ON THE USE OF THE TDR TRIME-TUBE SYSTEM FOR PROFILING WATER CONTENT IN SOILS.

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ABSTRACT

The TRIME-tube system manufactured by the German company Imko has been designed for profiling water-content in soils. A specific cylindrical 18 cm long probe "T3" is successively positioned at different depths into a 42 mm inner diameter, 1 mm thick plastic access tube where TDR measurements are taken using the associated "TRIME-FM" instrument which directly converts measured transit-times in terms of soil water-contents displayed on its front-panel. The use of this system is particularly straightforward because all the TDR measurement parameters are automatically recognized by the electronics when the probe is plugged. As it can appears like a possible and interesting alternative to the classical neutron probe technique, the purpose of our group was to evaluate the TRIME performances compared to other independent soil moisture measurement methods. Five experimental sites, exhibiting various real field conditions, have been equipped with plastic access tubes (fiberglass, polycarbonate or PVC) and water-content profiles monitored over long periods. This paper summarizes the main results of these tests. The problem of TRIME-tube calibration is particularly highlighted and two possible approaches are proposed. Finally, propositions are made to optimize its use and improve the system itself.

INTRODUCTION

In most countries, the use of nuclear techniques in agronomy is now drastically limited or, even, forbidden. For this reason, as an alternative to the "Soil Moisture Neutron Probe" (SMNP) many dielectric sensors and instruments have been developed during the last twenty years for measuring soil water content. Most of them give only local or average water-contents and only a few systems have direct profiling capabilities. The Imko TRIME-tube system is one of these and, in the frame of the French national research program in hydrology (PNRH), we wanted to test its performances under real field conditions. We will first present briefly this system. Then, we will describe the experiments that we have realized to compare it to, either, SNMP or classical gravimetric technique. Finally, the problem of TRIME-Tube calibration will be discussed.

THE TRIME-TUBE SYSTEM

Description

The TRIME system has been developed for various applications and, talking only about soil water content, several instruments and probes are available [Imko, 2000]. The TRIME-tube system considered here (Fig. 1) consists in two parts : the "TRIME-FM3" and a specific probe : the "T3" probe. The TRIME-FM3 is a battery powered TDR instrument with an internal impedance of 75 Ω. The T3-probe is a cylindrical TDR probe designed to be easily positioned inside a plastic access tube. With an overall length of 20 cm, it has to opposites rows of 4 metallic plates that forms a two-rods 18 cm long wave-guide mounted on springs to ensure a good and regular contact with the inner face of the access tube.

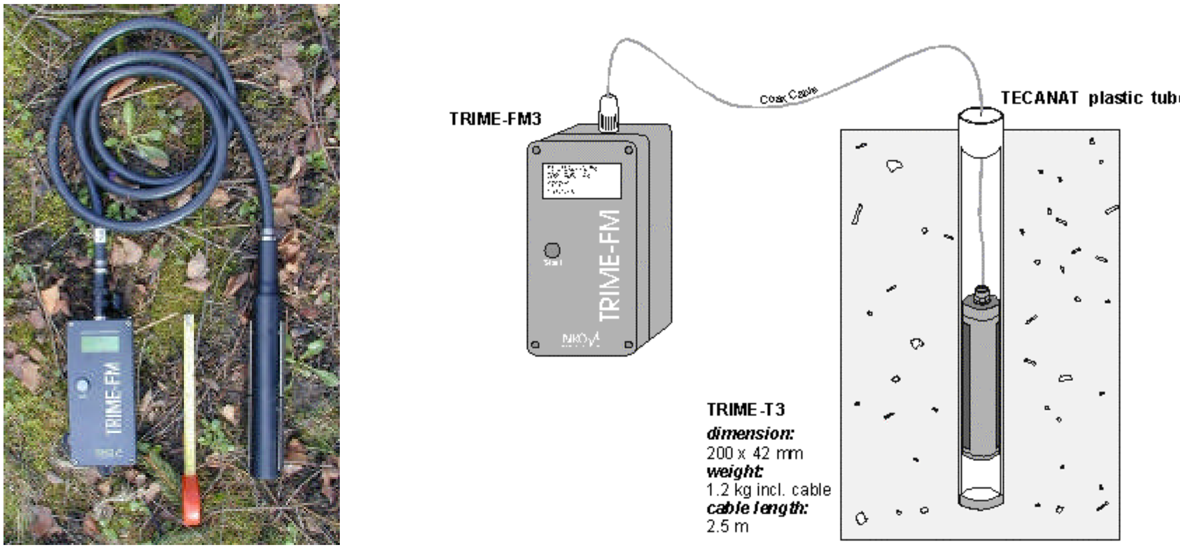

Fig. 1 : The TRIME-Tube system

Access tube installation

Correct installation of the access tube is a crucial point when using the TRIME-tube system. The objective is to keep the contact with the surrounding soil as good as possible. To allow wave propagation into the outer medium, TRIME access tubes must be made out of plastic materials. Initially, Imko sold fiberglass tubes which have been replaced, now, by polycarbonate Tecanat® tubes and we have also successfully tested PVC. The overall length of the T3-probe cable permits to work with access tubes up to 2.5 m but, in most cases, length of 1, 1.5 or 2 m are retained. TRIME access tubes have an inner diameter of 42 mm with a 1 mm wall-thickness. One can easily guess that introducing such relatively brittle tubes into a natural soil implies particular precautions and, actually, it's highly recommended to use a specific access tube installation kit. Two types are available from Imko (Fig. 2 from Imko TRIME-FM Operating Manual) but we consider that the "tripod" model in the one that offers the best guarantee of a good final result.

