FIELD CALIBRATION OF THE THETA PROBE
FOR DES MOINES LOBE SOILS

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ABSTRACT. *Knowledge of soil moisture is needed to understand crop water use, hydrology, and microclimate. A reliable, rapid technique is needed, and recently an impedance soil moisture probe (Theta Probe) has been accepted by the scientific community. The purposes of this study were to calibrate the probe for soils of Central Iowa through field sampling, to determine the number of samples needed for calibration, and to determine the effect of temperature on calibration. Laboratory calibration was conducted on Des Moines lobe soils across a range of water contents and temperatures. Including a temperature term increased the R^2 from 0.85 to 0.87. Field calibration was based on Theta Probe measurements on similar soils combined with gravimetric sampling and soil temperature determination. Although some scatter existed, the field calibration was adequate for Iowa soils ($R^2 = 0.77$). Inclusion of temperature did not significantly improve the calibration for the field data. To determine the appropriate number of samples needed for the field calibration, regression equations were determined from sample numbers ranging from 2 to 89, and the standard error was determined for each. Based on the standard error analysis, 20 samples was an adequate number, with no further improvement for additional data points.*

Keywords. *Calibration, Soil moisture, Impedance probe.*

oil water content is a critical component of numerous systems, including cropping, hydrology, and microclimate. Of special interest is the top few centimeters of soil, because spatial patterns are of interest in relation to landscape water patterns (Jacobs et al., 2004) and because of the influence of surface soil water content on the surface energy balance (Kustas et al., 2003; Bindlish et al., 2001). The near-surface soil moisture is also needed to ground-truth microwave remote-sensing measurements (Drusch et al., 2004; Walker et al., 2004a); at 1.4 GHz, the emitting depth of the soil is around 5 cm, thus effective methods for assessing near-surface soil water content are important for validating this type of data (Hornbuckle and England, 2004).

Many techniques are used to measure field soil water content, but not all are suitable for surface soil measurements. The standard is gravimetric sampling, but calculation of volumetric water content requires knowledge of the sample volume or a separate bulk density sampling. Also, repeated sampling is destructive. Another standard method, the neutron probe, is not accurate near the soil surface because the measurement volume extends into the air; radiation danger is also a concern. Time-domain reflectometry (TDR) also poses difficulties for measurement near the soil surface. To capture accurate waveforms, TDR waveguides often must be as long as 30 cm (Amato and Ritchie,

1995); thus the measurement depth is too great for near-surface studies unless probes are inserted at an angle. As pointed out by Topp (2003), current TDR models are not ideal for radar and microwave soil water content validation. Many capacitance probes are designed to be used in an access tube at multiple depths (Evett and Steiner, 1995; Paltineanu and Starr, 1997). Others have a flat design for single insertion and continual monitoring (Echo probe, Decagon Devices, Inc., Pullman, Wash.). Neither design is appropriate for surface soil water content monitoring. The heat-pulse method (Heitman et al., 2004) allows for shallow measurement, but the instrument used in this method is not well suited for portable use in field data collection.

Recently, an impedance probe (Theta Probe, Delta-T Devices, Cambridge UK, marketed in the United States by Dynamax, Inc., Houston, Tex.) has received acceptance for surface soil water content measurements, especially by the remote sensing community (Jacobs et al., 2004). The Theta Probe (fig. 1) generates a 100-MHz sinusoidal signal and measures the impedance of the sampling volume, which is roughly a cylinder 4 cm in diameter and 6 cm long surrounding the center prong of the probe. The manufacturer provides generalized probe calibrations for mineral and organic soils but recommends soil-specific calibration for improved accuracy. The rated accuracy if the general

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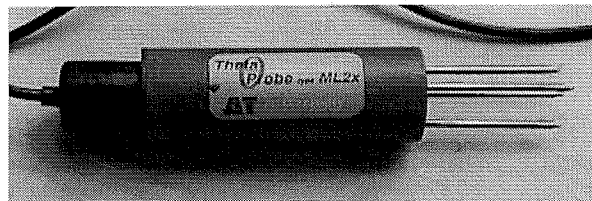

Figure 1. Theta Probe soil moisture sensor. Prongs are 6 cm in length. The volume of soil contributing to the voltage measurement is a cylinder approximately 4 cm wide and 6 cm long.

calibrations are used is ± 0.05 m^3 m^{-3} for temperatures between 0°C and 70°C. If soil-specific calibrations are used, rated accuracy increases to ± 0.01 m^3 m^{-3} for temperatures between 0°C and 40°C (Delta-T Devices Ltd., 1999).

