Measuring soil water content with time domain reflectometry and ground-penetrating radar
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Synthesis: Towards Combining Ground-Penetrating Radar and Time Domain Reflectometry Measurements for an Improved Spatio-Temporal Characterization of Soil Water Content

In this synthesis the scientific and practical implications of the research presented in this thesis will first be discussed separately for time domain reflectometry and ground-penetrating radar. After that the possibility of combining these techniques for an improved space-time characterization of soil water content is discussed.

9.1 Time Domain Reflectometry (TDR)

TDR is a well-established soil water content (SWC) measurement technique, particularly suited for monitoring the temporal development of SWC and soil bulk electrical conductivity at a specific location. In recent years, there has been an increased awareness that TDR measurements can also be used to determine the complex frequency dependent permittivity. In this thesis, attention was focused on the accuracy and reproducibility of measuring these three soil properties with TDR.

Traditionally, TDR waveforms are analyzed with travel time analysis, which requires subjective analysis parameters for reproducible SWC measurements. In this thesis, inverse modeling analysis of TDR waveform, also known as frequency domain analysis, was tested as an analysis algorithm because it does not require user-defined analysis parameters. A comparison of both analysis methods showed that the accuracy and reproducibility for measuring SWC were similar. It was concluded that frequency domain analysis of TDR waveforms is an accurate, reproducible and semi-theoretical analysis algorithm, which still has ample room for improvement. Of course, frequency domain analysis will not significantly improve the accuracy of SWC measurements with TDR as compared with travel time analysis because the accuracy is not limited by the accuracy of the analysis but by the accuracy of the calibration between SWC and permittivity. The potentially higher reproducibility of frequency domain analysis will mainly improve temporal
monitoring of SWC with permanently installed TDR sensors, where very small
differences between subsequent SWC measurements are interpreted.

Heimovaara and Huisman (2002) presented two improvements of frequency
domain analysis. The first improvement is the use of the multi-scatter function of
Feng et al. (1999), which improves modeling of the TDR waveform by including
the effects of cable, connectors and probe head. The second improvement is a
model for the input signal. The explicit modeling of cables, connectors and input
signal: 1) removes the need to measure input signals for each measurement set-up,
i.e. a single calibration of the TDR cable tester is sufficient, 2) allows optimization
of the waveform acquisition, as is common in travel time analysis and 3) allows
frequency domain analysis with commonly used 3-wire probes with high
impedance probe heads, fixed coaxial cables and inner probe wires that cannot be
removed. Although these improvements are appealing from the perspective of
frequency domain analysis as a waveform analysis algorithm, some care is
appropriate when using 3-wire probes for frequency domain analysis. This is
because the validity of the $S_{11}$-scatter function for this and any other probe is not
yet well understood. Network analyzer measurements indicated that non-ideal
probe behavior due to the use of a 3-wire probe instead of a more coaxial 7-wire
probe led to changes in the TDR waveform that could not be accounted for in the
$S_{11}$-scatter function underlying the frequency domain analysis. Other issues that
also need attention before frequency domain analysis can be considered as an
attractive alternative to travel time analysis are its sensitivity to 1) SWC variation
along the wires of the TDR probe and 2) deformation of the TDR probe geometry
due to insertion in the soil.

The accuracy of three scenarios of frequency domain analysis for the
determination of frequency dependent dielectric permittivity, $\varepsilon^*(f)$, was determined
with the SCEM-UA algorithm. The analysis of numerically generated
measurements with added instrument noise showed that all four Debye parameters
could be identified from TDR waveforms with this algorithm. This contradicts
earlier reports by Weerts et al. (2001) that Debye parameters could not be identified
when the true values of the Debye parameters fall beyond the frequency bandwidth
of the TDR equipment. It was also concluded that conversion of TDR waveforms
to the frequency domain and subsequent optimization was less accurate than time
domain optimization, due to accumulation of noise in the Fourier transformation.
Furthermore, the potential accuracy of $\varepsilon^*(f)$ determination was even higher for
direct frequency domain measurements with a network analyzer. Frequency domain
analysis of network analyzer measurements with different probes showed that the
actual accuracy of $\varepsilon^*(f)$ determination was reduced because of model errors due to
non-ideal probe behavior. Model errors were larger for 3-wire probes than for
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7-wire probes and were more apparent in the frequency domain than in the time domain.

