An analysis of the ground-penetrating radar direct ground wave method for soil water content measurement

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Abstract:

The spatial variability of soil water content can be measured with the ground wave velocity of ground-penetrating radar (GPR) using short antenna offsets, but picking the correct ground wave arrival time is rather difficult. In applying the GPR ground wave method to soil water content estimation it is also important to know the effective sampling depth of the method. Uniform drainage experiments were conducted with 100 and 450 MHz GPR antennas using 1-0 and 2-0 m fixed antenna separations on a sandy loam soil to investigate time zero picking methodologies and to estimate the sampling depth of the GPR method. The GPR water content data were compared with time-domain reflectometry (TDR)-measured data using six vertical TDR probes of different lengths. Time zero was calculated from an air calibration at a 2-0 m antenna separation and from wide-angle reflection and refraction data, and a difference was found between the two time-zero calibration methods. A method was analysed to determine the arrival time of the leading edge of the direct ground wavelet using the arrival time of the peak amplitude, since the arrival time of the leading edge of the ground wave can be difficult to pick. Regression analysis showed that the GPR (100 MHz) measured water content was not different from the water content measured with TDR at 0–0-1 m depth, implying that this may be a reasonable estimate of the GPR ground wave method’s sampling depth. A similar analysis based on the differences between the 0–0-2 m TDR and the GPR shows that the effective sampling depth of the direct ground wave of the 450 MHz data is less than the sampling depth of the 100 MHz data. Copyright © 2003 John Wiley & Sons, Ltd.

KEY WORDS water content; wide-angle reflection and refraction; common mid point; fixed offset method; single trace analysis

INTRODUCTION

Knowledge of the variability of soil water content in space and time is important in many fields, such as hydrology, soil and water resources development and protection, irrigation management, etc. Partitioning of rainfall into infiltration and runoff depends on soil water content. Also, the velocity of contaminant transport in soil is dependent on the soil water content and its variation with depth. As yet, no efficient method has been developed to measure the variability of soil water content at field or watershed scales, which is vital in applications that include agricultural water management and soil and water conservation. The gravimetric method using soil samples is the standard and direct method for soil water content measurement. Field disturbance, intensive labour and inability to carry out repeat measurements are the main disadvantages of the gravimetric method. Time-domain reflectometry (TDR) has become the most widely used and accepted method for soil water content measurement (Topp et al., 1980, 1982; Whalley, 1993; Nielsen et al., 1995). However, the sample volume of TDR is restricted to a small cylindrical volume along the probe length (Nadler et al., 1991; Zegelin et al. 1992). Remotely sensed microwave radiation has also been used to estimate accurate soil water content below 0-1 m depth over a large area by Whalley and Bull (1991) and Whalley et al. (1991).
Ground-penetrating radar (GPR), a non-intrusive geophysical method, has been identified and tested as a tool to measure the soil water variability at intermediate scales, between small-scale methods and large-scale remotely sensed methods (Chanzy et al., 1996; Du and Rummel, 1994; Huisman et al., 2001; Huisman and Bouten, 2002).

There have been numerous previous studies on the use of a variety of GPR methods for estimating soil water content. Soil water content measurements with surface GPR were compared with TDR-measured water contents by Huisman et al. (2001) and Weiler et al. (1998), to gravimetrical water contents by Chanzy et al. (1996) and to water contents from capacitance sensors by van Overmeeren et al. (1997). Also, soil water content variations and preferential flow areas have been mapped with borehole GPR (Parkin et al., 2000; Galagedara et al., 2002; Redman et al., 2000). The air-launched surface reflectivity GPR method was tested for estimating soil water content at different field sites by Redman et al. (2002). In another study, a strong correlation was found between surface reflectivity GPR data and soil water content, but the accuracy was comparatively lower than the surface GPR method (Chanzy et al., 1996).

**GPR ground wave method**

With the GPR method, soil water content can be estimated from the electromagnetic wave velocity using the Topp relationship (Topp et al., 1980). The main events observed on a GPR receiving antenna are the direct air wave, direct ground wave and reflected events, as described by Du and Rummel (1994) and Huisman et al. (2001) and others. The direct ground and air wave propagates directly from the transmitter to the receiver, the former just below the soil surface and the latter in the air. Unlike TDR, the direct ground wave is an unguided wave, with a poorly understood penetration depth.

