

DIVISION S-1-NOTES

SOIL WATER CONTENT DETERMINATION USING A NETWORK ANALYZER AND COAXIAL PROBE

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Abstract

A small-volume dielectric constant and soil water content sensor would be desirable in many laboratory experiments. Phase shift of the reflection coefficient in soil and various solutions was measured with a coaxial probe (CP) and a network analyzer operating at a frequency of 795 MHz. The CP had a measurement depth <1 cm. Five soils, varying widely in texture, bulk density, and organic matter content, were tested and comparison was made with other dielectric methods. Synthesized time domain reflectometry (TDR), resonant waveguide, CP, and conventional TDR measurements were in agreement for the sand. A simple mixing model for known dielectrics accurately predicted measurements of the apparent dielectric (K_a) for mixed solutions. A linear function ($r^2 = 0.90$), fit for the water content of all soil data, had a single measurement root mean square error (RMSE = $0.039 \text{ m}^3 \text{ m}^{-3}$). The uncertainty improved when individual linear soil calibrations (single measurement RMSE = 0.012 to 0.032; $r^2 = 0.95$ to 0.99) were used and further improved when repeated measurements were averaged (RMSE = 0.0073 to 0.026; $r^2 = 0.97$ –1.00). The CP method for measuring K_a is fast, simple, linear, easily repeated, and reasonably accurate, indicating that this instrumentation is useful for studying dielectric behavior of soil and various solutions and for rapid determination of soil water content in a small sample.

VOLUMETRIC SOIL WATER content, θ_v , may be inferred from measurements of dielectric constant. The most commonly used dielectric method is time domain reflectometry (TDR) (Topp et al., 1980). The typical approach to TDR (Topp et al., 1994) requires a waveguide type probe which is long enough to measure travel time of an electromagnetic wave traveling near the speed of light ($3 \times 10^8 \text{ m s}^{-1}$). Few reports on the use of TDR have been published where a probe less than 10 cm in length was used (Hilhorst and Dirksen, 1994). Kelley et al. (1995) reported on the use of 2.5-cm-long probes that required a high bandwidth TDR system. However, with measurements on the soil surface and in laboratory samples of soil or liquids, it is sometimes desirable to have a smaller measurement volume.

A broad range of probes and instruments with small measurement volumes fall under the category of frequency domain reflectometry (FDR). Capacitive FDR

probes (Thomas, 1966; Dean et al., 1987) designed to be inserted in access tubes were intended as an alternative to neutron scattering for field applications. However, evaluation of these capacitive instruments (Tomer and Anderson, 1995; Evett and Steiner, 1995) suggest that because of the small measurement volume, variations in soil structure or packing around the access tube can give rise to unacceptable errors. The use of FDR with coaxial probes (CP) for the measurement of dielectric constant has been used in electrical engineering (Atley et al., 1982; Misra, 1987; Fan and Misra, 1990). Results from these studies showed that a network analyzer (NA) is capable of measuring dielectric properties using a metal flanged termination of coaxial cable and such a unit is commercially available (Hewlett Packard, Santa Rosa, CA¹).

The objective of this study is to describe how a network analyzer and a coaxial probe may be used to measure K_a and θ_v in soil and solutions. Although network analyzers have been used to study dielectric properties of soil in the past (Campbell, 1990) by measuring the complex impedance of a waveguide embedded in soil, few if any researchers have reported on the use of CP and NA to measure θ_v in soil.

A coaxial probe has been designed and constructed for dielectric constant measurement and is similar to that of Fan and Misra (1990) but having a spiked extension of the center conductor which pushes easily into soil and extends the measurement volume somewhat. Although capacitance has been calculated in previous FDR studies (Tomer and Anderson, 1995; Evett and Steiner, 1995), it is $K_a^{1/2}$ that is needed for simplified calculation of θ_v (Walley, 1993; Topp et al., 1994; Hook and Livingston, 1996) and dielectric mixing relations (Whalley, 1993; Topp et al., 1994). Phase shift has been deemed more appropriate to use (Arndt and Nguyen, 1996) than capacitance because phase shift is a directly measured number from which $K_a^{1/2}$ and θ_v may be calculated.

