The time-domain reflectometry: theory, principles and applications

Santini A., D'Urso G.

in

Kirda C. (ed.), Steduto P. (ed.).
Soil water balance and transport processes: Review of theory and field applications

Bari : CIHEAM
Cahiers Options Méditerranéennes; n. 46

2000
pages 113-145

Alessandro SANTINI

Agric. Hydraulic Institute

University of Naples

NAPLES

ITALY

Guido D'URSO

APES Department

University of Molise

CAMPOBASSO

ITALY

The TIME-DOMAIN REFLECTOMETRY: THEORY, PRINCIPLES and APPLICATIONS

INTRODUCTION

The measurement of soil water status is of great importance in many studies involving agriculture, hydrology and water resources management. In agricultural and forestry problems, the soil water status influences plants growth and nutrient distribution within the root zone; it is a conditioning factor in the root zone aeration and in the soil gaseous exchanges, with direct consequences on the activities of the radical apparatus and of living micro-organisms and on the chemical processes of oxidation-reduction. The soil water status influences infiltration and run-off processes and it determines the partitioning of solar net radiation into latent and sensible heat flux in evapotranspiration phenomena. In irrigation practice, the continuos monitoring of soil water contents allows for the assessment of optimal criteria for water allocation. Furthermore, many soil mechanical and hydraulic properties depend on the soil water content, such as consistency, plasticity, conductivity; in clay soils, shrinking and swelling are direct consequences of variation in the soil water content.

Therefore, several methodologies with an always increasing technological level have been defined for evaluating soil water status, either continuously or at fixed time steps, with special attention to field conditions. These methodologies can be distinguished in direct and indirect ones. In the first case, soil water content is generally determined with destructive soil sample analysis, e.g. the widely used gravimetric method. The use of direct methods is severely hampered when a large number of samples or repetitive determinations are required.

The second category includes technique based on the measurement of other physical or chemical-physical properties which are strongly related to soil water content. In general, these techniques do not involve necessarily the destructive sampling and they require the use of instrumentation and sensors which can be either permanently installed in the soil or located on remote platforms (towers, aeroplanes or spacecraft). Indirect methods are generally particularly well suited for repetitive and automated measurements. Although the time required for the measurement itself is rather short in most cases, the additional cost of calibration may result a limiting factor when the relationships between the observed variable and the soil water content is of particular complexity.

Among the indirect methods, those techniques based on the relationship between soil water content and soil dielectric properties have greatly enhanced in the last decade due to progresses in electronics and to the development of remote sensing by means of active and passive microwave systems. The Time Domain Reflectometry, which will be examined here in detail, belongs to the sub-category of "capacitance methods" (Kutílek and Nielsen, 1994), which are based on *in-situ* measurement of soil dielectric behaviour.

DIELECTRIC METHODS

The dielectric properties of a generic material subjected to an electromagnetic field depend on the molecules polarisation of the material itself and they can be quantitatively described by means of the relative dielectric permittivity ε given by the following complex relationship:

$$\varepsilon = \varepsilon' - i\left(\varepsilon'' + \frac{\sigma_{cc}}{2\pi f\, \varepsilon_0}\right) \tag{1}$$

where i is the imaginary unit ($i=\sqrt{-1}$), ε_0 is the permittivity of free space ($\varepsilon_0 = 8.85 \cdot 10^{-12}$ F/m), f is the frequency and σ_{cc} is the d.c. electrical conductivity. The real part of permittivity in Eq.1, represents the quantity of stored energy due to orientation of dipoles and it slightly varies when the frequency lies below the threshold value of dipoles relaxation, f_R. The reciprocal of f_R is the time constant which characterises the decaying process of polarisation phenomenon consequent to the removal of the electromagnetic field. For pure water, the relaxation frequency is about 17 GHz. When the frequency is higher than f_R the dipoles are not susceptible any more to field variations; thus, the possibility of storing energy is reduced and the value of ε' rapidly decreases when the frequency approaches the visible spectrum region. In Eq.1 the imaginary part takes into account of energy losses in the medium with a peak value in correspondence of relaxation frequency.

When considering a heterogeneous medium with a complex structure, such as a wet soil which can be seen as a three-phase mixture of air, water, mineral and organic solid particles, a detailed description of dielectric behaviour is very difficult, especially at low frequency (Hoekstra et al., 1974); indeed, complex phenomena occurs such as interfacial polarisation induced by electric charges on the surface of empty pores, different relaxation effects and energy losses due to ionic and electronic resonance. Most of these phenomena vanish when operating at frequency higher than 50 MHz; this holds especially for macroscopic dipoles that are not sensitive to field variation and therefore they do not influence the permittivity. In the range of frequency from 50 MHz and 2 GHz the soil permittivity is basically determined by the volume fraction of air, water and solid particles; considering that the permittivity of water ($\varepsilon' \approx 80$) is much higher than that of air ($\varepsilon'=1$) and of solid phase ($\varepsilon'=3$–7), the value of soil permittivity is mainly dependent on the amount of dipoles in the water molecules. Because of bound water effects, the soil permittivity rapidly drops to unity at frequencies higher than 2 GHz (lower than the relaxation frequency of water).

Therefore, when operating in the frequency range [0.05÷2 GHz] the soil permittivity is very sensitive to variations of soil water content and their reciprocal relationship can be determined more easily. Two main techniques for measuring soil water content rely on the relationship between soil permittivity and soil water content. In the first case, capacitance measurements with conductors of various shape and the soil as dielectric medium allow an estimate of the real part of soil permittivity for frequency between 10 MHz and 100 MHz (Dean et al., 1987). In spite of their low cost and easy automation, the measurement technique is sensitive to geometry of sensors, small scale soil heterogeneity and presence of cracks or cavities surrounding the conductors; furthermore, a site-specific calibration is always needed after the sensor installation.

The second technique is the Time Domain Reflectometry, briefly indicated as TDR. This method has been introduced by Topp in early 1980s but it has proved his reliability in many field and laboratory applications; it is based on the measurement of propagation velocity of a pulse along a transmission line embedded in the soil, which allows the estimate of an "*apparent*" permittivity which is related to the actual soil water content. The measurement is performed by installing two conductors of known length in the soil and sending a steep pulse along this line by means of a special cable tester. The signal travel along this transmission line with a velocity that depends on the medium dielectric behaviour; at the end of the line the signal is reflected back to the tester, which can register the transmitting time, thus the propagation velocity. This technique has low sensitivity to probe geometrical characteristics and to soil type and it has been possible to define a unique calibration relationship which holds for most practical applications, as shown in one of the following sections.

OPERATING PRINCIPLES

The velocity of a pulse travelling as a transverse electromagnetic wave (TEM) along a transmission line made by two parallel conductors depends only on the dielectric and magnetic properties of the interested medium and it is not influenced by the geometry of the line. Assuming the spatial uniformity of these medium characteristics along the transmission line, the pulse velocity v is given by the following expression:

$$v = \frac{c}{\sqrt{\mu_r \varepsilon_a}} \tag{2}$$

where c is the velocity of TEM waves in the vacuum (c=3·10^8 m/s), μ_r the relative magnetic permeability and ε_a the apparent dielectric permittivity of the considered medium. This latter can be written as follows:

$$\varepsilon_a = \varepsilon' \frac{1 + \sqrt{1 + tg^2 \delta}}{2} \tag{3}$$

with $tg\delta$ representing the loss angle tangent given by the ratio between the imaginary and the real part of the relative dielectric permittivity ε_a:

$$tg\delta = \frac{\left(\varepsilon'' + \dfrac{\sigma_{cc}}{2\pi f\,\varepsilon_0}\right)}{\varepsilon'} \tag{4}$$

In most cases the relative magnetic permeability μ_r can be assumed equal to unity; it has been shown (Roth et al., 1992) that the magnetic properties does not influence significantly the relationship between the soil water content, θ, and the apparent dielectric permittivity ε_a when operating in the above mentioned frequency range. Thus, Eq.2 gives:

$$\varepsilon_a = \left(\frac{c}{v}\right)^2 \tag{5}$$

The graph in Fig.1 (Hilhorst and Dirksen, 1994) represents in a qualitative way the magnitude of the imaginary part compared to the real part of dielectric permittivity of a wet soil. As mentioned earlier, the soil dielectric permittivity can vary between 3 and 80 in dependence of the amount of water dipoles. The presence of ionic double layers on the surface of colloidal particles (which is higher in clay and loam than in coarser soils) determines an increase of dielectric permittivity when operating at frequency below the so-called Maxwell-Wagner relaxation frequency corresponding approximately to 10 MHz. It is important to evidence that for frequencies above 100 MHz, the effect of losses on the dielectric behaviour of soils is negligible and it can be assumed, in Eq.4, $tg\delta \ll 1$. From these considerations, it may be concluded that in the range between 500 MHz and 2 GHz the dielectric permittivity is essentialy determined by the real component:

$$\varepsilon_a = \varepsilon' \tag{6}$$

The presence of dissipation phenomena related to the imaginary part of relative permittivity does not affect in a substantial way the value of the velocity of propagation of a TEM wave (Topp et al.,1980; Dalton et al., 1986); this consideration holds also in case of high concentration of solutes in the soil. Nevertheless, these dissipation effects strongly attenuate the propagating wave amplitude, which may hinder the instrumental detection of the reflected signal.

The velocity v in Eq.5 may be determined by means of the TDR technique, which can measure the travelling and returning time of a TEM wave along a transmission line of known length L embedded in the soil; thus

$$\varepsilon_a = \left(\frac{c\,\Delta t_s}{2L}\right)^2 \tag{7}$$

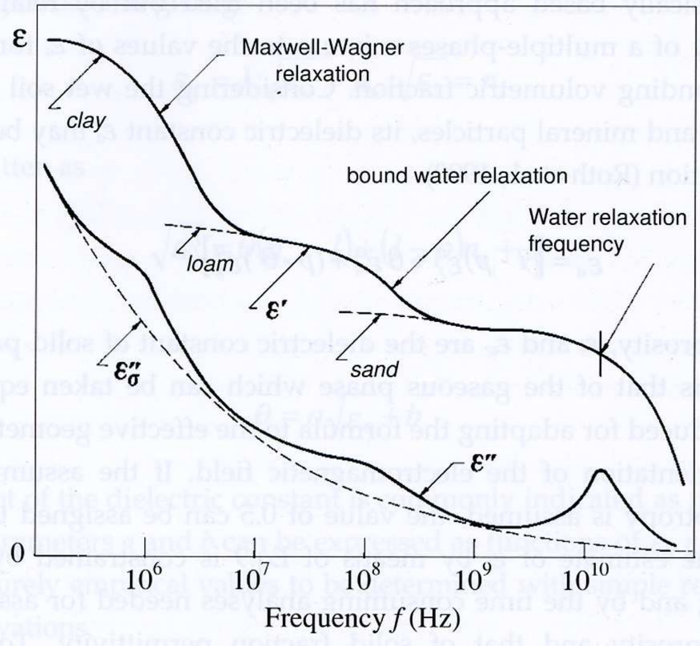

Fig. 1 - Qualitative relationship between soil dielectric permittivity and frequency (adapted from Hilhorst and Dirksen, 1994).