By measuring the direct ground wave travel time $t_{gw}$ from the transmitter to receiver, the ground wave velocity $V$ can be calculated simply by $L/t_{gw}$, where $L$ is the separation between the transmitting and receiving antenna. The ground wave velocity $V$ is converted to the relative dielectric permittivity of the soil using the electromagnetic wave velocity in free space:

$$K_r = \left(\frac{c}{V}\right)^2$$

where $c$ is the electromagnetic wave velocity in free space (Davis and Annan, 1989).

The relative dielectric permittivity $K_r$ is used to determine the volumetric water content using the empirical relationship developed by Topp et al. (1980).

The surface GPR ground wave method for measuring soil water content can be performed using three major survey types. The first type is called a common mid point (CMP) survey, in which both the transmitter and receiver antennas are moved apart from each other at a constant spatial increment (Figure 1a). Wide-angle reflection and refraction (WARR) is the second survey type, in which the transmitter antenna is kept at a fixed location while the receiver antenna is moved away from the transmitter at a constant spatial increment (Figure 1b). CMP and WARR surveys are normally used to estimate the subsurface velocity structure by analysing the dependence of arrival time on offset for events reflected from subsurface horizons. In both these survey types, the direct ground wave arrival time is zero at the 0 m antenna offset and for a laterally homogeneous media it increases linearly with increasing antenna offset. This variation between different antenna offsets and ground wave travel times is referred to as the time–offset relationship. The inverse slope of the time–offset relationship gives the average ground wave velocity between the minimum and maximum antenna offsets. Since multiple traces are used to estimate the radar wave velocity in both CMP and WARR survey types, the data analysis is called a multiple trace analysis (MTA). The third survey type is conducted by keeping a fixed transmitter–receiver antenna offset and moving both antennas at a constant spatial increment over the survey area, which is called profiling. This survey type is called the fixed offset method (FOM).
Figure 1. Schematic diagram to represent the three main survey types (five traces each) in measuring soil water content with the ground wave of GPR: (a) CMP; (b) WARR; (c) FOM; x represents the measurement station location in each survey type. GPR transmitter; GPR receiver

and the data analysis method is the single trace analysis (STA), since a single trace is used for the velocity estimation at each location (Figure 1c).

There have been many previous studies on the application of these methods to the measurement of soil water content. Seasonal soil water contents have been measured using the direct ground wave with CMP survey type by van Overmeeren et al. (1997) and Greaves et al. (1996). The WARR survey method was effectively used by Du and Rummel (1994) and Huisman et al. (2001) for soil water content measurements. Du and Rummel (1994) showed that a large-scale measurement of soil water content could be done using the surface GPR method starting with a WARR survey followed by an FOM survey. Volumetric water contents determined with soil samples supported the wetting front advancement, as observed with the FOM GPR under uniform irrigation by Vellidis et al. (1990). As shown by Huisman et al. (2001), the accuracy of the WARR method was higher than the FOM, using the TDR-measured soil water content. The advantages of the CMP and WARR survey types are: (1) the ability to measure the interlayer velocities and water contents when subsurface reflections are present; (2) the ability to measure the depth to the subsurface reflector, such as the water table; and (3) the ability to obtain the reasonably accurate average velocities between the minimum and maximum antenna offset. In both the WARR and CMP methods, soil water content can be calculated without estimating the absolute direct ground wave arrival time, since only the slope of the time versus offset relationship is required. The longer times taken to complete a survey and low spatial resolution are the main disadvantages. On the other hand, high spatial resolution when shorter antenna offsets are used and the ability to survey large areas in a short time period are the main advantages of the FOM.

Two issues with using the FOM are: the accuracy of the measured soil water content depends on the correct picking of the leading edge of the direct ground wave; and the air wave velocity calibration (time zero) of the GPR instrument (Huisman and Bouten, 2002). Time zero is defined as the start of the transmitter pulse and all other arrival times are measured with respect to this time. The amplitude versus time output (trace data) produced by the GPR instrument has an inherently defined time zero, but a more accurate time zero value has to be determined when estimating ground wave velocity with the FOM. Also, each GPR system’s time zero may vary due to thermal drift and flexing of the fibre-optic cables. Similar timing instability has been observed in borehole GPR studies, where an accurate estimate of time zero is also critical (Peterson, 2001). With the FOM method the time-zero value has to be estimated accurately using an air wave velocity calibration (time zero) of the GPR instrument (Huisman and Bouten, 2002).