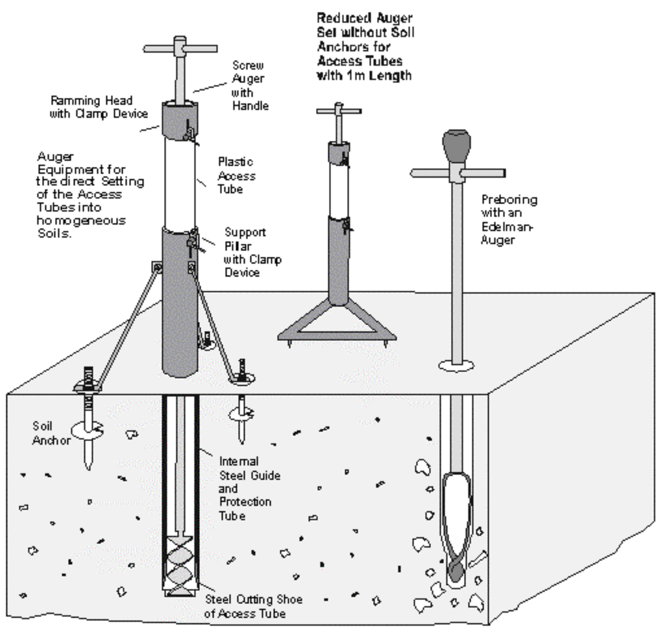

Fig. 2 : TRIME tube installation kits.

During the installation of the access tube with this tripod installation guide, a protection steel tube of the same length is placed inside the plastic tube to avoid to press directly on the top of it and to prevent abrasion when removing the soil with an auger. One has to proceed by successive steps – forcing down the whole set access tube + internal protection steel tube for approximately 10 cm striking with a sledge hammer on the ramming head, removing the corresponding excavated soil with the auger – again and again until the top of the tripod is reached that is to say about 45 cm above the soil surface. Then, the guide is removed and the installation is completed with the same procedure as described above without any mechanical guide. Three kind of problems may alter, or, even, compromise, this installation procedure : i) it's very hard to install tubes in dry soils. If it's compatible with further intended measurements, a solution may be to wet first the spots where the tubes have to been put in ; ii) on the contrary, high water contents can also create some problems : highly deformable soil consistency resulting in air gaps, difficulties to maintain the tube in place when extracting the auger ; iii) rocky soils present the worst situation : risks to break the tubes, locking at a given depth with the impossibility to go any deeper. If such conditions have to be faced, the only solution is to dig a hole with a diameter much larger, put the access tube in and refill with a material "similar" to the original soil which is not really easy to define clearly.

Signal processing and calibration

The TRIME-FM is a "push-button" TDR instrument. This means that it has, programmed in its internal electronics, all the signal processing and conversion functions necessary for displaying directly a water-content at the end of a measurement. It proceeds in four steps :

1. A transit-time t_p is measured by an original technique which can be schematized as follows (see "TRIME theory" section in [Imko, 2000]) : the starting of the TDR-generator rising step switches on a counter. Then a voltage comparator is active until the first reflection at the end of the probe is detected and the counter is stopped. The resulting counts is finally corrected to take into account the real shape of this reflection. This simple patented technique explains the relatively low cost of the TRIME-FM and its miniaturization degree. But, on the other hand, with this system, it is not possible to visualize full TDR-waveforms as other more sophisticated TDR instruments currently do. This is clearly a limitation when a physical interpretation of problematic results has to be searched for.

2. This measured transit-time (an integer) is then transformed into a "pseudo-transit-time" t'_p applying a linear relationship :

$$t'_p = \frac{t_p - Offset}{Divisor} \tag{1}$$

   where *Offset* and *Divisor* are two parameters adjusted normally once for all by operating a "basic calibration" of the TRIME-FM with its associated T3-probe. This operation is enabled by plugging a special "calibration-connector" on the left side of the device. At first approximation, this pseudo-transit-time can be seen as the part of the transit-time that is due to the propagation into the active part of the probe, only.

3. A "standard-moisture" q_1 is then calculated using a polynomial adjusted on measurements taken on several soils at various water-contents [Stacheder, 96] :

$$?_1 = -1.8161\ 10^{-1} + 1.9522\ 10^{-3}\ t'_p - 3.9357\ 10^{-6}\ t'^2_p + 2.4477\ 10^{-9} t'^3_p + 4.1356\ 10^{-12} t'^4_p - 3.0264\ 10^{-15} t'^5_p \tag{2}$$

4. Finally, a second "material-moisture" q_2 is evaluated again with a 5th degree polynomial :

$$q_2 = C_0 + C_1.q_1 + C_2.q_1^2 + C_3 q_1^3 + C_4.q_1^4 + C_5.q_1^5 \tag{3}$$

   where C_0, $C_1 \ldots C_5$ are the coefficients of a material calibration curve. This is this value witch is displayed on the LCD four lines screen of the TRIME device. Initially, $C_1 = 1$ and the other coefficients are set to zero. This means that, without any special calibration, $q_2 = q_1$ and the material moisture is taken as the standard moisture.

