

SOIL WATER CONTENT DETERMINATION USING NETWORK ANALYZER REFLECTOMETRY METHODS

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Abstract

Time domain reflectometry (TDR) can be a good automated system for measuring soil water content (θ_v); however, TDR can yield noisy data and cannot measure frequency dependence of the dielectric constant (K_s). Using a network analyzer (NA) with a low-noise synthesized TDR, parallel-rod probes, and a resonant waveguide approach, θ_v was measured from 0.02 to 0.25 m³ m⁻³ within the range of 50 to 900 MHz in sand. Below 100 MHz, K_s was higher than it was within the range of 100 to 900 MHz; however, in the 100 to 900 MHz range K_s did not change with frequency. The NA compared favorably with TDR.

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SOIL SCIENTISTS, ENGINEERS, AND OTHERS have been developing and evaluating new techniques for measuring soil water for over a half century. Following the implementation of neutron and gamma methods (Belcher et al., 1950), there was an hiatus in significant new developments until the introduction of time domain reflectometry (TDR) (Topp et al., 1980). Frequency domain reflectometry (FDR) has been used to study dielectric properties of soil in the past (Smith-Rose, 1933) by capacitive measurements on soil probes, but these methods were never entirely satisfactory because of limitations in technology. Capacitive measurements for soil water content sensing were recently renewed by Hilhorst and Dirksen (1994), who introduced a new design. However, the use of a network analyzer (NA) for such measurements is relatively new. Network analyzers are instruments traditionally used by electrical engineers for measuring reflection and transmission response characteristics of circuit elements as a function of frequency. Campbell (1990) used a NA to study the dielectric properties of soils as a function of frequency by measuring the complex impedance of a waveguide embedded in soil, but the focus of Campbell's study was

Abbreviations: C_p , probe constant; EM, electromagnetic; FDR, frequency domain reflectometry; K_s , dielectric constant; $K_{s(n)}$, dielectric constant at the n^{th} resonant frequency; L_{eff} , effective length; NA, network analyzer; ω_n , n^{th} resonant frequency; STDR, synthesized time domain reflectometry; TDR, time domain reflectometry; θ_v , volumetric soil water content.

not on its potential use to measure volumetric soil water content (θ_v).

Because apparent dielectric constant (K_a) is strongly dependent on soil water content (Topp et al., 1980), any device that measures K_a can be used as a water content sensor. With a NA, many methods have been developed and reported in electrical engineering literature for measuring dielectric properties in different materials. Most of these, however, are laboratory methods requiring carefully controlled conditions. The phase and complex impedance measurement capabilities of what is called a vector NA can be very useful in laboratory studies of frequency dependent dielectric properties of soil (Campbell, 1990) and soil water content (Starr et al., 1997). If a probe is connected to a NA from a remote field location with a transmission line (cable), a measurement of complex impedance or phase shift will have an undesirable sensitivity to bends in the cable and soil water conditions along the cable. Hilhorst and Dirksen (1994) circumvented this problem by building the wave generating and impedance measurement electronics into an integrated circuit mounted directly on the probe with no cable between the electronics and the parallel-rod probes. For a NA, this is not possible because the electromagnetic (EM) waves originate in the instrument and must be transmitted via transmission line to the probe. In field applications, it seems desirable to develop methods and probes that rely on measurement of reflected signal amplitude (rather than phase shift) as a function of frequency for two reasons: a less expensive instrument (a scalar NA) can be used, and the system response to transmission line effects should be minimal.

Resonant frequency methods rely on a measurement of the ratio of reflected to transmitted signal amplitude or reflection coefficient as a function of frequency, which does not require phase information. Resonant frequency approaches were conducted with capacitive probes (Thomas, 1966; Dean et al., 1987; Heathman, 1993) designed to be inserted in access tubes for measuring depth specific θ_v of soil profiles. Although a scalar NA is certainly capable of measuring the resonant frequency of a such a probe, evaluation of this approach (Tomer and Anderson, 1995; Evett and Steiner, 1995) has shown that the measurement volume is so small that sensitivity to soil packing and other small-scale nonhomogeneities in the immediate vicinity of the access tube can cause unacceptable errors. It should also be possible to measure the resonant frequencies of soil waveguides such as the probes (Spaans and Baker, 1993) that are used in this study with a NA and to relate these data to K_a and θ_v .

