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THE TDR TECHNOLOGY FOR SOIL MOISTURE MEASUREMENTS

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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 witch 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 witch remains the reference. It don't needs 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 sever controls. It is one of the reasons why electric methods, already known, have been developed.

Capacitive probes have been developed (Tran Ngoc lan, 1970; Wobschall, 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 permitivity.

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.

Velocity in soil

Velocity in vacuum

$$v = \frac{C_0}{\sqrt{\varepsilon_r \cdot \mu_r}} \qquad [1]$$

Dielectric constant of soil

Magnetic permeability = 1 for non magnetic materials

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***

velocity

$$v = \frac{21}{t} \qquad [2]$$

transit time

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

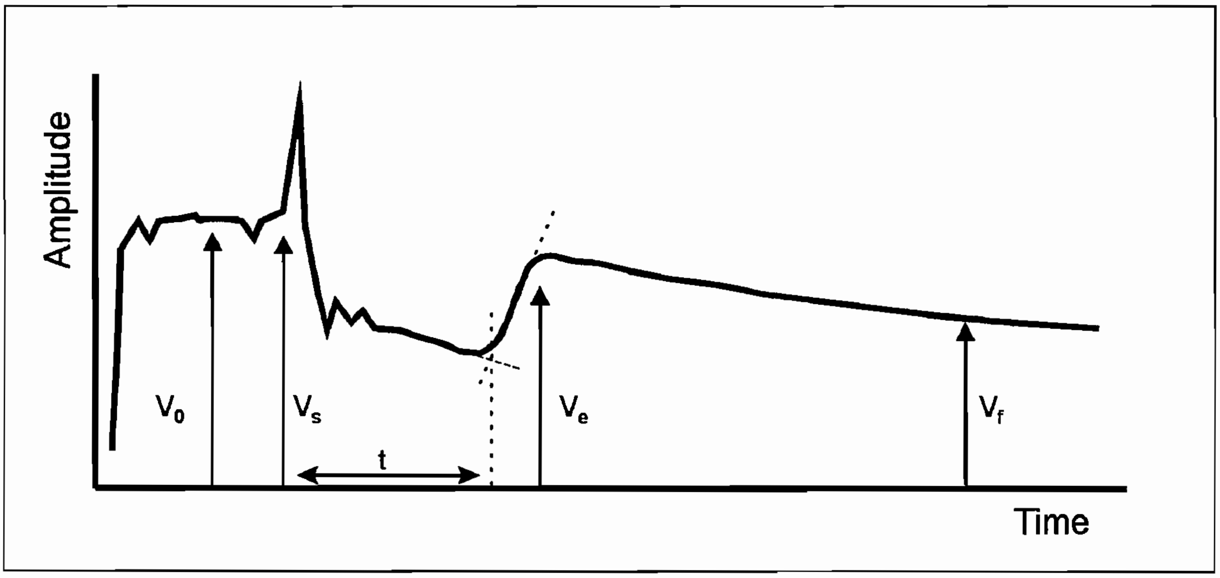

Fig. 1 : schematic TDR waveform

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.

$$t = \frac{2l}{C_o} \cdot \sqrt{\varepsilon_r} \qquad [3]$$

With

$$ta = \frac{0.3m}{3.10^8 ms^{-1}} \cdot \sqrt{1} = 1 \quad ns \qquad \text{And} \qquad tw = \frac{0.3m}{3.10^8 ms^{-1}} \cdot \sqrt{81} = 9 \quad ns$$

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 ε_r of a large number of soils and related it to volumetric water content Θ_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 $$\Theta_v = -5.3\ 10^{-2} + 2.92\ 10^{-2}\,\varepsilon_r - 5.5\ 10^{-4}\,\varepsilon_r^2 + 4.3\ 10^{-6}\,\varepsilon_r^3 \qquad [4]$$

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 :

Some researchers use this "universal" equation but expressed it with their own constants, others calculate calibration curve for mineral and organic soils (Roth et al., 1992) and i.e. Jacobsen and Schjonning (1993) includes organic matter, clay content and dry bulk density to improve the calibration.

