TDRPy Instruction Manual

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In this manual, operations to use the software TDRPy are described. Detailed information about the software and the algorithms can be found in Bittelli et al. (2015) and Bittelli et al. (2021). The software is available on GitHub and it is subject to Open Source regulations and in the website of the author www.marcobittelli.com

The program is executed by running the *main.py* file, contained in the directory *src* (source code). It is recommended installing the Anaconda Python distribution with Python version 3.7 or later or Spyder. Using Anaconda is convenient, since it includes modules needed to run the programs such as Tkinter, Numpy and MatPlotlib. Run the programs by typing IDLE in the terminal of Anaconda (CMD.exe Prompt), or using the IDE Spyder. From IDLE open the program (*main.py*) and run it. The program is organized with three main operations:

1. **Analyze a single TDR waveform** for soil water content and soil bulk density analysis with prescribed parameters. Probe calibration should be performed with this option on standards (water, air, ethanol or other dielectrics of known electric permittivity).

2. **Compute model parameters** Analyze multiple TDR waveforms and independently measured soil bulk density (SBD) values to obtain the fitting parameters for computation of soil bulk density.

3. **Analyze multiple waveforms** After having parameterized the model, the software allows for analyzing multiple TDR waveforms at a time to measure soil water content and soil bulk density.

1. Analyze a single TDR waveform

The first procedure implemented in the software is the possibility to open, calibrate and analyze a single TDR waveform. It is performed by selecting *Import data*. A windows interface will open allowing for selecting the waveform. Note that the parameters (a,b and c) used for computing SBD, based on the Curioni's equations (Curioni et al., 2018), are provided by the user at the window interface. Soil parameters are also provided used for computing soil water content using the dielectric mixing model of Roth et al. (1990). The section with blue colors list the results and are set at a default value of zero, when the interface is first opened.

The data format is the one used by the TDR100 (Campbell Sci. Inc.), where the first rows are information about the TDR settings and the remaining rows are waveform data. Travel time increments corresponding to the reflection coefficient values stored in the data file, are computed by the software, based on the information provided in the header.

The box *Header Values* allows for specifying the number of header rows, such that the first rows are not read by the software and the TDR settings are specified at the interface in the boxes below (*Vp, Probe length, Window begin, Window width, probe handle, ε handle*). Otherwise, if the box *Header Values* is set to zero, the parameters are read from the file. This option is implemented to allow for using other TDR systems beside the TDR100 or TDR200, where the settings are not specified in the data file or are specified in a different format. Figure 1 shows the Windows interface (left) and an example of TDR file obtained from the TDR100 (right). Note the file format for the TDR with the first 8 rows with the setting parameters. In the original data files the time increment is not written, but only the value of reflection coefficient. The time increment is computed by dividing the window length (Window width minus Window begin) by the number of data points (in this case 251). The TDR device allows for collecting also higher numbers of datapoints and it must be specified in the parameter *Points*, as described below.

The Windows interface (TDRPy) allows for modification of the TDR parameters for calibration. The section in red are used for input parameters, while the areas in blue are ouput computed values. Commonly the calibration procedure adjusts the electric permittivity of the probe handle (ε_{handle}), in case the value of electric permittivity is not specified by the manufacturer. This information is necessary to compute the travel time in the probe handle. Window begin and width can also be adjusted depending on cable length and TDR settings. If the density is known and it is not object of analysis, it can provided as input in the section Soil parameters, this value is necessary to compute the bulk density and hence soil porosity in the Malicky et al. (1996) and Roth et al. (1990) models. The value of Water temperature and is used to correct the liquid permittivity value, which is temperature dependent in the Roth et al. (1990) dielectric mixing model. *Solid electric permittivity* (ε_s) and *alpha* (α) are also input values needed to employ the Roth et al. (1990) dielectric mixing model. As described above the section Curioni parameters can be included as input parameters for computation of SBD.

