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SPATIAL TIME DOMAIN REFLECTOMETRY FOR MONITORING OF THE HYDROLOGICAL WATER BALANCE AT A LYSIMETER TEST SITE IN THURINGIA/GERMANY

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ABSTRACT

For monitoring of the hydrological water balance in top and subsoil during plant growth accurate knowledge of the spatial and temporal variation of soil water content is essential. In this context, a new full two port spatial time domain reflectometry (Spatial TDR) technique in combination with elongated microwave transmission line sensors were developed for advanced data acquisition and analysis. The technique is tested at a lysimeter station in Thuringia/Germany and compared with neutron moisture meter probes.

Index Terms— Spatial TDR, complex permittivity, soil moisture

1. INTRODUCTION

Conventional, water content measurements in agricultural applications are based on neutron moisture meter (NMM) methods which recently were replaced by electromagnetic based sensor techniques used from within access tubes [1]. Moreover, to estimate the soil water content in the upper top-soil layer active and passive remote sensing techniques where applied which require appropriate in-situ reference measurements [2, 3, 4].

In this context, the objective of the presented study is the determination of water content profiles in the top and subsoil for monitoring of the hydrological water balance during plant growth. According to crop types there are different rooting depth, e.g. winter wheat with up to 2 m [5]. For this reason moisture profiles need to be monitored at least to that depth. The test site is located at a lysimeter station in Thuringia/Germany. A new full two port time domain reflectometry (TDR) technique in combination with microwave transmission line sensors were developed for advanced data acquisition and analysis. At first, the applied sensors and the measurement principle will be depicted followed by a description of the applied processing steps. After that the sensor configuration of the test field and the layered arrangement of the soil will be shown. Based on this the measurement results of the proposed method will be compared for different probe geometries. Finally the TDR data will be compared to neutron probe reference measurements.

2. SENSORS AND MEASUREMENT PRINCIPLE

An ultra-wideband (UWB) sensor based on m-sequence technique [6] is used for the generation of the TDR signal. A block diagram of the overall system is depicted in Fig. 1. The received signal corresponds to an impulse response function (IRF) with a resulting bandwidth of the system from 2 MHz up to 4 GHz with an ambiguity range of 456 ns which corresponds to a distance of 137 m assuming free space propagation of the electromagnetic (em) wave. The device is capable of full two port (reflection and transmission) measurements. An internal calibration unit allows for full 8-term calibration to enhance the dynamic range up to -55 dB and sensitivity up to -80 dB. The sensor is connected to the probes via a coaxial line with a length of 2.25 m. Therefore a guided em-wave is passed across a three wire coplanar microwave transmission line structure. Either it is realized in cylindrical or flat ribbon cable design with two connecting ports. The maximum length of the applied probes is 2 m because of the useable bandwidth like shown in [7]. A deconvolution of the coaxial feeding lines to the probes with the measured signal permits the calculation of the S-Parameter set over the probes. The processing steps of a complete measurement cycle are depicted in Fig.2.

The measured signal is calibrated, and passed to the preprocessing. From this the signal is time gated and the reconstruction algorithm described in [8] is applied on it. Reflections from both ports and the reference input signal are used to perform a reconstruction of the time domain signal to a spatially resolved capacitance profile along the whole probe. Out of this a permittivity profile will be calculated as a function of the characteristic parameters of the probe [7]. With a given apparent permittivity profile a moisture profile can be calculated via a material calibration of the underlying soil layers or the application of a dielectric model.

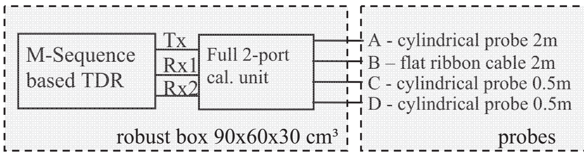

Fig. 1 Block diagram of TDR Measurement System.

