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# Field Calibration of Water Content Reflectometers

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## ABSTRACT

**Field monitoring of volumetric soil water content (VWC) is critical for a variety of applications. Recently developed electronic soil water sensors provide a relatively inexpensive monitoring option. However, the calibration of these sensors is more sensitive to variations in soil properties than for time domain reflectometry (TDR), which is generally regarded as the best electronic means of VWC measurement and which has a relatively robust calibration. Field calibration incorporates the effects of within-profile and between-site soil variations and individual variability on sensor response. The objective of this study was to evaluate the effectiveness of using TDR to field-calibrate the Campbell Scientific water content reflectometer (WCR), or CS-615, which is an example of a newly developed sensor in widespread use. We found that (i) there was a strong, linear correlation between the WCR-measured period and TDR-measured VWC; (ii) the WCR calibration varied with soil type; (iii) calibration of individual sensors resulted in excellent agreement between TDR and the WCR measurements; and (iv) calibration resulted in improved description of soil water dynamics and improved precision of VWC estimates.**

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Abbreviations: EC, electrical conductivity; TDR, Time domain reflectometry; VWC, soil volumetric water content; WCR, Water content reflectometer.

Many plant-soil-water and hydrological investigations depend on accurate measurement of VWC. The time-variant and episodic nature of the processes undergoing study often requires continuous measurement. Time domain reflectometry is a reliable method for making continuous, nondestructive measurements of VWC. With TDR, the apparent soil dielectric constant ($K_a$) is measured and related to VWC using a calibration equation. Topp et al. (1980) showed that a single empirical calibration curve could relate VWC to the soil dielectric constant for a wide range of soil types. It has since been confirmed that this equation accurately describes the $K_a$–VWC relationships for nonsaline, medium, and coarse-textured soils and TDR has become the most widely accepted electrical technique for measuring VWC (Cassel et al., 1994; Jones et al., 2002). In a review of TDR methodology, Jones et al. (2002) concluded that, in most mineral soils, the Topp equation yields VWC estimates with an estimation error of about 0.013 $m^3 m^{-3}$. However, the electronics required for TDR are relatively sophisticated and the distances sensors can be extended from the instrument are limited, making TDR prohibitively expensive for many applications. Several alternative sensors have been developed that use soil dielectric properties as the basis for VWC measurement (e.g., Dean et al., 1987; Campbell, 1990; Evett and Steiner, 1995; Paltineanu and Starr, 1997). These newer sensors measure dielectric properties with circuitry embedded within the instrument, thereby reducing the expense of the instruments for many applications and increasing the practical distance they may be deployed from a datalogger. The Campbell Scientific, Inc. WCR or CS-615[1], is an example of such sensors that is currently in widespread use. The WCR measures the equilibrium oscillation frequency or period of an applied voltage, which is directly related to $K_a$. The period is then related to VWC with an empirical calibration equation.

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[1] Mention of a specific product does not imply endorsement.

Although VWC measurement for both the TDR and WCR is based on soil dielectric properties, the two instruments use different measurement frequencies. The measurement frequency for the WCR varies with VWC and is generally between 15 and 45 MHz (Seyfried and Murdock, 2001), whereas the effective measurement frequency for TDR is up to about 1 GHz (Or and Wraith, 1999). This is critical because variations in soil solution concentration or composition and variations in clay content and type, which affect electrical conductivity (EC), have a greater effect on soil dielectric properties at low (WCR) frequencies than at high (TDR) frequencies (Campbell, 1990; Saarenketo, 1998; Lin, 2003; Seyfried and Murdock, 2004). For this reason, the WCR–VWC calibration will tend to be more sensitive to soil type than for TDR. In addition, because the effects of EC are strongly temperature dependent, it is expected that WCR data will also be temperature dependent for high EC soils.

In a laboratory study of WCR accuracy and precision in soils, Seyfried and Murdock (2001) found that the WCR is highly precise and, as would be predicted from the measurement frequency, the accuracy is more sensitive to changes in soil type than for TDR. In sand, with very low EC and clay content, the standard calibration supplied by the manufacturer agreed with measured data closely and temperature effects were small. There were substantial deviations from the standard curve and substantial temperature effects for the other three soils tested, which had relatively high clay contents and/or ECs. For all soils, however, there was a strong correlation between the WCR-measured period and VWC.

