An Improved Thermo-TDR Technique for Monitoring Soil Thermal Properties, Water Content, Bulk Density, and Porosity

Wei Peng, Yili Lu,* Xiaoting Xie, Tusheng Ren, and Robert Horton

The thermo-time domain reflectometry (thermo-TDR) technique is valuable for monitoring in situ soil water content (θ), thermal properties, bulk density (ρb), porosity (n), and air-filled porosity (n_a) in the vadose zone. However, the previous thermo-TDR sensor has several weaknesses, including limited precision of TDR waveforms due to the short probe length, small measurement volume, and thermal property estimation errors resulting from finite probe properties not accounted for by the heat pulse method. We have developed a new thermo-TDR sensor design for monitoring θ, thermal properties, ρb, n, and n_a. The new sensor has a robust heater probe (outer diameter of 2.38 mm and length of 70 mm) and a 10-mm spacing between the heater and sensing probes, which provides a sensing volume three times larger than that of the previous sensor. The identical cylindrical perfect conductors and the tangent line–second-order bounded mean oscillation theories were applied to analyze the raw data. Laboratory tests showed that θ values determined with the new sensor had a RMSE of 0.014 m^3 m\(^{-3}\) compared with 0.016 to 0.026 m^3 m\(^{-3}\) with the previous sensor. Soil thermal property estimates with the new sensor agreed well with modeled values. Soil ρb, n, and n_a derived from θ and thermal properties were consistent with those derived from gravimetric measurements. Thus, the new thermo-TDR sensor provides more accurate θ, thermal properties, ρb, n, and n_a values than the previous sensor.

Abbreviations: ICPC, identical cylindrical perfect conductors; ILS, infinite line source; TDR, time domain reflectometry; TL-BMO, tangent line–second-order bounded mean oscillation.

Dynamic measurements of soil temperature, water content (θ), and thermal properties are necessary for a quantitative description of soil coupled heat and water transfer. From simultaneous measurements of θ and thermal properties, additional soil properties and processes can be determined, including bulk density (ρb), porosity (n), air-filled porosity (n_a), degree of water saturation (Ochsner et al., 2001a; Ren et al., 2003a; Liu et al., 2014), soil water evaporation (Zhang et al., 2012), soil heat flux (Peng et al., 2017), unsaturated hydraulic conductivity of the surface soil (Tian et al., 2018), and water flux density (Ren et al., 2000; Mori et al., 2003; Kamai et al., 2008). Among the existing techniques, the thermo-time domain reflectometry (thermo-TDR) sensor, which consists of three parallel probes with 40-mm length (L), 1.3-mm diameter (d), and 6-mm probe-to-probe spacing (r), can measure soil temperature, θ, and thermal and electrical properties on a soil volume (Ren et al., 1999, 2005). The sensor has been used widely in monitoring soil physical properties (Ochsner et al., 2001b; Lu et al., 2007, 2014; Xie et al., 2018), and in studying coupled heat and water transfer in unfrozen and frozen soils (Heitman et al., 2008; Tian et al., 2015).

The small sensing volume of the thermo-TDR design makes it suitable for fine-scale measurements, but in some cases restricts the representativeness of actual field conditions. In addition, short probes can limit the accuracy and precision of TDR measurements (Noborio, 2001; Schwartz et al., 2014; Wang et al., 2015). Topp et al. (1984) reported that the errors in TDR θ with a 0.05-m-long probe were significant, with a standard deviation of 0.037 m^3 m\(^{-3}\), while an improved accuracy was observed for sensors with longer probes.
Several studies have been performed to improve the accuracy of thermo-TDR sensors for determining soil thermal properties. Olmanson and Ochsner (2008) developed a partial cylinder-shaped thermo-TDR sensor that had curved heaters and a central temperature probe. The sensor was almost twice the size of the Ren et al. (1999) sensor. This design enhanced the strength and robustness of the sensor, but it introduced other errors such as soil compaction caused by the curved heater (Olmanson and Ochsner, 2008). Liu et al. (2008) improved the original Ren et al. (1999) sensor design by adding pointed tips to the probe ends, increasing the probe diameter to 2 mm and from 8 mm. The pointed tips improved the ease of sensor insertion into soil, but the short probe length still limited its measurement accuracy. A similar design proposed by Yu et al. (2015) had pointed probe tips, 2-mm diameter (d), and 6-mm radius (r). Wen et al. (2018) increased the length to 60 mm with temperature sensors positioned at multiple locations in the sensing probes, which allowed for in situ self-corrections of changes in r due to probe deflection. They also reported that the longer probes significantly increased the accuracy of TDR results.

