

Dielectric Loss and Calibration of the Hydra Probe Soil Water Sensor

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ABSTRACT

Widespread interest in soil water content (θ , $\text{m}^3 \text{m}^{-3}$) information for both management and research has led to the development of a variety of soil water content sensors. In most cases, critical issues related to sensor calibration and accuracy have received little independent study. We investigated the performance of the Hydra Probe soil water sensor with the following objectives: (i) quantify the inter-sensor variability, (ii) evaluate the applicability of data from two commonly used calibration methods, and (iii) develop and test two multi-soil calibration equations, one general, "default" calibration equation and a second calibration that incorporates the effects of soil properties. The largest deviation in the real component of the relative dielectric permittivity (ϵ'_r) determined with the Hydra Probe using 30 sensors in ethanol corresponded to a water content deviation of about $0.012 \text{ m}^3 \text{m}^{-3}$, indicating that a single calibration could be generally applied. In layered (wet and dry) media, ϵ'_r determined with the Hydra Probe was different from that in uniform media with the same water content. In uniform media, θ was a linear function of $\sqrt{\epsilon'_r}$. We used this functional relationship to describe individual soil calibrations and the multi-soil calibrations. Individual soil calibrations varied independently of clay content but were correlated with dielectric loss. When applied to the 19-soil test data set, the general calibration outperformed manufacturer-supplied calibrations. The average θ difference, evaluated between $\epsilon'_r = 4$ and $\epsilon'_r = 36$, was $0.019 \text{ m}^3 \text{m}^{-3}$ for the general equation and $0.013 \text{ m}^3 \text{m}^{-3}$ for the loss-corrected equation.

KNOWLEDGE OF SOIL-WATER CONTENT (θ , $\text{m}^3 \text{m}^{-3}$) is critical for determination of local energy and water balance, transport of applied chemicals to plants and groundwater, irrigation management and precision farming. Time domain reflectometry (TDR) is generally regarded as the best available electronic technique for the determination of θ . Time domain reflectometry instruments use measured pulse travel times to determine the apparent soil dielectric permittivity (ϵ_a), which is then related to θ using a calibration equation. In most TDR applications it is assumed that ϵ_a is effectively equal to the real component of the relative complex dielectric permittivity of the soil (Topp et al., 2000). Extensive testing has shown that a single, "universal" calibration equation, developed by Topp et al. (1980), is reasonably accurate for many soils (Ledieu et al., 1986; Noborio, 2001; Robinson et al., 2003). The high cost of TDR and difficulties associated with the required waveform analysis (Wraith and Or, 1999; Evett, 2000) have led to the development of alternative soil water sensors that

also use soil dielectric properties to determine θ . These alternative sensors have received relatively little independent study; and critical practical issues related to calibration methodology and application have not been addressed.

The Hydra Probe is an example of the alternative sensors now available.¹ It is currently in widespread use (e.g., the Soil Climate Analysis Network of the Natural Resource Conservation Service) and has proven to be robust under a variety of field conditions. Previous research demonstrated that Hydra Probe measurements are precise and accurate in fluids with known dielectric properties and highly correlated with θ in soils, indicating the potential of the instrument for quantitative measurement (Seyfried and Murdock, 2004). It was also found that the calibration relationship varied considerably among soils and that the manufacturer-supplied calibrations were not accurate for some soils. Important practical considerations regarding the use of the Hydra Probe remain. These include: (i) the degree of variation in response among different sensors (i.e., the inter-sensor variability), which determines if sensor specific calibrations are required, (ii) the optimal experimental methodology for determining the calibration relationship, and (iii) the effects of soil properties on that relationship.

There are at least two basic methods used for laboratory calibration of these sensors. The more commonly used method, which we refer to as the mixed-cell method, uses measurements made in cells containing soil mixed with different known amounts of water to provide distinct points describing the relationship between the dielectric permittivity and θ (e.g., Dirksen and Dasberg, 1993; Hook and Livingston, 1995). This method often results in variable bulk densities, relatively few measurement points, and is time consuming. The other method, which we refer to as the infiltration-addition method, was described by Young et al. (1997). In it, water is added to dry soil from the bottom of a measurement cell and the water content of the entire cell (θ_{cell}) is calculated from the known cell volume and the weight of added water. The infiltration-addition method has the advantages of being rapid, providing more data within the full range of θ and, when there is little swelling, a constant bulk density. In using this method, it assumed that the sensor responds to the average water content within the sensing volume, independent of the distribution of water within that volume even though there is usually a sharp wetting front separating nearly saturated and dry soil.

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¹ Mention of manufacturers is for the convenience of the reader only and implies no endorsement on the part of the author or the USDA.

Abbreviations: CI, confidence interval; CV, coefficient of variability; DI, deionized; TDR, time domain reflectometry.

Previous work with TDR (Topp et al., 1982; Young et al., 1997) has shown this to be a good assumption. However, recent work (Chan and Knight, 2001; Schaap et al., 2003), also with TDR but considering different measurement frequencies, indicates that the effective ϵ_a measured in a layered medium depends on the thickness of the layers relative to the measurement wavelength. Applying their findings to an infiltration addition experimental conditions with a measurement cell of length l , a wetted portion of length l_w and permittivity ϵ_w , and a dry portion of length l_d and permittivity ϵ_d ,

$$\epsilon_a = \frac{l_w}{l}\epsilon_w + \frac{l_d}{l}\epsilon_d \quad [1]$$

applies if the measurement wavelength is greater than four times the thickness of the layers and

$$\sqrt{\epsilon_a} = \frac{l_w}{l}\sqrt{\epsilon_w} + \frac{l_d}{l}\sqrt{\epsilon_d} \quad [2]$$

applies otherwise. The measurement frequency of the Hydra Probe corresponds to a wavelength of 6 m, much more than four times the layer thickness within the measurement cell. If Hydra Probe response is consistent with this analysis, then the measured dielectric properties within an infiltration-addition cell will be the arithmetic average of the wet and dry layers, and a linear relationship (Eq. [1]) will result. Otherwise, a curvilinear (Eq. [2]) relationship will be observed.

Deviations in soil calibrations from the Topp equation using TDR are often associated with high clay content (Jacobsen and Schjonning, 1993) and it is commonly assumed that Hydra Probe (and other sensor) calibration variations among soils will be similarly associated with soil texture. This is reflected in the manufacturer-supplied calibration equations (Vitel, Inc., 1994), which are labeled “sand”, “silt” and “clay”, with the intention that they be applied to different soils depending on texture. However, it is known that two properties that may affect soil dielectric properties, the ion exchange capacity and specific surface area (Or and Wraith, 1999; Evett, 2000), vary considerably with clay mineralogy (e.g., Sposito, 1989), suggesting that texture alone may not be an effective means of categorizing soils for calibration purposes.