All the parameters appearing in (1), (2) and (3) are accessible trough the SM-TOOLS utility freely distributed by Imko (www.imko.de/download). It is extremely useful to store this configuration in a safe place when receiving a new system. Doing so will offer the valuable possibilities : i) of restoring the standard configuration in case of problem ; ii) of back-calculating pseudo-transit times if needed to re-calibrate afterwards existing TRIME measurements : see next section. The basic calibration already mentioned above is systematically done in the Imko factory. If an association TRIME-M/T3-probe uniquely characterized by its serial number is modified in any way, it has to be done again. For that purpose, the manufacturer recommends the use of two references media – dry and water-saturated fine glass-beads – conditioned in cylindrical containers of at least 20 cm diameter. The built-in basic-calibration procedure will adjust the display to 0 and 44 %, respectively, when taking measurements on the T3-probe placed successively in tube sections on the same type as the used access tube positioned vertically in the center of these two containers.

EXPERIMENTAL COMPARISON WITH THE SOIL MOISTURE NEUTRON PROBE

Experimental sites and measurement procedures

Two sites have been especially equipped for this experimental comparison : one in Grenoble in a urban environment and the other at the Lavalette experimental station of the Cemagref-Montpellier in a cultivated field. The installation in Grenoble took place in 1999 with three 1.5 m access tubes : Aluminum, Tecanat and PVC. During the whole summer and autumn 2000, measurements have been taken with a Troxler 4300 neutron probe and the TRIME S/N 7646. SMNP measurements were done on the three tube types. The installation in Montpellier has been realized in September 2000 with a single 1 m Tecanat tube in which systematic measurements with a SOLO 25 SNMP and the TRIME S/N 9112 have be done weekly until December 2000. In addition to these two main experiments dedicated only to the TRIME evaluation, three other sites of our French PNRH network (www.lthe.hmg.inpg.fr/medite) were also considered because of the particular problems they exhibit towards utilization of the TRIME-Tube technique. Table 1 summarizes the main characteristics of all these sites.

Table 1 : Main characteristics of the experimental sites considered here for evaluating TRIME performances

Place	Coordinates	Environment	Soil
Grenoble, University Campus	45°7' N 5°53' E	Urban area, Grass	Sandy Loam, negligible clay, low electrical conductivity pore-water
Montpellier Lavalette Station, Cemagref	43°40'N 3°50' E	Cultivated Soil	Silty-sandy-clayed texture, calcite
Avignon, St. Paul Station, INRA	43°57 N 4°48' E	Cultivated Soil , Calcite	Silt-loam (27% clay, 11% sand), calcite
Champenoux, INRA-Nancy	48°44' N 6°20' E	Forest	Silty Clay Loam, enriched clay horizon (45% Clay), hydromorphic
St Laurent de la Prée, INRA	45°59' N 1°1' O	Humid zone, Wheat, Corn, Grass	Nearly 100% clay : "Bri" (Chlorite)

Main results and discussion

When comparing straightforwardly SNMP data and TRIME measurements gathering all depths and dates for one tube (see examples of Fig. 3), it appears very clearly that the TRIME with its standard calibration over-estimates soil water-contents. This is particularly obvious at high water-contents. This results is somewhat surprising because earlier works [Laurent, 00] have shown a fairly good agreement between SNMP and TRIME-tube measurements without any particular calibration. Of course, we have tried to explain this behavior by verifying the validity of the standard calibration relation (2). For that purpose, since our TRIME-FM devices were initially factory-calibrated, we have inverted our water-contents readings q_1 in terms of pseudo-transit times t'_p using the following inverse form of (2) :

$$t'_p = 127.81 + 111\ ?_1 + 14956\ ?_1^2 - 65014\ ?_1^3 + 129340\ ?_1^4 - 1.35\,10^5\ ?_1^5 + 7.07\,10^4\ ?_1^6 - 1.45\,10^4\ ?_1^7 \qquad (4)$$

Plotting now SNMP water-contents vs. pseudo-transit times (Fig. 4), back-calculated by (4), illustrates that, at least for the cases of Grenoble and Montpellier, the corresponding points significantly deviate from the standard calibration (2). Two kinds of explanation can be proposed to justify this difference : i) the considered soils have "non-standard" dielectric behaviors or ii) "something" has changed since the standard calibration (2) has been established by Imko following the works of Stacheder [Stacheder, 96]. The former hypothesis is not likely to be predominant : we know the physical and dielectric properties of these soils and TDR measurements taken in it with other TDR systems have shown that offsets from the "standard" well-known Topp polynomial they could exhibit were interpretable in terms of fluctuations in measurable factors like density or mineralogical composition. On the hand, some elements in the TRIME-tube design might have altered the validity of the original standard calibration : replacement of the initial fiberglass tubes by polycarbonate, some changes in the electronics, in the signal processing algorithms ? … At the moment we write this paper, the question remains opened.

