Dielectric Constant Measurement of Soil with Portable Dielectric Probes and TDR Techniques

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ABSTRACT

Portable Dielectric Probe (PDP) and Time Domain Reflectometry (TDR) instruments are now available for rapid in-situ estimation of a targets' dielectric properties. These techniques can be very useful in field experiments where the logistics of gravimetric sampling can restrict the number of samples obtained. A number of experiments were conducted to relate the real part of the dielectric constant, measured by P-, L-, C-, and X-band PDP's, to soil water content for soils with a range of soil textures. The results were also compared to TDR measurements for the P- and L-band PDP's. The TDR and P- and L-band probes produced very comparable and good results while the C- and X-band probes were more sensitive to variability within a soil and to the effects of soil texture. Both TDR and PDP instruments may be useful for field soil moisture measurement campaigns as they sample different volumes. In general the TDR is best used for 0-5cm or deeper layers while the PDP can be used for measuring smaller volumes/layers.

1. INTRODUCTION

Information on soil moisture status is of considerable value to many disciplines including hydrology, agronomy, and meteorology (Schmugge et al., 1980). Microwave remote sensing techniques may offer a valuable tool for providing this information and much research is being conducted to develop the necessary understanding to utilize this technology effectively (Ulaby et al., 1985; Dobson and Ulaby, 1986; Schmugge et al., 1986). Soil sampling programs conducted to support remote sensing field experiments are frequently inadequate due to the time, cost, and logistical constraints associated with conventional gravimetric sampling techniques.

The recent development of a portable dielectric probe (PDP) may offer a field instrument which will improve the situation (Brunfeldt, 1987). This probe provides rapid in-situ measurements of the dielectric constant (real and imaginary parts) of the contact target. Volumetric soil water content (Tv) may then be calculated using an empirical relationship to convert the real part of the dielectric constant (e') to Tv. This is the approach used by Hallikainen et al., (1985) and can be quite successful due to the (angle dielectric constant of water at microwave frequencies (_ 60-80) when compared to the dielectric constant of dry soil (_ 8-5).

Time domain reflectometry (TDR) is another electromagnetic technique which has been applied to the determination of soil water content (Topp et al., 1980; Topp, 1987). The TDR systems, in use currently, provide information on a deeper soil profile (_0-5 cm or deeper) than the penetration depths which the PDP measures (_0-1 cm). In order to get depth profiles using the PDP it is necessary to make measurements at progressively deeper layers. Both types of instruments may therefore be used to provide estimates from different soil depths.

The objectives of this study were:

1. To relate e', as measured by P-, L-, C-, and X-band PDP's, to Tv for a variety of soil types at various water content levels.

2. To compare the dielectric constant measurements obtained from the PDP with those obtained by the TDR technique.

3. To recommend procedures for the field use of the PDP.

2. BACKGROUND

A brief description of each instrument is given concentrating on the operating principles only, and readers are referred to background literature cited in this section. Brunfeldt (1987) has given a more complete description of the theory and design of the dielectric probe. The PDP consists of an open-ended coaxial cable probe which contacts the material to be measured. A novel microwave reflectometer for measuring the reflection amplitude and phase from the probe, and a data processing computer for transforming the reflectometer data into the complex dielectric constant, er' - jer'' is contained in the instrument. The calculation treats the probe tip as a capacitor such that an increase in the capacitance at the end of the coaxial line results in an increase in the reflection coefficient. The measurements are referenced to observations in air and the probe electronics were calibrated using targets with known dielectric properties. Figure

1 shows the probe in operation. The probes used in this experiment operated at the following frequencies (GHz): P-.45, L-1.25, C-5.3 and X-9.3. Each probe has 3 different tips which cover a rnage of dielectric values from 0 to approximately 80.

TDR measurements relate the propogation constants of electromagnetic waves, such as velocity and attenuation, to in-situ soil properties such as water content and electrical conductivity (Topp et al., 1980; Topp, 1987; and Topp et al., 1988). The TDR technique uses a step voltage pulse propagated along parallel transmission lines. These parallel rods, or wires, serve as conductors while the soil serves as the dielectric medium. After propagation as a plane wave through the soil the signal is reflected from the end of the transmission line and returns back to the TDR receiver. The volumetric water content is related to the propagation velocity and thus to the real part of the dielectric constant.

3.0 EXPERIMENTAL METHODE

A series of experiments was conducted over a 2 year period to generate the PDP, TDR, and physical soils data needed to address the objectives. During the analyses of these data various problems with the PDP and/or the experimental desing were discovered and the need for additional experimentation identified. These problems will be identified and discussed in section 4.