Despite the need for site-specific calibration, limited published research on Theta Probe calibration is available. The manufacturer recommends a two-point technique, in which the probe is inserted into a soil sample which is then dried to obtain gravimetric water content; the probe is then inserted into the dry sample to obtain a second probe reading. Calibration coefficients are determined from the wet and dry readings compared with the water content. This approach of taking a probe reading from a dried sample is a difficult one for many soils, which either contract or become fragile upon drying; inserting a probe into the sample in either case is impractical. The accuracy of a two-point conversion is also a concern. A second approach is to perform a series of laboratory measurements on multiple soil samples. This approach has been used in calibration of Theta Probes (Robinson et al., 1999) and other dielectric instruments (Seyfried and Murdock, 2004; Veldkamp and O'Brien, 2000). Typical laboratory calibration uses a small number of soil samples under a wide variety of conditions. A potential drawback to this approach is that it may not indicate real-time field performance, particularly for surface sampling, where heterogeneity from one site to the next is likely. Thus field calibration by regression with numerous gravimetric samples may be a more appropriate option. This approach has been used in calibration of capacitance probes (Geesing et al., 2004; Kelleners et al., 2004; Morgan et al., 1999) and TDR probes (Walker et al., 2004b), but field calibration of the Theta Probe has been demonstrated infrequently in the literature (Tsegaye, 2004; Hornbuckle and England, 2004).

Other impedance probes, particularly those operating at 50 MHz and below, have been shown to have some dependency on soil temperature (Seyfried and Murdock, 2004). Early versions of the Theta Probe were shown to have a slight change in probe output across a 25°C range of temperatures, though this dependency was reduced in later designs (Gaskin and Miller, 1996). The extent to which soil temperature influences current Theta Probe calibration, if at all, is not documented in the literature.

If a field calibration is used, the destructive and time-consuming nature of gravimetric sampling makes using the minimum number of samples possible for accurate calibration a necessity. The effect of variable soil temperature under natural field conditions should also be investigated for its effect on calibration accuracy. Thus the objectives of this study were to: (1) test a field calibration approach for the Theta Probe; (2) determine the number of samples necessary to adequately calibrate the probe using field samples; and (3) evaluate the influence of soil temperature on calibration accuracy.

MATERIALS AND METHODS

A preliminary laboratory study was conducted using soils from the Des Moines lobe, which forms the southernmost extent of the Prairie Pothole Region of central North America. Five soils (table 1) were packed to a bulk density of 1.3 g cm^{-3} and two or three water contents. The range of water contents for the undisturbed samples was 0.092 to

Table 1. Disturbed soils used in preliminary laboratory calibration study.

Soil	Depth (m)[a]	Sand (%)	Silt (%)	Clay (%)	Surface Area (m^2 g^{-1})
Nicollet 2	0.25	45.2	29.1	25.7	79
Nicollet 3	0.45	52.8	30.7	16.5	81
Webster	0.45	47.4	29.8	22.8	109
Webster	0.60	41.5	35.1	23.4	119
Webster	0.75	41.8	34.2	24.0	113

[a] Depth refers to depth in the soil from which the sample was taken.

0.493 m^3 m^{-3}. All of the samples were equilibrated at three temperatures before measuring soil moisture with the Theta Probe. In addition, measurements were made in 18 undisturbed soil cores (table 2) at two temperatures and ambient water content ranging from 0.194 to 0.445 m^3 m^{-3}. For these samples, particle size (Gee and Bauder, 1986) was determined by hydrometer method on duplicate samples, and specific surface area was determined by humidification over MgNO$_3$ (56% relative humidity) on duplicate samples (Logsdon, 2000). Some of the field cores were compressed during sampling, thus some samples have a higher bulk density than one would see in the field.