As commonly found in literature, the term "dielectric constant" will be used for referring to the relative dielectric permittivity determined by means of Eq.7.

RELATIONSHIP BETWEEN THE DIELECTRIC CONSTANT AND THE SOIL WATER CONTENT

Several approaches have been tried out for relating the volumetric soil water content θ to the dielectric constant ε_a determined by means of TDR techniques. In many cases, empirical relationships have been defined by simply interpolating observed data without paying too much attention to their physical interpretation. A commonly used "universal calibration formula", in the form a third degree polynomial function, has been proposed by Topp et al. (1980):

$$\theta = -5.3 \cdot 10^{-2} + 2.9 \cdot 10^{-2}\,\varepsilon_a - 5.5 \cdot 10^{-4}\,\varepsilon_a^2 + 4.3 \cdot 10^{-6}\,\varepsilon_a^3 \tag{8}$$

This expression has been derived from a large laboratory data set considering different types of soils (Fig. 2) and for frequencies not higher than 1 GHz. The function in Eq.8 produces reliable results in the range $0.05<\theta<0.60$ if applied to mineral soils without high clay fractions and organic matter, but it does not match exactly the actual relationship between θ and ε_a when this latter approaches the extreme values of 1 or that of free water ($\varepsilon_a \approx 80$) or in soils with elevated organic matter contents.

Recently, a physically based approach has been tried out by relating the apparent dielectric permittivity of a multiple-phases mixture to the values of ε_a for each component and to their corresponding volumetric fraction. Considering the wet soil as a three-phases mixture of air, water and mineral particles, its dielectric constant ε_a may be found by means of the following equation (Roth et al., 1990):

$$\varepsilon_a = \left[(1-p)\varepsilon_s^{\alpha} + \theta\,\varepsilon_w^{\alpha} + (p-\theta)\,\varepsilon_g^{\alpha}\right]^{1/\alpha} \qquad (9)$$

where p is the soil porosity, ε_s and ε_w are the dielectric constant of solid particles and water respectively, and ε_g is that of the gaseous phase which can be taken equal to unity. The parameter α is introduced for adapting the formula to the effective geometry of the medium in relation to the orientation of the electromagnetic field. If the assumption of medium homogeneity and isotropy is assumed, the value of 0.5 can be assigned to α (Birchaketal, 1985). In practice, the estimate of ε_a by means of Eq.9 is constrained by the preliminary destructive sampling and by the time consuming analyses needed for assessing the correct value of the soil porosity and that of solid fraction permittivity. To overcome these limitations several authors have carried out experimental works for evaluating the values of uncertain parameters in Eq.9. Although the introduction of some empiricism diminishes the physical significance of Eq.9, the relationship is formally correct in the whole range of variability of θ ($0<\theta<1$).

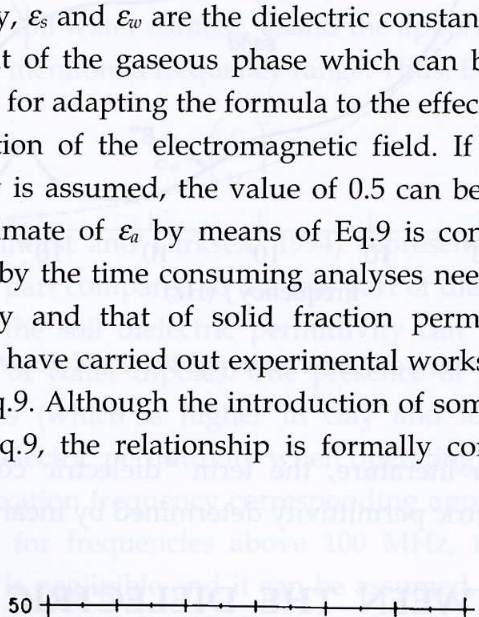

Fig. 2 - Empirical calibration formula (Topp et al., 1980)

Thus assuming α=0.5 and giving:

$$\varepsilon_g = 1; \sqrt{\varepsilon_w} = n_w; \sqrt{\varepsilon_s} = n_s \tag{10}$$

the Eq.9 can be written as

$$\sqrt{\varepsilon_a} = \theta(n_w - 1) + (1-p)n_s + p \tag{11}$$

that is:

$$\theta = a\sqrt{\varepsilon_a} + b \tag{12}$$

The square root of the dielectric constant is commonly indicated as the *"refraction index"*, *n*. Although the parameters *a* and *b* can be expressed as functions of ε_s, ε_w and *p*, they should be considered as purely empirical values to be determined with simple regression analyses of experimental observations.

The data set used for defining the Topp's formula in Eq.8 was re-analysed by Heimovaara (1993), which suggested the following relationship between θ and *n* to be applied for 1.5<*n*<7.5 with high correlation:

$$\theta = 0.103 \cdot n - 0.135 \tag{13}$$

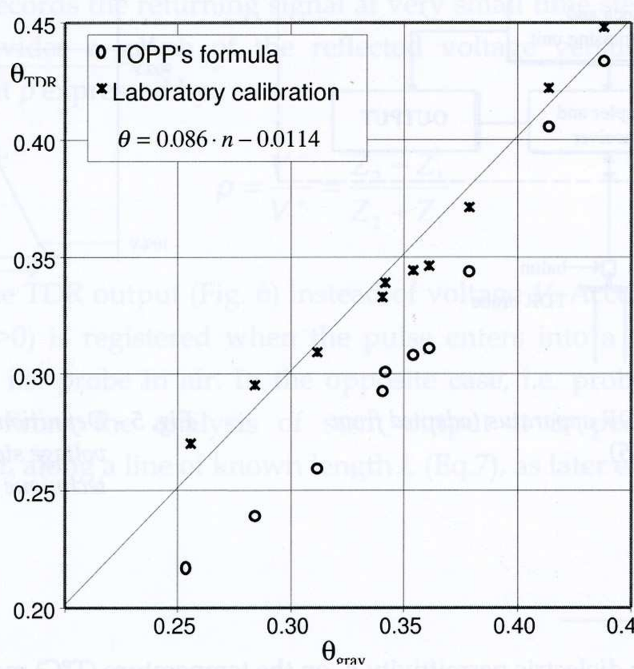

Fig. 3 *- Calibration results (r^2=0.965) for a clay-loamy soil (Sele plain, Salerno, Italy).*

Since the beginning, the large interest in TDR technique was given by the reliability of "universal" calibration formulae, such as Eq.8 and Eq.13, which validity has been proven in most practical applications. For precision measurements, the use of these general relationships is suitable only when no absolute determination of θ is required, such as its temporal variation in a fixed location (Zegelin et al., 1992). Indeed, in most cases the maximum absolute error of estimate is 0.05 (Jacobsen et al., 1995); if a better accuracy is needed, a soil-specific validation and calibration should be performed (Fig. 3). In most critical situations, other influencing factors should also be considered, i.e. the effect of large temperature variation on the value of water permittivity ε_w [1] when the measurements are taken near the soil surface, as shown by Roth et al. (1990).

DESCRIPTION OF TDR INSTRUMENTATION

The main components of a typical TDR instrumentation are schematically drawn in Fig. 4. The electronic apparatus includes a control unit, needed for the synchronisation of the pulse generator and the receiver, and the output device (generally a LCD monitor) and related peripherals (communication port and/or dot matrix printer). The apparatus is connected with a coaxial cable to the transmission line (TDR probe), which may have different shapes and configurations.

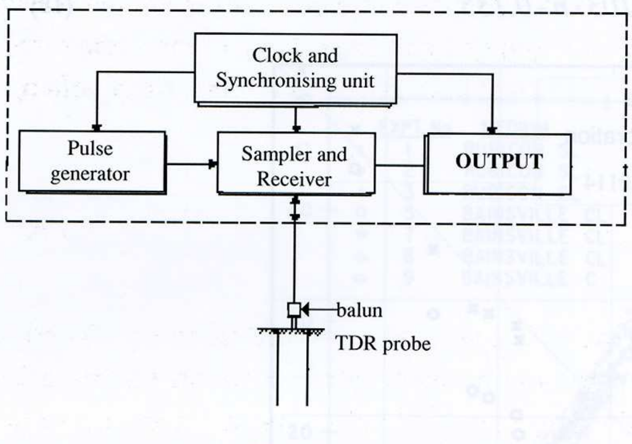

Fig. 4 - Schematic view of TDR apparatus (adapted from Topp and Davis, 1985)

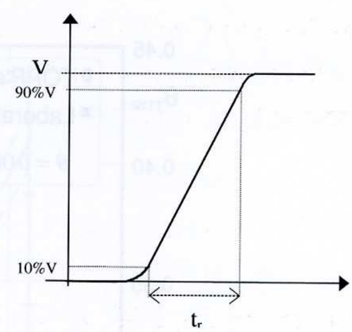

Fig. 5 - Definition of rise time t_r of a voltage step V_0; usually in TDR technique t_r<0.1 ns.

