Measuring soil water content with time domain reflectometry and ground-penetrating radar
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Summary:
Measuring Soil Water Content with Time Domain Reflectometry and Ground-Penetrating Radar: Accuracy, Reproducibility and Feasibility

Hydrologists, soil scientists and agronomists are studying the space and time variability of soil water content (SWC) at a wide range of scales for a variety of reasons. At the regional to continental scale, SWC is an important variable because of its interaction with the Earth’s climate system through the sensible and latent heat fluxes. At the catchment scale, the antecedent SWC influences the partitioning of precipitation into infiltration, evaporation and runoff and, therefore, exerts a strong control on soil erosion and flooding. At an even smaller scale, preferential flow of water can lead to an accelerated breakthrough of solutes and can, therefore, affect groundwater quality.

Available SWC measurement techniques either provide measurements at the small (point) support (Time Domain Reflectometry, TDR) or at the much larger support of remotely sensed data. At intermediate spatial scales, such as agricultural land and small catchments, reliance on sparse TDR measurements or coarse remote sensing measurements might not provide the accurate SWC information required at these scales. Therefore, there is a need for SWC measurement techniques that can provide dense and accurate measurements of spatial SWC variation at an intermediate scale. In this thesis, measuring SWC with the ground wave velocity of ground-penetrating radar (GPR) is tested as an intermediate scale SWC measurement technique.

The general aim of this thesis was to contribute to the improved characterization of the spatio-temporal behavior of soil water and solutes by studying the potentials and limitations of TDR and GPR for measuring SWC variation in space and time. This thesis consists of two parts. The aim of the first part on TDR (chapters 2 to 4) was to improve the accuracy and reproducibility of the TDR analysis for the determination of SWC, frequency dependent dielectric permittivity and soil bulk conductivity. The aim of the second part on GPR (chapters 5 to 8) was to establish the accuracy, reproducibility and feasibility of measuring spatial SWC variation with the ground wave velocity of GPR.
Summary

In chapter 2, two methods to remove subjectivity from the analysis of TDR waveforms were compared: 1) travel time analysis with optimized analysis parameters and 2) inverse modeling of TDR waveforms with a TDR wave propagation model and the Debye model for single relaxation, also known as frequency domain analysis. An outflow experiment showed that the accuracy and reproducibility of both methods were similar, despite the fact that the acquisition of TDR waveforms and the analysis parameters were optimized for travel time analysis. It was concluded that frequency domain analysis is a promising objective analysis algorithm because of its semi-theoretical foundation and lack of subjective analysis parameters. A drawback of frequency domain analysis is that the optimized Debye model parameters can only be given a meaningful interpretation when soils are clearly dispersive within the TDR frequency bandwidth. This was illustrated by modeling TDR waveforms with only an apparent permittivity, which also resulted in an accurate and highly reproducible TDR analysis for the sandy soil used in this chapter.

In chapter 3, the accuracy of three scenarios of frequency domain analysis for the determination of frequency dependent dielectric permittivity were compared with the Shuffled Complex Evolution Metropolis algorithm (SCEM-UA): 1) analysis of TDR waveforms in the time domain, 2) analysis of TDR waveforms after conversion to the frequency domain and 3) analysis of network analyzer (NWA) measurements in the frequency domain. An analysis of numerically generated measurements with added instrument noise showed that analysis of NWA measurements in the frequency domain potentially has the highest accuracy. Furthermore, the analysis of TDR waveforms in the time domain was found to be more accurate than analysis of these waveforms in the frequency domain. Analysis of real NWA measurements showed that reasonably accurate estimates of the Debye parameters can be obtained with the SCEM-UA algorithm, even when the true values fall beyond the upper limit of the frequency bandwidth. However, frequency domain analysis results were susceptible to model errors, which were higher for 3-wire probes than for 7-wire probes. The SCEM-UA algorithm proved to be a valuable tool in frequency domain analysis because reported problems with parameter identification and initialization of the optimization problem could be avoided with this more elaborate optimization algorithm. Furthermore, the confidence intervals provided by the SCEM-UA algorithm are useful to distinguish between well-identified and meaningless Debye parameters, which solves one of the problems discussed in chapter 2.

In chapter 4, two approaches to improve the accuracy of TDR bulk soil conductivity measurements with 3-wire probes in case of long cables and/or saline soils were compared. The first approach was based on direct measurement of the cable and probe properties. The second approach was based on the laborious
calibration of the TDR system in salt solutions with different electrical conductivities. The results showed that calibration provides the most accurate conductivity measurements with a 3-wire probe. Directly measured cable properties deviated from their calibrated (optimal) values and, therefore, direct measurements are not advisable to avoid the laborious calibration. Instead, a reduction of calibration time can be achieved by limiting the calibration procedure to two well-chosen combinations of cable length and solute concentration.

