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Short, Multineedle Frequency Domain Reflectometry Sensor Suitable for Measuring Soil Water Content

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Short, Multineedle Frequency Domain Reflectometry Sensor Suitable for Measuring Soil Water Content

Abstract
Time domain reflectometry (TDR) is a well-established electromagnetic technique used to measure soil water content. Time domain reflectometry sensors have been combined with heat pulse sensors to produce thermo-TDR sensors. Thermo-TDR sensors are restricted to having relatively short needles to accurately measure soil thermal properties. Short needle lengths, however, can limit the accuracy of the TDR measurement of soil water content. Frequency domain reflectometry (FDR) sensors are an alternative to TDR sensors that can provide an inexpensive measurement of soil water content. The objective of this study was to determine whether short FDR sensors can accurately measure soil water content. We designed and constructed a short FDR sensor. For four soil types across a range of water contents, temperatures, and salt contents, we measured soil dielectric spectra with the short FDR sensor. A vector network analyzer was used to obtain soil dielectric spectra in the 1-MHz to 3-GHz frequency range. The ideal frequency of a short FDR sensor is the frequency at which the permittivity is not altered by changing temperature or salt content. The 47- to 200-MHz range was an ideal frequency range for measuring soil water content, and 70 MHz was the frequency least influenced by temperature and salt content. The short FDR sensor provided quick, continuous, stable, and cheap measurements of soil water content. Because of the promising performance of the short thermo-FDR sensor in laboratory studies, sensors should be evaluated in future field studies.

Disciplines
Agriculture | Hydrology | Soil Science

Comments

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Time domain reflectometry (TDR) is a well-established electromagnetic technique used to measure soil water content. Time domain reflectometry sensors have been combined with heat pulse sensors to produce thermo-TDR sensors. Thermo-TDR sensors are restricted to having relatively short needles to accurately measure soil thermal properties. Short needle lengths, however, can limit the accuracy of the TDR measurement of soil water content. Frequency domain reflectometry (FDR) sensors are an alternative to TDR sensors that can provide an inexpensive measurement of soil water content. The objective of this study was to determine whether short FDR sensors can accurately measure soil water content. We designed and constructed a short FDR sensor. For four soil types across a range of water contents, temperatures, and salt contents, we measured soil dielectric spectra with the short FDR sensor. A vector network analyzer was used to obtain soil dielectric spectra in the 1-MHz to 3-GHz frequency range. The ideal frequency of a short FDR sensor is the frequency at which the permittivity is not altered by changing temperature or salt content. The 47- to 200-MHz range was an ideal frequency range for measuring soil water content, and 70 MHz was the frequency least influenced by temperature and salt content. The short FDR sensor provided quick, continuous, stable, and cheap measurements of soil water content. Because of the promising performance of the short thermo-FDR sensor in laboratory studies, sensors should be evaluated in future field studies.

Abbreviations: FDR, frequency domain reflectometry; TDR, time domain reflectometry; VNA, vector network analyzer.

Soil water content is very important for agricultural production. It is used for determination of the soil water balance and the transport of chemicals to plants and groundwater and for irrigation management. It is a basic hydrologic condition that affects groundwater recharge, surface water flow, and transpiration. Measuring soil water content quickly and accurately is important.

There are many ways to determine soil water content. Several nondestructive methods have been devised to measure soil water content, including neutron thermalization, electrical resistance, and soil dielectric properties (Topp and Ferré, 2002). The electrical techniques provide data that can be collected nearly continuously and either stored on site or transmitted to a computer via mobile telecommunications. They have gained wide acceptance because they can deliver fast, in situ, repeated, nondestructive, and accurate measurements. Soil dielectric properties are related to soil water content. Dielectric properties are intrinsic material properties. They can be used to develop robust models independent of specific measurement techniques. Studying the dielectric properties also contributes to the understanding of the dielectric behavior of the soil, which can lead to improved sensing technology. Time domain reflectometry, FDR, and capacitance are the three main ways to measure the soil water content based on dielectric properties.
Recent improvements in electronics have increased the accuracy of dielectric property measurements (Robinson et al., 2003; Kellerers et al., 2005).