For the accurate measurement of bulk soil electrical conductivity in saline soils, it is necessary to determine cable and probe properties. A comparison of direct measurements of cable and probe properties and calibration of these properties in different salt solutions showed that calibration provides more accurate conductivity estimates. Curiously, the calibrated (empirical) cable and probe properties deviated from the directly measured properties, which must be attributed to compensation for model errors in the calibration.

It can be concluded that the accuracy of measuring frequency dependent dielectric permittivity and soil bulk conductivity with TDR is currently limited by the quality of the modeling. Future research should be directed towards an improved understanding and modeling of TDR wave propagation on different probes. Network analyzers seem to be an obvious candidate for this work because of their superior frequency domain capabilities and the fact that model errors can be recognized more clearly in the frequency domain. For the accurate determination of frequency dependent dielectric permittivity, it seems worthwhile to study less common probe designs, such as the two-port coaxial cell described by Shang et al. (1999). This type of probe allows reflection and transmission measurements, which opens possibilities for improved system calibration and more accurate measurements.

9.2 Ground-Penetrating Radar (GPR)

The accuracy of measuring SWC with the ground wave of GPR was determined by relating measured GPR permittivities with the mean SWC of a 5x2x0.1 m plot measured with TDR and gravimetric samples. It was concluded that the accuracy of measuring SWC with GPR and TDR was similar, and in the order of 0.03 m$^3$m$^{-3}$. It was also shown that the GPR calibration equation was similar to the GPR calibration. The reproducibility of SWC measurements with the GPR ground wave was found to be in the order of 0.005 m$^3$m$^{-3}$. A field experiment where a heterogeneous pattern in SWC was created by irrigation showed that the large number of GPR measurements that can be acquired in a given time span results in reliable estimates of variogram model parameters, which are commonly used to characterize spatial variability. The high GPR measurement resolution also resulted in accurate mapping of boundaries between different SWC units. Generally, it was concluded that measuring SWC with the ground wave of GPR is an interesting alternative to existing SWC measurement techniques for the assessment of spatial variation of surface SWC of fields up to several thousands of square meters.

An important aim of the GPR chapters was to illustrate the potential of SWC measurements with the GPR ground wave and, therefore, some of the technical
difficulties of GPR might be underexposed. Chapter 6 discussed the problem of a
time zero offset between the arrival time of the air and ground wave but the
observed offset could not be explained. In chapters 7 and 8 the observed
differences between SWC measured with GPR and TDR could only partly be
explained by different sampling volumes and the uncertainty in spatial SWC
variation measurements. Especially the different temporal behavior of mean spatial
SWC measured with GPR and TDR (chapter 8) was significant. The inability to
explain these observations indicates that current understanding of both GPR
equipment and ground wave propagation for SWC determination needs
improvement. For example, the GPR antennas used in this study are designed to
function optimally for a relative soil permittivity of 11. Wollny (1999) showed that
a lower or higher permittivity leads to distortion of the emitted GPR pulse. In his
study with 100 MHz GPR antennas, these distortions introduced arrival time shifts
of up to 1 ns, which means an absolute error in SWC of up to 0.04 m$^3$ m$^{-3}$ for an
antenna separation of 1.5 m. However, the relevance of these distortions has not
yet been determined and quantified for other GPR antennas and systems.
Furthermore, it was argued that these effects of the imperfect electrical match are
highly sensitive to the antenna-soil contact. However, this seems in conflict with
the high reproducibility of the SWC increase maps presented in chapter 8, which
were measured with moving sleds with a highly variable antenna-soil contact.

Ground wave propagation, including the depth of influence, is not fully
understood either. Experimental and modeling efforts by Sperl (1999) and Wollny
(1999) reported influence depths ranging from 0.06 m for 900 MHz antennas to
0.20 m for 225 MHz antennas. The similarity between GPR measurements and
measurements with a vertical 0.1 m TDR probe reported in chapter 5 does not
contradict this range of depths. However, experimental results on depth of
influence are uncertain because of the difficult experimental conditions inherent to
studies of ground wave propagation. The experimental dilemma is that an
assessment of the depth averaging of the ground wave requires a near-surface
dielectric discontinuity. However, this discontinuity will also produce a reflected
wave, which will interfere with the ground wave and obscure its properties.
Modeling studies are also difficult because the ground wave belongs to the
so-called ‘near-field’, which has not yet been studied in much detail.

