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Frequency, electrical conductivity and temperature analysis of a low-cost capacitance soil moisture sensor

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Summary This study evaluated the family of ECH_2O sensors (EC-5 and ECH_2O-TE) for measurement of soil moisture content (θ), bulk electrical conductivity (EC_b) and temperature for a range of soils, across a range of measurement frequencies between 5 and 150 MHz. Measurement frequency is one of the primary factors affecting the sensitivity of capacitance sensor measurements to soil variables such as soil texture, electrical conductivity, and temperature. Measurements in both soil and solution demonstrated that the ECH_2O EC and TE measurements were accurate. Using a measurement frequency of 70 MHz, a single calibration curve was determined for a range of mineral soils, independent of soil salinity, suggesting there might be no need for a soil specific calibration. When combining all data for each soil type, the R^2 values remained high ($R^2 = 0.98$) with little probe to probe variability. After laboratory calibration, the error for θ was about 2%, independent of soil EC_b, up to a soil solution EC of about 12 dS/m. Our results showed that a single calibration curve could be used for all tested mineral soils, independent of soil salinity. The bulk soil EC_b – water content data were excellently described by a polynomial expression. Measurements of temperature sensitivity to soil water content and EC_b were sufficiently small. For example, for a temperature change of 10 °C, measurements of θ and EC_b were affected by about 0.02 cm^3 cm^{-3} and 0.02 dS/m, respectively. Limited sensor calibration requirements are important, when large networks of soil moisture sensors are being deployed. It is concluded that an accurate, cost-effective soil moisture sensor is available that operates at a measurement frequency of 70 MHz, with a low sensitivity to confounding soil environmental factors.

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Introduction

Accurate soil water content measurements are critical for estimation of energy and water balances, as well as for understanding chemical and biological processes in vadose zone, plant root zones, and in groundwater. Reviews of the state-of-the-art soil moisture measurement techniques were presented in Hopmans et al. (1999) and Robinson et al. (in press), including geophysical and remote sensing techniques. Recent advances in dielectric and electrical conductivity measurements in soils using time domain reflectometry (TDR) was presented by Robinson et al. (2003). Other promising techniques include ground penetrating radar (Huisman et al., 2003), electromagnetic induction, DC resistivity and electrical resistivity tomography (ERT), passive and active remote sensing, and heat pulse sensors (Mori et al., 2003). Among all the techniques developed to measure soil water content (θ), electromagnetic methods to infer water content have received the most attention. The ability of electromagnetic waves to determine characteristics of porous media has been recognized for most of the last century and earlier (Maxwell, 1881; Fricke, 1924; Velick and Gorin, 1940; Fricke, 1952; Thevanayagam, 1995), while the identification of the most effective measurement frequencies has been more recent (Rinaldi and Francisca, 1999). Because of the measurement ease and datalogging capabilities, TDR and capacitance measurements are increasingly becoming the method of choice.

Capacitance and frequency domain reflectometry techniques offer an excellent alternative to TDR, because of their lower cost, among other reasons such as allowing continuous monitoring, data logging capabilities, repeatability, and applicability to a wide range of soil types (Nadler and Lapid, 1996; Mohamed et al., 1997; Seyfried and Murdock, 2001; Seyfried and Murdock, 2004). But, because these sensors often operate at the low end of or below the frequency range of TDR, they are often criticized for being more susceptible to soil environmental effects (Chen and Or, 2006). Still, both types of measurement are widely used in research and commercial applications. Studies continue to determine the effects of soil environment variables like temperature, electrical conductivity (EC), and soil type that effect the accuracy and reliability of the measurement (Topp et al., 2000; Funk, 2001; Seyfried and Murdock, 2004; Zhang et al., 2004; Jones and Or, 2004; Chandler et al., 2004; Logsdon and Laird, 2004; Kelleners et al., 2005).

Measurement frequency is one of the primary factors affecting the sensitivity of capacitance sensor measurements to soil variables such as soil texture, electrical conductivity, and temperature. Considerable work has been done to determine optimal measurement frequencies, but some has been contradictory. Campbell (1990) determined that a measurement frequency of 50 MHz was required to result in stable real soil dielectric permittivity values. However, Kelleners et al. (2005) concluded that measurement frequencies must be above 500 MHz for stable dielectric permittivity values, whereas Chen and Or (2006) concluded that measurement frequency should be equal or greater than 100 MHz to minimize Maxwell–Wagner polarization. Interestingly, each of these three studies focused on different aspects of measurement sensitivity (i.e. temperature, salinity, and soil texture), thereby arriving at different conclusions. Yet, the general outcome of all studies was that high measurement frequencies are required for accurate soil water content measurement, while minimizing sensitivity to changes in soil electrical conductivity and temperature.

Several benefits are achieved by combining dielectric with soil temperature and electrical conduction measurements. First, by measuring several parameters at the same time and place, the coupling of related transport properties are determined in concert, thereby allowing examination of the nature of their interdependency, such as for the coupled transport of water and solute, as well as water and heat. Second, by using the same instrument for various measurements within approximately the same measurement volume at about the same time, the need to interpolate different measurement types in space and time is largely eliminated (Šimůnek et al., 2002; Mortensen et al., 2006). Third, including temperature and EC measurements allows correction for the capacitive measurements, if so required.

The recent development of the-ECH$_2$O-TE sensor (Decagon Devices Inc), as used in the current study, allows for detailed monitoring of soil water content, solute concentration and temperature. However, little is known about the accuracy of this sensor, and the dependency of measurements on soil type and temperature, for example as evaluated for TDR (Topp et al., 1980; Pepin et al., 1995; Or and Wraith, 1999; Seyfried and Murdock, 2004). Typically, prior to field deployment, soil water monitoring devices will require a rigorous laboratory evaluation and calibration for a range of soil types. Evaluation of soil moisture sensors were conducted by Leib et al. (2003), Jones et al. (2005), and Blonquist et al. (2005). Various ECH$_2$O probe models were recently evaluated by Bogena et al. (2007), pointing out the sensitivity of sensor readings to supply voltage, temperature and bulk soil electrical conductivity. Because of the advancing field of wireless and sensor technologies, there is the also the increasing need to deploy distributed soil moisture sensor networks across increasing spatial coverages. Consequently, soil moisture sensor costs is becoming among the more important sensor qualities.

The objective of the presented study was to evaluate the accuracy of the family of ECH$_2$O probes for soil moisture measurements, and to determine effects of measurement frequency in 5–150 MHz range. Moreover, we determined calibration relationships of bulk soil EC for various soil types. Laboratory experiments were designed to determine the accuracy of this particular sensor and the variation between probes, including temperature effects, and to calibrate the soil moisture sensor for a wide range of soil water content, soil salinity and temperature conditions. We anticipate that the results from this study will lead to better use of these sensors in future field soil water, EC and temperature monitoring programs, while facilitating better interpretation of data currently being collected.