Time domain reflectometry is a technique traditionally used to determine the spatial location of cable faults. Topp et al. (1980) extended TDR applications to determine soil volumetric water content. Topp et al. (1982) developed a TDR system that was able to measure in situ soil electrical properties (Petrinelli et al., 2002). Time domain reflectometry was adapted to estimate the soil water content (Hoekstra and Delaney, 1974; Topp et al., 1980) and soil bulk electrical conductivity simultaneously (Dalton et al., 1984). Many applications and enhancements have been reported, such as the design of TDR sensors (Robinson et al., 2003), the multiplexing of several sensors (Heimovaara, 1994), and the interpretation and modeling of TDR waveforms (Heimovaara et al., 1996; Noborio, 2001; Robinson et al., 2003).

Noborio et al. (1996) combined the functional capabilities of a TDR sensor and a heat pulse sensor into one unit. Ren et al. (1999) improved the thermo-TDR sensor design. Thermo-TDR was developed to simultaneously measure the soil water content \( \theta \), bulk electrical conductivity \( \sigma \), thermal conductivity \( \lambda \), heat capacity \( c_p \), and thermal diffusivity \( \alpha \). Time domain reflectometry was used to measure \( \theta \) and \( \sigma \), and the heat pulse (HP) method was used to determine \( \lambda, c_p \), and \( \alpha \). Ren et al. (2003a) developed thermo-TDR for vadose zone measurements. Ochsner et al. (2001) and Liu et al. (2008) used a thermo-TDR sensor to determine the soil bulk density. Heitman et al. (2008a, 2008b) and Xiao et al. (2011) developed it to measure soil water evaporation.

Commercially available TDR meters are hampered by high cost. The minimum probe length is determined by the permittivity of the soil, the voltage step rise, and the resolution of the TDR instrument (Zegelin et al., 1992). If the needle length is too short, the accuracy of water content measurements decreases. Problems with extracting accurate parameters from TDR waveforms, difficulties in detecting the reflected signals in saline soils and for short probes, and measurement dependence on the coaxial cable and probe length are additional drawbacks associated with the TDR method (Robinson et al., 2003). Thus, there are many reasons for developing a new sensor that can overcome the problems associated with short TDR and thermo-TDR sensors.

Frequency domain reflectometry is an alternative to TDR, offering an inexpensive measurement of soil water content. The geometry of FDR sensors is more advantageous than TDR sensors for making accurate measurements with short probes. It is possible to select suitable frequencies and measure different soil properties because FDR sensors are sensitive to different physical and chemical soil properties in different frequency ranges based on the dielectric spectra of the soil. The dielectric spectra are influenced by the water content, type of soil, sensor geometry, soil salinity, and temperature (Baumhardt et al., 2000; Chandler et al., 2004; Kellerers et al., 2005). Although Heimovaara (1994), Zhang et al. (2004), and Skierucha and Wilczek (2010) presented sensors with various geometries, the geometries are not suitable for thermo-FDR sensors because thermo-FDR sensors require a simple design that allows accurate heat pulse measurements. There is a need to determine whether a short FDR sensor with a simple design has the ability to accurately measure soil water content.

The objectives in this study were to: (i) design a short FDR sensor suitable for development into a thermo-FDR sensor; (ii) use the new FDR sensor to investigate the soil dielectric spectra; and examine the relationship between permittivity and water content in different soil types, temperatures, and salt contents; and (iii) quantify the ideal frequency of the short FDR sensor—the frequency at which the permittivity is not greatly affected by temperature and salt content.

**MATERIALS AND METHODS**

**Dielectric Properties**

The relative permittivity or dielectric constant is a measure of the extent to which the electrical charge distribution in a material can be polarized by an electrical field. In an alternating electrical field, a soil sample is characterized by a complex dielectric constant \( \varepsilon^* \):

\[
\varepsilon^* = \varepsilon_r - j \varepsilon_i
\]

where \( \varepsilon_r \) is the real part of the dielectric constant or the common dielectric constant of the material and \( \varepsilon_i \) is the imaginary part of the dielectric constant. The real part of the dielectric constant represents the capacitive behavior or polarizability of the soil, while the imaginary part (loss factor) represents the energy losses due to polarization and conduction (Lee et al., 2003). The imaginary component is the result of electrical conduction and molecular relaxation (Topp et al., 2000; Robinson et al., 2003; Seyfried and Grant, 2007).

