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Accuracy of soil water content measurements using ground penetrating radar: comparison of ground penetrating radar and lysimeter data

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Abstract

The ground penetration radar (GPR) can be used for soil water content measurements. To prove the accuracy of the GPR, measurements were carried out on four lysimeters (surface 1 m^2, depth 1.5 m) during one vegetation period. The lysimeters were planted with lucerne and filled with three different soils: a loamy sand, a sandy loam and a silt loam. The ground water tables were at 1.35 and 2.1 m. The lysimeters were weighed, so that it was possible to calculate the changes in water content with very high accuracy. For the GPR-measurements a 1 GHz-antenna was used. Only in the sandy loam reflected signal from the bottom of the lysimeter could be obtained. The standard deviation between the GPR and the lysimeter data was 0.01 m^3/m^3 using all data and 0.0026 m^3/m^3 using only measurements in the wetter range. For this material an experimental calibration curve between the soil water content (θ) and the relative dielectric constant (ε) was calculated by comparing GPR-results with lysimeter data. The data results in a linear function $\theta(\varepsilon)$ for the measured range of water contents. Compared to published calibration curves used for TDR-technique, the Topp-function gives the best results. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Ground penetrating radar; Soil water content; Dielectric constant; Calibration; Lysimeter

1. Introduction

The soil water content is an important variable in soil physics. At small scales, TDR-probes (time domain reflectometry) can measure the water content and especially changes of water content with very high accuracy (Roth et al., 1992; Jacobsen and Schjonning, 1993; Nissen et al., 1999). But there is still a lack of methods suitable for areas and measurements of heterogeneity of soil water content. Using TDR, a high number of probes have to be installed, which leads to considerable costs and work. To determine small-scale heterogeneities, the TDR also has the disadvantage of disturbing the area by installing probes. For these cases, ground-penetrating radar (GPR) is an alternative measuring device. It can be used for areas in the range of hectare, is non-destructive and gives data about the heterogeneity.

In geophysics, GPR is a standard method for detecting and determining the ground water table (GWT) or the structure of soils. The traveltime of the radar wave is determined by the depth of the reflector

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and the velocity of the wave, which is dependent on the relative dielectric constant. Above all, the relative dielectric constant is dependent on the soil water content. The relative dielectric constant can be calculated using a mixing model (Dobson et al., 1985) or empirical approaches like used by Topp et al. (1980) or Roth et al. (1992). An overview on the different models used in the TDR-technique is given by Bohl (1996).

Ground penetration radar (GPR) was used for measuring soil water contents in different ways. One method is the antenna separation (Huisman et al., 2001; Du, 1996; Sperl and Stanjek, 1997). It utilized the so called ground wave. This method is suitable for measuring the water content in the upper layer of the soil (10 cm according to Huisman et al. (2001)). Other authors like Chanzy et al. (1996) and Weiler et al. (1998) or Dannowski and Yaramanci (1999) used a reflected wave for measuring the velocity of the wave in the soil. This method measures the water content between the reflector and the surface of the soil, but a reflector or a reflecting layer is needed. Until now calibrations of GPR were done by comparing GPR to TDR or the gravimetric water content (Huisman et al., 2001; Weiler et al., 1998). Compared to these calibrations, the lysimeter measures directly the same volume as the GPR and gives the water content changes with very high accuracy.

GPR measurements can be carried out at different frequencies. Higher frequencies lead to higher spatial resolutions, but also to a higher attenuation and, therefore, to a lower depth of penetration. Frequencies commonly used are between 50 MHz and 1 GHz, referring to a wavelength between 6 m and 30 cm in air. The wavelength is shortened due to the higher relative dielectric constant in the soil. In sandy soils the wavelength of the 50 MHz antenna lies between 270 and 110 cm, the wavelength of the 1 GHz antenna between 13 and 5 cm (Table 1). The spatial resolution of the measurements is limited by the dominant wavelength and the effective bandwidth of the antenna (Forkmann and Petzold, 1989).

If the depth of the reflector is known, the effective relative dielectric constant can be calculated by:

$$\varepsilon_r = \left(\frac{ct}{2d}\right)^2 \tag{1}$$

ε_r is the relative dielectric constant of the soil; c is velocity of light; t is traveltime, d is the depth of the reflector.

If the water content θ is known, the results can be compared to different calibration functions. In this work, the results were compared to the following calibration functions:

$$\theta = -0.078 + 0.0448\varepsilon - 0.00195\varepsilon^2 + 0.0000361\varepsilon^3 \tag{2}$$

(Roth et al., 1992)

$$\theta = -0.053 + 0.0293\varepsilon - 0.00055\varepsilon^2 + 0.0000043\varepsilon^3 \tag{3}$$

(Topp et al., 1980)

$$\varepsilon = \sqrt{a\varepsilon_{\text{air}}^2 + \theta\varepsilon_{\text{water}}^2 + (1 - a - \theta)\varepsilon_{\text{solid phase}}^2} \tag{4}$$

(3-phase model, Dobson et al., 1985)

ε_i is the relative dielectric constant of the phase i; a is air content (m^3/m^3); θ is the water content (m^3/m^3).

