TDR vs Dielectric Probe for Measurement of Soil Dielectric Constant

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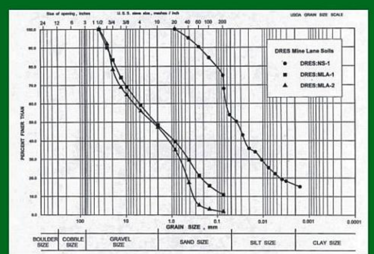
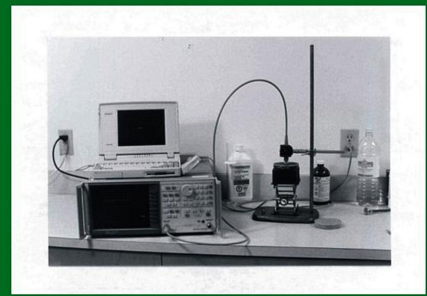
BACKGROUND

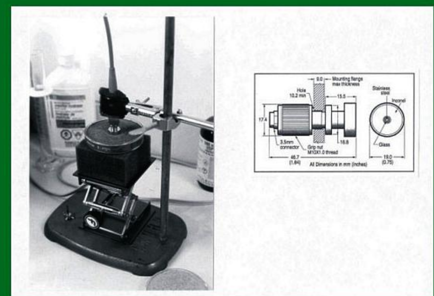
In connection with the Department of National Defence (DND) Improved Landmine Detection Project (ILDP) and related development and testing of integral sensor technologies, a test track was established at Defence Research Establishment Suffield (DRES), comprising approximately 30-50 cm of a sand-gravel aggregate placed directly on native loam soils. Baseline characterization of soil electromagnetic properties included a comparative study of time-domain reflectometry (TDR) and dielectric probe methods for measurement of moisture-dependent soil dielectric constant.

Prior to analyzing DRES soil samples, system performance was assessed via temperature-dependent measurements on four polar liquid standards, including ethanol, methanol, isopropanol and distilled water.

Following calibration, two sand-gravel aggregate samples (MLA-1, MLA-2) and a single Native loam soil (NS-1) were analyzed for a range of moisture levels as specified by gravimetric moisture content.







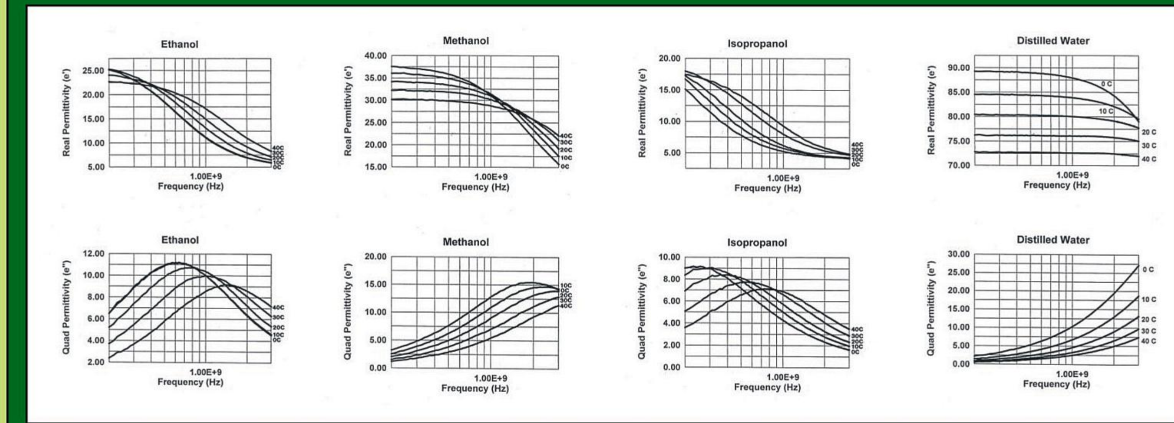
DIELECTRIC PROBE

Dielectric probe measurements were acquired using a HP85070A probe, configured with a computer-controlled HP8752C network analyzer.

Frequency-dependent complex permittivity spectra are determined via stepped-frequency (200 MHz - 3 GHz) continuous-wave excitation of the probe in direct contact with the sample under test.

The dielectric probe is, in effect, a terminated or open-ended coaxial transmission line. Because the radiation resistance of the terminated line is effectively infinite, no appreciable field is radiated and, consequently, effective sample volume is severely restricted. Corresponding fringe field interaction is quantified at discrete test frequencies via an associated S-parameter, quantifying the effective complex reflection coefficient at the probe-sample interface. The corresponding effective complex relative permittivity is subsequently computed via standard relations.

Due to restricted sample volume, measured permittivity spectra can be significantly skewed by local sample heterogeneity. Consequently, soil analyses were conducted on fine grained sample fractions having maximum grain diameter less than 2.0 mm (#10 sieve). Experiments indicate that this restriction represents a practical tradeoff between instrumental precision and accurate characterization of bulk soil permittivity.



COMPLEX PERMITTIVITY OF POLAR STANDARDS

Dielectric probe analyses of polar liquid standards yielded characteristic Debye dispersion spectra consistent with published data. Moreover, there is general agreement with corresponding TDR-based estimates of bulk dielectric constant (see below). However, precise correlation of temperature dependence for TDR and dielectric probe methods suggests that effective TDR measurement frequency is sample dependent. The observed effect is tentatively attributed to velocity dispersion and/or to TDR timing and effective probe length uncertainties.