In chapter 5 the accuracy of SWC measurements with the ground wave of GPR was determined. The SWC of 5×2×0.1 m³ plots on different soils was determined with gravimetry, TDR measurements and single and multi-offset GPR measurements. To compensate for the different measurement volumes, 15 TDR measurements and 10 gravimetric SWC measurements were aggregated to the plot size of 5×2×0.1 m³. For practical reasons, the GPR measurement volume was assumed to equal this volume. The results showed that the calibration equation between GPR measurements and aggregated gravimetical SWC was similar to the equation for aggregated TDR measurements. This suggests that available TDR calibrations can be used for GPR. Furthermore, the accuracy of multi-offset GPR measurements to measure SWC was similar to the accuracy of TDR. The accuracy of single-offset GPR measurements was somewhat lower. It was concluded that GPR can be used to measure SWC of soil from a wide array of textures, ranging from sand to loam. GPR is less suited for heavier textures because the high conductivity of these soils generally results in a strong attenuation of the ground wave. The similarity between SWC measurements made with the 225 MHz GPR antennas, 450 MHz GPR antennas and TDR measurements with a 0.1 m long TDR probe suggests that the depth of influence of the ground wave is confined to the upper centimeters of the soil and relatively independent of frequency, although no attempts were made to quantify SWC variation with depth.

Chapter 6 focused on two important requirements for accurate and reproducible SWC measurements with the GPR ground wave. The first requirement was that the extra equipment needed for SWC measurement (sleds, odometer, pull vehicle) should not interfere too strongly with the GPR measurements. The results showed that the presence of SWC measurement equipment caused a strong decrease in the amplitude of the ground wave, changed the pulse shape of the air and ground wave and caused disturbances in the air wave. However, the GPR data quality remained sufficient to allow accurate determination of air and ground wave arrival times. The second requirement was that it should be possible to calculate soil permittivity from the air wave and ground wave arrival time, despite reports by Sperl (1999) that there can be a significant extrapolated time difference between these arrival times at zero antenna offset. The results confirmed that there was a mean time difference of 0.5231 ns at zero offset with a
large standard deviation. A sensitivity analysis of this time difference as a function of positional uncertainty, time picking uncertainty and spatial heterogeneity of SWC within the radar volume showed that the large variation could be explained by these factors, but that the mean time difference remained unexplained. It was concluded that a time difference correction in the calculation of soil permittivity would improve the accuracy of absolute SWC measurements with GPR. However, the large variation in time difference makes it difficult to accurately estimate the mean time difference at zero offset needed in the correction.

Chapter 7 and 8 presented results of a field experiment where a heterogeneous SWC pattern was created by irrigation to explore the capability of GPR to measure spatial SWC variation. In chapter 7 the potential of GPR to measure spatial SWC variation of a 3600 m² field was discussed in detail. As a comparison, spatial SWC variation was also measured with TDR. The results showed that GPR is well able to measure spatial SWC as expressed by the variogram. The larger GPR measurement volume averaged small-scale variation (<1.5 m) and resulted in low nugget variances. The large number of easily acquired GPR measurements resulted in well-defined and smooth experimental variograms, as compared with the noisy experimental variograms for TDR. An unsuccessful attempt was made to compensate for the difference in measurement volume by using regularization theory. Possible explanations for the failure were: 1) the large scatter in the experimental variogram of TDR combined with the sensitivity of the results to a choice for the TDR nugget variance and 2) the uncertain depth of influence of the GPR ground wave. Interpolated SWC maps showed that GPR is better suited for mapping boundaries between areas with different SWC because of the large number of measurements. Small-scale features (1-5 m) were not mapped adequately by either GPR or TDR. However, the chance of detecting these features is higher for GPR, simply because of the higher sampling density.

In chapter 8 the capability of GPR and TDR to assess the temporal development of spatial SWC variation was compared by measuring spatial SWC patterns on 18 days with GPR and TDR in a 30-day monitoring period with two irrigation days. The temporal development of the spatial pattern was studied by means of the variogram and interpolated SWC maps. Confidence intervals of the experimental variograms and the variogram model parameters were calculated with a jackknife approach and a first-order approximation of model parameter uncertainty. The results showed that the confidence intervals of the GPR experimental variograms were much narrower than the confidence intervals of the TDR experimental variogram due to the larger number of GPR measurements. Consequently, the uncertainty in the variogram model parameters was also much lower for GPR. This meant that the temporal development of the fitted GPR variogram model parameters was easier to interpret. Interpolated maps showing the
increase in SWC due to irrigation and the subsequent gradual drying of the soil were more accurate and reproducible for GPR.

Finally, in the synthesis the potential of using spatio-temporal geostatistics and data assimilation for an improved characterization and understanding of spatio-temporal SWC variability by combining TDR and GPR was discussed. It was concluded that the success of an improved space-time characterization of SWC depends strongly on the quality of the SWC measurements. Therefore, developing and testing SWC measurements techniques that can provide accurate SWC measurements remains essential. 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 this topic.