Lysimeters are used in soil hydrology to measure evapotranpiration, capillary rise and ground water recharge. If the lysimeter is weighed, the changes of the total water content in the soil can be calculated with very high accuracy. For most cases in soil hydrology, the change of the water content is an important value. The measurements of GPR using a lysimeter offer, therefore, a very good opportunity to calculate the accuracy of GPR for water content changes in the vadose zone. An individual calibration curve can be calculated.

The aim of the study is to determine the accuracy of GPR in measuring differences in water content and to estimate the possibilities for measuring small-scale water content heterogeneity using GPR.

2. Material and methods

The measurements were carried out at the lysimeter station Berlin Dahlem. The station consists of twelve lysimeter-cylinders, each with an area of 1 m^2 (∅: 113 cm) and a depth of 1.5 m. The cylinders stand on a platform scale, which is connected to an electronic scale. The changes in water content can be measured with an accuracy of 100 g, which

Table 1
Wavelength of electromagnetic waves for different antenna frequencies

Frequency	Wavelength (cm)			
	Air ($\varepsilon_r = 1$)	Dry soil ($\varepsilon_r = 5$)	Wet soil ($\varepsilon_r = 30$)	Water ($\varepsilon_r = 81$)
50 MHz	600	268	110	66
400 MHz	75	34	14	8
1 GHz	30	13	5	3

corresponds to 0.1 mm of the area or 0.000067 m^3/m^3 of the volume of the lysimeter. The temporal solution of the measurement is 15 min. The twelve cylinders are filled with three different soil types: sand, loamy sand and silty clay. Soil parameters are shown in Table 2. The field capacity of the soils were calculated using the neuronal network program ROSETTA 1.0 (Schaap and Leij, 1998). In eight of the 12 cylinders, GWTs of 2.10 m were established using a suction system, in the other four cylinders (Lysimeter 3, 4, 9 and 10) a GWT of 1.35 m was kept. This led to a different reflection depth of the bottom wave. In the lysimeter with a GWT at 2.1 m, the bottom of the lysimeter at 1.5 m reflects the electromagnetic wave. The total length of the reflection path is then 3.0 m. In the lysimeter with the GWT at 1.35 m, the GWT reflects the electromagnetic wave. The reflection path is then 2.7 m. Using the reflection times, the effective relative dielectric constant of the soil can be determined.

The GPR measurements were carried out with the RAMAC/GPR system (Fa. MALA Geoscience). A 1 GHz antenna was used. The antenna is shielded, transmitter and receiver (length 24 cm, width 0.16 cm, antenna separation 11 cm) are in one box. Two diagonal profiles across the soil surface of the lysimeter were measured with a trace increment of 2 cm. The measurements were recorded at 12 times during the vegetation period from March to September. The signals were analysed with the program REFLEX (Fa. Sandmeier). The time from the beginning of the signal to the beginning of the bottom wave was determined. The time distance between two zero amplitudes of the reflected pulse is about 1 ns, so that in the cases for which the bottom wave could not be detected properly, there might be an uncertainty of ± 1 ns.

Four main pathways for the radar waves result from using the GPR on the lysimeter-cylinders. The direct wave between the antennas (1), two paths to the sidewalls of the cylinder (2 and 3) and the wave to the bottom (4) of the cylinder. The schematic traveltime picture of a diagonal profile across the lysimeter is shown in Fig. 1. The direct wave is the strongest and earliest wave. It is seen at all points of the profile at the same time, this leads to a horizontal line in the

Table 2
The soil parameter of the soils in the lysimeters

Horizon	Depth (cm)	Texture (%)			C_{org} (%)	pH	ρ_d (g/cm^3)	FC (m^3/m^3)	K_{sat} (cm/d)
		Sand	Silt	Clay					
Lysimeter 1–4: soiltyp Podsol (origin: Wildeshausen)									
Ap	0–40	81	15	4	4.0	6.2	1.5	0.179	140
Bsh 1	40–60	80	15	5	1.3	6.1	1.6	0.176	221
Bv	60–150	87	9	4	0.5	5.9	1.7	0.138	49
Lysimeter 5–8: soiltyp Cambisol (origin: Weckesheim)									
Ap	0–20	4	67	29	2.8	7.0	1.7	0.353	25
Bv1	20–60	5	69	26	1.0	7.4	1.5	0.400	3
C	60–110	6	75	19	0.4	7.7	1.7	0.346	4
Lysimeter 9–12: soiltyp Luvisol (origin: Parlow–Glambeck)									
Ap/Al	0–40	62	30	8	1.6	5.8	1.7	0.228	220
Bt–Sw	40–90	53	29	8	0.5	6.2	1.8	0.213	16
Cc–Sd	90–150	52	34	14	0.3	7.6	1.6	0.282	1

ρ_d dry density; FC: field capacity, calculated with ROSETTA (Schaap and Leij, 1998); K_{sat}: saturated hydraulic conductivity.

