TDR-LAB 2.0: IMPROVED TDR SOFTWARE FOR SOIL WATER CONTENT AND ELECTRICAL CONDUCTIVITY MEASUREMENTS

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RESUMEN. La técnica de Reflectometría de Dominio Temporal (TDR) permite estimar la humedad (θ) y la conductividad eléctrica aparente del suelo (σ_a). Esta comunicación presenta una nueva versión del programa TDR-Lab para la medida de θ y σ_a. El TDR-Lab 2.0 es compatible con tres ecómetros TDR diferentes y puede conectarse a multiplexores SDMX50 (Campbell Sci). Puede estimar θ y σ_a por métodos gráficos y numéricos y incluye nuevas aplicaciones para la medida de niveles de agua, potencial mátrico o conductividad eléctrica de la solución del suelo. Está disponible en una versión ligera que trabaja con ficheros XML y una versión completa que centraliza los datos en una base SQL. Una robusta interface de importación-exportación de datos permite comunicar ambas versiones.

ABSTRACT. Time Domain Reflectometry (TDR) is a widely used technique that allows real time estimation of soil volumetric water content (θ), and bulk electrical conductivity (σ_a). This work presents an enhanced release of TDR-Lab, software which controls instrumentation for measurements of θ and σ_a. TDR-Lab 2.0 supports three different TDR equipments and can be connected to a multiplexing system (SDMX50, Campbell Sci). Graphical or numerical methods can be used for the estimation of θ and σ_a. Additional features to carry out water-surface-level measurements such as matric potential and soil solution electrical conductivity are also available. A little and a full release, for field and laboratory applications have been developed. The light version works with XML-files instead of the SQL database engine of the extended TDR-Lab. A robust import/export graphical user interface facilitates transferring projects between the centralized SQL database and XML files.

1.- Introduction

Knowledge of soil water content and its distribution in the vadose zone is of paramount importance in many soil-related disciplines such as soil science, agriculture, forestry and hydrology. The Time Domain Reflectometry (TDR) has become a popular method for the accurate, quick, and non-destructive estimation of the apparent permittivity (σ_a), which is related to the volumetric soil water content (θ) and the bulk electrical conductivity (ε) (Topp and Ferré, 2002). Other TDR applications for soil science have been focused, for instance, on measurements of water levels in Mariotte tubes (Moret et al., 2004), estimation of the soil matric water potential (Or and Wraith., 1999) or the soil water solution electrical conductivity (Moret-Fernández et al., 2012). Estimations of the apparent permittivity by TDR, and consequently water content, are generally based on a graphical interpretation of the reflected TDR waveform from the probe length using the double-tangent waveform analysis (Herkelrath et al., 1991). The bulk electrical conductivity, however, is mainly estimated by analyzing the amplitude of the long-time TDR signal according to the Lin et al. (2008) procedure. Modelling of TDR signals by numerical inversion of the TDR waveform is becoming a robust alternative to the classical methods to estimate both water content and soil bulk electrical conductivity (Greco 2006; Heimovaara et al. 2004).

