
Theoretical Aspects on Measuring Moisture Using TRIME®

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Technology

Principle of Time Domain Reflectometry

Originally the Time Domain Reflectometry (TDR) was and still is used as „cableradar“ to detect faults in electronic systems, e. g. transmission lines and cables. A voltage pulse is generated in the cable tester and propagates along the coaxial cable as an electromagnetic wave. In coaxial lines this electromagnetic field is inside the cable, the field is both between and around the lines if the transmission lines are parallel. The pulse's shape (Figure 1) and the transit time depend on the cable properties, length, and the termination of the cable, where the pulse is reflected.

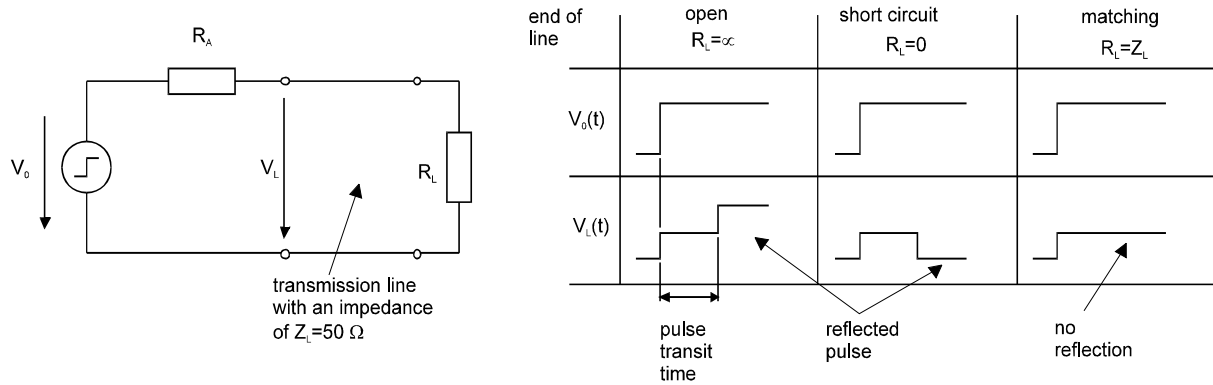


Figure 1 A: Equivalent circuit diagram B: Pulse shapes for various transmission line geometries.

The Time Domain Reflectometry (TDR) has established as a reliable and an easy to handle method to measure volumetric soil water content. In comparison to former approaches, e. g. the oven-drying-method, the TDR-technique allows rapid and non-destructive measuring.

The TDR-technique is based on the velocity or transit time measurement of an electromagnetic wave in a material sample.

$$c = \frac{c_0}{\sqrt{\epsilon_r \cdot \mu_r}} \quad [1]$$

In vacuum an electromagnetic wave has the velocity of light c_0 . The magnetic permeability μ_r can be set $\mu_r = 1$ in non-magnetic materials. Then the transit time c is only dependent on the dielectric constant ϵ_r . In order to determine the dielectric constant the velocity of the electromagnetic wave must be measured.

The pulse propagates along the two or three parallel wave-guides of the TDR-probe, is reflected at the end of the rods, and runs back to its source. The known transit distance $2l$ allows to transform the velocity measurement to a transit time measurement.

$$c = \frac{2l}{t} \quad [2]$$

The difference between the large dielectric constant of water $\epsilon_r = 81$ and the small one of dry soil and other porous materials ($\epsilon_r \approx 5$) is responsible for the fact, that the dielectric constant of moist soil is mainly a function of the water content, which then can be determined.

In 1980 the Canadian scientists G. C. Topp, J. L. Davis and A. P. Annan published the results of their investigations in soil water content measurement with the TDR-technique. They found a calibration function (3rd order polynomial equation), which describes the correlation between the dielectric constant ϵ_r and the volumetric water content θ_v of mineral soils (Figure 2).

$$\epsilon_r = 3,03 + 9,3\theta_v + 146\theta_v^2 - 76,7\theta_v^3 \quad [3]$$

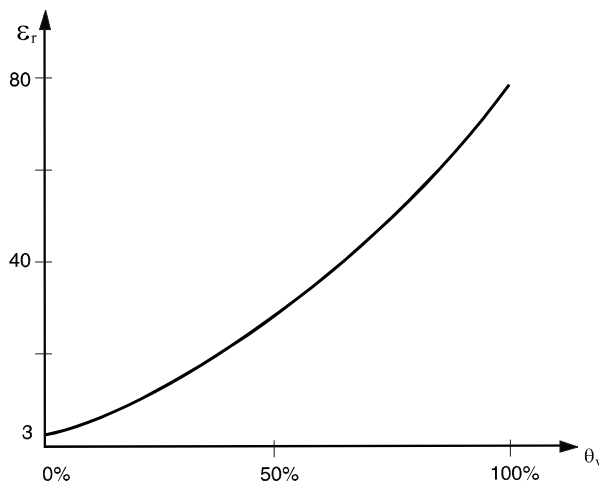


Figure 2 Relationship between soil moisture and dielectric constant

Conventional Technical Realisations

The main problem of the TDR-technique is to measure the extreme short transit time of the electromagnetic wave and to generate the very steep pulse edge (rise time $\ll 1$ ns). The transit time in air t_a and in water t_w with a 15 cm long TDR-probe ($l = 15$ cm) can be calculated as follows:

$$t = \frac{2l}{c_0} \cdot \sqrt{\epsilon_r}$$

$$t_l = \frac{0,3m}{3 \cdot 10^8 \text{ ms}^{-1}} \cdot \sqrt{1} = 1ns \quad [4]$$

$$t_w = \frac{0,3m}{3 \cdot 10^8 \text{ ms}^{-1}} \cdot \sqrt{81} = 9ns$$

The transit time difference between a water content of 0 and 100 % by volume is only 8 ns. A high-frequency pulse generator and a high-frequency sampling oscilloscope are necessary in order to measure this small time interval. In addition the impedances of generator and oscilloscope of $R_a = 50\Omega$ must be matched to the impedance of the probe with an impedance converter (balun).

Besides the complex and sensitive electronics, the high power consumption and the high price of the devices, the transit time is evaluated on the oscilloscope screen and the volumetric water content is derived.

Another approach is to use a cable tester, which is normally used to detect cable defects. This device needs an impedance converter, too. Cable testers are expensive, because of their electronic features to find breaks, short-circuits, and crushings of cables. They are hardly designed for the rough environment of field measurements (rainfall, great changes of temperature etc.). The evaluation of the TDR-pulse and the calculation of the water content must also be done manually.

