NON-INVASIVE PROBING OF THE NEAR-SURFACE SOIL MOISTURE PROFILE

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ABSTRACT: Time domain reflectometry imaging (TDRI) is a technique for non-invasive measurement of moisture content distribution. A solution to the 2-D problem has previously been described, and here we explain a configuration that provides a practical system for measuring a 1-D vertical profile of soil moisture. The measurement system consists of an enhanced TDR transmission line and reflectometer together with specialist software, to translate measurements of propagation times into a moisture content profile. We demonstrate a soil moisture accuracy of better than 2% for each 20 mm layer to 60 mm depth, with increasing accuracy loss for greater depths. However the attainable accuracy is dependent on the soil type and the dielectric model used for translation of permittivity profile to soil moisture profile. A practical depth limit for the current configuration is 100 mm. Assumptions and limitations of the technique will also be described.

Keywords: soil, moisture measurement, profile, non-invasive

INTRODUCTION

Determination of moisture content (θ) is of vital interest to a wide range of disciplines and industries. The range of materials is also diverse and includes soil, cereals, dairy products and timber. For soil, electrical methods now dominate θ measurement and typically employ probes or flexible transmission lines, inserted into the soil, although this process disturbs the profile and may provide preferential paths for water transport. The methods generally use either a direct measurement of soil capacitance or time domain reflectometry (TDR), both providing a measure of soil permittivity (εᵣ). In each case, the measured εᵣ is related to volumetric soil moisture content (θᵥ) via a suitable dielectric model.

Since soil disturbance is an issue for researchers investigating water movement in soil, efforts have been made to establish techniques for non-invasive measurement of θ. A further impetus has been to enable rapid measurements from a vehicle traversing a region, and hence mapping the spatial distribution of θ. In many instances, θ profiles add further useful information to measurements of the mean θ since they strongly affect moisture and heat transport, solute movement, and the activity of biological organisms, and are influenced by drainage, surface evaporation, plant water uptake and capillarity.

The few non-invasive methods for measuring θ profiles include unguided reflectometry in the frequency domain, also referred to as ground penetrating radar (GPR) [1,2] and electromagnetic induction [3]. The former is an immature technique, but seems likely to provide a depth range of approximately a metre, and resolve moisture content in 100 mm layers. The latter is dependent on soil type and conductivity. We have previously described a method for measuring the 2-D θ distribution [4] by ‘time domain reflectometry imaging’
(TDRI). Here we describe a 1-D application for the measurement of near-surface (0-100 mm), \( \theta_r \) profiles.

The TDRI probing signal comprises the lateral evanescent field of a parallel transmission line (PTL). A set of TDR measurements for different positions of the PTL relative to the nearby soil is inverted to obtain a representation of its \( \varepsilon_r \) distribution. In the present case \( \varepsilon_r \) is assumed invariant in the axial (z) and horizontal transverse direction (x), so the PTL is moved along the y-axis (normal to the soil surface) to resolve \( \varepsilon_r \) of flat sheets of soil in which \( \theta_r \) is assumed uniform (Fig 1). Having obtained the \( \varepsilon_r \) profile of the soil, a dielectric model is used translate the \( \varepsilon_r \) profile to \( \theta_r \).

![Figure 1 Arrangement of the PTL and the physical model of a layered soil profile. The apparatus at the left enables adjustment of the y-axis (vertical position) of the PTL.](image)

Use of the evanescent field as the EM probing signal contrasts with the more conventional microwave imaging method, and provides two important advantages. Scattering does not significantly attenuate the signal as occurs with microwave imaging [5], and the use of an evanescent field provides a spatial resolution that is not inherently limited by the wavelength \( (\lambda) \) as in GPR. However TDRI requires a very high time measurement resolution which in turn determines the depth resolution. Since transverse electromagnetic mode (TEM) propagation is assumed, the PTL waveguide separation must be small compared with \( \lambda \), so a practical penetration depth limit is approximately 100 mm with current instrumentation and measurement frequencies.