Picking of the leading edge transition of the direct ground wave event directly in a GPR trace is often difficult, but the peak of the ground wave event is relatively easy to identify and pick. Therefore, it is feasible that the peak time could be used to estimate the ground wave velocity rather than picking the more
difficult leading edge of the ground wave. We conducted several drainage experiments with two different GPR antenna frequencies to address the following issues. First this study will assess the accuracy of GPR-based soil water content measurements under a transient drainage state using the simple and more practical FOM rather than the WARR or CMP analysis. Secondly it will analyse the difference between GPR and TDR measurements of soil water content in relation to sample volume and scale. The objectives of this paper are: (1) to estimate the transient state (under drainage) soil water content variation with the FOM of GPR using two different frequencies; (2) to investigate the reliability of GPR air wave velocity (time zero) calibrations under different soil water contents; (3) to determine the direct ground wave penetration depth with two different GPR frequencies; (4) to describe and analyse a method of measuring GPR ground wave velocity based on the peak arrival time.

MATERIALS AND METHODS

Drainage experiments were conducted at the research station of the University of Guelph in Cambridge, Ontario, Canada. The location and site characteristics have been explained by Parkin et al. (2000). Uniform drainage experiments were conducted with the 100 and 450 MHz GPR antennas to estimate the direct ground wave penetration depth by comparing with TDR-measured water content. Vertical TDR probes of different lengths were installed between the GPR antennas (Figure 2). The method of Topp et al. (1980) was used to convert both GPR- and TDR-measured relative dielectric permittivity to soil water content throughout this

Figure 2. Field layout of the drainage experiment with fixed-offset GPR and vertically installed TDR probes. Tx: GPR transmitter; Rx: GPR receiver. Irrigated areas are shaded in both (b) and (c). (a) Longitudinal cross-section; (b) plan view of 450 MHz; (c) plan view of 100 MHz. Lengths of TDR probes: a = 0.1 m, b = 0.2 m, c = 0.3 m, d = 0.4 m, e = 0.5 m and f = 0.6 m.
study. These experiments were conducted on a selected area of 1.0 m × 2.0 m on a sandy loam soil with fixed antenna offsets for each frequency. The experimental area was covered with grass with a 6–8 cm thick organic layer (thatch) found at the soil surface.

For experiments with the 100 and 450 MHz antennas, the b, c, d, and e TDR probes (Figure 2) were used, whereas only for one experiment with 100 MHz antennas all TDR probe lengths were used. At the beginning of each experiment, five GPR wave traces were collected to measure GPR time zero. This was done by placing the antennas 2.0 m apart and on their sides to enhance the air wave. Also, at the end of the 100 MHz experiment with all TDR probes, five GPR wave traces were recorded in the same manner with and without the vertical TDR probes installed. These traces were taken to ensure that the TDR probes did not affect the GPR time-zero calibration.

If the calculated travel time of the air wave (electromagnetic wave in air) at 2.0 m separation is denoted by \( t_{\text{air}} \), and the observed time of the air wave arrival at 2.0 m separation is \( t_{\text{aw}} \), then time-zero calibration \( t_0 \) is calculated as

\[
    t_0 = t_{\text{air}} - t_{\text{aw}}
\]

WARR data were collected for soil water content determination at beginning of drainage, but only with the 450 MHz antennas. This was done by collecting four GPR traces with offsets of 0.25, 0.5, 0.75 and 1.0 m between the transmitter and receiver. These WARR data were also used to calculate the time zero. This was done by linearly extrapolating the WARR data to an antenna offset of zero.

