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# A quality assessment of spatial TDR soil moisture measurements in homogenous and heterogeneous media with laboratory experiments

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## Abstract

Investigation of transient soil moisture profiles yields valuable information of near-surface processes. A recently developed reconstruction algorithm based on the telegraph equation allows the inverse estimation of soil moisture profiles along coated, three rod TDR probes. Laboratory experiments were carried out to prove the results of the inversion and to understand the influence of probe rod deformation and solid objects close to the probe in heterogenous media. Differences in rod geometry can lead to serious misinterpretations in the soil moisture profile but have small influence on the average soil moisture along the probe. Solids in the integration volume have almost no effect on average soil moisture but result in locally slightly decreased moisture values. Inverted profiles obtained in a loamy soil with a clay content of about 16% were in good agreement with independent measurements.

## 1 Introduction

Only a minute amount of global water is stored as soil moisture: with an estimated volume of about  $16\,500\text{ km}^3$ , soil moisture represents 0.0012% and 0.05% of total and fresh water, respectively (Dingman, 1994). And yet, this tiny hydrological compartment exerts crucial control over interactions between the atmosphere, land surface and groundwater since soil moisture determines the partitioning of net radiation energy on latent and sensible heat flux and supply of water for the terrestrial biomass. Soil moisture influences, furthermore, plot scale generation of Hortonian and saturated excess overland flow (Chaves et al., 2008; Zehe et al., 2007), water repellency (Dekker et al., 2005; Blume et al., 2009), as well as hillslope and catchment scale runoff response to extreme precipitation (e.g., Merz and Bárdossy, 1998; Bronstert and Bárdossy, 1999; Meyles et al., 2003; Deeks et al., 2004; Zehe and Blöschl, 2004).

Spatially and temporally distributed Time Domain Reflectometry (TDR) and Frequency Domain Reflectometry (FDR) measurements are widely used to observe soil

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moisture dynamics at the plot to hillslope scale (e.g., Starr and Timlin, 2002). Conventional TDR measurements allow estimation of the mean soil moisture and the bulk electrical conductivity of the surrounding media based on travel time of a reflected electromagnetic wave guided in waveguide/TDR probe installed in soil. Excellent reviews are given by Robinson et al. (2003) and Cassiani et al. (2006). Several authors have shown that the shape of the reflected TDR signal, the reflectogram, contains information about the dielectric permittivity ( $\epsilon$ ) and thus, the soil moisture along the probe (Feng et al., 1999; Oswald et al., 2003; Schlaeger, 2005; Greco, 2006). The retrieval of this detailed information is achieved by inversion or by graphical interpretation of the signal (Moret et al., 2006). Inverse estimation of soil moisture profile seems to work well for synthetic data sets (Oswald, 2000), or homogeneous soils at the lab scale (Becker, 2004; Greco, 2006; Bänninger et al., 2008; Scheuermann, 2009) or volcanic ash soils with low bulk densities of  $\sim 1.0 \text{ g/cm}^3$  (Greco and Guida, 2008).

The overall objective of this paper is to shed light on the applicability of “Spatial TDR” in strongly heterogeneous field soils. The essential idea of Spatial TDR is to cluster several wave guides in a small area, operate them by a single sampling TDR and invert the reflectograms to elucidate the evolution of the soil moisture profile. Spatial TDR was originally proposed by Schlaeger (2002, 2005), Becker (2004), Huebner et al. (2005) and further tested by Scheuermann et al. (2009) to monitor moisture in sandy dams. The reflectogram of the TDR measurement is influenced by the probe geometry (Bänninger, 2008), solids in the sphere of influence (Knight et al., 1997), layered soils (Greco, 2008) or energy dissipation along the probe due to clay and salinity (Jones and Or, 2004; Chen et al., 2007; Kupfer et al., 2007). These different factors may hamper the application of Spatial TDR measurements in real world settings. The use of coated rods prevents the TDR signal from energy dissipation (Ferré et al., 1996, 1998; Knight et al., 1997; Jones et al., 2002; Nichol et al., 2002; Fujiyasu et al., 2004; Moret et al., 2006), increasing the signal-to-noise ratio and, thus, allows the use of longer TDR rods compared with uncoated rods, which is essential for Spatial TDR applications (Dalton and Van Genuchten, 1986; Robinson et al., 2003). The drawbacks of

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coated rods are that they are less sensitive to  $\varepsilon$ , that a coated material needs specific calibration (Ferré et al., 1996) and the measurement of bulk electrical conductivity is restricted (Moret-Fernández et al., 2009). As the high clay content of the soils in the study area is around 16% we preferred to use TDR probes with three coated rods. This allows 60 cm long probes to be used, which is favourable when infiltration processes into the subsurface are to be observed.

In general, it is assumed that the TDR rods are installed parallel, but it is difficult to fulfill this assumption during installation of probes in heterogenous natural soils, especially in the presence of stones, layers, or soil bulk density differences. Figure 1 shows an extreme example with rods converged or diverged with increasing depth for a rather heterogeneous soil located in the Ore Mountains, Germany.

So, the effect of the probe deformation on the reflectogram and the retrieved soil moisture has to be studied in detail, because for the Spatial TDR approach it is essential to use long TDR rods. The influence of insulating solids in the sampling volume was theoretically described by Knight et al. (1997) but we are not aware of any study which studied the influence of solids on the reflectogram.

Therefore, the questions posed for this research are: 1) How do coated probes of 60 cm length react in these soils (heterogeneous, electrical loss) and are these probes indeed better suited for these soils compared to uncoated probes? 2) How does the effect of a) different probe deformations, b) solids (insulators, conductors) in the integration volume and c) high clay content in combination with a bulk density gradient, influence the  $\varepsilon$  profile, the inverted moisture profiles and the average soil moisture along the probe? Different laboratory experiments were performed to shed light on these topics.

In Sect. 2 we give a review of different inversion techniques. Section 3 provides details on the technological components and discusses potential sources of errors observed in field applications; Sect. 4 introduces five different laboratory experiments. Section 5 discusses the step from applications in homogenous media or “the technical scale” to reliable applications in heterogeneous field soils, for instance, when designing

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a site-specific calibration of transmission line properties. This step is crucial for hydrology because, especially in heterogeneous soils, the relationship between soil moisture dynamics and runoff generation is not well understood yet. These results are furthermore necessary to interpret soil moisture observations obtained with two Spatial TDR clusters installed in the Eastern Ore Mountains presented in a closely related study by Zehe et al. (2009 this issue). That study will introduce the applicability of Spatial TDR in the field scale.

## 2 Theoretical background and signal constrained inversion

### 2.1 TDR inversion approaches

In this section we give an introduction to the inversion methodology and an overview of the different inversion techniques. Generally, for the estimation of the soil moisture profiles along the TDR probe it is necessary to simulate the propagation of the TDR signal in time domain by employing a numerical model (forward problem). This is achieved by simulating the forward and back propagation of the TDR signal along the wave guide and minimizing the differences between observed and simulated signals by the use of an optimizing algorithm which updates the parameter profile along the transmission line. Full wave approaches solve Maxwell's equations within the forward step (Pereira, 1997; Oswald, 2000; Rejiba et al., 2005). The target parameter of the optimization is the profile of the  $\epsilon$  along the wave guide. Other studies have proposed simplified approaches based on multi-section transmission lines (Hook et al., 1992; Feng et al., 1999; Heimovaara et al., 2004) or heterogeneous transmission lines (Lundstedt, 1995; Greco, 2006). The Spatial TDR approach (Schlaeger, 2002, 2005) belongs to the latter category. The wave propagation along the TDR probe is approximated by the telegrapher's equation. The transmission line is conceptualized as a series of bulk electronic components such as resistors, inductors and capacitors. Hence, the target parameter of the optimization is the electrical capacitance profile ( $C$ ). The Spatial TDR

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algorithm requires additional material laws that link  $C$ - $\varepsilon$ -soil moisture and – in the case where TDR probes with coated rods are used –  $C$  and electrical conductance  $G$  of the transmission line (Becker, 2004; Schlaeger, 2005; Huebner et al., 2005) (compare Sect. 2.3).