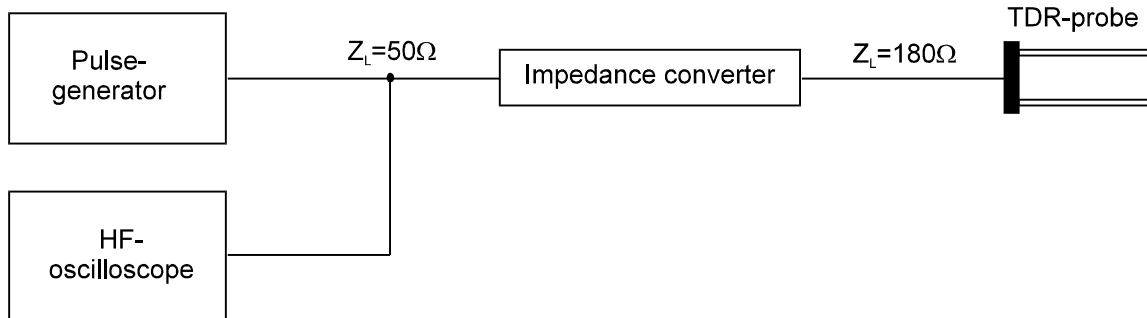


Figure 3 TDR-system with pulse generator and oscilloscope

So all former technical realisations use the same method of measuring the TDR-pulse (Figure 4):

They scan the reflected TDR-pulse with a "sampling method". Each point of the pulse signal is measured as a voltage value at a distinct time. Based on this voltage signal, the transit time is derived graphically. The main disadvantages are:

1. These measuring techniques require very expensive components of high-frequency electronics (track-and-hold-units, A/D-converters, PLL-circuits, etc.).
2. The evaluation of the "bath-tub curve" is problematic, particularly at low water contents and with short TDR-probe rods.

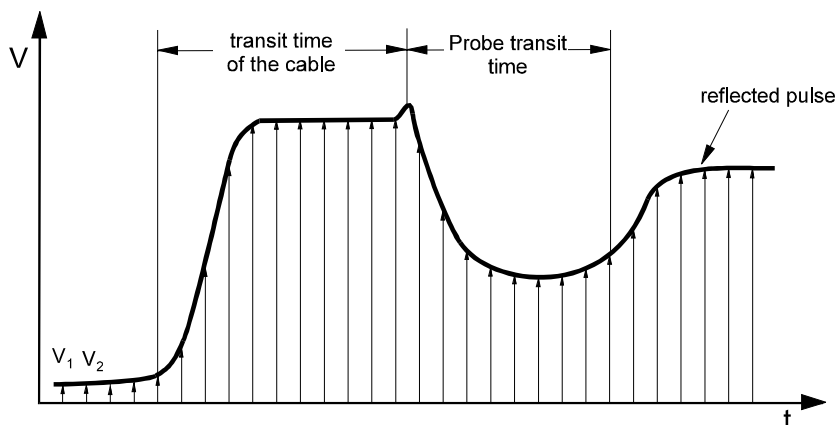


Figure 4 conventional TDR-pulse evaluation using the voltage sampling technique. The characteristic curve shape during the probe transit time led to the name „bath-tub curve“.

Moisture Measuring with the Patented TRIME TDR Method

The TRIME-method (Time Domain Reflectometry with Intelligent Micromodule Elements) is a specially designed TDR-technique to measure material moisture. The measuring of the TDR-pulse is carried out by time measurements instead of voltage measurements.

The TDR-curve is determined by **time measurements** at distinct voltage levels. No expensive electronic components, such as track-and-hold units and A/D converters are necessary. Thus we are able to produce a handy device with small dimensions and low power consumption.

Time sampling requires a change of the common TDR-pulse shape of the conventional methods (Figure 5). The level of the reflected pulse must be raised. An increase of the amplitude, i.e. a reduction of the attenuation.

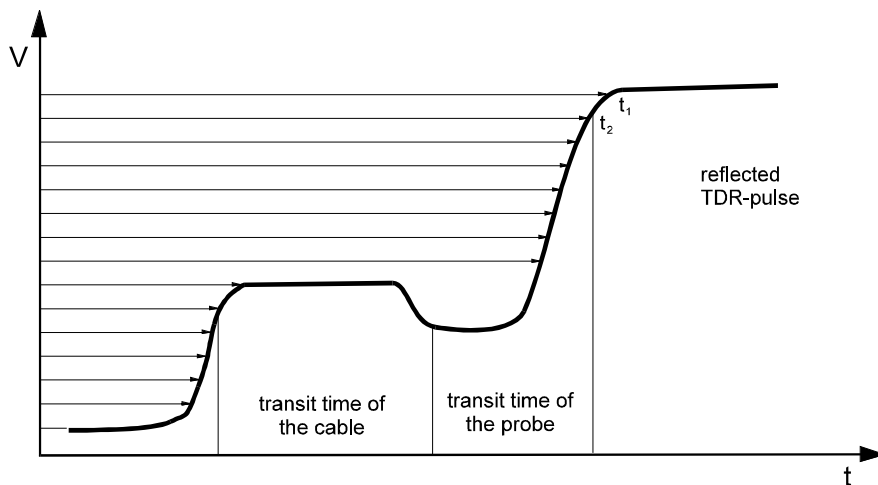


Figure 5 TRIME TDR pulse evaluation using the time sampling technique.

This was achieved by a suitable impedance matching between pulse generation output, HF-cable, and the probe. A coating of the metallic probe-rods with plastic (PVC) was the most important measure to get the TDR step-pulse signal. The coating decreases the attenuation similarly to a high-pass filter.

Low frequencies, such as the repetition frequency of the TDR-pulse (<9 MHz) are blocked. Only the higher frequencies (>300 MHz) of the electromagnetic wave propagate through the soil or material and are attenuated. Thus the total attenuation is essentially reduced and the amplitude of the reflected TDR-pulse is raised.

To evaluate the transit time it is not necessary to scan the whole TDR-signal. A special algorithm in the TRIME-device scans particular points of the curve in order to determine the amplitude of the reflected pulse. The advantages are shorter measuring times and lower power consumption.

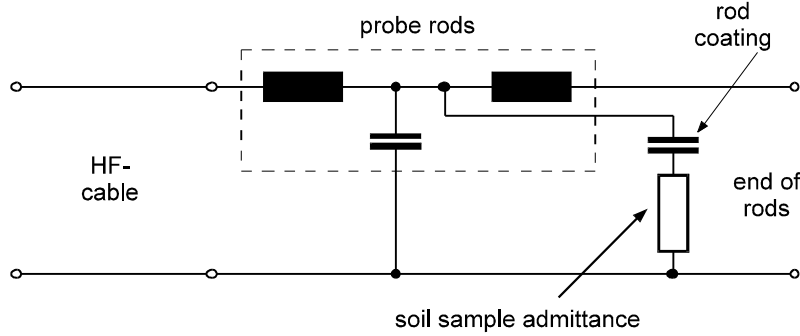


Figure 6 Equivalent circuit of the TRIME-probe

Since the amplitude is a function the electrical conductivity (Figure 7) of the soil the transit time can not be measured at a fixed voltage level. An iterative algorithm was developed that determines the transit time with a resolution of 3 ps. This enables the use of short probe rods even at low water contents.