Materials and Methods

A vector network analyzer (model HP8712B, Hewlett Packard) was used to measure apparent dielectric constant via a coaxial probe constructed from standard RG-58 coaxial fittings (Amphenol RF Div., Danbury, CT) and a stainless steel washer. The probe has a spike (male connector pin) cemented with epoxy at the end of the center conductor which extends 0.5 cm beyond the flange as shown in Fig. 1. The ground plane flange, consisting of a metal washer that has a diameter of 3.2

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¹Mention of company or product name does not constitute endorsement by the Univ. of Wisconsin-Madison to the exclusion of others.

Abbreviations: CP, coaxial probe; FDR, frequency domain reflectometry; K_a , apparent dielectric constant; K_m , dielectric constants of mixtures; MPS, mean phase shift; MPSA, mean phase shift in air; n , refractive index; NA network analyzer; TDR, time domain reflectometry; t , Kelvin temperature; θ_v , volumetric water content.

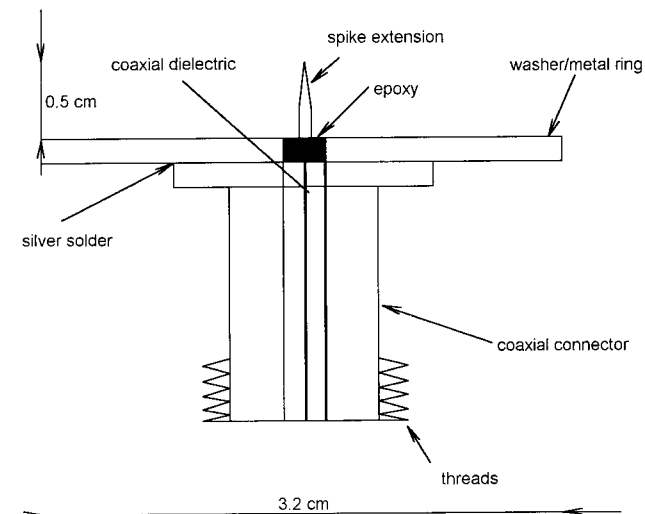


Fig. 1. Schematic of a coaxial probe.

cm attached with silver solder, serves to shield electromagnetic fields, making the probe insensitive to material properties behind the ground plane of the flange. The probe was connected to the network analyzer by RG-8 low loss cable. The analyzer was first calibrated for measurements using a one port reflection calibration (Hewlett Packard, 1995) to read reflection coefficient at the ground plane flange of the probe at a frequency of 795 MHz. The analyzer was set to measure 201 waves. Mean phase shift (MPS) was then calculated using the NA marker math functions.

The probe was tested with several solvents (benzene, acetone, methanol, and ethanol), water at a range of temperatures from 20 to 74°C, and mixtures of benzene-acetone, acetone-water, methanol-water, and ethanol-water. During the sol-

vent and soil testing, the probe was raised and lowered into contact with the sample using a pipette holder. A reading of MPS was taken on a dry probe in air (MPSA) as a reference before placing the probe into the top millimeter of soil or solution. Dielectric constants of mixtures of solvents were calculated with a two component mixing formula:

$$K_m^{1/2} = k_1^{1/2} \theta_1 + K_2^{1/2} \theta_2 \tag{1}$$

where K_m is the calculated dielectric constant of the mixture, K_1, K_2 are the dielectric constants of components, and θ_1, θ_2 are the respective volumetric fractions (calculated from the initial volumes of solvents added to the mixture). Equation [1] represents a natural extension of the three component model of Whalley (1993) for unsaturated soil to a two component system of mixed solutions. In Eq. [1], the refractive index of the mixture is the sum of refractive indices of the components weighted by their respective volume fractions. The refractive index (n) values for reference solvents were taken from Weast et al. (1997). The refractive index is the ratio of the phase velocity of an electromagnetic wave traveling in a vacuum ($3 \times 10^8 \text{ m s}^{-1}$) to the phase velocity in a given substance (Weast et al., 1997). Refractive index equals the square root of the dielectric constant only in substances with negligible conductive and dielectric losses. The apparent dielectric constant (Topp et al., 1980) is the square of refractive index (Whalley, 1993; Kelley et al., 1995) and is called "apparent" because the substance (soil) is assumed for simplicity to have negligible losses. Using this assumption, the coaxial probe calculation of dielectric constant is also simplified and only phase shift measurement is needed for the calculation.