Since all the necessary electronics are part of each WCR, it is important to consider the sensor response variability among individual sensors, or inter-sensor variability for WCRs. Seyfried and Murdock (2001) reported a statistically significant difference among individual sensors that amounted to about 0.02 $m^3 m^{-3}$. Their data indicated that these differences were, to a first approximation, independent of VWC and that differences among sensor readings in air could therefore be used to account for inter-sensor differences. The evidence for this, however, was based on only three sensors.

At present there are insufficient data to know, a priori, how much the calibration for a given WCR application might deviate from the standard calibration. However, it appears that the calibration will vary with soil properties, with deviations tending to increase with clay content, and that it may vary with each individual sensor. Although laboratory calibration is possible and informative, a field calibration has the advantage of incorporating actual measurement conditions that can't be duplicated in the lab, such as location-specific texture, structure, and bulk density. In addition, it is difficult to account for individual sensor variability, which may vary with site characteristics, in a laboratory setting. Soil sampling for gravimetric calibration can provide very accurate data but is destructive, especially with the collection of multiple samples. This approach also requires accurate bulk density measurement, which becomes more problematic as sample depth increases, and is potentially confounded by differences in soil properties between the sensor and sample location. Use of TDR as the basis for calibration may be done nondestructively, allowing for multiple-point calibration. Because the measurement geometry of TDR rods is almost identical to that of WCR sensors, this approach allows for measurement of virtually the same soil conditions. The absolute accuracy is, however, limited by the accuracy of TDR.

In this paper we evaluate the utility of a nondestructive field calibration technique using side-by-side TDR and WCR measurements to improve WCR-VWC calibration accuracy. The approach is to calibrate the continuously logging WCR to occasional simultaneous TDR readings. If effective, the result is continuous WCR data with an accuracy approximating that of TDR. It requires TDR rods, which can be manufactured or purchased at relatively low cost, and access to a TDR unit. The potential cost advantage over the use of TDR alone is that multiple sites can be calibrated with occasional access to a TDR unit, as opposed to dedicating separate TDR units to each site for the entire study duration.

## MATERIALS AND METHODS

The study was conducted at two sites within the Dry Creek Watershed near Boise, ID. At each site, two soil pits were excavated by hand, about 1.5 m apart. Below 15 cm, the soil was very uniform with increasing depth at both sites (Table 1). Pits 1 and 2 (P1, P2) were located at the lower site (1140 m) where soils are classified as coarse-loamy, mixed mesic, Pachic Ultic Haploxeroll. Pits 3 and 4 (P3, P4) were located at the upper site (1660 m) where soils are classified as coarse-loamy, mixed mesic Ultic Haploxeroll (Harkness, 1997). Soil samples were collected for each genetic horizon in P2 and P4. The soil textures were determined by the hydrometer method (Gee and Bauder, 1986) for five subsamples from each horizon and are presented in Table 1.

In each pit, sensors were installed horizontally at several depths ranging between 5 and 100 cm. Water content reflectometer measurements were replicated in the pair of soil pits at each site (one WCR profile per pit). Time domain reflectometry sensors, however, were installed in only one pit per site (Table 2). A 20 cm long, three pin TDR waveguide (Soil Moisture Equipment, Inc., Goleta, CA) was placed adjacent to the WCR probes for calibration in one of the pits at each site (P1 and P4). Sensor depths for the four pits are presented in Table 2. The WCRs were sampled at 15 min intervals and logged on a CR10X data logger (Campbell Scientific, Inc., Logan, UT). The TDR data were collected manually over 2 yr with a Trase TDR (Soil Moisture Equipment, Inc., Goleta, CA) at dates selected to capture the greatest range in soil moisture at the site, and converted to VWC using the Topp et al. (1980) equation.

