A method to increase vertical resolution of soil moisture measurements by TDR Trime FM3 tube sensor probe

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Abstract
A special method of overlapping measurements was proposed to increase the vertical resolution of a TDR tube soil moisture sensor-probe Trime FM3. An inversion algorithm has been developed to derive soil moisture profiles along single TDR sensor-probe, which is based on the hypothesis of linear contribution of soil moisture content of layers enclosed in a cylindrical soil volume. This model was tested during experimentation on an artificial soil monolith assembled from 18 homogeneous horizontal discrete macro layers of 5 cm of height fabricated from dark-chestnut soil and artificially moistened to different values. For the first step, a series of overlapping measurements was produced using a TDR device, with step size of 1cm. Measured values were then compared to calculations based on the proposed model using moisture values of discrete macro layers as input parameters. At this stage the best agreement between measured moisture values and proposed model was achieved with a height of the soil cylinder of about 15-16 cm. For the second step, moisture values of discrete macro layers were calculated by the proposed model from values of overlapping measurements. At this stage the best agreement was gained with a height value of the soil cylinder of 16cm, when comparing moisture values of discrete macro layers of the artificial monolith derived from overlapping measurements and determined by the conventional direct gravimetric method.

Key Words
Soil moisture, TDR, overlapping measurement.

Introduction
An accurate measurement of the moisture of a soil profile is essential in many areas of environmental and agricultural research. However, the design of standard probes does not allow using these devices for monitoring vertical soil moisture distribution with adequate resolution. Nowadays, time domain reflectometry (TDR) is a widely used technique for measuring volumetric soil moisture. Recently, TDR tube probe sensor - Trime FM3 was produced by IMKO to respond to this demand. The research carried out by the producer has shown that the geometrical body of measurement by a probe represents a cylinder with height about 15-16 cm and the basis in the form of an ellipse with the greatest radius around 40 cm. In this case, it is quite uncertain whether direct use of the results of soil moisture monitoring by this probe can be used for flow modelling in soil. Trime FM3 tube probe sensor was successfully used on an experimental site in Saratov region of Russia in the work of INTAS 2000-436, NATO Travel Grant ESP.NR.CLG 982355, FP6 Water Reuse 516731 and FP6 DESIRE 037046 projects to monitor moisture distribution in soil profiles during field experimentation on irrigated and not irrigated areas. For this study a special method of overlapping measurement was developed with the aim of increasing vertical resolution of soil moisture measurements.

Methods
Soil water content measurements
Standard methods of soil moisture measurement such as oven-drying are very time-consuming and destructive, neutron scattering or gamma attenuation measurements make use of potentially hazardous radioactive sources. The determination of moisture content with time-domain reflectometry (TDR) technology is based on measurements of travel-time of an electromagnetic pulse on a transmission-line of known length Top *et al.* (1980). A review of TDR techniques for the measurement of permittivity and bulk electrical conductivity along with description of probe design and probe construction are given in Robinson *et al.* (2003). However, standard measurement TDR-techniques gives only mean or point results.

Experimentation on soil water content with borehole TDR in soil monolith
At the first stage of experiment, a measurement with TDR Trime-FM3 (Figure 1) was carried out. Experimental data was obtained for a constructed soil profile with horizontal dimensions of 70x70 cm and height of 90 cm with soil layers with different moisture contents. The soil monolith was assembled from 18 homogeneous horizontal layers. The soil material of the monolith was selected from the top of upper horizons of dark-chestnut soil of Saratov region (Russia). The sides of this monolith as well as boundaries between layers with different moistures have been protected by impermeable film to prevent evaporation as well as transfer of moisture inside the monolith. To avoid formation of significant air cavities inside of a monolith, the soil material was exposed to preliminary processing (a removal of roots and crushing of large blocks), then the soil was placed in a monolith, which was made level-by-level (1 cm) by compressing to obtain homogeneous soil body of layers and planned values (gravimetric moisture in a range from 0.08-0.30 g/g, density from 1.1 up to 1.38 g/cm^3).

Figure 1. TDR Trime-FM3 probe for borehole moisture measurements. Picture from the site of the IMKO Company.

