THE TDR TECHNOLOGY FOR SOIL MOISTURE MEASUREMENTS

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Sortie à Palmyre (Syrie) du DEA Sciences de l’Eau du CREEN,
Beyrouth, 25-26 mai 2002
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INTRODUCTION

Among all the actions of water in a watershed, two of them are important in watersheds management. They respectively concern soil erosion and soil conservation. The measurement of water content in soils is necessary to estimate the plants uptake, the recharge of the ground water, solute transport through the unsaturated zone with salt or pollutants transport, and surface wetness which is known to be an important factor in surface runoff evaluation.

The main methods used for soil water measurements are classical gravimetric technique, neutron probe, and dielectric methods. The oldest is the gravimetric method which remains the reference. It doesn't need technology but human time, repetitive measurements are impossible on short time periods.

The neutron probe method is easy to use and fast for repetitive measurements but actually radioactive elements use is under severe controls. It is one of the reasons why electric methods, already known, have been developed. Capacitive probes have been developed (Tran Ngoc lan, 1970; Wobschail, 1978 Fumanal et al., 1989 Gaudu et al., 1993). They allow measurements in small volumes of soil but need to include temperature correction and an electronic circuit to compensate the electrical conductivity of the soil solution influence on permittivity.

Fellner-Feldegg (1969) used TDR for measuring the dielectric constant. The Time Domain Reflectometry has been developed in the late 1970's (Schmugge et al., 1980) and Topp et al. (1980) introduced this technique for soil moisture measurements.
PRINCIPLE OF THE Time Domain Reflectometry

Theory

Originally the Time Domain Reflectometry was only used to detect defaults in transmission lines and cables. A voltage pulse is injected into the cables. The pulse propagates along the cables as an electromagnetic signal in the frequency range of 1 MHz to 1Ghz. In coaxial lines the electromagnetic field is inside the cable. In parallel lines, the field is both between and around the cables. The pulse shape and the transit time depend on the cable properties, length and the termination of the cable where the signal is reflected. A TDR equipment typically consists of a 2 or 3 rods transmission line, a coaxial connecting cable and a TDR instrument to generate fast-rise-time pulses and to measure times. A probe is considered to consist of the transmission line and any structure or component between the transmission line and the connecting cable.

The TDR technique is based on the measure of the velocity $v$ of an electromagnetic wave in the soil. This velocity depends on the dielectric constant of the soil and the dielectric constant mainly depends on the water content of this soil.

\[
v = \frac{C_0}{\sqrt{\varepsilon \mu}}
\]

[1]

The large difference between the dielectric constant of water, about 80, and air (about 1) or dry soil (between 2 to 5) is the reason why the dielectric constant of a moist soil is highly dependent on his water content.

$V$ must be measured in order to determine the dielectric constant.
Velocity measurement is transformed to a transit time measurement, \( t \): the wave travels along the 2 or 3 rods of the probe with the length \( l \), is reflected at the end, and comes back.

So the velocity \( v \) is known by the measurement of the transit time \( t \)

\[
v = \frac{2l}{t} \quad \text{[2]}
\]

This transit time \( t \) is determined from the TDR waveform (Fig. 1)

![Schematic TDR waveform](image)

Fig. 1: schematic TDR waveform

For a 15 cm long TDR probe the difference between the transit time in air \( (t_a) \) and in water \( (t_w) \) is only 8 ns.

\[
t = \frac{2l}{C_o \sqrt{\varepsilon_r}} \quad \text{[3]}
\]

With

\[
t_a = \frac{0.3m}{3 \times 10^8 \text{ms}^{-1}} \sqrt{1} = 1 \text{ ns} \quad \text{And} \quad t_w = \frac{0.3m}{3 \times 10^8 \text{ms}^{-1}} \sqrt{81} = 9 \text{ ns}
\]
So short transit times to be measured introduces two major constrains: the use of a specific high frequency electronic device and a minimum length of 15 to 20 cm for the probe rods.