To date, the design of specific instruments to use the TDR technology in measuring soil water content has experienced a fast development, as shown by numerous companies that market TDR instruments for soil applications: Adcon, IMKO, Streat Instruments Ltd., Campbell Scientific, Global Water Instrumentation, Inc., Environmental Sensors, Inc. Automata Inc., Meteolabor AG, Dynamax, Soil Moisture Equipment Corporation. The earliest instrument commonly used for field investigations was the model 1502, Metallic Cable Tester, manufactured by Tektronix of Beaverton, Oregon. This instrument, only allowed to the users a manual determination of θ. This procedure was time consuming and sometimes inaccurate. These problems were solved by designing specific software that allowed automatic analysis of the TDR waveform. This is the case, for instance, of the TACQ program (Evett, 2000) (http://www.cprl.ars.usda.gov/programs/) developed in the early 1990s. This program allowed the users a complete control over multiplexer, individual settings for probe length, window width, averaging, distance to each probe, gain, and type of data acquired. Following this incipient project, the Soil Physics Group at Utah State University, Logan Utah, USA, created in the 1993 the WINTDR program, which being only compatible with the TDR cable testers Tektronix 1502, incorporated an easy and friendly Windows interface for accurate and efficient analysis under a variety of conditions (http://soilphysics.usu.edu/wintdr/download.htm). Other software also developed for water content estimations using TDR systems are, for instance, the WinTrase software from Soil Moisture that works only with the Soil Moisture TDR products and runs under MS Windows operating systems, or the free available PC-TDR software developed by Campbell Scientific Cop. developed exclusively for the TDR-100 Campbell Sci. cable tester. More recently, Moret-Fernández et al. (2010) developed new TDR software, TDR-Lab 1.0, for estimates of θ and σ_a. This software represented an improvement of previous TDR applications since, being compatible wiht two different TDR cable testers, it also included a user-friendly and dynamic file format to show and save the TDR waveforms and different methods of TDR waveform analysis.. However, this version, that resulted incomplete, did not include multiplexers and was developed on a heavy central database that restricted its use on low capacity computers.

In spite of the large expansion of the TDR technology for θ and σ_a estimations, the public release of software which is compatible with different TDR instruments is quite limited. On the other hand, the versatility for the analysis and storage of the recorded TDR waveform of the different free available TDR software is currently quite restricted. The objective of this paper is to present a new and improved version of the TDR-Lab 1.0 software (TDR-Lab 2.0) which, being compatible with three different TDR cable testers, has significant improvements regarding to the former version. Two different versions for laboratory (TDR-Lab) and field (TDR-Lab Lite) measurements have been developed. TDR-Lab Lite includes a reduced set of features and was designed to run on low-end ultraportable devices.

2.- TDR-Lab features: TDR-Lab and TDR-Lab lite

Two different linked versions for laboratory (TDR-Lab) and field (TDR-Lab Lite), with an easy Windows user interface, have been developed.

The TDR-Lab Lite, which works with XML-files, has been designed to run on low-end ultraportable devices. The main advances regarding to the former TDR-Lab 1.0 version are: compatibility with the Tektronix 1502C Metallic TDR, the TDR100 TDR Campbell Scientist and the TRASE (Soil-moisture Equipment Corp.) cable testers; compatible with the multiplexer system SDMX50 (Campbell Sci.); high resolution waveforms (up to 2048 samples) when connected with TDR100; self-calibration with graphical methods, and a more intuitive configuration manager for cables and TDR probes; an open interface to make important data visible, allowing recorded and stored TDR waveforms to be combined; multiple waveforms can be superimposed for on screen comparison; three different methods for water content estimations (manual, derivative, and tangent methods) and a single procedure for bulk electrical conductivity determinations; additional features to compute water-surface-level measurements, matric potential or soil solution electrical conductivity when using the specific probes; automated waveform readings; a new dynamic file format to show and save the TDR waveforms and analysis results and a simplified and improved display system; and a reliable import/export graphical interface (GUI) to allow transferring projects between TDR-Lab centralized SQL database and XML files.

The complete version of the TDR-Lab, which works with a SQL database, allows centralizing all data in the same computer. In addition to the features described in the TDR-Lab Lite release, this extended version included: a virtual TDR machine to simulate TDR waveforms; an additional method to estimate of θ and σ_a by numerical modelling of TDR waveform and the corresponding numerical procedure to calibrate TDR probes.

3.- Software description

The TDR-Lab 2.0 is programmed in C# with Microsoft®.Net Framework® 3.5. A new based layers implementation, which includes a module that interacts with the former version programming (TDR-Lab 1.0), has been developed. Three different levels have been defined (Fig. 1): (i) the Graphical User Interface (GUI), which allows the user selecting the available operations; (ii) the Bussines Logical Layard (BLL) layer, that controls the technical management involved in the data collection and data processing; and (iii) the Data Access Layer, where all information coming from the upper layers is stored and processed. A new module implemented in database layer allows simplifying and increasing the application efficiency. This module is compatible with the database storage features.

