Supplemental material for

An improved thermo-TDR technique for monitoring soil thermal properties, water content, bulk density, and porosity

1. The Experimental Setup to Determine the Sensing Volume of the New Thermo-TDR Sensor

![Diagram showing experimental setup](image)

Figure S1. A schematic diagram showing the procedures for determining the sensing volume of thermo-TDR sensors. Two scenarios were considered: (a) the probe plane was parallel to the container bottom (Horizontal position), and (b) the probe plane was vertical to the container bottom (Vertical position). The container was a rectangular glass container 22.5-cm in length, 16-cm in width and 8-cm in height. The red dashed line represents the initial water surface. Additional water was added in 2-mm increments, and TDR waveforms were collected after each water addition.

2. The Observed Values and Parameters Involved in the Thermo-TDR Measurements

To obtain detectable and clear temperature signals, a large amount of heat compared to that used with the early sensors is introduced to the soil, because of the
larger probe body and spacings of the new sensor. It is important to consider the possible consequences of water and vapor movement due to the thermal gradient created by the heat pulse. Thus, a series of experiments were performed to determine the optimum heat duration to produce an appropriate temperature rise in the sensor and to minimize possible errors caused by water and vapor flow. Figures S2 and S3 show the thermo-TDR measured temperatures in sensor and heater probes, respectively. Table S1 lists the parameter values for the measurements and curve-fitting procedure.

Figure S2. An example dataset of thermo-TDR measured temperature changes (circles) and the fitting results of the identical cylindrical perfect conductors (ICPC) model to the measured data (red lines) on a sand soil at soil water contents
(θ) of 0 and 0.25 m³ m⁻³, and in agar solution (5 g L⁻¹), respectively. The values 20 mm, 35 mm, and 50 mm indicate that data are collected at these three positions in a sensing probe. Table S1 lists the parameters used for curve fitting.

Figure S2 shows typical temperature changes as a function of time in agar solution and soil samples (dry and wet). The maximum temperature rise is lowest for the agar solution (~0.4°C). In the sand soil, the maximum temperature rises are 0.7-1.0°C, depending on soil water content. Additional water in soil increases the soil heat capacity, thus lowering the temperature rise of a heat pulse signal.

Table S1. The key parameters for curve-fitting: heat pulse intensity (q'), probe heat capacity (C₀) and probe radius (a₀) of the new thermo-TDR sensor, the heating duration (t₀) and the time range for the curve fitting (t_f). The values for the above parameters correspond to the data presented in Fig. S2.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Agar solution</th>
<th>Soil samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>q’ (W m⁻¹)⁵</td>
<td>47.13</td>
<td>47.04</td>
</tr>
<tr>
<td>C₀ (MJ m⁻³ K⁻¹)</td>
<td>3.68⁸</td>
<td>0.00119</td>
</tr>
<tr>
<td>a₀ (m)</td>
<td>30</td>
<td>25</td>
</tr>
<tr>
<td>t₀ (s)</td>
<td>31–350</td>
<td>31–300</td>
</tr>
<tr>
<td>t_f (s)</td>
<td></td>
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</tbody>
</table>

⁵ This value is calculated from the resistance and the current in the heater wire.

Table S1 lists the values of parameters used for fitting the model to measured data (Fig. S2). Considering the relatively large probe spacing (~10 mm) for the new thermo-TDR sensor, a heat intensity of about 47 W m⁻¹ with a long heating time (25-30 s) was used to make sure the temperature rise at the sensing probe was between 0.4 and 1.0°C.

The time length used for the curve-fitting is also listed in Table S1. To reduce the potential errors from the finite probe properties, the time length of temperature change data used for curve fitting should be carefully considered. If the temperature response curve has a flat peak (e.g., on a dry soil or in agar solution), the temperature data within
300-350 s are recommended (Fig. S2). When the temperature response curves have a well-defined peak (e.g., on wet soils), the data within the time range of 150 s are recommended.

Figure S3. Temperature rise dynamics at the heater probe during the heat pulse measurement. Parameter $\theta$ represents soil water content, $t_0$ and $q'$ represent the time duration and heating rate of the heat pulse measurement, respectively. The example datasets were collected on a sand soil at water content ($\theta$) of 0 and 0.25 m$^3$ m$^{-3}$, and in an agar solution (5 g L$^{-1}$).

The results show that the maximum temperature rises at the heater probe can reach 30°C in dry soils and 15°C in the agar solution (Fig. S3). The heating intensity should be carefully regulated to minimize the effects of water and vapor migration under thermal gradients in soil, and to obtain detectable and clear temperature signals, because of the relatively large probe spacings of the new sensor.

3. Sensor Overview

The thermo-TDR sensor directly measures state variables of soil temperature and TDR waveform. From these measurements, soil thermal properties and $\theta$ are determined, and $\rho_b$, $n$ and $n_a$ are estimated based on the functional relationships between soil thermal properties and particle-size distribution, $\theta$, and $\rho_b$. Figure S4 illustrates the
variables, parameters and estimation methods included in the thermo-TDR technique for determining soil physical properties.

**Figure S4.** An overview diagram for the thermo-TDR sensor to determine soil thermal properties, water content ($\theta$), bulk density ($\rho_b$), porosity ($n$), and air-filled porosity ($n_a$). $K_o$, $C$, $\lambda$, $c_s$, $f_s$, and $f_d$ represent soil dielectric constant, volumetric heat capacity, thermal conductivity, specific heat capacity of soil solids, the fractions of sand and clay, respectively. The dashed-line text box represents the ‘methods and calculations’, and the solid-line text box represents the ‘measured or the estimated variables/parameters’.