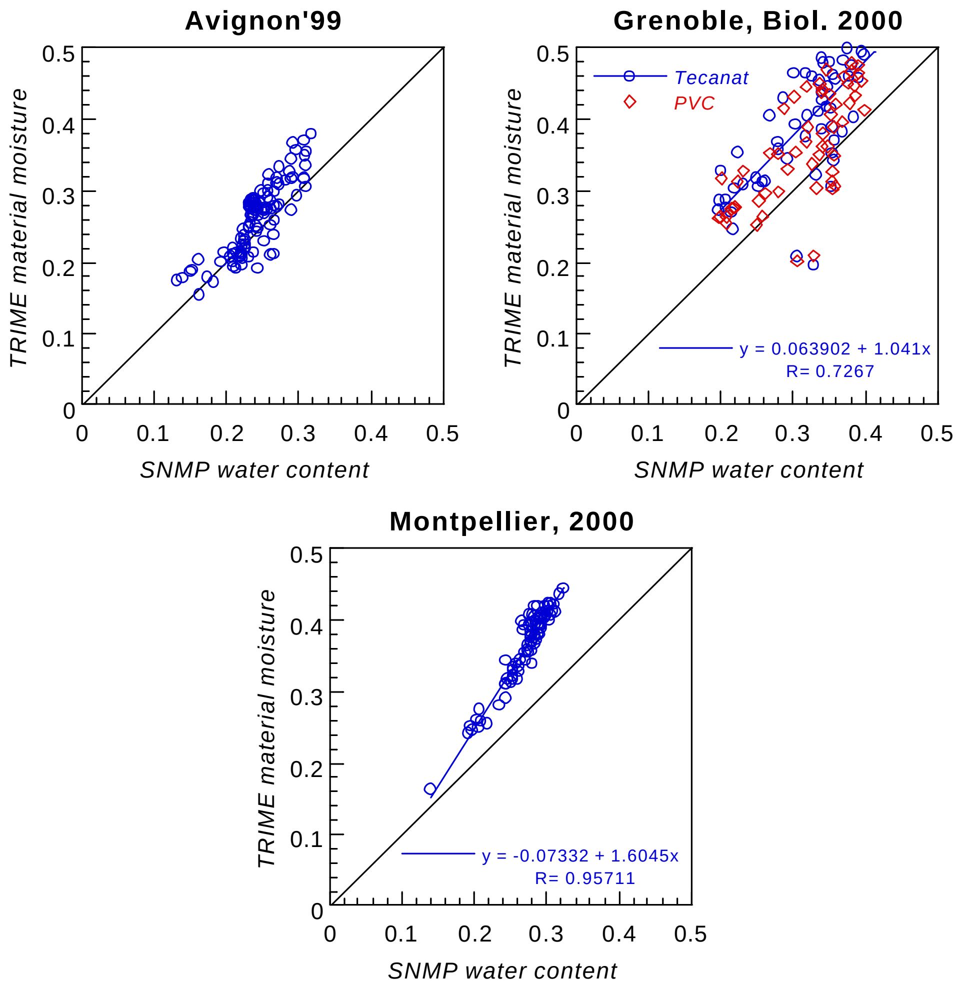

Fig. 3 : Direct comparison of measured water-contents for all dates and depths for three experimental sites.

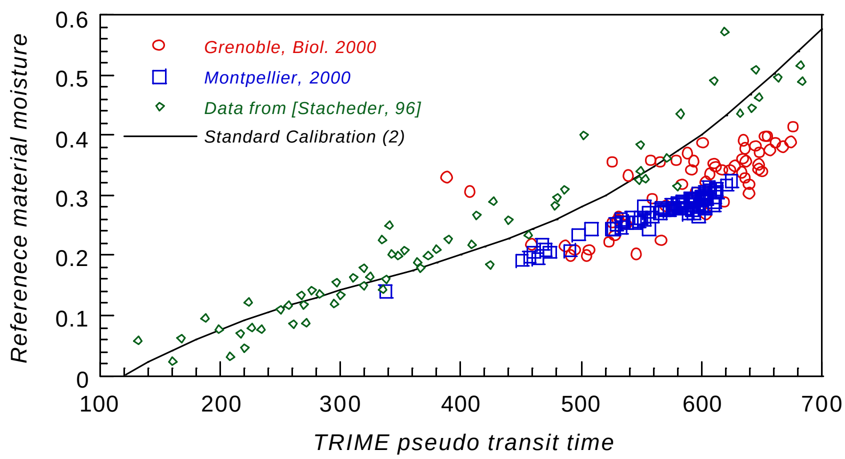

Fig. 4 : Deviation of our results on two sites from the TRIME standard calibration curve (2)