The plastic tube (1 m height) was vertically installed in the center of the monolith using borehole and pathway to measure the soil water content using the Trime-FM3 tube sensor probe. After completing the developing of soil monolith, a series of overlapping measurements of soil moisture were done from the bottom of the monolith up to its surface with steps of 1 cm. The repetition of overlapping measurements was carried out several times during three days and showed an absence of any soil moisture changes in the fabricated soil monolith. After the end of the measurements the fabricated soil monolith was disassembled. Soil samples from each layer were taken out to determine values of density and soil moisture by gravimetric methods. Obtained values of soil moisture and bulk density of were quite uniform inside each layer and were similar to the planed values.

Modelling of measurement of water content in soil using TDR Trime FM3.
A simple mathematical model has been chosen to describe the performance of the TDR during the measurement of soil moisture. This model simulates the contributions of horizontal micro layers inside a soil cylinder to the overall measured value and is based on the hypothesis of linearity of the moisture content of these layers and is expressed by following expression

$$\theta(h_2, h_1) = \frac{1}{h_2 - h_1} \int_{h_1}^{h_2} \theta(h)\, dh \qquad (1)$$

where $\theta(h_1,h_2)$ - volumetric soil water content measured by the TDR probe device placed between depth h_1 and h_2 representing upper and bottom positions of this device in the soil profile, $\theta(h)$ - is the vertical distribution of soil water content, dh - is the height of soil micro layers.
We assume that the smallest height of distinct macro layers is 1 cm (simplification). In this case integration of Eq.1 by height of micro layers into discrete macro layers gives an expression of overall measured value as the linear sum of soil water contribution of each macro layer as follows:

$$\theta(h_2, h_1) = \frac{1}{h_2 - h_1} \sum_{h_1}^{h_2} \theta_i \qquad (2)$$

where dh_i - height of discrete macro layer, N - number of discrete macro layers in the soil cylinder.
The determination of the vertical distribution of soil water content θ(h) is the key component to be achieved by reconstruction of the soil water content from overlapping measurements. This can be represented by the following matrix equation

$$\{\theta(h)\}[P] = \{\theta(h_1, h_2)\} \quad (3)$$

where {θ(h)} is a one-dimensional matrix of soil water content of 1 cm height macro layers, [P] is two-dimension vector of position of the soil probe device in the soil profile, $\theta(h_1,h_2)$ is one-dimension matrix of values measured with the soil probe device in the "sampled" soil cylinder. In order to reconstruct measurement data at different positions of the sensor-probe Trime FM3 for the soil water content profile, input data of soil water content of soil profile is needed as well as parameters describing the position of the sensor-probe in the soil profile.

The model expressed by Equation.2 provides a tool to calculate a curve describing outputs of model $\{\theta(h_1,h_2)\}$ with a set of input parameters related to the position of TDR probe device in the soil monolith [P] and water content of discrete macro layers of monolith {θ(h)} during the scanning procedure. Experimental values of volumetric water content of soil layers were received as a result of disassembly of monolith. This information is based on the soil water profile of the artificial monolith as well as a series of values measured by profile sensor-probe Trime FM3 and reconstructed data of these measurements based on Equation 2; shown in Figure 2. In contrast to the abrupt changes of this artificial soil water content example (related to the chosen spatial discretization step), natural soil profiles show smooth trends in the water content.