[1] The dependence of water dielectric permittivity ε_w on the temperature (T°C) may be expressed by the following relationship (Hasted, 1973):

$$\varepsilon_w = 87.4 - 0{,}4001T + 9.398 \cdot 10^{-4} T^2 - 1.410 \cdot 10^{-6} T^3$$

In the conventional or "step-type" TDR technique, the pulse generator emits voltage steps V^+ with a very high rising time (usually less than 0.1 ns) along the connection cable (Fig. 5). Any variation in the line geometry or in the dielectric characteristics determines a partial reflection of energy pulse toward the input source. The amplitude of reflected voltage V^- in correspondence of such discontinuity depends on the variation of impedance Z (or characteristic resistance, measured in Ohm) before (Z_1) and after (Z_2) the discontinuity itself

$$V^- = \frac{Z_2 - Z_1}{Z_2 + Z_1} V^+ \tag{14}$$

The impedance of the line is determined by its geometry (conductors diameter and distances) and by dielectric characteristics. In coaxial and balanced lines with a diameter d and a distance s between the axes of the conductors, the impedance can be estimated by means of the following relationship in case of very limited losses in the line:

$$Z = \frac{120}{\sqrt{\varepsilon_a}} ln\left(2s/d\right) \tag{15}$$

The returning signals are superimposed to the emitted ones and they are detected by the receiving unit, with a voltage decrease or increase depending on the phase of the reflection, as expressed in Eq.14 and 15. By means of its built-in hardware and firmware, the receiving unit samples and records the returning signal at very small time steps; in the same time, the output device provides a graph of the reflected voltage versus time. More often, the reflection coefficient ρ expressed by:

$$\rho = \frac{V^-}{V^+} = \frac{Z_2 - Z_1}{Z_2 + Z_1} \tag{16}$$

is represented in the TDR output (Fig. 6) instead of voltage V. According to Eq. 15 and 16, a voltage step-up (ρ>0) is registered when the pulse enters into a medium having a lesser dielectric constant, i.e. probe in air. In the opposite case, i.e. probe in water, a step-down transition occurs. From the analysis of such output it is possible to determine the propagation time Δt_s along a line of known length L (Eq.7), as later explained.

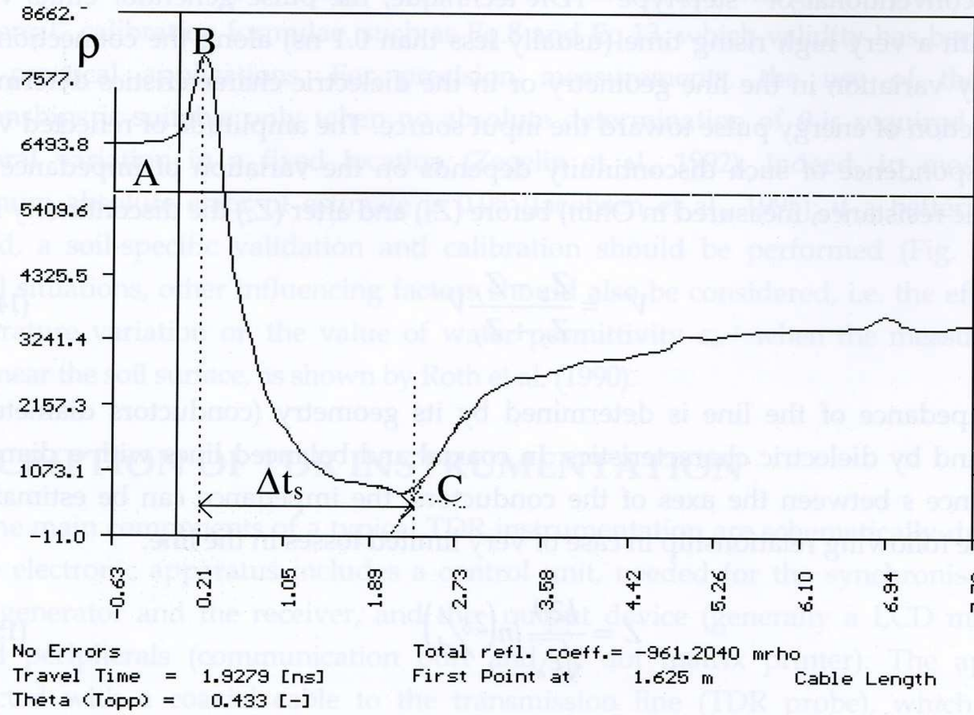

Fig. 6 - Example of TDR output with a balanced parallel line in a wetted soil.

A widely used TDR equipment is the Tektronix cable tester Mod.1502 B or C[2], which has been conceived as a portable measuring device and it can be easily connected to a personal computer through its communication port. In this case, the step-pulse is characterised by an amplitude of 300 mV, a rise time of 0.2 ns and a duration of 25 μs corresponding to a theoretical frequency range from 20 kHz and 1.75 GHz[3]. The effective frequency bandwidth is certainly restricted by attenuation effects induced by cable connections; the extent of this attenuation, which mainly affects the higher frequencies range, largely depends on the quality and on the length of cables. From the analysis of several estimates of soil dielectric permittivity on different types of soils by means of TDR, Heimovaara et al. (1994) estimated a frequency range between 200 MHz and 1 GHz, thus confirming the assumptions reported in section 3.

---

[2] Any reference to commercial products is made for reader information and text completeness and it does not imply any endorsement from the cited factory.

[3] Although a more correct estimate of frequency bandwidth in a step-type TDR apparatus may be carried out by means of Fourier analysis, the maximum frequency may be approximated from the rise time t_r (ns) as follows:

$$f_{max} = \frac{0.35}{t_r} \text{ (GHz)}$$

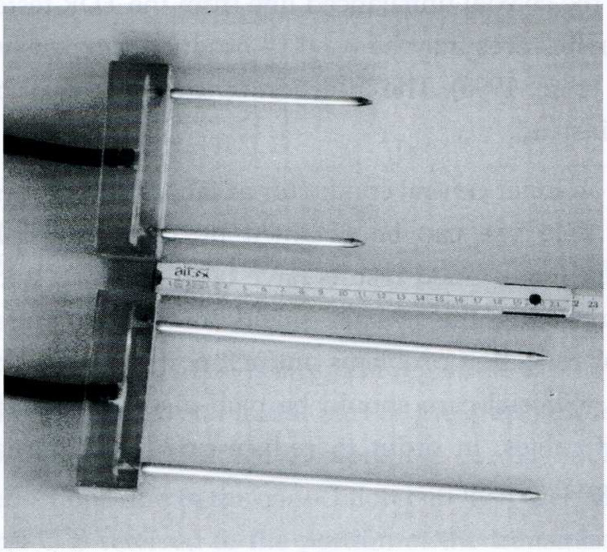

Fig. 7 - Balanced probes of different length.

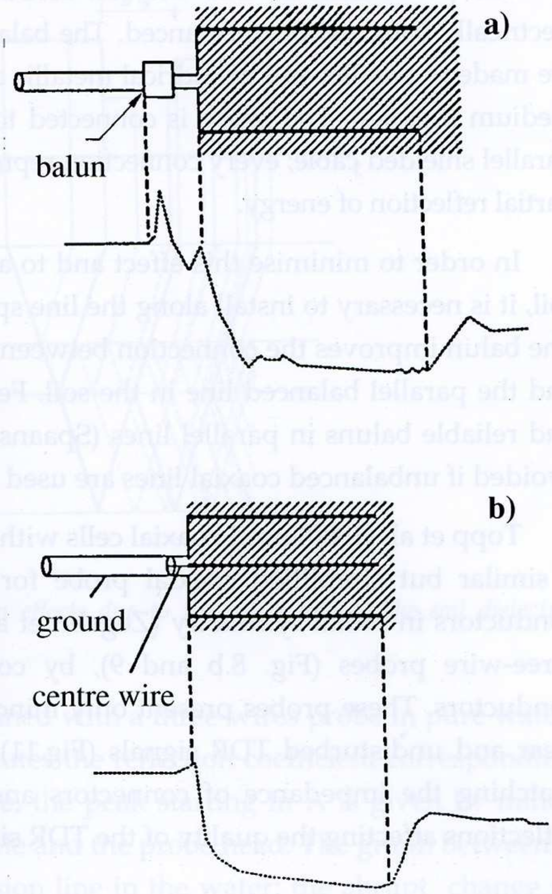

Fig. 8 - Parallel balanced (a) and unbalanced (b) TDR probes (from Whalley, 1993)

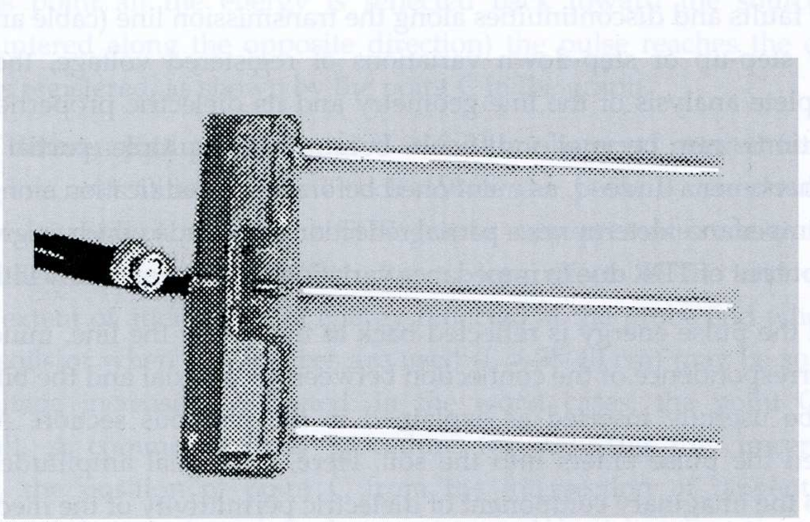

Fig. 9 - Unbalanced three-wire probe (L=14 cm) with coaxial cable and connector

The probe inserted into the soil constitutes the pulse transmission line which can be electrically balanced or unbalanced. The balanced lines (fig.7) are more widely used and they are made of parallel and cylindrical metallic conductors; the soil between them is the dielectric medium (fig. 8.a). The probe is connected to the TDR unit by means of a coaxial cable or a parallel shielded cable; every connection represents an impedance mismatching which causes a partial reflection of energy.

In order to minimise this effect and to allow that most of emitted energy enters into the soil, it is necessary to install along the line specific impedance matching transformers (*balun*). The balun improves the connection between the coaxial unbalanced line from the TDR tester and the parallel balanced line in the soil. Ferrite cores may be used to produce inexpensive and reliable baluns in parallel lines (Spaans et al., 1993). The insertion of the balun may be avoided if unbalanced coaxial lines are used instead.