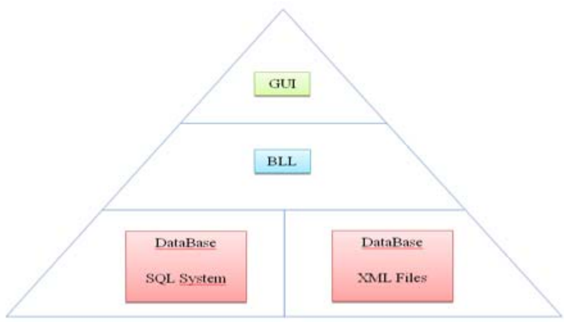

Fig. 1. Pyramidal structure layers of the application

The program architecture consists of five components that provide a unified user interface (UI) to operate different TDR cable testers (Fig. 2). These UI components are: (i) project manager and editor windows, (ii) equipment ($tdr \rightarrow probe$), (iii) waveform acquisition and measured waveforms, (iv) waveform analysis, and (v) data access. The first step to acquire new TDR waveforms involves, before connecting the cable tester, to select one of the TDR cable tester available in the program. Once the cable tester is connected, the user should create a new project defining the characteristics of the transmission line.

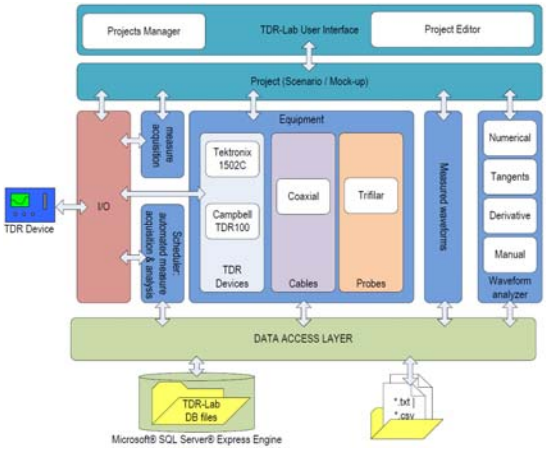

Fig. 2. Flowchart of the TDR software

3.1.- Project manager and editor windows

The TDR-Lab data is organized in projects, which are saved in the folders showed in the TDR-Lab Project Manager window (Fig. 3). This window is divided in three sections: (i) the folder tree on the left, that shows the set of folders that contains the TDR projects, (ii) the project window on the right, that shows the TDR project within each folder, and (iii) the menu bar that includes a repository application to show all TDR cable and probes and the import/export graphical interface to transfer projects between TDR-Lab centralized SQL database and XML files.

The project form storages information about the TDR cable tester related to the settings and communication setup. The Project Editor window (Fig. 4) is automatically opened by clicking on a project in the Project Manager window (Fig. 3). The Project Editor window is divided in:

(i) Equipment tree, where the TDR cable tester, and TDR probes and waveforms are defined.

(ii) TDR Screen, where TDR waveform acquisition, analysis and storage are executed.

(iii) The menu bar that includes all information about the TDR equipment, the TDR waveforms, cables and TDR probes, calibration and automated analysis options.