Nevertheless, even with this observed discrepancy, the TRIME-tube method can be set operational taking the opportunity of introducing a specific material calibration (3). As first approximation not taking into account the influence of different soil horizons, correlations like those of Fig. 3 can be used to build a linear correction q_2 = a + b x q_1 between the standard moisture q_1 and the corresponding "true" material moisture q_2. On our data, this simple approach yields a = 0.6243, b = 0.045 for the soil of Montpellier and a = 0.9605, b = -0.0614 for Grenoble. This correction has proved to be satisfactory both in terms of water-content profiles (Fig. 5) or water storages : Fig. 6. Doing this empirical calibration is more or less equivalent to calibrating a neutron probe. Here, SMNP measurements were taken as reference but, of course, the neutron probes we used were calibrated against gravimetric water-content measurements. Thus, these sampled gravimetric moistures could have been used directly to calibrate the TRIME measurements exactly like the common procedure for neutron probes.

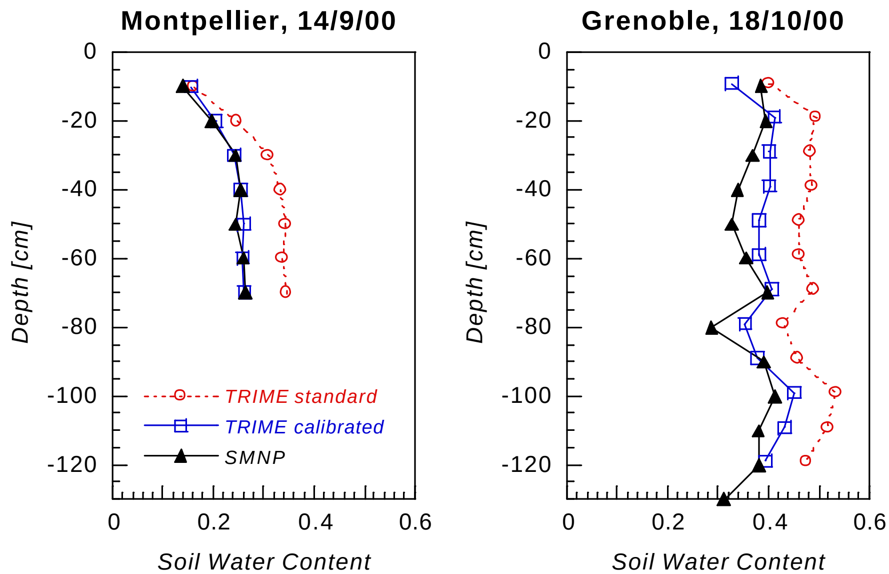

Fig. 5 : Examples of comparison of soil moisture profiles before and after TRIME calibration.

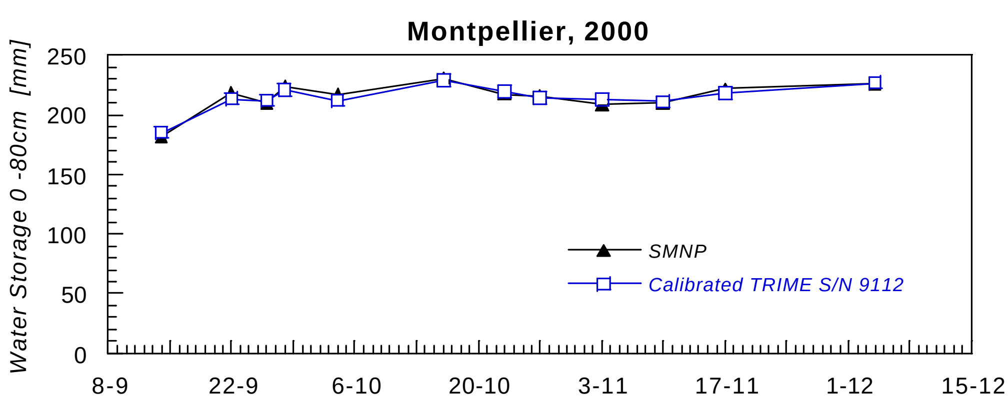

Fig. 6 : Example of water storage monitored by a calibrated TRIME compared to its equivalent estimated from SMNP data.

Moreover, we found out that TRIME-tube measurements on long periods have a good and realistic dynamic response : see example on Fig. 7. Water-content variations were always visible even near the surface and their hydrological interpretation in relation with external stresses (rain intake, evaporation) or internal processes (root uptake, infiltration, drainage) in agreement with what we knew and measured on the observed systems. Particular soil profile organizations were also detectable (for example, the soil profile on Fig. 7 has clearly three-layers central part acting as "capillary barrier") and the above described calibration technique can be applied independently to each layer to refine water-profile monitoring. For all these reasons, we consider that the TRIME-tube system offers real profiling capabilities even if a specific calibration is still needed.