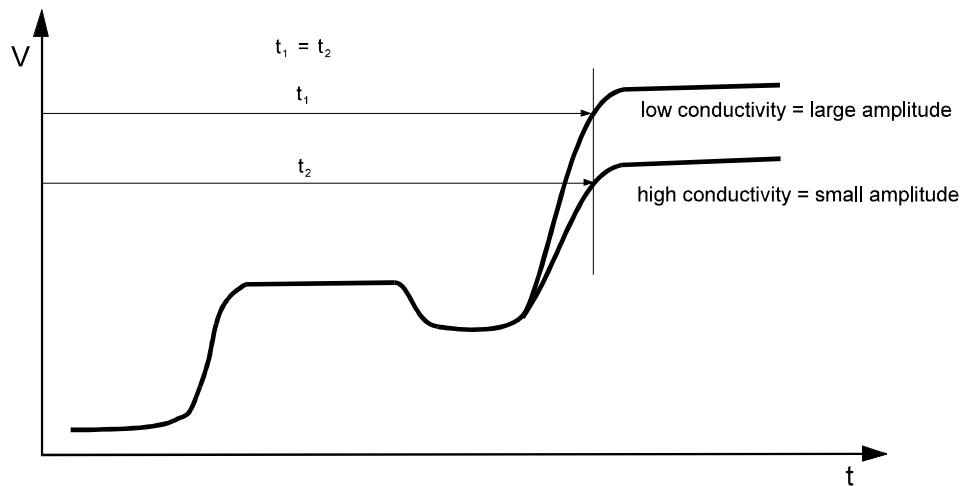


Figure 7 TRIME amplitude as a function of electrical conductivity.

Internal Measuring Procedure

Moisture is calculated with the measured transit time in three steps. All calibration coefficients are attached to the probe. They are stored in an EEPROM inside the probe connector.

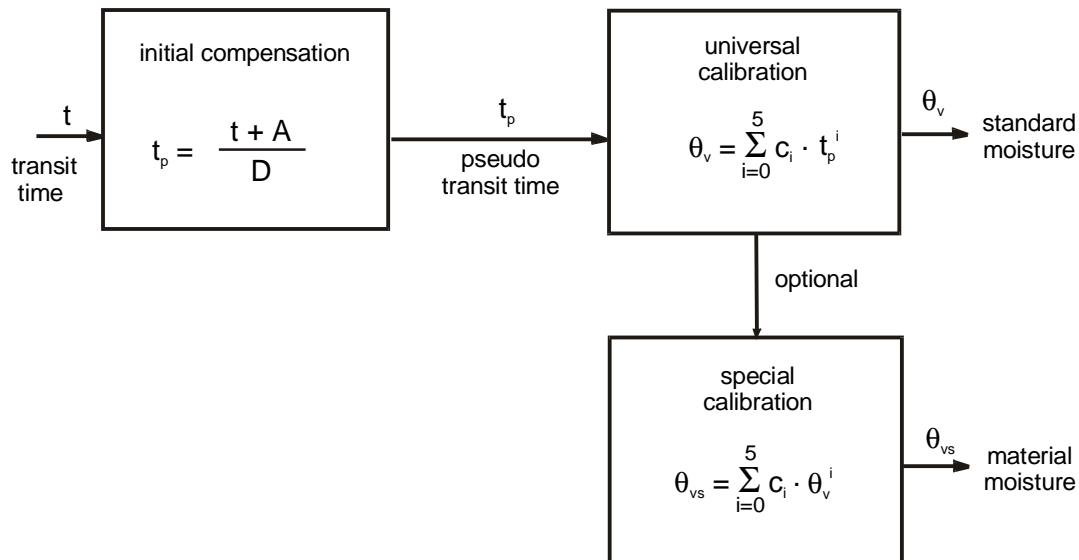


Figure 8 TRIME internal measuring procedure

Initial Compensation

Initially cable length and probe mechanics tolerances of every TRIME probe have to be compensated to supply proper measuring results. The compensation is carried out in dry and water saturated glass beads. The calibration coefficients A and D (Figure 8) are calculated by software.

Universal Calibration

A universal calibration enables determining moisture of common mineral soils. The coefficients $c_0 \dots c_5$ of the polynomial calibration function were empirically determined and cover a wide range of mineral soils.

Special Calibration

The customer is able to calibrate the probe for special materials. The calibration functions can simply be established using TRIME software. The new calibration coefficients $c_0 \dots c_5$ are stored in the probe connector.

Material calibrations might become necessary for materials with high clay content (> 50%, particularly swelling clay minerals), for materials with high organic compound (> 10%, e.g. mull, humus, pot-cultures), and for soils with very low bulk densities ($\rho < 1 \text{ g/cm}^3$, e.g. andosols). Note that the quoted values in brackets are rough estimates based on experiences and do not represent defined limits.

Influences on the TDR-Measurement

Material

One of the first applications of TRIME was the water content determination in mineral soils. The outstanding advantage was the low influence of soil type and the possibility of using a universal calibration function. As IMKO and TRIME become increasingly known internationally, the interest has been leading to moisture measuring in many other porous materials which often require specific material calibrations.

Material calibrations may become necessary for measuring materials with high specific surfaces, leading to a high amount of bound water, e.g. clays (> 40% clay content, particularly swelling clay minerals), and materials with high organic compounds (> 10%, e.g. mull, humus, pot-cultures). Also soils with very low bulk densities ($\rho < 1 \text{ g/cm}^3$, e.g. andosols) require a special calibration.

Please note that these values are rough estimates based on experience and do not represent defined limits.

The grain size distribution or the heterogeneity of a material can cause problems as well. There is either the risk of changing the structure when installing the sensor or the problem of covering a representative measuring volume. For both problems IMKO has excellent solutions by offering adequate drilling equipment and sensors with larger measuring fields (e.g. TRIME-P2G).

Electrical Conductivity (EC)

The soil electrical conductivity is considered an important property in agricultural practice, as it usually serves as an indicator of soil salinity (the readily soluble salts present in the soil; essentially the inorganic electrolytes contained in the soil solution). High salinity is of importance especially in dry regions, where irrigation is necessary. But also in experimental studies of soil leaching and chemical transport of nutritives, fertilisers or pollutants, changes in solution concentration within the soil profile are usually estimated in real time by interpretation of the measured electrical conductivity.