The selected 1.0 m × 2.0 m area was wetted uniformly by sprinkling water on the ground surface for about 30 min. As shown in Figure 2b and c, infiltration plots were slightly larger than the experimental area for the respective antenna frequencies. Just after the water application, a drainage experiment was conducted over a 1.5 h period with a 1.0 m fixed antenna offset for the 450 MHz GPR antennas. Two drainage experiments were conducted using the 100 MHz GPR antennas with a 2.0 m fixed offset for 0.85 and 1.30 h periods. In all three of these experiments, five GPR traces were recorded and TDR data were collected by connecting TDR probes to a Tektronix cable tester at each measurement time. For one of the experiments with 100 MHz antennas, five traces were collected before vertical TDR probes were installed and then five more traces after vertical TDR probes were installed, before water was applied to determine the background soil water content. Both GPR and TDR data were recorded as often as possible at the beginning of drainage, and with a gradually increasing time interval between measurements towards the end of the drainage. At each measurement time, five GPR traces were recorded and TDR data were collected from all the TDR probes over a period of about 1–2 min. By completing the measurement process this quickly, the temporal variability of soil water content between the GPR and TDR data, as well as between different lengths of TDR probes, was kept to a minimum.

RESULTS AND DISCUSSION

Water content measured with 100 MHz: GPR during drainage

To estimate temporal water content variation using fixed offset GPR, first a time zero was estimated by picking the leading edge of the direct air wave using the five in-air traces and then the leading edge of the direct ground wave was first picked manually. For this experiment, we collected five air wave traces each time to use for calibration at the beginning and end of each experiment when vertical TDR probes were present and absent. Therefore, three time-zero values were obtained and the respective absolute ground wave arrival times were calculated as given in Equation (3):

\[
    t_{\text{ab}} = t_{\text{gw}} - t_0
\]

Where \( t_{\text{ab}} \) is the absolute ground wave arrival time and \( t_{\text{gw}} \) is the measured ground wave arrival time (leading edge of the ground wave).
Air calibration of time zero (Equation (2)) was carried out at three different times in the 100 MHz experiment. Calculated average time zeros, and the respective water contents for background, end of irrigation, end of drainage and average water contents during the entire experiment, are presented in Table I. Standard deviations \((n = 5)\) of air wave arrivals are given next to calculated average time zeros (Table I). As seen in Table I, estimated time-zero values are relatively constant (less than 1 ns difference) and the respective water contents are also similar (less than 0.01 m³ m⁻³ difference). These data show that time-zero estimation with air wave calibration has not been affected substantially by the surface water content change, by GPR instrument drift or by the presence of vertical TDR probes between GPR antennas. A 1 ns difference in time-zero calibration would change the estimated soil water content change by about 1–2%.

Water content changes measured with fixed offset GPR (2.0 m offset) and TDR during the drainage experiment are shown in Figure 3. Error bars on GPR data represent the water content variability due to a ±0.5 ns uncertainty of the leading edge picking time and/or time-zero calibration error. It was found that over-estimation of the ground wave arrival time by 1.0 ns could lead to a water content estimate increase.

Table I. Average time-zero values \( (n = 5) \) calculated at different times with and without TDR probes installed and the respective background, end of irrigation and drainage and average soil water content values

<table>
<thead>
<tr>
<th>Average time zero (ns)</th>
<th>Soil water content ( (\text{m}^3 \text{m}^{-3}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Background</td>
<td>End of irrigation</td>
</tr>
<tr>
<td>−6.84 ± 0.03 (before water was applied)</td>
<td>0.188</td>
</tr>
<tr>
<td>−6.99 ± 0.01 (at end of drainage with TDR probes)</td>
<td>0.190</td>
</tr>
<tr>
<td>−7.23 ± 0.02 (at end of drainage without TDR probes)</td>
<td>0.195</td>
</tr>
</tbody>
</table>

Figure 3. Comparison of water contents estimated with fixed offset (2.0 m) GPR with 100 MHz antennas and TDR for background soil water content and during the drainage experiment. Numbers in legend show TDR probe lengths. (a) The first GPR measurement for the background soil water content without vertical TDR. (b) The second GPR measurement for the background soil water content with vertical TDR.
Table II. Calculated electromagnetic wave velocity and respective relative dielectric permittivity at three different times with fixed offset (2.0 m) GPR (100 MHz) and TDR (different depths) methods during drainage