- 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 α model where Θ_i and K_i are the volume fraction and dielectric permittivity of phase i and α is a soil geometry parameter.

$$K^{\alpha} = \sum_i \theta_i K_i^{\alpha} \qquad [5]$$

for a three phases system (air, water and soil matrix) α 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.

$$\Theta = (K_a^k - K_0^k) / (K_e^k - K_0^k) \qquad [6]$$

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

Ferré et al. (1996) Establish an other relationship

$$\Theta = e\sqrt{K_a} + f \qquad [7]$$

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).

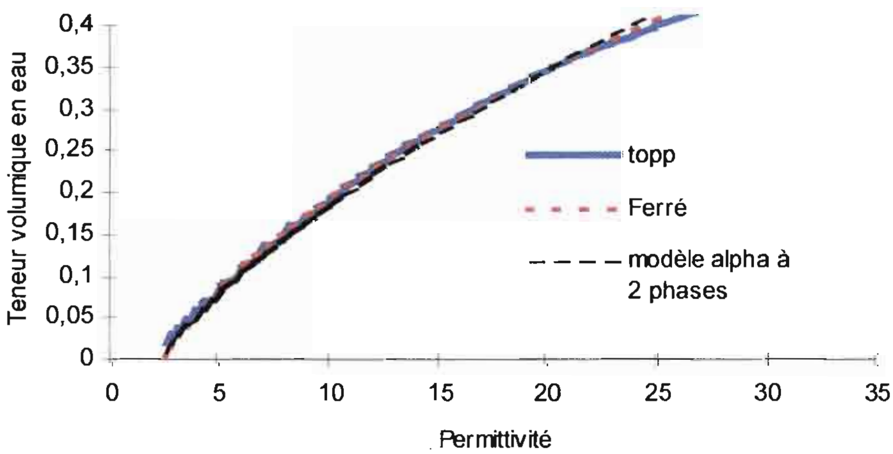

Fig. 2 : Topp third-order equation compared to Ferré and Roth mixing models (in Ruelle et al., 2000).

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

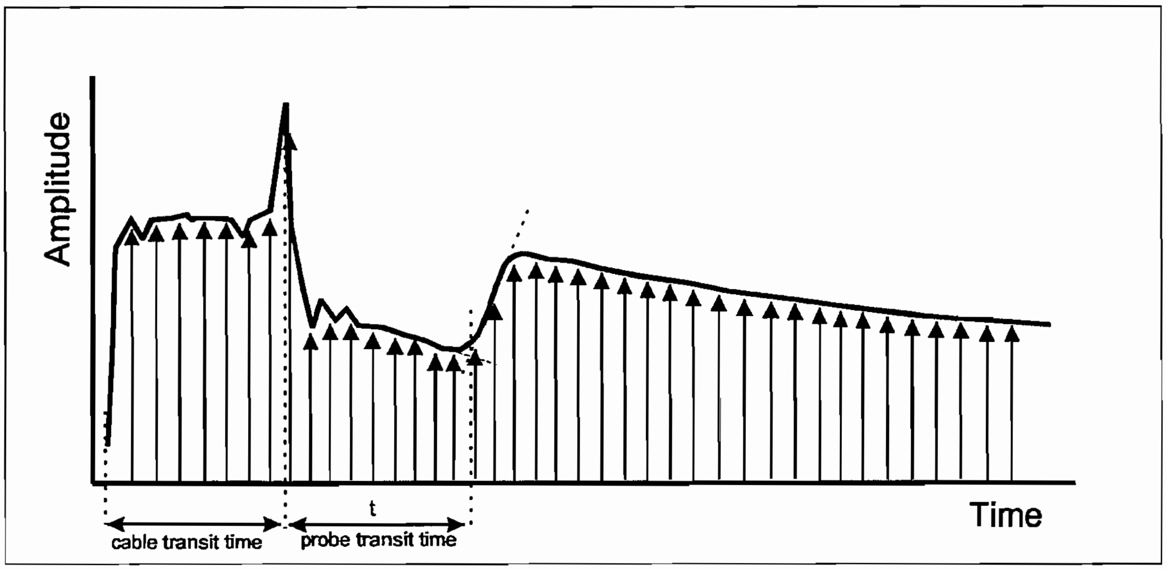

Fig. 3 : Classical TDR-pulse signal measurement (sampling technique)

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.