Because most soil minerals are insulators and there do not exist free electrons as for example in metals, the electric current is conducted through ions present in the soil solution and adsorbed to the matrix surface. The specific electrical conductivity is mainly dependent on temperature as well as species and concentration of the ions in solution. It is normally referred to a temperature of 25 °C, so that the differences are only a function of concentration and species of the dissolved ions. The bulk electrical conductivity of the soil is furthermore dependent on number and geometry of the pores, soil water content and electrical conductivity of the pore water and the minerals. RHOADES et al.(1976) described it with the following equation:

$$\sigma_a = \sigma_w \theta_v T + \sigma_s \quad [5]$$

with σ_a as bulk soil electrical conductivity, σ_w as electrical conductivity of the pore solution, θ_v as volumetric water content, σ_s as surface conductivity of the matrix and T as an empirically

determined transmission coefficient that accounts for the tortuous nature of the current lines and any decrease in the mobility of the ions near the solid-liquid interfaces. Note that the bulk soil electrical conductivity is in most cases essentially lower than the electrical conductivity of the pore water. A loess loam for example with a water content of 42 % by vol. and a pore water electrical conductivity of 9 dS/m yields a bulk soil electrical conductivity of only 2 dS/m.

Present methods of obtaining soil electrical conductivity are the measuring of aqueous extracts of soil samples with a conductance meter, removed from the soil by pressure or vacuum in the laboratory. There exist several methods with different dilution concentrations of sample and water (1:2; 1:2.5; 1:10), so that it is difficult to compare the results. Other methods determine the bulk soil conductivity in situ using instrumental techniques like the Four-Electrode-Probe of Rhoades & Van Schilfgaarde (1976). In this method, four electrodes, arranged usually on a line, are placed in the soil and an AC voltage is applied to the two outer electrodes. The current induced between the two inner electrodes is a function of the soil resistivity and the electrical conductivity can be determined.

These methods, however, are time consuming, expensive, destructive, and have the disadvantage that the closely related electrical conductivity and water content cannot be measured at the same location.

Conventional TDR-systems

Today the TDR-technique shows promising potential not only in water content but also electrical conductivity determinations. Early attempts by Dalton et al. (1984) to use TDR techniques for water content measurements in highly conductive soils showed that the TDR wave-form not only contained information about the pulse transit time but also information concerning the dissipation of electromagnetic energy that could be used to deduce the medium electrical conductivity and therefore soil water salinity.

Theoretical analysis and experimental correlation showed, that the transmitted voltage pulse was attenuated due to the bulk electrical conductivity of the media and could be expressed according to an exponential decay law (Dalton et al. 1984):

$$V_r = V_t e^{-2\alpha l} \quad [6]$$

where V_t is the transmitted voltage, V_r the ideal reflected voltage, l is the probe length. α represents an attenuation coefficient of electromagnetic waves, which can be described as:

$$\alpha = \frac{60\pi\sigma_a}{\sqrt{\epsilon_r}} \quad [7]$$

with ϵ_r as dielectric constant and σ_a as bulk electrical conductivity of the medium between the wave guides.

A combination of equation [6] and [7] yields the bulk electrical conductivity as:

$$\sigma_a = \left(\frac{\sqrt{\epsilon_r}}{120\pi l} \right) \cdot \ln \left[\frac{V_t}{V_r} \right] \quad [8]$$

The conventional TDR technique provides simultaneous measuring of not only soil water content but also of bulk soil electrical conductivity, each being an essential component of soil salinity. Yet the disadvantage is, that a higher electrical conductivity attenuates the reflected TDR-pulse so that the evaluation and the determination of water content and electrical

conductivity gets more and more difficult and inaccurate and finally the attenuation can make measurements impossible.

TRIME TDR-System

The TRIME-TDR-system uses a completely new approach in measuring and evaluating the TDR-pulse. But for electrical reasons and to allow a new pulse evaluation algorithm, the metallic probe rods had to be coated with PVC. This has the additional advantage, that the TDR-probes are able to measure in higher conductive materials. The coating of TDR probe-rods with a material having a low dielectric constant is a well known method to improve the TDR application in higher conductive soils, but other than conventional TDR-systems, the TRIME method does not show a considerable loss in resolution and accuracy of the water content measurements due to its different measurement algorithm.

The TRIME algorithm determines the reflected voltage in form of the amplitude of the TDR curve, which is attenuated by the bulk electrical conductivity of the medium. Yet the transmitted voltage of the TRIME voltage pulse can not be determined, thus making a determination of the bulk soil electrical conductivity according to equation [8] impossible.

Despite this fact, the determination of the electrical conductivity with the TRIME method is also possible, yet our approach is an empirical one, similar to the established relationship between transit time and water content. We established a relationship between the TRIME amplitude (due to electrical reasons measured in dimensionless discrete integers from 0-100) and the bulk electrical conductivity of the medium. As reference method in this approach we used either a conductometer for measurements in aqueous saline solutions or the above mentioned Four-Electrode-Measuring technique for in-situ measurements in solid materials. Both techniques are based on measuring the resistance of the material, which is the reciprocal of electrical conductivity.

Figure 9 shows the relationship between the TRIME amplitude and the bulk electrical conductivity in aqueous potassium chloride solutions for different TRIME-probes and devices. As can be expected from equation [6], the relationship is an exponential one, which appears linear in a half-logarithmic scale. Figure 10 shows the measured relationship for different soils and soil-like materials.

Two main conclusions can be drawn from these experiments:

- There exists an offset in the amplitude range between the different TRIME devices and probes, which means that each device and probe must be calibrated to a certain amplitude level to guarantee that every device measures the same electrical conductivity.
- There exists an offset between measurements in aqueous solutions/sand and clayey materials which we think is the result of the different dielectric characteristics of free and bound water. This is also the reason for a greater soil type dependence of the electrical conductivity measurement. Therefore, a universal calibration function, as it is possible for the water content measurements in mineral soils can not be used for measuring the bulk electrical conductivity. At least there have to be two functions that distinguish between cohesive and non-cohesive/aqueous materials. Best would be a material-specific calibration.

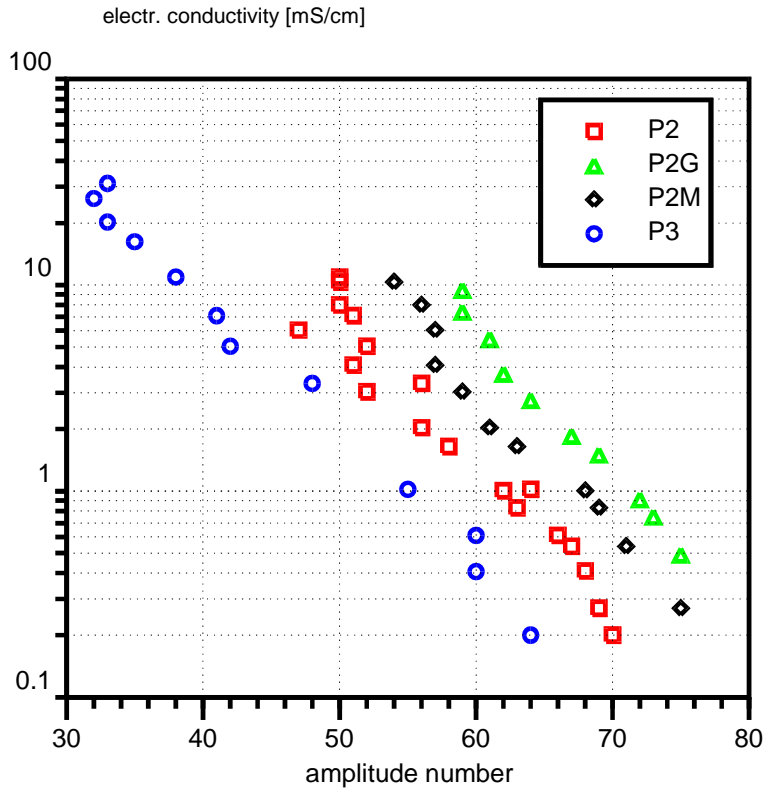


Figure 9 Relationship between the TRIME amplitude and the bulk electrical conductivity in aqueous potassium chloride solutions for different TRIME-probes and devices