In all experiments a range of soil types were used starting with air dry soil which had been passed through a 2mm seive to disperse soil aggregates. Known volumes of water were then added to known volumes of soil in several increments to generate a range of soil moisture contents. Wet and dry weights were obtained which allowed us to generate volumetric soil water content (Mv) for each soil sample measured with the PDP or TDR techniques. In all cases great care was taken to uniformly mix and prepare the soil samples in whatever container was being used. Statistical analysis (T-tests) and qualitative evaluating verified uniform mixing. However, the volume and mass information allowed us to calculate bulk density as well as soil moisture status. The soils were all selected from samples available at the Land Resources Research Centre of Agriculture Canada field that a wide range of chemical and physical properties of the soils were known. Table 1 presents the physical properties of the soils used in these experiments.

Seven PDP measurements were made of each soil sample and after visual scrutinization and removal of anthiers the remaining E' data points were averaged for analysis. Seven samples were obtained because a good contact of the PDP tip with the soil surface is essential to avoid artificially low dielectric measurements due to the presence of air-filled voids in the measured region. Triplicate TDR measurements were made, when a large enough container size was used, using 10cm long transmission lines. See Topp (1987) for a complete description of TDR measurement techniques. The 3 measurements were averaged for later analyses.

The TDR and PDP data were then plotted as a function of volumetric soil moisture and frequency, soil texture, container size, and probe tip effects were evaluated. This led to the removal of several data sets. The remaining data were combined by frequency and soil type and then used to generate 2nd order polynominal equations relating E' to Mv. The RS_1 computer software package was used for the plotting and analyses work (BBN Software Products Corporation, 1989).

4.0 Results and Discussion

During the 2 year experimental period several negative aspects of the PDP design and our experimental methods became apparent. Firstly, the sensitivity range for each probe tip reported by the manufacturer was less than specified. Thus probe tip 3 for C- and X-band was only reliable up to dielectric constants (real part) of approximately 15 rather than 20. For L- and P-band the range was up to 2' values of 25 rather than the unit of 30 specified by the manufacturer. Thus data obtained where the dielectric constant was approaching or exceeding these limits had to be removed from further analysis. By changing the probe tips to account for the dielectric range of the target of interest this problem can be avoided. Jackson (1990) did find good agreement between measured and predicted dielectric constant using all three available probe tips at L-band, especially for E'. Thus, for soil moisture evaluation using the X- and C-band probes tip 2 must be used while at L- and P-bands tip 3 can Pangely be used. Table 2 provides a summary of each tips suggested and practical measurement ranges by frequency.

Another problem which became apparent during the experimental period was an effect of container size on some of the data. At a combination of high target dielectric values and large contact areas the electromagnetic field becomes a propagating field rather than a statis field and the capacitance model becomes invalid. This problem was worst for the X- and C-band data and caused additional data exclusson for the analysis. This problem was overcome by using large containers and probe tips 2 for X- and C-band.

Finally the higher frequency probes (X, and C) were much more difficult to calibrate and keep calibrated then the power frequency PDPs (L- and P-bands). This caused additional data exclusion from the analyses as the X- and C-band probes had less temporal repeatability (ie between experiments).

The remaining data were plotted as a function of frequency and soil type (ie. E' vs Mv for all frequencies and then all soils) and then evaluated for agreement with previously published results. The frequency effects were generally as reported in the literature (Hockstra and Delaney, 1974; Halikainen et al., 1985; Dobson and Ulaby, 1986). Thus the lower frequency measurements produced higher E' values than the higher frequency measurements as can be seen in figures 2-4. This is attributed to the dielectric constant of water which decreases with frequency from approximately 80 at P-band to 60 at X-band.

Figures 5-8 show the effects of soil texture on the dielectric constant as measured by the multi-frequency PDPs. Note that very little texture dependency is observable at P- and L-band with C- and X-band exhibiting greater differences between the different soil types. Previous research has found increasing soil texture effects with decreasing frequency (Dobson et al., 1984) which led to the incorporation of a physical parameter describing some aspect of soil texture in dielectric models. Thus the dielectric mixing model developed by Wang and Schmugge (1980) had some sort of texture term (specific surface, field capacity etc.) in them.

However, the TDR approach developed by Topp and his colleagues (Topp et al., 1980), which uses a frequency range from -1 to 1 GHz, never produced soil texture effects. Indeed the relationship developed in 1980 even applies to soil which is 50% gravel (Drungil et al., 1989). This is desirable as there is no need to know the soil's texture or specific surface area which means a simple robust relationship between E' and Mv can be developed.