- IMKO Gmbh TRIME method

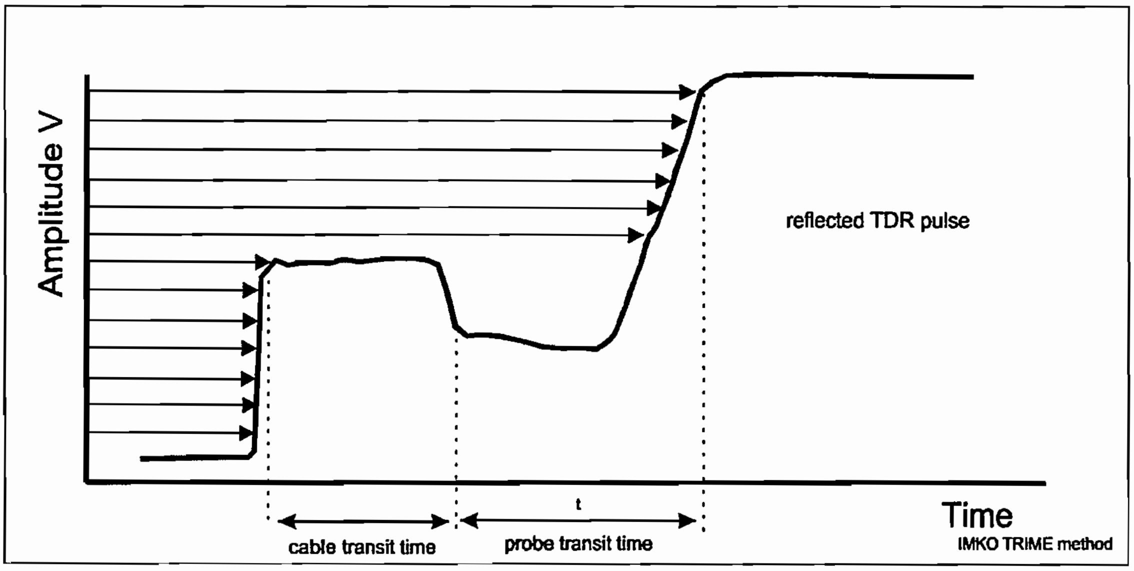

Fig. 4 : TDR pulse measurement with the TRIME Method (IMKO GmbH)

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:

$$t_p = \frac{t + A}{D} \qquad [8]$$

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 where 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.

$$\theta_v = \sum_{i=0}^{5} c_i t_p^i \qquad [9]$$

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.

Θ_{vs} is the value witch 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 Ω 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 witch 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 Ω TV antenna needs impedance-matching transformer cable but not for 50 or 75 Ω 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) witch contributes to lower water content readings compared to probe installed with pilot holes (Rothe et al., 1997).

APPLICATION EXEMPLE

<u>THE WATERSHED OF EL GOUAZINE</u> (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

0-30 cm: plowing layer on 12 cm, fresh to wet, brown, silty clay, fine subangular blocky structure, many fine roots, some calcareous pseudo-mycelium and soft nodules from 12 to 30,fine and medium

30-95 cm: dry, yellowish brown, silty clay, angular blocky structure when wet, massive when dry, some calcareous nodules, hard consistence, no roots.

> 95 cm : fresh to wet, yellowish brown, sandy clay loam, firm to friable consistence, fine pores.

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).

