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Electromagnetic Simulation of Time Domain Reflectometry Probes: Simplified Approaches to Assess Calibration Curves, Sensitivity, Field Extent and Transient Response

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Abstract

Probe calibration, sensitivity, and measuring volume are of major concern for nearly all time domain reflectometry (TDR) applications in soil science. However, the experimental determinations of these features are often laborious and the stochastic nature of the system "probe/soil" such as the poorly defined contact between probe and soil or the sensitivity distribution of the probe leaves some uncertainty in the interpretation of the experimental outcome. In this situation electromagnetic (EM) modeling is a supporting tool to characterize the theoretical probe performance leading to a better assessment of experimental findings.

Powerful modeling systems based on the full wave solution of Maxwell's equations in time or frequency domain could account for nearly all effects on the TDR measuring process such as dissipation due to soil bulk conductivity or signal dispersion in clay. However practitioners often do not have access to such sophisticated tools. Therefore, the focus of the current investigation is on less sophisticated but economical modeling tools, their applicability and limitations for simulating TDR probe performance.

We describe an electrostatic modeling system to determine a probe's electric field distribution in two dimensions and its capacitance for various water contents. TDR pulse propagation velocity, wave impedance, and field extent are derived from the model results. A simple parametric form of the probe capacitance as function of the material's dielectric permittivity is derived from an equivalent circuit model for a coated TDR probe. This relates the TDR pulse transit time to the material permittivity, which can be transformed further into soil water content by empirical calibration curves or dielectric mixing rules.

A lossy transmission-line model found in electronic circuit modeling systems can be used to study the effects of partial TDR signal reflections due to impedance mismatch. By using a general purpose circuit simulator TDR signals are simulated and analyzed.

Key Words electromagnetic modeling, TDR calibration, transient analysis

Introduction

The measurement of water content with time domain reflectometry requires knowledge in at least three areas:

- materials (relation between soil water content and dielectric properties),
- sensors (relation between dielectric properties and electrical equivalent circuits),
- signals (transient response to incident pulses and data analysis).

In this study simple and readily available software tools are investigated to predict the behavior of TDR sensors and calculate their transient response. Electromagnetic modeling software is used to determine sensor field extent, sensitivity and circuit parameters of an electrical equivalent circuit. Based on this result the response to an incident TDR pulse can be calculated by a general purpose circuit simulator.

Three different applications of the software tools are presented:

1) calculation of the electromagnetic field of a TDR probe with coated rods and its sensitive area with the electrostatic field solver MAXWELL2D,
2) determination of a theoretical calibration curve by means of MAXWELL2D and a model describing the total probe capacitance as a function of the material's dielectric permittivity. The result is compared to the experimental calibration curve of the particular TDR probe,
3) transient analysis of TDR wave propagation with the electronic circuit simulator MICROSIM PSPICE.

Electromagnetic field of a TDR probe and its extent

In principle an unshielded electric field has an infinite extent. Therefore, the measuring volume or "support" of a TDR probe is a priori not defined. Thus an appropriate measure has to be defined which is characteristic for the field extent. Such a measure is only acceptable if it enables us to compare the electric fields of different probe designs. Furthermore the measure should also give information about the different regions of sensitivity. A disturbance such as a changing soil moisture or a macropore can have different influences on the TDR signal depending on how sensitive the probe is at the location of disturbance. The total energy is not a suitable measure for sensitivity, since the probe does not become more sensitive when more energy is put into the system. The spatial sensitivity of a TDR probe is determined by the relative energy distribution of the electric field. The higher the relative energy density at a particular location, the higher is the interaction with the surrounding dielectric substance and thus the higher is the sensitivity.

Knight (1992)[1] analytically derived a spatial weighting function which describes the sensitivity of an uncoated TDR probe in the plane perpendicular to the main probe axis. Knight et al. (1997)[2] used a numerical model to study the influence of air and water filled gaps around the probe rods using the same function. This approach was also applied to determine the influence of rod coating on the TDR measurement. Ferré et al. (1998)[3] defined the TDR probe sample area on the same basis.

The spatial weighting function w describes how the distribution of relative dielectric permittivity $\varepsilon(\vec{x})$ in a plane A transverse to the TDR probe axis contributes to the effective or apparent dielectric permittivity ε_a value measured with TDR. The weighting function is defined to fulfill the following relationship:

$$\varepsilon_a = \int w(\vec{x})\varepsilon(\vec{x})dA\,. \tag{1}$$

The focus of the following investigation is on the spatial sensitivity of TDR probes with coating. The dielectric permittivity distribution of the material under test is assumed to be uniform. Only the permittivity of the rod coating may be different. The areawise constant permittivities of material and coating are denoted by ε_M and ε_C, respectively. The spatial weight function reads:

$$w(\vec{x}) = \vec{E}^2(\vec{x}) \Big/ \int \vec{E}_0^2(\vec{x})dA\,. \tag{2}$$

The vector $\vec{E}(\vec{x})$ is the electric field at location $\vec{x}$ on plane A for the coated TDR probe embedded in the material. The electric field $\vec{E}_0(\vec{x})$ would emerge in the same material if the TDR rods were uncoated. The integral in the denominator is constant for a given probe geometry and a fixed voltage difference between the rods. Following Ferré et al. (1998)[3] the isolines of the weighting function are an appropriate measure for the sensitive area of a TDR probe. For the current investigation the isoline encompassing 95% of the total weight is chosen as a measure of the field extent. It is convenient to normalize the weighting function first:

$$w_n(\vec{x}) = w(\vec{x}) \Big/ \int w(\vec{x})dA\,. \tag{3}$$

The task is to find a line $w_n^{(0.95)} \equiv const$ for which the following holds:

$$\int_R w_n(\vec{x})d\vec{x} = 0.95\,, \text{ with } R = \{\vec{x} : w_n(\vec{x}) \geq w_n^{(0.95)}\}\,. \tag{4}$$

We used the educational version (SV9) of the electrostatic field simulation software MAXWELL2D[4] to caculate the electric fields $\vec{E}(\vec{x})$ and $\vec{E}_0(\vec{x})$ in a transverse plane of the probe with and without rod coating, respectively. With these fields we can determine the weight function of equation (2). All calculations needed in equations (2) and (3) were conducted with the internal calculator of MAXWELL2D. The search algorithm for the 95%-percentile in equation (4) has been implemented in the computational software MATLAB[5].