## 5 2.2 STDR signal inversion

The TDR signal  $V_R^o(t, x_0)$  or reflectogram is a superposition of the input voltage  $V_1^o(t, x_0)$ , generated by the TDR device, and partial reflections of the input signal occurring at the junction of the probe and cable as well as at the end of the wave guide. The average  $\varepsilon$  along the transmission line is determined by the speed of the electromagnetic wave and can be calculated based on the travel time of the TDR signal. The average  $\varepsilon$  can be transformed into the average soil moisture content along the probe by appropriate calibration functions (see Sect. 3.4). The form of the reflectogram between the first and second main reflection at the probe's beginning and end is a finger print of the dielectric profile along the wave guide.

The principle of the Spatial TDR inversion is to estimate the capacitance profile  $C(x)$  along the wave guide by means of inverse modelling and transform it into a soil moisture profile  $\theta(x)$ . As explained above, the forward step of the Spatial TDR algorithm is based on the telegrapher's equation (Schlaeger, 2002), which describes the propagation of a voltage pulse  $V(x, t)$  along the transmission line:

$$\left( L(x)C(x) \frac{\partial^2}{\partial t^2} + L(x)G(x) \frac{\partial}{\partial t} + \frac{\partial L(x)/\partial x}{L(x)} \frac{\partial}{\partial t} - \frac{\partial^2}{\partial x^2} \right) V(x, t) = 0. \quad (1)$$

Hereby  $t$  is time and  $x$  the spatial coordinate along the wave guide. The capacitance  $C(x)$  and electrical conductance  $G(x)$  are both affected by the soil moisture profile  $\theta(x)$  along the transmission line. The inductance  $L(x)$  is a function of the transmission-line only and piecewise constant for the coaxial cable and moisture probe, *as long as the rods are parallel*. The spatial derivative of  $L$  in Eq. (1) accounts for the difference

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between coaxial cable and probe. Compared to the general telegrapher's equation it is assumed that resistive losses along the probe can be neglected and the electrical resistance  $R=0$ . All parameter profiles will be given as specific values per unit length. Nichol et al. (2002) have shown that the true electric conductivity  $\rho$  cannot be measured with coated probes. Therefore,  $G$  is not the real ionic conductance of the soil but an effective value of coating and soil conductivity.

Within the inverse procedure Eq. (1) is numerically solved with appropriate initial and boundary conditions to simulate  $V_R^s(t, x_0|C)$  for given parameter profiles  $C(x)$  and  $G(x)$  (Schlaeger, 2005). Based on the difference between the simulated  $V_R^s(t, x_i|C)$  and observed signal  $V_R^o(t, x_i)$  between the first (at  $t=0$ ) and the second main reflection (at  $t=T$ ) the transmission line parameters  $C(x)$  and  $G(x)$  are updated by the conjugate gradient method until the objective function  $J(C)$  in Eq. (2), is minimized.

$$J(C) = \int_0^T (V_R^s(t, x_i|C) - V_R^o(t, x_i))^2 dt \quad (2)$$

The high quality of the recorded signal of the TDR100 (Campbell Scientific Inc), which has a time to peak of roughly 200 ps, allows inversion at a spatial resolution of 1 cm (Oswald et al., 2003; Lin et al., 2005). The solution of Eq. (1) is a profile of  $C(x)$  which has to be related to the permittivity profile of the porous medium  $\varepsilon(x)$  and finally to the moisture profile  $\theta(x)$  (compare next sections). Subsequently, we will refer to the resulting soil moisture profile which is obtained after conversion as the inverted moisture profile. For more details see Schlaeger (2005).

### 3 Parameters and potential error sources of spatial TDR-measurements

#### 3.1 Technological components and setup of a Spatial TDR

We used a TDR100 by Campbell Scientific Inc. to generate TDR pulses. Coated three-rod probes of type SUSU03 of length 60 cm developed by Schädel (2006) were used

as wave guides. These consist of a stainless steel core of 6 mm diameter with a 1 mm thick PVC coating. The distance between the rods is 30 mm. The rods are screwed into the probe head that is connected to a 50 Ω coaxial cable of type RG213. The probes are connected to an eight channel multiplexer of type SNAPMUX (Becker, 2004) with coaxial cables of type RG213 with an impedance of 50 Ω and a length of 15 m. The TDR100 is controlled and the data are logged by an ARCOM VIPER 1.2 Industrial-PC with embedded LINUX operating system.

### 3.2 Calibration of probe parameters

The pulse velocity of the TDR signal  $v$  is given by

$$v = 2l / \Delta t, \quad (3)$$

where  $l$  is the probe length and  $\Delta t$ , the time difference between the first two main reflections in the reflectogram.

The equation to link  $v$  to  $\varepsilon$  with  $v = c_0 / \sqrt{\varepsilon}$  with  $c_0$  as the speed of light, does not apply for coated probes, because here the signal depends on an effective  $\varepsilon$  which is composed of the dielectric properties of the coating and of the surrounding medium and would lead to an underestimation of soil moisture (Ferré et al., 1996). Becker (2004) and Huebner et al. (2005) suggested that the pulse velocity  $v(\varepsilon)$  can be best expressed by the constant inductance  $L$  of probe and the effective capacitance  $C(\varepsilon)$  of the system probe and medium:

$$v(\varepsilon) = 1 / \sqrt{L \cdot C(\varepsilon)}. \quad (4)$$

In a second step  $\varepsilon$  of the medium is estimated with a relationship between  $C(\varepsilon)$  and  $\varepsilon$  in the case of our three rod TDR probe described by a simple circuit model consisting of a series of capacitors, representing the capacitor between the rods filled with the surrounding medium  $C_1$  and describing the constant capacitance of the coating  $C_2$  (Fig. 2):

$$1/C(\varepsilon) = 1/(\varepsilon \cdot C_1) + 1/C_2. \quad (5)$$

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According to Eqs. (4) and (5) the probe is characterized by the three parameters  $C_2$ ,  $C_1$ , and  $L$  which have to be estimated by calibration measurements.  $C_1$  and  $L$  are affected by the probe geometry, especially the distance of the wave guide rods. Becker (2004) and Huebner et al. (2005) found a good correspondence of the relationship between  $\varepsilon$  and  $C$  derived from full wave numerical simulations of coated three rod probes and the capacitance model shown in Eq. (5). Further laboratory observations corroborated the applicability of this capacitance model to parameterize the relationship between  $\varepsilon$  and  $C$ . Becker (2004) suggested a calibration approach based on measuring TDR pulse velocities  $v_j = v(\varepsilon_j)$  for two different media with well known dielectric permittivity values  $\varepsilon_1$  and  $\varepsilon_2$  (water and air) to determine  $C_2$ ,  $C_1$ , and  $L$ . Combining Eqs. (4) and (5) for the two media and solving them for  $C_1$  and  $C_2$  yields:

$$C_1 = (\varepsilon_2 - \varepsilon_1) / ((\varepsilon_2 \varepsilon_1 (v_1^2 - v_2^2)) \cdot L), \quad \text{and} \quad C_2 = (\varepsilon_2 - \varepsilon_1) / ((\varepsilon_2 v_2^2 - \varepsilon_1 v_1^2) \cdot L). \quad (6)$$

Finally  $L$  is estimated with the relationship to the rod impedance:

$$Z(\varepsilon) = \sqrt{L/C(\varepsilon)}. \quad (7)$$

The jump between the impedance of the probe plus the surrounding medium  $Z(\varepsilon)$  and the impedance of the connecting cable  $Z_0$  causes a partial reflection of the TDR signal at the junction of cable and probe. By measuring the amplitudes of incoming and reflected signal, denoted by  $A_I$  and  $A_R$ , we obtain the reflection coefficient that is linked to the impedance as follows (Becker, 2004):

$$r(\varepsilon) = A_R/A_I = (Z(\varepsilon) - Z_0) / (Z(\varepsilon) + Z_0). \quad (8)$$

Substitution of Eqs. (4) and (7) into Eq. (8) and solving for  $L$  yields:

$$L = (1 + r(\varepsilon)) / (1 - r(\varepsilon)) \cdot Z_0 / v(\varepsilon). \quad (9)$$

Based on Eqs. (6) and (9), the probe parameters  $C_1$ ,  $C_2$ , and  $L$  were derived from TDR reflectograms obtained in de-ionized water ( $\varepsilon=80$  at  $20^\circ\text{C}$ ) and air ( $\varepsilon=1$ ) for all probes are presented in Table 1. Based on the standard deviation of the dielectric permittivity values we could additionally quantify the relative measurement error to 5%.