Topp et al. (1980) used coaxial cells with an inner central conductor as laboratory probes; a similar but simplified coaxial probe for field use can be obtained by using multiple conductors in radial symmetry (Zegelin et al., 1989). Good results have been obtained with three-wire probes (Fig. 8.b and 9), by connecting the coaxial shield to the two outer conductors. These probes present only minor reflection problems and allow the retrieval of clear and undisturbed TDR signals (Fig.11). Special care should be paid also in correctly matching the impedance of connectors and cables, in order to reduce unwanted partial reflections affecting the quality of the TDR signal.

INTERPRETATION OF TDR REGISTRATIONS

The TDR registration is a plot of time variations of the emitted versus the reflected voltage. Since faults and discontinuities along the transmission line (cable and soil probe) are evidenced by step-up or step-down variations of registered voltage, the TDR diagrams enable a complete analysis of the line geometry and its dielectric properties. The lecture of TDR registrations can be made difficult because of multiple partial reflections and attenuation phenomena. Indeed, as mentioned before, any modification along the line causing a variation of impedance determines a partial reflection amplitude which is given by Eq.14. The effects on the output of TDR due to impedance variations are schematically illustrated in Fig.10.

Before all the pulse energy is reflected back at the end of the line, minor reflections are detected in correspondence of the connection between the coaxial and the bifilar cable, where a balun can be usefully inserted as explained in the previous section. A larger effect is observed when the pulse enters into the soil. Here, the signal amplitude is also reduced accordingly to the imaginary component of dielectric permittivity of the medium.

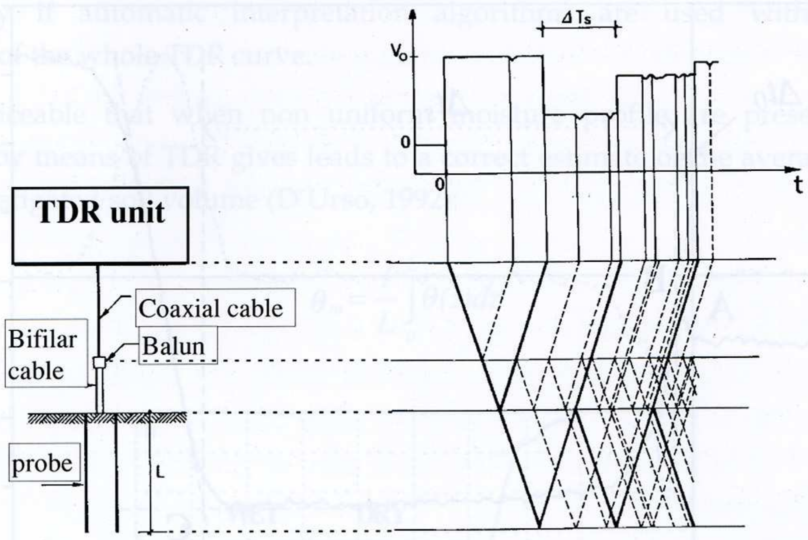

Fig. 10 *- Theoretical TDR wave with multiple reflection effects due to the balun and to the soil dielectric permittivity.*

In Fig. 11, there is a typical registration obtained with a three-wires probe in pure water. The sub-horizontal initial part of the graph indicates the reflection coefficient corresponding to the emitted voltage V_0 along the coaxial cable; the peak starting in A is given by minor reflections due to the connection between the cable and the probe head. The graph between B and C is referred to the portion of the transmission line in the water; the abrupt change in dielectric properties determines a strong reflection of energy; therefore the registered voltage drops rapidly. The remaining signal propagates itself along the probe wires until it reaches their end; at this point all the energy is reflected back toward the source. After new reflections (encountered along the opposite direction) the pulse reaches the emitter and a voltage increase is registered, as shown by the point C in the graph.

The abscissa difference of points B and C is the time interval needed for the pulse to travel along the line and to be reflected back. While the point B can always be clearly distinguished, the location of point C on TDR graphs may present some troubles. In first instance, the voltage rise is not very fast due to loss effects at the end of the probe; furthermore, the extent of attenuation of energy reflected at the probe end when measuring in clay or saline soils or when long probes are used ($L > 35$-40 cm) may be so relevant that only a small voltage increase is detected; in the worst cases, the point C can not be determined at all. A commonly used procedure for reducing this uncertainty is the identification of the position of point C from the intersection of tangent lines to the ascending portion of the graph and to the previous sub-horizontal section, as shown in Fig. 11.

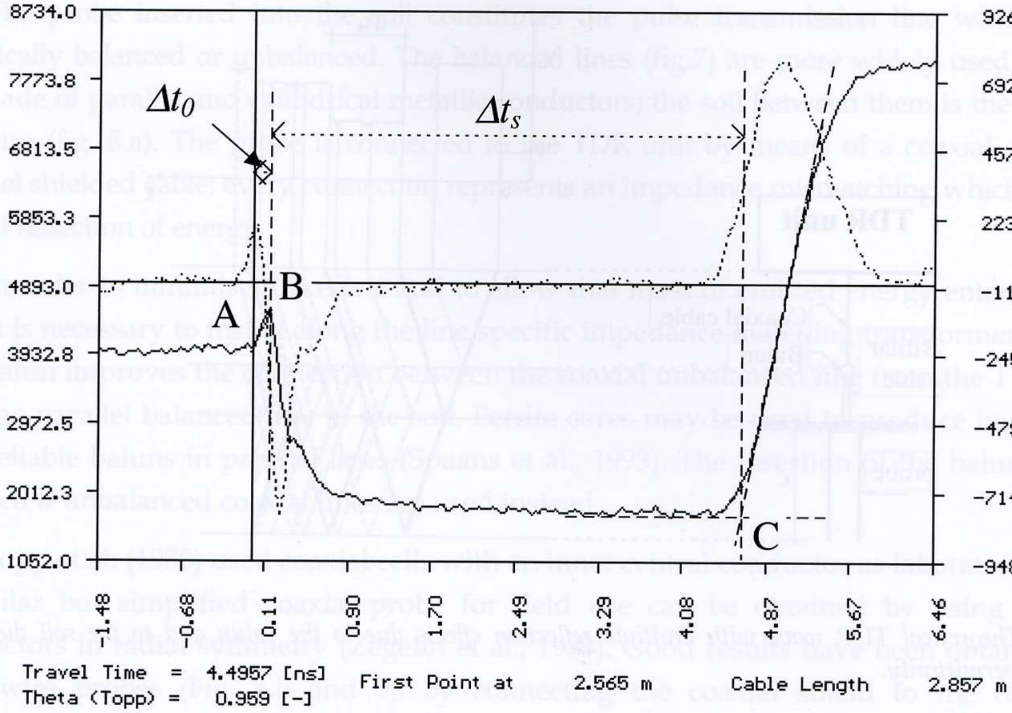

Fig. 11 - TDR wave-form in distilled water obtained with the three-wire unbalanced probe of Fig.10. On the left vertical scale of the graph is indicated the reflection coefficient and on the right scale the value of first order derivative, plotted with a dotted line.

Recently, zTDR apparatuses specifically designed for soil water content measurement provide an automatic interpretation of the registration, thus eliminating the need of a visual analysis of the TDR curve. Software have been developed for determining the position of points B and C by analysing the whole curve and its first derivative (Fig. 11) stored in discrete form, with finite differences numerical techniques (Heimovaara and Bouten, 1990).

A non uniform distribution of water content along the probe due to steep wetting front or to the presence of soil layers with different hydraulic characteristics causes a dielectric discontinuity and therefore an impedance mismatching. The consequent additional reflections may increase the difficulties when interpreting TDR registrations.

In the Fig. 12 the TDR curves registered in three different time steps during an infiltration process in a dry soil are shown. In this case, the dielectric constant in the lower part of the soil was much lower than that in the upper part. In the TDR curves of Fig.12, the partial reflection due to this discontinuity is clearly evidenced by the point B, while the probe end is represented by the point C. The presence of intermediate reflections along the probe may induce errors and uncertainty in the determination of the actual propagation time

Δt_s especially if automatic interpretation algorithms are used without a checking visualisation of the whole TDR curve.

It is noticeable that when non uniform moisture profile are present, the time Δt_s determined by means of TDR gives leads to a correct estimate of the average water content θ_m in the investigated soil volume (D'Urso, 1992):

$$\theta_m = \frac{1}{L}\int_0^L \theta(z)dz \tag{17}$$

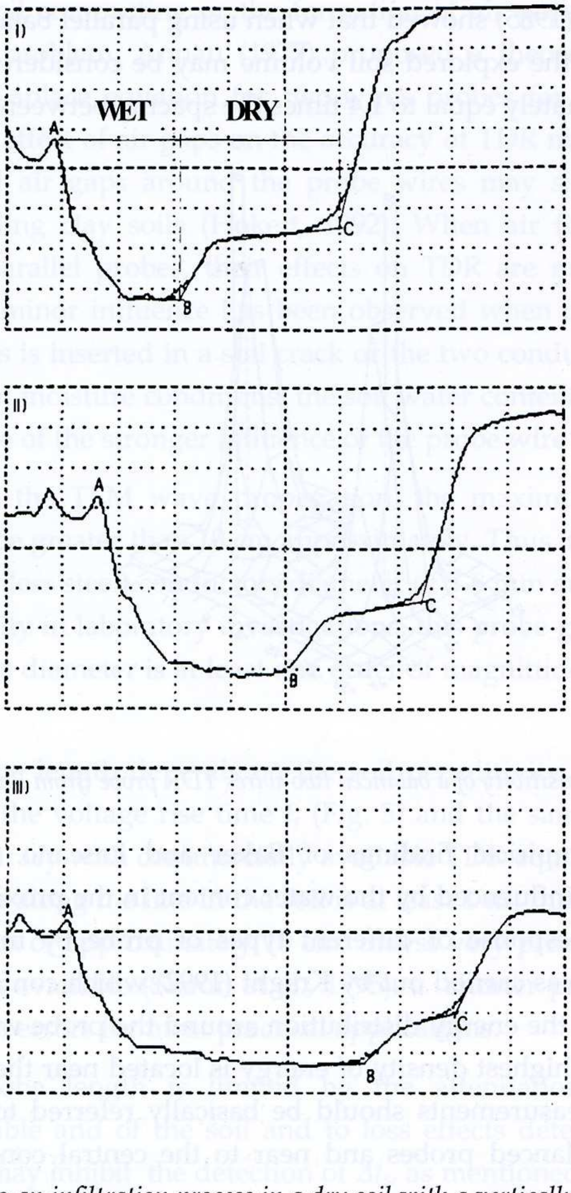

Fig. 12 - TDR output during an infiltration process in a dry soil with a vertically inserted probe (from D'Urso, 1992).