<table>
<thead>
<tr>
<th>GPR</th>
<th>TDR probes</th>
<th></th>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10 cm</td>
<td>20 cm</td>
<td>30 cm</td>
<td>40 cm</td>
<td>50 cm</td>
<td>60 cm</td>
</tr>
<tr>
<td>Velocity (m ns⁻¹)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BKD</td>
<td>0.098</td>
<td>0.099</td>
<td>0.106</td>
<td>0.113</td>
<td>0.113</td>
<td>0.116</td>
</tr>
<tr>
<td>EOI</td>
<td>0.063</td>
<td>0.061</td>
<td>0.064</td>
<td>0.067</td>
<td>0.069</td>
<td>0.068</td>
</tr>
<tr>
<td>EOD</td>
<td>0.080</td>
<td>0.084</td>
<td>0.084</td>
<td>0.092</td>
<td>0.093</td>
<td>0.091</td>
</tr>
<tr>
<td>Average</td>
<td>0.077</td>
<td>0.079</td>
<td>0.082</td>
<td>0.088</td>
<td>0.088</td>
<td>0.086</td>
</tr>
<tr>
<td>Standard deviation (±)</td>
<td>0.011</td>
<td>0.011</td>
<td>0.013</td>
<td>0.013</td>
<td>0.013</td>
<td>0.013</td>
</tr>
<tr>
<td>Relative dielectric permittivity</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BKD</td>
<td>9.4</td>
<td>9.2</td>
<td>8.0</td>
<td>7.1</td>
<td>7.0</td>
<td>7.4</td>
</tr>
<tr>
<td>EOI</td>
<td>22.9</td>
<td>24.0</td>
<td>22.1</td>
<td>20.1</td>
<td>19.1</td>
<td>19.2</td>
</tr>
<tr>
<td>EOD</td>
<td>14.1</td>
<td>12.9</td>
<td>12.9</td>
<td>10.7</td>
<td>10.4</td>
<td>10.8</td>
</tr>
<tr>
<td>Average</td>
<td>16.2</td>
<td>15.3</td>
<td>14.2</td>
<td>12.3</td>
<td>12.2</td>
<td>12.9</td>
</tr>
<tr>
<td>Standard deviation (±)</td>
<td>4.2</td>
<td>4.2</td>
<td>4.1</td>
<td>3.6</td>
<td>3.5</td>
<td>3.4</td>
</tr>
</tbody>
</table>

a BKD: background; EOI: end of irrigation; EOD: end of drainage.

of 0.017 m³ m⁻³. The calculated electromagnetic wave velocities and the respective soil relative dielectric permittivity values using GPR and TDR for background, end of irrigation and end of drainage, together with averages, are given in Table II. According to the water content profile acquired using TDR data, the highest water content was observed at shallow depths and the water content generally decreased with depth into the soil profile. As shown in Figure 3, the increasing and decreasing pattern of the water content is relatively uniform over the entire TDR depth range and the GPR-measured water contents follow the same pattern. The GPR-measured water contents were in closest agreement with 0–0.1 m TDR probe length. A regression analysis performed found no significant difference between GPR- and TDR-measured water contents at 0–0.1 m depth. Also, no difference was found between the rate of water content change during the entire drainage period estimated from the 100 MHz GPR method and TDR method for all TDR depths.

The first two points of the GPR data (Figure 3) are the background water contents estimated with the FO method when vertical TDR probes are present (point B) and absent (point A). The data show that the presence of the vertical TDR probes does not affect the GPR-measured soil water content substantially.

Water content measured with 450 MHz GPR during drainage

As discussed in the ‘Materials and methods’ section, three different surveys were performed during the drainage experiment with 450 MHz antennas. First, five GPR traces were collected for time-zero calibration, then a WARR data set with four antenna offsets was acquired and finally GPR traces were collected with the FOM at regular intervals during drainage. The calculated electromagnetic wave velocities and soil relative dielectric permittivity values using GPR (FOM) and TDR for background, end of irrigation and end of drainage, and their averages, are given in Table III. Figure 4 presents a comparison of water contents estimated with GPR ground wave velocity and four different TDR depths before and during the drainage experiment. It was found that the GPR-estimated water content was higher than the TDR-measured water contents for all TDR depths, but was closer in value to the shallowest depth. Error bars on the FOM GPR data represent the water content variability due to a ±0.5 ns uncertainty of the leading edge picking time and/or time-zero calibration error. It is important to note that the WARR-based data point is much more closely related to the TDR data. Both the WARR and the FOM analysis provide the average value of the radar velocity, and hence the average water content over the 1.0 m long transect.
Table III. Calculated electromagnetic wave velocity and respective relative dielectric permittivity at three different times\(^a\) with fixed offset (1.0 m) GPR (450 MHz) and TDR (different depths) methods during drainage