The procedure is explained by the example of an unbalanced 2-rod-probe IMKO TRIME-IT[6] (Fig. 1). The rods have a steel core of 2.5 mm diameter, are 110 mm long and 20 mm apart. The PVC coating of 0.5 mm wall thickness has a relative dielectric permittivity of $\varepsilon_C = 3$. The shaft of the metal cone ends and the metallic rod cores are electrically isolated with a 1 mm thick polyethylene plate inside the PVC tube.

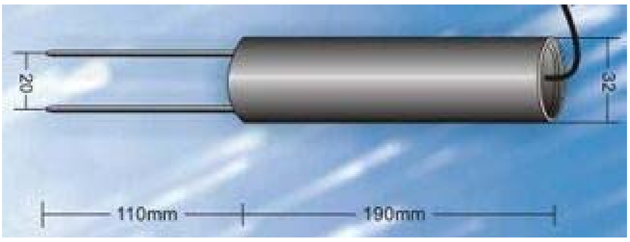

Fig. 1. Dimensions of the TRIME-IT TDR probe.

The two-dimensional plane perpendicular to the rods was mapped using Maxwell2D with a chosen calculation domain of 160 x 120 mm. The boundary was set to 'balloon', i.e. the outside of the domain is infinitely large. In the example the balloon type was chosen to be 'charge' which models the case where the charge at infinity matches the charge in the solution region. The source of the electrostatic field was a potential difference of 1V between the rods. In the solution option 'adaptive analysis' was marked so that the mesh generator of this finite element software was refining the mesh automatically until either the change in total energy fell below the selected threshold or the predefined number of refinement steps was reached. The resulting mesh is given in Fig 2.

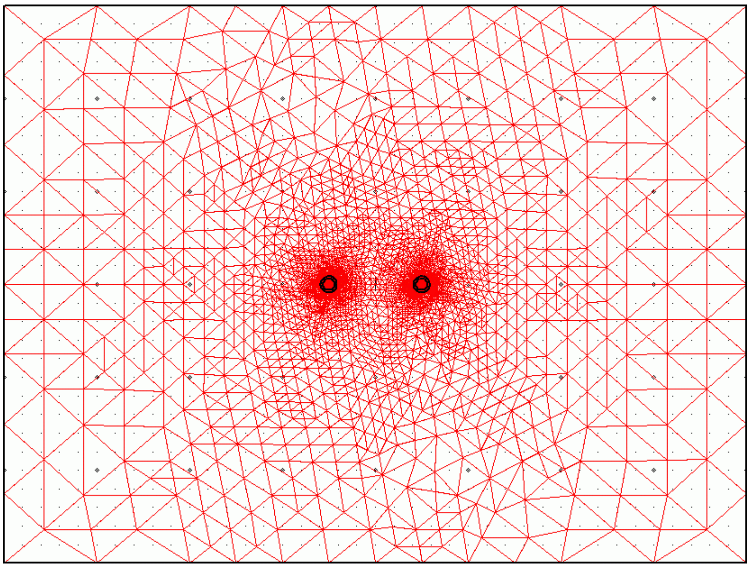

Fig. 2. Calculation domain (160 x 120 mm) and triangular mesh (approx. 6500 triangles) for TRIME-IT in MAXWELL2D. Rod centers and major grid points 20 mm apart.

The field calculation was done for background materials with different relative dielectric permittivities. Fig. 3 shows for example the calculated energy distribution for a material permittivity of $\varepsilon_M = 10$.

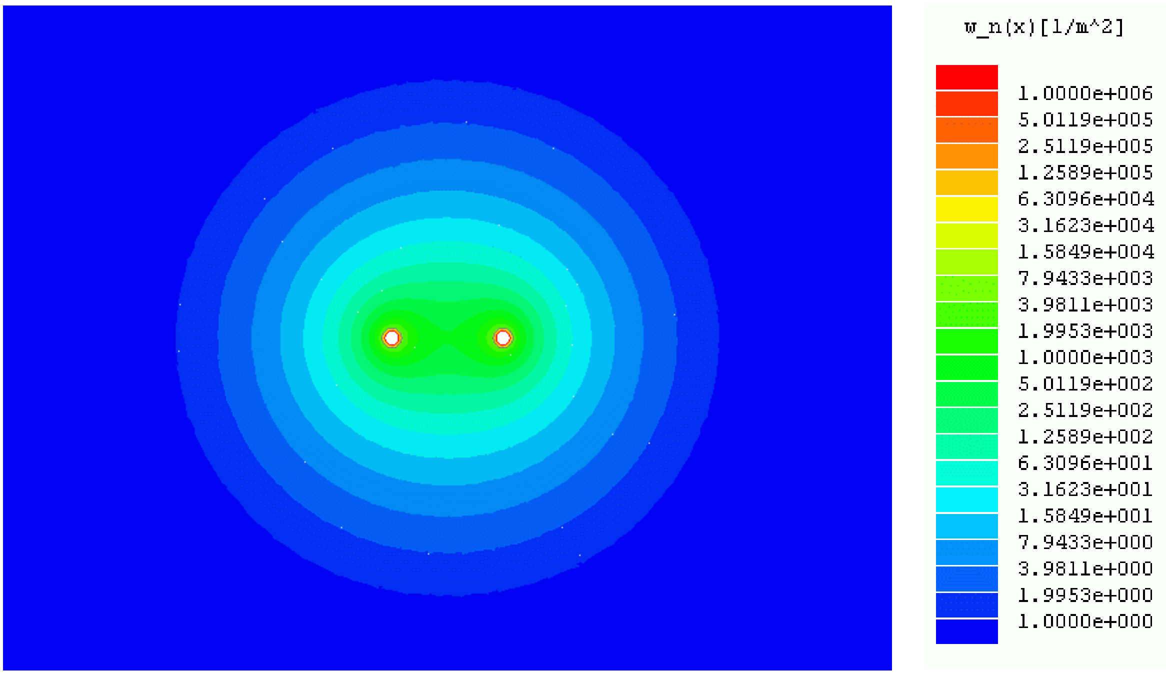

Fig. 3. Logarithmic plot of the normalized weighting function $w_n(\vec{x})$ for the TRIME-IT probe in a material of relative dielectric permittivity $\varepsilon_M = 10$ (θ=19.8 %vol). Voltage between rods:1V, total energy: 39 pJ. Screenshot of MAXWELL2D output.