### 3.3 C-G relation

As coated rods do not allow direct measurements of the electrical conductivity we employ a function that relates  $C(x)$  to  $G(x)$ , as proposed by Hakansson (1997), to close our set of equations:

$$G(C) = \begin{cases} G_{\infty} \cdot (1 - \exp(-(C - C_0)/C_d)), & \text{if } C \geq C_0, \\ 0, & \text{if } 0 \leq C \leq C_0. \end{cases} \quad (10)$$

$G_{\infty}$  is the conductance at saturation,  $C_0$  is a capacity threshold below which conductance is zero and  $C_d$  determines how fast  $C$  reaches its maximum value. Becker (2004) showed with numerical simulations that Eq. (10) is a suitable model. In general,  $C_d$ ,  $G_{\infty}$ , and  $C_0$  have to be determined empirically and one could expect that soil layers with high clay content might require parameter sets for Eq. (10). In a clay-rich soil one could furthermore expect  $G$  to be non-zero for a  $C$  smaller than  $C_0$ . The parameter estimation requires manual calibration during inversion of a known soil moisture profile.

### 3.4 $\varepsilon - \theta$ relation

In this study, the soil moisture from  $\varepsilon$  is calculated using the empirical relation proposed by Topp et al. (1980) for sand and glass beads. The  $\varepsilon - \theta$  relation was developed using 11 undisturbed soil samples in a plastic core cylinder (diameter=5.7 cm, length 10 cm) from different horizons of the study area. In the laboratory samples were saturated and in each sample a 3-rod 7.5 cm long TDR probe (CS640-L connected to a TDR100, both Campbell Scientific Inc.) were inserted. The samples were slowly dried. Once or twice a day the soil moisture was estimated by gravimetric method and the dielectric permittivity by TDR measurements. Different approaches to link  $\varepsilon$  and  $\theta$  were tested (Alharthi and Land, 1987; Roth et al., 1992; Malicki et al., 1996; Friedman, 1997). For the soils in the study area the linear relationship between the refractive index and  $\theta$  (Herkelrath et al., 1991; Huisman et al., 2001) was found to be most suitable:

$$\theta = a + b \cdot \sqrt{\varepsilon}. \quad (11)$$

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The parameters  $a$  and  $b$  are simple fitting parameters.

### 3.5 Field soils and error sources

#### 3.5.1 Probe deformations during installation

We investigated whether Spatial TDR clusters allows assessment of distributed soil moisture profiles under natural conditions in the headwater of the Weißeritz catchment close to the village of Rehefeld in East Germany. Soils are mainly formed by Cambisols in periglacial drift covers. In summer 2006 we installed two Spatial TDR clusters at two hillslopes close to the village Rehefeld. Table 2 shows the mean soil characteristics determined from 20 undisturbed soil samples extracted in profiles excavated up to depth of 70 cm close to one of the clusters. Additional details on the project context, the spacing of TDR probes and the catchment are discussed in Zehe et al. (this issue). The importance for the present study is that the installation of the 60 cm long Spatial TDR probe at this field site was a challenging task, due to the large amount of gravel of up to  $0.4 \text{ kg kg}^{-1}$  (Landesamt für Umwelt, Landwirtschaft und Geologie, 2006), the increasing density with depth and the heterogeneity of the soils. We used a steel template with three holes set at the right distance as well as a power drill with a 60 cm long auger. Several attempts (on average about two) were necessary to drill three holes with the appropriate distance and depth due to gravel blocking. Nonetheless, we had difficulties in ensuring that the rods of the probes were parallel. Figure 1 illustrates typical deformations of the probes; the rods converge towards the end (Fig. 1a) or diverge with increasing depth (Fig. 1b). As the theory of the inversion assumes parallel geometry of the rods, these deformations will likely cause errors in the estimated soil moisture profiles, because  $C_1$  and  $L$  cannot be assumed as constant over the profile. In Sect. 3.2 we describe the experimental setup to investigate the influence of simple rod deformations on the inversion.

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### 3.5.2 Gravel and stones

The pulse velocity measured with TDR is related to the average volumetric soil moisture. This can, as suggested by Topp and Davis (1982), lead to misinterpretations when abrupt water content changes along the transmission lines are present. Knight et al. (1997) discussed theoretically the influence of “gaps” in the integration volume which were filled with materials with either a lower than average or higher than average permittivity. They found materials with lower than average permittivity to have stronger impacts on TDR measurements. From a soil physical view, coarse gravel and stones in the integration volume of the TDR probe reduce the total volume of the pore space  $\Phi$  at that depth.

## 4 Laboratory experiments to quantify error sources

In this section we explain the setup of our five different laboratory experiments.

### 4.1 Experiment 1: effect of uncoated and coated probes on the reflectogram in field soils

We compared two SUSU3 probes, one of each with and without coating. Experiments were accomplished in a plastic box with a height of 70 cm and edge length of 30 cm by 30 cm (Fig. 3a). Both probes were installed in the middle of the box and we placed a wooden template at 59 cm depth to secure ideal probe geometry (Fig. 3a). The box was carefully filled with glass beads that were moderately compacted to ensure good contact between soil and TDR probes (Table 2). The experiment was conducted at two different wetness conditions, namely  $0.08\text{--}0.09\text{ m}^3\text{ m}^{-3}$  (dry) and  $0.20\text{--}0.21\text{ m}^3\text{ m}^{-3}$  (wet).

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## 4.2 Experiment 2: performance in homogeneous media during transient conditions

To ensure that our performance test took place in a truly homogeneous pore space we conducted this experiment with glass beads of a grain size of 0.25–0.5 mm diameter, ensuring a homogeneous pore space of the media. Figure 4 shows the experiment setup. The experiment was conducted in a 1 m high and 0.15 m wide PVC tube. Glass beads were filled into the tube and compacted, resulting in a bulk density of  $1.51 \times 10^3 \text{ kg m}^{-3}$  and a saturated water content of  $0.38 \text{ m}^3 \text{ m}^{-3}$  (Table 2). Two T-pieces in the tube allowed for the installation of THETA probes (THETA, Delta-T-Devices). One probe of type SUSU03 was installed in the centre of the tube with rods pointing from the upper edge of the tube to the bottom. Independent soil moisture measurements were obtained with two THETA probes placed at a depth of 30 and 55 cm, which work in the FDR domain with a measurement error of  $\pm 0.01 \text{ m}^3 \text{ m}^{-3}$  (Gaskin and Miller, 1996). We started the experiments with a tube that was fully saturated with de-ionized water and reduced the soil moisture by sucking off water at the bottom of the tube. Soil moisture profiles were inverted at saturated, intermediate and dry moisture conditions and compared to the THETA probes.

## 4.3 Experiment 3: effect of probe deformations

The effect of probe deformation on the estimated soil moisture profile was studied by deforming the two outer rods under controlled conditions. Here we studied four different cases: parallel rods, converged rods, diverged rods and strong diverged rods (Fig. 3b and Table 5). The experiment was conducted with glass beads in a plastic box and a template for ensure the probe deformation (Fig. 3a). The experiment was conducted at three soil moisture levels, namely  $0.04\text{--}0.05 \text{ m}^3 \text{ m}^{-3}$ ,  $0.07\text{--}0.09 \text{ m}^3 \text{ m}^{-3}$ , and  $0.20\text{--}0.23 \text{ m}^3 \text{ m}^{-3}$ . The values were cross-checked with THETA probe measurements along the experimental box. TDR measurements were performed and inverted into a soil moisture profile. The procedure was repeated for all selected deformations.