These are related to \( \varepsilon_i \) as follows:

\[
\varepsilon_i = \varepsilon_{\text{ind}} + \frac{\sigma_{dc}}{2\pi f \varepsilon_0}
\]

where \( \varepsilon_{\text{ind}} \) is the loss factor due to dielectric relaxation losses, \( \varepsilon_0 \) is the absolute dielectric constant of a vacuum \( (8.854 \times 10^{-12} \text{ F/m}) \), \( f \) (Hz) is the measurement frequency, and \( \sigma_{dc} \) (S/m) is the direct-current electrical conductivity (Logsdon, 2005; Seyfried and Grant, 2007).

Equations [1] and [2] indicate that complex dielectric constants of soil are affected by the soil electrical properties, the direct-current electrical conductivity, and the measurement frequency. The frequency dependence has been described by the Debye (1929) and the Cole–Cole (Cole and Cole, 1941) models for one relaxation:

\[
\varepsilon^*(f) = \varepsilon_\infty + \frac{\varepsilon_0 - \varepsilon_\infty}{1+(if/\omega_0)^{-\beta}}
\]

where \( \varepsilon_0 \) is the low-frequency and \( \varepsilon_\infty \) the high-frequency value of \( \varepsilon^* \), \( \omega_0 \) is the relaxation frequency, and \( \beta \) is an exponent that describes the spread of the relaxation peak. If the relaxation is Debye, then \( \beta = 0 \) and the spread is small (Logsdon, 2005).
Permittivity can be understood as a measure of the polarization in a medium that is submitted to an alternating electromagnetic field. Dielectric polarization is the inherent nature of insulator materials. Research on dielectric polarization and dielectric relaxation properties provides a theoretical basis for material properties studies. Soil is a multiphase medium. It consists of materials that exhibit electrical, ionic, and orientational polarizations, which are represented by multiple polarization mechanisms (Santamarina, 2001). These include Maxwell–Wagner relaxation (kHz), bound-water relaxation (MHz), and free-water relaxation (GHz). These are attributed to the types and extent of interactions inside and between the soil particles and water (Zambrano et al., 2006). At the same time, the dielectric spectra are related to the microgeometry of the pore spaces in addition to the petrophysical parameters (Malik et al, 1998). Investigating the soil dielectric spectrum is a key to developing a FDR sensor useful in soil. Additional experiments are required to confirm the best frequency for thermo-FDR use.

Soil is a dielectric mixture material. The dielectric mixture is described in terms of the fractional volume and permittivity of each constituent. Several mixture models, such as the Kraszewski model; the Landau, Lifshitz, and Looyenga model; and the Lichtenecker model, have been proposed (Subedi and Chatterjee, 1993; Jusoh et al., 2011). The models indicate the basic forms of the relationship between dielectric constants and water contents at high frequencies.

**Sensor Design**

The geometry of thermo-FDR sensors is limited by two factors: the distance between needles for soil thermal property measurements and the characteristic impedance of the sensor. Typical heat pulse sensors have needle lengths ($L$) of 0.028 to 0.04 m, needle diameters of 0.0008 to 0.002 m, and needle-to-needle spacing of 0.006 m (Bristow et al., 1994). Ren et al. (1999) chose a needle length of 0.04 m, a needle diameter of 0.0013 m, and a needle-to-needle spacing of 0.006 m for the thermo-TDR sensor design. If needle-to-needle spacing increases, it takes more heating power to produce a certain temperature increase at the sensor needles, which could result in convective heat transfer around the heating needle. To avoid the need for large heating power, we chose 0.006 m as the needle spacing. A FDR sensor is essentially a coaxial transmission line. The basic geometry of a FDR sensor consists of a set of needles encircling a middle needle. We compared electromagnetic simulations for FDR sensors with different numbers of needles. We found that the sensor with six outer needles was better than sensors with fewer needles because the electrical field distribution with six outer needles was similar to that of a coaxial transmission line (Fig. 1). This sensor design results in a well-defined electrical-field volume with almost no field leakage outside of the sensors (Campbell, 1990).

![Fig. 1. Electromagnetic simulations for sensors of different geometry, including (a) a sensor with three outside needles, (b) a sensor with four outside needles, (c) a sensor with six outside needles, and (d) a coaxial transmission line.](image-url)
The characteristic impedance of a sensor in air can be calculated based on sensor dimensions:

\[
Z_p = \frac{60}{\sqrt{\kappa_a}} \ln \left( \frac{b}{a} \right)
\]

where \(Z_p\) (\(\Omega\)) is the impedance of the thermo-FDR sensor, \(b\) is the radius (m) of the outer conductor, \(a\) is the radius (m) of the inner conductor, and \(\kappa_a\) is the permittivity of air (\(\kappa_a = 1\)).