The absolute accuracy of this paired-sensors calibration approach is dependent on the accuracy of the TDR measurements. To verify this accuracy, laboratory calibration was conducted with soil collected from the lower site, which had higher clay content and was therefore less likely to behave according to the Topp equation (Topp et al., 1980). For the laboratory calibration, a 33 cm long, 10 cm diameter polyvinyl chloride (PVC) column was packed uniformly with four predetermined water contents (0.08, 0.16, 0.24, and 0.34 $m^3$ $m^{-3}$). Time domain reflectometry measurements were made with a 30-cm three-rod probe and TDR100 wave generator (Campbell Scientific Inc., Logan, UT). Soil volumetric water content was determined after each measurement by determining the weight change on oven drying of the soil volume. Use of these results to verify the accuracy of the Trase TDR measurements taken in the field relies on the assumption that since the TDR units operate at approximately the same frequency (1 GHZ), any difference between TDR units is likely to be very small relative to the difference with the WCR, which operates and a much lower frequency (around 50 kHz). A previous (unpublished) comparison between the Trase and Tektronix TDR (Tektronix, Inc., Beaverton, OR) and found that $K_a$s determined manually from the waveforms (using standard tangent approach) yielded practically the same results over a wide range of $K_a$ and with four different soils.

Given the established high precision of the WCR (Seyfried and Murdock, 2001) we were interested in the accuracy of the standard calibration (provided by the manufacturer) relative to the TDR reference measurements and the effects of differing soil type and individual sensor response on the TDR–WCR calibration. We used combined data from all depths at P1 and P4 to evaluate the standard calibration accuracy. For the soil-specific calibrations, overall regressions were developed for data collected from TDR–WCR sensor pairs in P1 and P4, respectively. Individual sensor calibrations were developed between TDR probes in P1 and WCR probes at similar depths in P1 and P2, and between TDR probes in P4 and WCR probes in P3 and P4 (Table 2). The relationships between field TDR and WCR measurements were quantified using both linear and quadratic regressions, with TDR as the dependent variable and WCR as the independent variable. Linear regressions were selected because the quadratic form did not provide an appreciably better fit and was nearly linear in any case (e.g., Risler et al., 1996). Uncertainty in field calibrations was estimated by the maximum standard error of the individual predicted values obtained from regression analyses (Table 3). All regressions were fit using PROC REG in SAS version 8.2 (SAS Institute Inc., Cary, NC).

## RESULTS AND DISCUSSION

The sites provided ideal field conditions for sensor performance in that the most common TDR calibration (Topp et al., 1980) has been shown to be especially effective for coarse-textured soils. The soils of the two sites were both coarse loamy, but differed appreciably in both sand and clay content. The soil at the upper site (P3, P4) is a sandy loam and contained an average of 75% sand and 8% clay, as compared with the loam soil at the lower site (P1, P2), that contained an average of 49 and 16% sand and clay (Table 1). In laboratory tests using soil from the lower site, the Topp et al. (1980) TDR calibration was found to fit the gravimetrically determined VWC data very well ($R^2 = 0.995$, $n = 4$), with the maximum calculated standard error (0.015 m $m^{-3}$) similar to the typical error in application of the Topp et al. equation (Jones et al., 2002). Since the clay content of the upper site was less than that of the lower site, we assumed the TDR calibration performed at least as well for that soil.

The overall regression developed for all paired TDR–WCR probes in the study did not result in an appreciably better calibration than the standard factory calibration. The maximum standard error for the in situ regression approach (0.025 $m^3$ $m^{-3}$) (Table 3) is similar to the error estimate associated with the standard calibration (0.03 $m^3$ $m^{-3}$). We attribute this to the high degree of scatter in the data within and between the two sites.

The site-specific regressions show a difference in accuracy of WCRs between the P1 and P4. The linear regression and associated standard error values are compared with the standard WCR calibration curve and the manufacturer's specified range of error in Fig. 1. The overall in situ linear regression for P1 (Table 3) fitted the data much better than the standard WCR calibration curve (Fig. 1a), perhaps due to the influence of the higher clay content (Table 1) at the lower site on the WCR response. This is consistent with Seyfried and Murdock (2001), who found that increasing clay content generally resulted in higher measured periods for a given VWC. On the other hand, the TDR–VWC data for P4 were reasonably well represented by both the overall in situ linear regression relationship and the (quadratic) standard WCR calibration curve (Fig 1b). Much of the data for both sites fell near or outside the ±3% error bounds specified by the manufacturer (Fig. 1). Assuming this range of error, and that the differences in sensor response conspire to populate the full range of error, the total measurement error of 6% VWC is approximately one quarter of the annual range in VWC for these soils. The overall in situ calibration reduced the error estimate to ±1.9% VWC for P1 and ±2.7% VWC for P4. Whereas the accuracy of the standard WCR calibration may be improved for some soils by developing a soil-specific in situ calibration, (Fig. 1a) the degree of scatter in the data remained a considerable obstacle to the error estimate associated with the overall calibration.