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To establish homogeneous soil moisture during a single experiment was rather difficult and could only be approximately achieved.

#### 4.4 Experiment 4: effect of solid objects in the integration volume

Here we studied the influence of different solids on the reflectogram and the estimated soil moisture profile by placing different objects close to the probe. A coated TDR probe was installed in the same box as used in experiment 1 (Fig. 3a); ideal parallel geometry was ensured by installing a wooden template at a depth of 59 cm. An iron block (a conductor), a dry and a saturated piece of wood (insulator), a PVC block (insulator), a brick or a boulder from the study area, all with a volume of approximately 1.5 l was placed at a depth of 30 cm close to the probe and the box was filled with glass beads (Table 2) at a uniform soil moisture of approximately  $0.20\text{--}0.23\text{ m}^3\text{ m}^{-3}$ . TDR measurements were performed and inverted for each setup.

#### 4.5 Experiment 5: measurement of soil moisture in disturbed field soil

The applicability of TDR in soils of high clay content is generally hampered because of relaxation phenomena and high energy losses along the transmission line (Chen et al., 2007; Kupfer et al., 2007). As the soil at the field sites contains around 16% clay, we performed experiments using field soil material (Table 2) in the box described in experiment 1 with the wooden template to guarantee ideal geometry. The base plate was perforated to enable exfiltration. To set up the experiment we half-filled the box with disturbed soil material from the field site, installed the SUSU 3 probe in the template, installed two THETA probes at a depth of 25 and 50 cm and then filled the remaining volume. Additionally, we installed a 30 cm uncoated TDR probe of type CS610 (Campbell Scientific Inc.) vertically from the top into the box to measure the bulk electrical conductivity. After filling and probe installation the soil material was compacted to avoid air gaps between the rods and the surrounding soil. The spin-up time of the experiment was two months with an irrigation amount of 74 mm every fourth

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day to achieve stable initial conditions. The actual irrigation experiment lasted 10 h, with a temporal sampling interval of the soil moisture data before irrigation of 20 min and during and after irrigation of 10 min. The soil was irrigated twice (74 mm/4 min) using de-ionized water. During the inversion we used the profile information of the previous time step as the initial condition for the following step. Inverted soil moisture profiles obtained with Spatial TDR were compared to measurements with the THETA probes at two different depths.

## 5 Results and discussion

### 5.1 $C$ – $G$ relation, $\varepsilon$ – $\theta$ relation and constraining of inverted moisture profiles

We estimated the three parameters  $C_d$ ,  $G_\infty$ , and  $C_0$  of Eq. (10) within experiments 2 and 5. The results are listed in Table 3. The parameters of Eq. (11)  $a$  and  $b$  were estimated to  $-0.2291$  and  $0.1324$ , respectively. The coefficient of determination was  $0.9837$ .

The last crucial step to ensure that the inverted soil moisture profiles complied with soil physics is to constrain the inversion by a physical range. The upper end is defined by soil saturated water content ( $\theta_S$ ) and the lower end by permanent wilting point (PWP). This can be easily achieved by using the inverse  $\varepsilon$  to  $\theta$  and the inverse  $C$  to  $\varepsilon$  relationships to obtain upper and lower limits for  $C$ . The parameters for the different soil substrates are listed in Table 2.

### 5.2 The effect of uncoated and coated probes on the reflectogram in field soils

Figure 5 shows the reflectograms of a coated and an uncoated rod probe at two different soil moistures in glass beads. In both cases the travel time of the coated probe is smaller compared to the uncoated; which is an effect of the isolating PVC coating. Estimated bulk electrical conductivity based on the method suggest by

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Huisman et al. (2008) and Lin et al. (2007) yielded values of  $1.0 \times 10^{-2} \text{ dS m}^{-1}$  and  $6.7 \times 10^{-2} \text{ dS m}^{-1}$  for the dry and wet case, respectively. For the case of uncoated rods, low electrical conductivity has already a strong influence on the shape of the reflectogram. Especially in the wet case there is a strong attenuation between 2 and 14 ns that is much less pronounced for the coated rods. Despite the low bulk electrical conductivity its influence on the uncoated probe is significantly strong. We thus may state that coated rods will deliver the more reliable reflectograms and should be used in these soils when using a probe length of 60 cm.

**5.3 Performance in homogeneous media**

Figure 6 presents inverted moisture profiles in comparison to the THETA probe obtained during the experiment. For the inversion the parameter set “exp. 1” in Table 3 was used for the inversion. The profile data were aggregated to 5 cm for a better comparability. Table 4 shows the absolute error of the inverted profiles to the THETA probes and goodness of fit criteria for the inversion calculated from observed and reconstructed reflectograms. Both data sets are generally in good agreement except for day 1.5 and 2.5. Finally, it is important to stress that even a glass bead medium is not perfectly homogeneous. The variation in the moisture in profile at the beginning of the experiment clearly reflects small differences in saturated water content.

**5.4 Effect of rod geometry**

Figure 7 presents the reflectograms and the inverted soil moisture profiles at different average soil moistures of  $0.05 \text{ m}^3 \text{ m}^{-3}$  (Fig. 7a and d),  $0.08 \text{ m}^3 \text{ m}^{-3}$  (Fig. 7b and e) and  $0.20 \text{ m}^3 \text{ m}^{-3}$  (Fig. 7c and f) for the four different rod geometries shown in Fig. 3b. During inversion we used the parameter set for glass beads (Table 3). It has to be noted that due to installation and de-installation of the probe, which required refilling of the box, the soil moisture and bulk density profiles varied slightly between different experiments (Table 5 and Fig. 7a–c) when comparing the different geometries.

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A decreasing distance between the wave guide rods means an increasing capacitance of the transmission line. Hence, the probe parameters  $C_1$  and  $L$  should vary along the transmission line. However, they are currently assumed to be constant, because we are studying the effect of rod deformation on the retrieved soil moisture profile. In the case of convergent rods, soil moisture appears to increase with depth in all three cases. It strongly underestimates soil moisture in the upper half and strongly overestimates soil moisture in the lower half, especially for intermediate conditions and wet conditions.

In the case of divergent rods, the apparent soil moisture profile is just flipped in comparison to the convergent case. Thus, it appears to be wetter in the upper half and clearly drier in the lower part. It is important to note that the average soil moisture calculated from the travel time is in most cases within the error range almost unaffected by deformations of the probe (Table 5). The experiments were also repeated in coarse sand of 0.06 to 0.60 mm grain size, with similar results (not shown). Thus, we state that unknown changes in probe geometry will lead to a systematic bias in inverted soil moisture profiles but will leave the average values unchanged and, through interpretation of the relative soil moisture, we consider this to be negligible it is negligible.

As a first step we tested a quality measure to assess a deformed probe by introducing the amplitude coefficient CA, defined as:

$$CA = (V_{\max 1} - V_{\min}) / V_{\max 1} \tag{12}$$

where  $V_{\max 1}$  = maximum voltage of the first reflection and  $V_{\min}$  is the inflection point before the second reflection in the reflectogram. The corresponding values for the deformation cases are listed in Table 6. In the convergent case CA has positive values and is negative in the standard and divergent case. With increasing divergence CA values become larger. This is consistent with the theory of a plate capacitor. An increasing distance between the rods corresponds to a decreasing conductance. The amplitude at the end of the reflectogram will thus increase, which yields a negative value for CA. In the convergent case the conductance increases at the end of the probe, which means small amplitude and thus a positive CA.