Materials and methods

The fundamental relationship between soil dielectric permittivity and volumetric water content, θ, is well understood. Because the dielectric of water is about 80, while other soil constituents are between 1 and 5, changes in soil dielectric permittivity are highly correlated with soil water content. However, it is well known that other soil environmental factors affect the measurement, such as soil texture, electrical conductivity (*EC*), and temperature (Seyfried and Murdock, 2001; Seyfried and Murdock, 2004; Chandler et al., 2004; Czarnomski et al., 2005).

Consequently, many dielectric techniques require soil specific calibrations which create an added level of soil input that is not necessarily available. In addition, permittivity is a function of temperature, so that temperature changes affect the measured θ, however, it has proven difficult to deal with, because of the complex nature of the underlying processes. Or and Wraith (1999) reported on the complex interactions between soil particle surfaces and surrounding water molecule dipoles that cause water to be invisible to the TDR measurement at high measurement frequencies. Changes in the complex dielectric constant due to temperature and electrical conductivity have also been reported at frequencies below 100 MHz (Thevanayagam, 1995; Rinaldi and Francisca, 1999; Chen and Or, 2006). This study combines two sets of experiments with different capacitive soil moisture sensors of the same family of ECH_2O probes, which combined yield a comprehensive evaluation of the effects of frequency, *EC*, and temperature on the soil moisture measurement.

The ECH_2O family of sensors measures the water content of the soil using a capacitance technique (Campbell and Greenway, 2005; Bogena et al., 2007). By rapidly charging and discharging a positive and ground electrode (capacitor) in the soil, an electromagnetic field is generated whose charge time (t) is related to the capacitance (C) of the soil by

$$t = RC \ln\left[\frac{V - V_f}{V_i - V_f}\right] \tag{1}$$

where R is the series resistance, V is voltage at time t, V_i is the starting voltage and V_f is the applied or supply voltage. Further, for a capacitor with a geometrical factor of F, the capacitance is related to the dielectric permittivity (ε) of the medium between the capacitor electrodes by

$$C = \varepsilon_0 \varepsilon F \tag{2}$$

where ε_0 is the permittivity of free space. Thus, the ε of the soil can be determined by measuring the change time (t) of a sensor buried in the soil. Consequently, as water has a dielectric permittivity that is much greater than soil minerals or air, the charge time t in the soil of Eq. (1) can be correlated with soil water content.

Probe types

Several prototype soil moisture probes were constructed following the basic design of the original ECH_2O EC-20 probe (Decagon Devices Inc., Pullman, WA), with the new probes having 5.2 cm long prongs. Testing was done with two types of commercialized sensors (EC-5, with a supply voltage of 3.0 V, and ECH_2O-TE), each having the same water content measurement circuitries, but different designs because of the added soil EC and temperature measurements for the ECH_2O-TE, so that the number of prongs was increased from 2 (EC-5) to 3. A thermistor installed in the sensor body provided for soil temperature (°C/°F), and two pairs of gold-plated electrodes on the surface of two prongs of the ECH_2O-TE types acted as a four-probe array to measure bulk soil electrical conductivity, EC_b (dS m^{-1}). Reported calibration experiments were conducted with five randomly selected probes for each of the 2 sensor types. Whereas the results of the EC-5 were achieved over a range of measurement frequencies from 5 to 150 MHz, the ECH_2O-TE probe measured dielectric permittivity measurements at 70 MHz solely. Unless otherwise stated, experiments were conducted in a laboratory with an average air temperature of approximately 22 ± 1 °C, and measured θ (m^3 m^{-3}) was determined from the mineral soil factory calibration for the ECH_2O-TE sensor. All presented soil moisture data for the EC-5 are reported in mV output. A known amount of water was added to a fixed mass of dry soil to achieve pre-determined soil water content values, followed by careful packing of the soil-solution mixture around the sensor (Cobos, 2006). Care was taken to pack the soil evenly so as not to bias the measurements.

Measurement frequency analysis: EC-5

A specially designed EC-5 probe was fabricated to determine the effect of changing EC_b on probe output for a range of measurement frequencies, by submersion in solutions at different electrical conductivities. Data were normalized to an *EC* of 1 dS/m, to facilitate comparison of the acquired data. Additional comparisons were conducted in rockwool (Master, Grodan, Roermond, the Netherlands), to further test the effect of *EC* on probe output across a wide range of water content values.

EC-5 sensors were calibrated by adapting the technique recommended by Starr and Paltineanu (2002). After a reading was taken from the sensor, volumetric water content (θ) was determined after oven-drying (Topp and Ferre, 2002). Four mineral soils (dune sand, Patterson Sandy Loam, Palouse Silt Loam, and Houston Black Clay) were collected to represent a broad range in soil types (Table 1). Soils were crushed in a soil grinder to allow for uniform packing in a 1 L beaker with bulk density ranging between 1.2 g cm^{-3} and 1.6 g cm^{-3} for the various soil types. To achieve a range in bulk soil salinity, water solutions were prepared with different *EC* values, ranging from about 1 to near 12 dS/m, by dissolving pre-determined amounts of salts (Miracle-Grow All Purpose Plant Food (15-30-15), Marysville, OH), prior to soil mixing. After the permittivity measurements, soils

Table 1 Soil texture and EC_w of tested soils

Soil	Sand	Silt	Clay	EC_w
	kg kg^{-1}			dS m^{-1}
Dune sand	0.87	0.03	0.10	0.04
Patterson sandy loam	0.79	0.09	0.12	0.34
Palouse silt loam	0.03	0.71	0.26	0.12
Houston black clay	0.13	0.34	0.53	0.53
Oso flaco sand	1.0	0.0	0.0	0.0
Columbia silt loam	0.68	0.22	0.10	0.33

were oven dried, crushed, and a saturation extract was used to determine soil *EC* (U.S.Salinity Laboratory Staff, 1954).

Sensor calibration: ECH_2O-TE

A simple evaluation of sensor performance was obtained by partial vertical immersion of each sensor's prongs in known salt solutions. The resulting water content output should approximately agree with the fraction of prongs immersed relative to the total prong length (Baker and Lascano, 1989). For example, it is expected that immersion of 1 cm of the sensor corresponds with a sensor output water content of about 20%. This evaluation of the sensor was done for solution concentrations of 0, 0.01, 0.03, 0.06, 0.08, and 0.1 M KCl. Corresponding salinity values when expressing EC_w in dS/m were 0.0, 1.2, 3.5, 7.0, 9.3, and 11.6 dS/m.