The scalar field $w_n(\vec{x})$ can be exported on a regular grid to an ASCII file by means of the MAXWELL2D post-processor. The exported file consists of three columns: x, y, and value. In order to be processible by MATLAB, a Perl script was written to reformat the data, i.e. values are mapped to a 2D matrix and the no data indicator string '-NoSoln-' of MAXWELL2D has to be substituted by 'NaN' for MATLAB. No data values occur e.g. on grid cells within the metallic rod cores since the electrostatic field vanishes inside the metallic bodies.

MATLAB was used to find $w_n^{(0.95)}$. The w_n matrix is already normalized so that all the matrix entries sum up to one. First an appropriate level of w_n is chosen and all matrix entries are integrated (summed up) which have a weight higher than this level. A simple optimization scheme was used to find the level which leads to an integral of 0.95.

The whole procedure was repeated for several permittivities. In case of simple mineral soils as background material, the permittivities can be translated into volumetric water content by use of the Topp-function[7]. Fig. 4 shows the water content dependent field extent.

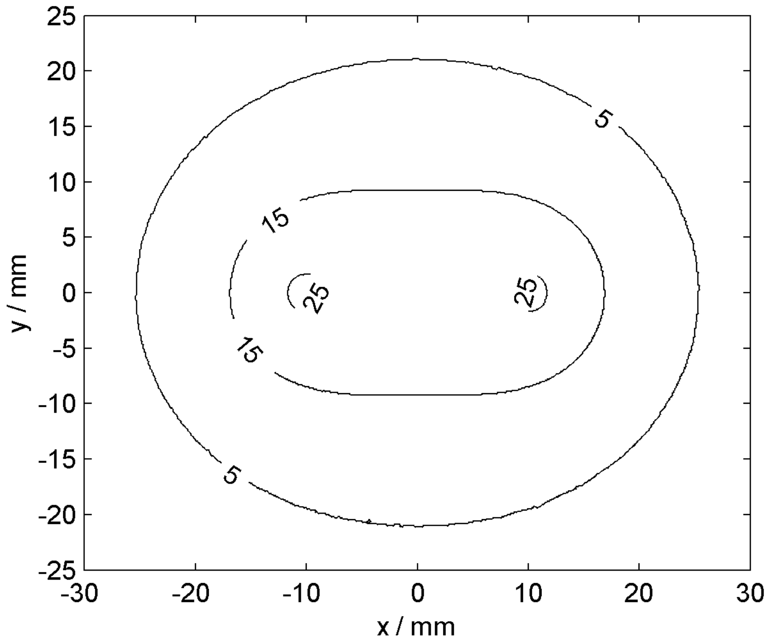

Fig. 4: Isolines encompassing 95% of the weighting function for three different dielectric permittivities 5, 15 and 25. According to the simulation a material of $\varepsilon_M = 25$ confines the field extent to the surface of the coated rods. Figure generated with MATLAB.

The field extent becomes smaller for higher water contents while the total amount of stored energy increases. This effect can only be obeserved with coated rods. The sensitivity expressed by the normalized weighting function does not depend on the material's permittivity, if the rods are uncoated. The strength of the simulated field confinement in materials with high dielectric permittivities is remarkable and should be checked experimentally.

We were able to reproduce the results of Ferré et al. (1998)[3] with the presented framework of readily available software.

Sensitivity of a TDR Probe to Moisture

The sensitivity of a TDR probe is its change in total pulse travel time as function of changing material properties, i.e. permittivity or moisture (Ferré et al., 2000[8]). The relative dielectric permittivity ε is a measure for the actual polarization of a material's molecules in an electric field of particular strength. For unshielded waveguides embedded in a material of permittivity ε the propagation velocity of an electromagnetic wave reads:

$$v(\varepsilon) = c_0 / \sqrt{\varepsilon}\ , \qquad (5)$$

with c_0 as the speed of light in vacuum. This equation is not true if the waveguide is coated like the TRIME-IT rods. Therefore another approach is necessary to describe the pulse propagation velocity. A simplifying one-dimensional smodel often used to explain the wave propagation along waveguides is the transmission-line model, in which the waveguide is described by an equivalent electric circuit. Fig. 5 shows an infinitesimally small segment of the transmission-line. It is used to express the spatial variation of voltage V and current I for a short instant. The model comprises four parameters, namely series resistance *R*' (Ω/m), series inductance *L*' (H/m), shunt capacitance *C*' (F/m), and shunt conductance *G*' (S/m). Primes indicate that the parameters are given per unit length. *R*' and *L*' are constants of the probes, *C*' and *G*' are generally dependent on moisture and may vary along the transmission-line.

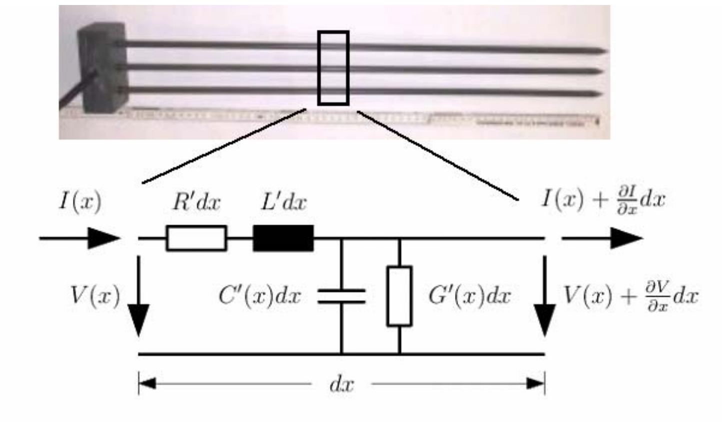

Fig. 5. Simplifying model of a transmission-line as a chain of infinitely small bulk electric parts. Explanation of symbols in the text.