U1		D1		D2	
P1	P2	P3	P4	P5	P6
45-60 cm	75-90 cm	45-60 cm	80-95 cm	30-45 cm	80-95 cm

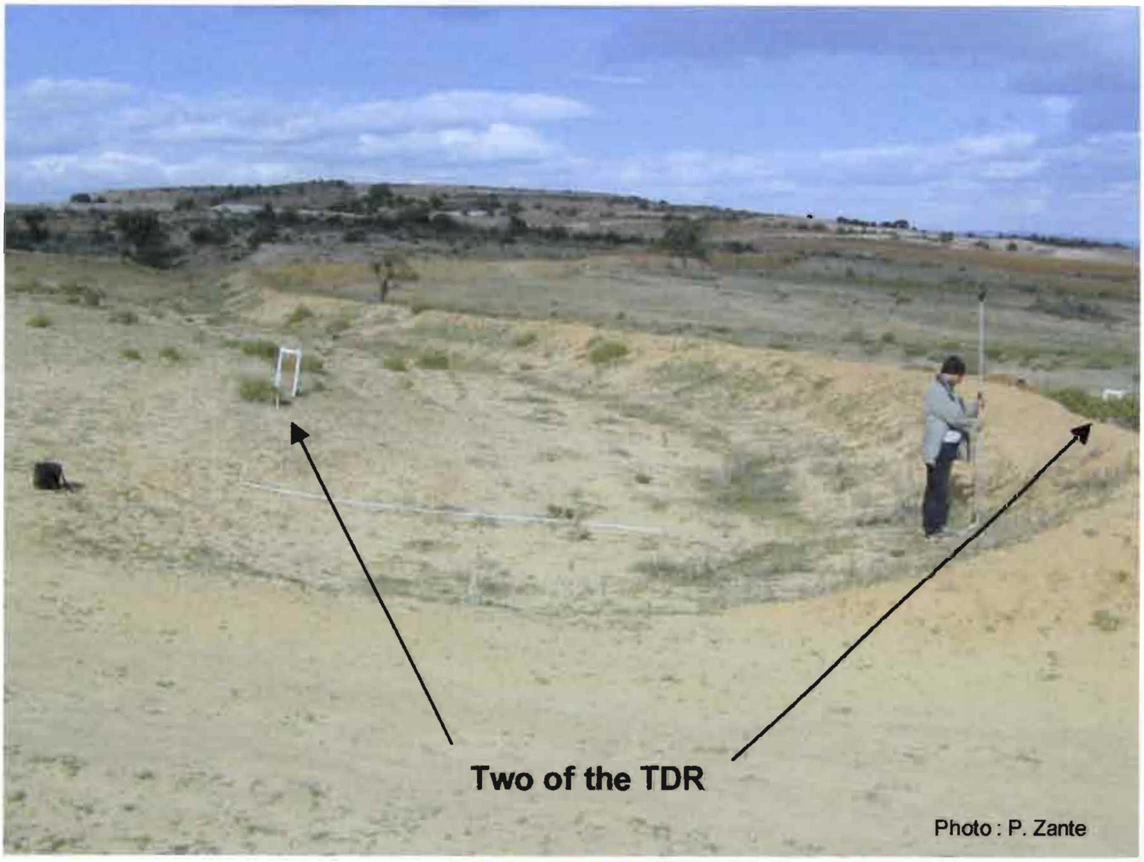

Fig. 13 : TDR location at El Gouazine, Tunisia

- <u>The field measurement devices</u> (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 protable computer.