Although it is understood that highly accurate determination of θ requires a soil-specific calibration, a more accurate, general calibration equation would greatly facilitate use of these sensors for a number of applications in much the way that the Topp equation has served TDR. Alternatively, a calibration approach that incorporates the effects of soil properties may serve the same purpose but with added precision. This study was intended to improve the application and interpretation of Hydra Probe data, and to some extent, that of other alternative sensors, by addressing basic calibration issues. Specifically, our objectives were to: (i) quantify the inter-sensor variability, (ii) determine the proper interpretation of calibration data collected using the infiltration-addition method, and (iii) develop and test two calibration approaches, one to provide a general,

“default” calibration equation and the other incorporating the effects of soil texture and/or other soil properties on the calibration relationship.

MATERIALS AND METHODS

Hydra Probe Description

Conceptual Background

The dielectric permittivity of a material (e.g., soil) is, in general, complex and evaluated relative to the free space permittivity (ϵ_0) so that

$$\epsilon_r^* = \frac{\epsilon^*}{\epsilon_0} \quad [3]$$

and

$$\epsilon_r^* = \epsilon_r' - j\epsilon_r'' \quad [4]$$

where ϵ^* is the complex dielectric permittivity, ϵ_r^* is the relative complex dielectric permittivity, ϵ_r' is the real component of ϵ_r^* , ϵ_r'' is the imaginary component of ϵ_r^* and $j = \sqrt{-1}$. The real component is related to the amount of energy stored in a material as molecules shift alignment in an alternating electronic field. The ϵ_r' of water is practically constant at constant temperature within the measurement frequencies commonly used for soil water content measurement (10–1200 MHz) and is much greater than the ϵ_r' of solid soil constituents (4–7) or air (1). These differences are the basis for the dielectric approach to measuring soil water content. It has been noted, however, that the ϵ_r' of soil-water mixtures may increase with decreasing measurement frequency within the 10 to 1200 MHz range (Hoekstra and Delaney, 1974; Campbell, 1990; Saarenketo, 1998).

The imaginary component, sometimes called the loss factor, is related to the energy lost to a similarly exposed material in an alternating electronic field. Dielectric losses can be attributed to two basic processes, electrical conduction and molecular relaxation (Topp et al., 2000; Robinson et al., 2003). These are related to ϵ_r'' as follows,

$$\epsilon_r'' = \epsilon_{r,mr}'' + \left(\frac{\sigma}{2\pi f\epsilon_0} \right) \quad [5]$$

where $\epsilon_{r,mr}''$ is the relative permittivity due to molecular relaxation, σ is the low frequency (dc) electrical conductivity, and f is the measurement frequency. The magnitude of the loss factor relative to ϵ_r' , known as the loss tangent ($\tan \delta$) is a useful measure of the impact of ϵ_r'' on measurements and is defined as:

$$\tan \delta = \frac{\epsilon_r''}{\epsilon_r'} \quad [6]$$

Soil properties that enhance electrical conductivity, such as soluble salts or exchangeable ions, result in an increased ϵ_r'' . Similarly, soil properties that cause molecular relaxation of soil water, which are often associated with strong interactions between the soil surface and the solution (Or and Wraith, 1999), also result in an increased ϵ_r'' . Where there is molecular relaxation, both ϵ_r' and ϵ_r'' are affected. Note that the contribution due to electrical conductivity is inversely proportional to f . In addition, $\epsilon_{r,mr}''$ may be frequency dependent within the measurement frequency range, increasing with decreasing f (Hoekstra and Delaney, 1974; Or and Wraith, 1999).

The frequency dependence and sensitivity of ϵ_r'' to soil properties has important implications for the calibration of relatively low frequency instruments like the Hydra Probe. Most

TDR applications implicitly assume that $\epsilon'_r \gg \epsilon''_r$ or $\tan \delta \ll 1$ (Topp et al., 2000), which turns out to be a good approximation for many soils (Heimovaara, et al., 1994). Due to the dependence of ϵ''_r and, to a lesser extent, ϵ'_r on f , this assumption is less applicable to Hydra Probe measurements ($f = 50$ MHz) than to TDR ($f \approx 1000$ MHz).

Measurement Approach

The design and measurement approach behind the Hydra Probe are based on the work of Campbell (Campbell, 1988, 1990). When a voltage is applied to a coaxial probe, the reflected signal is related to the probe impedance (Z_p) such that

$$\frac{Z_p}{Z_c} = \frac{1 + \Gamma}{1 - \Gamma} \quad [7]$$

where Z_c is the characteristic impedance of the coaxial cable (determined independently) and Γ is the complex ratio of the reflected voltage to the incident voltage. Under these conditions, the probe impedance is determined by the characteristic impedance of the probe itself (Z_0) and the ϵ_r^* of the media in the sensing volume (e.g., soil). These are related by

$$Z_p = \frac{Z_0}{\sqrt{\epsilon_r^*}} \cot \operatorname{anh} \frac{\omega L \sqrt{\epsilon_r^*}}{c} j \quad [8]$$

where Z_p is the probe impedance, L is the electric length of the probe, and c is the speed of light (Campbell, 1990). By inverting Eq. [8], ϵ_r^* (and therefore ϵ'_r and ϵ''_r) can be solved for given the measured reflected voltages. Note that the value of ϵ_r^* obtained in this way does not distinguish between $\epsilon_{r, \text{mr}}^*$ and σ .

Sensor Description

The Hydra Probe consists of a 4-cm diameter cylindrical head which has four, 0.3-cm diameter tines that protrude 5.8 cm. These are arranged such that a centrally located tine is surrounded by the other three tines in an equilateral triangle with 2.2-cm sides. A 50 MHz signal is generated in the head and transmitted via planar waveguides to the tines, which constitute a coaxial transmission line. In addition, the Hydra Probe has a thermister embedded in the head to measure temperature.

The raw signal output is four analog dc voltages that are

transmitted to a data logger (or other voltage measuring device). Manufacturer-supplied software uses the first three voltages to calculate ϵ'_r and ϵ''_r and the fourth to calculate temperature. The following parameters are derived from this basic information: temperature corrected ϵ'_r and ϵ''_r , soil water content, soil salinity, soil conductivity and temperature-corrected soil conductivity. The calculation of each derived parameter relies on assumed relationships, for example, between ϵ'_r and temperature, which do not necessarily apply to all soils. In this paper we focus on the calibration relationship used to convert the Hydra Probe-determined ϵ'_r to soil water content. The manufacturer supplies three such relationships intended to cover different soil types according to texture (Vitel, Inc., 1994).

Experimental Procedures

Inter-sensor variability

In order to determine inter-sensor variability we tested 30 sensors in four different fluids of known ϵ'_r . By using fluids we eliminated sensor-media contact as a possible source of variability. The four fluids used were air; distilled, deionized (DI) water; ethanol; and 0.001 M KCl. Each sensor was read 14 to 16 times in each fluid. All tests were conducted at room temperature.

Soil Water Content Calibration

Twenty soil samples were taken from a total of 12 soil profiles (Table 1). Samples were selected primarily to represent a wide range of textures, but given the wide geographic distribution of the soils used, a wide range of other soil properties, such as mineralogy, is also represented. For example, clay content ranged from 3 to 63% and sand content ranged from 2 to 88%. In some cases, multiple samples from the same soil profile, representing different textures, were used. In these cases the soil is identified by the soil name and depth it represents. For example, the Tunica 20 and Tunica 50 samples were collected from the same soil profile but at depths of 20 and 50 cm, respectively. All soils except the Breaks were sampled by the NRCS and are part of the SCAN network. One organic soil, Mansfield, is included. Full characterization is available from the NRCS except for the Breaks, Little Washita, and Fort Reno soils.

