MULTI-FREQUENCY PORTABLE DIELECTRIC PROBES FOR IN-SITU SOIL MOISTURE MEASUREMENT

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ABSTRACT

Portable Dielectric Probe (PDP) and Time Domain Reflectometry (TDR) instruments are increasingly being used for rapid in-situ determination of soil moisture contents. These techniques provide alternatives for acquiring soil moisture data in field experiments where the logistics of gravimetric sampling can restrict the number of samples obtained. The real part of the dielectric constant of soils, measured by P-, L-, C-, and X-band PDP's , was empirically related to soil water content for soils with a wide range of textures. The results were compared to TDR measurements. The P- and L-band probes and the TDR produced very comparable and accurate results while the C- and X-band probes showed sensitivity to variability within a soil, the measurement technique, and soil texture. Both TDR and PDP instruments complement one another as they sample different depths/volumes. In general the TDR is suitable for 0-5 cm or deeper layers while the PDP can be used for measuring layers on the order of a cm in thickness.

INTRODUCTION

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. This problem can also occur in agronomic studies and thus there is a well defined need for a more suitable field technique.

The recent development of a portable dielectric probe (PDP) may offer a field instrument which will be useful for field experiments [1]. This probe provides rapid in-situ measurements of the dielectric constant (real and imaginary parts) of the contact target. If the target is a soil then volumetric soil water content (Mv) may be calculated using an empirical relationship to convert the real part of the dielectric constant ($*_r$') to Mv. This approach has been used by others [2,3] and is possible because of the large dielectric constant of water at microwave frequencies (* 60-80) compared to the dielectric constant of dry soil (* 2-5).

Time Domain Reflectometry (TDR) is another electromagnetic technique which has been applied to the in-situ determination of soil water content

[4,5]. The current TDR systems provide information on a greater soil profile (*0-5 cm or deeper) than the penetration depths measured by the PDP (*0-1 cm). This is because the TDR uses a waveguide inserted into the target medium for signal propagation whereas the PDP uses a capacitance model at the probe tip/soil interface. On the other hand, the PDP is able to generate detailed depth profiles by making measurements at progressively deeper layers. The two types of instruments may therefore complement each other for rapid in-situ construction of a soil moisture profile.

This paper will present the results of experiments conducted to establish the relationship between the real part of the dielectric constant, as measured by the PDP, and volumetric soil moisture. This will be done for X-, C-, L-, and P-band probes. The PDP results are also compared to TDR results and recommendations are made for field programs.

EXPERIMENTAL METHODS

A number of experiments were conducted over a 2 year period to generate the PDP, TDR, and physical soils data needed to address the objectives. The soils were selected from field samples available at the Land Resource Research Centre of Agriculture Canada for which chemical and physical properties were studied previously. The three soils used were a sandy loam (Rubicon), a clay loam (Bainesville), and a clay (Rideau). For each soil air dry samples were passed through a 2 mm sieve to disperse soil aggregates. Known volumes of water were added to known volumes of soil in several increments to generate a range of soil moisture contents. In all cases the soil samples were thoroughly mixed. Statistical analysis (T-tests) was used to verify uniform mixing when duplicate samples were available. Wet and dry weights were obtained which allowed calculation of volumetric soil water content (Mv) and bulk density (B) for each sample measured with the PDP or the TDR technique.

Seven PDP measurements were made of each soil sample 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. The seven data points were visually scrutinized and outliers were removed prior to averaging. Triplicate TDR measurements were made, when a large enough sample was used, with 10 cm long transmission lines and averaged for later analyses.

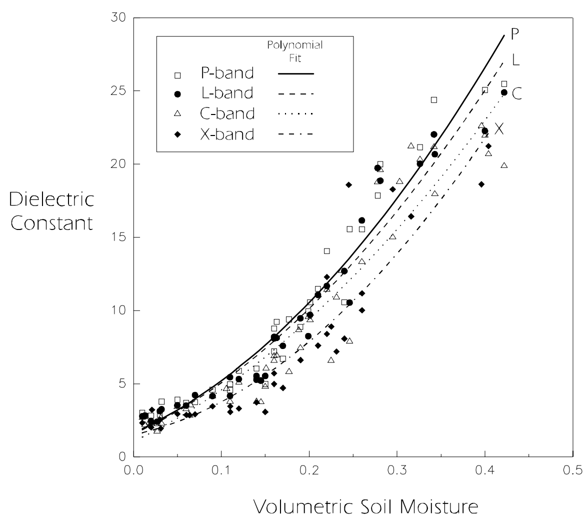
The measured TDR and PDP dielectric constant values were plotted as a function of volumetric soil moisture and the effects of frequency, soil texture, sample size (container size), and probe tip evaluated. This led to the removal of several data sets which is described in detail in [6]. The remaining data were combined by frequency and soil type and then a structural analysis was used to relate ε_r' to Mv. Due to space constraints in these proceedings the structural analysis results are presented in [6].