One approach to the calculation (Starr, 1997) assumes a linear relationship between n and the ratio of phase shift in the substance to phase shift in air for plane waves and transverse electromagnetic mode propagation. This approximation, when applied in the coaxial probe geometry, has small systematic

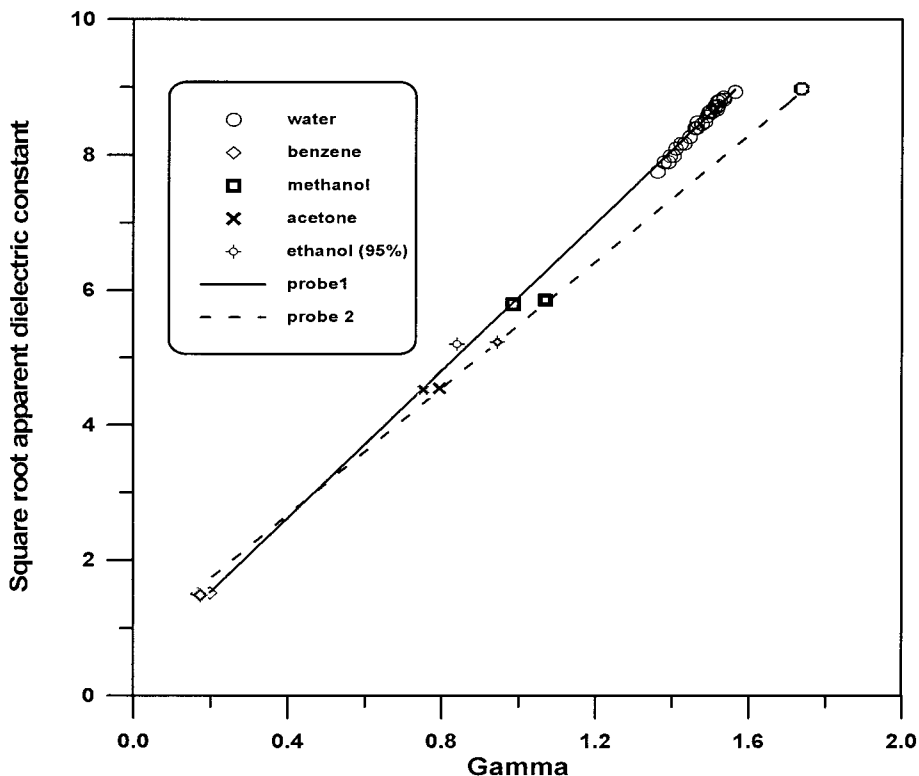


Fig. 2. Linear calibration data for two coaxial probes in known standards.

deviations from linearity (Starr, 1997) that can be mostly eliminated by using a different approach to making the calculation. The relationship between measured phase shift and refractive index for the fixed frequency in this study and fixed probe geometry can be expressed as

$$n = a\gamma + b \tag{2}$$

$$\gamma^2 = -\sin(\text{MPS} - \text{MPSA}) / [\cos(\text{MPS} - \text{MPSA}) + 1] \tag{3}$$

where a and b are constants determined by measurements in standard materials with known refractive index, MPS is the mean phase shift measured by the NA, and MPSA is the MPS measured on a dry probe in air. Figure 2 shows the predicted linearity of the calibration. The slight difference in calibration lines of two probes shown in the figure was probably the result of differences in the amount of epoxy used or some other aspect of their construction. Equations [2] and [3] were derived from the relationship between MPS, capacitive reactance, and dielectric constant for a low loss material. The finer points of this derivation go beyond the scope of this article. The probe in air represents a reasonable approximation to an open circuit at the ground plane of the flange and the calibration fit parameters (a and b in Eq. [2]) account for specific geometry of the probe, connectors, and electrical standards. Calculations from other authors (e.g., Atley et al., 1982; Misra, 1987; Fan and Misra, 1990) are also available. However, our approach allows for the use of inexpensive probes (combined cost of probe hardware and the network analyzer was about \$13 000 USA) and circumvents much of the cost and complexity of implementing the method (for comparison, the HP8070M coaxial probe, 3 GHz measurement system costs about \$43 000 USA, Hewlett Packard, Santa Rose, CA). Soil water content is approximately linear in relation to n measured with TDR (Hook

and Livingston, 1996). By choosing a frequency in the commonly used TDR frequency band, and assuming negligible losses in the calculation, we hoped to observe the same type of linearity.