New developments in GPR equipment could improve the accuracy of SWC
measurements based on the ground wave velocity. Recently, multi-channel GPR
systems have become commercially available. These GPR systems allow
simultaneous measurements at multiple antenna separation and could, therefore,
achieve the accuracy of measuring SWC with multi-offset GPR measurement, while
at the same time providing the mobility and acquisition speed of single-offset GPR
Towards Combining GPR and TDR measurements. Measuring ground wave arrival times at several antenna separations could also reduce the uncertainty about the time zero offset.

9.3 Space-time characterization of soil water content

Notwithstanding the technical problems mentioned in the previous section, the results of this thesis confirm the potential of the GPR ground wave for measuring spatial SWC variation. The high potential of TDR for measuring temporal SWC variation at a specific location has long been recognized. However, both TDR and GPR alone are less suited for simultaneously studying spatial and temporal SWC variation. This hampers the study of processes that vary strongly in both space and time, such as infiltration and root water uptake. An integrating framework allowing a combination of the strong temporal features of TDR and the strong spatial features of GPR could overcome this problem. The purpose of such a framework would at least be twofold. First, it should provide SWC predictions at unmeasured space-time points. Second, it should provide insight in the processes governing the spatio-temporal SWC behavior. An obvious choice for such a framework is spatio-temporal geostatistics.

Theoretically, spatio-temporal geostatistics allows integration of TDR and GPR measurements by using regularization theory. However, the regularization of the (temporal) TDR measurements to the support of the (spatial) GPR measurements requires an accurate estimate of the spatial SWC variation at the TDR support. Unfortunately, a reliable estimate of spatial SWC variation is difficult with a TDR acquisition system. This is because the TDR signal quality deteriorates for long cables, which causes spatial clustering of automatic TDR sensors around the central acquisition unit. Of course, this could be solved by additionally measuring spatial SWC with manual TDR measurements, but this is laborious and impractical. Another important drawback of spatio-temporal geostatistics is the limited flexibility to include process knowledge (see Snepvangers et al., 2002). This not only limits the accuracy of SWC predictions with spatio-temporal geostatistics, but also reduces its potential to gain insight in the processes governing SWC variation in space and time.

In recent years, there has been an increasing use of data assimilation as a group of techniques that merges measurements with a deterministic model (McLaughlin, 1995). Current data assimilation schemes used in atmospheric and oceanic sciences can cope with data sources with different measurement volumes and varying accuracies. Furthermore, data assimilation provides optimal SWC predictions at unmeasured locations, while both relying on physical laws, such as the law of continuity and Darcy’s law, and exploiting the information contained in the measurements. Therefore, data assimilation seems to have a high potential as a framework for combining GPR and TDR measurements. There have been a
number of data assimilation studies focusing on SWC. These were mainly studies of one-dimensional problems (e.g. Galantowicz et al., 1999; Hoeben and Troch, 2000; Walker et al., 2001), but there were also studies explicitly considering both spatial and temporal SWC variation (e.g. Houser et al., 1998; Pauwels et al., 2001; Reichle et al., 2001). These spatio-temporal 4-D studies often use simplified model formulations that capture the key physical processes governing SWC but neglect horizontal interactions due to the large computational burden of data assimilation (Reichle et al., 2001). In the near future, it is expected that improved computational methods and advances in computer technology will allow 4D-data assimilation to become a practical method for predicting and studying spatio-temporal SWC variation.

The success of data assimilation and spatio-temporal geostatistics for an improved space-time characterization of SWC depends strongly on the quality of the measurements. Without accurate measurements of SWC in space and time, the SWC predictions and the resulting insight in the governing processes will be highly uncertain. Therefore, developing and testing SWC measurements techniques that can provide these accurate measurements remains essential for an improved space-time SWC characterization. Hopefully, the assessment of the accuracy, reproducibility and feasibility of measuring SWC with TDR and GPR as presented in this thesis has made a meaningful contribution to providing these accurate measurements.