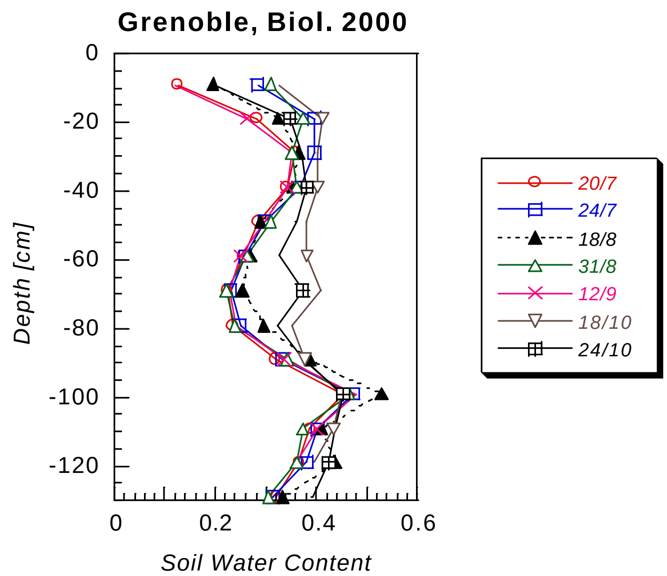

Fig. 7 : Example of water profile monitoring with a TRIME-tube system.

TENTATIVE DEVELOPMENT OF A "PHYSICAL" TRIME CALIBRATION TECHNIQUE

The empirical – or "field" – calibration method proposed in the previous section may be sufficient for many applications but it has some disadvantages : i) a field campaign will have necessarily two phases : a first in which measurements are gathered to build a calibration curve and a second when it can be used or re-applied to previously acquired data ; ii) in a given field situation, the whole range of water-content, texture, density… is rarely accessible. Therefore, it would be very useful to develop a more general calibration approach for the TRIME-tube technique. Of course, the built-in standard calibration curve (2) could probably be improved but we think that it would better to try to develop a more physically based approach. To go in this direction, we suggest to split the problem in two parts : instead of converting directly measured pseudo-transit times into water-contents, let us first consider the relation between the quantity measured by the instrument (pseudo transit time, for instance) and a parameter characterizing the dielectric properties of the surrounding soil (propagation time, dielectric constant) and then, only, the relation between this parameter and the water-content. Presented like this, it's easy to see that this latter calibration is not different of what is required for other types of TDR measurements and we can hope to solve the former – than we can call "instrument calibration" – once for all.

To investigate this instrument calibration problem, experiments have been made both in the field and in our laboratories. Immediately, a difficulty has to be faced : although pseudo-transit times measured by the TRIME-FM instrument are directly accessible when it is controlled under the SM-TOOLS utility from a PC through its serial interface, we have already mentioned that it is not possible to visualize its TDR-waveforms and, consequently, no classical TDR analysis can be made. To overcome this problem, a special DIN-BNC adaptor have been wired that allows TDR waveforms to be acquired connecting a Tektronix 1502B/C or a Trase system at the extremity of the T3-tube probe cable. Fig. 8 shows how such TDR waveforms look like. With this "trick", we are able to determine which propagation time is really "seen" by the probe inside its access tube and to quantify the permittivity K_{mes} the TRIME should measure in these conditions. Fig. 9 illustrates measurements acquired with this procedure on reference media listed in Table 2. This kind of tests clearly shows that – at least for the investigated experimental conditions : negligible electrical conductivity, good contact between a liquid and the tube – the pseudo-transit time t'_p measured by the TRIME-FM device is actually a realistic image of the "true" TDR waveform propagation time along the active part of the T3-probe. Moreover, it provides empirical models of the soil permittivity K vs. measured permittivity K_{mes} or K vs. t'_p relationships.

At Avignon during summer 1999, we tried to verify these relations under real field conditions comparing K_{mes} data with corresponding K measurements taken directly on three-rods TDR probes placed in the surrounding soil. The results were somewhat disappointing. Two main reasons could explain that : i) water-content spatial variability on short distances ; ii) dependence of the above mentioned relations on soil/tube contact nature and quality. Of course, if the latter is the principal explanation, it would reduce the interest of the suggested instrument calibration which should be then re-done or adapted for each new installation. To clarify this point, we are now in the process of designing laboratory experiments on undisturbed core-sample of soils of all our sites. Numerical simulation of the TRIME measurement could also help.

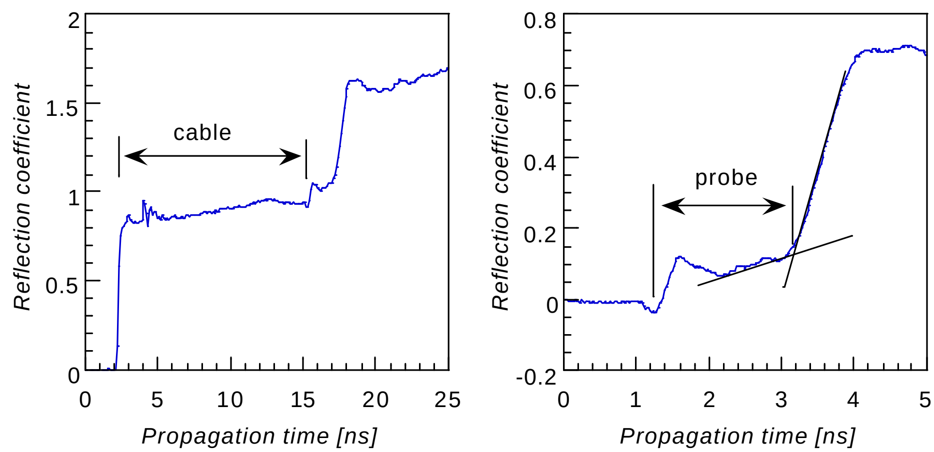

Fig. 8 : Example of TDR signals acquired with a Tektronix on a T3-Probe. Water-saturated glass beads. Left : complete signal, right : detail of the useful part corresponding to the propagation in the probe itself.