The C-horizon of Sparta sand (uncoated, mixed mesic Typic Quartzipsamments, 99% sand, bulk density = 1.5 g cm⁻³), B horizon of Griswold (fine-loamy, mixed, mesic Typic Argiudolls, bulk density = 1.23 g cm⁻³, 30% clay, 10% sand), A horizon of Plano (fine-silty, mixed, mesic Typic Argiudolls, bulk density = 1.17 g cm⁻³, 22% clay, 5% sand) and Dubuque (fine-silty, mixed, mesic Typic Hapludalfs, bulk density = 1.04 g cm⁻³, silt loam), and a golf course green mixture (80% sand and 20% peat, referred to as 80-20 mix, bulk density = 1.5 g cm⁻³) were tested. These soils were oven-dried, then packed to approximately the above bulk densities at water contents ranging from 0.02 m³ m⁻³ to 0.49 m³ m⁻³. Oven-dry soil samples of measured weight were mixed with predetermined amounts of de-ionized water and packed into a 150-mL volume in a 500-mL plastic container. Approximately 10 measurements of MPS were made for each water content by moving the probe to different locations on the surface of the sample. Errors caused by flexing the cable or moving the probe were determined by air measurements to be less than about 1 degree MPS. The MPS measurement was referenced to a reading in air, taken before each of the θ_v soil samples or liquids were analyzed.

Apparent dielectric constant of Sparta sand at the same bulk density was also measured with synthesized TDR, resonant waveguide, and conventional TDR (see Starr et al., 1999 for a description of resonant waveguide and synthesized TDR techniques) for comparison. Measurement volume for the MPS method was determined by moving the probe near the edge and bottom of a 300-mL glass beaker of water and noting where the system began to respond to the edge of the beaker.