Here we describe some theory of the TDRI technique, and present early results from a laboratory trial using a physical model of a layered soil profile.
THEORY

Fundamental to TDRI is a forward solution to provide a prediction of the pulse propagation time \( t_p \) on a PTL surrounded by a prescribed, discretised, inhomogenous \( \varepsilon_r \) distribution. A suitable numerical procedure using a moment method (MM) has been described [6], and is used in conjunction with a solution to the inverse problem [4], to quantify the \( \varepsilon_r \) distribution given a set of propagation velocities representing different positions of the PTL. The assumption of lossless soils is common in the use of TDR for soil moisture measurement and although the forward model is currently limited to real \( \varepsilon_r \), it could be adapted to handle complex values. The MM is a volume integral electromagnetic modelling technique but was adapted to provide rapid calculation in 2-D [7].

Given an impressed electric field \( \mathbf{E}_i(r) \) in a region, the total resultant electric field distribution \( \mathbf{E}_{tot}(r) \), for a material of arbitrary permittivity distribution \( \varepsilon(r) \) is:

\[
\mathbf{E}_{tot}(r) = \mathbf{E}_i(r) + \mathbf{E}_{pol}(r)
\]

so that

\[
-\mathbf{E}_r(r) = \mathbf{E}_{pol}(r) - \frac{\mathbf{P}(r)}{\varepsilon_0 \chi(r)} = K(\mathbf{P})
\]

\( K \) is a linear operator acting on the polarization \( \mathbf{P} \) and \( \chi(x,y,z) \) is the electric susceptibility \( (\varepsilon(x,y,z) - 1) \). The resultant polarisation field \( \mathbf{E}_{pol}(r) \) is obtained from a numerical integral of the individual polarisation fields from all cells within the region.

\[
\mathbf{E}_{pol} = \frac{1}{4\pi\varepsilon_0} \nabla \left( \sum_i \frac{\mathbf{P} \cdot \mathbf{r}}{r^3} \Delta \tau \right)
\]

where \( \Delta \tau \) defines the size of a cell. The polarisation region may now be discretised, and following the MM [8], we calculate the matrix of polarisation vectors \([\mathbf{P}]\):

\[
[\mathbf{P}] = -[K]^{-1} [\mathbf{E}_i]
\]

Next the electric field strengths are extracted.

\[
\mathbf{E}_{tot}(r) = \frac{\mathbf{P}(r)}{\varepsilon_0 \chi(r)}
\]

Finally, to complete the solution for the case of a PTL, the voltage between the lines is obtained from a line integral over a suitable integration path \( I \) to obtain the line capacitance \( C \)

\[
C = \rho \int \mathbf{E}(r) \cdot dl
\]

where \( \rho \) is the linear charge density used to define the impressed field. \( t_p \) for a pulse reflected on the PTL is then calculated using the telegrapher’s equation for a lossless PTL.
The inverse solution may be described by:

\[ m = g^{-1}(d) \]  

(7)

where \( m \) is a set of model parameters or values of \( \varepsilon \), \( g \) describes the forward transfer function or forward model, and includes reliance on \( \varepsilon \) and other parameters such as PTL geometry and fundamental constants, and \( d \) is a set of observations or readings of \( t_p \). We chose conjugate gradient (CG) optimisation to solve this non-linear inverse problem. The procedure begins with an estimate of the \( \varepsilon \) distribution \( m_0 \), usually employing a priori information. The key parameter in the steepest descent method that also forms the basis for the CG method, is the weighting factor \( \alpha \) in the recurrence relation:

\[ m_{i+1} = m_i - \alpha_i J_i^{-1} \Delta t_i \]  

(8)

Here the new model \( m_{i+1} \) is derived from the previous permittivity model \( m_i \), corrected by the weighted product of the sensitivity \( J_i^{-1} \), and the error in propagation time \( \Delta t_i \). The magnitude of \( \alpha_i \) controls the step size and its optimal value depends on the local curvature of \( g \), the accuracy of \( J_i^{-1} \), and the distance to the solution. \( \alpha_i \) is determined dynamically.