In this case the propagation velocity of the pulse is not constant but it varies with the dielectric constant according to Eq.5. Considering that the square root of the dielectric constant, $\sqrt{\varepsilon_a}$ may be assumed as linearly related to the water content (Eq.13), it is possible to conclude the pulse velocity is inversely proportional to the soil water content. Therefore, the propagation time Δt_s is linearly related to the integral of water content along the whole TDR probe of length L.

PROBE GEOMETRY

The geometry of the TDR soil probes is determinant for assessing the investigated volume. Topp and Davis (1985) showed that when using parallel balanced probes (similar to that illustrated in Fig. 8) the explored soil volume may be considered as a coaxial cylinder with a diameter approximately equal to 1.4 times the spacing between the two wires.

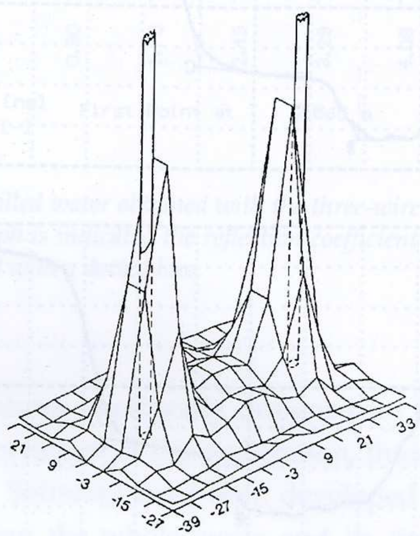

Fig. 13 - 3-d Plot of the sensitivity of a balanced two-wires TDR probe (from Baker and Lascano, 1991).

According to the empirical findings of Baker and Lascano (1989; 1991), the TDR measurement is strongly influenced by the water content in the proximity of wires (Fig. 13). The analysis of spatial response of different types of probe by means of electrical field perturbation techniques was carried out by Knight (1992) which confirmed the sensitivity of TDR measurements from the energy distribution around the probe wires. When using small diameter conductors, the highest density of energy is located near the conductors; therefore, in this case, the TDR measurements should be basically referred to soil volume near the wires for the parallel balanced probes and near to the central conductor for unbalanced multi-wire probes. As a consequence, any variation or perturbation around the probes has a great influence on the measurement of soil water content.

The fraction of soil volume affecting the TDR measurement may be enlarged by increasing the ratio between the diameter of conductors and their spacing; conversely, the insertion of probes with large diameter conductors may compact the soil and modify the soil water flow in the measured volume. A satisfactory compromise for having the minimum insertion disturbance with an adequate explored soil volume is achieved assuming a ratio $s/D \approx 10$. Nevertheless, the sensitivity of TDR probes in the immediate proximity of wires imposes some precautions. The probe should be carefully inserted in the soil in order to prevent an excessive soil compacting or the formation of air gaps around the conductors. Concerning this latter problem, Annan (1977) proposed a theoretical model based on a particular solution of Laplace equation for two-wires probes for evaluating and possibly taking into account the effect of air gaps on the accuracy of TDR measurements. Indeed, the presence of cracks and air gaps around the probe wires may significantly influence the measurements in swelling clay soils (Hokett, 1992). When air filled cracks occur in the middle of two-wires parallel probes, their effects on TDR are more relevant in wet soil conditions, while only minor influence has been observed when cracks are water filled. If one of probe conductors is inserted in a soil crack or the two conductors are inserted in two soil layers with different moisture conditions, the soil water content may result substantially underestimated, because of the stronger influence of the probe wire in the dry portion.

In order to assure the TEM wave propagation, the maximum spacing between the conductors should not be greater than 10 cm approximately. Thus, field probes are generally built with metallic (stainless steel) conductors diameter of 5-6 mm and spacing of 5-6 cm; due to better soil homogeneity in laboratory investigations, this probe geometry may be reduced assuring that conductors diameter is at least one order of magnitude larger than average soil particle diameter.

The minimum probe length depends on the soil permittivity and on the instrumental characteristics, such as the voltage rise time t_r (Fig. 5) and the sampling resolution of TDR apparatus. Enough accuracy with commercially available TDR equipment can be achieved if the pulse travelling time along the line in the soil is at least 1 ns; this latter condition requires a minimum probe length of approximately 10 cm; unless very precise hardware with larger frequency bandwidth is available (Shaun et al., 1995), a shorter probe length minor of 5÷6 cm implies unacceptable errors for most practical applications.

The maximum probe length is limited by the attenuation due to the dielectric characteristics of the cable and of the soil and to loss effects determined by soil electrical conductivity σ_{cc} which may inhibit the detection of Δt_s, as mentioned before. Although under optimal conditions in sandy soils probe length up to 1-2 m have been used, in most cases and with standard TDR apparatuses it is advisable to restrict the maximum length to 0.5 m. Hard or compacted clay soils further limits the probe length to 0.15-0.20 m; the presence of gravel and stones may obstacle a correct insertion of TDR probes.

The conductor parallelism and linearity are not compulsory: curvilinear and equidistant wires can be used, i.e. when measurements in axial symmetric conditions are performed (Kachanoski et al., 1990). Minor spacing variations hindering a perfect parallelism do not affect in a critical way the accuracy of dielectric permittivity measurements.

MEASUREMENT PROCEDURE

Within the limitations described in the previous section, the TDR technique is rather flexible about positioning and orientation of probes in the soil. Depending on each specific application needs, TDR probes may be installed in the soil in vertical position, or more in general with any angle between the axis plane and the soil level surface; as mentioned before, the propagation time will provide in every situation the average water content along the transmission line.

Most common applications refer to vertically inserted probes; they can be easily installed either for permanent continuous monitoring or for temporary measurements. Multiple probes with different length may be used for describing the water content profile distribution with resolution depending on the length difference; the same task could be achieved by performing several measurements at different insertion depths of the probe. It should be considered that vertical insertion of metallic rods may alter the soil thermic regime or create preferential water flow paths along the probe; furthermore, it has already been discussed before how the formation of vertical cracks in proximity of the probe in clay soils may substantially reduce the measurement accuracy.

Oblique insertion with an angle greater than 30° between the probe axis and the soil surface can be used for reducing the effect of small scale spatial variability and for crossing vertical cracks caused by soil shrinking or organisms living in the soil. At an angle of 30°, although the difficulty of insertion is maximal, the risk of soil fractures is reduced and the depth of investigated soil is equal to half of a vertically inserted probe of the same length.

Horizontal installation of TDR probes requires a pit of appropriate dimensions (Fig. 14). Minimum soil disturbance should be assured in opening the pit and in the consequent refilling, in order to recreate as much as possible the former soil stratification nearby the probes. It is advisable that probe length is large enough to investigate soil volumes where only limited disturbance occurred in the pit and to reduce the effect of spatial variability. Multiple depth installation provides the most accurate way for monitoring soil water content distribution profile.

In such situations, a minimum distance from the soil surface equal to half the spacing between the TDR probe conductor ($s/2$) should be considered (Nielsen et al., 1995).

Independent of the orientation, the installation of TDR probes should be carefully made to minimise soil disturbance and to avoid formation of air gaps around the probes, where there is maximum measuring sensitivity. These effects can be reduced if the soil is sufficiently wet; a guide positioned on the soil surface is often used to assure orientation, parallelism and correct distance of probe wires, when using loose conductors. The metallic rods or the probe head are gently and continuously pushed in the soil by hand or by means of an hydraulic jack. Better results are obtained if holes with diameter smaller than that of probe wire and at the same distance are preliminary drilled.

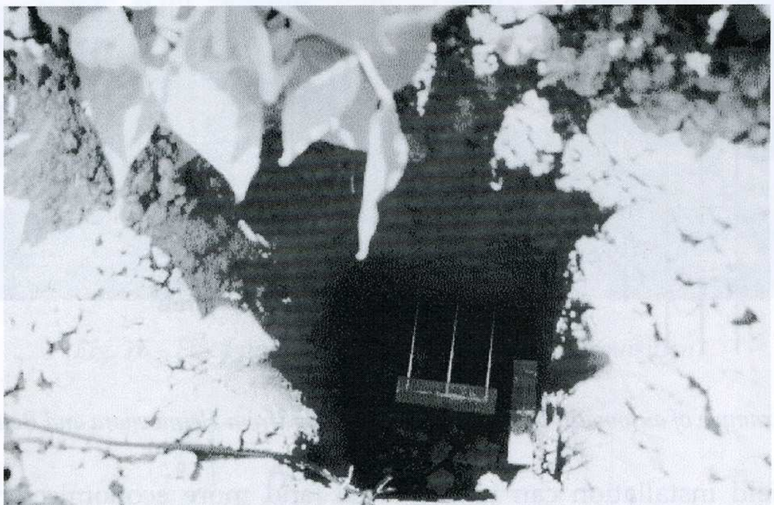

Fig. 14 -. Installation of three-wire horizontal probes for profile monitoring.

The use of data loggers allows a continuous monitoring in several location within the same plot (Baker et al., 1990; Heimovaara et al., 1990). The probes are installed in different locations and in various positions, either vertically or horizontally, and each cable connected to automatic acquisition station. In most cases, one TDR apparatus is used in conjunction with an acquisition and control unit (i.e. a personal computer linked via a serial port to the TDR) and multiple probes are connected and scanned by using appropriate multiplexing device (Fig.15), suitable for coupling the frequency bandwidth of TDR.