## 5.5 Effect of gravel/stone in the integration volume

Figure 8 presents the reflectograms as well as the inverted soil moisture profiles for the brick, the iron block, the dry and saturated wood, and the boulder block. Table 7 lists the soil moisture observed with THETA probe measurements along the profile, the mean soil moisture estimated with the SUSU03 including the object and the soil moisture in the area of the object. During inversion, parameter set “exp. 2” (Table 3) was used to characterize the transmission line. As the iron block is an ideal conductor, the electric conductivity is strongly increased at a depth of 30 cm. Consequently, soil moisture appears to be much higher in the profile, which is indicated in the reflectogram by the pronounced decrease in the amplitude at 5 ns in Fig. 7b. The inversion yielded a value of  $0.40 \text{ m}^3 \text{ m}^{-3}$  at 30 cm, although the true value was around  $0.20 \text{ m}^3 \text{ m}^{-3}$ . The brick and the boulder block show up as a slightly drier region in the reflectogram, marked by the minimal increase in normalized voltage at 5 ns in Fig. 7b. Inversion yields slightly lower soil moisture at 30 cm when compared to the values below and above. The effect of stones and the iron block agree with the expected behaviour.

It is important to stress that an ideal conductor in the integration volume has the same influence on the reflectogram and the inverted moisture profiles as a convergent probe geometry (compare Figs. 7a and 8a). Both lead to a strong decrease in the amplitude of the reflectogram. Fortunately, gravel, boulder blocks and other solid objects of low electric conductivity and low permittivity seem to be not as critical as were expected. Their effect on the reflectogram is rather small.

## 5.6 Measurement of soil moisture in field soils

Figure 9 presents the temporal development of the inverted soil moisture profile during two irrigations of approximately 74 mm in a period of 4 min at 5:20 h and 6:40 h (a), the absolute error of inverted profile compared to THETA probe measurements (b), the objective function of the inversion (c), and the inverted profiles (d). The range of the bulk conductivity measured with a CS610 was 0.04–0.10 dS/m. The spatial

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resolution was aggregated to 5 cm length for a better comparability with the THETA probe measurements. During inversion, parameter set “exp. 2” (Table 3) was used to characterize the transmission line.

The soil column was relative dry before the irrigation, with a dry top layer and a slightly increase in soil moisture towards the bottom. During the irrigation the infiltration front reaches a depth of approximately 15 cm in the first 10 min and then the bottom is reached and saturated. Exfiltration starts at the bottom of the soil column, with some 10 mm leaving the column in the first few minutes after the irrigation. The top layer runs dry while the lower layers remain saturated for 2 h, after which the second irrigation experiment is initiated. The wetter soil reacts much faster upon irrigation. Drying then starts again and the profile evolves to the initial conditions. First the top layer to a depth of 8 cm dries out from  $0.56$  to  $0.25 \text{ m}^3 \text{ m}^{-3}$  in a few hours. The deeper parts have lower rates of drying depending on the depth and at the end of the experiment the lowest 12 cm were still saturated.

The estimated absolute error (Fig. 9c) of the inverted value minus the measured soil moisture with THETA probes in the depths 20 and 50 cm, shows that the measurements slightly underestimate the soil moisture measured with the THETA probes before the irrigation. During the irrigations, the inversion overestimates the soil moisture and during the recession it is underestimated again. During the drying phase, the upper probe is slightly under- and the lower overestimated. A possible explanation for these differences between inverted soil moisture and THETA probe measurements during the drying period is small scale heterogeneity in the soil column.

Figure 9c shows the temporal development of the objective function for the inversions. The objective function is decreasing during the beginning of the experiment and is then increasing which means a lower quality for the inverted profiles. Between the irrigations the quality has no trend. It increases again after the second irrigation and then improves continuously but with a few breaks.

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## 6 Conclusions and outlook

Different laboratory experiments were carried out to investigate the feasibility of retrieving soil moisture profiles with Spatial TDR technology in heterogeneous loamy soils with substantial clay content. Firstly, we conclude that coated rods allow assessment of the more credible reflectograms and should be used in these soils when using a probe length of 60 cm. Reflectograms obtained with a 60 cm long probe with uncoated rods in glass beads were strongly deformed by energy dissipation along the probe and, when compared to a coated probe of the same length, this was especially so during wet conditions. Observation of the infiltration processes in cohesive soils requires installation of sufficiently long probes, even longer than 60 cm. Coated rods are indeed favourable in this case for these soils, as signal to noise ratio in the reflectogram obtained with uncoated rods becomes worse with increasing rod length (Dalton and Van Genuchten, 1986).

We found evidence that unknown changes in probe geometry, which are surely frequent is surely the rule when installing these probes into heterogeneous soils, cause a systematic bias in inverted soil moisture profiles and characteristic fingerprints in the reflectogram. In the case of divergent or convergent rods, neither the inductance  $L$  nor the capacitance  $C_1$  can be assumed to be constant along the transmission line. Fortunately, probe deformations leave the average moisture content along the probe almost unchanged. The average value is determined from the pulse travel time between the first and second main reflections in the reflectogram. Their location is not affected by probe deformations. This is actually good news for many field studies that work with conventional TDR data, as in the case presented by Zehe et al. (this issue).

It is also good news that solid objects like gravel, wood or boulder blocks have only a small effect on the inverted soil moisture profiles. They show up as slightly drier regions in the reflectogram. However, when a solid electrical conductor (an iron block) is present, soil moisture in this region is strongly overestimated by the inversion. Similar problems could occur in soils with a high content of iron-rich minerals, as discussed by

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Robinson et al. (1993) and Van Dam et al. (2002).

Finally, we found that observations with THETA probes and soil moisture values retrieved from the same depths were generally in good accordance both in glass beads and disturbed natural soil from the field site. We demonstrated furthermore that Spatial TDR is capable of monitoring fast infiltration and redistribution of irrigation water in soil.

We have analyzed the sources and subsequent impacts of different kind of errors. The biggest problem is certainly the biases that are introduced by probe deformations. For field applications a careful selection of TDR probes based on frequent inspections of the reflectogram is necessary to avoid misinterpretations of signals caused by deformed probes. The suggested measure  $CA$  can give a hint of whether the probe is convergent or divergent. During the experiments we found positive values in the case of convergent rods. Negative values are observed for parallel and divergent rods. The absolute value of the negative values increases with increasing divergence. Thus, if the reflectogram of a probe shows strongly negative or positive values under different conditions, it is likely not well installed. Furthermore, the closely related field study of Zehe et al. (this issue) underpins that Spatial TDR in the present state of development already allows many valuable insights to understand soil moisture variability at the field and small headwater scale and the interplay of soil moisture dynamics and runoff production. Future steps should further elaborate the calibration of transmission line parameters. Especially for soils rich in fine particles, Eq. (10) should be revisited, to check whether the assumption of zero conductivity is reasonable when  $C$  drops below  $C_0$ . We think that independent data on the electrical conductivity of the soil will facilitate solving that problem. It might also be necessary to introduce separate parameterization of the  $C - G$  relationship in Eq. (10) for strongly different soil horizons.

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## HESSD

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**Table 1.** Probe parameters estimated based on Eqs. (5) and (9) and absolute errors calculated with Gauss' law.

Parameter	Value	Abs. Error
$L$ [nH/m]	625.0	23.0
$C_1$ [pF/m]	22.4	0.9
$C_2$ [pF/m]	304.6	30.0

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**Table 2.** Soil texture (following the United States Department of Agriculture (USDA), 1993 classification), bulk density  $\rho_b$ , saturated soil moisture  $\theta_s$  and Permanent wilting point (PWP) of the dominating Cambisoiil at the study area Rehefeld, and experimental glass beads.  $\rho$  and  $\theta_s$  were estimated on  $100\text{ cm}^3$  soil cores with grain density of  $2.65\text{ g/cm}^3$ . PWP is the soil moisture at 160 m pressure head. The glass beads have grain size ranging from 0.25 to 0.5 mm diameter. Standard deviation is shortened with SD.

Soil type	Sand [%]	Silt [%]	Clay [%]	$\rho_b$ [ $\text{g/cm}^3$ ]	SD $\rho_b$ [ $\text{g/cm}^3$ ]	$\theta_s$ [ $\text{m}^3\text{ m}^{-3}$ ]	PWP [ $\text{m}^3\text{ m}^{-3}$ ]
Cambisoiil Rehefeld	52	32	16	1.15	0.11	0.56	0.08
Glass beads	100	–	–	1.50	0.05	0.38	0.03

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**Table 3.** Parameter sets characterizing the  $C - G$  relations for inversion of the reflectograms into soil moisture profiles both for glass beads and soils.