The infiltration-addition method was applied to all soils.

Table 1. Properties of soils tested.

NRCS ID	State	Site	Depth	Clay	Sand	Mineral†	Horizon
			cm	%	%		
2030	AR	Lonoke Farm	20	15.1	7.6	ND	A
2026	AZ	Walnut Gulch	10	11.7	70	ND	A
			25	22.4	48.2	ND	Bk1
			50	21	40.4	ND	Bk2
2013	GA	Watkinsville	5	10.8	73.8	KK	Ap1
			50	63.2	25.4	GI, KK	Bt1
	ID	Breaks	30	17	59	ND	A3
2010	MS	Newton (21)	10	6.3	45.5	KK, VR	Ap
			20	6.4	49.6	ND	E
2033	MS	Onward (25)	5	27.8	6.2	MT	Ap
			20	35.8	3.8	ND	Bg
			50	10.9	21.7	ND	Bw
	MS	Tunica (26)	20	30.8	27.4	MT	A1
			50	42.7	1.5	MT	BgB1
	OK	Little Washita	50	20.4	26.4	ND	ND
2041	VT	Mt. Mansfield	0-3			Organic	Oi
2027	GA	Little River	5	2.8	88.1	ND	Ap
	OK	Fort Reno	10	15	67	ND	Ap
			50	35	47	ND	Bt
2031	IA	Ames	5	36	17.6	MT	A

† Dominant clay mineral, ND = not determined, KK = kaolinite, GI = gibbsite, VR = vermiculite, MT = montmorillonite.

Three replicates of each soil sample, oven dried at 105° for 18 to 24 h, were packed uniformly into a plexiglas Tempe cell 6.0-cm high with an inside diameter of 5.1 cm. At the lower boundary, the ceramic plate was replaced with a plexiglas disk of equivalent thickness drilled with many fine holes and covered with filter paper. The surface was covered with parafilm to prevent evaporation and the sensor was placed vertically (tines inserted downward from the top) into the cell. Distilled, deionized water was added from below until glistening at the surface indicated that the soil was effectively saturated. The three replicates were run simultaneously. Cell soil water content (θ_{cell} , $\text{m}^3 \text{m}^{-3}$) was determined from the weight change in the source flask, which was placed on a recording balance. For high hydraulic conductivity soils, water was added via a pump. In most cases, water entered via gravity (i.e., the water source was placed above the soil sample). All data were collected and stored on a data logger. Bulk density (BD, kg m^{-3}) and saturated water content (θ_{sat} , $\text{m}^3 \text{m}^{-3}$) were determined at the end of each run after oven drying at 105° C for 18 to 24 h. Samples were usually allowed to equilibrate for 12 to 48 h after each run and practically no change in dielectric values was observed. Somewhat surprisingly, none of the soils tested exhibited a large amount of swelling during the tests. Height changes did not exceed about 1 to 2 mm, which was difficult to accurately quantify. Because this had little impact on the results, it was ignored.

In order to determine the effective instrument response to the layered cell environment produced by the infiltration-addition method, we performed infiltration-addition experiments using the system described above with no soil. The water-air system will result in a linear $\epsilon'_r(\theta_{\text{cell}})$ relationship with a slope of $\epsilon_w - 1$ if Eq. [1] describes the effective response. If Eq. [2] describes the relationship the $\epsilon'_r(\theta_{\text{cell}})$ relationship will be curvilinear ($\sqrt{\epsilon'_r} = f(\theta_{\text{cell}})$). Schaap et al. (2003) conducted similar experiments with TDR and showed that ϵ_a measured with TDR was nonlinear with respect to θ_{cell} , with values consistent with Eq. [2].

We then determined the $\epsilon'_r(\theta)$ relationship for soils in well mixed conditions more representative of field conditions. Three soils that exhibited a wide range of $\epsilon'_r(\theta_{\text{cell}})$ response observed using infiltration-addition method, the Tunica 20, which had a high response, the Lonoke, which had an intermediate response, and the Newton 10, which had a low response. In each case we mixed predetermined amounts of water to oven-dry soil to obtain a range of water contents. Each test was duplicated.

We note that, although oven-dry samples are sometimes used when determining the $\epsilon'_r(\theta)$ relationship (e.g., Hook and Livingston, 1995; Wraith and Or, 1999), oven drying may alter soil dielectric properties, thus creating a measurement artifact. At this point, however, we are not aware of studies documenting or quantifying this impact.

Data Analysis

We used linear regression and visual analysis to determine whether Eq. [1] or [2] described the effective ϵ'_r response measured by the Hydra Probe in the layered, water-air system or for the well-mixed soils. Results from the well-mixed soils determined the functional relationship (linear or proportional to $\sqrt{\epsilon'_r}$) for individual soil calibration equations. This relationship was fit to the oven-dry and saturated data, measured in triplicate, during the infiltration-addition experiments. This two-point calibration procedure, similar to that suggested by Topp and Reynolds (1998), eliminated complications stemming from interpretation of intermediate values determined

from the infiltration-addition experiments. The result was a single individual soil calibration relationship for each soil.

A baseline equation was developed to use as a reference for comparing different individual soil calibrations. The equation is based on the refractive index model presented by Herkelrath et al. (1991) and widely used in various forms for TDR calibration (Roth et al., 1990; Whalley, 1993; Hook and Livingston, 1995; Yu et al., 1999). This equation may be written:

$$\sqrt{\epsilon'_r} = \theta\sqrt{\epsilon_w} + \theta_s\sqrt{\epsilon_s} + \theta_g\sqrt{\epsilon_g} \quad [9]$$

where θ ($\text{m}^3 \text{m}^{-3}$) is the volumetric fraction and ϵ the relative real permittivity of soil constituents denoted by the subscripts, “w” for water, “g” for gas, and “s” for solids. (The “ θ ” symbol, without subscript, is used to denote soil water content, consistent with the text). Note that $\epsilon_g = 1$, $\theta_s = \text{BD}/\text{PD}$, with PD the particle density (assumed to be 2650 kg m^{-3}) and $\theta_g = 1 - \text{BD}/\text{PD} - \theta_w$. For the baseline equation, we considered only the real component of complex permittivity, as is often assumed with TDR, and used typical values of $\epsilon_w = 80.2$, $\epsilon_s = 5$ and a bulk density of 1460 kg m^{-3} . It is expected that the calibrations of low dielectric loss soils, as measured at 50 MHz, will be closely approximated by the baseline equation, while those with substantial dielectric loss (i.e., high ϵ''_r) will yield ϵ'_r values exceeding the baseline equation for a given θ .