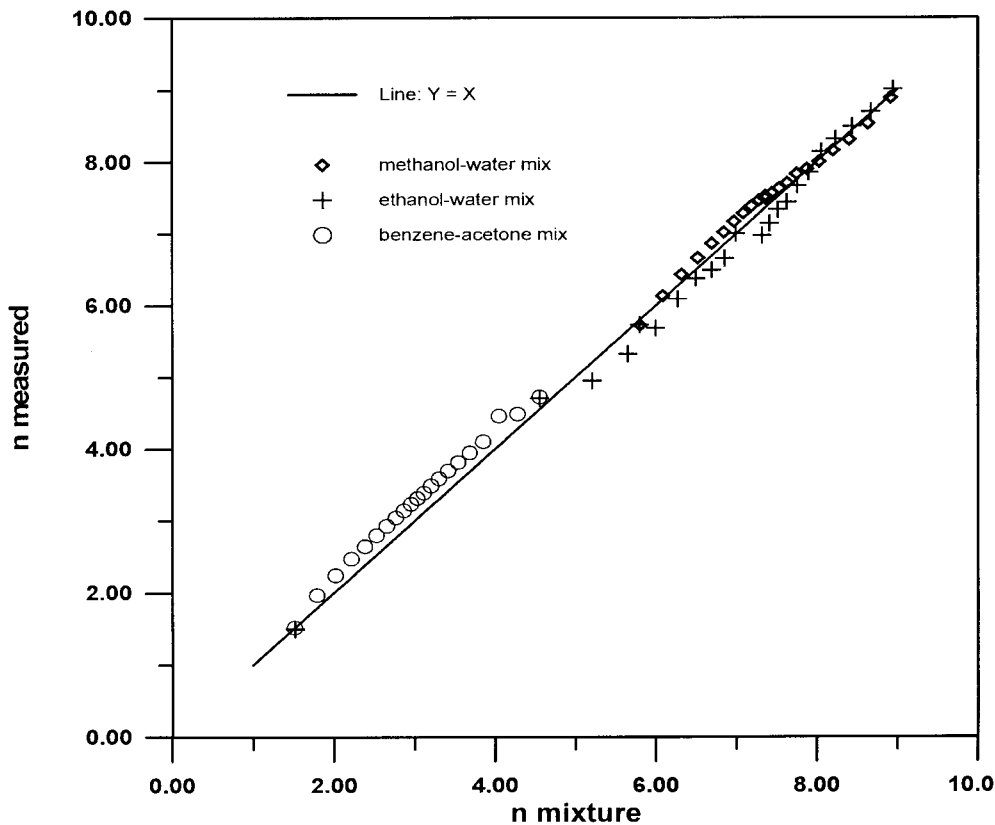


Fig. 3. Measured refractive index ($K_v^{1/2}$) of liquids and air vs. refractive index calculated by a mixing model.

Table 1. Parameters for linear regression of water content vs. refractive index for tested soils.

Soil	RMSE†	Slope	Intercept	R ²	Data points
All data					
All soils	0.039	0.099	-0.11	0.9	305
Griswold	0.032	0.0967	-0.108	0.95	70
Plano	0.027	0.103	-0.135	0.96	68
Dubuque	0.033	0.091	-0.042	0.92	73
Sparta	0.014	0.112	-0.184	0.99	77
8-20 mix	0.012	0.0981	-0.0866	0.99	17
Means					
All soils	0.033	0.0964	-0.101	0.93	33
Griswold	0.026	0.0997	-0.119	0.97	7
Plano	0.027	0.103	-0.139	0.97	7
Dubuque	0.021	0.0965	-0.0534	0.98	7
Sparta	0.0095	0.113	-0.187	0.99	8
80-20 mix	0.0073	0.0988	-0.889	1	4

† RMSE, root mean square error.

A linear regression model was applied to compare measured values of refractive index with values calculated from Eq. [1]. Regression parameters were calculated to assess the linearity of θ_v vs. $K_a^{1/2}$ relationship and to estimate root mean square errors (RMSE) associated with the linear calibrations following the method outlined in Snedecor and Cochran (1989).

RESULTS AND DISCUSSION

A plot of measured n vs. predicted (Eq. [1]) n for solvents and liquid mixtures (Fig. 3) indicated that measured refractive index using the MPS method was in agreement with expected values. The small deviations from the line $Y = X$ appear to be systematic rather

than random (consistently high or low over certain regions and mixtures) and may be caused by model or measurement errors, or by some artifact of the experimental procedure (e.g., temperature or evaporation induced n changes). The two approaches to calculating n agreed to within about 0.2.

Each data point (Fig. 3) is the mean (MPS) of 201 measurements of phase shift with a standard deviation of about 0.5 degree. Standard deviation of 50 repeated measurements of MPS in water is only 0.028 degree when the probe remains fixed. However, moving the probe, cabling or assembly can result in MPS changes of about 1 degree in air. These small errors may be compared with the MPS range between air (about -19 degrees) and water (about -155 degrees) of about 136 degrees between the two extremes of dielectric constant. Calculation of MPS requires less than 1 s and individual phase measurements take less than 10^{-3} s. Although time resolution was not a great concern in this study, it is worth noting that high measurement speed and stability are available with this network analyzer.

A plot of θ_v vs. $K_a^{1/2}$ for the five test soils indicated that all the data fall within a fairly narrow region surrounding the Topp et al. (1980) universal equation (Fig. 4). The approximate linearity of the method is evident from the linear regression parameters and root mean square errors calculated for several ways of approaching the analysis (Table 1). Separate regressions were performed for: all soil data combined (RMSE = $0.039 \text{ m}^3 \text{ m}^{-3}$, $r^2 = 0.90$), all data for individual soils (RMSE = 0.012 to 0.032; $r^2 = 0.95-0.99$), and means of repeated