<table>
<thead>
<tr>
<th></th>
<th>GPR</th>
<th>TDR probes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Velocity (m nS(^{-1}))</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>20 cm</td>
</tr>
<tr>
<td>BKD</td>
<td>0.085</td>
<td>0.086</td>
</tr>
<tr>
<td>EOI</td>
<td>0.062</td>
<td>0.065</td>
</tr>
<tr>
<td>EOD</td>
<td>0.087</td>
<td>0.093</td>
</tr>
<tr>
<td>Average</td>
<td>0.080</td>
<td>0.082</td>
</tr>
<tr>
<td>Standard deviation (±)</td>
<td>0.003</td>
<td>0.008</td>
</tr>
<tr>
<td></td>
<td>Relative dielectric permittivity</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>20 cm</td>
</tr>
<tr>
<td>BKD</td>
<td>12.5</td>
<td>12.3</td>
</tr>
<tr>
<td>EOI</td>
<td>23.5</td>
<td>21.6</td>
</tr>
<tr>
<td>EOD</td>
<td>11.8</td>
<td>10.4</td>
</tr>
<tr>
<td>Average</td>
<td>14.6</td>
<td>14.0</td>
</tr>
<tr>
<td>Standard deviation (±)</td>
<td>3.5</td>
<td>376</td>
</tr>
</tbody>
</table>

\(^a\) BKD: background; EOI: end of irrigation; EOD: end of drainage.

Figure 4. Comparison of water contents measured with GPR (450 MHz, WARR and FOM) and vertically installed TDR at different depths for background soil water content and during the drainage experiment. Numbers in legend show the TDR depths.

In this experiment, we would expect there to be significant differences in the velocities estimated with the FOM and the WARR method because the procedures used to estimate the velocities are quite different. In the WARR method, the average wave velocity is calculated using the slope of the time–offset relationship, whereas in the FOM the absolute travel time has to be estimated. In analysing WARR data, the slope of the time–offset relationship was calculated by picking the peak amplitude of the ground wave. We found that
the arrival time of the wavelet peak was easier to find and to pick automatically than the leading edge. In the FO method, the leading edge of the ground wave had to be picked when estimating the absolute travel time. Automatic picking of the leading edge of the ground wave was not always possible, and manual picking is subjective and more prone to errors.

A time-zero correction of $-4.0$ ns was found using the in-air calibration method for the FOM. Using the WARR data, a time-zero correction of $-2.9$ ns was determined from the intercept of the offset versus time relationship (Figure 5a) for the leading edge pick of the ground wave. A similar analysis of the WARR data also gave a time-zero correction of $-2.9$ ns for the air wave. Then water content values were recalculated using time zero estimated with WARR analyses and again compared with TDR-measured water contents (Figure 5b). As shown in Figure 5b, these GPR-measured water contents agree slightly better with TDR-measured water contents than water contents estimated using the in-air time-zero calibration (Figure 4).

It is obvious from both Figures 4 and 5b that the difference between GPR- and TDR-measured water contents increases with drainage time. The GPR-measured water content is much more similar to TDR-measured water content at the wet end than the dry end. As the drainage continued, the depth dependence of TDR-measured water contents also increased and the highest water content was found at the shallowest depth (10 cm probe). As shown in Figures 4 and 5b, water content decrease measured with GPR method was lower than the TDR-measured water content during drainage. The high water content observed near the soil surface by GPR could be due to the high water-holding capacity of the grass thatch layer (high organic matter layer $0–10$ cm) compared with the low water-holding capacity of deeper and high sand content layers (below 10 cm). The effect of evapotranspiration loss could be neglected, since the total time of the drainage was less than 2 h. The highest water content found near the soil surface from TDR data and the presence of the grass thatch layer suggest that the ground wave method sampling depth of the 450 MHz antennas is concentrated within the very near surface of the soil profile.