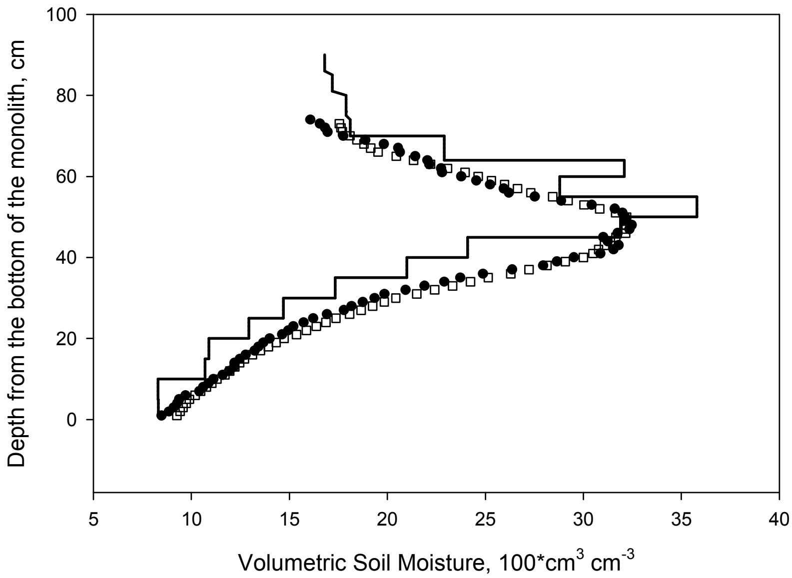

Figure 2. Results of comparison the measured soil moisture averaged from four measurements with different horizontal directions of the TDR-probe, and the results calculated by the additive model.

Results of inverse problem resolving

The aim of the calculation based on Eq.2 is to determine a unknown distribution of {θ(h)} with input data of overlapping measurements $\{\theta(h_1,h_2)\}$ obtained with profile sensor-probe Trime FM3 at different positions [P]. For this purpose a new simple inversion algorithm has been developed to derive soil moisture profiles from a series of measurements. The inversion algorithm starts calculation from one side of soil profile at either top or bottom. First layer height about 15cm is considered to be known. Using this parameter for soil distribution in this layer and following consecutive measurement the soil water content of engaged layers can be calculated without any optimization of parameters. Calculations have been carried out for various combinations of size of active and inactive zones of a probe at a scanning step of 1 cm. As a result of comparison of derived curves with measured data, it has been shown, that the best reproduction (coefficient of pair correlation 0,994) corresponds to sizes of an active zone in a range of 15-16 cm. Results of deriving the soil moisture profile of artificial soil monolith from overlapping measurements by sensor-probe Trime FM3 with a step of 1 cm for an active zone equal to 15 cm are shown in Figure 3. One can see that for the artificial soil monolith there is a good approximation of the given soil moisture profile.

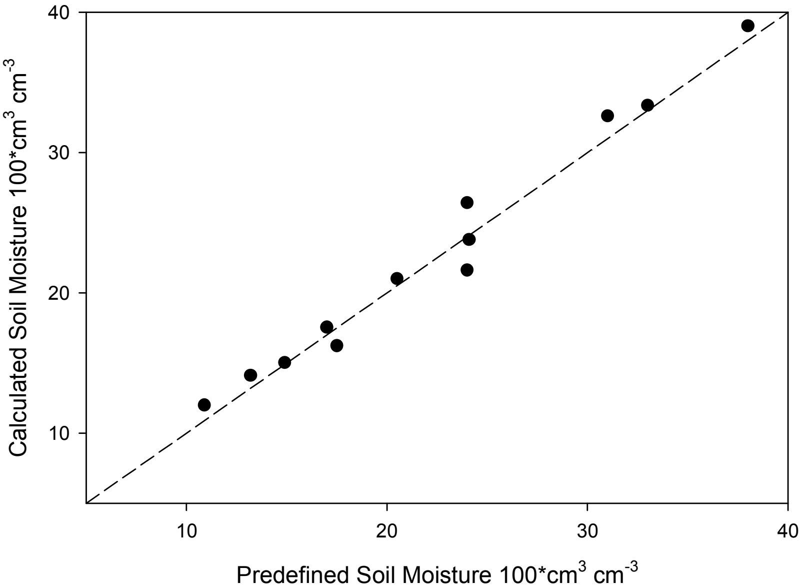

Figure 3. Comparison between the created soil moisture distribution of the artificial soil monolith and soil moisture derived from overlapping measurements with sensor-probe Trime FM3.

Conclusion

A new simple inversion technique is presented that derives a soil moisture profile with higher resolution from overlapping TDR measurements with the Trime-FM3 sensor probe device. The algorithm is based on a resolution matrix equation. The algorithm leads to a reliable soil moisture profile which is derived from overlapping standard transformations provided by the TDR device. The presented inversion technique is also suitable for the simultaneous reconstruction of data on the soil water profile during infiltration or subsequent water redistribution. Using laboratory tests - artificial soil monolith with specially formed soil moisture profile - it is shown that TDR overlapping data is suitable for reconstruction of soil moisture profiles.

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