Much of the Topp et al. (1980) argument that a "universal" calibration equation could be found for TDR is centered around the notion that the frequency range of measurement was 10 MHz to 1 GHz. In addition to the specific measurements found in Topp et al. (1980), many studies of dielectric properties in soil were cited as evidence for the universal equation where the frequency was indeed in this range. The conclusion (Topp et al., 1980) that this was a good frequency band to work TDR measurements because of the low dispersion, high time

resolution, and relatively low wave attenuation appears to be quite valid. With a NA, it is possible to sweep through a preselected band of frequencies, making a series of measurements of reflection coefficient at discrete values of frequency, and from these data a TDR trace may be synthesized (STDR). The inverse Fourier transform technique, a method of adding up the individual sine waves measured by the NA to form a STDR response (Hewlett Packard, 1995), is programmed into the NA microprocessor and can be used by an operator with little or no experience in this complex transformation. The objective of this study was to describe the STDR and resonant waveguide methods and make comparisons with TDR.

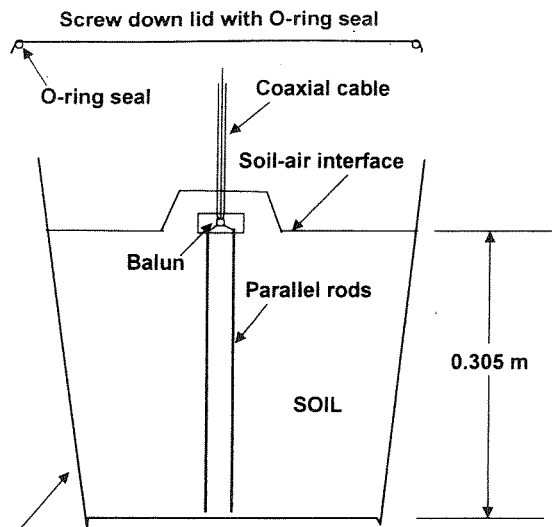
With a network analyzer TDR measurement of K_a , a synthesized, bell-shaped, pulsed waveform is derived from a sweep of selected discrete frequencies, and the location of specific points of reflection are found by searching for maxima in the synthesized reflection trace. Jackson (1975, p. 296-298) describes the propagation of bell-shaped electromagnetic pulses through media with frequency dependent dielectric properties, such as soil, and he details the theory of the Fourier transformation. Provided that the waveform peak is used as a reference, and in the absence of severe distortion of the waveform caused by the attenuation of some frequency components and not others, it may be assumed that K_a is measured at the average (or center) frequency of the range (or band) of frequencies measured. Because the center frequency and the band of frequencies are variable, STDR has a form of versatility that TDR does not have.

Materials and Methods

A Hewlett-Packard HP 8712B (Hewlett-Packard, Santa Rosa, CA)¹ economy vector network analyzer was used in this study, although it should be noted that the measurements described in this section do not require all the capabilities of the HP-8712B. In particular, its abilities to measure phase shift and complex impedance were not used. For comparison, data were collected using a 1502B cable tester (Tektronix Inc., Redmond, OR) as well as a computer for auto-sampling and performing TDR waveform analysis (Baker and Allamaras, 1990; Spaans and Baker, 1993). Network analyzers have a wide range of prices and the instruments are expensive; however, a scalar NA in the frequency range used for this study can be obtained at comparable cost to a TDR cable tester.

Water content standards were established by filling 18.9-L containers with 18.6 L of oven-dried Sparta sand (uncoated, mixed, mesic Typic Quartzipsamments, C horizon, 99% sand) and mixing in predetermined volumes of water. The containers were packed to a bulk density of 1.5 g cm⁻³, which is the in situ bulk density of Sparta sand (Hart, 1992). Water contents were 0.020, 0.060, 0.080, 0.100, 0.120, 0.160, 0.200, and 0.250 m³ m⁻³. The containers (Lab Safety Supply, Janesville, WI) were equipped with O-ring seals that prevented water loss by evaporation (Fig. 1). Parallel-rod TDR probes (Midwest Specialty Services, Minneapolis, MN) were inserted and fully embedded so that their measurement volume extended over the vertical height of the containers. Three probes were in-

¹ Mention of company and/or product does not constitute endorsement by the Univ. of Wisconsin, Madison.



18.6 L of soil

Fig. 1. Schematic of a parallel-rod probe embedded in soil container.

sented in each container to obtain an average measurement of θ_v .