Materials and Methods

Evaluation of TDRI for measurement of soil moisture profiles used a physical model of a soil profile. The model comprised a perspex housing 400 by 200mm in plan, containing five, 20mm thick layers of fine sandy loam, separated by 1mm polycarbonate separator sheets. To obtain similar dry bulk densities in each layer, one layer was filled with oven dry screened soil while the housing was gently shaken, and then the soil was removed and weighed. In several sub-layers, the measured mass (1509g) of soil was used to fill each 20mm layer. Each sub-layer was interspersed with a predetermined quantity of water sprayed on the soil surface to obtain the target moisture content for that layer. The final step in the process was to sprinkle an additional quantity of dry sieved soil to fill the layer, hence compensating for the slight differences in packed volume. As a result, there were minor differences in the dry bulk density between layers. The weight of the model was monitored at regular intervals throughout the trial.

The PTL was constructed from 6 mm diameter brass rods spaced 60mm apart, with an active length of 300mm. Although stainless steel PTL rods have been used for conventional TDR measurement of \( \theta \), degradation in the risetime \( (t_r) \) of the voltage step from the balun was approximately 100 ps, hence leading us to use a lower loss material. The brass PTL had a negligible effect on \( t_r \).

The beginning of the active portion of the PTL was defined by a shunt diode. The diode, a HP5082-3188 PIN diode (on-resistance \( R_s = 0.6 \Omega \) at a diode current \( I_d = 10 \text{ mA} \), and reverse bias capacitance \( C_r < 1 \text{ pF at 20 V} \)) was employed in a manner similar to that of Hook et al. [9], and a bias network enabled the diode to be switched on to provide a reference measurement. However, contrary to their findings when applied to the less demanding
measurements using a buried PTL, we detected the effect of diode impedance changes up to a
reverse bias on the diode of 20 volts, although the forward current had little effect once the
diode was forward biased. Consequently, a forward current of 10 mA was chosen for the
reference measurement and minus 20 V to measure total propagation time.

Measurements were made with a Hewlett Packard (since renamed Agilent) HP54121T
digitising oscilloscope which incorporates a step generator for TDR measurements. The PTL
assembly was connected to the HP54121T by a semi-rigid coaxial cable, a balun and the
diode bias network. A Guanella type balun was constructed similar to the 1:4 balun described
by Spaans and Baker [10] but used 3.5 mm diameter, grade S3 ferrite toroids with three turns
of 0.125 mm enamelled wire for both isolating and splitter baluns. PTL positioning was
achieved by a 1 mm pitch lead screw driven from a 7.5° stepper controlled from a standard
PC printer port and power interface (Fig 1).

The measured and reference waveforms were retrieved from the HP54121T and the difference
waveform was smoothed and differentiated using 25 point least squares fitting routines [11].
Both reference and measured reflection times on the difference waveform were determined
from the intersection of tangents to the maximum slope of the returned edge and the
preceeding plateau in a manner similar to that used by van Gemert [12]. The time difference
provided a measurement of $t_p$ for the active section of the PTL. The end effect, which
increases mean $t_p$ due to end capacitance, was ignored.

Next, the vector of measured $t_p$ was solved for the $\theta_e$ profile, using the inversion process
outlined above. A plane, transverse to the PTL, was discretised into a 16 by 16 array of 10-
mm square cells. The cells in the six upper rows were assigned values of $\varepsilon_r=1$ and
represented the space above the soil surface in which the PTL was positioned, and the lower
10 rows represented 5 layers of soil, each 20 mm thick. The cells in the soil layers were all
assigned an a priori value (used as the starting distribution in the iterative inversion
procedure), of $\varepsilon_r = 20$, corresponding to $\theta_e = 0.33$. Conversion between $\varepsilon_r$ and $\theta_e$ used the
equation of Topp [13].

The single calibration used a reading of $t_p$ with the PTL in air. The measured $t_p$ (with the
PTL far from the physical soil model) was compared with the predicted reading for a uniform
distribution of $\varepsilon_r = 1$, and the difference (46 ps) was used to offset the predicted $t_p$.