RESULTS AND DISCUSSION

The PDP ε_r' data plotted as a function of Mv are presented in

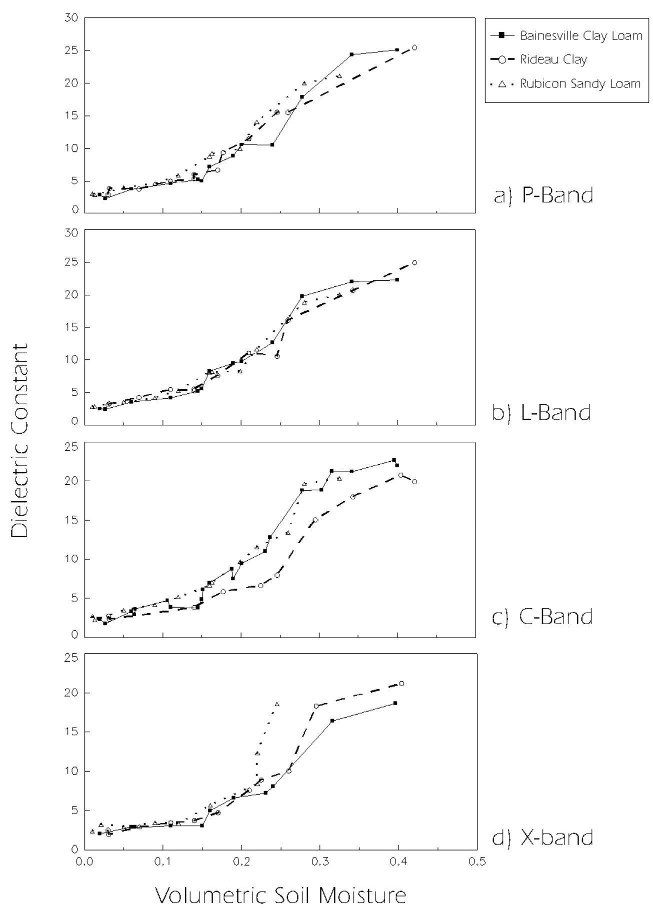
Figure 1. Individual symbols represent the data from all 3 soils from each frequency probe with the polynomial curve included as well. The data points show considerable overlapping indicating that the frequency dependence was not definitive. The curve fitting, however, showed that the lower frequency measurements resulted in higher ε_r' for all water contents. Thus, the greatest difference was found between the curves for P- versus X-band data. The frequency effects shown here are consistent with those reported by other researchers [2,7,8]. The observed frequency effects in soil can be attributed to the changes in the dielectric constant of water which decreases from approximately 80 at P-band to 60 at X-band. At Mv=0.30, the corresponding values are 18 and 14, which have approximately the same ratio.

Figure 1. Dielectric constant versus volumetric soil moisture for three soils measured by P-, L-, C-, and X-band PDPs.



The presentation in Figure 1 has ignored any soil texture effects. Figures 2 (a), (b), (c), and (d) present these data to show explicitly the soil texture effects on the PDP response at each frequency. The coarser textured Rubicon generally gave higher dielectric values than the finer textured Rideau soil, at the same water content. The medium textured soil usually resulted in a value between the other two, but not consistently. Thus we conclude the texture effects are minimal at all frequencies. The coefficient of determination ,R^2, for the polynomial fits at P-, L-, C-, and X-band were .95, .95, .91, and .86 respectively.

Figure 2. Dielectric constant versus volumetric soil moisture for each frequency PDP with all three soils differentiated.