The soil moisture reconstruction algorithm developed by Schlaeger (2006)[9] and applied to coated 3-rod-probes by Becker (2004)[10] uses the same model to calculate the TDR wave propagation along a TDR probe with varying water content in longitudial direction.

For the current investigation the moisture along the probe is assumed to be constant. The application of Kirchoff's laws to the equivalent circuit and setting *R*'=0 leads to the following wave equation:

$$\left(L'C'(\varepsilon)\frac{\partial^2}{\partial t^2} + L'G'\frac{\partial}{\partial t} - \frac{\partial^2}{\partial x^2} \right) V(x,t) = 0\,. \tag{6}$$

This so-called telegraph equation is a wave equation (second derivative in time proportional to second derivative in space) with a loss term. The propagation velocity can be derived from this equation:

$$v(\varepsilon) = 1/\sqrt{L'C'(\varepsilon)} \tag{7}$$

This equation describes, both for bare and coated probes, how the permittivity of the material under test determines the TDR pulse travel time. Capacitance $C'(\varepsilon)$ is dependent on the dielectric permittivity of the material whereas L' is a constant for the probe, if the material is not interacting magnetically (magnetic susceptibility μ=1). The capacitance function represents the performance of the probe. It finally expresses how the pulse travel time changes with changing material permittivity and thus material moisture. The form of the capacitance function is determined by the probe geometry and the coating. For many probes a simple parametric form describes the permittivity dependent capacitance nearly perfectly (Huebner et al., 2005[11]):

$$C'(\varepsilon) = \frac{\varepsilon C_1' C_2'}{\varepsilon C_1' + C_2'} + C_3'\,. \tag{8}$$

The first term on the right hand side represents two capacitors in series, namely the soil filled capacitor $\varepsilon C_1'$ and the coating C_2'. The third capacitor C_3' is in parallel to the first both and describes the effect of a continuous dielectric junction between the TDR probe conductors. In case of a 2-rod-probe without a plastic boby between the coated rods, the parameter C'_3 is zero.

The three parameters C'_1, C'_2, and C'_3 can be determined experimentally by TDR measurements in materials with different but known permittivities. For very precise moisture measurements, the particular probe should be calibrated experimentally. The capacitance model can also be determined theoretically by means of electrostatic field simulations with a precision sufficient to investigate the probe performance. MAXWELL2D can be used to determine the probe capacitance under different material moisture conditions. First the inductance is needed. It is determined in Maxwell2D by setting all non-metallic materials to vacuum. The resulting capacitance is denoted by C'_{00}. The following relationship holds:

$$c_0 = 1/\sqrt{L'C'_{00}} \ . \qquad (9)$$

This equation is to be solved for L'. It yields an inductance of L' = 1109 nH/m for TRIME-IT. From L' and C' other related characteristic parameters can be determined such as wave impedance

$$Z = \sqrt{\frac{L'}{C'}} , \qquad (10)$$

specific travel time

$$ts = \frac{1}{v} \text{ in } ps/cm , \qquad (11)$$

or reflection factor

$$\rho = \frac{Z - Z_0}{Z + Z_0} , \qquad (12)$$

with Z_0 = 95 Ω as intrinsic impedance of the measurement electronic. Table 1 summarizes the most important parameters of a probe for various water contents.

Table 1. TRIME-IT dynamics. ε: relative dielectric permittivity of the material, θ: volumetric water content (Topp), W: total energy, C': capacitance, Z: impedance, v/c_0: velocity relative to vacuum, t_s: specific travel time (one way) t: total TDR pulse travel time (probe length $l = 11$ cm); Δt: change in travel time with respect to air, ρ: reflection coefficient.

ε -	θ %vol	W pJ	C' pF/m	Z Ω	v/c_0 %	t_s ps/cm	T ps	Δt ps	ρ %
1	-	5.5	10.9	318.5	95.8%	34.8	766	0	54.0%
4	5.6%	19.3	38.6	169.5	51.0%	65.4	1439	673	28.2%
5	9.0%	23.2	46.4	154.6	46.5%	71.7	1578	812	23.9%
10	19.8%	39.1	78.1	119.1	35.8%	93.1	2048	1282	11.3%
15	27.5%	50.6	101.2	104.7	31.5%	106.0	2331	1565	4.8%
20	33.9%	59.4	118.8	96.6	29.1%	114.8	2525	1759	0.8%
25	39.8%	66.3	132.6	91.5	27.5%	121.3	2668	1902	-1.9%
30	45.2%	71.9	143.7	87.8	26.4%	126.3	2778	2012	-3.9%
35	50.4%	76.5	152.9	85.2	25.6%	130.2	2865	2099	-5.5%
40	55.4%	80.3	160.6	83.1	25.0%	133.5	2936	2170	-6.7%
50	65.3%	86.4	172.8	80.1	24.1%	138.4	3046	2279	-8.5%
60	75.2%	91.0	182.0	78.1	23.5%	142.1	3126	2359	-9.8%
70	85.8%	94.6	189.2	76.6	23.0%	144.9	3187	2421	-10.7%
81	99.1%	97.8	195.5	75.3	22.7%	147.2	3239	2473	-11.6%

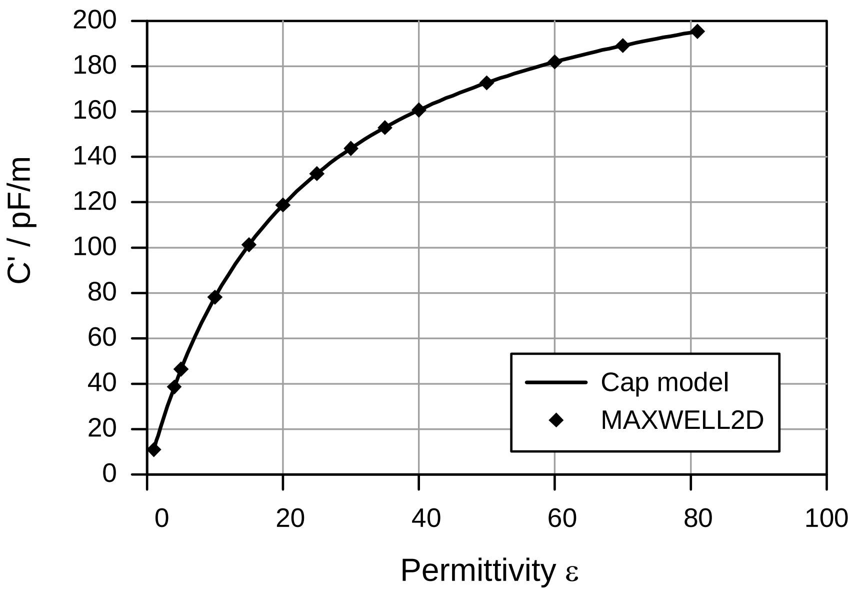

Fig. 6. Probe capacitances simulated with MAXWELL2D and fitted parametric capacitance model ("Cap model") with two parameters (Eq. 8 with C'_3=0).