The thermo-FDR sensor consists of seven 28-mm-long stainless steel tubes (hypodermic needles) held by a printed circuit board equipped with a BNC-type connector (female jack BNC, 50 \(\Omega\)). The spacing between the external tubes is 6 mm, the diameter of the outer tubes is 1.2 mm, and the middle tube diameter is 1.46 mm. Each outer tube contains a thermocouple (40 AWG Nichrome 80 with enamel) and a thermocouple. After the heater and thermocouples were positioned in tubes, high-thermal-conductivity epoxy glue was drawn into the tubes to provide a water-resistant electrically insulated probe (Ren et al., 1999). The schematic view of a thermo-FDR sensor is shown in Fig. 2.

**Table 1. The particle sizes and densities of the soils used in the study.**

<table>
<thead>
<tr>
<th>Soil†</th>
<th>Clay (kg/kg)</th>
<th>Silt (kg/kg)</th>
<th>Sand (kg/kg)</th>
<th>Packed bulk density (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hanlon</td>
<td>0.094</td>
<td>0.163</td>
<td>0.743</td>
<td>1.36</td>
</tr>
<tr>
<td>Ida</td>
<td>0.250</td>
<td>0.701</td>
<td>0.049</td>
<td>1.17</td>
</tr>
<tr>
<td>Nicollet</td>
<td>0.235</td>
<td>0.325</td>
<td>0.440</td>
<td>1.12</td>
</tr>
<tr>
<td>Webster</td>
<td>0.336</td>
<td>0.341</td>
<td>0.323</td>
<td>1.17</td>
</tr>
</tbody>
</table>

† Hanlon is a coarse-loamy, mixed, superactive, mesic Cumulic Hapludoll; Ida is a fine-silty, mixed, superactive, calcareous, mesic Typic Udorthent; Nicollet is a fine-loamy, mixed, superactive, mesic Aquic Hapludoll; and Webster is a fine-loamy, mixed, superactive, mesic Typic Endoaquoll (Soil Survey Staff, 2010).

**Experiment**

Bristow et al. (1994), Kluitenberge et al. (1995), Noborio et al. (1996), and Ren et al. (1999, 2003b, 2005) presented accurate measurements of soil thermal properties with 6-mm tube-to-tube spacing heat pulse sensors. Thus, the heat pulse design selected for the thermo-FDR sensor has already been verified in the literature. The critical part remaining for thermo-FDR sensor development is to find a measurement frequency that accurately determines soil water content. By means of a vector network analyzer (VNA), soil dielectric spectrum analysis is a good way to quantify the proper measurement frequency of thermo-FDR sensors.

Four different soils, representing a range of clay and sand contents, were used in the experiment (Table 1). Hanlon is a coarse-loamy, mixed, superactive, mesic Cumulic Hapludoll; Ida is a fine-silty, mixed, superactive, calcareous, mesic Typic Udorthent; Nicollet is a fine-loamy, mixed, superactive, mesic Aquic Hapludoll; and Webster is a fine-loamy, mixed, superactive, mesic Typic Endoaquoll (Soil Survey Staff, 2010). The soils were air dried, sieved through a no. 18 sieve, and then oven dried at 105°C for 24 h. The soils were then thoroughly mixed with water to different water contents before being packed into polyvinyl chloride (PVC) cylinders (80-mm height, 60-mm diameter). Polyvinyl chloride cylinders have been successfully utilized by many researchers for testing and calibration experiments.

To determine the validity of the thermo-FDR sensor, we performed complex permittivity measurements for each soil/water mixture and used an open-ended technique in this study. The complex dielectric constants of soil samples were measured by an HP 8753ES vector network analyzer (Agilent Technologies). The VNA measurement range was 1 MHz to 3 GHz, and 1601 data points were collected. The power level was set to 1 mW (0 dBm) with a dynamic range of at least 0.0001 mW (~40 dBm). The one-port S11 (reflection) measuring mode and Smith chart format were selected. The phase-preserving cable was connected to Port 1 of the VNA and the BNC connector of the probe. An open load (50 \(\Omega\)), short calibration using suitable calibration standards (Maury Microwave 85050B BNC calibration kit or equivalent) was performed in accordance with the manufacturer’s specification. After calibration, the following were verified: the open standard produced an open trace on the Smith chart, the broad band 50-\(\Omega\) standard load produced a dot trace at 0°, with a phase angle of 180°. Each measurement was repeated three times.