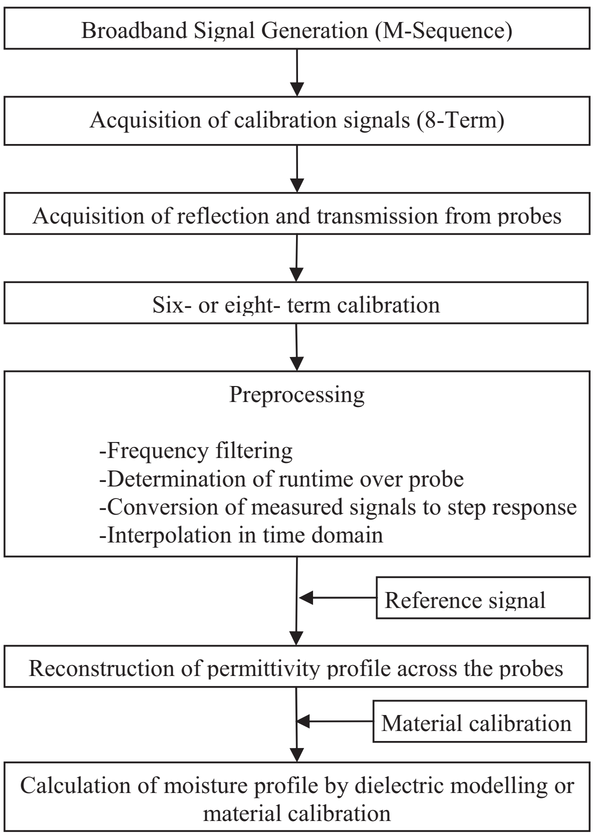

Fig. 2 Schematic of measurement cycle.

3. TEST SITE INSTRUMENTATION

The test site consists of an UWB device with four probes (Fig. 3). Two removable cylindrical probes (CP 2, 3) with a length of 60 cm are placed in the upper 60 cm organic rich top soil. A cylindrical probe (CP 1) and a flat ribbon cable (FBK) each with a length of 2 m have been installed in the silty loam subsoil in a depth of 60 cm up to 260 cm (see Fig.3). In between the two probes are point wise installed spade ring oscillators (S 1-12) and temperature probes with a spacing of 20 cm in depth. Within a radius of five meters are installed two NMMs and two capacitive based tube sensors as reference.

During installation of the probes ten undisturbed and two disturbed soil samples are taken each 20 cm up to a depth of 2.50 m to determine in situ water content, bulk density, texture, chemical as well as hydraulic soil properties. Specific surface area and mineralogical composition were obtained on samples from four depths (two for top soil and two for subsoil). To determine the high frequency electromagnetic material properties undisturbed soil samples are taken in each 20 cm up to a depth of 2.50 m with a new technique developed by Lauer et al. [9].

4. MEASUREMENRT RESULTS

The monitoring system was installed during the last quarter of 2011 and continuously records data since January 2012. All HF and temperature sensors collect data six times a day. An important influence on the measurement accuracy has the injection and coupling of the probes to the surrounding media under test [7]. The coaxial feed lines and the quality of the connections in between them affect the appearance of multiple reflections and impede the robustness of the further data processing in a major way.

The dielectric spectra are measured for 16 moisture levels of the undisturbed soil samples taken during instrumentation. After the material calibration the reference volumetric water content was determined by oven drying. The spectra indicate moderate dispersion and losses as well as the possibility to separate the material in two main groups (upper layer soil from 0-70 cm and subsoil from 70 cm-250 cm). In Figure 4 is represented the relationship between volumetric water content θ and effective complex relative permittivity $\varepsilon^*_{r,eff}$ at a frequency of 1 GHz for the appropriate soil horizon. As reference is given the apparent permittivity obtained with the empirical equations according to Topp et al. (1980) [11] for organic free (mineral) and organic soils. The provided values are used to calculate the moisture level for the reconstructed apparent permittivity.

During plant growth there are also made neutron probe and capacitance based moisture measurements from within an access tube. The neutron probe measurements are taken point wise for 12 different depths from 15cm and from 30 to 210 cm with a step width of 20 cm. The values are integral values over 15 cm depth. In Fig.5 is depicted the spatial soil moisture profile of NMM measurements versus the reconstructed UWB measurement for CP1 and FBK. In Fig. 6 represents the obtained volumetric water content in a depth of 130 cm with the different probes. In a first step, the volumetric water content is derived by the equation according to Topp et al. (1980) for organic free soils.