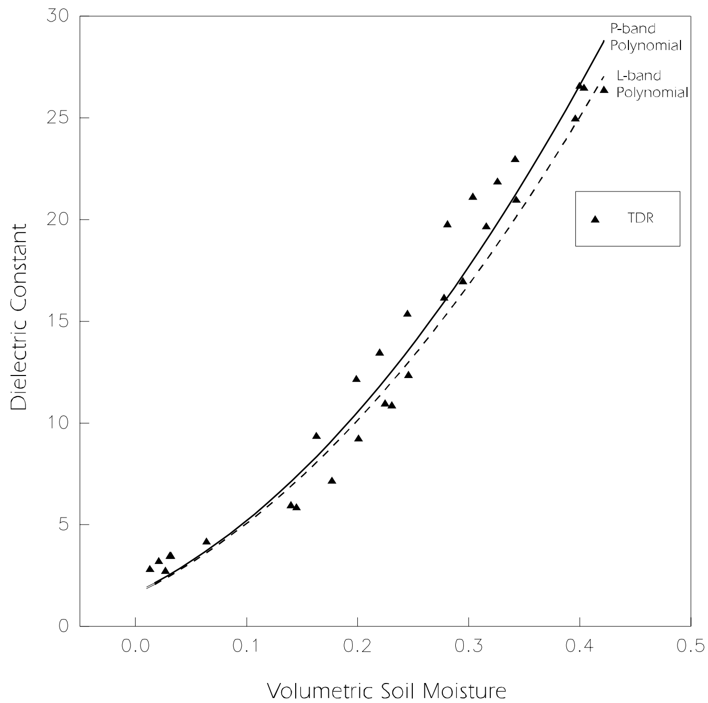


The consistently low dielectric constants measured for the Rideau soil when using the C-band probe appear to be anomalous and may be due to the nature of the probe measurement itself. The authors attribute some of the soil texture effects observed in our data (see Figures 2(a)-(d)) to the small sample volumes at X- and C-band and the physical changes in this sample area by the contact of the probe. Thus more water may be redistributed within the soil matrix in a sand than a clay due to the physical contact of the probe itself. This problem is aggravated by the small sample volumes (mm^3) at the higher frequencies and by the ratio of tip size to dielectric constant for wet soils. Sample preparation may also be a factor as clays will likely pack different than sands when replaced into whatever container is being used during the experiment.

Some other researchers have found soil texture effects to increase at lower frequencies [2,3,9]. As a consequence, the models used to portray the dielectric constant as a function of soil properties have included texture related parameters such as % clay, % sand, specific surface area, and field capacity [2,3,10]. Jackson [11], however, found no significant textural differences using an L-band PDP when working with three different soils. This textural effect has been attributed to the different amounts of bound versus free water contained in heavy versus light textured soils. It has been assumed that bound water has a lower dielectric constant. These bound versus free water effects appear to be of consequence at only low volumetric water contents [12]. At higher soil water contents (ie. above 0.10) it appears that the higher dielectric constant of the free water and the increasing relative content of free water allows it to dominate and control the resulting dielectric constant of the soil.

The TDR approach developed by Topp and his colleagues [4,5], which uses a frequency range of about .1 to 1 GHz, has never exhibited significant soil texture effects. Indeed the relationship developed in 1980 even applies to soil which is 50% gravel [13]. This is desirable for a field instrument as there is no need to know the texture or specific surface area of the soil which means a simple robust relationship between ε_r' and Mv can be developed. The comparison of performance of the PDP's with that of the TDR was achieved by comparing the fitted curves from the PDP's with measured data points from the TDR (Figure 3).

Figure 3. A comparison of PDP and TDR results for all three soils.



There is little difference between TDR and P- and L-band PDP measurements. The TDR, as expected, gives higher dielectric values than the C- and X-band PDPs so these comparisons were not made. The comparable performance was expected because of the similar frequency band of the TDR (.1-1 Ghz) to the P- and L-band PDPs. Due to the interest in generating surface soil water profiles for backscatter modelling and the need to understand the relationship between the surface and sub-surface water content for hydrological modelling [14,15] these two instruments are both very useful for field investigations. Thus, they can both be used to generate detailed in-situ depth profiles of either ε_r' or Mv.

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 when using them caution must be exercised to avoid problems resulting from sample size, calibration, and probe tip sensitivity. For these reasons P- and L-band are preferred to X- and C-band.

2) There is no significant soil texture effect in the P- and L-band PDP data. The texture effects at 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) The P- and L-band PDP data compared very favourably with the TDR data. The two approaches can be considered complementary however, because TDR measures layers 5 or more cm thick while the PDP can measure layers approximately 1 cm thick. Different studies or applications may require different depths of sampling and thus both instruments may be used interchangeably.

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