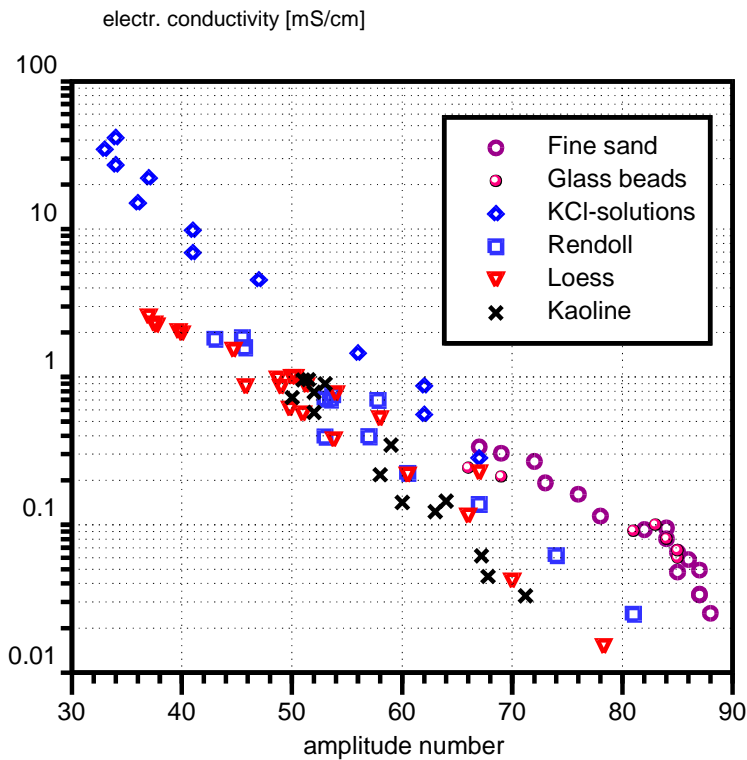


Figure 10 Relationship between the TRIME amplitude and the bulk electrical conductivity in different soils and soil-like materials for a 3-rod probe (P3Z).

Calibrating TRIME for Measuring the Electrical Conductivity

Despite the difficulties and influences on the TDR-level mentioned above, we think that a calibration of the TRIME TDR-level to determine the bulk soil electrical conductivity is possible. Since the calibration depends on both sensor and material, we recommend the customer to calibrate on site.

The calibration of the displayed TDR-level can be achieved in the following way:

Every TRIME device and probe should be calibrated in the desired material by determining the bulk electrical conductivity with a reference method as for example the Four-Electrode-Probe by Rhoades (1976) and establishing the TDR-level - bulk electrical conductivity relationship. The calibration material should be as homogeneous as possible and a close contact between 4-Electrode -Probe and material is important. Different electrical conductivities can be achieved by adding water and if necessary (for a wider measuring range) water with electrolytes (for example KCl).

Then a regression function (exponential regression) can be calculated for determining bulk electrical conductivity.

The pore water electrical conductivity can be deduced by bulk soil - pore water electrical conductivity relationships. These relationships are soil specific and must be determined empirically according to Rhoades & Van Schilfgaarde (1976). These relationships are also dependent on water content. The simultaneous measurement of bulk electrical conductivity and water content with TRIME finally enables the determination of pore water electrical conductivity and salinity.

Measuring Accuracy for the Electrical Conductivity

The measuring accuracy depends on parameters such as probe type, soil type, soil homogeneity, level and range of electrical conductivity and water content. For a P3-EC-calibration in a fine sand (best case!) we achieved an absolute accuracy for the EC-measurement of +/- 0.023 dS/m bulk soil electrical conductivity in a conductivity range of 0.01dS/m...0.33 dS/m. The accuracy usually decreases with increasing water- and clay content, heterogeneity, and electrical conductivity.

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Density of Material

Experiments showed that TDR measurements are dependent, to a certain degree, on material density.

The universal calibration functions for soils were established at a dry density of 1.4 kg/dm^3 . If the density of the soil is significantly higher ($> 1.7 \text{ kg/dm}^3$), TDR tends to overvalue the moisture and if density is considerably lower ($< 1.0 \text{ kg/dm}^3$), moisture is undervalued.

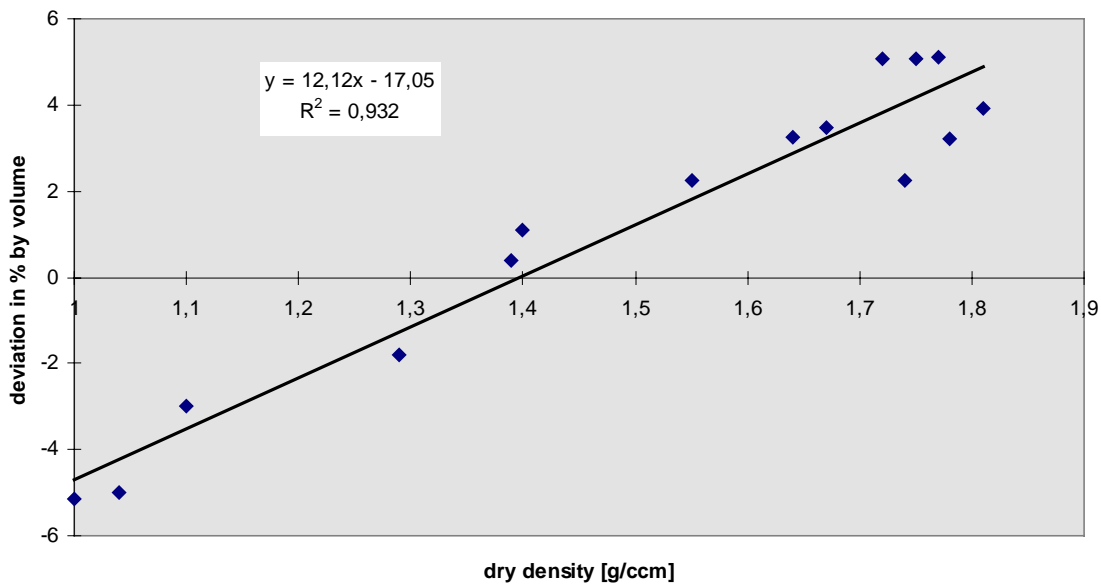


Figure 11 Deviation of TRIME values to the thermogravimetric reference as a function of dry density. At top the correction equation is shown. ($y = \text{deviation}$, $x = \text{dry density}$)

This is due to a change in the dielectric constant of the mixture of soil water, soil matrix and soil air. If density increases, the amount of the soil matrix increases and the amount of air decreases. Since the soil matrix has a higher dielectric constant than air, TDR overvalues the water content.