For purposes of calibration, θ is expressed as a function of ϵ'_r . The basic calibration relationship of the form

$$\theta = A\sqrt{\epsilon'_r} + B \quad [10]$$

has been widely applied to TDR (Ledieu et al., 1986; White et al., 1994; Spaans and Baker, 1996). Deviations of individual soil calibration equations from the baseline equation were quantified by the average θ difference ($\Delta\theta_{\text{avg}}$) between each individual soil calibration equation and the baseline equation integrated from $\epsilon'_r = 4$ to $\epsilon'_r = 36$, which approximates the full range of θ in most soils. These calculated $\Delta\theta_{\text{avg}}$ values were then related to parameters such as clay content to quantify their effect on the calibration.

Note that Eq. [9] can be rearranged into the following form consistent with Eq. [10],

$$\theta = \frac{\sqrt{\epsilon'_r}}{\sqrt{\epsilon'_{w,a}} - 1} + \frac{(\text{BD}/\text{PD})(1 - \sqrt{\epsilon'_{s,a}}) - 1}{\sqrt{\epsilon'_{w,a}} - 1} \quad [11]$$

where subscript “a” has been added to indicate that these values are not independently measured but obtained by curve fit of the data and are therefore estimates subject to the limitations inherent in Eq. [9]. The advantages of Eq. [11] are that it incorporates the effect of BD and allows for a differentiation of ϵ_w and ϵ_s as possible sources of variation among calibrations.

Multi-soil calibration equations, intended to describe a wide range of soils, were derived from the data set. These relationships were compared with three manufacturer-supplied calibration equations. The effectiveness of these equations was evaluated on the data set described above and additional data from four soils obtained from a different study and described by Seyfried and Murdock (2004). The degree of fit between the multi-soil equations and individual calibration equations was evaluated using the $\Delta\theta_{\text{avg}}$ evaluated between $\epsilon'_r = 4$ and $\epsilon'_r = 36$.

RESULTS

Inter-sensor Variability

The overall precision and accuracy of the Hydra Probe sensors was good (Table 2), in agreement with previous

Table 2. Measured ϵ_r accuracy and inter-sensor variability with 30 Hydra Probe sensors.

Media	Maximum	Minimum	Average	SD	CV	Standard
						%
Air	1.53	1.05	1.29	0.12	9.3	1
Deionized water	80.97	72.63	78.27	1.88	2.4	78.54†
Ethanol	24.19	22.32	23.47	0.45	1.9	24.3†
0.001 M KCl	80.68	76.86	79.10	0.87	1.1	78.54†

† Standard values from Weast (1986).

findings (Seyfried and Murdock, 2004). Individual sensor measurements in air had the highest coefficient of variability (CV), with the maximum being 1.5%. In general, the CV for individual sensors was <1% in air, <0.3% in ethanol and <0.1% in DI water and 0.001 M KCl. In terms of accuracy, the largest deviation of the overall mean from the standard handbook value (Weast, 1986) was 0.56 dielectric units measured in 0.001 M KCl (Table 2).

Partly due to the high precision and relatively large number of measurements, there were significant ($\alpha = 0.05$) differences among sensors in all media. However, with the exception of two readings in DI water, average values were close to the overall mean. For air measurements, the largest deviation from the mean was 0.24 dielectric units, for DI water it was 5.64 dielectric units, for 0.001 M KCl it was 2.14 dielectric units and for ethanol it was 1.15 dielectric units. In DI water, two sensors gave exceptionally low readings, between 72 and 73, resulting in the relatively large deviation from the mean. A similar deviation is not apparent from these sensors in the KCl solution. The overall CV of average values for the 30 sensors was <2.5% except in air.

We put these data in the context of soil water measurements by considering the ethanol data, which lie within the ϵ_r range measured in soil. If we apply the general calibration equation developed later in this text, the overall average ϵ_r corresponds to a θ of $0.351 \text{ m}^3 \text{ m}^{-3}$, which compares with $0.359 \text{ m}^3 \text{ m}^{-3}$ for the standard value. In terms of individual sensor precision, the 95% confidence interval (CI) about the mean of the least precise sensor was $0.0048 \text{ m}^3 \text{ m}^{-3}$ and the 95% CI of 28 of the 30 sensors corresponded to water contents of $<0.0004 \text{ m}^3 \text{ m}^{-3}$. In terms of inter-sensor variability, the lowest and highest average sensor values correspond to θ 's of $0.339 \text{ m}^3 \text{ m}^{-3}$ and $0.359 \text{ m}^3 \text{ m}^{-3}$, respectively, for a maximum deviation from the mean of $0.012 \text{ m}^3 \text{ m}^{-3}$. Of the 30 sensors tested, 29 had average values that correspond to differences of $<0.01 \text{ m}^3 \text{ m}^{-3}$ and 21 had values within $0.005 \text{ m}^3 \text{ m}^{-3}$ of the mean. In general, these data indicate that a sensor-specific calibration is not necessary for most applications.

Infiltration-Addition ϵ_r (θ_{cell}) Response

Consistent with the tests in fluids, there was close agreement among the three test sensors in all soils. For example, there was no significant difference ($\alpha = 0.05$) among sensor measured ϵ_r or ϵ_r'' for the oven-dry soil. For purposes of illustration, we plotted the measured ϵ_r and ϵ_r'' for one sensor vs. θ_{cell} for seven soils represent-

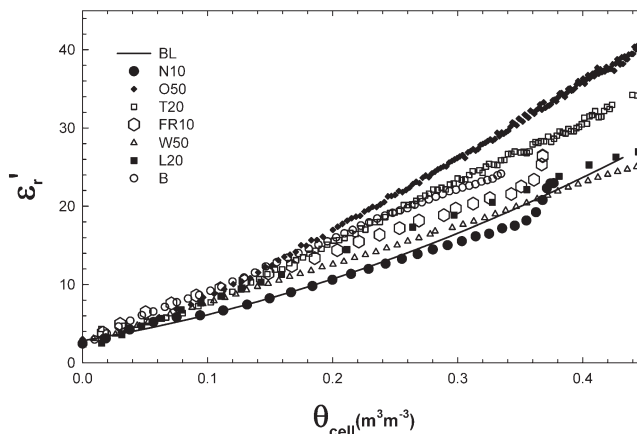


Fig. 1. Real relative dielectric permittivity vs. θ_{cell} for seven soils representing the range of observed response relative to the baseline calibration equation. BL is the baseline equation, N10 is Newton 10, O50 is Onward 50, T20 is Tunica 20, FR 10 is Fort Reno 10, W50 is Watkinsville 50, L 20 is Lonoche, and B is Breaks.

ing the range of responses observed (Fig. 1 and 2). This relationship is highly variable among soils. For ϵ_r' , all soils are in close agreement when oven-dry and diverge with increasing θ_{cell} . The θ range at $\epsilon_r' = 5$ is about $0.048 \text{ m}^3 \text{ m}^{-3}$ but at $\epsilon_r' = 20$ is $>0.170 \text{ m}^3 \text{ m}^{-3}$. Excepting the value of 2.1 for the Mansfield soil, oven-dry ϵ_r' values range from 2.4 to 3.1, with an average of 2.7, which is consistent with TDR data. The baseline equation roughly delimits the minimum response and is less linear than the measured values.