Based on the results in Table 1, the parameters C'_1, C'_2, and C'_3 can be determined (Tab. 2).

Table 2. Parameters of the capacitance model.

C'_1	pF/m	11.41
C'_2	pF/m	247.92
C'_3	pF/m	0.00

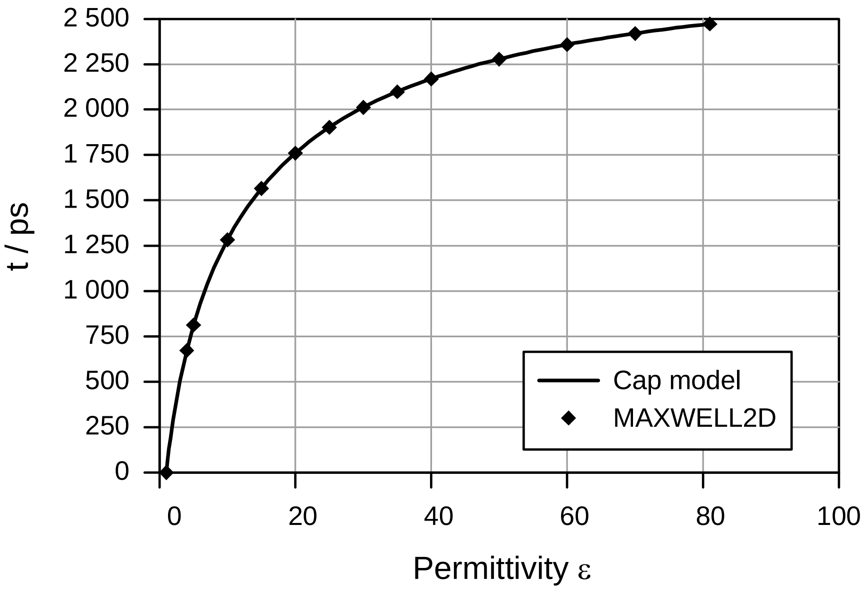

Fig. 7: Two way pulse travel time of TRIME-IT in material of different permittivities. Simulation results of MAXWELL2D and fitted capacitance model ("Cap model", Eq. 8 with C'_3=0).

Stacheder (1996)[12], investigated a P2-probe connected to an external TRIME TDR device with a RF cable of variable length but with the same geometry as the TRIME-IT probe in 10 different soils and soil-like materials with a total of 192 samples. The measured travel time is given in the normalized travel time tp (so-called pseudo travel time). The relationship between the travel time t and normalized travel time tp is given by:

$$tp = (t - A) / D \qquad (13)$$

A and *D* are probe specific parameters. The normalization is such that measurements in dry and wet glass beads yield *tp* = 145 and *tp* = 625, respectively. Dry and wet glass beads are used as substitutes for soils with water contents of approximately 3 % and 44 % by volume. For TRIME-IT/P2 the slope is *D* = 3.090. The offset A depends on the varying connecting cable lengths. To be comparable to the simulation results with Maxwell2D, tp was transformed back to t. The offset A between measurement and simulation was adapted.

TRIME-IT displays the volumetric water content directly. The TRIME method does not sample the voltage of the TDR waveform for a given instant of time like other TDR instruments do. It measures the time it takes for the TDR waveform to exceed a predefined voltage level which is adjustable in a certain range. The reflected wave is scanned in this voltage range and evaluated to derive the reflection time. Advantages of this method are a very precise time measurement with a resolution better than 10 picosenconds and the realisation of the measuring procedure in a single chip, which makes the device robust and cost effective compared to other instruments.

The results of the simulation are summarized in Table 1. The water content is based on the Topp-equation. Fig. 8 displays the match between measurement and simulation with only the time offset as free parameter.