A 3 cm tall and 8 cm diameter plexiglass column, with a volume of 0.134 L was used for all soil measurements with the ECH_2O TE. The predetermined soil bulk density used was 1.39 and 1.33 g cm^{-3} for the Oso Flaco sand and Columbia loam soil, respectively. For each of the pre-determined water content values, sensor measurements were conducted for a series of 6 solution concentrations (EC_w) by adding pre-determined amounts of KCl. Approximate soil water content and soil solution concentrations (EC_w) were 0%, 5%, 10%, 15%, 25%, 30%, and 45%, and 0.0, 1.2, 3.5, 7.0, 9.3, and 11.6 dS/m, respectively. Separate soil samples were prepared for each $\theta - EC_w$ combination for a total of 210 soil cores. The measured bulk electrical conductivity (EC_b) data were fitted to the Rhoades et al. (1976) relationship, using the Solver algorithm of MS Excel (Wraith and Or, 1998):

$$EC_b = c_1 EC_w \theta^2 + c_2 EC_w \theta + c_3 \tag{3}$$

where c_1, c_2, and c_3 are the regression coefficients, with c_1 and c_2 related to the soil's tortuosity (Tuli and Hopmans, 2004), and c_3 corresponding to the surface conductance of the soil particles.

Temperature effects: ECH_2O-TE

Since both the EC-5 and ECH_2O-TE have identical water content measurement circuitries, tests were conducted with the ECH_2O-TE only. However, two separate temperature sensitivity experiments were conducted that combined assessed the temperature sensitivity to both θ and soil EC_b.

Temperature sensitivity of θ

A small thermally isolated chamber (43 cm × 37 cm × 20 cm) was constructed to control temperature. A sinusoidal temperature cycle was programmed into the controlling 21X micrologger (Campbell Scientific, Logan, UT) to mimic diurnal temperature changes. Because the 21X controlled air temperature in the range of +5°—45 °C, peak-to-peak media temperature varied depending on thermal properties, but was typically in the range of ±15 °C.

To test the sensitivity of the electronics to temperature, two dielectric sensors were placed in air for several temperature cycles. Subsequently, to evaluate the temperature sensitivity in water, sensors were placed in a beaker of water at a range of temperatures. Sensor response was measured in the standard digital output of the ECH_2O-TE sensor (Counts) that has a range of ~400 in air to ~1300 in water. To test the temperature response in soil, air-dry soil samples of the Dune sand, Patterson sandy loam and Palouse silt loam (Table 1) were mixed with predetermined amounts of water and packed into 250 ml beakers. After complete insertion of the ECH_2O-TE sensor, the soil surface was covered with paraffin wax to prevent soil drying by evaporation and the beaker was placed in the temperature chamber. Soil temperature ranged from +10 to +40 C. Subsequently, two volumetric soil samples were extracted and oven dried to determine the gravimetric θ and these values were averaged to determine θ. The slope, $\Delta\theta/\Delta T$, was determined by linear regression of sensor θ (using the factory calibration) versus temperature for several thermal cycles (>100 data points).

Temperature sensitivity of EC_b

For the ECH_2O-TE sensor, the temperature effect on sensor response was determined by immersion of a column with saturated Oso Flaco sand (0.03 M KCl solution) and the ECH_2O TE sensor in a temperature-controlled water bath (68 cm × 40 cm × 37 cm). This was done to evaluate the internal temperature correction of the ECH_2O TE probe for EC measurements. For each set temperature level, the soil was given ample time to equilibrate before the EC measurement. Temperature data were fitted to a relationship similar to that suggested by Heimovaara et al. (1995) and Amente et al. (2000)

$$EC_b^T = EC_b^{ref}[1 + \alpha(T - T^{ref})] \tag{4}$$

where EC_b^T is the measured bulk electrical conductivity at a given temperature, EC_b^{ref} is the measured bulk *EC* at a reference temperature (25 °C) and α is the temperature coefficient of the bulk electrical conductivity (1/°C). The temperature coefficient was estimated from regression of EC_b^T vs. $(T - T^{ref})$. We note that bulk soil resistance was internally corrected for temperature using a polynomial fit to the saturation paste data presented in US Salinity Laboratory Staff (1954).

Results and discussions

Measurement frequency analysis: EC-5

There were considerable differences in sensor output between measurement frequencies, when immersed in water (data not shown). The 10 MHz sensor changed from approximately 10% full scale (FS) in distilled water to 5% FS in 5 dS m^{-1} water. The sensitivity of the probe to changing salinity decreased with increasing frequency, reaching less than +/− 2% FS for the 75 MHz probe, with results similar to Bogena et al. (2007). Further increases in measurement frequency did not reduce the probe sensitivity any further.

Testing sensor output in rockwool made it possible to determine the effect of EC_b on sensor output for a wide range of water content values. Since measurements for all three frequencies were taken simultaneously, any secondary effects as caused by probe insertion and heterogeneities were eliminated. Rockwool was used for this test, to minimize sensor interactions with the solid phase, because of its high porosity and thus low contribution to bulk dielectric permittivity, and negligible ion interactions in solution. Results for a single sensor in rockwool showed the same reduced sensitivity to bulk *EC* with increasing measurement frequency (Fig. 1), as was observed in water. Interestingly, although the 33 MHz measurement frequency showed some scatter, the 66 and 132 MHz measurements both showed very little EC effects across the volumetric water range between 0 and 0.8 $cm^3\ cm^{-3}$. Therefore, we expect little advantage in further increasing measurement frequency.

A single sensor evaluated in dune sand showed similar results (Fig. 2A and C) to earlier analyses, with a considerable salinity effect at 10 MHz (Fig. 2A), especially for soil saturation extract (EC_w) values larger than 0.65 dS/m. In fact, probe sensitivity to changes in volumetric water content