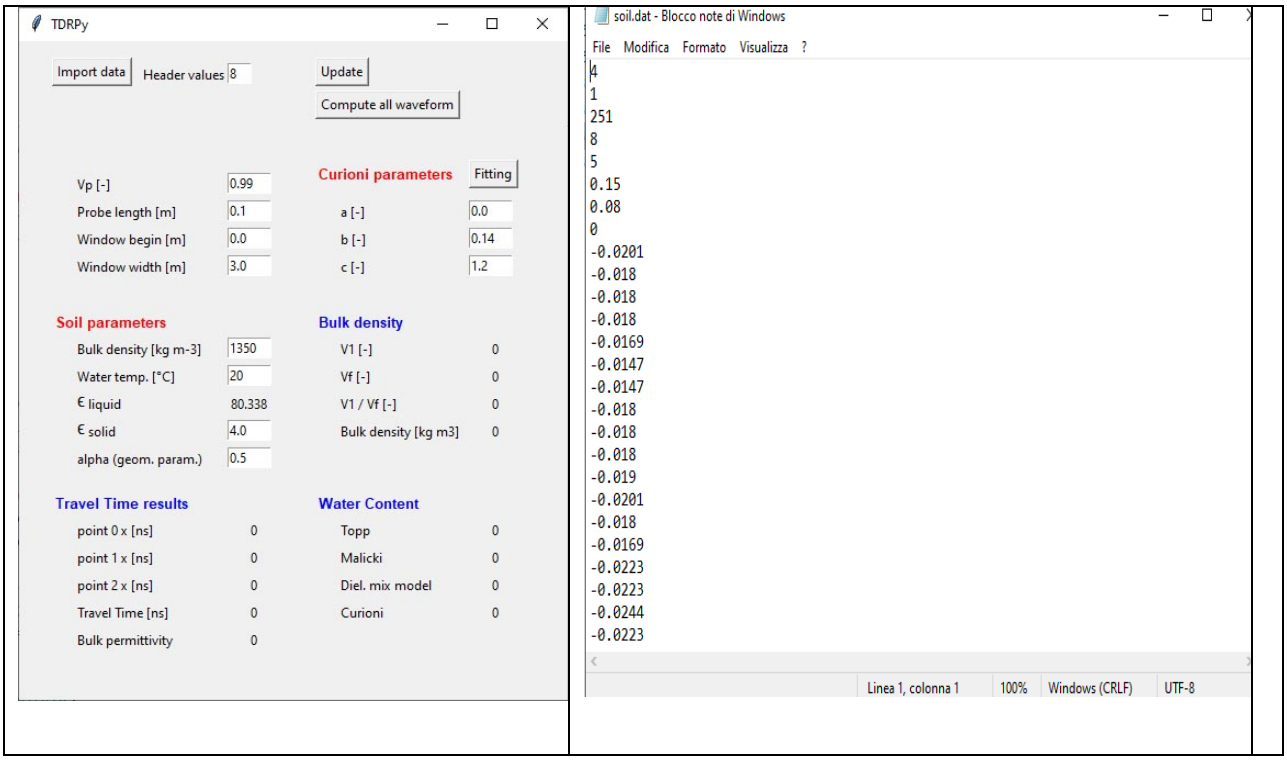

Figure 1. TDRPy interface (left), data format (right)

Specifically, the eight values for the TDR100 parameters (TDR 100 Manual) listed in the file in Figure 1, are:

1. *WaveAvg:* The WaveAvg parameter is used to define the number of waveform reflections averaged by the TDR100 to give a single result. A waveform averaging value of 4 provides good signal-to -noise ratio under typical applications.

2. *Vp:* The Vp parameter allows you to enter the propagation velocity of a cable when using the instruction to test for cable lengths or faults. Vp adjustment is not necessary for soil water content or electrical conductivity measurement and should be set to 1.0.

3. *Points:* The Points parameter is used to define the number of values in the displayed or collected waveform (20 to 2048). An entry of 251 is recommended for soil water measurements. The waveform consists of the number of Points equally spaced over the Window Length.

4. *CableLength:* The CableLength parameter is used to specify the cable length, in meters, of the TDR probes. If a 0 is entered for the Option parameter, cable length is used by the analysis algorithm to begin searching for the TDR probe. If a 1 or 2 is entered for the Option parameter, cable length is the distance to the start of the collected waveform.

5. *WindowLength*: The WindowLengthparameter specifies the length, in meters, of the waveform to collect or analyze. The waveform begins at the CableLength and ends at the CableLength + WindowLength. This is an apparent length because the value set for Vp may not be the actual propagation velocity. For water content measurements, the WindowLength must be large enough to contain the entire probe reflection. For probes with 20 to 30 cm rods. A Vp = 1 and Window length = 5 is recommended.