Jackson (1990) in an evaluation of soils with three different textures also found no significant difference between the soils using an L-band PDP. The rationale for the texture effect has been the different amounts of bound versus free water in heavy textured versus lighter textured soils. However, this difference is much less than 5% volumetric water content (for naturally occurring soils) and it appears that the amount of free water, regardless of soil texture, controls the value of the dielectric constant.

The authors attribute the soil texture effects observed in our data (see Figures 5-8) to the small sample volumes at X- and C-band and the physical changes in this sample area by the contact of the probe itself. Thus more water is extruded from the soil matrix in a sand than a clay due to the physical contact of the probe itself. This problem is exaccerbated by the small sample volumes (mm^3) t the higher frequencies. Sample preparation may also be a factor as clays will undoubtably pack different than sands when replaced into whatever container is being used duing the experiment.

A comparison of the L- and P-band PDP data with TDR data supports this observation. As figures 9-11 show the results are very comparable.

To generate Mv from field acquired E' data the polynominal equations given in Table 3 were generated. Note the improved performance of P- and L-band over the X- and C-band data. Due to the previously described problems associated with the higher frequency probes, ie the calibration, tip sensitivity, and soil texture effects, the P- and L-band PDP's appear much better suited for soil moisture estimation in the field. If C- and/or X-band data are needed for modelling purposes extra caution must be exercised to obtain useful data. This suggests that these types of studies are more suited to a laboratory environment.

The TDR and PDP can be considered complimentary tools for soil moisture measurement campaigns. TDR is very useful for profiles ranging from 5cm in depth up to 30cm while the PDP can be very good at generating profiles with cm increments. Both types of information are required depending on the particular study or application.

5. SUMMARY

The major results of this study are as follows:

1) The portable dielectric probes are a new and useful tool for soil moisture estimation but caution must be exercised when using them to avoid problems due to sample size, calibration, and probe tip sensitivity. For these reasons P- and L-band are preffered to X- and C-band.

2) There is no significant soil texture effect on the P- and L-band PDP data. The texture effects in C- and X-band may be due to the small sample volumes and physical changes induced in the soil matrix by the measurement procedure.

3) Second-order polynomial equations between E' and Mv were calculated for each frequency with R^2's ranging from .85 at X-band to .95 at P- and L-bands.

4) The P- and L-band PDP data compared very favourably with the TDR data. The two appraoches can be considered complimentary however, because TDR measures layers 5 or more cm thick while the PDP can measure layers approximately 1cm thick. Different study's or applications may require different depths of smapling and thus both instruments may be used interchangeably.

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Table 1. Soil texture and classification of the mineral soils used in the experiments

Name	Texture		Textural	Canadian
	% Sand	% Clay	Designation	Soil Classification
Rubicon	65	9	Sandy Loam	Gleyed Humo-Ferric Podzol
Bainesville	30	34	Clay Loam	Humic Gleysol
Rideau	2	53	Clay	Eutric Brunisol

Table 2. Probe tip sensitivity ranges for the portable dielectric probes.

Frequency	Tip #	Manufacturers Suggested Range	Practical Range for Soils
X	1	7-70	--
	2	2-40	--
	3	1-20	1-10
C	1	8-80	--
	2	2-40	--
	3	1-25	1-15
L,P	1	10-100	-
	2	3-50	--
	3	1-30	1-25

Table 3. **Second order polynominal equations between the real part of the dielectric constatn (E') and volumetric water content (Mv) for all soils by frequency.**

Frequency	Equations			R²
	Intercept	X	X²	
X	1.52	13.11	93.68	.86
C	1.06	28.77	65.10	.91
L	1.58	26.92	79.24	.95
P	1.66	26.51	89.57	.95

Table 4. **The dielectric constant measurements, volumetric moisture, and bulk density for the Grenville soil.**

Real Part Dielectric Constant (e')	Imaginary Part Dielectric Constant (e'')	Volumetric Soil Moisture (%)	Bulk Density (gm/cc)
2.9	0.1	0.8	1.4
3.9	0.4	5.3	1.4
5.3	0.5	9.4	1.2
8.8	3.0	15.4	1.3
17.6	7.8	23.4	1.5
16.7	7.9	25.8	1.4
16.6	7.8	33.8	1.7

Table 5. The dielectric constant measurements, volumetric moisture, and bulk density for the Carp soil.

Real Part Dielectric Constant (e')	Imaginary Part Dielectric Constant (e'')	Volumetric Soil Moisture (%)	Bulk Density (gm/cc)
3.1	0.2	5.6	1.2
3.5	0.4	9.1	1.0
4.6	0.6	13.1	1.0
5.0	1.0	17.3	1.0
7.6	1.8	20.7	1.0
10.2	3.9	26.6	1.0
11.7	6.6	32.7	1.1
14.4	7.9	38.5	1.2
13.9	6.7	45.7	1.2
13.6	5.9	51.4	1.2

Table 6. The dielectric constant measurements, volumetric moisture, and bulk density for the Newdale soil.