Individual calibrations of each WCR–TDR sensor pair by linear regression were developed based on the observation that the trends between individual sensor pairs in Fig. 2 are quite linear and the error in the overall relationship is primarily due to variability in the offset constant among the individual WCR sensors. We also extended this approach to develop calibration relationships for unpaired WCR sensors at the same depths, but in different soil pits as the reference TDR probes (Fig. 2). The linear form of this calibration is much simpler than the quadratic factory calibration and fits the data well for all WCR-TDR sensor pairs.

Considerable improvement in the accuracy of the WCR output was achieved by reducing uncertainty related to the specific offset value for each sensor. Individual sensor calibration also improves the precision of the measurement technique by reducing the error estimate for most of the WCRs to near ±1% VWC, relative to TDR (Table 3).

The significant differences between sensor pairs may be attributed either to inter-sensor variability or to soil differences between profile locations that result in a linear calibration difference. We think the former explanation more likely because (i) the approximately linear differences between sensors are consistent with previous observations of inter-sensor variability (Seyfried and Murdock, 2001), (ii) the profiles are separated by a short distance (1.5 m) and soils at both sites are quite uniform with depth, and (iii) correlations, in terms of $R^2$, are about the same in mated and unmated profiles. These data contradict the previous finding of Seyfried and Murdock (2001) that inter-sensor variability could be effectively described with a linear calibration offset determined from a single reading in air. We found that the use of pre-installation air readings did little to describe inter-sensor variability in these field soils. Apparently, the small sample size (three) in the Seyfried and Murdock (2001) investigations was insufficient to characterize WCR sensors.

Application of the in situ linear regression calibrations to the time series output from the WCR probes resulted in more sensible and useful representations of the VWC records from both sites. At the upper site, correction of the subtle positive and negative offsets in period output for the 15- and 30-cm probes rectified an apparent inversion of the soil moisture profile record between P3 and P4 at these depths. Using the factory calibration, the continuous data record from P4 15 cm appears offset to relatively higher VWCs than the records from the P4 30-cm, P3

15-cm, and P3 30-cm probes (Fig. 3a). Under dry summer conditions, this shift results in a higher representation of residual VWC at P4 15cm than at P4 30cm. Under the relatively steady drainage flux from the bottom of the snowpack, the factory calibrated soil moisture content at P4 15 cm dramatically exceeded that at P4 30 cm (Fig. 3a), despite their very similar soil textures (Table 1). These inconsistencies are resolved by the linear calibration approach, for which the data record shows similar and sensible soil moisture patterns at both P3 and P4 (Fig. 3b), with the summer VWC decrease greater near the surface at 15 cm and similar soil moisture contents within P4 and P3 at the 15- and 30-cm depths under wet conditions.

Comparison of the time series data from P1 and P2 (Fig. 4) by both the factory and in situ calibration further demonstrates the utility of extending the in situ calibration to sensors nearby, but not adjacent to, the reference measurements. The soil moisture representations by the standard calibration for P1 (Fig. 4a) and P2 (Fig. 4b) show a considerably different range of soil moistures within the profile, primarily due to the relative offsets in response in the P2 sensors. Although the soil moisture representations from P2 increase systematically with depth, the data do not make hydrologic sense. Given the relative uniformity of the soil texture, and the small water inputs to the pits, either from precipitation or lateral subsurface flow, it is highly improbable that the soil moisture content at 100 cm during the dry season would exceed that at 5 cm during the wet season. Application of the linear regressions to P1 sensors reduces the magnitude of the soil moisture representations at all depths somewhat, but similar calibration of the WCR data for P2 results in a dramatic decrease in the soil moisture representations for all sensors. Thus the soil moisture records at both pits were similar and made hydrologic sense for all probes at the depths of the reference (TDR) measurements.