In recent years, improved theories have been put forward to calculate thermal properties and θ. Knight et al. (2012) identified errors due to finite probe properties that were ignored in the infinite line source (ILS) model. They proposed the identical cylindrical perfect conductors (ICPC) model to improve estimations of soil thermal properties by accounting for finite probe heat capacity and finite probe radius. Kamai et al. (2015) showed that errors in soil heat capacity (C) estimations were reduced significantly by using a large heater probe (d = 2.38 mm) with a thick tubing wall and adoption of the ICPC theory. Wang et al. (2015) proposed a tangent line/second-order bounded mean oscillation (TL-BMO) approach to determine the reflection positions of TDR waveforms, which increased the accuracy of the relative dielectric permittivity (K_a) and θ results. However, these theories have not been fully integrated into the thermo-TDR system.

It is desirable to develop a more robust and accurate sensor that overcomes the limitations of conventional ILS theory, small sampling volumes, and thin probes of the previous thermo-TDR sensors. The objective of this study was to develop and test a new thermo-TDR sensor design with a sampling volume larger than that of the previous thermo-TDR sensor. Determinations of θ, thermal properties, ρ_a, n, and n_a with the new sensor were tested under laboratory conditions.

### New Sensor Design

#### Thermo-TDR Sensor Design Criteria

The design criteria of thermo-TDR sensors were introduced by Ren et al. (1999), who showed that L, d, and r were the three major sensor design factors affecting heat pulse and TDR measurements. For a TDR waveguide, a small d (compared with r) affects the electromagnetic field distribution around the probes, and any local nonuniformity around the sensor can impact θ measurements, while a large d may cause soil compaction and disturbance (Ghezzehei, 2008). Knight (1992) suggested that r/d should be <10. Meanwhile, waveforms generated by short sensors are prone to errors resulting from multiple superimposed reflections (Wang et al., 2015, 2017). With longer TDR sensors, the position of the second reflection point is more identifiable and stable, resulting in more reliable TDR θ results (Noborio, 2001; Schwartz et al., 2014).

The heat pulse sensor configuration also requires an appropriate sensor size for accurate soil thermal property estimations. For example, to limit the axial heat flow error to <1%, Blackwell (1956) suggested that the ratio of L to d should be >25 for the single-probe method to determine soil thermal conductivity (λ). To limit the relative errors for C and thermal diffusivity (κ) to <2%, Kluitenberg et al. (1995) suggested that L/2r > 2.2 and d/2r < 0.13, with the purpose of reducing the ILS model errors caused by the finite sensor size associated with the dual-probe heat pulse sensor. It should be noted that the analysis of Blackwell (1956) and Kluitenberg et al. (1995) considered the heater probe as a line heat source.

### The New Thermo-TDR Sensor

We propose a new thermo-TDR sensor design by including a relatively large heater to reduce probe deflections during sensor insertion into the soil, a relatively large L to improve the accuracy of TDR θ measurements, and a relatively large r to satisfy the design criteria. Figure 1 depicts the details of the new thermo-TDR sensor. Compared with the original design of Ren et al. (1999), the main changes incorporated in the new sensor are: (i) L is increased to 70 mm; (ii) the heating probe is larger and more rigid (2.38-mm outer diameter and 0.71-mm wall thickness); (iii) the sensing probes are larger and more rigid (2-mm outer diameter and 0.25-mm wall thickness); (iv) r is increased to 10 mm, and three thermocouples (chromel-constantan, 40 American wire gauge [AWG]) are enclosed in each sensing probe, located at 20, 35, and 50 mm away from the sensor base.