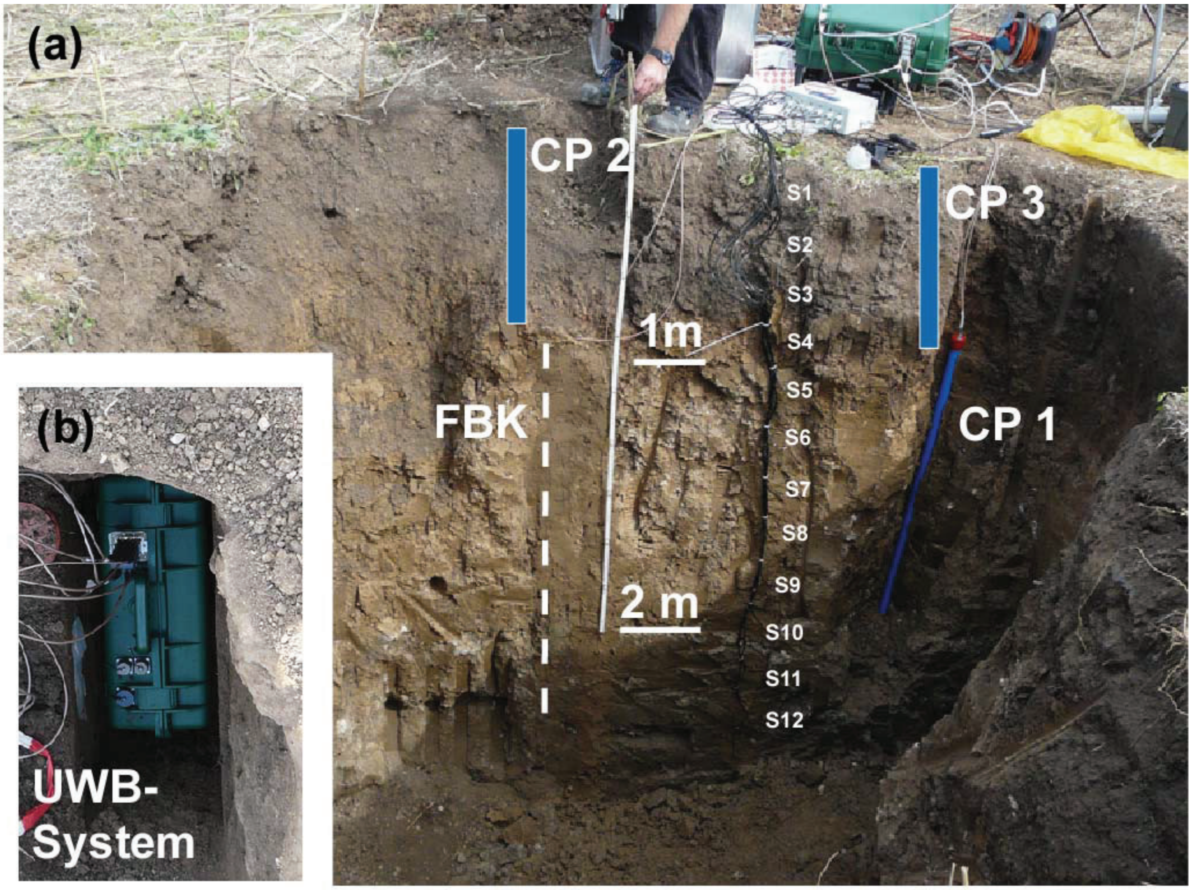

Fig. 3 Overview of the measurement location (a) installed sensors (CP 1, FBK and S 1 -12 as well as location of the sensors CP 2 and 3 after filling up the hole) and (b) measurement system after instrumentation of the measurement site.