The ϵ_r'' response range is even greater than that for ϵ_r' (Fig. 2). Minimum values are near 0 for all soils, but maximum values range from about 5 to >50 . As with ϵ_r' , the responses are roughly linear. Note that, in general, soils with high ϵ_r'' responses (e.g., Onward 50 and Tunica 20) also tend to have high ϵ_r' responses and those with low ϵ_r'' responses (e.g., Watkinsville 50 and Newton 10) tend to have corresponding low ϵ_r' responses. These responses are not closely related to clay content. For example, the Watkinsville 50 and Newton 10 samples have similar responses but the clay content of 63% for Watkinsville 50 is much higher than the 6.3% for Newton 10. Similarly, Onward 50 and Tunica 20 have similar,

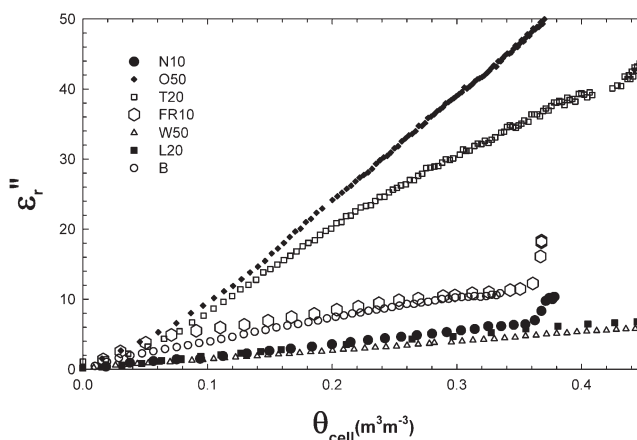


Fig. 2. Imaginary relative dielectric permittivity vs. θ_{cell} for the same seven soils displayed in Fig. 1.

high responses with clay contents of 10.9 and 30.8%, respectively.

Effective ε'_r in Layered Media

Our experiments with the Hydra Probe in the air-water cells resulted in strongly linear relationships between ε'_r and θ_{cell} , with $r^2 > 0.99$ for both replicates and slopes near 80 (81 and 82). These results conform to Eq. [1] and indicate that the Hydra Probe “sees” the arithmetic average of the two layers under our experimental conditions. If the wetting front separating oven-dry and saturated soil during infiltration is perfectly abrupt, a linear relationship will result when the data are expressed as in Fig. 1 and 2. This is true even if the $\varepsilon'_r(\theta)$ relationship in well-mixed soil, which is the more common field condition, is nonlinear.

The degree to which the infiltration-addition measurements made in soils conform to Eq. [1] depends on whether the hydraulic properties of the soil and the rate of water addition result in a perfectly abrupt wetting front. This condition appears to have been closely approximated in some soils (e.g., Lonoke and Watkinsville 50 soils, Fig. 1). In other soils it appears that the infiltration water content is somewhat less than the eventual saturation value, resulting in an abrupt increase in ε'_r when θ_{cell} approaches saturation (e.g., Newton 10 and Fort Reno 10, Fig. 1). A final condition appeared to have occurred when the wetting front was diffuse due to relatively rapid imbibition. This results in nonlinear responses tending towards Eq. [2] (e.g., Tunica 20, Fig. 1). We believe that this condition dominated during our previous use of the infiltration-addition method (Seyfried and Murdock, 2004) because we performed the infiltrations at a much lower rate than in this study.

The results from the mixed soil tests for all three soils indicated that, in fact, the $\varepsilon'_r(\theta)$ relationship in well-mixed soil is nonlinear and in agreement with Eq. [10]. The r^2 values calculated fitting Eq. [10] to the mixed soil data for the three test soils were: Lonoke 20, 0.985; Tunica 20, 0.988; and Newton, 0.997. The two-point calibration equations determined using the oven dry and saturated values from the infiltration-addition experiments matched the mixed soil data almost as well. We illustrate these results with the Lonoke 20 soil (Fig. 3). Note the difference between the response for Lonoke 20 soil in layered media (Fig. 1) and well-mixed media (L20 in Fig. 3). The solid line in Fig. 3 represents the best fit to the data fit to Eq. [10] and the dashed line represents the individual calibration curve determined from oven-dry and saturated values during the infiltration-addition experiments. This agreement with Eq. [10] is consistent with other data collected with the Hydra Probe (Campbell, 1990; Rial and Han, 2000). The close agreement between the fitted and two-point calibration curves (similar for all three soils) indicates that the two-point calibrations reasonably represent mixed soil conditions.

Individual Soil Calibration Equations

Based on the results described above, an individual soil calibration was determined for each soil by fitting

Eq. [10] to the oven-dry and nearly saturated data collected during the infiltration-addition experiments. Since all individual soil calibrations were fitted to similar oven-dry ε'_r values, all calibrations are similar at low ε'_r (and θ) values. Thus, the calibration slope is primarily what distinguishes the soil calibrations in the measurement range. We quantified differences among soils by calculating the $\Delta\theta_{\text{avg}}$ between each individual calibration and the baseline equation. When interpreting these differences two points need to be taken into consideration. First, the differences are between calibration curves, not actual measured data, and so do not include the “scatter” commonly observed around fitted equations. Second, all comparisons are for the same ε'_r range and correspond approximately to the difference at $\theta = 0.23 \text{ m}^3 \text{ m}^{-3}$. Since all curves diverge from a nearly common value at oven-dry, the agreement among curves always improves as ε'_r is reduced. In some cases, such as sands, the reported average value may be close to the maximum value observed under freely drained conditions.

Excepting the Mansfield soil, the $\Delta\theta_{\text{avg}}$ between the baseline and individual soil calibrations was either close to zero or greater, ranging from -0.01 to $0.07 \text{ m}^3 \text{ m}^{-3}$ (Table 3). Note that, when θ is expressed as a function of ε'_r in a calibration relationship, the baseline equation is expected to plot above most soils and therefore have a positive $\Delta\theta_{\text{avg}}$. Mansfield, the lone organic sample, had a $\Delta\theta_{\text{avg}}$ of $-0.02 \text{ m}^3 \text{ m}^{-3}$, thus plotting substantially above the baseline equation.

The values of both the A and B parameters (Eq. 10) vary considerably among the test soils (Table 3), as would be expected from the $\varepsilon'_r(\theta_{\text{cell}})$ data (Fig. 1). They do, however, fall within the range reported for TDR calibrations reported by Heathman et al. (2003) and the overall mean parameter values of $A = 0.110$ and $B = -0.180$ are very similar to those obtained by Ledieu et al. (1986) for TDR of $A = 0.114$ and $B = -0.176$.