Table 2 : TRIME and TDR measurements on the T3-Probe in reference media. Tecanat tubes. t'_p : pseudo transit-time measured by the TRIME-FM, t_p : real propagation time determined on the acquired TDR waveforms, K_{mes} : corresponding measured permittivity inside the tube, K : material dielectric constant measured with a three-rod 20 cm long probe

	t'_p	t_p [ns]	K_{mes}	K
Air	-1.7	1.73	2.08	1.12
∅ 4 mm dry glass beads	123.8	1.85	2.38	2.90
∅ 450µm dry glass bead	129.1	1.91	2.53	3.69
Ethanol-saturated ∅ 4 mm glass beads	400.8	2.66	4.91	13.12
Ethanol	590.1	2.94	6.00	22.75
Water-saturated ∅ 4 mm glass beads	608	3.18	7.02	31.56
Distilled water	803	3.71	9.56	76.61

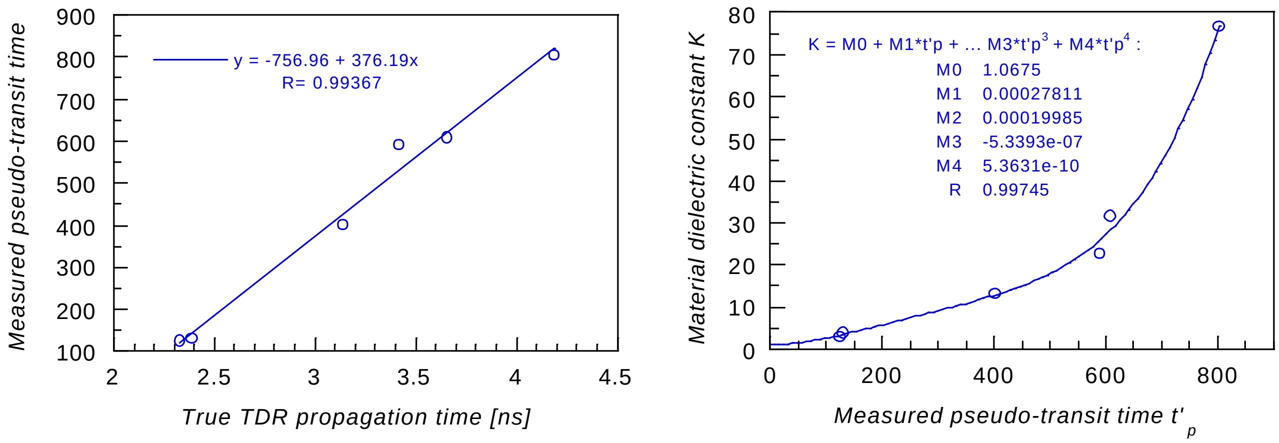

Fig. 9 : TRIME and classical TDR measurements taken in reference media of Table 2.

Nevertheless, unless we consider that TRIME instrument calibration is still an ongoing research topic for us, we have applied the above conceptual frame to two unsolved problems concerning the application of this system : i) at St. Laurent de la Prée, in the western part of France near the sea, TRIME measurements taken in long 2.5 m tubes installed in a humid zone led to erroneous very high water content readings : Fig. 10 left ; ii) at Champenoux, in the eastern part of France, the same kind of measurements in a forest environment gave fairly erratic results : either the instrument displayed more or less realistic water-contents or the measurement were impossible because of an internal error "Salinity too high".

We have been able to solve the first one in the following manner : TDR waveforms have been systematically acquired with a Trase on the T3-probe positioned at every depths and the corresponding permittivity K_{mes} determined on it. A $K(K_{mes})$ relation has been assumed and the soil permittivity K vs. water-content was supposed to follow the Topp polynomial. So, it has been possible to build a set of reference material moistures which plotted versus TRIME readings allow to adjust a material moisture calibration : Fig. 10, right. This calibration introduces clearly a very strong "correction" which can be justified by the particular nature of the considered soil (Table 1).