The probes are made of stainless steel tubes with pointed tips. The resistance heater wire is made of 38-gauge Nichrome 80 wire (two loops). Both the heater wire and thermocouples are kept in place with high-thermal-conductivity epoxy, which also serves to provide water resistance and electrical insulation. A coaxial cable is connected to the sensor by soldering the inner conductor to the central probe and the shield to the outer probes. A casting epoxy resin (CR-600, Micro-Mark) is used to fix each part in place in the sensor head (Fig. 1). He et al. (2018) provided additional sensor construction insights.

### Materials and Methods

#### Sensing Volume of the New Thermo-TDR Sensor

A simple experiment, which used distilled water at 20°C as the medium, was performed to determine the approximate TDR measurement volume of the new sensor. The schematic diagram for the experiment setup can be found in Supplemental Fig. S1.

A thermo-TDR sensor was placed in a rectangular glass container (16-cm width, 8-cm height, and 22.5-cm length) in such a
way that all three probes were laterally arranged so that the probe plane was parallel to the container bottom and the outer probes were at the same height as the central probe (Supplemental Fig. S1a). Distilled water was initially added to the container to a level just above the probe plane; additional water was added in 2-mm increments, with TDR waveforms collected after each increment. In another case, a thermo-TDR sensor was placed in the container with the longitudinal arrangement for the probes so that the probe plane was vertical to the container bottom and the outer probes were above and below the central probe (Supplemental Fig. S1b). Distilled water was initially added to the container to a level just above the central probe; additional water was added in 2-mm increments, with TDR waveforms collected after each increment. The water-filling process ceased when no changes in the TDR waveforms were observed.

The zones of greatest energy have an elliptical shape (Robinson et al., 2003). From the above measurements, we determined the long axis and short axis of the elliptical measurement range or the maximum detectable boundaries of the TDR sensor (Ren et al., 2005).

**Measurements on Disturbed and Intact Soil Samples**

Both disturbed and intact soil samples were used in this study. The textures of the disturbed soil samples ranged from sand to silt loam. Soil samples were air dried, crushed, and sieved through a 2-mm screen before being used for measurements. The intact soil samples were obtained at the Experimental Farm of China Agricultural University, Beijing, China. Soil samples were collected from the surface layer (0–8 cm) of a field plot using a cutting ring (70-mm inner diameter and 80 mm long). Soil particle-size distributions were measured with the pipette method (Gee and Or, 2002). The physical properties of the soil samples are listed in Table 1. The apparent \( L \) and \( r \) of the thermo-TDR sensors were determined using agar-immobilized water (5 g L\(^{-1}\)) at 20°C. For details on thermo-TDR sensor calibrations, see Lu et al. (2017). Sieved soil samples were moistened to seven \( \theta \) values (0, 0.05, 0.10, 0.15, 0.20, 0.25, and 0.30 m\(^3\) m\(^{-3}\)) and then packed into cylinders (70-mm inner diameter and 80 mm long) at known \( \rho_b \) (Table 1). After equilibration at room temperature, a thermo-TDR sensor was inserted into the soil columns vertically to measure \( \theta \) and thermal properties. For TDR measurements, the waveforms were recorded with a TDR200 reflectometer device (Campbell Scientific). A constant current of 0.23 A was applied to the central heater for 25 to 30 s to generate the heat pulse, which was controlled with a datalogger (CR3000, Campbell Scientific). The temperature changes at the sensing probes were collected at 1-s intervals for 480 s. Five repeated heat-pulse determinations were taken on each soil column at 60-min intervals. Finally, \( \theta \) and \( \rho_b \) values were determined by oven drying the samples at 105°C for 24 h. These values were used as reference values to evaluate the accuracy of the \( \theta \) and \( \rho_b \) values derived from the new thermo-TDR sensor measurements.