Figure 6 presents a comparison between water contents estimated with the 100 MHz data and the 450 MHz data, for both air-calibrated time zero and the WARR-calibrated time zero, and the TDR data for shallow depths. The two experiments with 100 and 450 MHz GPR systems were conducted on two different days at the same site. The soil types and ground surfaces were similar in both experiments, but the locations were not exactly the same. The initial water contents measured with TDR were not identical: the 450 MHz experiment...
Figure 6. Comparison of soil water content estimated during drainage with two GPR frequencies (100 and 450 MHz). The 450 MHz data with antennas in-air-calibrated time zero and WARR-calibrated time zero are both given. TDR-measured soil water contents (shallow depth) are also shown for the two different experiments. TDR probe lengths and respective experiments are given in the legend.

had higher initial water content (comparing the 0–0.2 m TDR data from the two experiments, Figure 6). In both experiments at the end of the irrigation, maximum water contents of 0.39 m$^3$ m$^{-3}$ and 0.37 m$^3$ m$^{-3}$ were achieved with 100 MHz experiment for the 0–0.1 m and 0–0.2 m TDR probes respectively and 0.39 m$^3$ m$^{-3}$ was achieved with the 450 MHz experiment for 0–0.2 m TDR probe.

When comparing TDR data from the two experiments (Figures 3, 4 and 6), the shallow depths had the higher water content throughout the drainage phase. As shown in Figure 6, the drainage pattern is very similar for both the 100 and 450 MHz data. The 100 MHz data and the 450 MHz data using the WARR-calibrated time zero show similar drainage characteristics. The 450 MHz WARR-calibrated time-zero data compare well with both the 0–0.1 m TDR and the 100 MHz data. In previous studies, Du and Rummel (1994) stated that the depth of penetration or sampling depth of the ground wave method was a function of the wavelength, and hence of the antenna frequency and soil water content. The sampling depth of the direct ground wave decreases with decreasing wavelength due to the increasing antenna frequency and water content. Huisman et al. (2001) found that the GPR ground wave penetrating depth was independent of the antenna frequency. The sampling depths of the 100 and 450 MHz data cannot be compared directly, because the data were collected from two separate experiments with a different vertical water content variation (Figure 6). In both cases, either air calibrated or WARR calibrated, the difference with respect to the 0–0.2 m TDR data is greater for the 450 MHz data, implying that the 450 MHz antennas have a shallower sampling depth. Our future research will be focused on time-zero estimation with air wave calibration and WARR calibration, as well as the drift in time zero with time.

All experiments conducted with 100 and 450 MHz GPR antennas showed that the GPR-measured water contents were similar or higher than the TDR-measured water contents (Figures 3 and 4). There are two potential explanations for the GPR-estimated and TDR-measured water content differences. (1) The GPR ground wave method at 450 MHz in this experiment has a sampling depth that is less than or equal to the shortest TDR probe (0.2 m in the 450 MHz experiment). The test site has grass on the surface, which adds a
6–8 cm thick organic layer in the profile. This high organic layer held more water during the drainage, as was indicated by the 0–0.1 m TDR probe during the 100 MHz GPR experiment. The other TDR probes, longer than 0.1 m, measured average vertical water content of the organic layer and the low water-holding sand layers below the organic layer. The GPR method had a sampling depth comparable to or less than the shortest TDR probe, resulting in a higher measured water content by the GPR, especially at 450 MHz. (2) The GPR and TDR methods average heterogeneous water content in the vertical direction differently in this experiment. The GPR ground wave method will give an unbiased average water content estimate only for water content gradients along a horizontal axis between the transmitter and receiver. Conversely, TDR gives an unbiased average estimate only for water content gradients along the axis of the TDR probe, which is vertical in this experiment. For both the TDR and GPR the water content gradient must be aligned along the direction of propagation of the electromagnetic energy to produce an unbiased average estimate. This line of reasoning is also supported by the increasing differences between the TDR- and GPR-measured water contents as the experiment proceeded from a uniform water content distribution at the start of the drainage to a large vertical gradient at the end of the drainage experiment.