Field measurements were collected on eight occasions during the summer and fall of 2004. The time of day of sampling, soil temperature, and soil water contents varied with occasion. Four locations within a 25-ha field in the Des Moines lobe region of central Iowa were sampled. Soil temperatures ranged from 13°C to 38°C, and volumetric water contents ranged from 0.17 to 0.40 m^3 m^{-3}. Particle-size analysis, organic matter content, and mean dry bulk density are given in table 3. Site 47 is mapped as Nicollet loam (fine-loamy, superactive, mesic Aquic Hapludoll), sites 53, 127, and 147 are mapped as Clarion loam (fine-loamy, mixed, superactive, Typic Hapludoll), and site 200 is mapped as Webster clay loam (fine-loamy, mixed, superactive, mesic Typic Endoaquoll). At each location, three samples per occasion were obtained; on several occasions, due to field conditions, not all locations were sampled. In all, 91 samples were collected.

Table 2. Undisturbed soil core samples used in preliminary laboratory calibration study.

Soil	Depth (m)[a]	Sand (%)	Silt (%)	Clay (%)	Bulk Density (g cm^{-3})	Surface Area (m^2 g^{-1})
Nicollet 1	0.04				1.57	
Nicollet 1	0.15	57.6	27.0	15.4	1.72	26
Nicollet 1	0.25	53.8	30.1	16.1	1.65	73
Nicollet 2	0.15	64.4	21.1	14.5	1.74	50
Nicollet 3	0.04				1.58	
Nicollet 3	0.15				1.75	48
Nicollet 3	0.25	63.5	23.0	13.5	1.70	61
Nicollet 3	0.35	54.1	29.6	16.3	1.79	59
Webster	0.04				1.58	
Webster	0.15	63.9	20.0	16.1	1.43	43
Webster	0.25				1.65	
Webster	0.35	58.4	23.2	18.4	1.48	120
Webster	0.45	47.4	29.8	22.8	1.46	109
Webster	0.60	41.5	35.1	23.4	1.47	119
Webster	0.75	41.8	34.2	24.0	1.69	113
Webster	0.90	46.1	27.5	26.4	1.53	122

[a] Depth refers to depth in the soil from which the sample was taken.

Table 3. Soil properties for field sampling locations.

Site	Sand (%)	Silt (%)	Clay (%)	Organic Matter (%)	Dry Bulk Density (g cm^{-3})[a]
47 (Nicollet loam)	27.8	45.8	26.4	7.1	1.00 (0.06)
53 (Clarion loam)	31.5	45.2	23.3	5.1	1.10 (0.09)
127 (Clarion loam)	55.5	27.7	16.8	2.6	1.31 (0.08)
147 (Clarion loam)	45.0	35.0	20.0	3.6	1.26 (0.09)
200 (Webster clay loam)	38	37	25	4.3	1.03 (0.07)

[a] Standard deviation for dry bulk density is shown in parentheses.

For each sample, the prongs of a ML2x Theta Probe were inserted into the soil surface to a depth of 6 cm (the length of the prongs). A voltage measurement was then recorded. The Theta Probe was carefully removed so as not to disturb the soil. A digital temperature probe was then inserted to a depth of 3 cm into the hole left by the center prong of the Theta Probe. After the temperature reading stabilized, the temperature was recorded and the probe was then carefully removed. Finally, a thin-walled aluminum cylinder 6 cm in length and 6 cm in diameter was inserted into the soil, centered around the center prong hole. To decrease the effects of compacting the soil sample during insertion of the cylinder, the bottom edge of the aluminum cylinder was bevelled to a thin edge. The cylinder and the volume of soil contained within it were then extracted, the soil was trimmed from the bottom to the edge of the cylinder, and the soil sample was emptied into an airtight tin. Upon return to the laboratory, the samples were weighed and then placed in a 105°C oven for 25 h before re-weighing. Volumetric water content θ (m^3 m^{-3}) was then calculated for each soil sample. For several soil samples, some material was lost on sample removal. For these soil samples, an average dry density for samples collected at that location was used in calculation of the volumetric water content according to the following equation:

$$\theta = \frac{(\text{sample wet mass} - \text{sample dry mass})(\text{dry density})}{\text{sample dry mass} - \text{container mass}} \quad (1)$$

In both the laboratory and field calibrations, the square root of the dielectric constant ε was calculated from the Theta Probe output voltage V using the following 3rd order polynomial ($R^2 = 0.998$) per the manufacturer's guidelines (Delta-T Devices Ltd., 1999):

$$\sqrt{\varepsilon} = 1.07 + 6.4V - 6.4V^2 + 4.7V^3 \quad (2)$$

We then developed regression equations for water content as a function of $\sqrt{\varepsilon}$. We also expanded the calibration equations to include a temperature term.