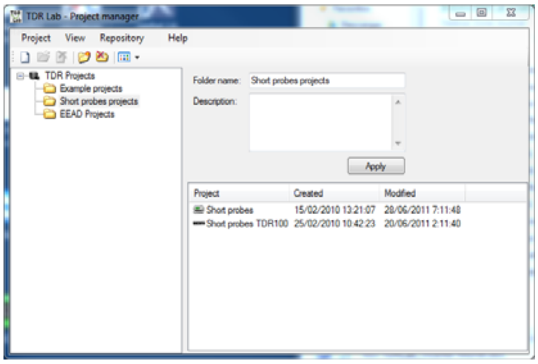

Fig. 3. TDR-Lab project Manager window

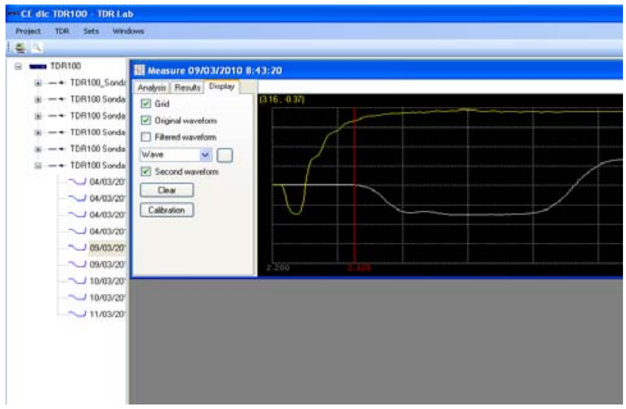

Fig. 4. Project editor window and large and small scale TDR waveforms. Red line denote the first peak of the TDR waveform

3.2.- Equipment

Three different components have been defined (Fig. 2): (i) communications component that allows TDR-Lab to send commands and acquire waveforms from the cable tester; (ii) unified cable tester interface that makes possible the acquisition and analysis of the TDR waveforms to be independent of the type of TDR cable tester; and (iii) coaxial cable and TDR probes components that defines the properties of the coaxial cables (propagation velocity, impedance and length) and the probe characteristics. Self-calibration methods for coaxial cables and TDR probes have been included in this component.

3.3.- TDR waveform acquisition

Three different forms of TDR waveform acquisition are available: (i) manual or automatically acquisition of the current TDR waveform just recorded by the TDR cable tester; (ii) opening previously saved TDR waveforms which are displayed in the third of the Project Manager windows (Fig. 4); and (iii) importing TDR waveforms from an external text file. Two differently scaled TDR waveforms can be simultaneously acquired. The first one, which is defined on a large scale and allows estimating the soil water content, and a small scale waveform used to estimate the bulk electrical conductivity from long-time TDR signal (Fig. 4).

Analysis of TDR waveform for soil properties measurements can be performed on current TDR waveforms, on TDR waveforms previously saved in the central database or on imported data. Four different methods of waveform analysis for water content estimations are included: three graphical methods (manual, tangent, derivative) and a numerical inverse analysis of the TDR waveform for three-wire probes immersed in homogeneous media. The soil bulk electrical conductivity can also be estimated by either a graphical or a numerical procedure. While the manual, tangent or derivative methods can be used either on recently recorded or stored waveforms, the numerical method, which is only available in the complete TDR-Lab version, should be used on previously saved TDR signals. An option for automating the analysis of a collection of saved TDR traces has been included in the program.

3.3.1.- Estimations of volumetric water content and bulk electrical conductivity

Graphical methods

Estimations of water content using the graphical TDR waveform analysis (manual, derivative or tangent procedure) are based on

$$\varepsilon_a = \left(\frac{ct_L}{2L}\right)^2 \tag{1}$$

where ε_a is the soil bulk dielectric constant of the embedded material, c is the velocity of light (3 x 10^8 m s^{-1}) and t_L (s) is the travel time for the pulse to traverse the length L (m) of the TDR guide. The value t_L is the distance between bump created by the impedance mismatch between cable and TDR probe head (first peak) (Fig. 4) and the time when the trace arrives at the end of the TDR probe (second reflection point or ending point). The relationship between ε_a and θ is commonly calculated with a polynomial empirical relationship (Topp and Ferré, 2002).

The bulk electrical conductivity (σ_a) estimated with the long-time analysis of the TDR waveform is calculated according to Giese and Tiemann (1975) (Fig. 4):

$$\sigma_a = \frac{K_p}{Z_r}\left(\frac{1-\rho_{\infty,\text{Scale}}}{1+\rho_{\infty,\text{Scale}}}\right) \tag{2}$$

where Z_r is the output impedance of the TDR cable tester (50 Ω), K_p (m^{-1}) is the probe-geometry-dependent cell constant value, and $\rho_{\infty\ Scale}$ is the scaled steady-state reflection coefficient for ideal condition calculated according to Lin et al. (2008)

$$\rho_{\infty,Scale} = 2\frac{(\rho_{air}-\rho_{SC})(\rho-\rho_{air})}{(1+\rho_{SC})(\rho-\rho_{air})+(\rho_{air}-\rho_{SC})(1+\rho_{air})}+1 \tag{3}$$

where ρ, ρ_{air} and ρ_{SC} are the long-time reflection coefficient measured in the studied medium, in air and in a short-circuited probe, respectively (Fig. 6).