Real Part Dielectric Constant (e')	Imaginary Part Dielectric Constant (e'')	Volumetric Soil Moisture (%)	Bulk Density (gm/cc)
2.6	0.1	4.6	1.1
3.9	0.4	8.7	1.1
3.5	0.4	12.8	1.1
5.2	0.8	15.4	0.9
5.7	1.1	21.7	1.1
7.0	1.5	24.9	1.0
11.2	5.5	31.3	1.1
13.8	7.2	37.8	1.2
14.0	6.8	45.1	1.2
13.7	6.2	48.1	1.2

Table 7. The dielectric constant measurements, volumetric moisture, and bulk density for the Hemaruka soil.

Real Part Dielectric Constant (e')	Imaginary Part Dielectric Constant (e'')	Volumetric Soil Moisture (%)	Bulk Density (gm/cc)
3.2	0.3	4.4	1.4
3.3	0.4	7.6	1.2
4.3	0.6	10.9	1.1
4.3	0.6	16.9	1.0
7.9	2.2	21.4	1.1
9.3	3.0	29.0	1.1
13.4	6.5	37.7	1.2
13.3	7.1	44.0	1.2
13.0	6.4	48.2	1.2
11.4	4.4	58.3	1.3

Table 8(a). The dielectric constant measurements, volumetric moisture, and bulk density for the Rideau soil.

Real Part Dielectric Constant (e')	Imaginary Part Dielectric Constant (e'')	Volumetric Soil Moisture (%)	Bulk Density (gm/cc)
2.7	0.2	2.3	1.2
3.6	0.4	6.7	1.2
4.1	0.5	10.7	1.2
5.0	0.7	14.2	1.1
5.9	1.0	18.0	1.1
9.3	2.3	22.5	1.1
15.7	6.8	29.4	1.2
17.2	7.9	36.1	1.3
16.1	6.7	38.7	1.3

Table 8(b). The dielectric constant measurements, volumetric moisture, and bulk density for the Rideau (.25 KCl) soil.

Real Part Dielectric Constant (e')	Imaginary Part Dielectric Constant (e'')	Volumetric Soil Moisture (%)	Bulk Density (gm/cc)
3.6	0.4	6.4	1.2
4.4	0.5	10.5	1.2
5.7	0.8	13.9	1.1
6.1	1.2	18.3	1.1
9.0	3.0	22.9	1.2
12.8	6.3	30.2	1.3
15.7	8.2	35.9	l.3

Table 8(c). The dielectric constant measurements, volumetric moisture, and bulk density for the Rideau (.5 KCl) soil.

Real Part Dielectric Constant (e')	Imaginary Part Dielectric Constant (e'')	Volumetric Soil Moisture (%)	Bulk Density (gm/cc)
3.9	0.4	7.0	1.2
4.6	0.6	10.3	1.1
5.3	0.8	14.9	1.2
5.8	1.2	18.5	1.1
9.1	3.6	21.9	1.1
12.0	7.2	29.9	1.3

Table 9. The dielectric constant measurements, volumetric moisture, and bulk density for the organic soil.

Real Part Dielectric Constant (e')	Imaginary Part Dielectric Constant (e'')	Volumetric Soil Moisture (%)	Bulk Density (gm/cc)
3.8	0.7	19.5	0.4
4.5	0.9	28.0	0.4
5.3	1.1	29.5	0.3
8.6	3.2	33.0	0.3
11.5	5.4	36.4	0.3
12.8	7.7	44.3	0.3
13.2	7.8	46.8	0.3
13.3	5.3	59.6	0.4
13.1	4.8	57.6	0.4

Table 10. The polynomial expressions computed for each of the six mineral soils used to calibrate two C-band portable dielectric probes.

SOIL	POLYNOMIAL EQUATION
Charlottetown	$e' = 0.11\ Tv^2 + 0.144\ Tv + 3.015$
Grenville	$e' = 0.028\ Tv^2 - 0.034\ Tv + 3.064$
Carp	$e' = 0.004\ Tv^2 + 0.196\ Tv + 1.544$
Newdale	$e' = 0.002\ Tv^2 + 0.204\ Tv + 1.306$
Hemaruka	$e' = 0.006\ Tv^2 + 0.78\ Tv + 2.544$
Rideau	$e' = 0.010\ Tv^2 + 0.088\ Tv + 2.193$

Where: Tv = volumetric moisture content (expressed as a fraction).
e = real part dielectric constant.

LIST OF FIGURES