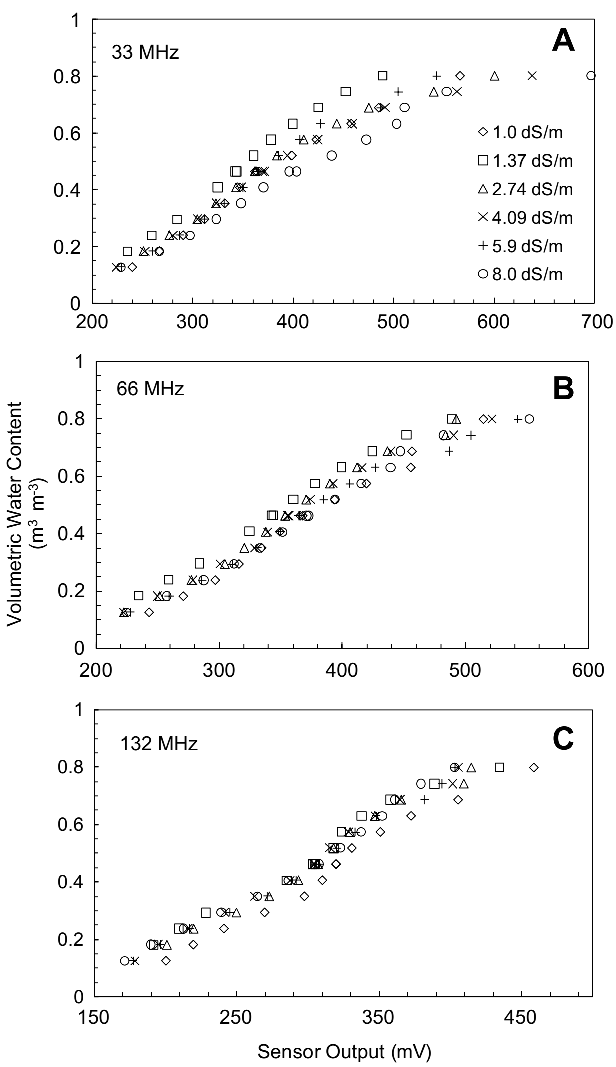

Figure 1 Changes in sensor output voltage over a range of volumetric water contents and solution electrical conductivities in rockwool. A single sensor was programmed to measure dielectric permittivity at 33 (A), 66 (B), and 132 (C) MHz measurement frequency simultaneously.

was noticeably reduced for water content values larger than 0.05 $cm^3\ cm^{-3}$ at the EC_w value of 7.6 dS m^{-1}. However, if a measurement frequency of 70 MHz was applied (Fig. 2C), *EC* effects were negligible or absent, as was found for the rockwool experiment. Results for the Palouse soil did not show much difference between the 10 and 70 MHz frequencies (Fig. 2B and D), though the scattering for the lower frequency was slightly larger. These data support earlier findings by Campbell (2001), who concluded that the *EC* effect was small for a silt loam, using a measurement frequency of 10 MHz. We speculate that the reduced *EC* sensitivity for the silt loam is related to the soil's buffering capacity.

The calibration results of five standard EC-5 sensors for the four soil types combined (Table 1) for a range of EC_w levels are shown in Fig. 3. A least squares analysis of the data provided a linear fit with a model accuracy of +/− 0.033 $m^3\ m^{-3}$ (95% confidence interval). No significant sensor to sensor variation was determined between all tested probes. Statistical comparisons between the slopes of the calibration curves for individual soil type/EC combinations showed no significant difference between 11 of the 12 calibration curves (Table 2). The lack of significant differences between calibration curves for the different salinity levels was not surprising, considering the results of Figs. 1 and 2. Though, we were generally surprised with the similarity of calibrations between the different soils tested, in contrast to similar calibration tests conducted using the EC-20 sensor that showed considerable differences between soil types (Campbell, 2001). It should be noted that the range of the water contents in this dataset was limited to θ values of less than 0.30 $m^3\ m^{-3}$, so it is not clear if these findings will hold true for near soil saturation.

In a similar study, Bogena et al. (2007) collected EC-5 sensor output for a wide range of dielectric solutions (2.2–41.3). Fig. 3 also includes their fitted function (calculated from fitting parameters given in their Table 2 at a supply voltage of 3.0 and converted to θ using Topp et al. (1980)) in comparison to the soil calibration. Interestingly, our data for $\theta > 0.20\ m^3\ m^{-3}$ approximated the Bogena et al. (2007) function very well, however, for $\theta < 0.08\ m^3\ m^{-3}$ there is a considerable offset between the liquid dielectric fit (dashed line in Fig. 3) and our linear soil calibration (solid line). We propose two possible causes, with the first one less likely. The first cause of the discrepancy in the low water content range might be related to the effect of the sealed plastic sensor body (''head'') on the EC-5 sensor reading. Whereas, we buried the entire sensor body for the soil calibration, we expect that the plastic sensor body was not exposed to the dioxane solution in the immersion tests of Bogena et al. (2007). However, effects are expected to account for differences less than 0.01 $m^3\ m^{-3}$ and would have to apply across the whole tested water content range. The second cause for differences could be related to the possible interactions between measurement frequency and dielectric solution type. Specifically, Bogena et al. (2007) used dioxane below a dielectric of 10.8 (0.203 $m^3\ m^{-3}$), while 2-isopropoxyethanol–water mixtures were used for the higher water content range. Interestingly, our data in Fig. 3 coincide with the dielectric data of Bogena et al. (2007) for θ values larger than 0.20 $m^3\ m^{-3}$. Further investigation is warranted.