We used the VNA to measure soil dielectric constants. The scattering parameter (S11) was obtained from the VNA, and it was converted to permittivity using the procedure of Logsdon and Laird (2002) and Logsdon (2005), who based their procedure on that of Campbell (1990) and Kraft (1987).
First, S11 was converted to electrical conductivity:

\[
\sigma^* = \frac{Z_p \varepsilon^*}{LZ^*} = \frac{Z_p \varepsilon^*}{LZ_0 + 1} - 111^* \quad [5]
\]

where \(Z_p (\Omega)\) can be calculated by Eq. [4], \(Z_0\) is the characteristic impedance of the 50-Ω extension cable, \(\varepsilon^*\) is the permittivity of a vacuum \((8.854 \times 10^{-12} \text{ F/m})\), \(c\) is the speed of light \((3 \times 10^8 \text{ m/s})\), and \(L\) is the electrical length of the thermo-FDR sensor.

The electrical conductivity was converted to the complex permittivity (relative to the permittivity of a vacuum):

\[
\varepsilon^*(f) = \pi f \varepsilon_0 \arctan \left( \frac{2 \sigma^*/\sigma^*}{} \right) \quad [6]
\]

where \(\sigma^*\) is the complex electrical conductivity, \(\sigma^r\) is the real part of \(\sigma^*\), and \(\sigma^i\) is the imaginary part of \(\sigma^*\). The real and imaginary permittivities can be combined into an apparent permittivity, which allows direct comparison with TDR data. The complex spectra were converted via the square root of the apparent permittivity (Logsdon, 2005, 2008):

\[
\varepsilon_{ai}^{1/2} = \sqrt{1 + \frac{1 + \tan^2 (\varepsilon^*/\varepsilon^*)}{2}} \varepsilon^* \quad [7]
\]

Heimovaara et al. (1996) and Logsdon (2005) reported a quarter-wavelength procedure to determine the square root of the apparent permittivity at one or two high-frequency points. It is necessary to have an estimate of the impedance of the sensor and the electrical length. Both can be back-fitted from expected S11 calculations using measured spectra for liquids with known properties (Heimovaara et al., 1996; Logsdon, 2005), e.g., methanol, isopropanol, and 0.02 mol/L NaCl solution.

**RESULTS AND DISCUSSION**

All of the experiments were performed at the USDA-ARS National Laboratory for Agriculture and the Environment and at Iowa State University. To ensure instrument stability, all of the VNA measurements were made at least 2 h after the VNA was powered on. Matlab (The MathWorks) codes were programmed for the calculation procedures. Figure 3 presents the real and imaginary permittivities of the soil samples. Each soil had a range of water contents but negligible salt content. The real and imaginary permittivities decreased with increasing frequency. The large values in the low-frequency range are attributed to polarization and conduction of the electrical double layers, which are the signature characteristics of aqueous colloidal materials including wet soils (Shang et al., 1999). For frequencies between 1 and 30 MHz, the real and imaginary permittivity sharply decreased, and the data were sensitive to the gap between the printed circuit board and the soil, the errors of the VNA, and the electromagnetic noise. It was difficult to measure the water content in this unstable range because the Maxwell–Wagner relaxation (which occurs in the kilohertz range) and bound-water relaxation (which occurs in the megahertz range) made the dielectric mechanisms complex (Zambrano et al., 2006). For frequencies greater than 30 MHz, the real dielectric constant showed some increase before declining near 1 GHz. The imaginary dielectric constant decreased with increasing frequency and had a rapid rise at a frequency of 1 GHz. The frequency at which the real dielectric constants rapidly declined was the dispersion frequency, \(f_d\) (Shang et al., 1999). The frequency between 30 MHz and \(f_d\) should be used for measuring the soil water content.

The flatter the curve with increasing frequency, the more ideal it is for measuring the soil water content. The real part of the dielectric constant, \(\varepsilon_r\), represents the capacitive behavior or polarizability of the water. The graph of the real dielectric constant (Fig. 3) shows that the ideal frequency ranges to measure the water contents for the Hanlon, Ida, Nicollet, and Webster soils were 20 to 180, 47 to 366, 45 to 360, and 50 to 270 MHz, respectively, so 50 to 180 MHz represents an ideal frequency range for these soils, and the imaginary dielectric constants will change based on the dielectric losses in this range.