6. *ProbeLength:* The ProbeLength parameter specifies the length, in meters, of the probe rods that are exposed to the medium being measured. The value of this parameter only has an affect when Option 0, La/L, is used for the measurement

7. *ProbeOffset:* The ProbeOffset is an apparent length value used to correct for the portion of the probe rods that may be encapsulated in epoxy and not surrounded by soil or other medium being measured. This value is supplied by Campbell Scientific for the probes. The value of this parameter only has an affect when Option 0, La/L, is used for the measurement.

8. *Mult, Offset*: The Mult and Offset parameters are each a constant, variable, array, or expression by which to scale the results of the measurement.

Calibration

Commonly TDR calibration is performed with dedicated software such as the PCTDR by Campbell Sci, otherwise it can be performed manually. This software allows for calibration. Since the algorithm implemented in this paper computes the travel time after the probe handle and does not consider the travel time in the cable and in the probe handle (Bittelli et al. 2015), probe handle length and permittivity are not calibration parameters. For calibration the experimenter should collect waveforms in water, air or materials of known dielectrics and modify the parameters (probe length, window begin and window width). Since the probe length (although a real length) is also an apparent length that changes with electric permittivity it can be used as calibration parameter.

After having set the parameters, by clicking *Import data.* A file window interface will open and **one waveform** can be selected. After selecting the file, the computation automatically starts and perform the analysis. A plot of the waveform and results are produced. Note that the number of header points allows for not reading the parameters of the TDR file, and using the one set by the user in the interface.

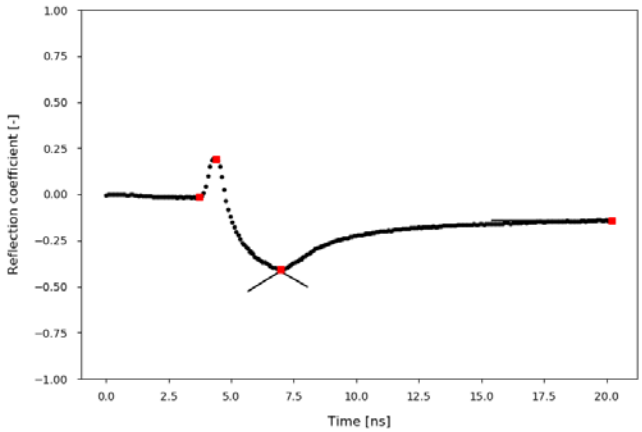

Figure 2. Waveform (file *soil.dat*), inflection points and fitted tangent lines.