To determine the minimum number of samples, n samples (from $n = 2$ to $n = 89$) were selected at random from the full field data set, and a regression model was developed from these n samples. This model was used to predict the water content for the remaining samples. The standard error for each calibration equation was calculated according the following equation,

$$E(n) = \sqrt{\frac{\sum_{i=1}^{n_{total}-n}(y_i - y_i)^2}{n_{total} - n}} \quad (3)$$

where

$E(n)$ = standard error of the calibration

y_i = the estimated water content of sample i based on the regression equation developed from n samples

y_i = the true water content of sample i

n_{total} = the total number of samples in the original data set

For each value of n, this process was repeated 100 times, and the resulting values of $E(n)$ were averaged. This development of 100 regressions from n observations was replicated five times. We also determined the percent decrease in sample error when another sample was added.

RESULTS

A regression on the laboratory data (fig. 2) gave the following equation, with $R^2 = 0.85$,

$$\theta = 0.118\sqrt{\varepsilon} - 0.176 \cdot \quad (4)$$

The laboratory calibration was slightly affected by temperature. The regression equation which included temperature had an $R^2 = 0.87$:

$$\theta = 0.12\sqrt{\varepsilon} - 0.162 - 0.00143T \cdot \quad (5)$$

The field data are shown in figure 3. Sites 127 and 147 both exhibited more spread than the other sites, indicating that there might have been more surface heterogeneity at these sites. Nonetheless, all of the sites followed the same trend, indicating that it was suitable to lump together all of the observations for the field calibration. The field calibration deviated from the manufacturer's calibration for mineral soils (organic content < 7% C), which overestimated water contents at the wet end. Robinson et al. (1999) observed similar overestimation for packed samples across the full range of water contents. Below 0.22 m^3 m^{-3}, the manufacturer's calibration tended to underestimate water content, but large data spread existed at these water contents. A regression analysis of observed water content versus theta probe output gave the following model, also plotted in figure 3:

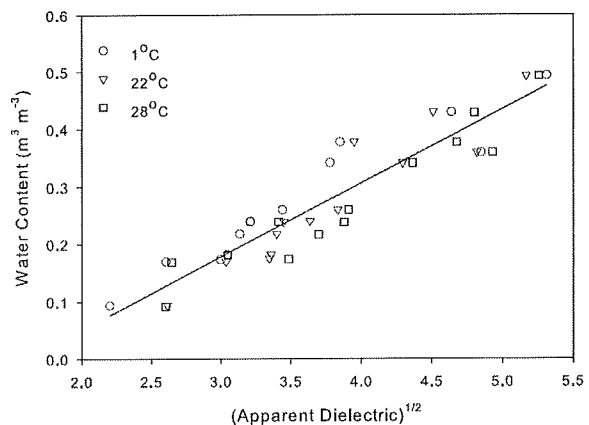$$\theta = 0.0730\sqrt{\varepsilon} - 0.0249 \quad (6)$$