If you want to measure in materials that have significantly lower or higher densities than 1.4 kg/dm^3 , there are two possibilities of correcting this effect:

1. Correct the results with a simple linear correction equation ($y=12.12x-17.05$). The corrected measuring value is calculated as follows:

$$\text{moisture}_{corrected} = \text{moisture}_{measured} - (12.12 * \text{drydensity} - 17.05)$$

2. Carry out a material calibration with the corresponding material and the characteristic density.

Air Gaps

Air gaps between sensor and material should be avoided, since air has the lowest dielectric constant and, therefore, TDR would considerably undervalue the actual moisture.

Especially the application of TDR in swelling and shrinking materials is delicate, since cracks tend to develop especially along the rod (access tube)-soil-interface. Frequent controls of the measuring spot are necessary in this case.

It is also important to fully insert the sensors into the material to be measured. Repeated insertion of the probes at the same measuring spot should also be avoided. In both cases, the water content can be significantly undervalue.

TRIME Compared to Other Dielectric Moisture Measuring Systems

The TRIME-TDR-technique is a specially designed TDR-technique to determine the moisture content of porous materials and offers some advantages in comparison to other techniques based on the principle of measuring the dielectric constant.

Summary of the Advantages of TRIME

Low Influence of Conductivity

The bulk soil electrical conductivity with TRIME extends up to 10mS/cm. In this range a precise and separate measurement of water content and conductivity is possible. With the probes TRIME-IC and TRIME-EC difficult applications are possible, e.g. the measurement in soils with salt concentrations up to 20.000ppm or measurements in copper ore which is saturated with sea water and 20% sulphuric acid for the extraction of copper.

Wide Measuring Range

The measuring range of TRIME extends up to 70% (with a special re-calibration up to 95%). Measuring applications in clayey soils or pure clay are possible.

Large and Small Measurement Fields

With different probe geometries and varied waveguide lengths (50...150mm) it is possible to measure in homogeneous and heterogeneous soils (note that long waveguides may cause interference problems in layered materials).

Comparison with Conventional TDR

Conventional TDR systems, such as electronic cable testers, were originally developed for detecting short cuts and damages of electrical transmission lines. These devices were adopted by soil scientists in the late '70s to determine the dielectric constant of wet soils and to derive the water content.

Main disadvantages are the expensive, complex and heavy hardware and the many features, important for cable detecting are unnecessary for water content determination. The evaluation of the characteristic TDR-bath-tub curve is difficult, sometimes impossible.

In dry soils (< 10 % water content) and when using short probes (< 0.1 m), the

pulse transit time can become very short (Figure 12) or the dropping and rising display trace can even be superimposed. An exact determination of the entry of the pulse into the probe or the reflection at the end of the probe can not clearly be determined. Consequently an evaluation of the transit time on the rods by the intersection of two tangents is not possible.

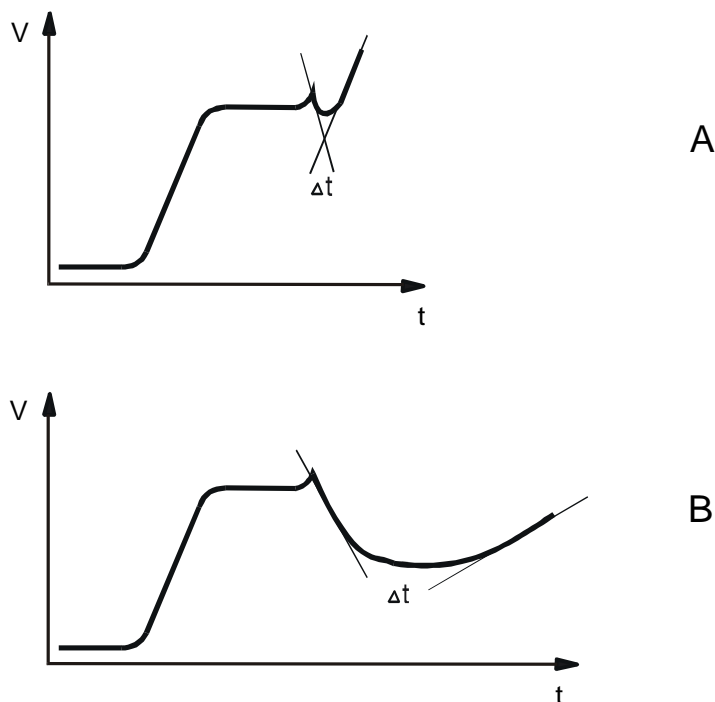


Figure 12 *Characteristic traces of conventional TDR technology by voltage sampling.*
 A: *TDR trace when using probes with short rods in soils with low water content.*
 B: *TDR trace in soils of high salinity or when using long probe rods or long coax cables between probe and device.*

In soils with high clay content or soils that are intensively fertilised, there is the problem, that the electrical conductivity of the material leads to a strong attenuation of the amplitude of the bath-tub curve (Figure 12B). The curve becomes too flat to determine the point of reflection at the end of the rods. Long coax-cables (> 50 m) between TDR-probe and device lead to the same effect.

Due to the different pulse evaluation method of the TRIME-system these problems do not occur.

Comparison with Capacitive Techniques

The capacitive measuring systems are the second group of dielectric moisture measuring systems based on the high dielectric constant of water. The name originates from the measuring principle of the dielectric constant, which is based on measuring the capacity between the electrodes of the sensor.

In contrast to TDR voltage pulse signal with short voltage rise times (< 200 ps) containing broad frequency bands (1 MHz ... 1 GHz) the capacitive systems use single measuring frequencies. They are also called Frequency Domain (FD) sensors.

Despite its name, the dielectric constant is not a constant at all. In an alternating electric field it depends mainly on the applied frequency. This frequency dependence can be described by a complex dielectric constant ϵ^* :

$$\epsilon^*(\omega) = \epsilon'(\omega) - j(\epsilon''_d(\omega) + \frac{\sigma_{dc}}{\omega \cdot \epsilon_0}) \quad [1]$$

The real part ϵ' denotes the dielectric constant, from which the water content can be deduced. The imaginary part denotes the dielectric loss, consisting of the dielectric absorption ϵ''_d and the bulk soil electrical conductivity σ_{dc} (ω is the angular frequency and ϵ_0 the permittivity of vacuum). ϵ''_d is a measure for the energy absorption and increases with increasing frequency, whereas at lower frequencies the imaginary part is dominated by the bulk electrical conductivity σ_{dc} .