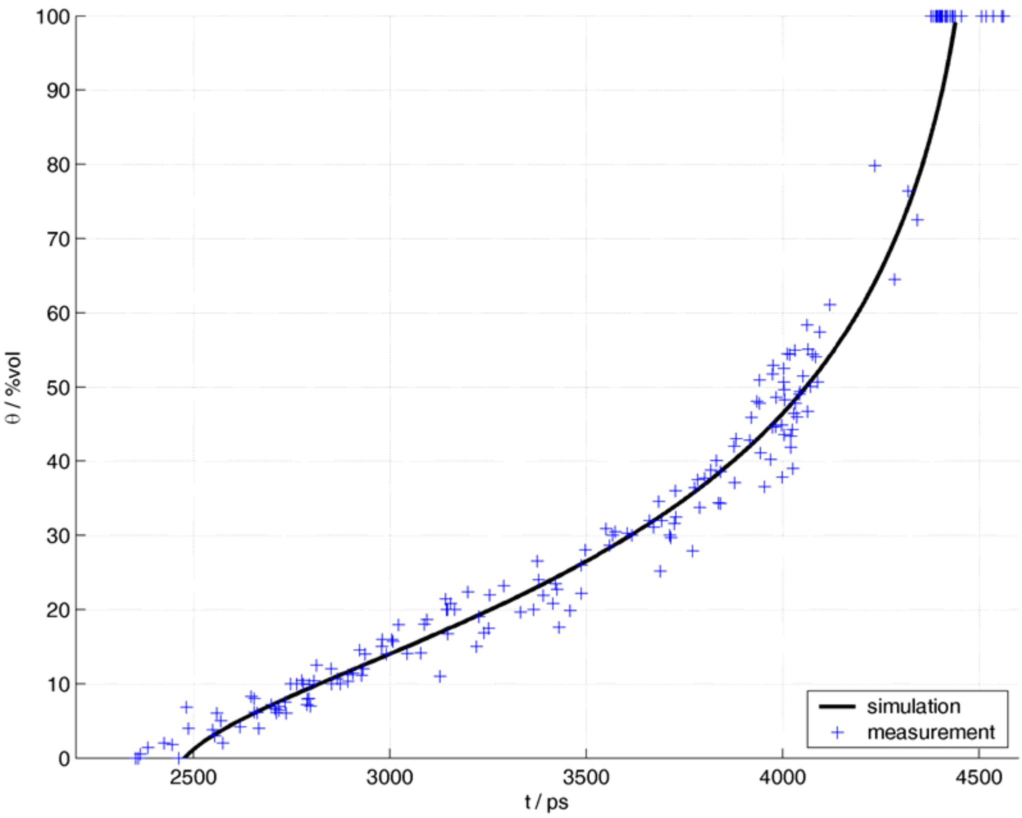

Fig. 8. Comparison between measurements with P2 (TRIME-IT) of Stacheder (1996)[8] and MAXWELL2D simulations. An appropriate time offset was chosen to compensate for the additional travel time of the P2 connecting cable.

Transient analysis

The transient response of a transmission line can be calculated in the time domain or by Laplace/Fourier transformation from the frequency domain to the time domain (Huebner et al. 2005[4]). The advantage of a frequency to time domain transformation is the simple incorporation of dispersive line parameters. Time domain methods are usually restricted to non-dispersive *L'*, *C'*, *R'* and *G'*. To understand the principle properties of the transient response of a transmission line, it is sufficient to investigate the non-dispersive case. Easy to use software packages are available to perform this task. They are based on SPICE (Simulation Program with Integrated Circuits Emphasis), which is a general purpose analog circuit simulator. The authors tried MICROSIM PSPICE Evaluation Version 8.0.

First draw a schematic with a signal source (part VPULSE), a source resistor which usually is 50 Ω, a transmission line (part TLOSSY) and a terminating resistor simulating the open end of the transmission line.

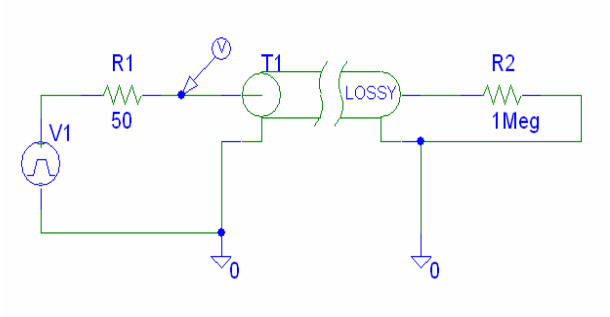

Fig. 9. Schematic of a uniform transmission line connected to a pulse generator and a voltage marker for signal trace recording.

The rise time of the pulse is 200 ps with an amplitude of 1 V as shown in the part parameter window in Fig. 10. The pulse will stay on 1 V for about 1 s.

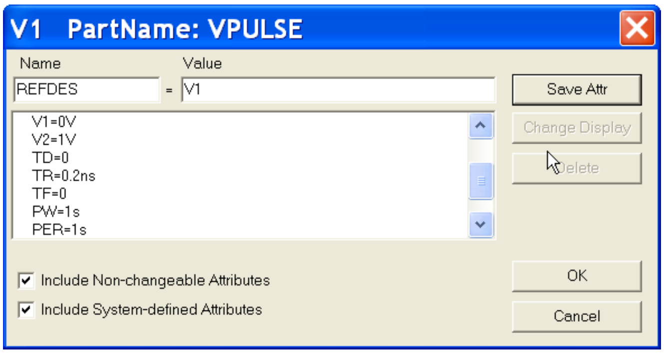

Fig. 10: Definition of the pulse generator parameters.

The length of the lossless transmission line is 1 m. L and C are arbitrarily chosen in this example and correspond to a wave impedance of about 83 Ω ($Z = \sqrt{L/C}$).

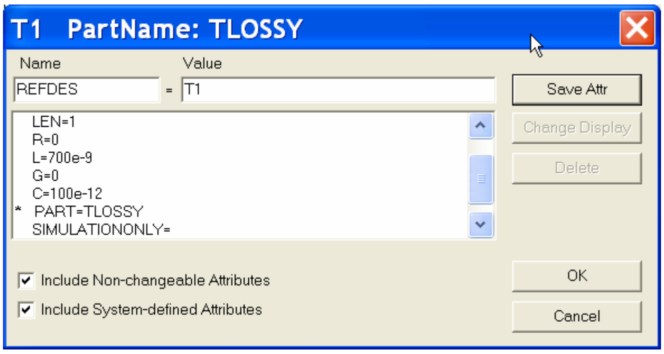

Fig. 11. Definition of the transmission line parameters

The transient simulation defined in analysis setup starts at t = 0 s and ends a t = 100 ns. An adjustment of the step ceiling may be required to achieve a sufficient time resolution (see Fig. 12)

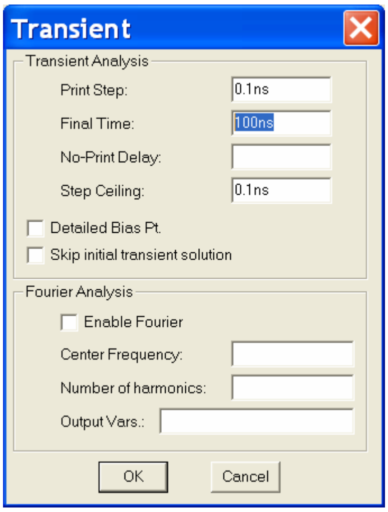

Fig. 12: Definition of the simulation parameters

The results of the simulation can be viewed in the waveform analyzer (MICROSIM Probe) or exported for graphical presentation.