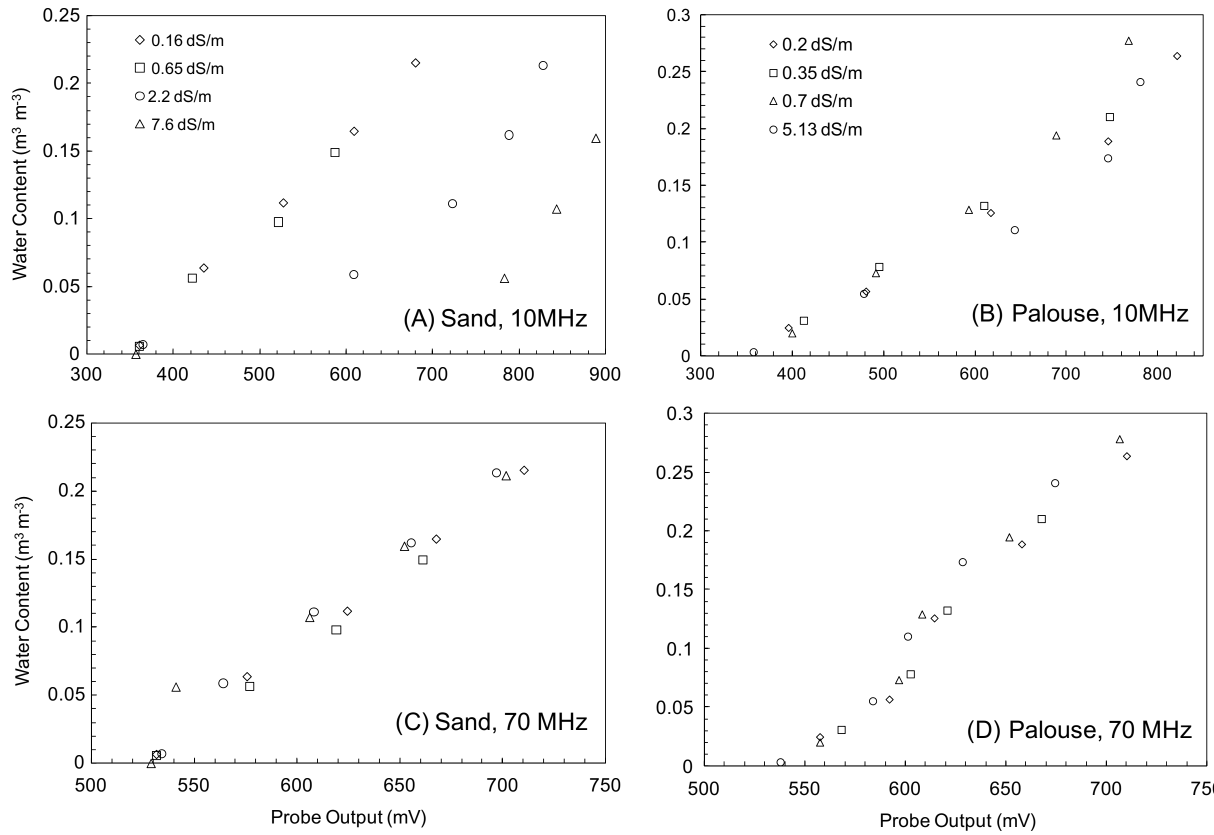

Figure 2 Effect of varying electrical conductivity on the output of 10 (A, B) and 70 (C, D) MHz prototype sensors in dune sand (A, C) and Palouse silt loam (B, D) over a range of water content values.

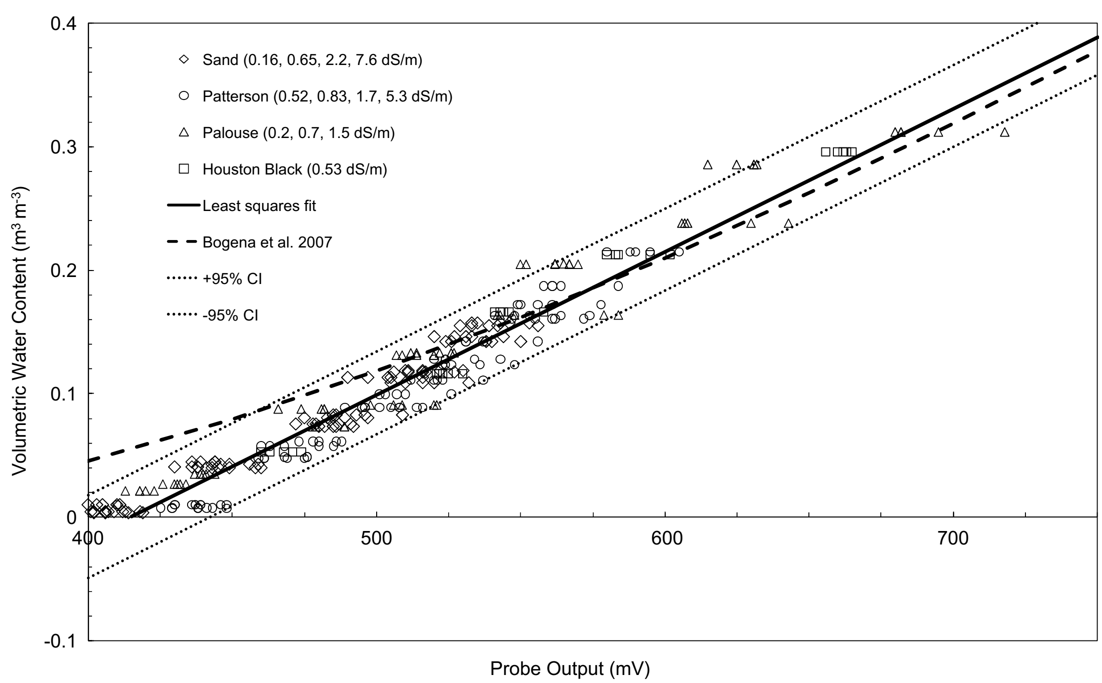

Figure 3 Calibration data for five water content sensors running at 70 MHz in four mineral soils over a range of electrical conductivities (shown in parenthesis). The fitting curve from Bogena et al. (2007) is show for comparison (dashed line), as are the +/ − 95% confidence interval (CI) lines (dotted).

Table 2 Slopes and statistical comparisons between individual soil type/electrical conductivity (EC) combinations

Soil Type	EC_w (dS m^{-1})	Slope of Calibration Curve ($\times 10^{-4}$)*
Sand	0.16	9.8a
Sand	0.65	9.8a
Sand	7.6	9.9a
Patterson	5.3	10.3a
Palouse	1.5	10.3a
Sand	2.2	10.5ab
Patterson	0.52	11.9ab
Patterson	0.83	12.1ab
Palouse	0.2	12.5ab
Patterson	1.7	12.7ab
Houston Black	0.53	12.8ab
Palouse	0.7	13.4b

* Slopes followed by the same letter are not significantly different ($p < 0.01$).

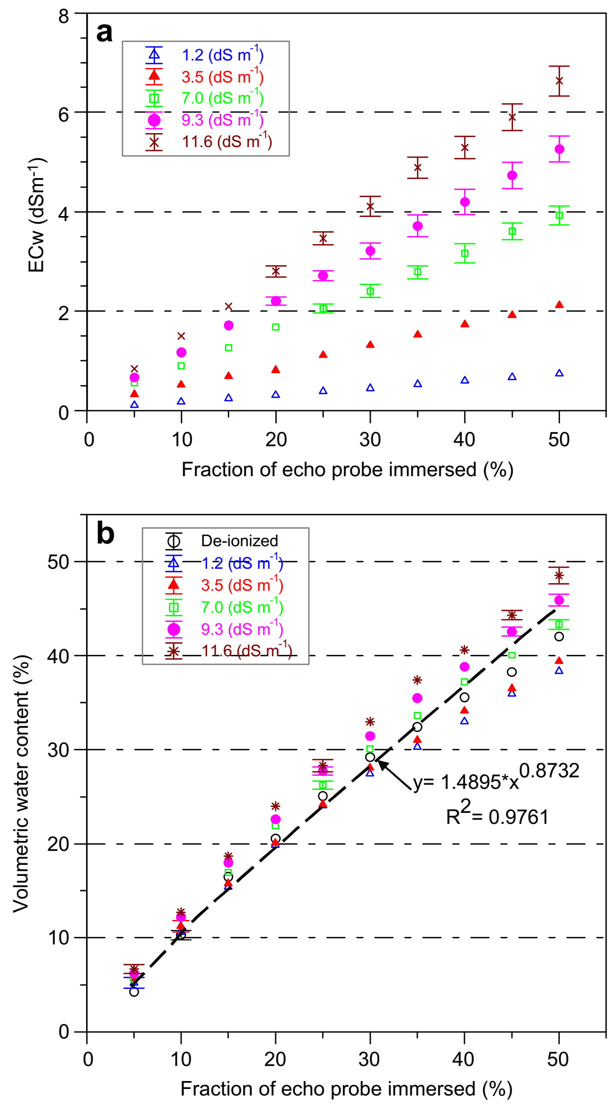

Figure 4 ECH_2O-TE response to partial probe immersion.