Four significant voltage values can be determined from the TDR Trace (fig. 1):

- $V_0$: the amplitude of the TDR pulse
- $V_s$: the amplitude after reflection at the start of the probe
- $V_e$: the amplitude after reflection from the end of the probe
- $V_f$: the reflected signal after a very long time

Transit time is used to determine water content, and many researchers have also derived relationships between the attenuation of the signal and bulk electrical conductivity (Dalton et al., 1984; Topp et al., 1988; Yanuka et al., 1988; Nadler et al., 1991; Heimovaara et al., 1995, Persson M., 1997 etc...).

### Dielectric models

Several models have been developed to estimate the dielectric properties of wet soil for establishing relationships to water content.

- **Third-order polynomial equation**

In 1969 Fellner-Feldegg used TDR for measuring the dielectric constant of liquids. In 1980, Topp, Davis and Annan based their method on the work of Fellner-Feldegg and introduced TDR for the measurement of soil moisture (Topp et al., 1980); They measured the apparent dielectric constant $\varepsilon_r$ of a large number of soils and related it to volumetric water content $\Theta_v$ using an empirical third-order polynomial equation.

$$\varepsilon_r = 3.03 + 9.3\Theta_v + 146\Theta_v^2 - 76.7\Theta_v^3$$

Or

$$\Theta_v = -5.3 \times 10^{-2} + 2.92 \times 10^{-2} \varepsilon_r - 5.5 \times 10^{-4} \varepsilon_r^2 + 4.3 \times 10^{-6} \varepsilon_r^3$$ [4]

Most of the researchers found it appropriate for their soils, but it is also possible to fit a relationship by a specific calibration. Two ways are used:

- **Dielectric mixing models**

Dielectric mixing models are also used by some researchers. A review can be find in Jacobsen and Schjonning (1995) and Persson M. (1997). They consider that the wet
soil is a two or three phases system with soil matrix, water and air and calculate the bulk dielectric constant from the dielectric properties and volume of each fraction.

*Birchak et al.* (1974) produce a semi-empirical $\alpha$ model where $\theta_i$ and $K_i$ are the volume fraction and dielectric permittivity of phase $i$ and $\alpha$ is a soil geometry parameter.

$$K^\alpha = \sum_i \theta_i K_i^\alpha$$

for a three phases system (air, water and soil matrix) $\alpha$ is about 0.5 and then it results a linear relationship between $K^{0.5}$ and soil water content (*Ledieu et al.*, 1986).

*Roth et al.* (1990) produce a two phases model where $K_0$ is dry soil permittivity, $K_a$ wet soil permittivity and $K_e$ water permittivity.

$$\Theta = (K_a^k - K_0^k) / (K_e^k - K_0^k)$$

with $K_0 = 2.3$, $K_e = 80$ and $k = 0.637$

*Ferré et al.* (1996) establish an other relationship

$$\Theta = e \sqrt{K_e} + f$$

with $e = 1 / (K_e^k - K_0^k) = 0.118$ and $f = - K_0^k / (K_e^k - K_0^k) = -0.814$ if $k = 0.5$

*Ruelle et al.* (2000) compared Topp third-order equation, with Ferré and Roth mixing models and show that these three relationships are not significantly different for the range of water moisture in agricultural soils (fig. 2).

![Fig. 2: Topp third-order equation compared to Ferré and Roth mixing models](image-url)

Fig. 2: Topp third-order equation compared to Ferré and Roth mixing models (in *Ruelle et al.*, 2000).
TDR probes with 2 or 3 rods are now also used to measure soil solution electrical conductivity for transient conditions with varying water content. This application allows also non destructive measurements of solute transport in the unsaturated zone (Persson M., 1997; Persson M. and Berndtsson R., 1998b).