Exp.	Name	$G_{\infty}$ [mS/m]	$C_0$ [pF/m]	$C_d$ [pF/m]
1	Glass beads	1.5	50	18
2	Rehefeld soil	2.0	50	18

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**Table 4.** Difference of inverted soil moisture to point measurements with THETA probes as absolute error (AE) of the soil moisture in  $\text{m}^3 \text{m}^{-3}$ ; goodness of fit criteria calculated from observed and reconstructed reflectograms: root mean square error (RMSQ), mean error (ME), standard deviation of error (STDE), Nash-Sutcliffe efficiency (NSE) and the objective function (Eq. 2).

Time [d]	0	1.5	2.5r	3.5	4.5
AE 30 cm	-0.022	-0.032	0.022	-0.002	-0.003
AE 55 cm	0.003	0.000	0.010	-0.029	0.019
RMSQ	$1.50 \times 10^{-3}$	$4.52 \times 10^{-3}$	$6.18 \times 10^{-3}$	$8.05 \times 10^{-3}$	$6.65 \times 10^{-3}$
ME	$-1.02 \times 10^{-3}$	$-3.06 \times 10^{-3}$	$-4.60 \times 10^{-3}$	$-5.95 \times 10^{-3}$	$-4.51 \times 10^{-3}$
STDE	$1.10 \times 10^{-3}$	$3.35 \times 10^{-3}$	$4.02 \times 10^{-3}$	$5.06 \times 10^{-3}$	$4.81 \times 10^{-3}$
NSE	0.995	0.994	0.992	0.990	0.993
Objective Function	$3.35 \times 10^{-14}$	$3.06 \times 10^{-13}$	$5.69 \times 10^{-13}$	$9.63 \times 10^{-13}$	$6.55 \times 10^{-13}$

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**Table 5.** Mean soil moisture observed with different probe deformations at soil moisture of approximately  $0.04 \text{ m}^3 \text{ m}^{-3}$ ,  $0.08 \text{ m}^3 \text{ m}^{-3}$  and  $0.20 \text{ m}^3 \text{ m}^{-3}$  estimated with SUSU03 and THETA probes. Standard deviation is shortened with SD.

Type of deformation	Convergence	Standard	Divergence	Strong Divergence	Mean THETA probes	SD THETA probes
Distance between the outer rods [cm]	3	6	10	14	–	–
$0.04 \text{ m}^3 \text{ m}^{-3}$	0.036	0.038	0.039	0.039	0.040	0.005
$0.08 \text{ m}^3 \text{ m}^{-3}$	0.077	0.081	0.079	0.073	0.080	0.010
$0.21 \text{ m}^3 \text{ m}^{-3}$	0.207	0.199	0.200	0.195	0.200	0.020

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**Table 6.** Amplitude coefficient (CA) for different probe deformations at soil moisture of approximately  $0.04 \text{ m}^3 \text{ m}^{-3}$ ,  $0.08 \text{ m}^3 \text{ m}^{-3}$  and  $0.20 \text{ m}^3 \text{ m}^{-3}$ .

Type of deformation	Convergence	Standard	Divergence	Strong Divergence
Distance between the outer rods [cm]	3	6	10	14
$0.04 \text{ m}^3 \text{ m}^{-3}$	0.11	-0.33	-0.58	-0.75
$0.08 \text{ m}^3 \text{ m}^{-3}$	0.22	-0.20	-0.66	-0.80
$0.21 \text{ m}^3 \text{ m}^{-3}$	0.46	-0.25	-0.58	-1.31

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**Table 7.** Mean soil moisture observed with THETA probes and estimated with the different objects and the soil moisture in the area of the object.

Type of Object	Mean THETA probe	Soil moisture between 27.5–32.5 cm depth					
		Iron	Boulder	Dry Wood	Sat. Wood	Plastic	Brick
0.04 m <sup>3</sup> m <sup>-3</sup>	0.04	0.094	0.034	0.031	0.034	0.031	0.340
0.16 m <sup>3</sup> m <sup>-3</sup>	0.16	0.240	0.131	0.135	0.152	0.142	0.140
0.30 m <sup>3</sup> m <sup>-3</sup>	0.30	0.378	0.306	0.308	0.307	0.299	0.328
		mean soil moisture					
0.04 m <sup>3</sup> m <sup>-3</sup>	0.04	0.037	0.034	0.034	0.033	0.034	0.035
0.16 m <sup>3</sup> m <sup>-3</sup>	0.16	0.160	0.147	0.147	0.154	0.166	0.161
0.30 m <sup>3</sup> m <sup>-3</sup>	0.30	0.310	0.313	0.313	0.312	0.315	0.316

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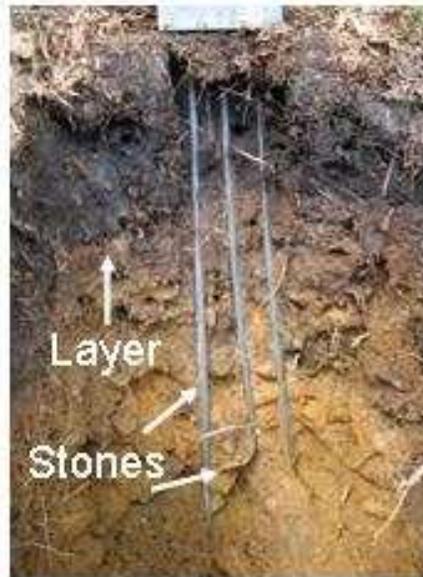
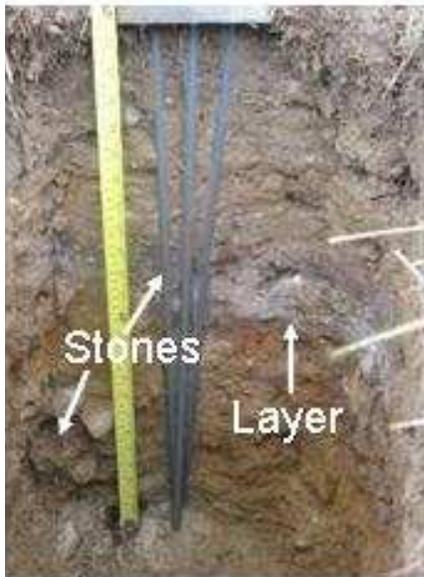
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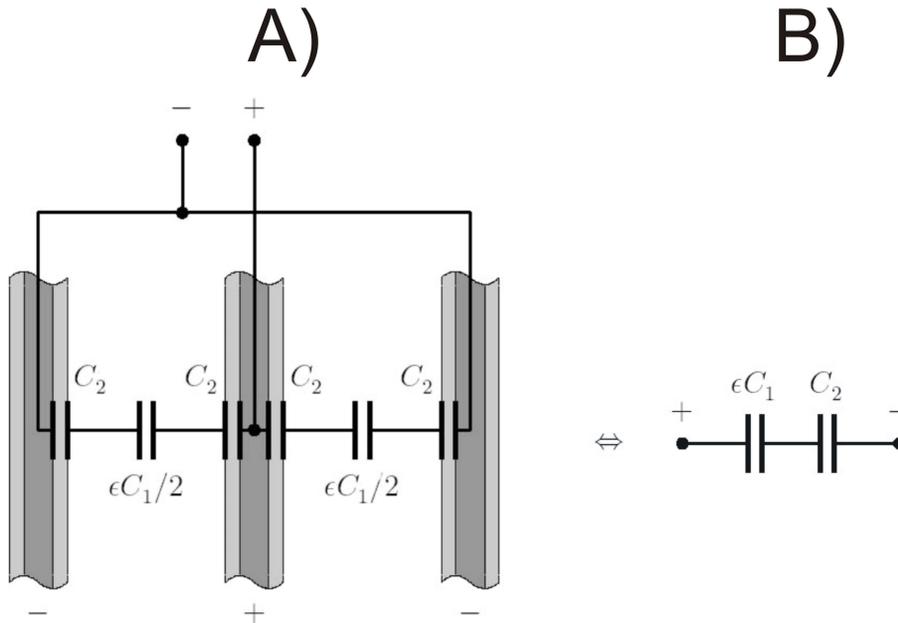
A) B)



**Fig. 1.** Typical soil profiles with different horizons and coarse gravel and possible deformations of the TDR wave guides when installed in the soil (**A** and **B**).