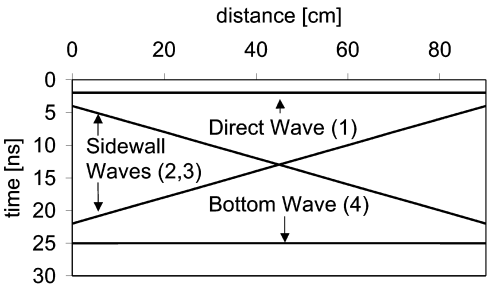

Fig. 1. Schematic traveltime picture of GPR measurement of a diagonal section across the lysimeter.

radargram picture of the profile. The reflection from the sidewalls of the lysimeter leads to a diagonal in the radargram pictures of so called diffraction waves, each diagonal referring to one sidewall. The reflection from the bottom leads to a second horizontal line.

3. Experimental results and evaluation

The measurements were carried out using three different soil materials. However, only on the sand it was possible to detect the reflected signals from the bottom. At the lysimeter with loamy sand and silty clay the attenuation of the signal was too high. Measurements with lower frequencies (which would have stronger reflection signals) could not be carried out on the lysimeter, because the antennas are too large. In some cases, the reflection signals could not be even detected for the sand, especially for the lysimeters with a GWT at 1.35 m. At the lysimeters with a GWT of 2.1 m, the signals were better; maybe the reflection at the bottom of the lysimeter (in 1.5 m) is stronger than the reflection at the GWT because of a certain capillary effect.

Fig. 2 presents the traveltime picture of a measurement in spring with wet soil and in summer with dry soil. Due to the higher water content the velocity of the wave is lower in spring, so that the bottom waves appear at 26 ns. For the measurement at the drier soil, the bottom wave appears earlier, after 18 ns.

The measurements of the lysimeter during the year shows the drying of the soil during the summer (Fig. 3). Rainfall events lead to a rise of the weight, drying periods to a drop of the weight. Due to the lower capillary rise of water, the lysimeters with a GWT at 2.10 m dry out much more during the summer than those with a higher GWT. The lysimeter 1 and 2 lose up to 140 mm, while the lysimeter 3 and 4 lose only about 50 mm water. Correspondingly, the changes in the reflection times were different. In lysimeter 1 and 2, the reflection time of the bottom wave changed during the vegetation period by 9 ns, in the lysimeter 3 and 4 only by less than 5 ns (Fig. 4).

During the vegetation period, the reflection times were correlated to the changes of the water content of the lysimeters. In Fig. 5 the relation between the water storage change and the change in reflection time is shown. There are two different curves for both types of lysimeters (GWT 2.1 m and GWT 1.35 m). The scattering is higher in the dry range and lower in the wet range. The relative dielectric constant was calculated from the reflection times. The water content was calculated using the lysimeter data. The results of the measured relation between the relative dielectric constant and the water content are shown in Fig. 6. For the lysimeters with GWT 2.1 m, the following calibration curve can be fitted:

$$\theta = 2.45\varepsilon - 3.04 \tag{5}$$

The standard deviation between the fitted curve and data is 15 mm ($= 0.01$ m^3/m^3). Using only data of the wetter range, where the scattering of the GPR-measurements was lower, the standard deviation is reduced to 4 mm ($= 0.00026$ m^3/m^3).

The results were compared to the calibration curves of Topp, Roth and Dobson shown in Eqs. (2)–(4). The $\varepsilon(\theta)$ relation from the lysimeter with GWT 2.1 m fits to the calibration curves (Fig. 6). The best correspondence is reached using the Topp-equation.

4. Conclusions and outlook

The reflected wave from a GPR with higher frequencies can only be used for sandy soils. In order to apply the method to the field, the reflector should be not deeper than 1–1.5 m in the soil. An individual calibration curve from the sandy material was calculated using a linear relationship between soil water content and relative dielectric constant. Using the bottom of the lysimeter as a reflector, the calibration curve of Topp et al. (1980) leads to the