Signal processing

- Classical methods

![Classical TOR-pulse signal measurement (sampling technique)](image)

The reflected TDR pulse is scanned by the sampling method. Each point of the pulse signal is measured as a voltage value at a distinct time. The transit time is graphically derived from the voltage signal (fig. 3). That needs very expensive high frequency electronic components: a high frequency pulse generator and a high frequency oscilloscope. The cable testers (e.g. Tektronix) where the first devices based on this method but they are not design for measurements in rough environments. The TRASE system (Soil Moisture Eq. Corp., Santa Barbara, California) is based on a cable tester equipment but especially designed for soil moisture measurements. The evaluation of the probe transit-time part of the curve is difficult for low water contents or short TDR-probes rods. But this method allows to visualise full TDR waveforms which can be very useful to search physical interpretation of problematic results.
With this method, the points of the TDR pulse are determined by direct time measurements at distinct voltage levels. This requires another pulse shape with a high amplitude of the reflected pulse and a reduction of the attenuation (fig. 4). This shape is allowed by a suitable impedance matching between pulse generation output, the connecting cable and the probe. The coating of the rods with PVC is the second important measure to get this kind of signal:
- low frequencies are blocked
- only high frequencies (>> 300MHz) travel through the soil and can be attenuated.

Thus the total attenuation is reduced and the amplitude of the reflected pulse is higher.

The start of the generator switches on a counter and the counter is stopped when the voltage comparator detects the first reflection at the end of the probe. A special algorithm derives the amplitude of the reflected pulse from measurements of particular points of the curve. When the amplitude, which depends of the electrical conductivity of the soil, has been determined, the transit time $t_p$ is measured at the corresponding voltage. This gives short measurement times and low power consumption.

Because of averaging of many measurements, transit time can be known with a resolution of 3 ps. This allows also to work with short rods and with low water contents. But with this system it is not possible to visualise the TDR wave.
Calibration for the TRIME-FM

The IMKO TRIME-FM device displays directly the water content and the level of the signal because it has signal processing and calibration functions in its internal electronic. It is not possible to show the wave form but all the parameters used for calibration are accessible through the free software SM-TOOLS.

Two or three steps are used to calibrate the probes. (Imko Gmbh, 1991, 2000)

- step 1: “Basic calibration”

The transit time \( t \) is transformed into a “pseudo-transit-time” \( t_p \) using a linear relationship:

\[
\frac{t_p}{D} = \frac{t + A}{D}
\]  

Where \( A \) and \( D \) are two parameters calculated by a calibration program (SMCAL) or by plugging a special calibration connector on the left side of the TRIME FM box. This basic calibration is done to calibrate the hard ware (to compensate the cable length, and to take in account the design of the probe). Every TRIME Probe is precalibrated by IMKO, but calibrated probes can only be used according to the TRIME FM box they were calibrated with.

After two measurements, one in dry and one in water saturated glass beads, the calibration data is done and stored in an Eeprom in the Trime probe connector.

- step 2: “Standard moisture” calibration

This standard calibration is calculated from the pseudo transit time \( t_p \) with a five order calibration function established for mineral soils.

\[
\theta_v = \sum_{i=0}^{s} c_i t_p^i
\]  

Each probe type (e.g. two or three rods) needs its own calibration function. The calibration coefficients \( C_0, C_1 ... C_5 \) are determined by measurements in several mineral soils at various water content.

- step 3: “Specific material moisture” calibration

This calculation is for the customer, to adjust the standard calibration coefficients to his particular soil.

\[
\theta_{vs} = c_0 + c_1 \theta_v + c_2 \theta_v^2 + c_3 \theta_v^3 + c_4 \theta_v^4 + c_5 \theta_v^5
\]
The customer takes measurements at different soil water contents in the soil he wants to calibrate the probe and he establishes relations between reference values (e.g. 105°C oven drying method) and TRIME values to create a table of measuring points. A calibration program calculates the coefficients $C_0$, $C_1$,..., $C_5$ and stores them in the probe connector.

$\Theta_{vs}$ is the value which is displayed on the screen of the probe. Factory setting is $C_1 = 1$ and $C_2$...$C_5$ are set to zero, so without specific calibration, $\Theta_{vs} = \Theta_v$ and the standard moisture is displayed on the screen.