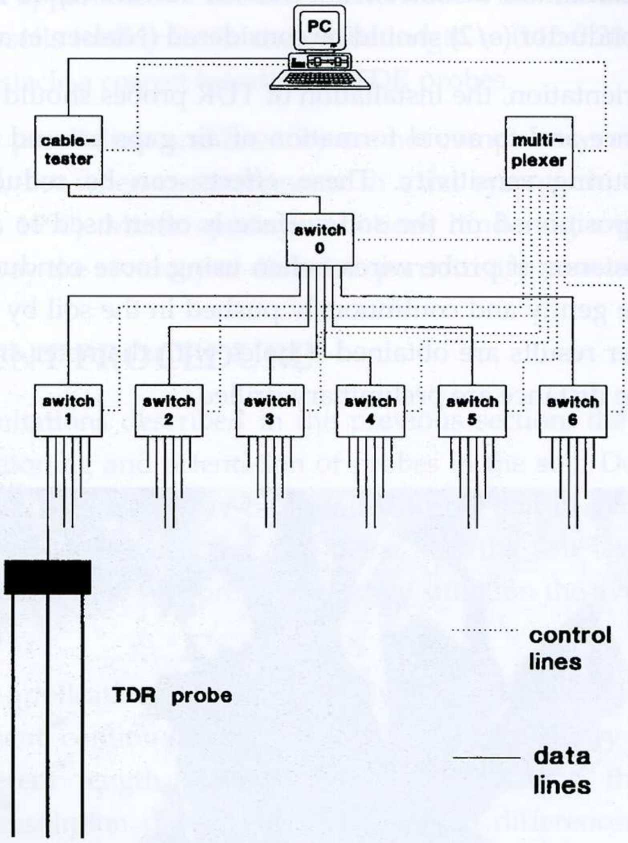

Fig. 15 - Example of automatic TDR acquisition system (from Heimovaara and Bouten, 1990).

The same field installation can usefully be (and more economically) adopted when manual measurements are performed when periodic but not continuous measurements are needed (Fig.16).

An excessive length of the cable connecting the probe to the TDR unit causes attenuation which may impede the interpretation of the curve due to loss of higher frequency signal. This may occur especially in dry conditions.

From the comparison of measurement made in air and water with different cable length and triple-wire coaxial lines (Heimovaara, 1993), it has been shown that, although the propagation time of the pulse Δt_s is not greatly affected (Fig. 17), the cable lengths above 10 m may cause problems unless special low-loss cable are used.

Before the installation, each probe should be tested for determining the effective electrical length L to be used in Eq. 7; this preliminary step is usually based on measurements on a medium with a known dielectric permitivity, such as water or other liquid substances. An example of calibration procedure will be discussed in one of the following sections.

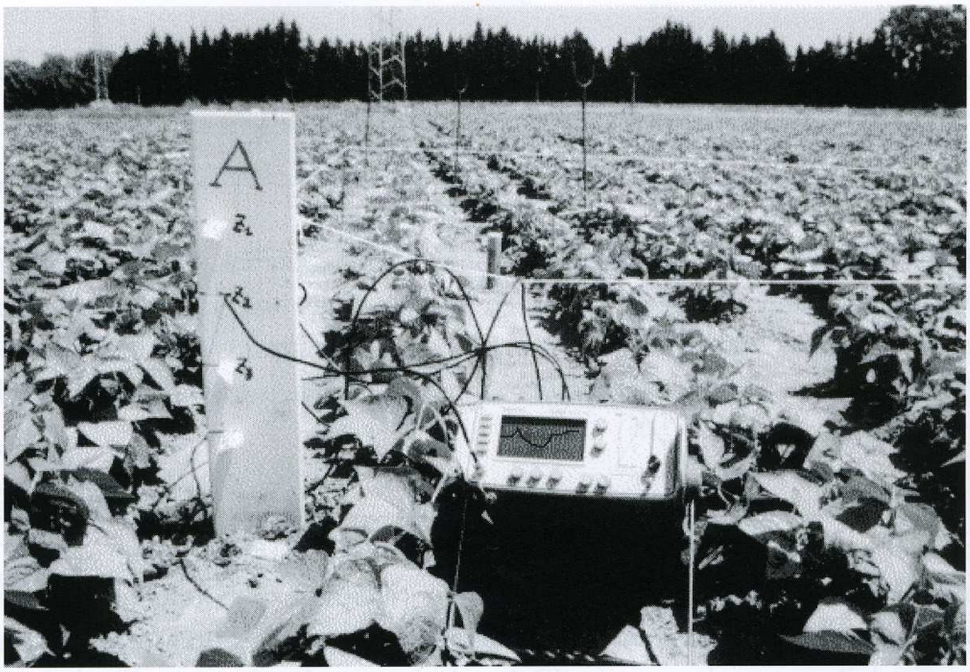

Fig. 16 - Fixed probe installation with manual acquisition.

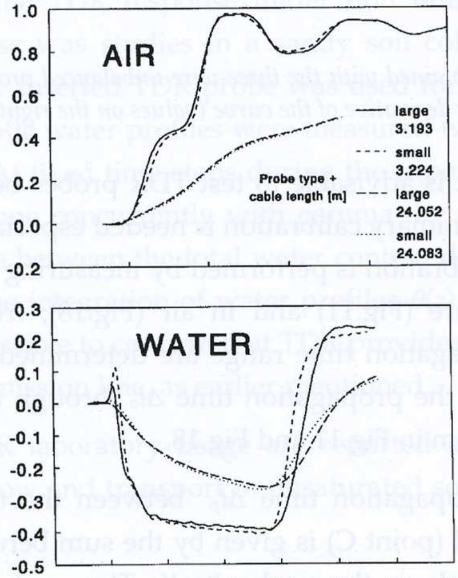

Fig. 17 - Effect of different cable length on the response of TDR in air and water (from Heimovaara, 1993).

EXAMPLE APPLICATIONS

In this section several examples of TDR applications carried out by the authors in laboratory and field conditions are discussed.

Probe Calibration Procedure

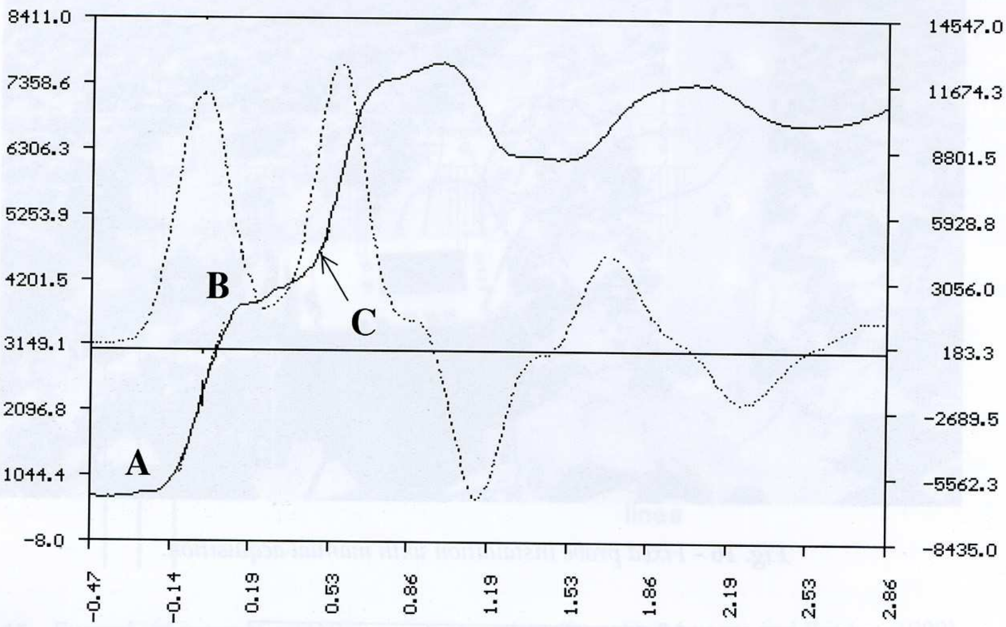

Fig. 18 - TDR waveform in air obtained with the three-wire unbalanced probe of Fig. 9 (L=14 cm). Dotted line represents the first order derivative of the curve (values on the right vertical axis).

As mentioned before, it is advisable to test TDR probes before their use for measuring soil water content. The preliminary calibration is needed especially when short probe lengths are used. In general, the calibration is performed by measuring the propagation time in pure water at known temperature (Fig.11) and in air (Fig.18); from these measurements the extreme values of the propagation time range are determined. This procedure would also enable the measurement of the propagation time Δt_o through the probe head, identified by the section A-B of the diagram in Fig.11 and Fig.18.

The total measured propagation time Δt_p between the terminal section of the cable (point A) and the probe end (point C) is given by the sum between the propagation time in the probe head and that along the probe itself. Thus, when measuring in water and indicating with n_{water} the refraction index, the total propagation time (Fig.11) along the probe may be expressed as follows:

$$\Delta t_{p,water} = \Delta t_0 + \frac{2L}{c} n_{water} \tag{18}$$

Similarly, in air (Fig.18)

$$\Delta t_{p,air} = \Delta t_0 + \frac{2L}{c} n_{air} \tag{19}$$

Assuming in Eq.18 for n_{water} the value of refraction index of the water at the measurement temperature and letting n_{air}=1 in Eq.19, these two equations can be easily solved to find the unknown quantities Δt_0 and L. This preliminary calibration is especially useful when automatic interpretation algorithms of the TDR curves for short probes are used.

Laboratory Studies.

The TDR technique is particularly suitable for monitoring soil water flow processes under controlled laboratory conditions. In this case, TDR can usefully be adopted along other measuring techniques. For example, small TDR probes and micro-tensiometers can be inserted horizontally in soil columns during infiltration and evaporation processes for studies on soil water retention and unsaturated hydraulic conductivity.

In order to investigate the TDR response under non uniform distribution of water content, an infiltration process was studies in a sandy soil column of height 40 cm and diameter 14.5 cm. A vertically inserted TDR probe was used for monitoring the total water content in the soil column, while water profiles were measured with a gamma-ray apparatus mounted on a vertical slide. At fixed time steps during the experiment, TDR measurements (illustrated in Fig.12) were done concurrently with gamma-ray scanning along the column (Fig.19). From the comparison between the total water content data acquired with TDR and the value determined from the integration of water profiles $\theta(z)$ obtained with the gamma-rays apparatus, it has been possible to confirm that TDR provides a good estimate of average water content along the transmission line, as earlier mentioned.

Several examples of TDR laboratory usage are reported in literature for monitoring complex processes of water flow and transport in unsaturated soils and for the validation of numerical simulation models.