Numerical TDR waveform analysis

The soil θ and σ_a are numerically estimated by an inverse analysis of the TDR waveform (Heimovaara et al. 2004). The transmission line used in the model is driven by a step source voltage $V_s(t)$ of height V_{s0} with a source impedance R_s (usually 50 Ω) and ends in an open termination with $Z_L = \infty$. The cable and probe are modelled as lossy transmission lines in the frequency domain. Fourier analysis is used (Heimovaara et al., 2004; Huebner and Kupfer, 2007) with direct and inverse FFT algorithms for switching from the time to frequency domain and vice-versa. The frequency domain transfer function of the soil-probe-cable set is that of a voltage divider constituted by R_s (nominally 50 Ω) and the frequency-dependent input impedance of the cable-probe-soil set (Z_i). The transmission lines are characterized with four parameters (Ramo et al., 1984): capacitance C (F m^{-1}), inductance L (H m^{-1}) conductance G (S m^{-1}) and resistance R (Ωm^{-1}). The ε_c is estimated by computing the frequency-dependent permittivity of pure water $\varepsilon_w(\omega)$ at a given temperature (currently 25ºC) (Meissner and Wentz, 2004). For a given θ we obtain $\varepsilon_a(\theta)$ with a polynomial (Topp- and Ferré, 2002) formula (Eq. 2) and finally

$$\varepsilon_c = \varepsilon_{a0} + \frac{\varepsilon_a - \varepsilon_{a0}}{\varepsilon_{a1} - \varepsilon_{a0}}(\varepsilon_w - \varepsilon_{a0}) \tag{4}$$

where $\varepsilon_{a0} = \varepsilon_a(\theta = 0)$ and $\varepsilon_{a1} = \varepsilon_a(\theta = 1)$. The estimation of the soil parameters (θ and σ_a) is achieved by the golden-section search technique (Kiefer, 1953), after minimizing the root mean square (RMSE) from a comparison of the measured and modeled TDR waveforms. This procedure requires a previous calibration process to determine the effective length (l_{eff}) of the TDR probe and the initial time (t_0) at which the electromagnetic pulse enters the TDR probe.

3.3.2.- Water level estimations with TDR

Using a vertical coated TDR probe of length L immersed in a water column, the water level (L-x) can be calculated according to (Moret et al., 2004)

$$x = L\frac{\sqrt{\varepsilon_{TDR}} - \sqrt{\varepsilon_w}}{\sqrt{\varepsilon_{air}} - \sqrt{\varepsilon_w}} \tag{5}$$

where x is the probe length above water level, ε_{TDR} is the apparent dielectric constant measured by the TDR cable tester, and ε_{air} and ε_w are the relative dielectric constants of air and water previously measured with the same probe, respectively. To compute water level measurements, values of ε_{air} and ε_w and L should be previously introduced in the TDR-Lab application.

3.3.3.- Soil matric potential and soil solution electrical conductivity estimation

The soil matric potential (ψ) or the soil solution electrical conductivity can be estimated from the σ_a and θ values measured with a ceramic-TDR sensor. This consists on a set of commercially available porous ceramics plates arranged along the axis of a TDR probe (Or and Wraith, 1999). For matric potential estimation a θ-ψ relationship for each sensor should be previously established (Or and Wraith, 1999). In the case of the TDR-Lab 2.0, a simple Van Genutchten (1980) water retention function relating θ and ψ is so far available,

$$\theta = \left[\left(\theta_{sat} - \theta_r\right) \left[\frac{1}{1 + (\alpha\psi)^n} \right]^m \right] + \theta_r \qquad (6)$$

where n is the pore-size distribution parameter, m = 1-(1/n), α [kPa] is the scale factor, and θ_{sat} and θ_r are the saturated and residual volumetric water contents of the ceramic plates, respectively. These parameters should be obtained from previous calibration experiments and introduced in the TDR-Lab.