RESULTS AND DISCUSSION

Table 2 shows the constituents of each soil layer. The mass of water was calculated to
provide the given profile of $\theta_e$. Although not used, the dry bulk density has been calculated
for each layer since it does affect the Topp dielectric model, most notably at low values of $\theta_e$. 
Table 2: Results showing quantity of fine sandy loam and water in each layer, the volumetric water content, and the dry bulk density.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Depth (mm)</th>
<th>Mass dry soil (g)</th>
<th>Mass water (g)</th>
<th>Soil volume (cc)</th>
<th>Moisture content (V/V)</th>
<th>Dry bulk density (g/cc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0-20</td>
<td>1554</td>
<td>136</td>
<td>1360</td>
<td>0.1</td>
<td>1.143</td>
</tr>
<tr>
<td>2</td>
<td>20-40</td>
<td>1594</td>
<td>204</td>
<td>1360</td>
<td>0.15</td>
<td>1.172</td>
</tr>
<tr>
<td>3</td>
<td>40-60</td>
<td>1566</td>
<td>272</td>
<td>1360</td>
<td>0.2</td>
<td>1.151</td>
</tr>
<tr>
<td>4</td>
<td>60-80</td>
<td>1584</td>
<td>408</td>
<td>1360</td>
<td>0.3</td>
<td>1.165</td>
</tr>
<tr>
<td>5</td>
<td>80-100</td>
<td>1596</td>
<td>476</td>
<td>1360</td>
<td>0.35</td>
<td>1.174</td>
</tr>
</tbody>
</table>

Six measurements were made at distances from the soil surface of 5 to 55 mm. Errors could reasonably be expected due to the influence of the polycarbonate ($\varepsilon_r = 3$) sheets separating the layers, so the first measurement positioned the PTL rods in line with the centres of the cells used for the forward problem model, i.e. with 5 mm spacing between the rod centres and the soil surface (half the cross-sectional dimension of each cell). Hence the upper polycarbonate sheet was included in the row of cells immediately above the soil surface.

Measured and predicted (using the forward model) readings for $t_p$ are listed in Table 3. The inversion process stopped after 60 iterations and errors in $t_p$ (between the measured values and those predicted from the model $\theta_v$ profile) ranged from 0.06 ps to 0.3 ps. Although Table 3 indicates a very close correlation between simulated and measured values, no account has been taken of the effect on the forward model of the polycarbonate separator sheets, since the effect is very non-linear. Figure 2 shows the measured and actual (as defined in Table 2) $\theta_v$ profiles.

Table 3 Simulated and measured values of $t_p$ (ns) and their difference (ps). No correction was made for the 1 mm polycarbonate sheets separating the soil layers.

<table>
<thead>
<tr>
<th>Simulated</th>
<th>Measured</th>
<th>Error (ps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.721</td>
<td>2.714</td>
<td>-7</td>
</tr>
<tr>
<td>2.248</td>
<td>2.241</td>
<td>-7</td>
</tr>
<tr>
<td>2.134</td>
<td>2.128</td>
<td>-6</td>
</tr>
<tr>
<td>2.090</td>
<td>2.084</td>
<td>-6</td>
</tr>
<tr>
<td>2.070</td>
<td>2.064</td>
<td>-6</td>
</tr>
<tr>
<td>2.060</td>
<td>2.054</td>
<td>-6</td>
</tr>
</tbody>
</table>
There have been too few trials to date to confidently predict accuracy of the technique, but theory dictates that accuracy will diminish with depth. For the current configuration, a practical depth limit of 100 mm would probably apply since the $\theta_v$ reading for the 80 to 100 mm soil layer had a discrepancy of 0.088. As noted earlier, accuracy is dependent on the measurement accuracy of $t_p$. However it is also dependent on the accuracy of the forward model and on the inversion technique. The forward model assumes a uniform moisture distribution within each layer. For this trial, the assumption is violated by the presence of the polycarbonate separators, and in a real measurement situation, the actual shape of the profile will affect accuracy. On the other hand, optimisation of the inversion process and the use of a more realistic \textit{a priori} distribution may improve accuracy. Future work will consider approaches to further improve performance, and will also assess the accuracy using a range of soil profiles and for several soil types. We will also investigate the use of a reflectometer that is more appropriate for unattended field operation.

CONCLUSIONS
A novel TDRI method has been developed to non-invasively measure the near-surface moisture profile of soil in the range 0 to 100 mm. Measurements were made using precision TDR equipment, and reconstruction of the soil moisture profile used a moment method solution to solve the forward problem, and a conjugate gradient approach for the iterative inverse solution. An instrument based on the approach described here should have broad application in both research and commercial applications where a non-invasive method of measuring near-surface soil moisture profiles is required.

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REFERENCES


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