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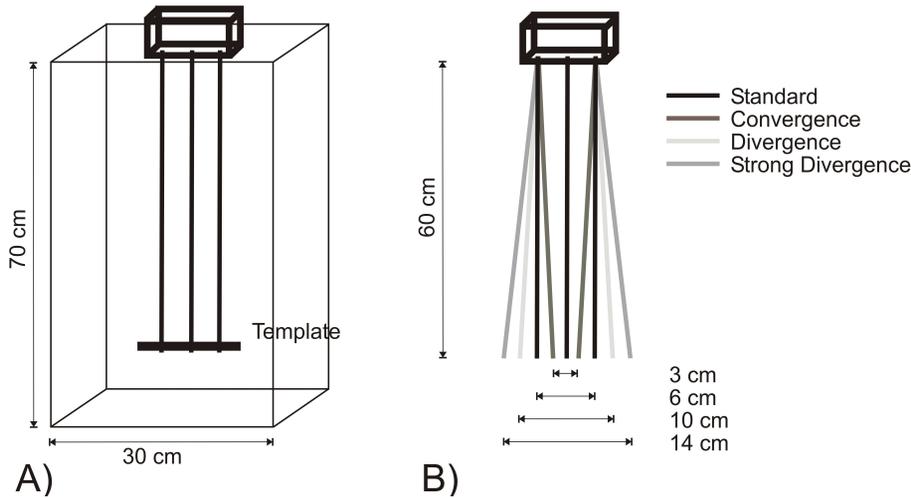
**Fig. 2.** Total capacitance  $C$  of a 3-rod-probe as a function of the soil’s dielectric permittivity  $\epsilon$ . **(A)** segment of three parallel rods encompassed by soil; light grey: PVC coating; dark gray: metallic core; **(B)** equivalent circuit.  $C_1, C_2$ : constant capacitance parameters determined by the probe’s geometry (Becker, 2004).

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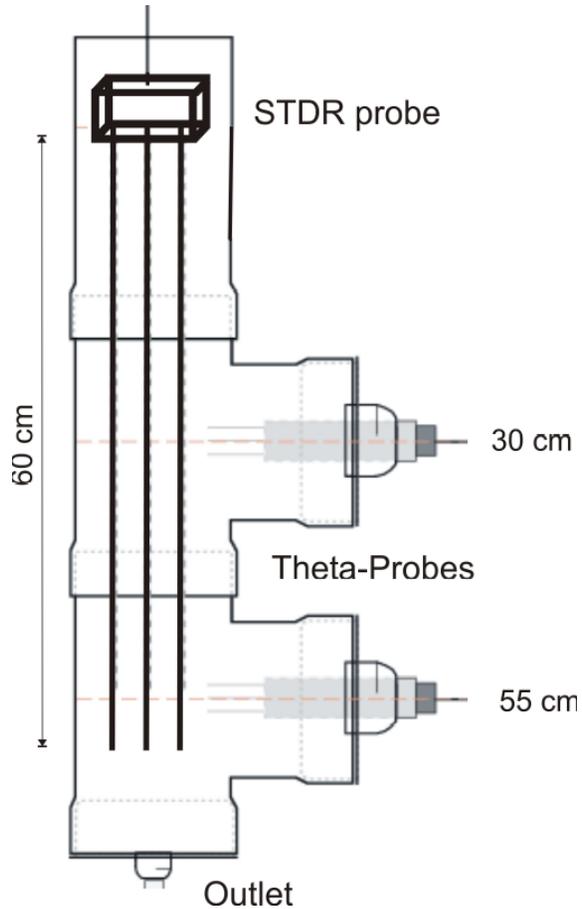
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**Fig. 3.** Sketch of the plastic box with installed SUSU03 and position of the wooden template **(A)**, and sketch of the four different probe geometries **(B)**.

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**Fig. 4.** Sketch of the PVC tube with installed SUSU03 and two Theta probes. At the bottom of the tube there is an outlet to drain the tube with a water pump.

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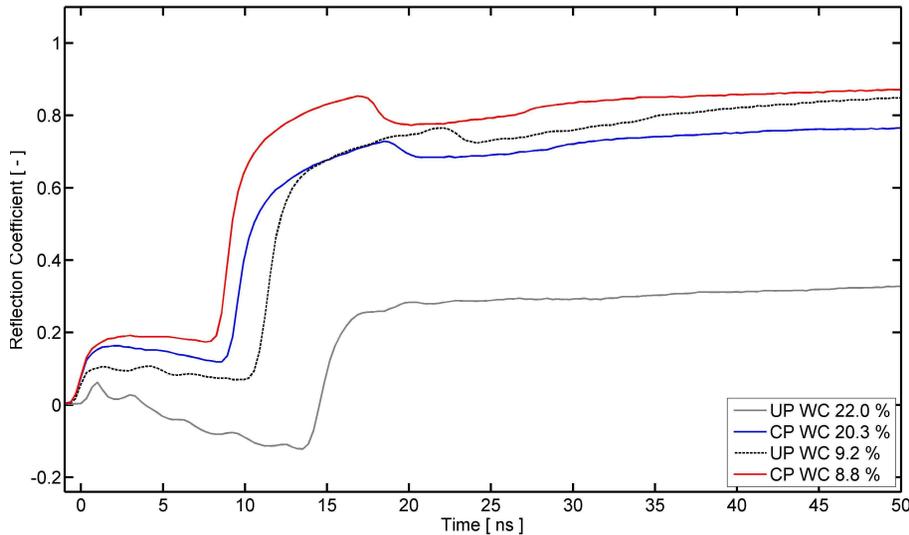
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**Fig. 5.** Reflectograms obtained with coated (CP) and uncoated (UP) SUSU03 probe with 60 cm rods at two different soil moistures, measured in a experimental box with glass beads (Table 2). Bulk electrical conductivity was  $1.0 \times 10^{-2} \text{ dS m}^{-1}$  for the dry case and  $6.7 \times 10^{-2} \text{ dS m}^{-1}$  for the wet case.