TRIME-TDR

Because of the relatively high frequencies of a TDR-pulse, the real part of ϵ^* is a function of the water content in porous materials. The imaginary part can be neglected, since the frequencies are either so high that the ionic conductivity does not have a significant influence or they are low enough, so that the energy absorption does not play an important role. Due to a coating of the metallic probe rods, the TRIME-system has the advantage, that it can be used for water content measurements in high conductive media. With a thicker coating, as for example for the TRIME-IC, measurements in materials with very high electrical conductivities (> 15 dS/m) are possible.

Capacitive Devices

The capacitive sensors on the other hand, can only achieve a single frequency, due to electrical reasons with a maximum of about 100 MHz, mostly they are far below that. But the lower the frequency, the higher gets the influence of the ionic conductivity and the imaginary part of the dielectric constant can not be neglected any more and distorts the water content measurement. That is the reason, why there is a greater dependence of FD sensors on the bulk electrical conductivity or salt content and - in the end - on the soil type. This greater sensitivity and differences between soils present a greater need for FD calibrations and there is a greater complexity of processes occurring at lower FD frequencies (Dirksen & Hilhorst 1994).

Measuring Results

A TRIME P2 two-rod- probe and a FD-sensor with four rods were tested in different materials. Figure 13 shows a comparison of water content measurements in glass beads. The beads were gradually mixed with different pore water solutions until saturation ranging from distilled water up to solutions with electrical conductivities of 3 dS/m.

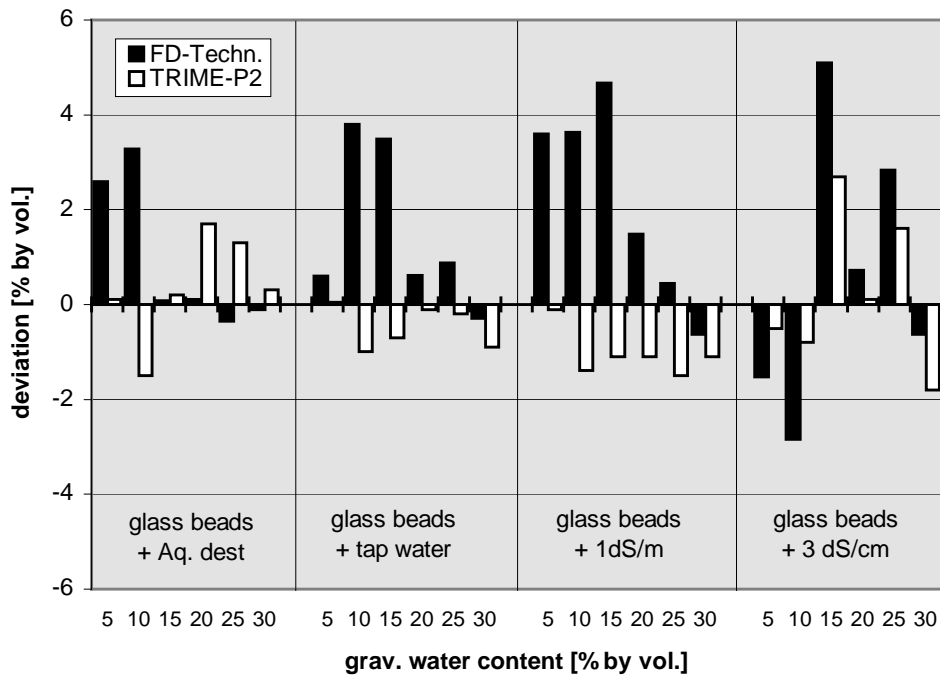


Figure 13 Comparison of moisture measurements with TRIME and FD in glass beads (special calibration) with different pore water electrical conductivities. The zero line indicates 1:1 correlation.

The measurements were both carried out with the commercially proposed universal calibration functions and with a specially determined calibration for glass beads.

The root mean square deviation (rmsd) was determined according to the following equation:

$$rmsd = \sqrt{\frac{\sum_{i=1}^n (\theta_{grav.} - \theta_{TRIME/FD})^2}{n}} \quad [2]$$

The universal calibrations gave a rmsd of 3.5 % by vol. for the FD sensor and of 2.3 % by vol. for the TRIME-P2 probe. With the special calibration for the glass beads, the accuracy could be increased, yielding a rmsd of 2.7 % by vol. for the FD sensor and of 1.2 % by vol. for the TRIME probe.

In a second experiment the influence of electrical conductivity on the measurement was tested. The glass beads were saturated with solutions of different electrical conductivities ranging from tap water 0.5 dS/m up to 5 ds/m. The results are shown in Figure 14.

Whereas the TRIME probe shows no influence on the pore water electrical conductivity except a slightly higher value at 5 dS/m (3 % by vol.), the measured water content of the FD-sensor decreases significantly with increasing conductivity, resulting in a drop of 6 % by vol. at 5 dS/m.

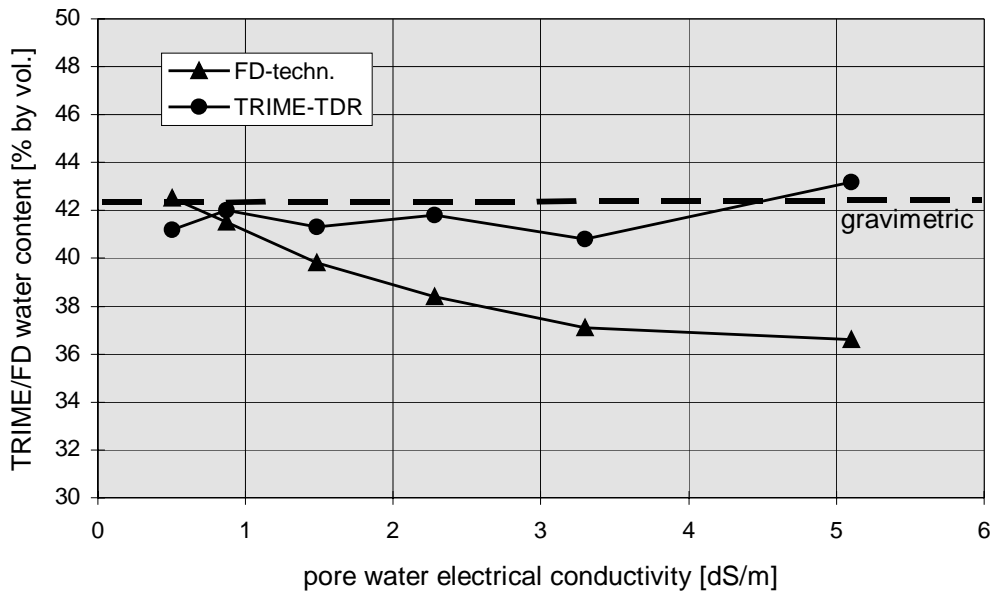


Figure 14 Comparison of measured TRIME and FD values in glass beads saturated with pore water solutions of different electrical conductivities.