Figure 2. Volumetric soil moisture vs. Theta Probe response for laboratory calibration. The observed calibration equation is $\theta = 0.118\sqrt{\varepsilon} - 0.176$ ($R^2 = 0.85$).
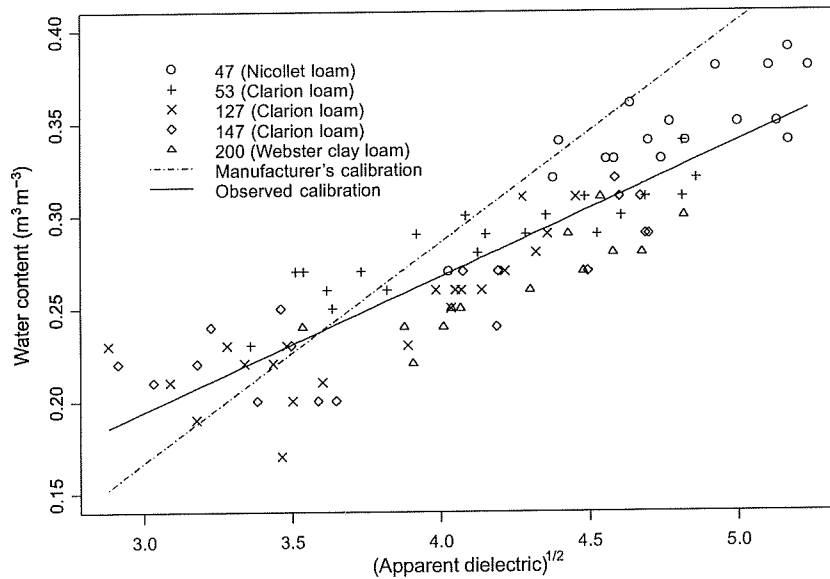
Figure 3. Volumetric soil moisture vs. Theta Probe response for field calibration. The observed calibration equation is
$\theta = 0.0073\sqrt{\varepsilon} - 0.0249$ $(R^2 = 0.77)$.

with an R^2 of 0.77. This lower R^2 than found for the laboratory data value was probably due to heterogeneity inherent in surface sampling as influenced by organic residues, macropores including worm holes, and other confounding factors. Nonetheless, the results imply that while there are complexities to field calibration of the Theta Probe, it is a valid approach.

The field data suggest a small temperature effect when one examines the calibration residuals (observed minus predicted values of water content, fig. 4), which were mainly positive above 25°C. A regression analysis including temperature gave the following equation ($R^2 = 0.77$):

$$\theta = 0.0733\sqrt{\varepsilon} - 0.0317 + 0.0002T \qquad (7)$$

This did not represent a significant improvement over equation 6. Furthermore, the direction of the temperature influence in this equation is opposite of that in equation 5, and the order of magnitude is smaller.

The average standard error for 100 fitted calibration models as a function of sample number (fig. 5) showed that two samples would be inadequate to accurately determine calibration coefficients. On the other hand, the improvement in standard error was minimal beyond 20 samples (fig. 6).

CONCLUSION

In this study, we have demonstrated that the Theta Probe can be field calibrated. The relationship between the sensor
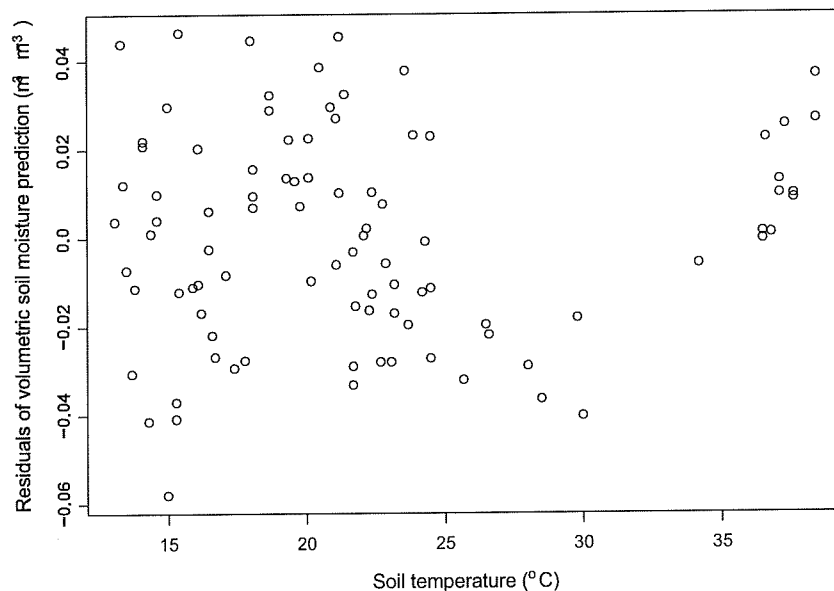