Many current commercially available FDR sensor dataloggers determine the apparent permittivity, \(\varepsilon_{ai}\), rather than \(\varepsilon_r\) and \(\varepsilon_i\). The apparent permittivity is derived from the combined imaginary component as well as the real component (Logsdon, 2008). Figure 4 shows that the apparent permittivities of all the samples share common features. The apparent permittivities of the samples decrease with increasing frequency. The permittivity measurements break down due to longitudinal resonance at higher frequencies (Shang et al., 1999). Every soil has distinctly different curves because the samples have different water contents. The measurement range should be wider than the real permittivity. The ideal frequency ranges to measure the water content for the Hanlon, Ida, Nicollet, and Webster soil are 10 to 400, 40 to 780, 39 to 500, and 40 to 360 MHz, so 40 to 360 MHz is the ideal frequency range for determining the soil water content in these soils.

The real dielectric constant is related to the amount of energy stored in a material as molecules shift alignment in an alternating electromagnetic field, and the imaginary dielectric constant, sometimes called the loss factor, is related to the electrical conduction and molecular relaxation (Topp et al., 2000; Robinson et al., 2003). The real and imaginary dielectric constants are affected by temperature because the molecular relaxation and electrical conduction are sensitive to material temperatures. Seyfried and Grant (2007) reported that temperature responses were positive or negative for different soils. In this experiment, measurements were made in the temperature range of 20 to 60 °C. Figure 5 shows the traces of permittivity for the 0.41 m3/m3 Ida soil. The ideal frequency range in which there was no temperature effect was 46 to 180 MHz for the real dielectric constant and 45 to 195 MHz for the apparent permittivity. The real dielectric constant changed much in the low-frequency range. The range for the Hanlon soil was 40 to 106 MHz for the real dielectric constant and 46 to 161 MHz for the apparent permittivity. The range for the Nicollet soil was 45 to 208 MHz for real dielectric constant.
The range for the Webster soil was 47 to 279 MHz for the real dielectric constant and 47 to 231 MHz for the apparent permittivity. The ideal frequency range, therefore, was 47 to 231 MHz for obtaining measurements without temperature interference.

It is important to know how salinity affects soil dielectric constants. Potassium chloride solutions of 0.02, 0.04, 0.06, 0.08, and 0.1 mol/L were mixed with the soils at various water contents. Figure 6 shows that the real dielectric permittivities in the Ida soil are almost unchanged at the different salt contents.

Fig. 3. The real and imaginary permittivities vs. frequency for four soils with increasing soil water contents (1–5).
The apparent permittivity was unchanged in the high-frequency range and had little change below 46 MHz. The critical frequencies below which salt affected the dielectric constant were 18 MHz for the Nicollet soil, 47 MHz for the Webster soil, and 39 MHz for the Hanlon soil. The ideal frequency range for measuring the soil water content free from temperature and salt effects, therefore, is 47 to 200 MHz.

Figure 7 shows the apparent permittivity–water content relationship at 70 MHz. The 70-MHz relationship had the largest $R^2$ value ($R^2 = 0.9345$) for the following equation indicating water content as a function of apparent permittivity:

$$0 = 0.0032(\varepsilon_{a}^{1/2})^{3} - 0.051(\varepsilon_{a}^{1/2})^{2} + 0.3646(\varepsilon_{a}^{1/2}) - 0.635$$

[8]

CONCLUSIONS
A short thermo-FDR sensor was designed with the aid of electromagnetic simulations and literature heat pulse measurements. A short thermo-FDR sensor was constructed and tested for its ability to measure the soil water content. Soil dielectric spectra measured with the short FDR sensor showed dielectric trends for four soil types with various water contents, temperatures, and salt contents. A frequency of 70 MHz appeared to be
Fig. 7. Relationship between apparent permittivity ($\varepsilon_a$) and water content (θ) at 70-MHz frequency for four soils.

the best, where the measured apparent permittivity of the four soils did not change for a range of temperatures and salinities. The newly designed short thermo-FDR sensor provides quick and stable determination of the soil water content. Accuracy of the short thermo-FDR sensor in field soils needs future examination.

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