TIME DOMAIN REFLECTOMETER (TDR)

TDR measurements were acquired, utilizing a specially developed test cell configured with a Tektronix 1502C TDR. In contrast with dielectric probe measurements, the TDR method yields a broad-band estimate of the effective dielectric constant by determining the effective propagation velocity of a guided wavelet within the sample under test.

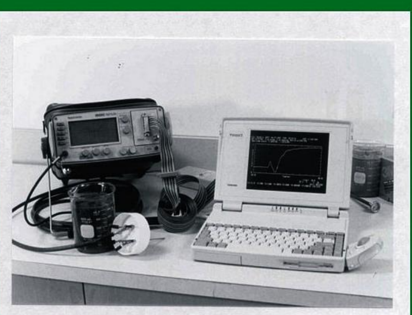
Like a propagating radar wavelet, the TDR pulse is partially reflected on encountering contrasts in electromagnetic impedance. The composite returned waveform is recorded as an oscilloscope-like trace with reference to a precise sampling time-base. Subsequent analysis-interpretation determines two-way transit-time $t_{2\text{-way}}$ along the known l-length probe and, consequently an effective propagation velocity v_{TDR} for the sample. Assuming that the soil is effectively dielectric over the TDR bandwidth, effective dielectric constant is estimated according to the relation

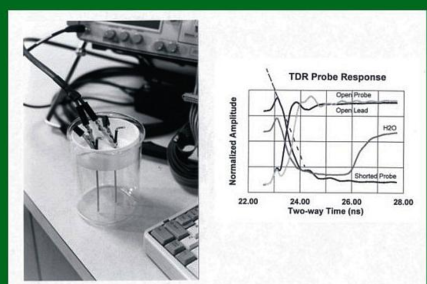
$$k_{TDR} = (v_0 t_{2\text{-way}}/2l)^2$$

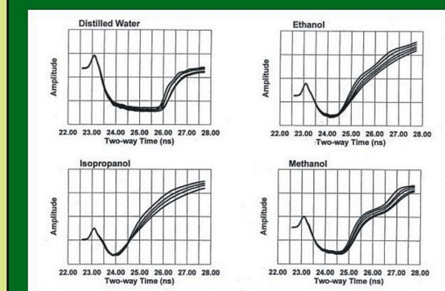
where v_0 denotes the electromagnetic propagation velocity in free space.

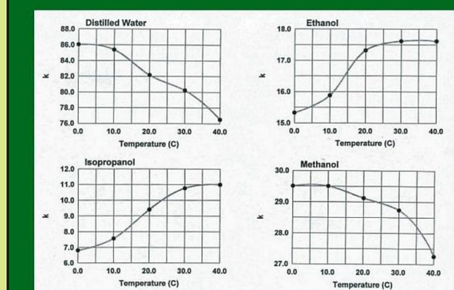
Given two-way transmission through the sample volume, the TDR method is inherently less susceptible to local sample heterogeneity and presumably more representative of bulk sample properties. However, accuracy of the method is limited by subsequent waveform analysis.

A range of techniques was investigated for identification and timing of reflection onsets, including standard linear regression-based methods, local curvature and inflection point techniques. None of these automated methods were determined to be satisfactorily robust. Although manual picking yields improved consistency, experience suggests development of full waveform inversion techniques.









RESULTS - DRES SOILS

Despite limitations of standard time-domain waveform analysis methods, there is surprisingly good agreement between TDR-derived dielectric constant and corresponding dielectric probe measurements at 1-3 GHz. TDR estimated dielectric constant is systematically higher and displays a marginally lower rate of increase with gravimetric moisture content.

Inter-calibrated best-fit exponential relations for moisture-dependent dielectric constant facilitate approximate prediction of variable soil conditions, including estimation of effective attenuation rates on the basis of field-based TDR and/or soil moisture monitoring.

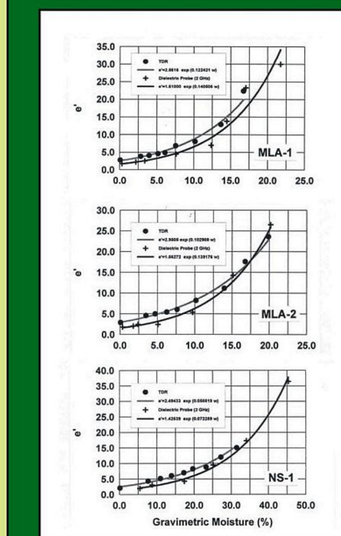
CONCLUSIONS - TDR vs DIELECTRIC PROBE

In connection with the characterization of DRES soils, comparison of TDR and dielectric probe methods has identified the following benefits and limitations of the two methods.

DIELECTRIC PROBE
- Direct measurement of frequency-dependent complex permittivity. Restricted sample volume
- Susceptible to sample heterogeneity
- High-cost
- Low-portability

TDR
- Broadband average dielectric constant
- Effective conductivity estimate requires separate analysis.
- Representative and flexible sample volume
- Lower susceptibility to sample heterogeneity
- Portable- In situ soil characterization
- Low-cost

On the basis of preliminary investigation, the TDR method appears to be uniquely well suited for robust in situ soil characterization and monitoring. Although standard waveform analysis techniques currently restrict the method's potential, full waveform inversion techniques are currently being developed for improved time and frequency domain analysis.



FOR DETAILS:
Cross, G. M., 1999, Soil Properties and GPR Detection of Landmines, DND Contract Report DRES CR 2000-091.