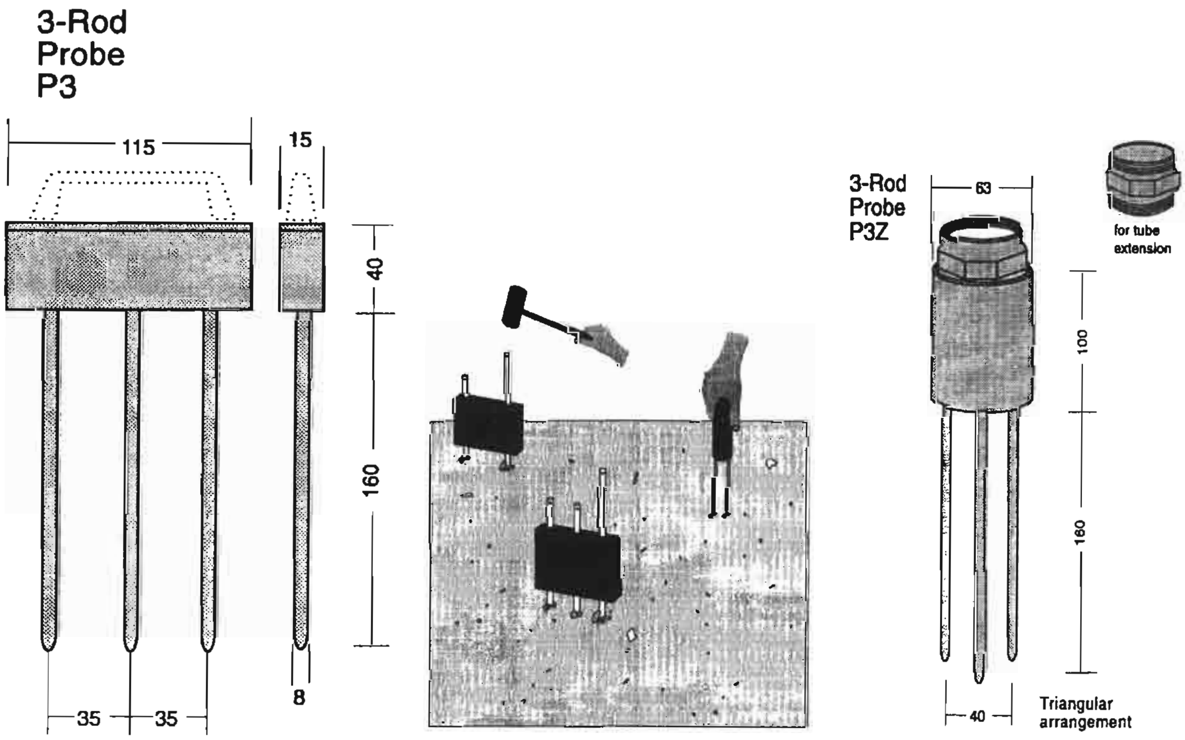

Fig. 14 : The 3 rods probes for 15 cm thickness measurements (from IMKO manual)

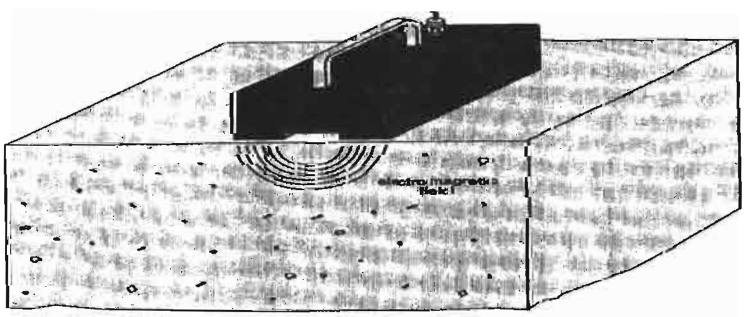

Fig. 15 : The probe for surface measurements (3 rods) (from IMKO manual)