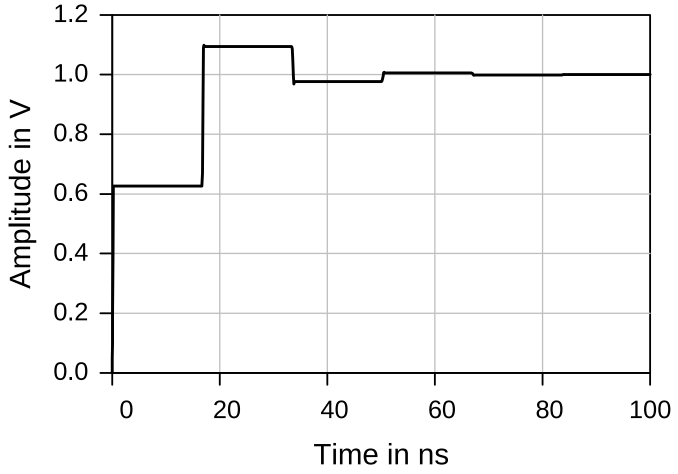

Fig. 13: Result of the simulation of the circuit shown in Fig. 9.
Transmission line length: $l = 1$ m, $C = 100$ pF/m, $L = 700$ nH/m, $R = 0$ Ω/m, $G = 0$ S/m.

Fig. 13 shows the results of the transient simulation. The wave impedance of the transmission line is higher than the impedance of the voltage source. Therefore a part of the incident voltage pulse is positively reflected at the beginning of the transmission line. The total voltage at the beginning of the simulation depends on the differences in source and wave impedance and can be calculated to 0.5V*(1+(83 Ω-50 Ω)/(83 Ω+50 Ω)) = 0.626 V. The reflection at the open end of the transmission line at about 17 ns is clearly visible in this example. After a certain amount of time the amplitude reaches a constant level of 1 V which is the expected DC-level for this configuration.

In case of a lossy transmission line, the horizontal sections of the trace shown in Fig. 13 turn into slopes. Fig. 14 shows the simulation results after changing from $G = 0$ S/m to $G = 0.005$ S/m.

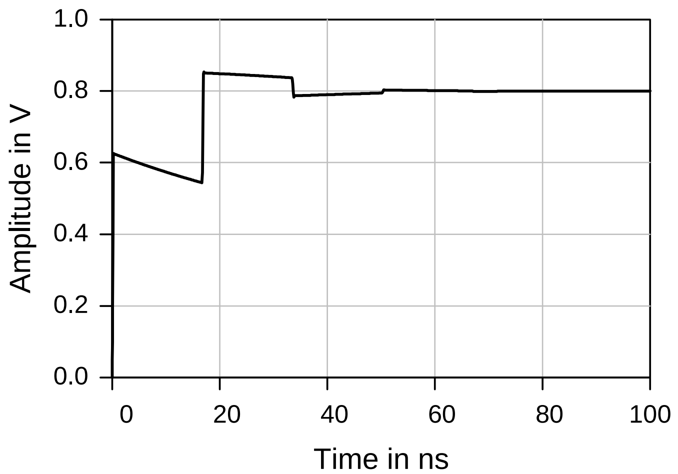

Fig. 14: Simulation results. Transmission line length: l = 1 m, C = 100 pF/m,
L = 700 nH/m, R = 0 Ω/m, G = 0.005 S/m.

With PSPICE it is also possible to simulate inhomogeneous transmission lines by chaining multiple TLOSSY elements as shown in Fig. 15.

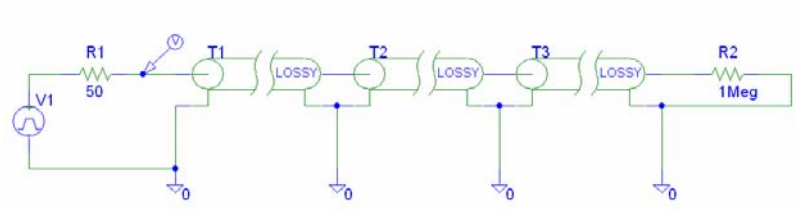

Fig. 15. Simulation of a inhomogeneous transmission line with three sections by using three TLOSSY elements connected in a chain.

The simulation result in Fig. 16 shows reflections at wave impedance changes. Multiple reflections along the transmission line complicate the analysis of the transient response. Nevertheless the dominant reflection at the open of the transmission line is still clearly visible at about 52 ns.

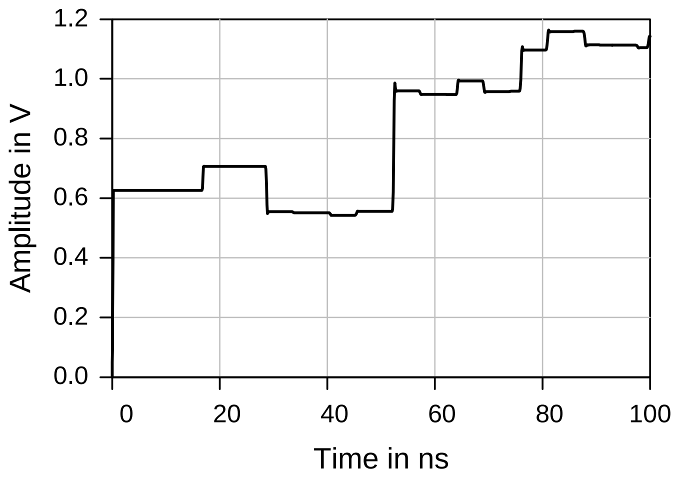

Fig. 16. Simulation results. Transmission line lengths: $l_1 = l_2 = l_3 = 1$ m, $C_1 = 100$ pF/m, $C_2 = 50$ pF/m, $C_3 = 200$ pF/m, $L_1 = L_2 = L_3 = 700$ nH/m, $R_1 = R_2 = R_3 = 0$ W/m, $G_1 = G_2 = G_3 = 0$ S/m.