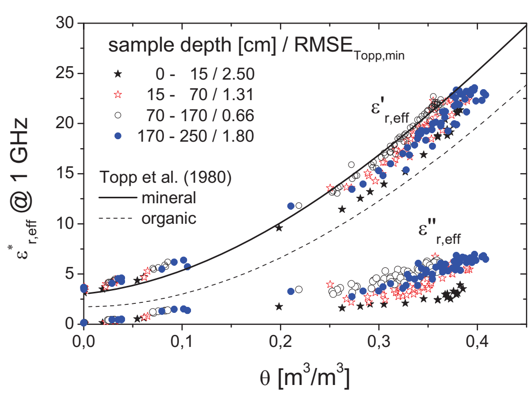

Fig. 4 Relationship between volumetric water content θ and relative effective permittivity $\varepsilon^*_{r,eff} = \varepsilon'_{r,eff} - j\varepsilon''_{r,eff}$ at a frequency of 1 GHz obtained with the methodology according to Lauer et al. (2012) [9] and Wagner & Lauer (2012) [10].

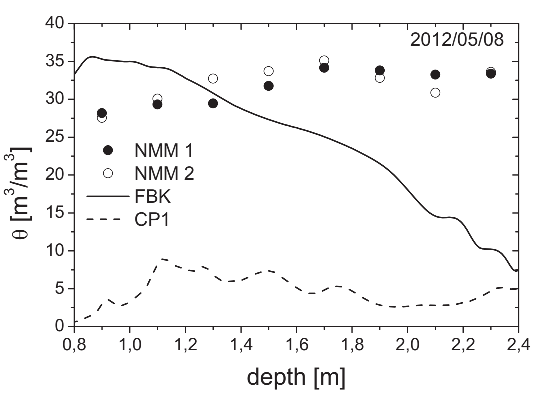

Fig. 5 Comparison of spatial soil moisture profiles of NMM measurements and reconstructed UWB measurement.

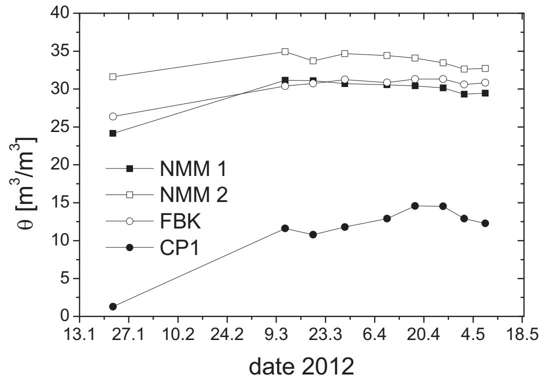

Fig. 6 Comparison of NMM and spatial TDR measurements of volumetric water content θ and data from first two quarters of year 2012 at a depth of 130 cm.

5. DISCUSSION

The measurement results obtained with the UWB-system show reasonable agreement with meteorological data (temperature and precipitation) from a basis station at the lysimeter. The results from the empirical Topp equation matches the permittivity at 1 GHz best (RMSE 0.66) for the soil layer in between 70 to 170 cm. For the other layers a soil specific empirical or semi-empirical calibration function has to be applied (e.g. see [10]).

The comparison between the different techniques used for spatial resolved water content estimation presented in Fig. 5 indicates clear differences in the determined water content as a function of depth. Assuming accurate volumetric water contents obtained with the neutron probes and a possible comparison of the probed locations the observed differences are results of the Spatial TDR technique. This could occur due to (i) the preprocessing process and assumptions of the input signal, (ii) assumptions of the transmission line parameters used in the reconstruction algorithm and (iii) the frequency dependence of the material properties [12].

Nevertheless, the values from the flat ribbon cable at a depth of 130 cm in Fig.6 are in reasonable agreement with the NMM measurements. The measurements with the cylindrical probe show the same trend as the compared one but differ strongly in amplitude. There are two main explanations for this: first is the coupling of the probe to the surrounding media, so if there are any air gaps, permittivity is effected and seems to be lower which also can be clearly indicated in the raw UWB signal. This results in smaller values of the related volumetric water content. A second possible explanation is the implementation of the new probes in the reconstruction algorithm which are currently systematically evaluated.

6. CONCLUSION

A measurement setup for spatial moisture monitoring in an agricultural application was presented. The developed system provides a flexible tool for engineering applications. The next step will be the comparison of further sensors (capacitance probes, Spade) and measurement devices.

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