The sources of the observed parameter value variations can be linked to $\varepsilon_{s,a}$ or $\varepsilon_{w,a}$ via Eq. [11]. With the exception of the Mansfield soil, the $\varepsilon_{s,a}$ values calculated from the calibration parameters agree closely with the

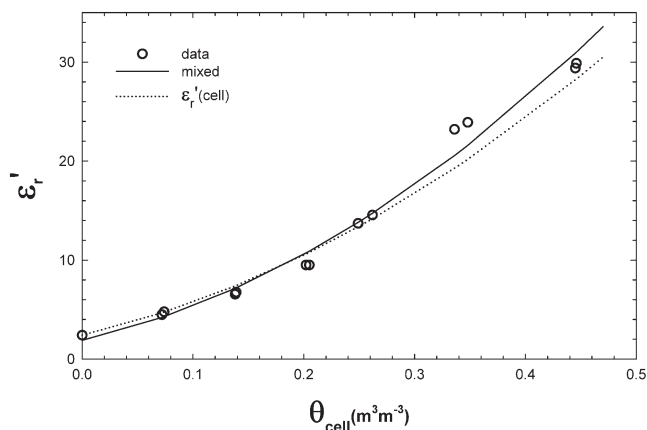


Fig. 3. Average ε'_r vs. θ_{cell} for the Lonoke soil measured in well-mixed conditions. The “mixed” line was calculated from a linear regression of ε'_r against the measured, mixed cell water contents. The $\varepsilon'_r(\text{cell})$ line was calculated using saturated and oven-dry parameters derived from the infiltration-addition experiments.

commonly reported range for soil solids of 4 to 7 (Alharthi and Lange, 1987) and exhibited relatively little variation. In contrast, the calculated $\epsilon_{w,a}$ values range from near 80, indicating near pure water dielectric values, to >130 . Thus, variations in calibrations among soils are primarily related to $\epsilon_{w,a}$. The physical mechanisms causing such high $\epsilon_{w,a}$ values are not evident and may be the result of faulty assumptions in Eq. [9], although there are other reports of $\epsilon_{w,a}$ being greater than that of pure water in the literature (Campbell, 1990; Saarenketo, 1998). Alternatively, they may be due to measurement inaccuracies, although we suspect this is not the case. In previous research, Seyfried and Murdock (2004) found that ϵ'_i accuracy and precision progressively deteriorated when $\tan \delta$ increased above 1.45. The maximum value measured in this study of 1.37 is close to that value, but most values were much lower and the measurement precision did not deteriorate.

Influence of Soil Properties

We attempted to segregate soils using texture, as represented by clay content, to establish a texture-dependent, multi-soil calibration equation. To determine the potential for such an approach we evaluated the relationship between clay content and $\Delta\theta_{avg}$. Some of the data are consistent with texture control of the $\epsilon'_i(\theta_{cell})$ relationship. For example, the three soils with the lowest clay content, Newton 10 and 20, and Little River, had calibrations close to the baseline, as would be expected. However, regression analysis of the data set indicated no significant correlation ($\alpha = 0.05$) and an r^2 value of 0.052 (Fig. 4). Note that the organic soil was not included in this analysis.

This weak relationship may be explained by the highly variable electrical properties of different soil clays. For example, in kaolinite samples, Saarenketo (1998) found almost no difference in ϵ'_i or ϵ''_i measured 50 MHz and 1 GHz. This suggests that soils with clay mineralogies dominated by kaolinite will have calibrations similar to the baseline. On the other hand, he found that, for measurements made in Beaumont clay, which is proba-

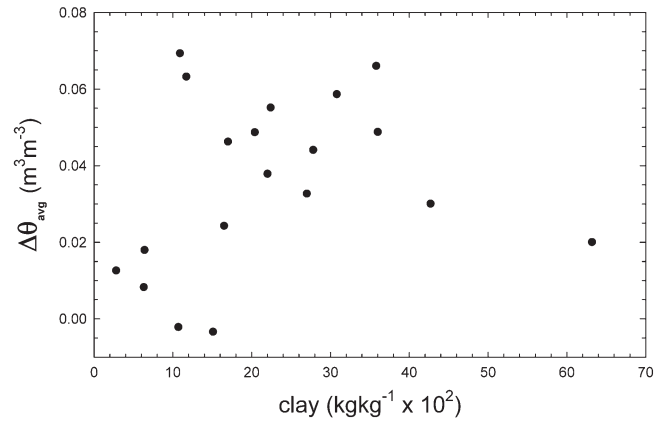


Fig. 4. The $\Delta\theta_{avg}$ between each individual soil calibration equation and the baseline equation between $\epsilon'_i = 4$ and $\epsilon'_i = 36$ vs. the clay content (expressed as the gravimetric percent).

bly smectitic, ϵ'_i decreased from about 65 measured at 50 MHz to about 28 when measured at 1.01 GHz. Similarly, ϵ''_i declined from about 68 measured at 120 MHz to 10 measured at 1.01 GHz. This suggests that soils dominated by similar clays would have large $\Delta\theta_{avg}$ values. Although our clay mineralogy data are incomplete, they are consistent with this interpretation. The Watkinsville 50 soil, with a very high clay content dominated by kaolinite, had an individual calibration close to the baseline, while the Tunica soils, which are dominated by montmorillonite, had large $\Delta\theta_{avg}$ values (Tables 1 and 3).

These results suggest that dielectric loss may better segregate the individual calibrations because dielectric loss is affected by clay properties such as surface area and CEC that are associated with different clay types. Due to a lack of intermediate ϵ''_i values, we used the loss tangent for saturated soil ($\tan \delta_s$) as an index to describe the effect of dielectric losses on the individual calibrations. Excluding the Mansfield soil (organic) which plots as an outlier in Fig. 5 ($\Delta\theta_{avg} < -0.02 \text{ m}^3 \text{ m}^{-3}$), there was a significant relationship ($\alpha = 0.05$) between $\Delta\theta_{avg}$ and $\tan \delta_s$ with an r^2 of 0.49.

Table 3. Calibration parameters, apparent permittivity and $\Delta\theta_{avg}$ from baseline for all soils.

Soil	A	B	$\epsilon_{w,a}$	$\epsilon_{s,a}$	$\Delta\theta_{avg}$
Mansfield	0.1228	-0.1792	83.6	7.72	-0.020
Lonoke	0.1226	-0.1903	83.9	5.03	-0.008
Watkinsville 5	0.1251	-0.2065	80.9	4.53	-0.002
Newton 10	0.1170	-0.1847	91.1	4.24	0.008
Little River	0.1204	-0.2025	86.6	4.29	0.013
Newton 20	0.1161	-0.1909	92.3	4.67	0.018
Watkinsville 50	0.1110	-0.1725	100.1	5.37	0.020
Fort Reno 10	0.1105	-0.1747	100.9	4.19	0.024
Tunica 50	0.1088	-0.1738	103.8	5.13	0.030
EL Reno 50	0.1078	-0.1723	105.5	4.38	0.033
Walnut Gulch 20	0.1132	-0.1989	96.7	6.30	0.038
Onward 5	0.1031	-0.1648	114.5	5.01	0.044
Breaks	0.1070	-0.1825	107.1	5.06	0.046
Little Washita	0.1004	-0.1588	120.0	5.10	0.049
Ames	0.1033	-0.1702	114.1	5.67	0.049
Tunica 20	0.1033	-0.1768	114.0	5.72	0.055
Walnut Gulch 5	0.1017	-0.1786	117.2	5.41	0.063
Onward 20	0.0967	-0.1613	128.5	5.43	0.066
Onward 50	0.0958	-0.1610	130.8	5.72	0.069
Baseline	0.1257	-0.2111	80.2	5.0	0.000