Sensor response may vary with production run or field installation or both. Once the accuracy deficiency associated with the individual sensor offset is addressed we note that the sensors are sensitive to small changes in soil moisture content and may allow precise measurement of the absolute value as well as the changes in soil moisture content.

The lower uncertainty from individual sensor pair calibrations has as dramatic an effect on the utility of the data as does the improvement in accuracy, when applied to the WCR VWC time series data. Use of the factory calibrated WCR response and associated range of error (±3%) resulted in no significant difference between the VWC traces at 15 and 65 cm for the 3 yr of record (Fig. 5). On the other hand, the field calibrated VWC values were significantly different at 15 and 65 cm for much of the period of record (Fig. 5). Whereas Seyfried and Murdock (2001) found individual WCR sensors to be very precise in response to changes in VWC, this precision is only of value for measuring changes in VWC at a point and is overwhelmed by the measurement uncertainty when comparing the VWC at two or more points. Therefore, we consider the reduced uncertainty in WCR response from field calibration as a clear improvement in the technique for quantitative research.

## Method Limitations

Our data indicate that soil and inter-sensor variability can be effectively field calibrated with TDR resulting in water content measurements that approximate the accuracy of TDR. The ultimate limitation of the method is tied to the limitations of TDR. Thus, paired-sensor calibration in saline or high clay content soils will be problematic if not impossible. Although the TDR calibration (Topp et al., 1980) is relatively robust, issues of TDR calibration arise for some soils and applications. A second limitation is that the method requires installation of TDR waveguides and access to a TDR unit, which both result in additional costs. The cost benefit of the method relative to the use of dedicated TDR are most evident where multiple, dispersed sites are instrumented. The additional cost of TDR compared with gravimetric sampling, which can provide an alternative calibration, must be weighed against the destructive nature of gravimetric sampling, the difficulty of obtaining accurate bulk density data and the confounding effects of spatial variability on soil water content between the sample and measurement location. The latter may be considerable in soils with strong horizonation or nonuniform vegetation or microtopography because small variations in clay content, wetting front distribution, or plant extraction of water may result in significant variations in VWC at a specific depth.

## SUMMARY

The WCRs were precise and reliable, responding to both annual and event based changes in soil moisture content under field conditions for 4 yr. There was strong correlation between WCR period and TDR VWC within the experimental sites and excellent correlation between individual WCR/TDR sensor pairs. At the upper site, the standard calibration equation described data well for the overall sensor comparison, but there was a fairly large degree of scatter. Examination of the data indicated that the scatter was due to variable performance of individual sensors. At the lower site, the standard calibration substantially misrepresented the overall WCR/TDR relationship, apparently due to the higher clay content at that site. Individual sensor calibration greatly improved the WCR representation of soil moisture by correcting for inter-sensor variability. The inter-sensor variations can be largely described by offsets, as represented in the developed linear regression equations, which are different from those previously derived from measurements in air. Application of the individual in situ calibrations resulted in much more reasonable soil water profile comparisons between pits at the lower site and less uncertainty in the VWC values than did the standard calibration. The effectiveness of the calibration procedure depends on soil properties, experimental design, and the objectives of the research.

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**Fig. 1. Overall linear regression and associated standard error values, as compared with the standard WCR calibration curve and the manufacturer's specified range of error for P1 and P4.**

**Fig. 2. Linear regression calibrations for individual WCR-TDR sensor pairs.**

**Fig. 3. Comparison of soil moisture records in P3 and P4 at 15 and 30 cm, as represented by the standard WCR calibration (a) and individual in situ calibrations (b).**

**Fig. 4. Comparison of application of standard WCR calibration curves to time series WCR sensor output from (a) P1 and (b) P2 to application of individual linear calibration curves developed in situ at (c) P1and (d) P2.**

**Fig. 5. Upper and lower bounds to the ranges of error for the (a) factory calibrated and (b) in situ calibrated 15 and 65 cm WCR response for the period May 1999 to April 2002.**