**Determination of Soil Thermal Properties Based on Identical Cylindrical Perfect Conductors Theory**

The pulsed ILS model has been used widely for calculating thermal properties from heat pulse data (Bristow et al., 1994). The

<table>
<thead>
<tr>
<th>Soil no.</th>
<th>Texture</th>
<th>Particle size distribution</th>
<th>( \rho_b )</th>
<th>( \rho_b )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>sand</td>
<td>94 1 5</td>
<td>1.50–1.68</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>loamy sand</td>
<td>80 12 8</td>
<td>1.41–1.47</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>loam</td>
<td>48 38 14</td>
<td>1.19–1.35</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>silt loam</td>
<td>15 67 18</td>
<td>1.30–1.58</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>loam</td>
<td>52 36 12</td>
<td>1.07–1.54</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>loam</td>
<td>40 48 12</td>
<td>1.07–1.54</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>silt loam</td>
<td>34 53 13</td>
<td>1.07–1.54</td>
<td></td>
</tr>
</tbody>
</table>
model assumes that heat is conducted from an infinite line heat source into a homogeneous, isotropic medium of infinite extent (Kamai et al., 2015). In practice, however, the sensor probes have finite \( d \) and \( L \) and have thermal properties that differ considerably from those of soils (Knight et al., 2012). The ICPC theory, which accounts for the finite probe radius and finite probe heat capacity, has been shown to provide relatively accurate soil thermal property determinations (Knight et al., 2012; Lu et al., 2013; Kamai et al., 2015). The ICPC model begins with a Laplace-domain solution that represents the case where heat is released continuously at a rate of \( q' \) (Knight et al., 2012):

\[
\hat{T}_c (p) = \frac{q'K_0 (\mu L)}{2 \pi \lambda p \left( \mu a_0 K_1 (\mu L) + (\mu a_0^2/2) K_0 (\mu a_0) \right)^2} \tag{1}
\]

where \( p \) is the Laplace transform parameter and \( \hat{T}_c (p) \) is the Laplace transform of \( T_c (t) \), which is the temperature increase with time for the case of continuous heating; \( \mu = \sqrt{(p/\kappa)} \), \( \beta_0 = C_0/C_s \), and \( K_u (z) \) denotes the modified Bessel function of the second kind of order \( u \) and argument \( z \). The radius \( (a_0) \) and volumetric heat capacity \( (C_0) \) of the heater probe must be known when using Eq. [1]. Equation [1] can be numerically inverted using the Stehfest algorithm to solve for \( T_c (t) \) and \( T_c (t - t_0) \) for the conditions of the pulsed heating scheme. Details regarding the numerical inversion can be found in Knight et al. (2012). Thus, the temperature in the sensing probe, \( T (t) \), can be expressed using

\[
T (t) = \begin{cases} 
T_c (t) & 0 < t \leq t_0 \\
T_c (t - t_0) & t > t_0 
\end{cases} \tag{2}
\]

Equations [1] and [2] represent the ICPC solution (Knight et al., 2012). Here, the values for \( a_0 \) and \( C_0 \) are 1.19 mm and 3.68 MJ m\(^{-3}\) K\(^{-1}\), respectively (Supplemental Table S1). Based on the ICPC model, soil \( C \) and \( \kappa \) were determined by fitting Eq. [1] and [2] to heat pulse sensor measured temperature changes as a function of time, \( T (t) \). A MATLAB (The Mathworks) program was used to perform the curve-fitting. Soil \( \lambda \) was calculated as the product of \( C \) and \( \kappa \).

The typical temperature response data obtained in this study and the curve-fitting results are presented in Supplemental Fig. S2 and S3 for the sand soil (at \( \theta \) of 0 and 0.25 m\(^3\) m\(^{-3}\)) and the agar solution. The parameters involved in the curve-fitting process are listed in Supplemental Table S1. It is worth noting that the time range of the temperature change data used for curve fitting depends on the shape of the temperature response curves (Supplemental Table S1).