Sensor calibration: ECH_2O-TE

Typical results of the partial to full immersion of 5 ECH_2O TE probes for a range of solution concentrations are presented in Fig. 4a (EC_w) and Fig. 4b (θ). Error bars represent the standard error of the mean (SE) among the five sensor measurements. Although not perfect, the immersion test is a quick and simple way to evaluate probe performance. However, we do not suggest that the partial immersion test suffices for soil water content calibration. We specifically note the small SE-values for EC_w-values < 2 dS/m (Fig. 4a), and the presence of a salinity effect on the permittivity readings (Fig. 4b), with increasing data scatter in the higher water content range. In their work on spatial sensitivity of time domain reflectometry, Baker and Lascano (1989) revealed a linear relationship of water content output with the fraction of prongs immersed relative to the total prong length. However, our data suggest that the ECH_2O TE response was slightly nonlinear, and was fitted with an exponential function (Fig. 4b), thus confirming the curvilinear behavior as modeled by a second order polynomial by the manufacturer (Decagon Devices, 2006, 2007).

Regression of sensor temperature and EC in solutions with independently measured temperature and solution EC measurements yielded R^2 values of 0.996 and 0.997 (Table3), respectively, for temperature and EC ranges of 0–45 °C and 0–12 dS m^{-1} respectively. For salinity levels larger than 12 dS m^{-1}, the ECH_2O TE probe significantly underestimated EC, though such salinity levels are rarely attained in most agricultural soils. Likely, relatively high salinity levels are sensitive to the presence of contaminants on the prong surfaces. In the low soil EC range the effects of contamination are expected to be relatively small, because the resistance in the soil dominates the total resistance (Decagon Devices, 2007). The manufacturer stipulates that the optimal probe working range would be 0.1–7.3 dS m^{-1} (Decagon Devices, 2006).

A comparison of the ECH_2O TE measurements with known volumetric water content values for each of the five selected probes and all five probes combined is presented in Fig. 5 for both Oso Flaco and Columbia soil, for the complete range of solution salinity (EC_w) between 0 and 11.6 dS/m. The individual data points for specific water content values represent the various prepared soil solution concentrations. The data show that uncertainty increases with increasing water content, likely because of the corresponding increase of bulk soil salinity with larger water content values. When combining the data of all five sensors into a single calibration, the R^2-value remained near 0.98 (Table 3), indicating that no specific probe calibration might be needed. Standard error values varied between 0.012 and 0.026 m^3 m^{-3} between the low and high water content ranges. Our calibration results for the two soils combined support the earlier conclusion that no soil-specific calibration is required for the mineral soils tested in this study.

Whereas separate EC calibrations were conducted for each probe separately, we present the combined data and fitted calibration for all five sensors combined for the Columbia loam (Fig. 6a) and Oso Flaco sand (Fig. 6b).

Table 3 Summary of combined probe calibration functions of the form: $y = \beta_0 + \beta_1 x$

Parameters	β_0	β_1	RMSE*	CV[a](%)	R^2
Probe EC_w (dS m^{-1})	0.181	1.084	0.26	3.08	0.997
Probe temperature (°C)	0.113	1.005	0.09	0.40	0.996
Oso Flaco θ (m^3 m^{-3})	0.005	0.985	0.0147	2.04	0.969
Columbia θ (m^3 m^{-3})	0.010	0.961	0.0181	4.43	0.984
Soils θ combined	−0.003	1.005	0.026	4.58	0.977

* RMSE: root mean square error.
[a] CV: coefficient of variation.