**Table 1. Soil texture and depths of genetic horizons for one soil pit from each site.**

| | Genetic horizon | Depth | Sand | Silt | Clay |
|---|---|---|---|---|---|

| | | cm | % | | |
|---|---|---|---|---|---|
| **P2** | **A11** | **0–14** | **48.6** | **39.6** | **11.9** |
| | **A12** | **14–50** | **50.0** | **34.6** | **15.5** |
| | **B21** | **50–88** | **50.3** | **34.0** | **15.7** |
| | **B22** | **88–115** | **46.1** | **34.7** | **19.2** |
| | **> B22** | **90–130** | **50.8** | **31.8** | **17.4** |
| **P4** | **A11** | **0–8** | **76.3** | **16.8** | **6.9** |
| | **A12** | **8–26** | **73.6** | **18.2** | **8.2** |
| | **B2** | **26–54** | **74.4** | **17.1** | **8.5** |
| | **C1** | **54–70** | **77.2** | **15.7** | **7.1** |

**Table 2. Sensor locations and depth of placement from soil surface (cm).**

| TDR P1 | WCR P1 | WCR P2 | WCR P3 | TDR P4 | WCR P4 |
|---|---|---|---|---|---|
| 5 | 5 | 5 | 5 | 5 | 5 |
| 15 | 15 | 15 | 15 | 15 | 15 |
| 30 | 30 | 30 | 30 | 30 | 30 |
| 50 | 50 | 60 | 60 | 45 | 45 |
| 100 | 100 | 100 | 100 | 60 | 60 |

**Table 3. In situ calibration equations obtained for each WCR-TDR sensor pair by linear regression of paired response.**

| TDR | WCR | slope | intercept | $R^2$ | Maximum std. error |
|---|---|---|---|---|---|
| P1,P4 | P1,P4 | 0.62 | -0.45 | 0.84 | 0.025 |
| P1 | P1 | 0.70 | -0.54 | 0.92 | 0.019 |
| P4 | P4 | 0.60 | -0.42 | 0.81 | 0.027 |
| P4 5cm | P3 5cm | 0.55 | -0.40 | 0.93 | 0.016 |
| P4 5cm | P4 5cm | 0.60 | -0.43 | 0.88 | 0.022 |
| P4 15cm | P3 15cm | 0.77 | -0.58 | 0.98 | 0.009 |
| P4 15cm | P4 15cm | 0.70 | -0.54 | 0.99 | 0.008 |
| P4 30cm | P3 30cm | 0.82 | -0.62 | 0.99 | 0.004 |
| P4 30cm | P4 30cm | 0.77 | -0.56 | 0.99 | 0.006 |
| P4 45cm | P4 45cm | 0.87 | -0.66 | 0.99 | 0.006 |
| P4 60cm | P3 60cm | 0.78 | -0.60 | 0.99 | 0.006 |
| P4 60cm | P4 60cm | 0.72 | -0.57 | 0.97 | 0.009 |
| P4 60cm | P3 100cm | 0.74 | -0.57 | 0.99 | 0.005 |
| P1 5cm | P1 5cm | 0.71 | -0.53 | 0.93 | 0.021 |
| P1 5cm | P2 5cm | 0.96 | -0.71 | 0.96 | 0.016 |
| P1 15cm | P1 15cm | 0.75 | -0.61 | 0.99 | 0.009 |
| P1 15cm | P2 15cm | 0.85 | -0.63 | 0.97 | 0.013 |
| P1 30cm | P1 30cm | 0.80 | -0.66 | 0.98 | 0.009 |
| P1 30cm | P2 30cm | 0.72 | -0.59 | 0.97 | 0.011 |
| P1 50cm | P1 50cm | 0.84 | -0.67 | 0.98 | 0.008 |
| P1 50cm | P2 60cm | 0.84 | -0.74 | 0.94 | 0.014 |
| P1 100cm | P1 100cm | 0.82 | -0.66 | 1.00 | 0.002 |
| P1 100cm | P2 100cm | 0.66 | -0.59 | 0.98 | 0.010 |