Some results

Impact of a contour bank on soil wetness

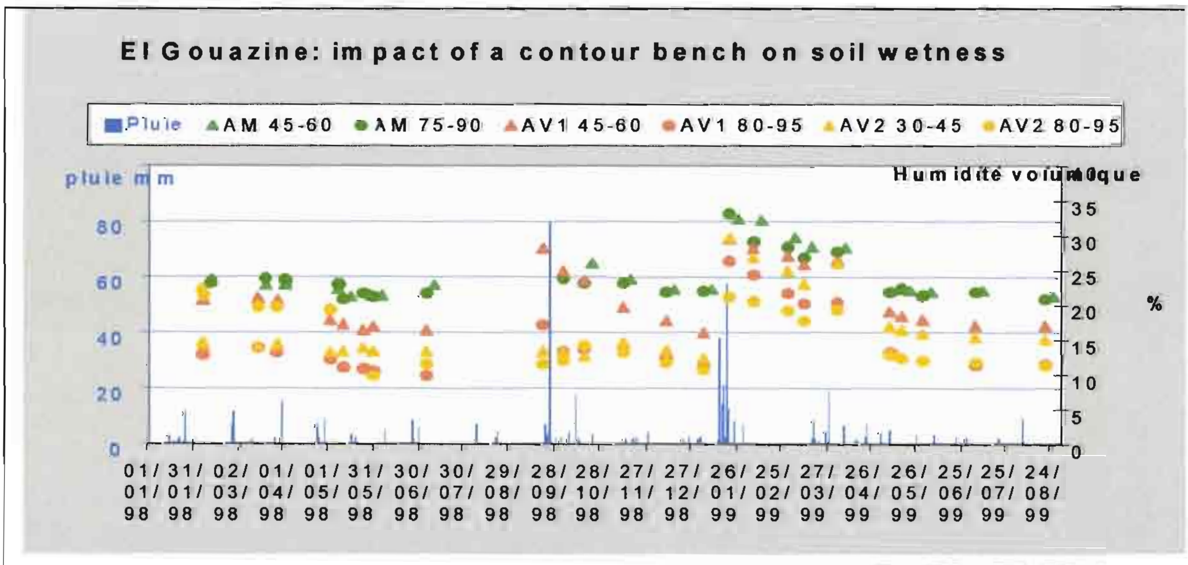

Fig. 16 : Wetness variation along the rainy season

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

- 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)

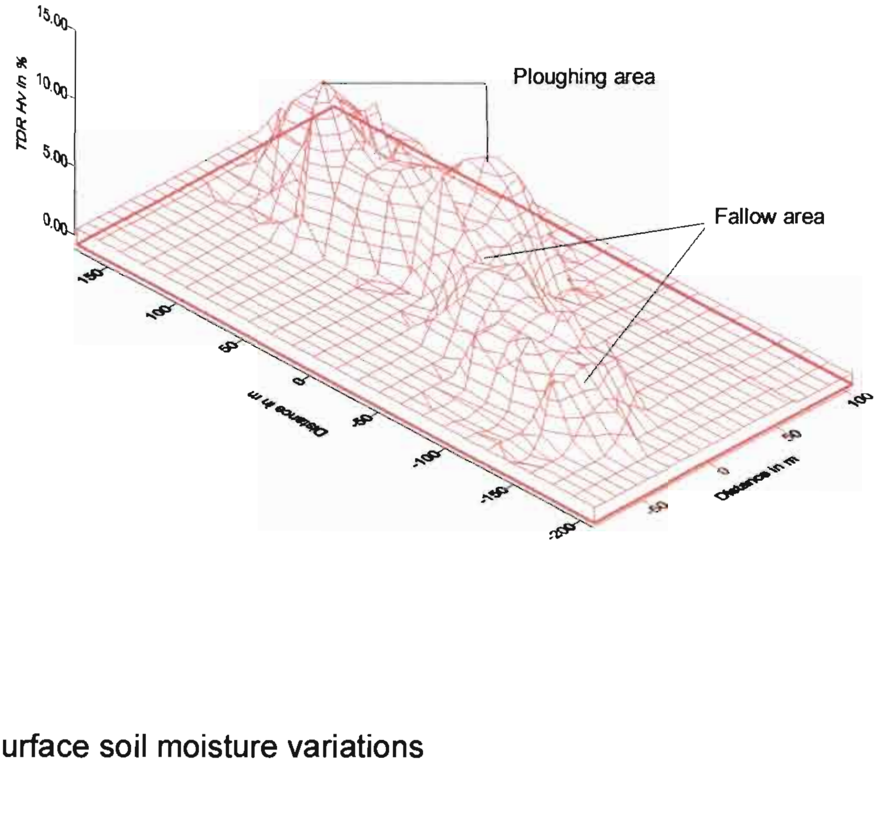

Fig. 17 : Surface soil moisture variations

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.

SOME REFERENCES

Web sites

- Campbell Scientific, inc.
http://www.campbellsci.com/centers/soil-a.html
http://www.campbellsci.com/tdr.html#probes

- ESI environmental sensors inc.
http://www.esica.com/products/index.html

- IMKO GmbH
http://www.imko.de/mitte.htm

- Soil moisture Equipment
http://www.soilmoisture.com/prodinfo.htm

- TEKTRONIX Inc.
http://www.tektronix.com/

Bibliography

Annan A. P., 1977: Time domain reflectometry: air gap problem for parallel wire transmission lines. Geol. Surv. Can. Paper, 77-1B, 59-62.