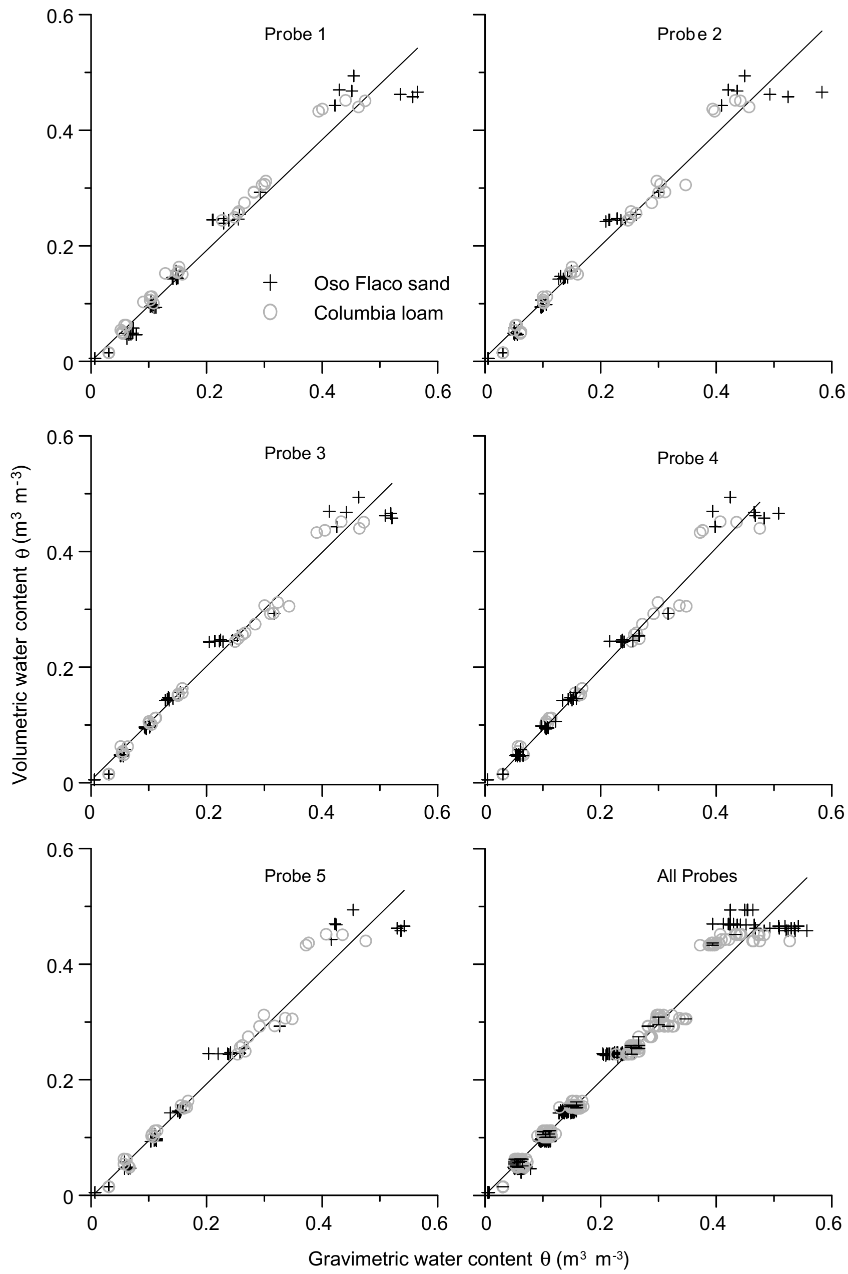

Figure 5 Comparison of individual and combined probe water content (%) with gravimetrically determined volumetric water content (θ gravimetric) for Oso Flaco sand and Columbia sandy loam.

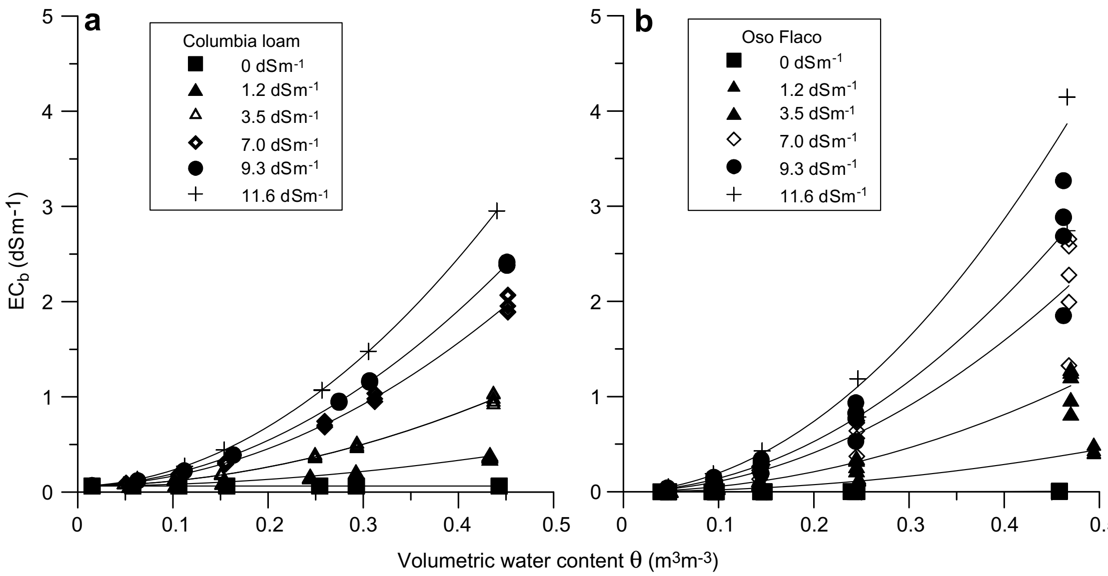

Figure 6 Calibration of 5 $ECHO_2$-TE probes combined for measuring EC_b as a function of water content and solute concentration for Columbia sandy loam (a) and Oso Flaco sand (b).

Table 4 Optimized parameters for Eq. (3) of ECH_2O-TE probe

Oso Flaco sand probe #	Regression coefficients (dS/m)				RMSE (dS/m)
	c_1	c_2	c_3*	R^2	
1	1.28	0.01	–	0.997	0.115
2	1.25	0.05	–	0.995	0.107
3	1.39	0.05	–	0.992	0.097
4	1.50	0.02	–	0.991	0.114
5	2.29	0.01	–	0.975	0.299
All probes combined	1.45	0.02	–	0.990	0.147
Columbia soil probe #					
1	1.04	0.02	0.06	0.999	0.133
2	1.01	0.05	0.07	0.992	0.180
3	1.19	0.02	0.06	0.999	0.161
4	1.18	0.02	0.06	0.996	0.151
5	1.13	0.02	0.05	0.998	0.162
All probes combined	1.12	0.02	0.06	0.997	0.158

* Oso Flaco sand was assumed to have negligible specific surface conductance.

Regression coefficients for each individual probe are listed in Table 4. Except for probe five of the Oso Flaco soil, all R^2 values were larger than 0.99, indicating an excellent fit to the general calibration model of Eq. (3). When combining all data for each soil type, the R^2 values remained high ($R^2 = 0.99$) with little probe to probe variation as evidenced by the small RMSE values of 0.147 and 0.158 dS/m for Oso Flaco and Columbia soil, respectively. As expected, EC_b increases with increasing θ and EC_w, with dependency controlled by the geometry of conducting pore space (soil tortuosity) and soil particles surface conductance (C_3 in Eq. (2)), hence, calibrations to infer soil solution salinity from sensor measurements will be soil specific.

Temperature effects: ECH_2O-TE

The temperature sensitivities of the soil moisture sensor in air and water are presented in Fig. 7. The air data test shows very little sensitivity to temperature, suggesting little effect of temperature on sensor electronics (Fig. 7a). The temperature sensitivity data in water is consistent with theory that dielectric of water decreases with temperature (Fig. 7b). Although Fig. 7b shows some variation in sensor output, it was only about 1% of the full scale sensor output.

The sensitivity of the ECH_2O-TE soil moisture probe to temperature for three soils (Table 1) at various water contents is shown in Fig. 8, with sensitivity values of $\Delta\theta/\Delta T$

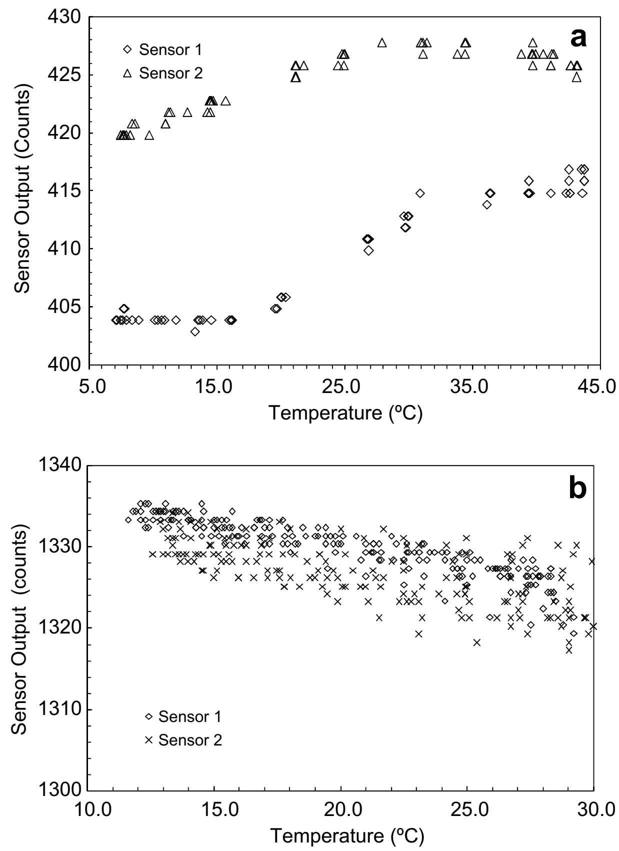

Figure 7 Response of ECH_2O-TE sensor to temperature variation in air (a) and water (b). Sensor data represent the standard raw digital output of the sensor (Counts) where the range from air to water is ~400 counts to ~1300 counts.