The soil solution electrical conductivity corrected at 25 ºC ($\sigma_{w/25}$) is estimated according to (Moret-Fernández et al. 2012)

$$\sigma_{w/25} = \sigma_w f \qquad (7)$$

where f is an empirical factor expressed as (US Salinity Laboratory Staff, 1954)

$$f = 1 - 0.20346(T) + 0.03822(T^2) - 0.00555(T^3) \qquad (8)$$

and $T = (T_{ºC}$ -25)/10. σ_w is the measured soil solution electrical conductivity expressed as

$$\sigma_w = \frac{\sigma_a}{\theta_{sat}^{\tau} \left(\frac{\theta}{\theta_{sat}} \right)^{\beta}} - \sigma_{a-s} \qquad (9)$$

where $\sigma_{a\text{-}s}$ is the bulk electrical conductivity of the solid phase of the dry ceramic plates; β is a factor depending on the ceramic plate water transmission porosity and τ is a transmission coefficient of the saturated ceramic plate (Mualem and Friedman, 1991). The σ_a and θ are estimated by TDR and the $\sigma_{a\text{-}s}$ (negligible), θ_{sat}, β and τ values, which are obtained from previous calibration experiments, must be introduced in the TDR-Lab..

3.4.- Data access

Within the complete version of the TDR-Lab 2.0, all data are saved in a centralized data base. This includes project information, TDR devices, TDR settings, the repository of cables and probes, saved waveforms and analysis results. The results obtained from the TDR waveform analysis are organized in the Analysis Results Manager window (Fig. 5).

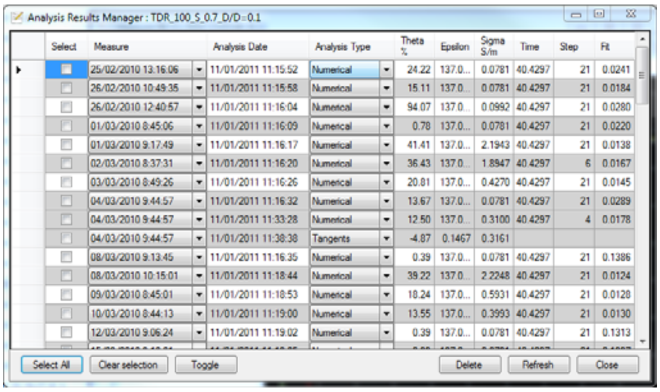

Fig. 5. Results manager window

These data include the following items: the date and time of the TDR waveform analysis and storage, type of TDR waveform analysis, the values of the volumetric water content, dielectric permeability, bulk electrical conductivity and details of the numerical analysis (time-analysis), number of iterations and fitting value. Selected data from the centralized data base can be exported to a *.csv* format file that contains the following information: the name of the TDR probe, settings of the TDR waveforms, pairs of points of travel time and reflection coefficients for the different TDR waveforms, the results and method used to calculate the water content, dielectric constant and bulk electrical conductivity, if estimated.

4.- Conclusions

This paper presents a new version of the software TDR-Lab, which being compatible with three different TDR cable testers, allows soil water content and bulk electrical conductivity to be estimated using different methods of analysis of the TDR waveforms (the manual, derivative, tangent and numerical methods). The software also allows estimations of water level, matric potential or soil solution electrical conductivity when specific probes are used. Two different versions for laboratory (TDR-Lab) and field (TDR-Lab Lite) measurements have been developed. TDR-Lab Lite includes a reduced set of features and was designed to run on low-end ultraportable devices. In conclusion, this new version results, compared to previously available TDR software, a significant advance for TDR waveform management and analysis. The TDR-Lab software is free and can be downloaded, after a requested registration, from http://digital.csic.es/handle/10261/9238.

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