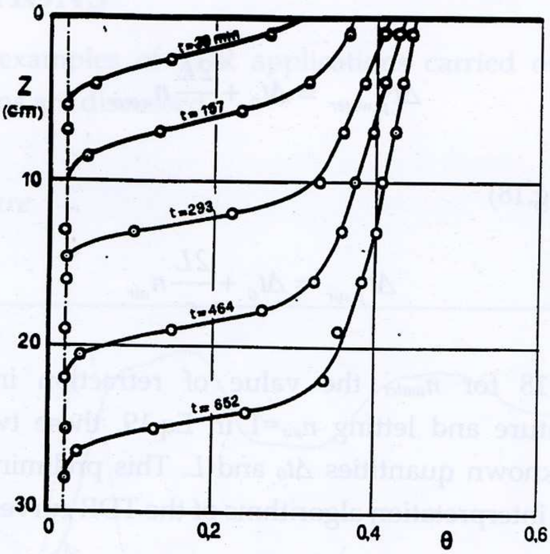

Fig. 19 - Detection of water content distribution in laboratory soil columns during an infiltration process with gamma-rays apparatus used in conjunction with TDR (see Fig. 12).

Field investigations

Portable probe and automatic acquisition

One of the greatest advantage in using the TDR technique is the possibility of performing large number of measurements in a rather short time. By using the appropriate software, the instrumentation can communicate with a portable computer for control and acquisition made with a hand-probe. The operator is only asked to take care of the correct probe insertion and he does not to worry about TDR curve interpretation; the whole curve is stored and analysed at a later stage. By using this technique, large ground data set, i.e. for remote sensing studies, can be acquired.

In order to investigate on the possible use of Synthetic Aperture Radar from satellites, several field campaigns have been carried out in coincidence of ERS-1 platform passes on a test site area in southern Italy (D'Urso et al., 1994; Mancini et al., 1994). In this case, a measurement grid with 15 m spacing was adopted; the transmission line was consisting of a parallel hand probe with an impedance transformer; the probe length was of 10 cm approximately with a distance between the conductor of 7.5 cm, similar to that illustrated in Fig. 8. Over 100 measures were taken in approximately three hours in coincidence of satellite pass (Fig. 20). These large data sets enable accurate studies concerning the spatial variability of soil water content with geostatistical techniques and the comparison with high resolution remote observations (D'Urso et al., 1996).

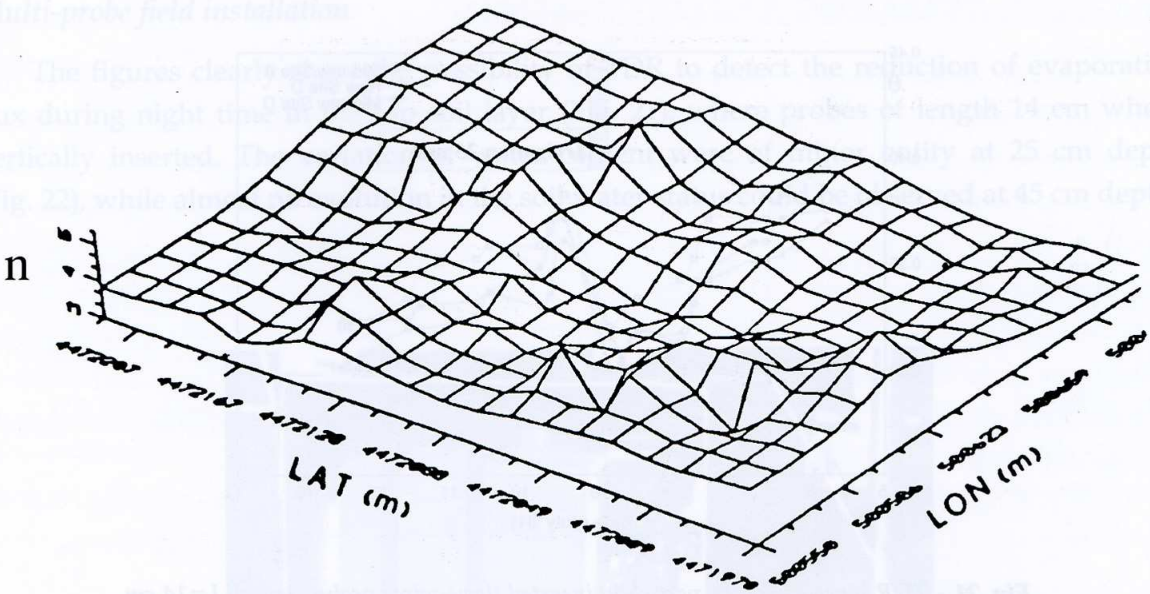

Fig. 20 - Spatial variation of refraction index n, determined by means of TDR at interval of 15x15 m on a test site plot of 2 ha in the Sele plain (I), Nov.'93.

When monitoring temporal variations of water content in selected locations, it is suggested to leave permanently the TDR probes embedded in the soil as earlier described, they may be inserted either vertically or horizontally, after digging an access hole. Automatic recording may be usefully installed for this purpose, but special care should be devoted to data storage. Indeed, unless TDR interpretation is automatically performed by the acquisition system, the storage of TDR curves might require large memory space if many probes and/or many measurements are required (at least 250 points should be stored for each single TDR curve in order to perform an accurate interpretation). If observations are confined to a few days or data logging facilities are not available, a manual acquisition can be made without large installation efforts. In an experimental plot in Southern Italy, vertically and horizontally inserted probes were used to monitor hourly variations during irrigation applications; measurements were manually performed at regular intervals during each day. The results shown in the Figures 21 and 22 refer to been-crops.

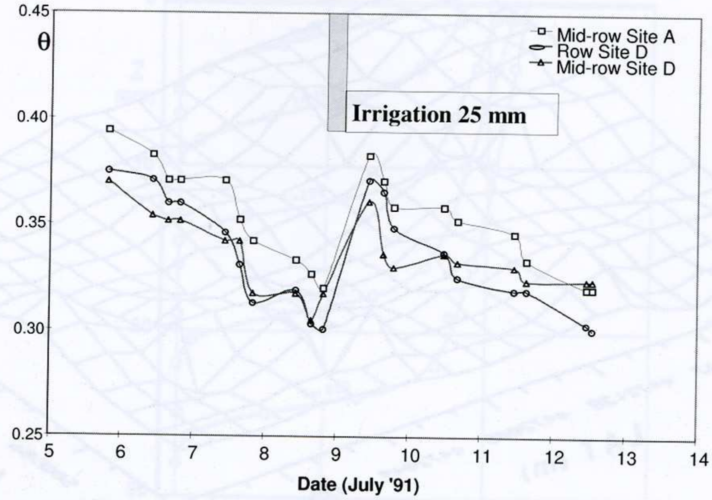

Fig. 21 - TDR measurements, vertically inserted three-wires probes, length L=14 cm.

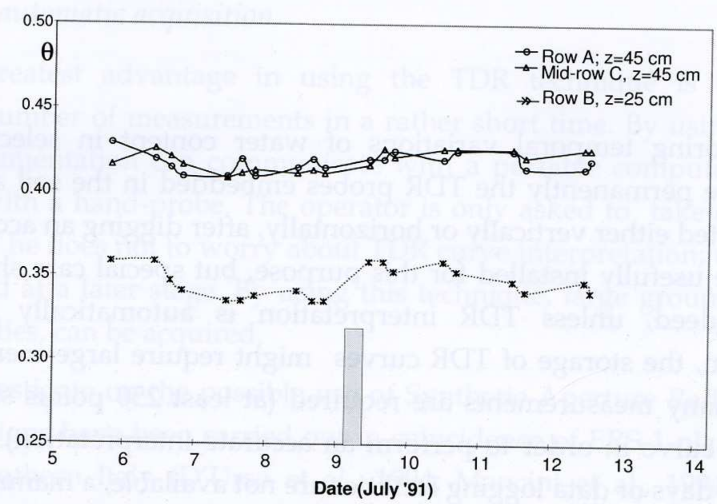

Fig. 22 - TDR measurements, horizontally inserted three-wires probes, length L=14 cm.

Multi-probe field installation

The figures clearly show the possibility of TDR to detect the reduction of evaporative flux during night time in the top soil layer (Fig. 21), where probes of length 14 cm where vertically inserted. The variation of water content were of minor entity at 25 cm depth (Fig. 22), while almost no evolution in the soil water status could be observed at 45 cm depth.

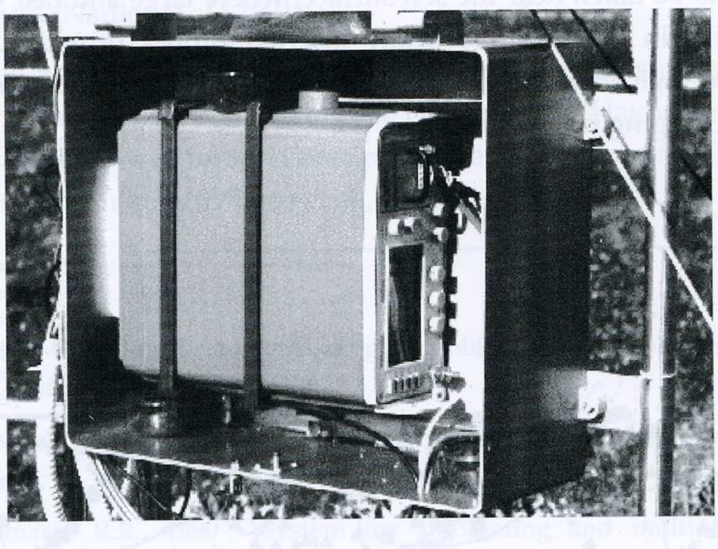

Fig. 23 - Installation of TDR apparatus in the meteo station.

Automatic recording is of great use when prolonged periods of monitoring are required (i.e. several weeks). During 1994, an automatic agro-meteorological station equipped with a TDR apparatus and solid state mass storage was installed in an experimental artichoke field in an irrigated area in Southern Italy. The whole instrumentation was battery-operated, and data logger software was adequate for complete control of the TDR unit (Fig. 23). Two series of four coaxial probes were installed up to a depth of 70 cm. The water profiles was acquire every day at 16.00 hrs.and the TDR unit was switched off after each measurement in order to save battery power. The time interval between data downloading and battery change was 16 days. The measurements were finalised with calibration of a one-dimensional model of unsteady soil water flow. The graph shown in Fig. 24 is referred to the acquisition of water profile during a period of three months approximately.