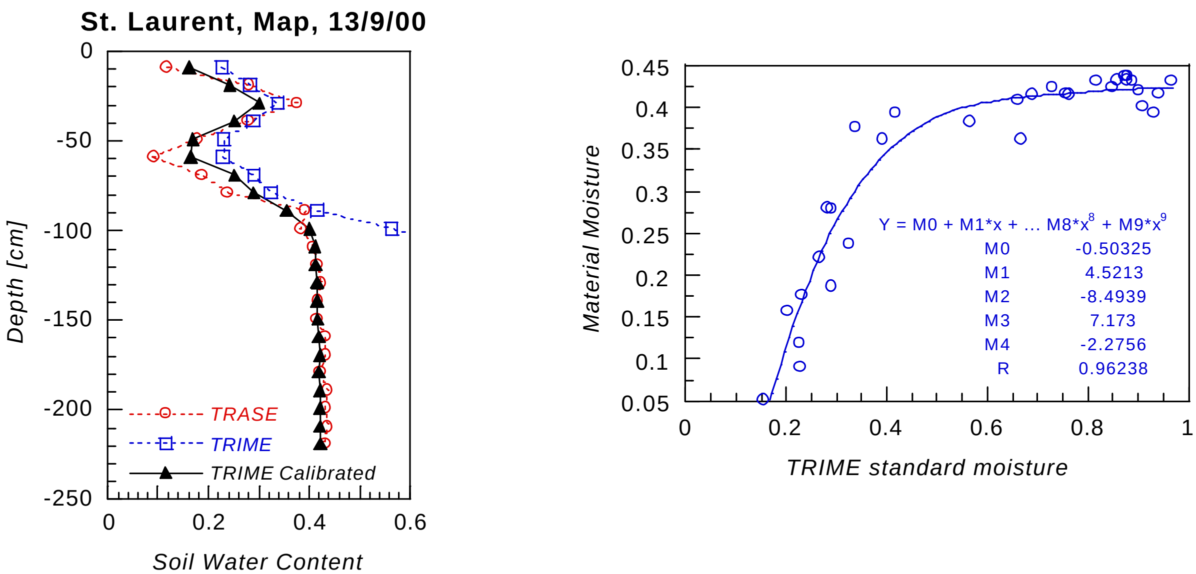

Fig.10 : Calibration of the TRIME-tube measurements at St. Laurent de la Prée (see text).

We try to reproduce this procedure at Champenoux but we failed although SMNP et gravimetric data were also available for this site. The reason for this is illustrated on Fig. 11 : reflections at the end of the probe exhibit heavy scattering. The deeper the measurement is acquired, the smoother the reflected pulse. This drives the TDR-level on the propagation step to fall under the level on the incident step and the internal algorithm of the TRIME-FM is not designed to treat correctly such a situation.

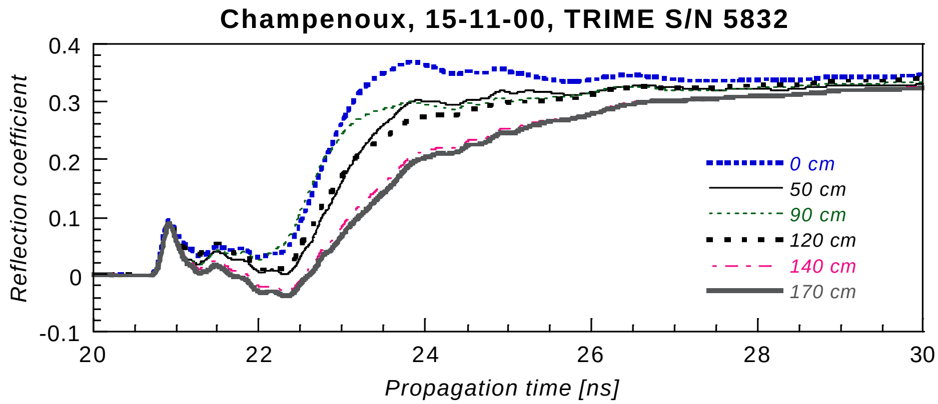

Fig. 11 : Examples of TDR-waveforms acquired on the T3-probe in a tube in the Champenoux forest.

Among our sites, Champenoux is not the one with the highest clay content. The electrical conductivity is not particularly high, either. Complementary works have then to be undertaken to understand why such relaxing behavior has been observed and to evaluate the probability of finding again such a situation.

CONCLUSION

The TRIME-tube method for profiling soil water content have been extensively tested in various real field conditions. The results have been compared with independent water-content measurements. Complementary laboratory tests have been undertaken to clarify some points about the TRIME internal calibration and signal processing. An adaptor have been developed to be able to connect directly a T3-probe on a classical TDR-system in order to analyze more closely the physics of such a TDR measurement inside an access tube..

At the end of this work, we consider that : i) in most cases, the TRIME-tube system is really operational for profiling soil water-content ; ii) it has to be calibrated. For that purpose, a simple field calibration similar to that of a neutron probe can be applied ; iii) when calibrated, it leads to fairly accurate and sensitive readings that can be used for monitoring a profile on long periods.

Some points can be improved : a parameter directly linked to the internal measurement (pseudo-transit time, for instance) should be always displayed, the standard calibration may be updated, the ergonomics of the installation guide could be enhanced… Nevertheless, the Trime-tube is already one of the very few dielectric soil water-content profiling systems designed especially for soil physics. From a theoretical point of view, the relation between the permittivity measured inside the tube and the soil permittivity outside has to be investigated both experimentally and by numerical simulation. This is a condition for developing a more general, physically based, calibration approach.

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