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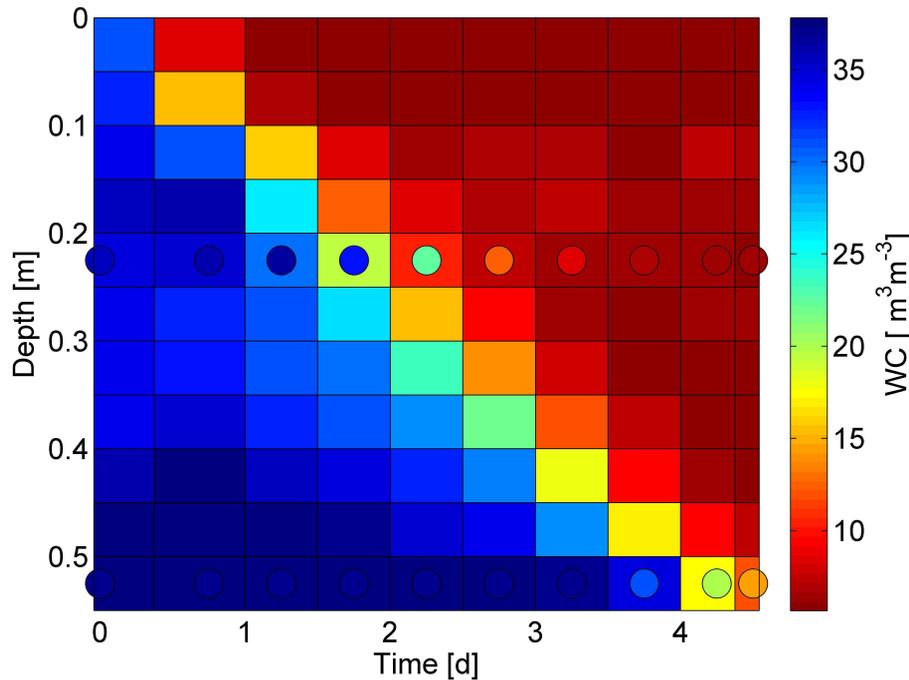
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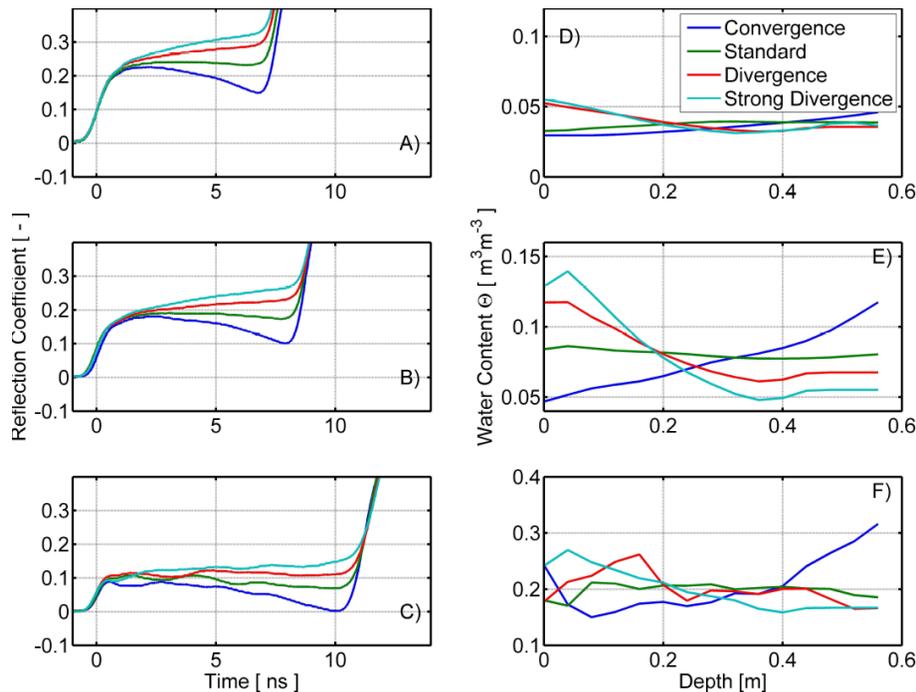


**Fig. 6.** Comparison of inverted soil moisture profiles obtained within glass beads with independent soil moisture measurements by means of THETA probes (marked with circles). The colour coding is the same for both data sets.

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**Fig. 7.** Reflectograms and inverted soil moisture profiles obtained with different probe deformations at a soil moisture of approximately  $0.04 \text{ m}^3 \text{ m}^{-3}$  (A) and (D);  $0.08 \text{ m}^3 \text{ m}^{-3}$  (B) and (E); and  $0.20 \text{ m}^3 \text{ m}^{-3}$  (C) and (F). Standard denotes according to Fig. 3 ideal geometry, Convergence means convergent rods with increasing depth, Divergence and Strong Divergence values signifies a divergent probe as described in Fig. 3.

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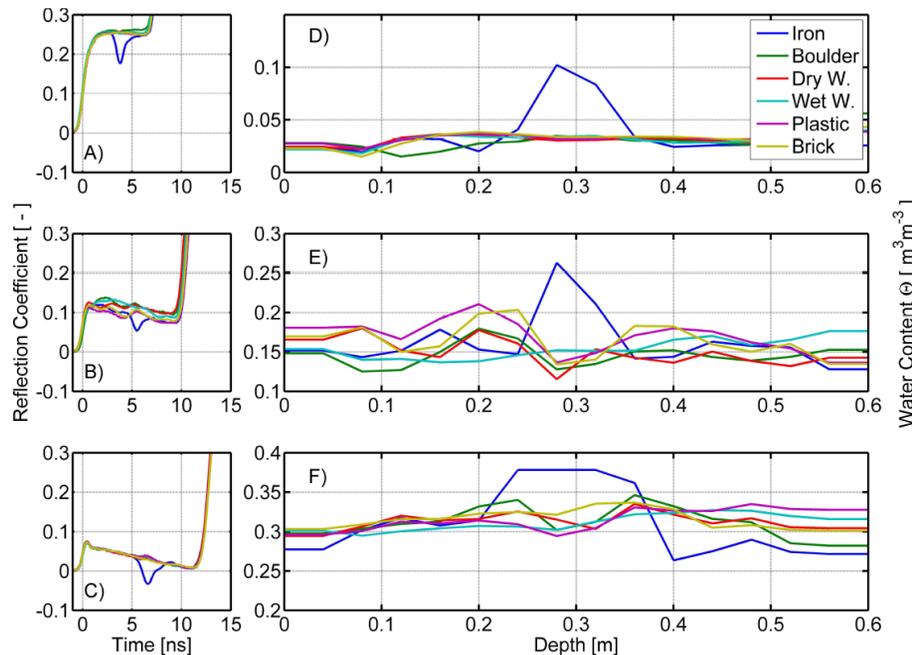
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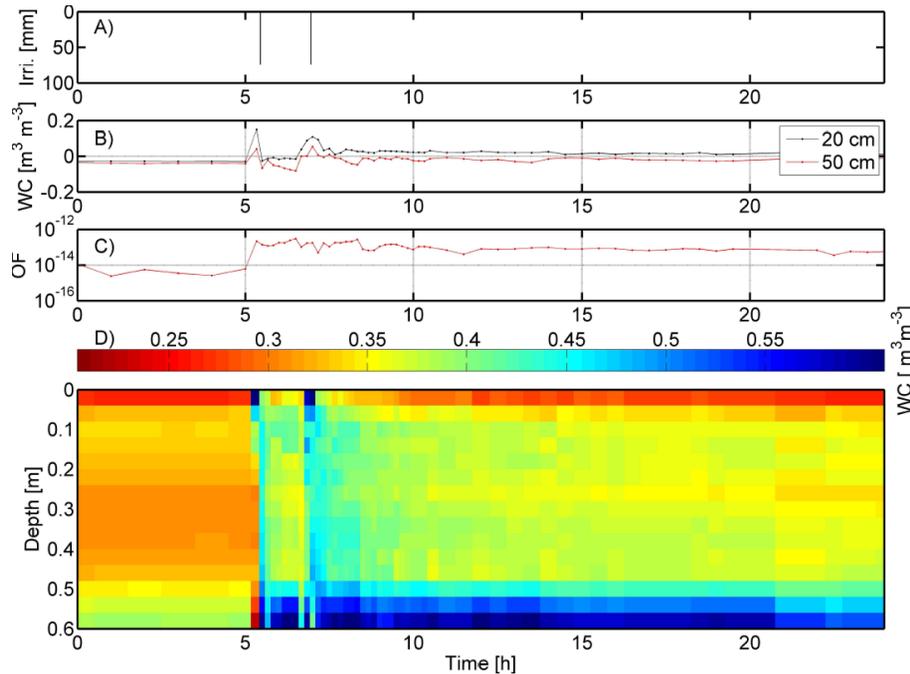


**Fig. 8.** Reflectograms and inverted soil moisture profiles with an iron block, dry and wet wood, PVC block, brick and boulder with a volume of approximately 1.5l at a depth of 30 cm. All probes were measured with ideal geometry. The mean soil moisture is about  $0.04 \text{ m}^3 \text{ m}^{-3}$ , (**A** and **D**)  $0.16 \text{ m}^3 \text{ m}^{-3}$  (**B** and **E**) and  $0.30 \text{ m}^3 \text{ m}^{-3}$  (**C** and **F**). Wood is shortened with W.

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**Fig. 9.** Inverted soil moisture profiles obtained in an experimental box filled with soil from Rehfeld with **(A)** the irrigation, **(B)** the absolute error of inversion compared to measurement with THETA, **(C)** the objective function (shortened with OF) of the inversion and **(D)** the inverted profiles to a depth of 55 cm.

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