**Determination of TDR Water Content Using the Tangent Line–Second-Order Bounded Mean Oscillation Method**

The TL-BMO method can be used to determine the reflection positions in TDR waveforms (Wang et al., 2015). It is a prediction-correction model based on a combination of the tangent line method and the second-order BMO method. The tangent line method is used to approximate the second reflection position \( (t_2) \) of a TDR waveform to establish a prediction interval, then the second-order BMO is applied to the same TDR waveform, and the local maximum of the second-order BMO curve within the prediction interval is selected as \( t_5 \). The first reflection position \( (t_1) \) is unaffected by the probe length.

Once \( t_1 \) and \( t_5 \) are determined, \( K_a \) is estimated, and \( \theta \) is determined from \( K_a \) with (Topp et al., 1980)

\[
\theta = 2.92 \times 10^{-2} K_a - 5.5 \times 10^{-4} K_a^2 + 4.3 \times 10^{-6} K_a^3 - 5.3 \times 10^{-2} \tag{3}
\]

**Determination of Soil Bulk Density and Porosity Using the Combination of Heat Capacity and Thermal Conductivity Based Methods**

We used both \( C \)-based and \( \lambda \)-based methods to estimate \( \rho_b \) from thermo-TDR measured \( \theta \), \( C \), and \( \lambda \). The \( C \)-based method is based on the mixing model of Campbell (1985):

\[
\rho_b = \frac{C - C_w \rho_w \theta}{\epsilon_s} \tag{4}
\]

where \( \rho_w \) (1.0 Mg m\(^{-3}\)) and \( C_w \) (4.18 kJ kg\(^{-1}\) K\(^{-1}\)) are the density and specific heat capacity of water, respectively, and \( \epsilon_s \) represents the specific heat capacity of the soil solids. Wang et al. (2019) reported \( \epsilon_s \) values on nine mineral soils using a differential calorimetry method considering drying temperature and organic matter and clay contents (their Table 3). Based on their published values, we obtained an average \( \epsilon_s \) value of 0.742 kJ kg\(^{-1}\) K\(^{-1}\) for soils with an organic matter content <3% and clay content <30%. For soils with either >3% organic matter or 30% clay, an average \( \epsilon_s \) value of 0.768 kJ kg\(^{-1}\) K\(^{-1}\) is obtained. Here, we used 0.742 kJ kg\(^{-1}\) K\(^{-1}\) as the \( \epsilon_s \) value for all soils in this study.

Lu et al. (2016) introduced the \( \lambda \)-based method for estimating \( \rho_b \) from measurements of \( \theta \) and \( \lambda \) with known soil texture information. The empirical equation that relates \( \lambda \) to \( \rho_b \), \( \theta \), and soil particle-size information is (Lu et al., 2016)

\[
\lambda = \lambda_{\text{dry}} + \exp \left( \beta - \theta^\alpha \right) \tag{5}
\]

where \( \alpha \) and \( \beta \) are shape factors determined by soil particle sizes and \( \rho_b \):

\[
\alpha = 0.67 f_{\text{cl}} + 0.24 \tag{6}
\]

\[
\beta = 1.97 f_{\text{sa}} + 1.87 \rho_b - 1.36 f_{\text{cl}} \rho_b - 0.95 \tag{7}
\]

where \( f_{\text{sa}} \) and \( f_{\text{cl}} \) are the mass fractions of sand and clay from the USDA soil texture classification system. The thermal conductivity of a dry soil, \( \lambda_{\text{dry}} \) (W m\(^{-1}\) K\(^{-1}\)), is calculated as (Lu et al., 2016)

\[
\lambda_{\text{dry}} = -0.56 \left( 1 - \frac{\rho_b}{2.65} \right) + 0.51 \tag{8}
\]

where 2.65 (Mg m\(^{-3}\)) is the soil particle density.
Finally, $\rho_h$ is inversely estimated with the least-squares method by fitting Eq. [5–8] to the thermo-TDR measured $\theta$ and $\lambda$, and $n$ and $n_a$ are calculated as

$$n = 1 - \frac{\rho_h}{\rho_s}$$  \hspace{1cm} [9]
$$n_a = -0$$ \hspace{1cm} [10]

Compared with the $C$-based method, the $\lambda$-based method has the advantage that the $\lambda$ results are not affected by probe deflection errors (Lu et al., 2016; Tian et al., 2018). However, sensitivity analysis has shown that the $\lambda$-based method gives unstable results when $\theta$ is lower than a critical water content (Tian et al., 2018; Lu et al., 2018). In this study, we combined the $C$- and $\lambda$-based methods for estimating $\rho_h$, using the $\lambda$-based method at $\theta > 0.1$ m$^3$ m$^{-3}$ and the $C$-based method at $\theta \leq 0.1$ m$^3$ m$^{-3}$.