We used the analyzer to locate a discontinuity at the balun (a transmission line circuit element designed to connect coaxial cable to parallel-rod waveguides) and a discontinuity (an open circuit) at the end of the probe. In this respect, the approach and data analysis for STDR are similar to TDR (Spaans and Baker, 1993). The synthesized time domain response is displayed as reflected signal amplitude in decibels (dB) vs. effective length (m) (Fig. 2a, printed directly from the NA). Figure 2b shows the frequency domain response (dB vs. MHz). To generate Fig. 2b the NA swept through a band of frequencies making individual measurements at a series of distinct frequencies on a probe embedded in Sparta sand at θ_v of $0.16 \text{ m}^3 \text{ m}^{-3}$. These data were transformed using the Fourier transform technique (Hewlett Packard, 1995) to give an STDR trace.

In analyzing the data in Fig. 2a, a probe constant (C_p) was subtracted from the distance between the two major reflections, and the resulting distance is effective length (L_{eff}). The distance between maxima were measured with the probe in air, where EM waves travel at the speed of light ($3 \times 10^8 \text{ m s}^{-1}$). With the reference velocity of the NA set to $3 \times 10^8 \text{ m s}^{-1}$, apparent length between balun and probe end is measured. The measured apparent probe length value corresponds to the actual length of the parallel rods plus a length (C_p) associated with EM waves traveling through the balun and probe housing. For example, one probe had a distance between discontinuities of 49 cm in air; however, the waveguide is only 30 cm in length. The difference (19 cm) is C_p (more detail on probe constants and their variability is available in Starr, 1997). A C_p was measured for each probe. Apparent dielectric constant may be calculated from the simple formula:

$$K_a^{1/2} = L_{\text{eff}}/L \quad [1]$$

Apparent dielectric constant was determined by placing a marker on the reflection from the balun and another on the reflection from the probe end, recording the distance between the two, and then calculating K_a . This is shown in Fig. 2a, where the apparent distance between balun and probe end is $1.01 \pm 0.005 \text{ m}$. The center frequency for measurement in Fig. 2a was 650 MHz, and the frequency band was from 300 KHz to 1300 MHz.

To analyze data in Fig. 2b we needed a formula that relates the resonant frequencies, shown as distinct minima in the data,

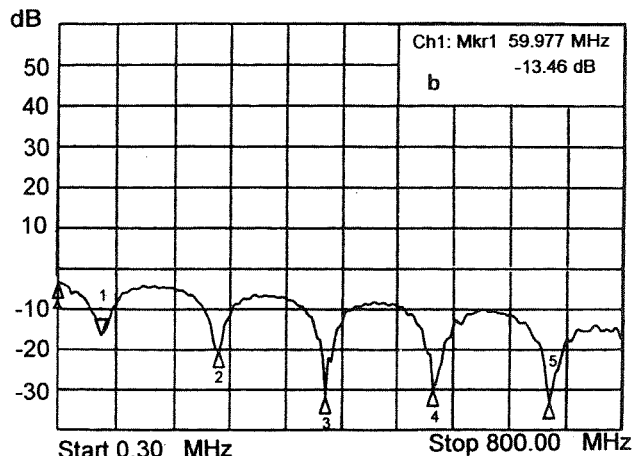
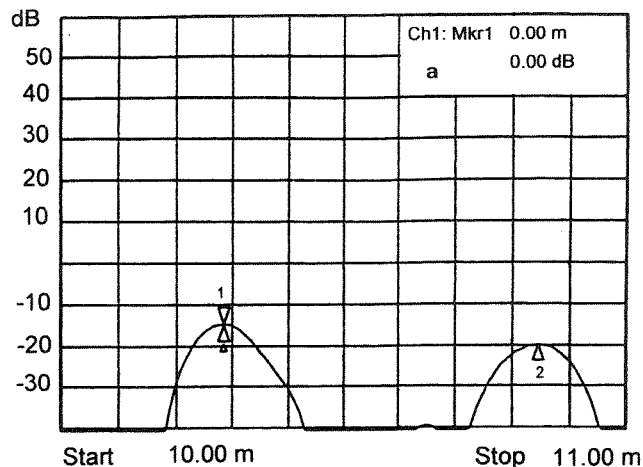


Fig. 2. Graphs printed directly from a network analyzer with markers (Δ) showing the local maxima and minima of (a) synthesized time domain reflectometry data trace in decibels (dB) vs. meters (m), and (b) frequency domain data trace in dB vs. frequency (MHz).