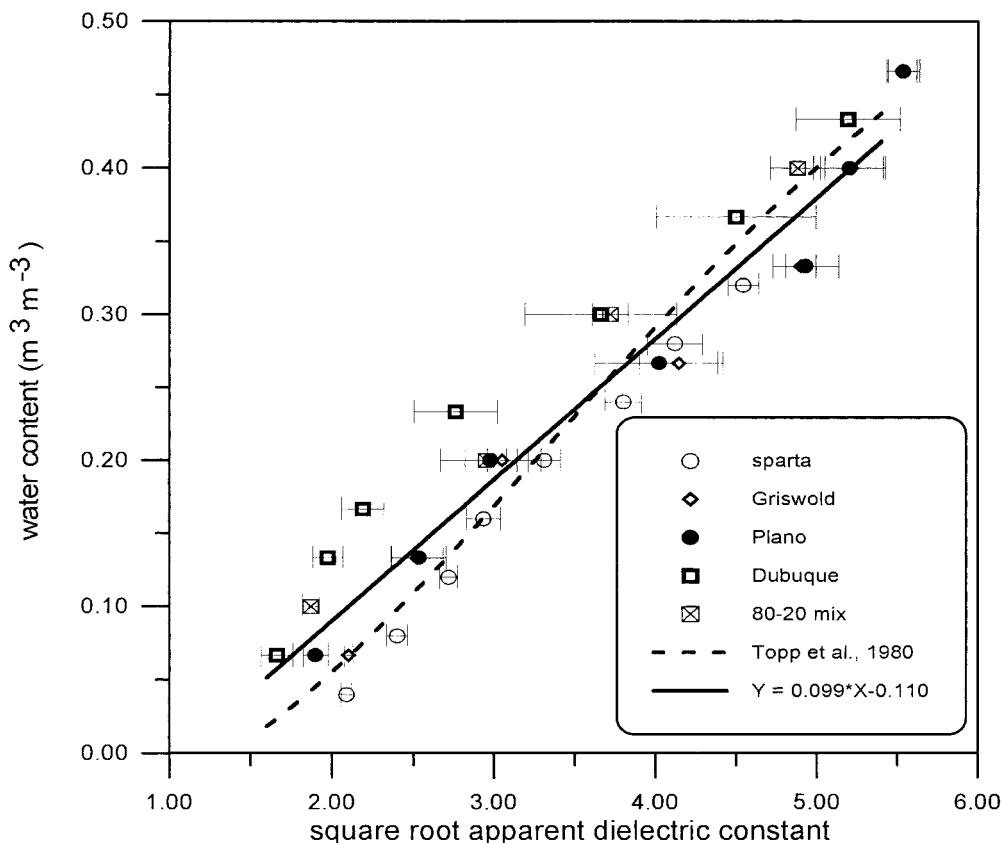


Fig. 4. Water content vs. refractive index for several soils. Data points are the means of about 10 measurements and error bars denote standard deviations.

measurements (RMSE = 0.0073–0.026; $r^2 = 0.97$ –1.00) in individual soils. There was improvement in both the coefficient of determination and RMSE when means of repeated measurements were used instead of individual measurements. Because this measurement is easy to repeat, it is advisable to do this in practice as it reduces the measurement uncertainty. The value of performing individual calibrations is also evident as this improved the RMSE and coefficient of determination.

A comparison between refractive index measured with the MPS method and resonant waveguide, synthesized TDR, and conventional TDR (Fig. 5) showed good agreement in Sparta sand, although two different probes gave slightly different results in dry soil. We had previously measured K_a for Sparta sand at a bulk density of 1.5 g cm^{-3} with synthesized TDR at a center frequency of 650 MHz, resonant waveguide over a band from 520 to 900 MHz, and with conventional TDR at unknown frequency (see Starr et al., 1999, for additional data and analysis). Synthesized TDR, resonant waveguide and TDR measurements for Sparta sand show that θ_v is a linear function of $K_a^{1/2}$ as would be expected for all coarse and medium textured soils (Topp et al., 1994; Hook and Livingston, 1996) and this is in agreement with CP data.