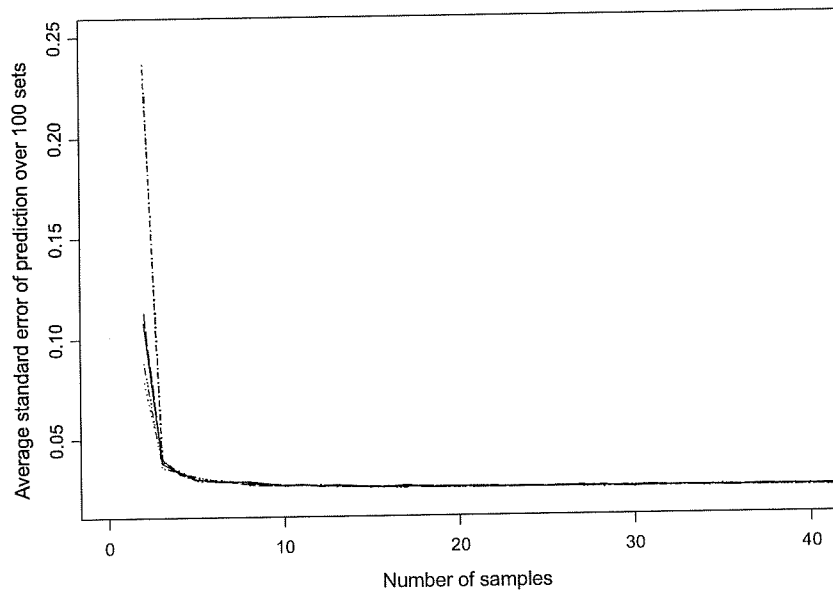**Figure 4. Residuals (actual minus predicted values of moisture content) vs. temperature.**

Figure 5. Standard error of prediction vs. number of samples *n* used for regression. Prediction error was averaged over 100 sets of *n*. Five replications are shown.
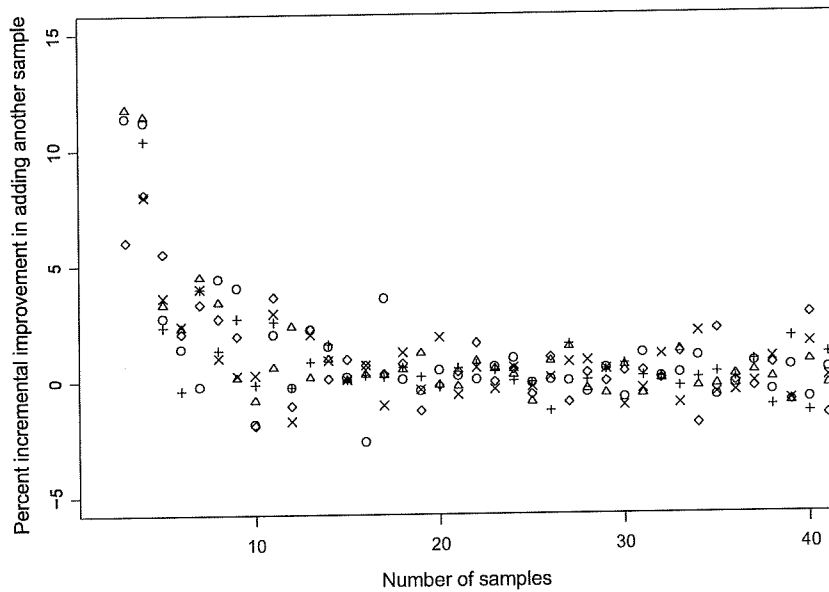

Figure 6. Percent decrease in standard error for adding one additional sample vs. number of samples used for regression, for five replications of 100 regression models. Each replication is plotted with a different symbol.

output and volumetric water content in this study was somewhat weaker than typical laboratory calibrations, however. This is likely due to the heterogeneous nature of near-surface soil. While the R^2 values for field calibrations may be lower than controlled laboratory studies, the field calibration may better reflect real-world variability. Furthermore, we determined that temperature can influence calibration, however, this influence is likely overshadowed by other factors in the field. Finally, 20 samples are recommended for a valid field calibration, as our analysis of calibration standard error indicated minimal improvement for additional samples beyond 20. To obtain a suitable range of water contents from which to develop a robust calibration, repeated gravimetric sampling on a variety of occasions with a wide

of water contents would likely be necessary. This is a significant limitation of the approach.

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