Supplemental Fig. S4 presents an overview of the thermo-TDR technique for determining soil physical properties. Briefly, three steps are needed to complete the process. First, a temperature change–time curve is obtained by applying a heat pulse to the soil sample, and a TDR waveform (the voltage or reflection coefficient as a function of time) is generated by launching a fast-rise electromagnetic pulse. Second, soil thermal properties ($C$ and $\lambda$) are derived from the temperature curve following the ICPC theory, and $K_a$ is calculated from the TDR waveform using the TL-BMO algorithm, from which $\theta$ is determined with Eq. [3]. Finally, $\rho_h$ is estimated from $\theta$, $C$, or $\lambda$ with Eq. [4–8], and $n$ and $n_a$ are calculated with Eq. [9] and [10].

### Estimation of Thermal Properties Using Existing Models

The performance of the new thermo-TDR sensor was evaluated by comparing the measured thermal property values with model estimates. The de Vries (1963) model, Xie et al. (2018) model, and Lu et al. (2014) model were used to estimate $C$, $\kappa$, and $\lambda$, respectively. Model inputs included $\rho_h$, $\theta$, $f_{sa}$, and $f_{cl}$.

The accuracy of the new thermo-TDR sensor determinations was evaluated using root mean square error (RMSE) and bias:

$$\text{RMSE} = \sqrt{\frac{\sum (A_d - A_e)^2}{m}}$$  \hspace{1cm} [11]
$$\text{bias} = \frac{\sum (A_d - A_e)}{m}$$ \hspace{1cm} [12]

where $m$ is the number of data points. For thermal properties ($C$, $\kappa$, $\lambda$), $A_d$ represents the sensor value and $A_e$ represents the model value. For $\theta$, $\rho_h$, $n$, and $n_a$, $A_d$ and $A_e$ represent the values determined by the thermo-TDR sensor and the oven drying method, respectively.

### Results and Discussion

#### Sensing Volume of the New Sensor

Figure 2 shows the recorded TDR waveforms obtained at different water levels above the central probe in the vertical and horizontal plane directions with respect to the container bottom. Because the electromagnetic energy concentrates around the central probe, the greater the distance away from the central probe, the less the electromagnetic energy and the smaller the influence on the TDR waveform (Knight, 1992). When the water–air interface was just on the probe plane, the apparent distance of the TDR waveform was quite small. With further increases in water level, the TDR waveform became wider as the second reflection position grew larger. A full waveform was not obtained until the magnitude of $K_a$ approached the dielectric permittivity value of water. At that point, the outer boundary of the TDR measurement was about 9 mm when the probe plane was parallel to the container bottom.
bottom (Fig. 2a) and 15 mm when the probe plane was vertical to the container bottom (Fig. 2b). Thus, the new thermo-TDR sensor measures an elliptical cylindrical shape with a short axis of 9 mm and long axis of 15 mm. The volume of the TDR measurement, 29.7 cm³, is almost three times that of the Ren et al. (1999) sensor.

According to Knight et al. (2007), the effective measurement outer boundary (which contains 99% of the total spatial sensitivity) of a heat pulse sensor is close to an ellipse with a major axis 2.6 times the probe-to-probe spacing. Thus, the Ren et al. (1999) thermo-TDR sensor has a major axis of 20.8 mm, while the corresponding value is 26 mm for the new thermo-TDR sensor. Therefore, the sampling volume of the new sensor for both heat pulse and TDR measurements is larger than that of the previous sensor.