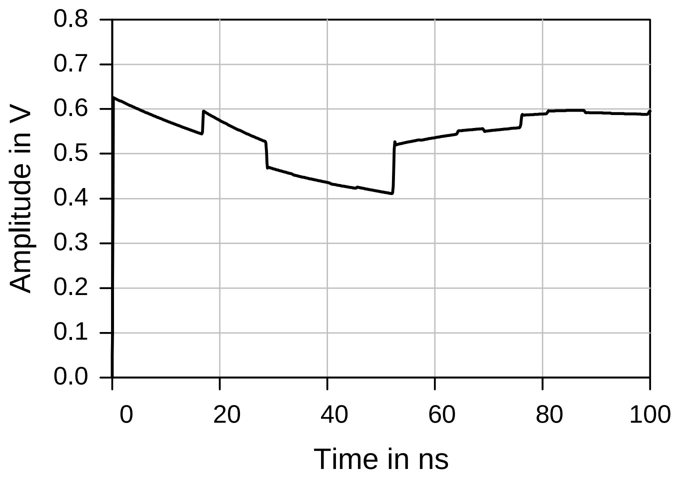

Fig. 17: Simulation results. Transmission line lengths: $l_1 = l_2 = l_3 = 1$ m, $C_1 = 100$ pF/m, $C_2 = 50$ pF/m, $C_3 = 200$ pF/m, $L_1 = L_2 = L_3 = 700$ nH/m, $R_1 = R_2 = R_3 = 0$ W/m, $G_1 = G_2 = G_3 = 0.005$ S/m.

The situation gets worse when losses are included in the simulation as shown in Fig 17. Then the hard reflection at the open end of the transmission line is much smaller. In this case sophisticated data analysis methods are required to distinguish between wave impedance variations along the transmission line and end reflections [10].

Conclusions

Calibration curves, sensitivity and field extent of TDR probes have been determined with an electromagnetic modeling software and compared with measurement results. It has been shown that a simple electrostatic approach is sufficient in this case and agrees very well with measurements. Full wave solutions of Maxwell's equations may be required when the probe length is smaller and spacing is wider.

The field extent of the electromagnetic field and therefore the measurement volume can be determined. Isolines of the spatial weighting function are an accepted measure for the field extent. It still has to be tested experimentally if this definition of field extent does not underestimate the sensitive area of coated rod probes.

The transient response of a transmission line (TDR probe) has been determined with readily available circuit analysis software tools. Even inhomogeneous and lossy arrangements can be calculated and investigated. This will improve understanding of wave propagation including multiple reflections and signal attenuation.

References

[1] Knight, J. H., (1992), Sensitivity of Time Domain Reflectometry Measurements to Lateral Variations in Soil Water Content, *Water Resources Research,* Vol. 28, pp. 2345-2352.

[2] Knight, J. H., Ferré, P. A., Rudolph, D. L. and Kachanoski, R. G., (1997), A Numerical Analysis of the Effects of Coatings and Gaps upon Relative Dielectric Permittivity Measurement with Time Domain Reflectometry, *Water Resources Research,* Vol. 33, pp. 1455-1460.

[3] Ferré, P. A., Knight, J. H., Rudolph, D. L. and Kachanoski, R. G., (1998), The Sample Areas of Conventional and Alternative Time Domain Reflectometry Probes, *Water Resources Research,* Vol. 34, pp. 2971-2979.

[4] www.ansoft.com

[5] www.mathworks.com

[6] www.imko.de

[7] Topp, G. C. , Davis, J. L., and Annan, A. P., (1980), Electromagnetic determination of soil water content: measurement in coaxial transmission lines, *Water Resources Research,* Vol. 16, pp. 574-582.

[8] Ferré, P. A., Knight, J. H., Rudolph, D. L. and Kachanoski, R. G., (2000), A numerically based Analysis of the Sensitivity of Conventional and Alternative Time Domain Reflectometry Probes, *Water Resources Research,* Vol. 36, pp. 2461-2468.

[9] Schlaeger, S., (2005), A fast TDR-inversion Technique for the Reconstruction of Spatial Soil Water Content, Hydrol. Earth Sys. Sci., Vol. 9(5), pp. 481-492

[10] Becker, R., (2004), Spatial Time Domain Reflectometry for Monitoring Transient Soil Moisture Profiles, PhD Thesis. Univ. of Karlsruhe.

[11] Huebner, C., Schlaeger, S., Becker, R., Scheuermann, Brandelik, A., Schaedel, W., and Schuhmann, R., (2005), Advanced Measurement Methods in Time Domain Reflectometry for Soil Moisture Determination, in K. Kupfer (ed) *Electromagnetic Aquametry*, Springer

[12] Stacheder, M., (1996), Die Time Domain Reflectometry in der Geotechnik (TDR for Geotechnical Applications; *in german*). PhD Thesis. Schr. Angew. Geol. Karlsruhe, Vol. 40, pp. 170, Karlsruhe (Germany).

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Rolf Becker studied Physics at the University of Bonn. He worked as research assistant in Hydrology at the University of Karlsruhe and is co-founder of the Soil Moisture Group. He received his doctoral degree in 2004 for his dissertation about infiltration monitoring with profiling time domain reflectometry techniques. Today Rolf Becker is head of development at IMKO Micromodultechnik GmbH.

Christof Huebner received his diploma degree and doctoral degree in high frequency engineering from the University of Karlsruhe in 1992 and 1999, respectively. From 1992 to 2001 he was with the Electrophysical Aquametry Laboratory at the Forschungszentrum Karlsruhe GmbH as a researcher. From 2001 to 2004 he was professor for electrical engineering at the University of Cooperative Education in Heidenheim. From 2004 he has been with the University of Applied Sciences in Mannheim, where he is currently the head of the Institute for Industrial Data Processing and Communication. His research interests include dielectric measurement methods and their application in industry, civil engineering and agriculture with special emphasis on moisture determination in various materials.

Markus Stacheder studied Geology and Mineralogy at the Universities of Stuttgart and Munich. In 1995 he received his doctoral degree at the University of Karlsruhe for his studies on the use of TDR for geotechnical applications. In his professional career he worked several years as a scientist for IMKO Micromodultechnik GmbH and the Forschungszentrum Karlsruhe GmbH with emphasis on electromagnetic moisture measurement methods for soils and other capillary porous materials. He is currently at the Institute of Mineralogy and Geochemistry at the University of Karlsruhe.