Birchak J.R., Gardner C.G., Hipp J.E., Victor J.M., 1974: high dielectric constant microwave probes for sensing soil moisture. IEEE 62: 93-98.

Dalton F. N., Herkelrath W.N., Rawlins D.S., Rhodes J.D., 1984: Time-domain reflectometry: Symultaneous measurements of soil water content and electrical conductivity with a single probe. Science, 224:989-990.

Fellner-Feldegg J., 1969: The measurement of dielectrics in time domain reflectometry. J. Phys. Chem., 73:616:623.

Ferré P.A., Rudolph D.L., Kachanoski R.G., 1996: Spatial averaging of water content by Time Domain Reflectometry: implication for twin rods probes with and without dielectric coating. Water Resour. Res., 32 (2): 271-279.

Ferré P.A., Redman J.D.,Rudolph D.L., Kachanoski R.G., 1998: The dependence of the electrical conductivity measured by time domain reflectometry on the water content of sand. Water Resour. Res. 34, 1207-1213.

Fumanal JC, Gaudu JC, Mathieu JM, Stengel P., 1989: Sonde capacitive pour la mesure in situ de la teneur en eau d'un sol. Brevet français 89.15135, 17/11/1989.

Gaudu JC, Mathieu JM, Fumanal JC, Bruckler L., Chanzy A., Bertuzzi P., Stengel P., Guennelon R., 1993: Mesure de l'humidité des sols par une méthode capacitive: analyse des facteurs influençant la mesure. Agronomie, Elsevier/INRA, 13, 57-73.

Giese K., Tiemann R., 1975: Determination of complex permittivity from thin –sample time domain reflectometry, improve analysis of the step response waveform. Adv. Mol. Relax. Process. 7:45-49.

Heimovaara T.J., Focke A.G., Bouten W., Verstraten J.M., 1995: Assessing temporal variations in soil water composition with time domain reflectometry. Soil Sci. Soc. Am. J. 59:689-698.

Imko GmbH, 1991: Operating manuel, TRIME-FM, 28p.

Imko GmgH, 2000: Trime Product Guide, 55p. www.imko.de/download

Jacobsen O.H., Schjonning P., 1993a: A laboratory calibration of time domain reflectometry for soil water measurements including effets of bulk density and texture. J. of Hydrol. 151:147-157.

Jacobsen O.H., Schjonning P., 1993b: Field evaluation of time domain reflectometry for soil water measurements. J. of Hydrol. 151:159-172.

Jacobsen O.H., Schjonning P., 1995: Comparison of TDR calibration functions for soil determination. In L.W. Petersen and O.H. Jacobsen (Ed.) Proceedings of the symposium: time-Domain reflectometry applications in science. Research Centre Foulum, denmark, 16/09/94. SP report n°11 vol. 3 pp. 25-33. Danish Institue of Plant and Soil Sci. , Lyngby, Denmark.

Kachanoski R.G., Pringle E., Ward A., 1993: Field measurements of solute travel times using time domain reflectometry. Soil Sci. Am. J., 56, 47-52.

Knight P.A., Ferré P.A., Rudolph D.L., Kachanoski R.G., 1997: A numerical analysis of the effects of coating and gaps upon relative dielectric permittivity measurements with time domain reflectometry. Water Resour. Res., 33, 1455-1460.

Laurent J.P., Ruelle P., Delage L., Bréda N., Chanzy A., Chevallier C., 2001: On the use of the TDR trime-tube system for profiling water content in soils. TDR'2001, Evanston-Illinois, USA 5-7 sept. 2001.

Nadler A., Dasberg S., Lapid I., 1991: Time domain reflectometry measurements of water content and electrical conductivity of layered soil columns. Soil Sci. Soc. Am. J. 55:938-943.