Soil Thermal Property Values Determined with the New Thermo-TDR Sensor

Figure 3 compares the \( C \), \( \kappa \), and \( \lambda \) values derived from the new thermo-TDR sensor with the values estimated with the de Vries (1963) \( C \) model, the Xie et al. (2018) \( \kappa \) model, and the Lu et al. (2014) \( \lambda \) model, respectively. Each data point represents the mean of measurements from two outer probes (i.e., mean of six values). In the case of probe deflections during the experiment, the Liu et al. (2013) spacing-correction method was used to correct \( r \) in situ based on the temperatures measured by the six thermocouples in the two sensing probes. During our measurements, there was very little change in \( r \), possibly due to the rigidity of the probes. Thus, the soil thermal property values derived from all six thermocouples were averaged.

Previous studies have indicated that a heat pulse sensor could overestimate the actual \( C \), especially for relatively dry soils (Tarara and Ham, 1997; Ren et al., 2003b; Knight et al., 2012; Lu et al., 2013). The ILS model has been reported to overestimate \( C \) by 5.2% (Ren et al., 2003b) or even by 6.4% on dry soils (Knight et al., 2012). In this study, using the ICPC model, the average \( C \) error was about 3% in the \( C \) range of 0 to 0.3 m³ m⁻³. The de Vries (1963) model estimates of \( C \) vs. the heat-pulse \( C \) values were distributed randomly around the 1:1 line, mostly within the ±10% error lines (Fig. 3a).

The heat pulse \( \kappa \) values vs. the Xie et al. (2018) modeled estimates were generally within the ±10% error lines (Fig. 3b). The few outliers might be due to non-uniformities in the soil cores. The heat pulse \( \lambda \) values vs. the Lu et al. (2014) model estimates were consistent, with nearly all values within the ±10% error lines (Fig. 3c). Thus, by using the ICPC theory, the new thermo-TDR sensor is able to avoid the overestimation errors in \( C \) values and underestimation errors in \( \kappa \) values associated with the previous sensors.

Heat Pulse Derived vs. TDR Derived Water Content

Figure 4 presents thermo-TDR sensor derived \( \theta \) values (\( \theta_{\text{TDR}} \)) vs. \( \theta \) values determined by oven drying soil samples. The data points are distributed around the 1:1 line, and a linear regression fit to the points had a coefficient of determination (\( R^2 \)) of 0.980. Compared with oven-dried \( \theta \) values, the \( \theta_{\text{TDR}} \) values had a RMSE of 0.014 m³ m⁻³ and a bias of −0.004 m³ m⁻³, suggesting that the new sensor provided accurate TDR \( \theta \) values. This is a significant improvement over the accuracy of the previous thermo-TDR sensors, which was within 0.016 to 0.026 m³ m⁻³ of the actual \( \theta \) values (Ren et al., 2003a; Liu et al., 2008; Wen et al., 2018).

Soil water content can also be estimated with heat pulse sensor estimates of \( C (\theta_{\text{HP}}, \text{Eq. [4]}) \). Previous work concluded that this method was more appropriate for determining changes in \( \theta \) rather than in actual values of \( \theta \) (Basinger et al., 2003; Knight et al., 2012; Lu et al., 2013). Overestimation of \( \theta_{\text{HP}} \) from actual \( \theta \) were reported to be mostly within a range of 0.026 to 0.067 m³ m⁻³ (Tarara and Ham, 1997; Song et al., 1998, 1999; Ren et al., 2003b; Lu et al., 2013). Figure 5 shows the results of \( \theta_{\text{HP}} \) determined with the new thermo-TDR sensor vs. oven-dried \( \theta \) values. In general, the \( \theta \) values agreed well, as indicated by the random distribution of data points around the 1:1 line and an \( R^2 \) value of 0.961 for the correlation between \( \theta_{\text{HP}} \) and \( \theta \). Averaged across seven soils, the
RMSE and bias of $\theta_{HP}$ from the ICPC model were 0.034 m$^3$ m$^{-3}$ and −0.007 m$^3$ m$^{-3}$, respectively, lower than the corresponding RMSE (0.039 m$^3$ m$^{-3}$) and bias (0.020 m$^3$ m$^{-3}$) of $\theta_{HP}$ from the ILS model. Thus, the new sensor provided satisfactory $\theta_{HP}$ results, and a greater accuracy was achieved with the ICPC model than with the ILS model.