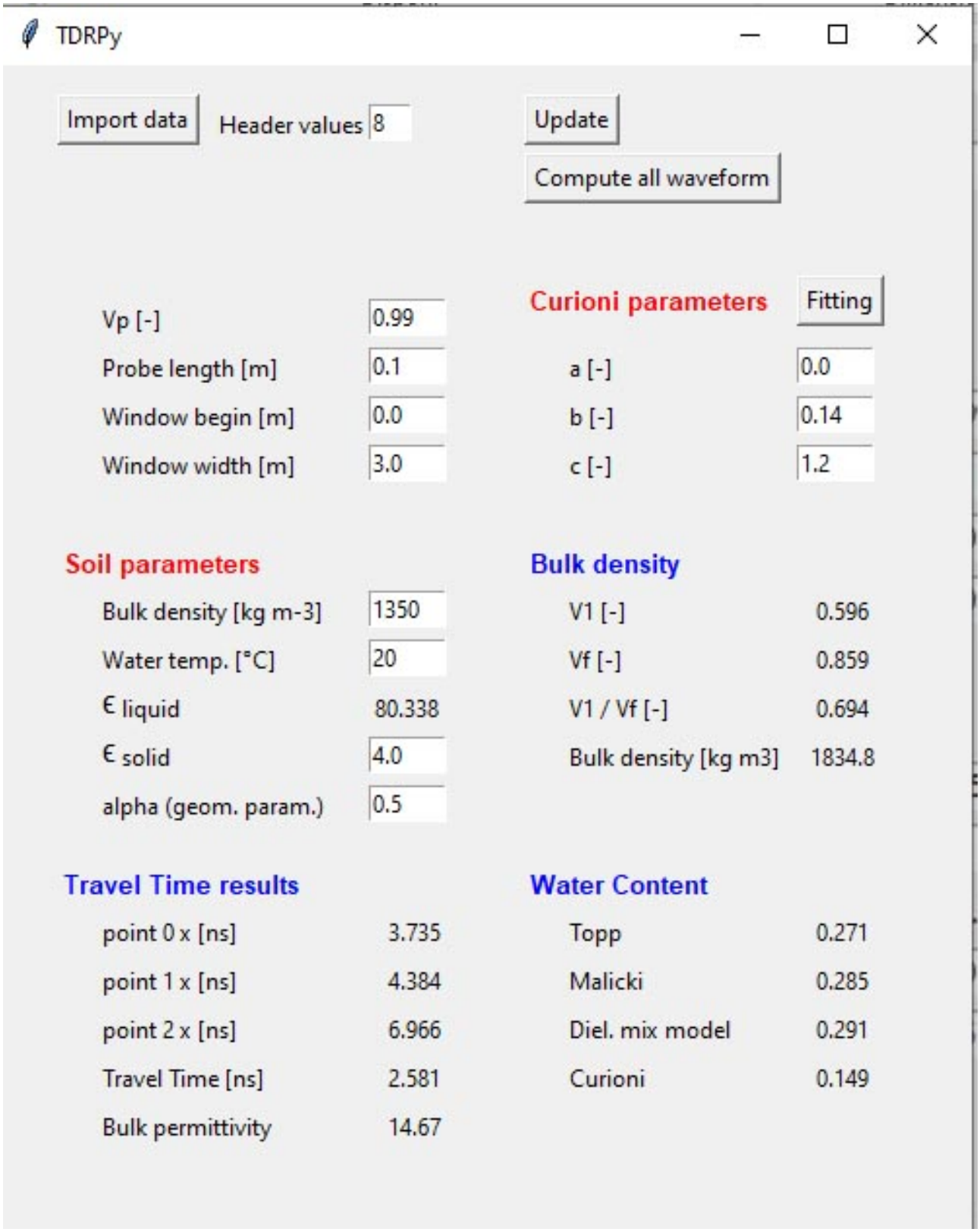

Figure 3. Results of the analysis.

Figure 3 shows the results of the analysis. The section Travel Time results lists the three inflection points from left to right (Figure 2), used to identify *point 0* where the wave enters the probe handle, *point 1* where the wave leaves the probe handle and enters the metal rod and *point* 2

which is reflection at the end of the metal rods (see Bittelli et al. 2021 for details). The difference between *point 1* and *2* is the travel time used for computing the *bulk electric permittivity* (ε_b).

In the section Bulk density the voltage attenuations parameters and the computed SBD are listed, based on the Curioni's equation. The section Water Content lists the output with the SWC values computed with the four models described by Bittelli et al. (2021). Anbazhagan et al. (2020) provides a discussion about the differences of the different models and therefore the differences in the SWC output. When the software is used in the *single waveform option* the output is provided in the interface only. In the next two options, when multiple waveforms are analyzed, the output data are saved into a .cvs output file.

2. Compute model parameters

This section of the software is written to parameterize the Curioni's model for estimation of SBD: The software implements a non-linear fitting using the Marquardt (1963) least squares minimization algorithm to obtain the parameters for computation of SBD. The algorithm aims at minimizing the sum of squared residuals for a non-linear equation, by optimizing the parameters space. Specifically, the parameters *a*; *b* and *c* in Eqn. 1 are estimated.

An input file (*obs_density.csv*) must be prepared by the user containing the independently measured SBD. A screen shot of the *obs_density.csv* is shown in Figure 4

Figure 4. Example of input file with independently measured SBD, to be prepared and saved into the directory *data*.

By clicking the button *fitting* on the right side of Curioni parameters, an input windows interface will open allowing for loading the folder where the file *obs_density.csv* is stored and where the output will be saved. It is advisable to organize the folder data with directories containing values for different soil types or experiment as in the example presents in the file associated with the software.

The first column of the input file contains the soil name and the second column the SBD values in kg m^{-3}. The SBD values are obtained from independent experiment of density as described by Bittelli et al. (2021). The file must have a header with the words: *soil, obs density*. The algorithm

reads these data and use it to run the Marquardt algorithms, combined with the travel time analysis software, to return the estimated parameters.

An output file (*fitting.csv*) is then saved in the same folder, containing the output bulk electric permittivity, the voltages (V_1 and V_r), the observed independent SBD (*obs density*) and the estimated density (*est density*).