Noborio K., McInnes K.J., Heilman J.L., 1996, Field measurement of soil water content, heat capacity, and thermal conductivity with a single TDR probe. Soil Sci., 161, 22-28.

Noborio K., 2001, Measurement of soil water content and electrical conductivity by time domain reflectometry:a review. Comput. Electron. Agri., 31, 213-237.

Petersen L.W., Thomsen A., Moldrup P., Jacobsen O.H., Rolston D.E., 1995: High-resolution time domain reflectometry: sensitivity dependency on probe design. Soil Sci., 159, 149-154.

Persson M., 1997: Non-destructive measurements of solute transport in the unsaturated zone using Time Domain Reflectometry. Thesis, Report 3212, Department of Resources Engineering, Lund Institut of technology, Lund University, Sweden. pp. 1-48 + annexes.

Persson M., Berndtsson R., 1998a: Textural and electrical conductivity effects on temperature dependency in Time Domain Reflectometry. Soil Sci. Soc. Am. J., 62, (4):887-893.

Persson M., Berndtsson R., 1998b: Noninvasive water content and electrical conductivity laboratory measurements using Time Domain Reflectometry. Soil Sci. Soc. Am. J., 62, (6):1471-1476.

Ren T., Noborio K., Horton R., 1999: Measuring soil water content, electrical conductivity, and thermal properties with a thermo time domain reflectometry probe. Soil Sci. Soc. Am. J., 63, (6): 450-457.

Roth C.H., Malicki M.A., Plagge R., 1992: Empirical evaluation of the relationship between soil dielectric constant and volumetric water content as the basic of calibrating soil moisture measurements by TDR. J. Soil Sci. 43 : 1-13.

Roth K., Schulin H., Flühler H., Attinger W., 1990: Calibration of time domain reflectometry for water content measurement using a composite dielectric approach. Water Resour. Res. 26:2267-2273.

Rothe A., Weis W., Kreutzer K., Matthies D., Hess U., Ansorge B., 1997: changes in soil structure caused by the installation of time domain reflectometry probes and their influence on the measurement of soil moisture. Water Resour. Res., 33, 1585-1593.

Ruelle P., Zairi A., Ben Nouna ., Laurent J.P., Delage L., Quinones H., Ajmi T., 2000: Métrologie TDR des sols de la basse vallée de la edjerda et suivi de l'état a hydrique sous culture. Séminaire "économie d'eau en irrigation" Hammamet, Tunisie, 14-16 nov. 2000.

Schmugge T.J., Jackson T. J., McKim H.L., 1980: Survey of methods for soil moisture determination. Water Resour. Res., 27:961-979.

Selker J.S., Graff L., SteeenhuisT., 1993:Noninvasive time domain reflectometry moisture measurement probe. Soil Soc. Sci. Am. J., 57, 934-936.

Spaans E.J.A., Baker J.M., 1995: Examining the use of time domain reflectometry for measuring liquid water contend in frozen soils. Water Resour. Res. 31, 2917-2925.

Topp G.C., Davis J. L., Annan A.P., 1980: Electromagnetic determination of soil water content: Measurements in coaxial transmission lines. Water Resour. Res., 16:574-582.

Topp G.C., Yanuka M., Zebchuk W.D., Zegelin S., 1988: Determination of electrical conductivity using time domain reflectometry: soil and water experiments in coaxial lines. Water Resour. Res. 24:945-952.

Tran Ngoc Lan, Chaigne P., Philippe A., 1970: Expérimentation d'une méthode capacitive pour l'évaluation de l'humidité des sols. Bull. Liaison Lab. Ponts et Chaussées, 60, 155-165.

Whalley W.R., 1993: Considerations on the use of time domain reflectometry (TDR) for measuring soil water content. J. Soil Sci., 44, 1-9.

Wobschall D., 1978: A frequency shift dielectric soil moisture sensor. IEEE Trans Geosci Electron 16, 2, 112-118.

Yanuka M., Topp G.C., Zegelin S., Zebchuk W.D., 1988: Multiple reflection and attenuation of time domain reflectometry pulses: Theoretical considerations for applications to soil and water. Water Resour. Res. 24:939-944.