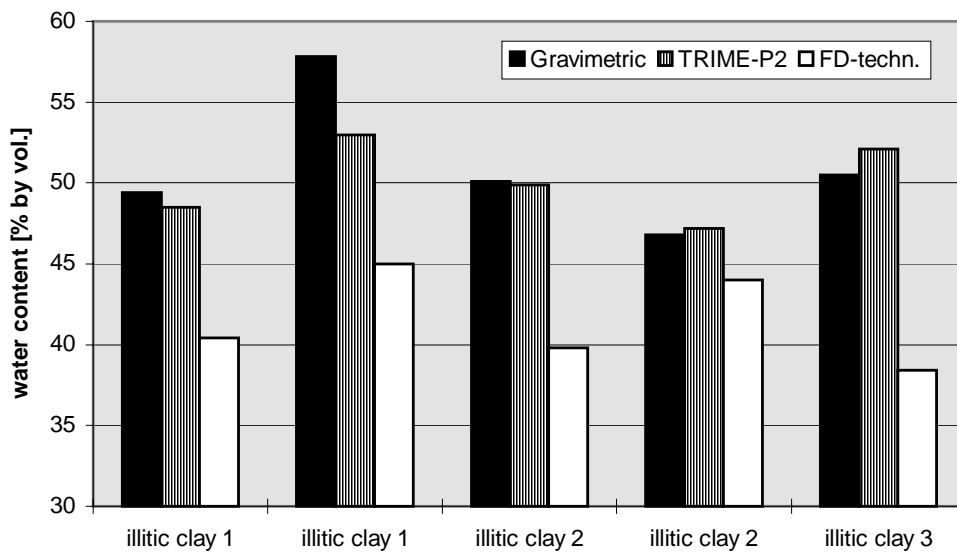


Figure 15 Comparison of moisture measurements with TRIME-TDR, FD-technique and oven drying method in illitic clays with high water contents.

Finally the two sensors were tested in clays with high water contents. Figure 15 shows a comparison of TRIME-P2 FD- and thermogravimetric values of three different illitic clays and a kaolin. It can be seen, that the FD-sensor has difficulties in determining very high water contents showing an underestimation which can reach more than 15 % by volume. This may be due to the high electrical conductivity that corresponds with the high water contents in clayey materials. For reasons of objective comparison a standard P2 probe was chosen for these measurements. But measuring accuracy can be significantly increased by the use of a TRIME-IC probe, especially designed for high saline soils.

Discussion and Comments

The experiments and the data show that the investigated FD-sensor cannot compete with the accuracies of the TRIME-technique. Even with a special material calibration for the used glass beads, the FD-sensor showed a higher deviation than the water content measurements determined with the TRIME universal calibration. With a special calibration of the TRIME-sensor, the accuracy was twice as high as with the special calibration of the FD-sensor.

There was also a stronger influence of pore water electrical conductivity on the water content measurements of the FD-sensor causing significant deviations with conductivities of more than 1 dS/m.

It could be finally demonstrated, that the FD-sensor has difficulties in determining higher water contents, resulting in a significant underestimation of the measured water contents. This might be also due to influences of electrical conductivity but another reason might be the fact, that accuracy and resolution of FD sensors are highest at high impedances, i.e. at low water contents, because the voltage developed across a high impedance is large and thus easy to measure. The higher the water content gets, the lower is the accuracy of FD sensors.

It was also found that the probes were more sensitive to changes in the geometry of the probe-rods and mechanical stress. A slight bending already distorted the measurements, whereas the TRIME rods could even be bound together at the tip, without influencing the measurement value. Another limitation in this context is the difficulty in constructing FD-sensors with probe-rods longer than 6 cm, so that the measurement volume is relatively small, limiting the application range of the sensors.

All measurements are done under laboratory conditions. Under field conditions requirements are harder especially in heterogeneous soils and with varying environmental parameters like changing conductivities with fertilisers, soil porosity, disturbance of soil structure with rods, and so on.

References

DIRKSEN, C. & HILHORST, M.A. (1994): Calibration of a new frequency domain sensor for soil water content and bulk electrical conductivity.- Symp. on TDR in environmental, infrastructure, and mining applications, 07.-09.09.1994, Evanston, Ill., U.S. Bureau of Mines Spec. Publ. SP 19-94: 143-153.

Moisture Definitions

Definition of Volumetric Moisture

The volumetric moisture indicates the relationship between the volume of water of a sample and the total volume of the sample. Due to physical reasons, TRIME[®]-GM measures basically the volumetric moisture described by equation [10]:

$$\theta_{vol} = \frac{V_w}{V_{tot}} \cdot 100 \quad [10]$$

with θ_{vol} = volumetric moisture of sample in % by volume
 V_w = volume of water inside the sample
 V_{tot} = total volume of sample

Definition of Gravimetric Moisture

The gravimetric moisture $\theta_{grav.}$ indicates the relationship between the mass of the water m_{H_2O} present in the sample and either the dry mass or the total mass. It is:

$$\theta_{grav.;dr} = \frac{m_{H_2O}}{m_{dr}} \cdot 100 \quad [11a]$$

with $\theta_{grav.;dr}$ = gravimetric moisture on a dry mass basis in % by weight
 m_{H_2O} = mass of water present in the sample
 m_{tr} = dry mass of the sample

$$\theta_{grav.;w} = \frac{m_{H_2O}}{m_{tot}} \cdot 100 \quad [11b]$$

with $\theta_{grav.;w}$ = gravimetric moisture on a wet mass basis in % by weight
 m_{H_2O} = mass of water present in the sample
 m_{tot} = wet or total mass of the sample

Definition of Dry Density

The dry density ρ_{dr} describes the relationship between the dry mass m_{dr} and the total volume V_{tot} of the sample:

$$\rho_{dr} = \frac{m_{dr}}{V_{tot}} \quad [12a]$$

Definition of Wet Density

The wet density ρ_w describes the relationship between the wet or total mass m_{tot} and the total volume V_{tot} of the sample:

$$\rho_w = \frac{m_{tot}}{V_{tot}} \quad [12b]$$

Relationship between Gravimetric and Volumetric Moisture

Between gravimetric and volumetric moisture exists the following relationship:

$$\theta_{vol} = \theta_{grav.;dr} \cdot \frac{\rho_{dr}}{\rho_{H_2O}} \quad [13a]$$

resp.

$$\theta_{vol} = \theta_{grav.;w} \cdot \frac{\rho_w}{\rho_{H_2O}} \quad [13b]$$

with $\theta_{grav.;dr/w}$ = gravimetric moisture in % by weight (dry or wet weight basis).

ρ_{dr} = dry density of sample

ρ_w = wet density of sample

ρ_{H_2O} = density of water (≈ 1)

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