**Probes design**

Most of the probes are two or three rods type. Some others are design for surface measurements, others to be introduced in access tubes. Noborio (2001) made a good review about design and installation of TDR probes. Laurent et al. (2001) studied the use of TDR Trime -tube system.

Davis introduced the two wire probe with an impedance matching transformer (in Noborio, 2001), but Spaans and Baker (1993) considered that an ordinal matching transformer is not suitable for electrical conductivity measurements (because the amplitude of the reflected signal decrease due to low frequencies attenuation). Yet an ordinal matching transformer with a 200 $\Omega$ TV antenna cable did not affect electrical conductivity measurements (Kachanovski et al., 1992, Ferré et al., 1998).

Three-wire type probes doesn’t need an impedance-matching transformer and give simpler waveforms with a more distinct reflection wave and a better determination of travel time which is suitable for measurements in saline conditions, but the reflection signal from the beginning of the probe differs in very dry and very wet soils.

Rectangular and flat probes have also been developed for surface measurements (Selker et al., 1993). Multipurpose TDR probes have also been developed, to measure simultaneously water content, heat capacity and thermal conductivity of soils (Noborio et al., 1996, Ren et al. 1999).

Probes are generally stainless steel made, and the minimum probe length is between 0.1 to 0.2 m for a 20 - 25 m cable length. The use of 200 $\Omega$ TV antenna needs impedance-matching transformer cable but not for 50 or 75 $\Omega$ coaxial cable. Yet for EC measurements it is important to have the same impedance between the cable tester output and the cable of the probe if using Eq. 11 (Giese – Tiemann 1975).

To minimise the skin effect around the rods Knight (1992) suggested that for two or three rods probes, $d/s = 0.1$ (with $d$ diameter and $s$ spacing) and Petersen et al. decreased to $d/s = 0.02$.

**Effect of air gap:** air gap around the rods can introduce errors of K measurements (Annan, 1977, Ferré et al., 1996), but EC is insensitive to quality of contacts between the rods and the soil (Nadler et al., 1991). Air gap surrounding less than 1/12 of rods circumference has no significant effect on the dielectric constant measurement, but three rods probes seems to be more sensitive to air gap than two rods ones (Knight et al., 1997). But Whalley (1993) found no difference about air gap.

**Effect of pilot holes:** there is a packing of the soil around the directly pushed probe (5 to 25% of increasing bulk density) which contributes to lower water content readings compared to probe installed with pilot holes (Rothe et al., 1997).
APPLICATION EXEMPLE

THE WATERSHED OF EL GOUAZINE (Tunisia)

The lake and the watershed

El Gouazine is situated in the centre of the Tunisian Dorsal mountain, at 50 km in the N-O of Kairouan. The climate is "semi-aride inférieur à hiver tempéré" classified (Gounot M., Le Houerou H.N., 1967) Annual rainfall is very erratic and can vary from 200 to 800 mm with a median rainfall of 358 mm (Ousseltia, 47 years). The rainfall for 1996-97 at El Gouazine was 252.5 mm.

The dam of El Gouazine was built in 1990. The dike is 232 m and 10.6 m high.

The initial volume of the lake was 233 370 m3 with a surface at overflow of 9 597 ha.

On 10/06/97, silting reached 16 030 m3 that is to say a useful volume of 217 340 m3.

The area of the watershed is large: 1694 ha but the difference of level is not so important, 199 m, for a slope index of 18 m/km. This watershed is long (11.3 km) and narrow (1.6 km). Most of the soils are developed on quaternary deposits (silt and clay), often with calcareous crusts. The higher parts are on geological calcareous outcrops of the end of upper cretaceous era (Campanien and Maestrichien).

Soil occupation is divided between forest (35%) and agriculture (55%). Forest with pine trees and xerophytic shrubs occupy the hilly parts. Annual crops (wheat and fallow) grow on lower parts with some olive trees. Range lands are on calcareous crusts. Nearly all the cultivated areas are protected by large benches.

The soil profile

Fig. 12 : Soil profile at El Gouazine station
The TDR station

The site is established on a slope (6 to 11%), protected by large new banks. Soil occupation is cereals and fallow.