to K_a . This may be obtained by assuming that a resonant frequency is reached when reflections from the balun and probe end are out of phase and destructively interfere with one another. Resonance occurs at a harmonic series of resonant frequencies; however, the exact value of a resonant frequency depends on the value of K_a at that frequency. Analysis of the waves on these parallel-rod probes resulted in the following relation (described in Starr et al., 1999):

$$K_{a(n)}^{1/2} = [\pi + 2\pi n - (2\omega_n C_p/c)] (c/2L\omega_n) \quad [2]$$

where ω_n are the resonant frequencies (rad s^{-1}), c is the speed of light ($3 \times 10^8 \text{ m s}^{-1}$), and $K_{a(n)}$ is the dielectric constant at the n^{th} resonant frequency, and n is an integer ($n = 0, 1, 2, \dots$), indicating the order of the harmonic series, $n = 0$ being the lowest frequency or fundamental resonance, $n = 1$ being the first harmonic, $n = 2$ the second harmonic, and so forth. We were able to measure resonant frequencies up to $n = 4$ and to then calculate $K_{a(n)}$ for each of the resonances, giving an independent measure of K_a over several frequency ranges. Topp et al. (1994) and Hook and Livingston (1996) concluded that a linear model is appropriate for nearly all non-clay soils. A linear regression model was used to derive a $K_a^{1/2}$ vs. θ_v relationship for both STDR and TDR. Confidence intervals for prediction were calculated at the $P = 0.05$ level using the

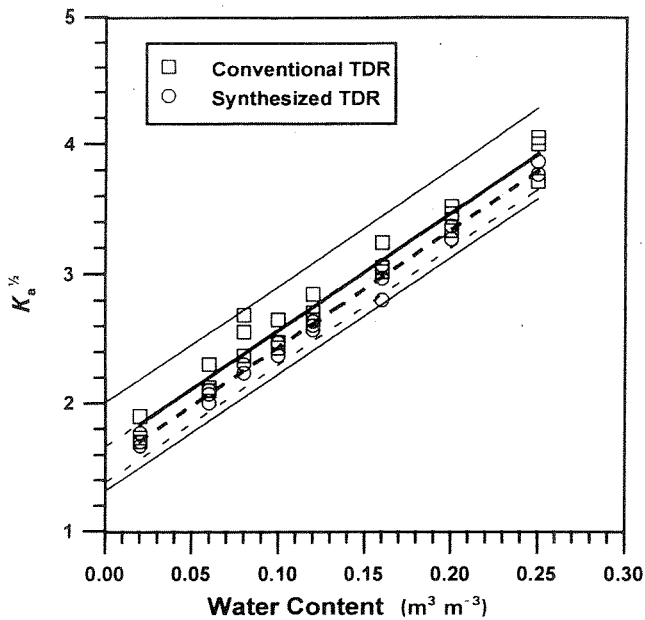


Fig. 3. Synthesized (dashed lines) and conventional (solid lines) time domain reflectometry (TDR) measurement of dielectric constant (K_a) as a function of water content. Regression fits are shown as thick lines, and $P = 0.05$ intervals are shown as thin lines.

method outlined in Snedecor and Cochran (1989). Resonant waveguide measurements of K_a vs. frequency and θ_v were then compared with the STDR regression line and confidence intervals.

Results and Discussion

Using a NA, we have determined resonant frequencies on dual-rod probes designed for in situ TDR measurements of θ_v and have found these to give repeatable and accurate results in sand where the probes were well tuned to resonate, as evidenced by the distinct minima in the frequency domain reflection traces. The ability to preselect a frequency band and the use of the built-in microprocessor functions allowed for greater versatility with this NA for soil water content studies.

A comparison of data generated with STDR and TDR (Fig. 3) showed the expected linearity of $K_a^{1/2}$ vs. θ_v for both methods. The thick dashed line represents a linear regression fit to measurements from three probes, while the thin dashed lines denote the $P = 0.05$ interval for predictions based on a single STDR measurement. Thick and thin solid lines represent fit and $P = 0.05$ intervals, respectively, for a single measurement with TDR. Although the confidence intervals overlap, indicating agreement between STDR and TDR, the $P = 0.05$ intervals were about half as wide for STDR measurements.