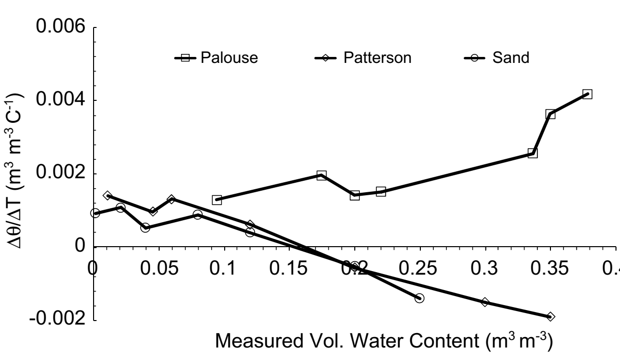

Figure 8 Slopes of the change in θ vs. temperature relationship ($\Delta\theta/\Delta T$) plotted against true θ for the ECH_2O-TE sensor in three soils at various water contents.

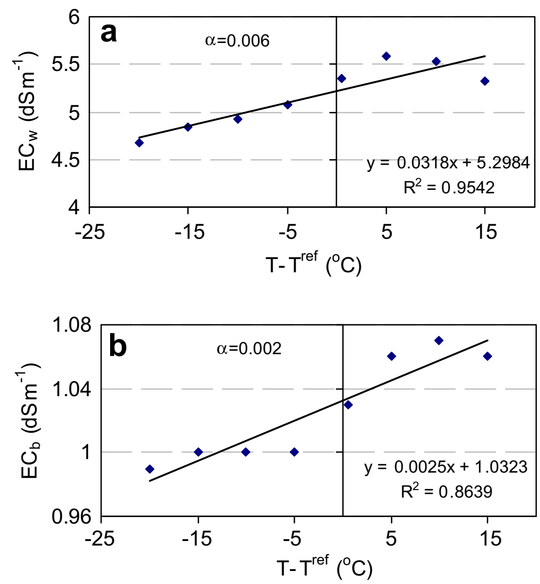

Figure 9 Variation of electrical conductivity with temperature difference in (a) 0.03 M KCl solution and (b) saturation paste of Oso Flaco sand.

around −0.002 to +0.004. Hence, a 10-degree temperature swing causes a change in measured volumetric water content of −0.02 (low θ) to +0.04 $cm^3\,cm^{-3}$ (high θ). The negative $\Delta\theta/\Delta T$ — relationship for the low surface area wet soils (Patterson and sand), and positive $\Delta\theta/\Delta T$ — relationship for the high surface area wet soils (Palouse) supports the theory of Or and Wraith (1999) noted earlier. They suggested that water near the particle surfaces of the finer-textured soils is increasingly becoming ''invisible'' to the dielectric measurement because of surface forces. However, with increasing soil temperatures these surface forces reduce in strength, thereby causing a positive relationship between water content and temperature. However, Seyfried and Murdock (2004) found a low temperature sensitivity of another capacitance sensor at 50 MHz measurement frequency. Interestingly, in their analysis the real and imaginary portions of the dielectric were separated, and they used only the real portion to calculate volumetric water content. Because the imaginary portion of the dielectric contains an electrical conductivity term that is positively correlated with temperature, the true source of the temperature sensitivity needs further investigation. It should be noted that our temperature sensitivities were significantly lower than those reported by Czarnomski et al. (2005), who tested the low-frequency ECH_2O sensor. In practice, soil moisture sensors are buried in the soil, thus dampening air temperature fluctuations.

For the temperature range 0–40 °C, ECH_2O-TE electrical conductivity values displayed minimal sensitivity to temperature changes with α coefficients of 0.006 and 0.002 in solution (Fig. 9a) and for the Oso Flaco sand (Fig. 9b), respectively. The increase of α from 0.002 (Oso Flaco) to 0.006 (solution) may indicate that the temperature effect increases with bulk EC. However, both α-coefficients were much smaller than 0.019 (Heimovaara et al., 1995; Amente et al., 2000), considered to be the default temperature correction value for EC. This suggests that the default internal compensation for temperature is adequate.

Conclusions

The ECH_2O-TE probes yielded accurate and repeatable results hence the calibration equations hold validity for the range of soil moisture and electrical conductivity sampled in this study. Probe uncertainty increased with increasing water content and relatively high EC values may also attenuate the probe pulse signal. Combined calibration equations for soil moisture, electrical conductivity and temperature showed high correlation coefficients suggesting that no specific probe calibration is needed. The study indicates that the ECH_2O-TE probes did not reveal significant differences in θ from the two soils studied but need specific soil calibration relationships to infer soil solution salinity, EC_w.

Increasing the sensor measurement frequency to 70 MHz resulted in various desirable affects. Probe sensitivity to soil electrical conductivity decreased considerably at the higher freqencies, both in salt solutions and in soil compared to the lower frequencies, up to about 150 MHz. No additional improvements were found by increasing the measurement frequency further. In addition, using the 70 MHz frequency, our results showed that a single calibration curve could be used for all tested soils, independent of soil salinity. Although our calibrations applied to five soil types only, the data do suggest that sensor calibration is fairly robust over a limited range of soil types, bulk densities, and electrical conductivities. Limited sensor calibration needs will be an important factor, when large networks of soil moisture sensors are being deployed.

Temperature sensitivity did not change as a result of the higher frequency, but appears to be correctable through data processing. Still, the temperature dampening effect of soil will reduce the need for temperature correction in many applications.

Although other studies have suggested that higher measurement frequencies are attractive to mitigate the effects soil type, temperature and EC, this study shows significant improvement even at the 70 MHz level. Because the move to higher frequencies is concomitant with increasing expense of electronics and therefore sensors, it is an important conclusion of this work that a sensor can be produced to accurately measure volumetric water content with a low sensitivity to confounding environmental factors.

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