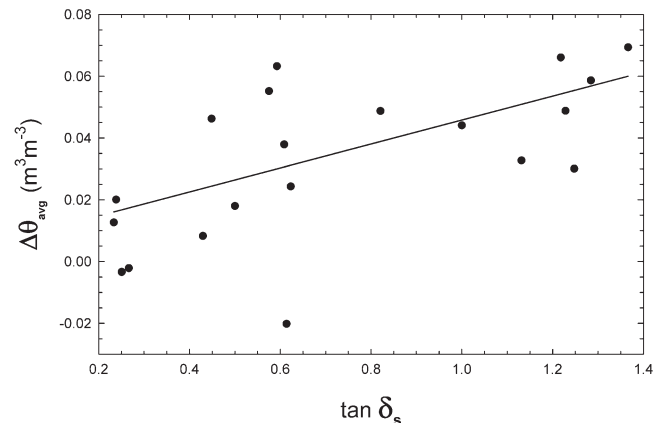


Fig. 5. The $\Delta\theta_{avg}$ between each individual soil calibration equation and the baseline equation between $\epsilon'_i = 4$ and $\epsilon'_i = 36$ vs. $\tan \delta_s$. Linear regression was determined for mineral soils only. The Mansfield (organic) soil is the point substantially below 0.

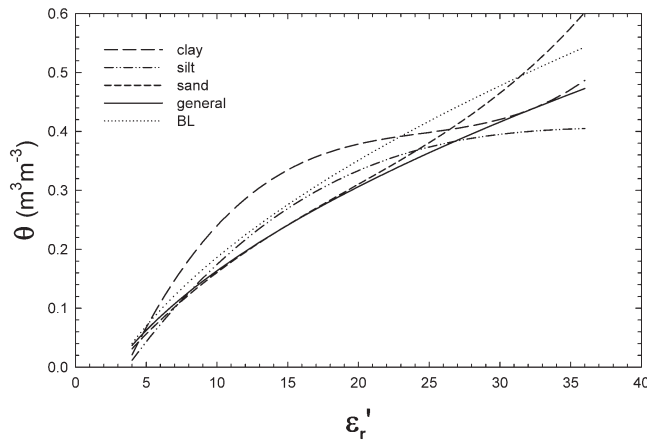


Fig. 6. Comparison of the manufacturer-supplied calibration equations with the mean and baseline (BL) equations. The loss-corrected equation was not included because it is not a simple function of ϵ_r' .

Multi-Soil Calibration Equation Evaluation

The following analysis pertains only to the mineral soils, excluding Mansfield. We excluded the Mansfield soil for two reasons: (i) it is an outlier in terms of calibration parameters and its relation to the baseline equation, and (ii) TDR data indicate that dielectric properties of organic soils are considerably different from mineral soils. Since we had only one organic sample, any kind of general statement about calibration of organic soil does not seem justified.

We developed two multi-soil calibration equations intended to be applied to different soils without specific calibration. The first uses the mean A and B parameter values for the mineral soils. The resultant, “general” calibration equation, $\theta = 0.110 \sqrt{\epsilon_r'} - 0.180$, being comprised of mean parameter values, roughly bisects the population of individual soil calibrations. It also approximates the curve developed by Campbell (1990) for measurements made at 50 MHz on six different soils.

The general calibration equation is plotted with the three manufacturer-supplied equations and the baseline equation to illustrate the differences among them (Fig. 6). The manufacturer-supplied calibrations matched sections of the baseline or general equations but diverged sharply at other sections, suggesting that they were based on limited portions of the overall ϵ_r' (θ) relationship. Thus, the “sand” calibration curve matches the general calibration closely for ϵ_r' values up to about 21, and then diverges sharply from it. Similarly, the clay curve approximates the general equation for ϵ_r' values between 27 and 36 but is very different when ϵ_r' is <27 . The “silt” calibration approximates the baseline equation up to an ϵ_r' of about 15 and then it diverges rapidly. Since the general calibration roughly bisects the individual soil calibrations, it would appear that it must provide an overall better fit to our data, because roughly half the calibrations fall below it. Only the “silt” calibration crosses below the general equation, and it does so in an unrealistic manner, being essentially constant for $\epsilon_r' >28$.

The second multi-soil calibration equation takes advantage of the observed relationship between $\tan \delta_s$ and

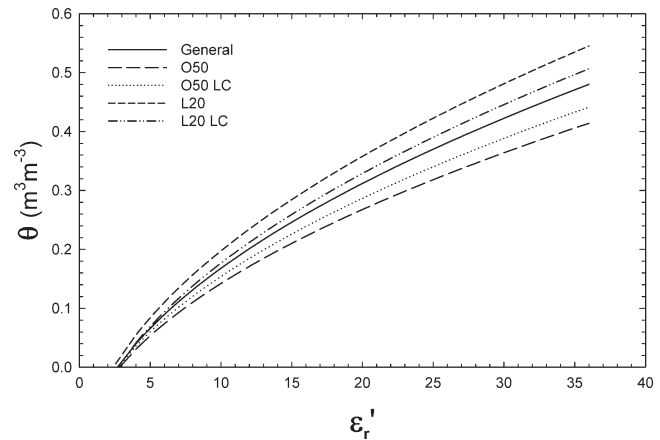


Fig. 7. Illustration of the loss-corrected calibration (LC) relative to the general calibration for two soils, Onward 50 and Lonoke, representing the upper and lower extremes of calibration.

$\Delta\theta_{\text{avg}}$ (Fig. 5) and has the same form as Eq. [10]. Since most of the variation in soil calibrations was due to variations in A among the individual calibrations, a loss-corrected A parameter value (A_{lc}) was developed based on the following regression obtained between A and $\tan \delta_s$: $A_{lc} = -0.0153 \tan \delta_s + 0.1202$ ($r^2 = 0.529$). The corresponding B parameter value (B_{lc}) was determined given a known A_{lc} and assuming that when $\theta = 0$, $\epsilon_r' = 2.7$, which is the average for the data set. Thus, each soil can be characterized by unique A_{lc} and B_{lc} values that depend on $\tan \delta_s$.

We illustrate the range of soil calibrations relative to the general calibration and the effect of loss-corrected calibration in Fig. 7. The two soils plotted, Lonoke and Onward 50, represent the two extremes in terms of deviations from the general equation. Thus, the remaining 17 mineral soils plot between those two curves. Given a measured ϵ_r' of 27, the calibration θ for the Onward 50 soil ($0.337 \text{ m}^3 \text{ m}^{-3}$) is $0.055 \text{ m}^3 \text{ m}^{-3}$ lower than that calculated using the general calibration whereas the loss corrected estimate of $0.360 \text{ m}^3 \text{ m}^{-3}$ is only $0.023 \text{ m}^3 \text{ m}^{-3}$ different from the soil calibration value. The degree of improvement provided by the loss-corrected calibration is similar for the Lonoke soil. In these examples, the loss-corrected calibration was a substantial improvement compared to the general calibration. In general, the effect of applying the loss-correction was to reduce the spread of individual calibrations around the general calibration.