GENERAL REMARKS AND COMMENTS

The main attractiveness in estimation of soil water content from measurements of the propagation speed of a TEM relies on the minimal influence of soil salinity and temperature and of probe geometry. Variation of dimensions and imperfections in parallelism of the conductors do not hamper the accuracy of determination in most practical applications; therefore, probe geometry and insertion criteria may be adapted for each specific measurement requirements. The use of TDR is particularly advantageous when measurements are to be taken near the soil surface, where large and fast variations of water content are possible. In this case, vertically inserted probes provide quick and reliable measurements of average water content; some difficulties arise if measurements are required at large depths and digging is required.

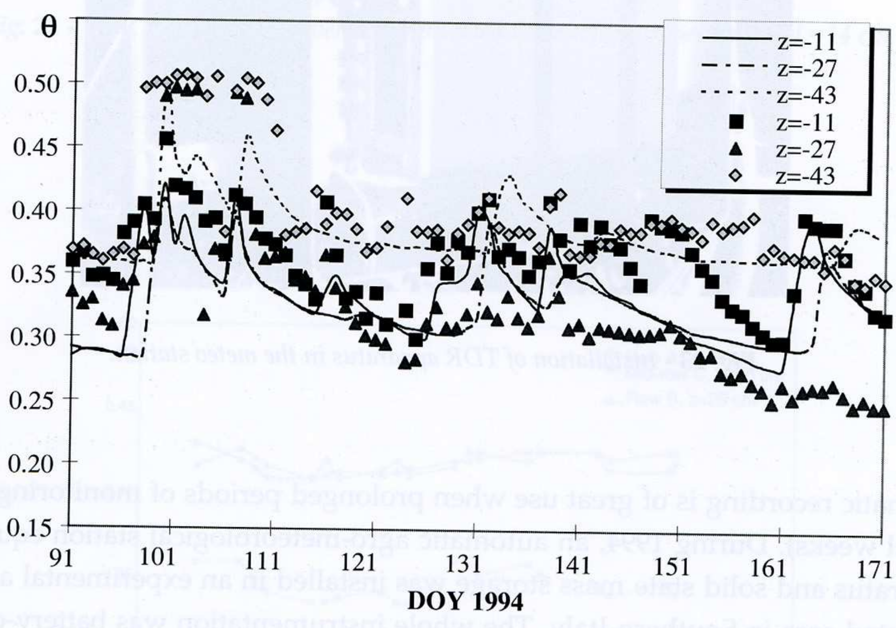

Fig. 24 - Comparison between simulated and measured water content. Continuos lines represents the simulated soil water content.

Repetitive and automatic measurements can be more easily performed with respect to other techniques and several equipments have been designed for this purpose (Baker et al., 1990; Herkelrath et al., 1991; Heimovaara et al., 1993).

The TDR technique is particularly suitable in mineral soils with low values of clay contents and conductivity; in such soils "universal" calibration formulae can be used for accurate predictions of θ. This approach leads to accurate estimation of the total water storage in a profile with an error less than 10% (Zegelin, 1992). In clay and/or organic soils site-specific calibration or semi-empirical relationships, such as Eq.9, are suggested; in this case, the use of TDR is certainly more difficult.

In presence of soil heterogeneity within the volume investigated by the TDR probe, multiple reflections cause troubles in the analysis of TDR data; air gaps and soil cracking near the conductors should also be avoided.

Another source of inaccuracy is soil conductivity higher than 600 mS/m, although the entity of signal attenuation by means of TDR technique is often used for soil electrical conductivity estimates (Nadler et al., 1991).

TDR has proved to be particularly suitable for several specific studies, i.e. the detection of the thickness of frozen soil layers limiting the crop growth (Hayhoe et al., 1983) and for the interpretation of microwave backs scattering in the estimation of soil water with space borne remote sensing techniques (D'Urso et al., 1994).

REFERENCES

Annan A.P., 1977. Time-domain reflectometry air gap problem for parallel wire transmission lines. *Geol. Survey of Canada*, paper 77-IB, pp. 59-62.

Baker J.M. and Lascano R.J., 1989 The spatial sensitivity of time-domain reflectometry. *Soil Sci.*, 147: 378-384.

Baker J.M. and Allmaras R.R., 1990 - System for automating and multiplexing soil moisture measurement by Time-domain reflectometry. *Soil Sci. Soc. Am. J.*, 54: 1-6.

Baker J.M. and Lascano R.J., 1991 - Response to the letter to the editor. *Soil Sci*, 151: 256-257.

Dalton F.N. and van Genuchten M.Th., 1986 - The time - domain reflectometry method for measuring soil water content and salinity. *Geoderma*, 38: 237-250.

Dean T.J., Bell J.P. and Baty A.J.B., 1987 - Soil moisture measurement by on improved capacitance technique: I. sensor design and performance. *J. Hydrol.*, 93: 67-78.

D'Urso G., 1992 - Impiego della riflettometria in dominio temporale (TDR) per la misura del contenuto d'acqua dei suoli in presenza di profili di umidità non uniformi - *Rivista di Ingegneria Agraria*, 23, 35-44.

D'Urso G., Mancini M. and Santini A., 1994 - Satellite S.A.R. data sensitivity to soil dielectric and moisture patterns. Proc. XII World Congress on Agricultural Engineering, CIGR, Marelbeke, Belgium, vol.I: 35-43.

D'Urso G., Coppola A., Santini A., 1996 - Spatial and temporal variability of soil dielectric patterns on the Sele test site.. Proceed. 2nd Workshop on "Spatial and Temporal Soil Moisture Mapping (Proj. EV5V-CT94-0446), Rennes, giu.'95; Lab. Hydrology, Gent University (Belgium)

Hasted J.B., 1973 - Aqueous dielectrics. Chapman and Hall Ltd. London, pp.302

Hayhoe H.N., Topp G.C. and Bailey W.G., 1983 - Measurement of soil water contents and frozen soil depth during a thaw using time-domain reflectometry. *Atnas-Ocean*, 21: 299-311.

Heimovaara T.J., 1993 - Design of triple-wire time domain reflectometry probe in practice and theory. *Soil Sci. Soc. Am. J.*, 57: 1410-1417.

Heimovaara T.J. and Bouten W., 1990 - A computer controlled 36-channel time domain reflectometry system for monitoring soil water content. *Water Resour. Res.*, 26: 2311-2316.

Heimovaara T.J., Bouten W. and Verstraten J.M., 1994 - Frequency domain analysis of time domain reflectometry waveforms 2. A four-component complex dielectric mixing model for soils. *Water Resour. Res.*, 30: 201-209.

Herkelrath W.N., Liamburg S.P. and Murphy F., 1991 - Automatic, real - time monitoring of soil moisture in a remote field area with time domain reflectometry. *Water Resour. Res.*, 27: 857-864.

Hilhorst M.A. and Dirksen C., 1994 - Dielectric water content sensors: Time-Domain versus Frequency-Domain, personal communication

Hokett. S. L., Chapman J.B. and Cloud S. D., 1992 - Time domain reflectometry response to lateral soil water content heterogeneities. *Soil Sci. Soc. Am. J.*, 56: 313-316.

Hoekstra P. and Delaney A., 1974 - Dielectric properties of soil at VHF and microwave frequencies. *J. Geophys. Res*, 79: 1699-1708.

Jacobsen O.H. and Schjønning P., 1995 - Comparison of TDR calibration functions for soil water determination. In A.Correll (Ed.); Proceed. Symposium on TDR applications in Soil Science, Foulum (D) 1994; Danish Institute of Plant and Soil Sci.,SP Report n.11 Vol.3: 25-33

Kachanoski R.G., Nan Wesenbeeck I.J., Von Bertoldi P., Ward A. and Hamlen C., 1990 - Measurement of soil water content during three - dimensional axial - symmetric water flow. *Soil Sc. Soc. Am. J.*, 54: 645-649.

Knight J.H., 1992 - Sensitivity of time domain reflectometry measurements to lateral variation in soil water content. *Water Resour. Res.*, 28: 2345-2352.

Kutílek M. and Nielsen D.R., 1994 - Soil hydrology. CATENA VERLAG, Germany, 370 pp.

Mancini M., Giacomelli A., Troch P. and D'Urso G., 1994 - Remote sensing of surface soil moisture from spaceborne SAR sensors over the Sele plain. Proceed. The European Symposium on Satellite Remote Sensing, Europto, 26-30 sett. 1994, C.N.R., Roma; SPIE, Bellingham, Washington 98227-0010 (U.S.A.); Vol.2314: 516-523

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

Nielsen D.C., Lagae H.J., Anderson R.L., 1995 - Time-Domain Reflectometry measurements of surface soil water content. *Soil Sci. Soc. Am. J.*, 59: 103-105

Roth, Schulin R. Fluehler H. and Attinger W., 1990 - Calibration of TDR for water content measurement using a composite dielectric approach. *Water Resour. Res.*, 26: 2267-2273.

Roth C.H., Malick M.A. and Plagger., 1992 - Empirical evaluation of the relationship between soil dielectric constant and volumetric water content as the basis for calibrating soil moisture measurements by TDR, - *J. Soil. Sci.*, 43: 1-13.

Shaun F.K., Selker J.S. and Green J.L., 1995 - Using short soil moisture probes with high - bandwidth time domain reflectometry instruments. *Soil Sci. Soc. Am. J.*, 59: 97-102.

Shumugge T.J., Jackson T.J. and Mckim H.L., 1980 - Survey of methods for Soil moisture determination. *Water Resour. Res.*, 16: 961-979.

Spaans E.J.A. and Baker J.M., 1993 - Simple baluns in parallel probes for Time Domain Reflectometry. *Soil Sci. Soc. Am. J.*, 57: 668-673

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

Topp G.C. and Davis J.L., 1985 - Time - domain reflectometry (TDR) and its application to irrigation scheduling. Advance in irrigation, vol.3 (Hillel D. ed.), Academic Press. Inc. New York pp. 107-127.

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

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

Zegelin S.J. and White I., 1989 - Improved field probes for soil water content and electrical domain reflectometry. *Water Resour. Res.*, 25: 2367-2376.

Zegelin S.J., White I. and Russel G.F., 1992 - A critique of the time domain reflectometry technique for determining field Soil - water content, in "Advances measurement of soil physical properties: bringing theory into practice (Topp G.C., Reynolds W.R. and Green R.E. ed.). Soil Sci Soc. Am. publ. n°30, Madison, Wisconsin, USA