Larger deviations of $\theta_{HP}$ from $\theta$ were observed for the intact soils than for the disturbed soils (Fig. 4). The disturbed samples were packed uniformly, while the intact samples probably had non-uniform soil structure.

Thermo-TDR Bulk Density, Total Porosity, and Air-Filled Porosity

On the five soils, the new thermo-TDR sensor provided $\rho_{b}$ results that generally agreed with the oven-dry values (Fig. 6), with a RMSE of 0.105 Mg m$^{-3}$ and a bias of −0.017 Mg m$^{-3}$. Previous studies on laboratory samples reported that the RMSE of thermo-TDR-derived $\rho_{b}$ values was in the range of 0.134 to 0.178 Mg m$^{-3}$ with either $C$-based or $\lambda$-based methods (Ochsner et al., 2001a; Ren et al., 2003a; Lu et al., 2016; Tian et al., 2018). Apparently, the new sensor and the combined analysis method are effective in improving $\rho_{b}$ measurement accuracy.

The sensor-estimated $n$ values and the actual $n$ values agreed well, with a RMSE of 0.039 and a bias of 0.003 (Fig. 7a). The $n_a$ values derived from the new thermo-TDR sensor measurements agreed well with the actual $n_a$ values, with a RMSE of 0.035 and a bias of 0.007 (Fig. 7b). Ochsner et al. (2001a) and Ren et al. (2003a) reported RMSEs of about 0.050 for $n_a$ values determined with previous thermo-TDR sensors, which is slightly larger than the results obtained here. Thus, with accurate thermal property and $\theta$ measurements, the new thermo-TDR sensor provided relatively accurate $\rho_{b}$, $n$, and $n_a$ values.

Source of Errors

The potential error sources with the new sensor include heat-induced water and vapor redistribution in the soil sample, probe deflections at insertion, and thermal instability under field applications. To minimize thermal-induced water and vapor movement in the soil while obtaining a clear heat pulse signal at the sensing probe, it is critical to regulate the heat pulse strength applied to the heater probe. An optimum heating scheme is obtained by doing a series of tests in agar solution and on repacked soil cores at various water contents (Supplemental Fig. S2 and S3). For this purpose, it is recommended to record the temperatures of both heater and
sensor probes. Furthermore, a sensor with a large diameter may be affected by the end effects resulting from a finite probe length, which requires further quantitative investigation, e.g., a simulation study that quantifies the errors of end effects, axial heat flow, as well as the probe–soil interface heat flow. Finally, we tested the new sensor on only a limited number of soil types with clay contents <20%. Future studies are required to test the sensor performance under field conditions and on soils with relatively large clay and organic matter contents.

Conclusions

We introduced a new thermo-TDR sensor to measure soil thermal properties and \( \theta \) directly, and then derived \( \rho_b \), \( n \), and \( n_a \) from the thermal property \( \theta \) values. The new sensor has longer and more rigid probes and a larger probe-to-probe spacing than the previous sensor. The sensing volume of the new sensor is almost three times that of the previous sensor. The ICPC and TL-BMO theories were used to analyze the heat pulse data and TDR waveforms, respectively. Laboratory tests on disturbed and intact soil cores demonstrated that the new sensor provided greater accuracy in thermal property and \( \theta \) values than did the previous thermo-TDR sensor. The average RMSEs of \( \theta \), \( \rho_b \), and \( n \) from the new sensor were 0.014 m \(^3\) m\(^{-3}\), 0.105 Mg m\(^{-3}\), and 0.039, respectively. Due to improved probe rigidity and greater sensing volume and measurement accuracy, the new thermo-TDR sensor has the potential to monitor \( \theta \), thermal properties, \( \rho_b \), \( n \), and \( n_a \) in situ.

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References