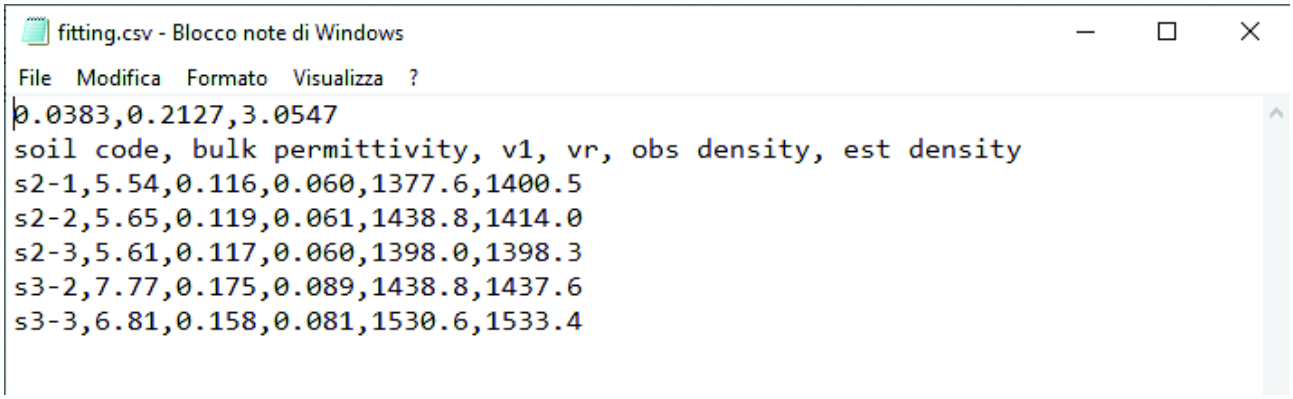

Figure 5. Example of the output file (*output.csv*) with the fitted parameters *a*, *b* and *c* in the first row (left to right). Below are listed the columns with: soil code, bulk permittivity, voltage attenuation parameters (V_1 and V_r), the observed input density and the estimated density.
After having obtained the parameters for a given soil, it is then possible to apply the third option of the software to analyze multiple TDR waveforms at a time to measure soil water content and soil bulk density.

3. Analyze multiple waveforms.

After having parameterized the model, the software allows for analyzing multiple TDR waveforms at a time to measure soil water content and soil bulk density.

When the data are imported with the button *Import data*, it automatically analyze the data, therefor the button *Update* is used to investigate the effect of the parameters a,b and c on the SBD computation. The button *Compute all waveform* works in a similar way to the button *fitting*: a directory is selected and all the files .dat that are found in the directory are analyzed. The waveform data must be saved in a file with the extension .dat, to be recognized by the algorithm.
This analysis saves an output file with *output.csv* with: soil code, bulk permittivity, v1, vr, bulk density, wc Topp, wc Malicki, wc MixModel, wc Curioni, where the *soil code* is the file name (without the extension *.dat*) and the different SWC are computed with the estimated SBD, therefore not the one with the parameters written in the interface.

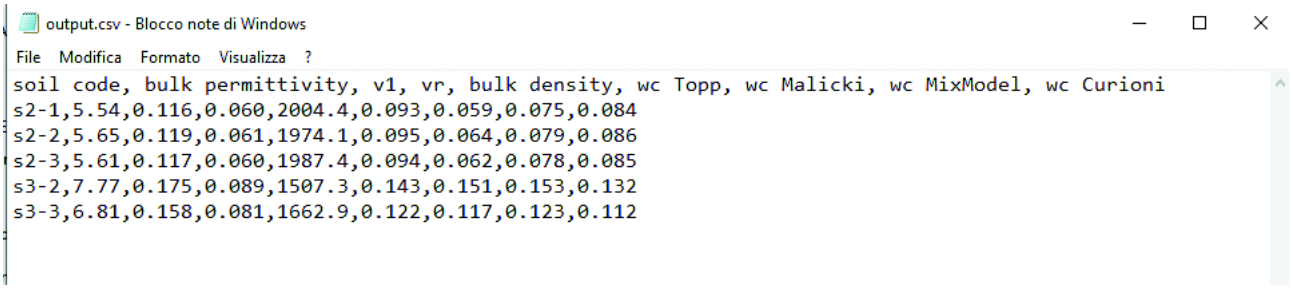

Figure 6. Output file with the results of multiple analysis of TDR waveform.

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