An alternative method to estimate the direct GPR ground wave travel time using the ground wave amplitude peak

Accurate picking of the direct ground wave arrival time for FOM was often difficult, especially when the soil was relatively dry and the antenna separation distance was short. This problem can be avoided by using the WARR method, but the time required for WARR surveys is greater and the spatial resolution is lower. Both WARR and FOM data were collected during the same drainage experiment using the 450 MHz antennas. For these data, a method to calculate the direct ground wave velocity using the picked arrival time of the peak amplitude was analysed. As shown in Figure 7, both the leading edge and the peak of the direct ground wavelet were picked manually using the WARR data. For this experiment, the leading edge of the direct ground wave could be easily identified and picked for all antenna separations used (0.25 to 1.0 m). Often, the leading edge is difficult to pick due to excessive noise or interference between the direct air and ground waves. The manually picked leading edge of the ground wave \( t_{\text{edge}} \) was plotted against the manually picked peak of the ground wave \( t_{\text{peak}} \) using the WARR data (Figure 8a). A strong \( R^2 = 0.98 \) linear relationship was found between the leading edge and the half-period peak travel time of the ground wave:

\[
t_{\text{edge}} = 0.974t_{\text{peak}} - 1.821
\]  

Amplitude peaks of the remaining fixed offset data were automatically picked and then the respective leading edge arrival times were calculated using Equation (4). Calculated ground wave edge arrival times were converted to absolute ground wave arrival times using the time zero (−2.9 ns) estimated with the same WARR data as discussed above. These absolute ground wave arrival times were used to calculate the ground wave velocity using the fixed offset of 1.0 m and the water contents were computed from the equation of Topp et al. (1980). The leading edge arrival times of the ground wave were also manually picked for all the fixed offset traces and the respective water contents were calculated and compared with water contents from peak arrival time data (Figure 8b). It was found that the automatic peak picked and manually picked leading edge data are not significantly different, since they have a correlation coefficient of 0.99, a slope of unity and an intercept of zero. The same peak method was tested using other GPR data (obtained with 450 MHz antennas) and was also found to be highly correlated with the associated manually picked leading edge data. The relationship between the peak time and the leading edge of the ground wave (Equation (4)) has to be tested further using a range of field conditions, since the relationship will be influenced by changes in the electrical properties of the soil affecting the wavelet shape; also, the effectiveness of the technique will depend on the GPR trace noise levels.
CONCLUSIONS

Soil water content variation during transient drainage was estimated using 100 and 450 MHz GPR antennas and vertically installed TDR probes. Fixed-offset GPR traces were collected with 2.0 m and 1.0 m antenna separations for 100 MHz and 450 MHz antennas respectively. It appears from comparison with TDR-measured water contents that the direct ground wave of 100 MHz GPR antennas is concentrated within the shallowest 0.1 m depth in the soil profile. The time-zero air wave velocity calibration was found to be quite accurate and stable, resulting in water content errors of less than 0.01 m$^3$ m$^{-3}$, based on measurements performed under different soil water content conditions and both with and without TDR probes installed.

The water content measured during drainage with 450 MHz GPR antennas at 1.0 m fixed offset is higher than the TDR-measured values. Based on a comparison with the TDR data, this experiment shows that the direct ground wave sampling depth is less than 0.2 m for the 450 MHz GPR system.

The comparison between water contents from both 100 and 450 MHz GPR systems and TDR data suggest that the GPR direct ground wave does not penetrate beyond 0.1 m under the experimental conditions present in
Figure 8. (a) Relationship between the edge and the half-period peak of the ground wave and (b) the water content measured with manually picked leading edge data and peak calibrated data using Equation (4).

this study (see Huisman et al. (2001) for comparison). The differences in the sampling depth and heterogeneity in soil water in the vertical direction are the principal causes of the differences in the measured water content for the GPR and TDR methods. For the FOM, with both 100 and 450 MHz frequencies, 1–2 ns error in absolute ground wave travel time estimates can be caused by: (1) difficulty in picking the wavelet leading edge; (2) inaccuracies in the time-zero calibration; and/or (3) partly due to the uncertainty in ground wave travel distance.

A method was analysed to estimate the ground wave arrival time automatically by picking the arrival time of the ground wave peak for fixed-offset data. Water contents calculated with this peak-calibrated method agreed well with the water contents calculated by manually picking the ground wave leading edge. From the results of this study, it is suggested that for all fixed-offset surveys a time-zero air wave calibration and a WARR survey should be performed at both the first and last station of a data set. These data can be used to obtain an accurate estimate of time zero, to ensure that the time-zero calibration is stable, to correct for time-zero drift and to identify the ground wave clearly.

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REFERENCES