2 kinds of data are collected:

- spatial soil moisture with a surface probe, on the area between two contour banks,
- linear variations along the slope with 3 groups of 2 probes.

One group upstream a contour bank (U1), the 2 others downstream (D1 and D2).

<table>
<thead>
<tr>
<th></th>
<th>U1</th>
<th></th>
<th>D1</th>
<th></th>
<th>D2</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>45-60 cm</td>
<td>P2</td>
<td>75-90 cm</td>
<td>P3</td>
<td>45-60 cm</td>
</tr>
<tr>
<td>P4</td>
<td>80-95 cm</td>
<td>P5</td>
<td>30-45 cm</td>
<td>P6</td>
<td>80-95 cm</td>
</tr>
</tbody>
</table>

Fig. 13 : TDR location at El Gouazine, Tunisia
The field measurement devices (IMKO GmbH)

For this kind of study, on a large area and in ploughing fields it is impossible to use a Datalogger with a network of connecting cables. The TRIME-FM is a portable instrument developed for mobile field use. The four lines of the LC-display are used to moisture %, TDR level, status and error messages, battery level. The TRIME-FM for 3 rods probes don't accept 2 rods probes. Three kinds of probes are used: one for surface measurements, one for upper layer (0-15 cm) and others for deeper measurements (P3Z probes), (fig. 14 and 15).

The probe for surface measurements is only available with a three rods technology. It means that if the surface probe is needed, all the other probes must be three rods probes unless to use tow TRIME-FM! The device has no inner memory, the datalogging is possible with a portable computer.

Fig. 14 : The 3 rods probes for 15 cm thickness measurements (from IMKO manual)

Fig. 15 : The probe for surface measurements (3 rods) (from IMKO manual)
Some results

Impact of a contour bank on soil wetness

![Contour bank at El Gouazine, Tunisia](image)

*Fig. 16: Wetness variation along the rainy season*
- The increase of water content is always higher for the upstream station (AM), so there is an effect of the collector dig.

- There is a better storage just downstream the bench (AV1).

- The table shows an increase of the water reserve in the soil, equal to rainfall just downstream the bank, and a bit lower for the farthest station.

### Surface soil moisture between two contour banks

**El GOUAZINE: Surface soil moisture, between two contour banks**

*measurements December 22. 1997*

<table>
<thead>
<tr>
<th>Humidité volum.%</th>
<th>AM 45-60</th>
<th>AM 75-90</th>
<th>AV1 45-60</th>
<th>AV1 80-95</th>
<th>AV2 30-45</th>
<th>AV2 80-95</th>
<th>Pluie</th>
</tr>
</thead>
<tbody>
<tr>
<td>09/01/99</td>
<td>22,1</td>
<td>23</td>
<td>17</td>
<td>12,1</td>
<td>13,3</td>
<td>11,6</td>
<td></td>
</tr>
<tr>
<td>26/01/99</td>
<td>32,4</td>
<td>34,2</td>
<td>30,5</td>
<td>27,4</td>
<td>30,6</td>
<td>22,2</td>
<td></td>
</tr>
<tr>
<td>Stocks mm</td>
<td>10,3</td>
<td>11,2</td>
<td>13,5</td>
<td>15,3</td>
<td>17,3</td>
<td>10,6</td>
<td></td>
</tr>
<tr>
<td>Stock 0-50 cm</td>
<td>51,5</td>
<td>67,5</td>
<td>86,5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stock 50-100 cm</td>
<td>56</td>
<td>76,5</td>
<td>53</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stock 0-100 cm</td>
<td>107,5</td>
<td>144</td>
<td>139,5</td>
<td>146 mm</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

This kind of measurement is coupled with the use of a Leica "laser tacheometer TC 805" to have the spatial position of each point of the TDR measurement on the field. The TDR data are obtained by the TRIME-FM connected to the surface probe. This use of a TDR probe is very efficient for a quick control of spatial variations of wetness. Figure 20 shows an example of this use between two benches, one part is a fallow area and the other one has been ploughed.
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