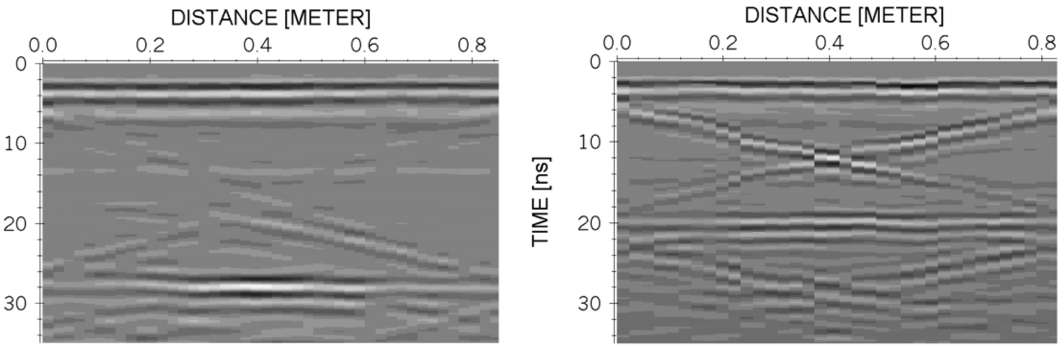

Fig. 2. Traveltime picture of the GPR measurement in a lysimeter for wet (left) and dry (right) conditions.

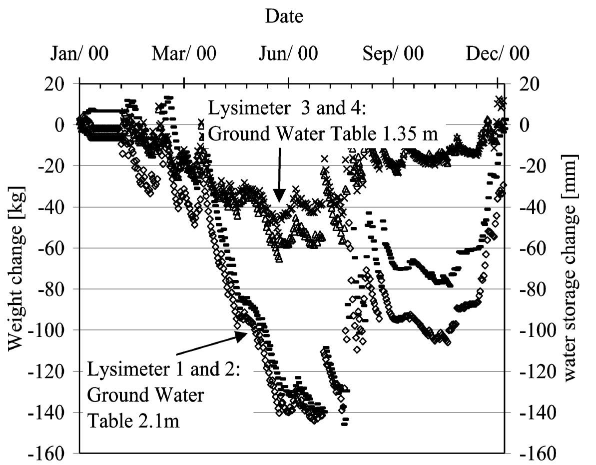

Fig. 3. Changes in weight and water content of the sandy lysimeters with different GWTs.

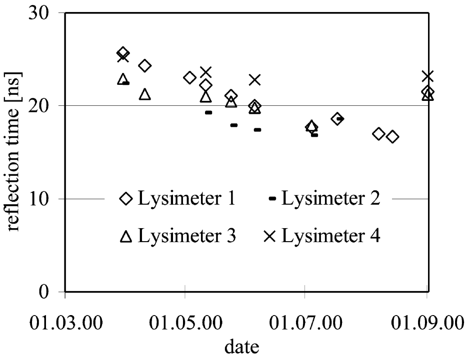

Fig. 4. The reflection times of the bottom wave from the GPR measurements during a vegetation period for four sandy lysimeters. Lysimeter 1 and 2 have GWTs at 2.10 m, lysimeter 3 and 4 at 1.35 m.

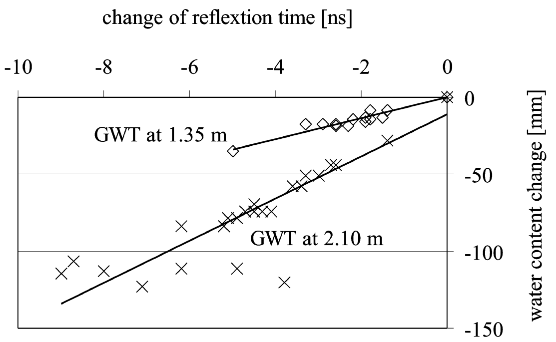

Fig. 5. Correlation between changes in water content and reflection time.

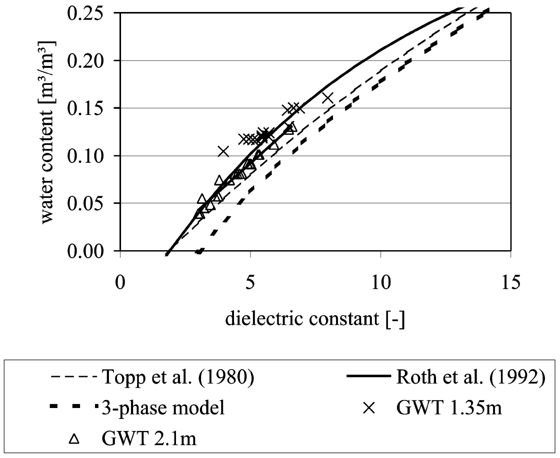

Fig. 6. The measured relative dielectric constant and the water content compared to different calibration models.

best results. The results shows, that it should be possible to detect small-scale heterogeneity in water content changes in the field if the differences in water content are much higher than 0.01 m^3/m^3. For example Dekker et al. (1999) measured water content differences from 0.07 to 0.18 m^3/m^3 at distances in the range of decimetres. Field experiments to measure the small-scale heterogeneity are set up.

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