Although an exact determination of the volume of influence is impossible, moving the probe near the bottom of a 300 mL glass beaker filled with water showed that MPS variations in excess of 1 degree were noted when the probe was about 1 cm from the bottom. Similar experiments showed a very high sensitivity near the spiked extension. A hemispherical drop of water sus-

pended from the ground plane and covering the spike extension with a radius of about 0.5 cm caused a refractive index reading of about 70% of the n measured when the probe was fully immersed in water. It is clear that this CP allows for measurement of much smaller samples than is typical for TDR. However, as has been determined in past studies on capacitive probes (Evet and Steiner, 1995), a small measurement volume will result in sensitivity to air gaps and other small scale non-uniformities. By repeatedly measuring at different locations on the surface of a sample and averaging the results, this uncertainty is reduced.

Conclusions

An approach to measuring solution K_a and estimating θ_v has been developed using CP and NA. This approach is useful as a quick, simple measurement on small laboratory samples or in applications where high resolution in both space and time is required. Sensitivity to changes in dielectric constant is good when signal averaging is employed. Soil water content may be linearly calibrated against measured refractive index with the network analyzer on this coaxial probe. The probe was used to measure K_a in a variety of solvents and mixtures showing a 1-to-1 correspondence between measured K_a , and K_a calculated from a two-component mixing model of solution. Results from five soils support data trends previously observed in TDR studies. All soils data fit within a narrow range surrounding the universal equation and the system exhibited considerable linearity in individual calibrations. Averaging repeated measurements on the

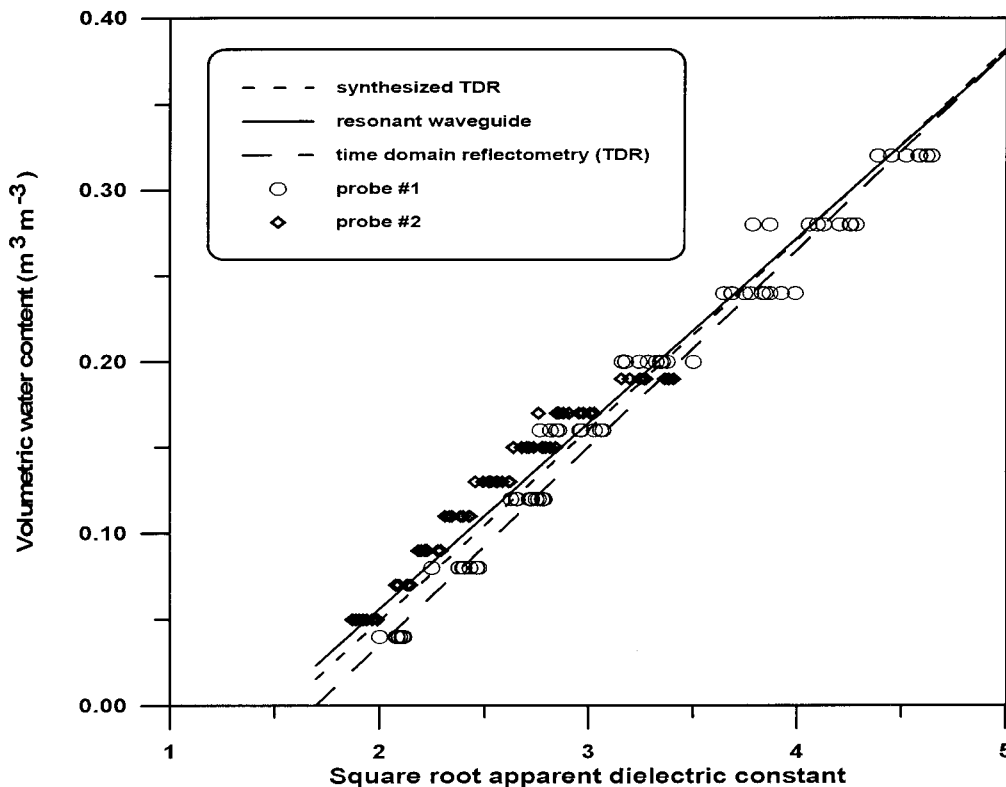


Fig. 5. Refractive index ($K_a^{1/2}$) vs. water content relationship in Sparta sand showing coaxial probe (CP) data and regression lines from other methods including time domain reflectometry (TDR).

surface of samples is advisable because it reduces data scatter and uncertainty associated with the small measurement volume of the probe.

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