For a more quantitative analysis of the differences between the various calibration equations and the individual soil calibrations, we calculated the $\Delta\theta_{\text{avg}}$ between each individual soil calibration and the multi-soil calibrations. The $\Delta\theta_{\text{avg}}$ values, averaged across all mineral soils for each calibration equation were as follows: “clay”, $0.053 \text{ m}^3 \text{ m}^{-3}$; “silt”, $0.027 \text{ m}^3 \text{ m}^{-3}$; “sand”, $0.029 \text{ m}^3 \text{ m}^{-3}$; general, $0.019 \text{ m}^3 \text{ m}^{-3}$ and loss-corrected, $0.013 \text{ m}^3 \text{ m}^{-3}$. Thus, as expected from the comparisons in Fig. 6, the general calibration offered a substantial improvement over the manufacturer-supplied calibration curves. The effectiveness of the loss-corrected calibration is also apparent. An added advantage of both the general and

Table 4. Average difference ($\Delta\theta_{\text{avg}}$) between individual soil calibrations and multi-soil calibration equations.

Soil	Calibration equation				
	LC [†]	General	Sand	Clay	Silt
			$\text{m}^3 \text{m}^{-3}$		
Foothill	0.023	0.038	0.054	0.085	0.041
Sheep Creek	0.002	0.013	0.028	0.06	0.025
Sand	0.010	0.035	0.027	0.039	0.034
Summit	0.030	0.025	0.04	0.072	0.031
Average	0.017	0.028	0.037	0.064	0.033

[†] The loss-corrected calibration.

loss-corrected curves is that they provide more accurate estimates of changes in θ because the curves have a more realistic shape over the measurement domain.

We performed a similar analysis on the data collected independently from four soils. This gives an indication of the applicability of these findings to soils not included in the development of the calibration equations. The overall results (Table 4) are similar to those obtained from the 19-soil data set in terms of the magnitude of the differences and the relative rankings of the five calibrations. Although this test data set is admittedly small, the results indicate that the loss-corrected calibration applies to other soils and that the general calibration equation is generally superior to any of those supplied by the manufacturer. In both data sets, the poor performance of the "sand" equation relative to the "silt" equation is somewhat misleading because the "sand" plots very close to the general equation for much of the range and part of the close fit obtained with the "silt" equation is due to its unreasonable shape.

To put these results in perspective, a sort of "rule of thumb" regarding the accuracy of the Topp equation for TDR for most soils is that measured values are expected to be within ± 0.02 to $0.03 \text{ m}^3 \text{ m}^{-3}$ of the Topp-calculated value (Noborio, 2001). This is usually accompanied with a caveat that high clay content soils may not fall within that range. In addition, measurements usually do not include the full range of water contents, and as we have pointed out, the largest errors are expected to be near saturation. Our test data include high clay content soils and the full range of θ . Even so, the range of calibrations around the general equation is greater than would be expected from TDR. On average, across all soils, the maximum error using the general equation (i.e., the difference between the soil calibration θ and the general equation θ) was $0.033 \text{ m}^3 \text{ m}^{-3}$, so most soils exceeded the $0.03 \text{ m}^3 \text{ m}^{-3}$ expected for TDR. This reflects the fact that soil dielectric properties are more variable when measured at 50 MHz than when measured at 1 GHz so that an average curve must have a wider spread around it. The loss-corrected calibration improves the situation, so that on average, the maximum difference between loss-corrected equation and the individual soil calibrations is $0.022 \text{ m}^3 \text{ m}^{-3}$ and 14 of the 19 soils tested are within $0.03 \text{ m}^3 \text{ m}^{-3}$. Thus, the level of accuracy using the loss-corrected calibration begins to approach that of TDR. This is primarily because the loss-corrected equation better describes soils with extreme calibration values.

Extensions

The water-air system tests and the results from the well-mixed soil water cells indicate that the effective measurement criteria in layered media developed by Chan and Knight (2001) for TDR also apply to the Hydra Probe. This suggests that it may also apply to other alternative sensors. This has implications not only for calibration methodology but also for interpretation of field data. Since most applications we are aware of use horizontal placements at a variety of depths, we expect that a well-mixed calibration most generally applies. However, when vertical measurements are made near the soil surface this may not be the case because strongly contrasting soil water layers are more likely. This problem is more likely to occur in sensors with longer probes.

The general, multi-soil calibration we developed appears to represent a reasonable approximation of soil behavior that is an improvement over the current equations in use. Of course the general calibration will, on average, always outperform a fixed calibration when applied to the data from which it is derived. However, the magnitude of the improvement, the consistency of the curve shape over the entire measurement range, and the improved fit seen with the independent data, all indicate the superiority of the general equation. We note that field Hydra Probe data recently reported by Bosch (2004) are well described by the general calibration equation.

The degree of spread in calibration relationships for individual soils we measured almost certainly exceeds what would have been observed with TDR. Thus, any overall, multi-soil calibration such as the general calibration equation will provide a less precise description than would be expected from a similar equation, like the Topp equation, using TDR. This reflects a basic limitation of alternative sensors in general, which use measurement frequencies much lower than that of TDR and are therefore more sensitive to soil-specific variations in properties such as ion exchange capacity and specific surface area. This problem can be mollified, to some extent, by using sensors with relatively high measurement frequencies.

The relative success of the loss-corrected calibration equation indicates that much of the observed calibration variation among soils is correlated with $\tan \delta_s$. This is consistent with data indicating that, as measurement frequency decreases, increases in ϵ_r' are associated with larger increases in ϵ_r'' (Campbell, 1990; Saarenketo, 1998). However, $\tan \delta_s$ only described about half of the $\Delta\theta_{\text{avg}}$ variability we measured. One reason for this may be that the measured ϵ_r'' does not distinguish between molecular relaxation and electrical conductivity, which probably have different effects on the measured ϵ_r' . Thus, it may be possible to further improve the calibration by incorporating independent measurements of electrical conductivity.

An alternative calibration approach might combine both $\epsilon_r'(\theta)$ and $\epsilon_r''(\theta)$. This is attractive because it requires no separate measurements. A problem with this approach is that ϵ_r'' is much more sensitive to temperature

than ϵ'_r (Seyfried and Murdock, 2004). To further pursue this approach it will be critical to obtain a range of simultaneously measured ϵ'_r , ϵ''_r and temperature under well-mixed soil water conditions. Since the Hydra Probe also measures temperature, this approach has some potential.

Finally, we note that, to our knowledge, no other commercial alternative soil water sensor produces outputs that distinguish between ϵ'_r and ϵ''_r although all are affected by both. Examination of the ϵ''_r data presented indicates that a large amount of variability in dielectric response among soils remains "hidden" from these sensors and indicates that calibration variations among soils using these sensors would be much greater than we have observed with the Hydra Probe.

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