like other mixtures involving water, the dielectric constant of moist soil is not the weighted average of its constituent components. Water in the soil has at least two distinct dielectric phases: Free, and bound. The free water has a high dielectric constant ($e' = 80$) which is attributed to the fact that the water molecule dipoles are free to rotate at microwave frequencies [8]. Bound water has a lower dielectric constant because these water molecules are adsorbed on the surfaces of particles and the dipoles are immobilized.

Bonding occurs on the surfaces of soil particles. In a soil system this surface area is variable, but depends primarily on the amount, size and shape of the clay particles. Within a volume of soil, the two physical parameters that describe the available bonding area are the specific surface area of the soil (m^2/gm) and the bulk density of the soil (gm/cm^3). Increasing either of these values in a given volume will increase the surface area. Fig. 3 illus-

Fig. 2. Laboratory soil moisture and dielectric constant (e'), and reference [14] model predictions.

trates the effect of changing these values on the volume of bound water determined by using Dobson *et al.*'s assumptions [6]. These assumptions include the use of a 3-Å thick layer to represent the maximum bound water and a dielectric constant of $e' = 15$.

Two features should be noted from Fig. 3. First, for a

Fig. 3. Effects of specific surface area and bulk density on the bound water fraction using reference [6] assumptions.

given bulk density, say 1.3 gm/cm^3 , the range of bound water is only on the order of 0.05 for all of the soils one might encounter ($0\text{--}150 \text{ cm}^3/\text{gm}$). Secondly, for a given soil in this range, bulk density will cause a variation in bound water only as large as 0.02. From these results it was concluded that for typical soils, specific surface = $50 \text{ cm}^3/\text{gm}$ and bulk density = 1.3 gm/cm^3 , that the bound water should vary within ± 0.02 of a mean value. This could explain why the observed data in this study tend to fail within a limited range at a given soil moisture. Fig. 4 shows the range of response in the relationship between soil moisture and ϵ' as predicted by using the Dobson *et al.* model [6] and the soil properties measured for the sandy-loam and clay-loam soils.

Another cause of variation between the observed and predicted data may be the localized bulk density changes caused by compression when the probe tip contacts the soil. In order to obtain a good contact, the probe tip was twisted and pressed into the soil. This results in a localized compression of the soil and a higher bulk density in this region than the value measured for the whole sample. For example, a limited test showed that for the silt-loam soil the bulk density when compressed was 1.65 gm/cm^3 , as opposed to 1.38 gm/cm^3 beforehand.

The net effect of those factors described above causes the actual volumetric soil moisture at the probe contact point to be higher than that estimated by using the gravimetric moisture and bulk density of the total sample. Therefore, the observed data points for low-density soils may be plotted at lower soil moistures than they should be. Because the soil moisture may be underestimated, the data look more like sandy higher density soils than they should.

These results indicate that as a soil-moisture measurement device, the L-band probe will do a good job for almost all soils up to a 0.30 volumetric soil moisture without any other information. A single relationship can be used. However, if dielectric properties are needed, a great deal of care is necessary in order to avoid variations caused by soil compression.

Fig. 4. Comparison of the reference [6] dielectric mixing model and laboratory observations.

V. SUMMARY

An L-band field-portable dielectric soil-moisture probe was evaluated under laboratory conditions. Comparisons with liquids of known dielectric properties produced good estimates of the real component, even though poor results were obtained for the imaginary component. Since soil moisture estimates are made using only the real component of the dielectric constant, the error in the imaginary component is not important in this application.

Comparisons of laboratory measurements of soil-moisture samples and dielectric constant prediction models, considering only the real component, indicated that the sample data exhibited less variability than the model predictions. This divergence is attributed to localized compaction at the probe contact point.

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