Conventional TDR was computer-automated for data reduction, but the analysis of a TDR trace requires finding two inflection points. This determination of inflection points is susceptible to electronic noise that is much more prevalent with TDR and is at least part of the reason for the increased data scatter. With STDR, a probe constant was measured for each probe used; a sample of nine probes had a mean C_p of 10.9 cm and a

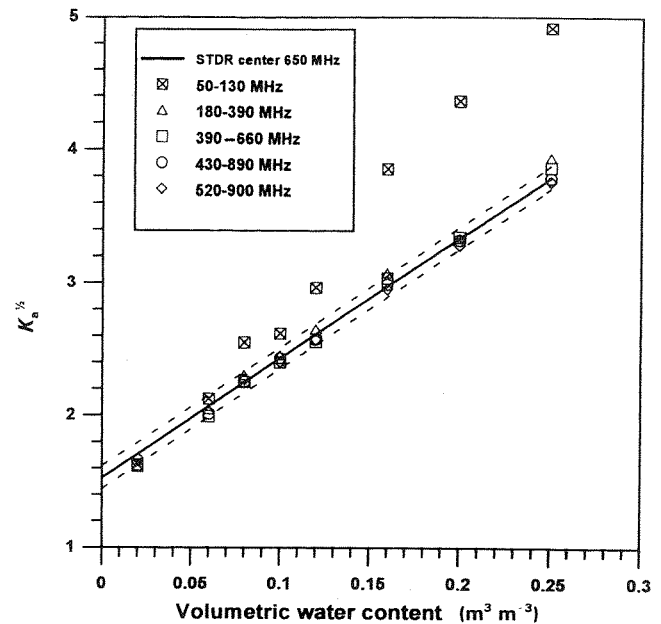


Fig. 4. Dielectric constant (K_a) as a function of water content data for five frequency (MHz) bands, synthesized time domain reflectometry (STDR) regression line (solid), and $P = 0.05$ interval (dashed line) for the average of three trials.

standard deviation of 4.2 cm. Although the same probes were used to generate TDR data, attempts to use individual probe constants for the TDR analysis only broadened the $P = 0.05$ interval for prediction, so the manufacturer-recommended C_p of 6.9 cm was used for TDR.

A linear calibration model was assumed in the regression analysis, and a coefficient of determination of $R^2 = 1.0$ for STDR and $R^2 = 0.97$ for TDR both support the hypothesis of a linear model. Equations [3] and [4] represent the relationship between θ_v and K_a in Sparta sand as measured by STDR and TDR, respectively.

$$\theta_v = 0.109K_a^{0.5} - 0.165; \text{STDR} \quad [3]$$

$$\theta_v = 0.107K_a^{0.5} - 0.172; \text{TDR} \quad [4]$$

The Topp et al. (1980) "universal" calibration lies within the $P = 0.05$ intervals of both TDR and STDR measurements for Sparta sand.

The raw data for ω_n were analyzed with Eq. [2], and a measure of $K_{a(n)}$ vs. water content (Fig. 4) showed the frequency dependence of measured dielectric constant. Each data point is an average of three measurements which use the same three probes used to generate Fig. 3. We were able to track five resonances ($n = 0, 1, 2, 3, 4$) in this experiment, which gave measures of K_a within the five frequency bands given in Fig. 4. Above 900 MHz, the raw data contained too much noise to track resonances. The regression fit (solid line) for STDR data had a narrow $P = 0.05$ interval (dashed lines) for an average of three measurements.

The percentages of resonant waveguide data points that fell within the $P = 0.05$ interval of STDR were 25%, 63%, 88%, 100%, and 100% for $n = 0, 1, 2, 3, 4$, respectively. The STDR and resonant waveguide measures of K_a agreed quite well for all but the lowest frequencies. A higher K_a at frequencies below ≈ 100

MHz was observed. It appears that K_a was independent of frequency in the range of ≈ 100 to ≈ 900 MHz because the data in this range had no clear deviation. Because the STDR waveforms (Fig. 2a) did not show any dramatic distortion in this sandy soil, we suspect that STDR measured K_a near the center frequency of 650 MHz. It is interesting to note that the $n = 3, 4$ waveguide resonances, with frequencies between 430 and 900 MHz (average of 665 MHz), had the best agreement with STDR.

Summary and Conclusions

Synthesized TDR is an extension in the technology of FDR, and breakthroughs made with TDR over the last two decades may be furthered with STDR. In addition, studies may be conducted that take advantage of the capabilities of a network analyzer to measure dielectric properties as a function of frequency, which could not be done easily using TDR. The low-noise network analyzer-STDR method compared favorably with TDR. Using a waveguide resonance approach, K_a was derived as a function of frequency and θ_v . The $n = 0, 1, 2, 3, 4$ harmonic resonances with frequencies in the range 100 to 900 MHz showed measures of K_a that were substantially independent of frequency and agreed with STDR measurements at a center frequency of 650 MHz, and with TDR. A significantly higher K_a at frequencies lower than ≈ 100 MHz was noted.

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