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THE TACQ COMPUTER PROGRAM FOR AUTOMATIC MEASUREMENT OF WATER CONTENT AND BULK ELECTRICAL CONDUCTIVITY USING TIME DOMAIN REFLECTOMETRY

by

Steven R. Evett

USDA-Agricultural Research Service
Conservation and Production Research Laboratory
2300 Experiment Station Road
Bushland, TX 79012, USA

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Summary:
The TACQ computer program, a program for **T**ime domain reflectometry (TDR) data **ACQ**uisition, allows control of multiplexed systems supporting up to 256 TDR probes. The program is DOS-based in order to ease creation of low-power, embedded computer systems; and, to avoid resource conflicts and timing difficulties inherent to Windows-based operating systems. It runs on IBM PC/XT or AT compatible computing platforms with 640 kbytes of RAM and 1 Mbyte of expanded memory, and with Hercules, ATT, EGA, or VGA graphics. Embedded computer systems based on the PC-104 specification have been implemented using TACQ. The program controls multiplexers from both Campbell Scientific, Inc., and Dynamax, Inc. The user has complete control over multiplexer address assignments, interconnection of multiplexers, and probe locations on each multiplexer; including individual settings for probe length, window width, averaging, distance to each probe, gain, and kind of data acquired (wave form, travel time, apparent permittivity, water content, BEC, or a combination of these). Interfaces to TDR instruments including Tektronix 1502 (modified), 1502B, and 1502C cable testers are implemented through an RS-232 port. System power control is implemented through the computer's own power management capabilities, and through direct control of power to the TDR instrument and video subsystem where applicable, thus allowing creation of very low-power systems. Wave form interpretation methods are user-controlled, and include various methods from the literature or methods available only in TACQ.

Keywords:
TDR, time domain reflectometry, bulk electrical conductivity, computer program, soil water content, TACQ

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THE TACQ COMPUTER PROGRAM FOR AUTOMATIC MEASUREMENT OF WATER CONTENT AND BULK ELECTRICAL CONDUCTIVITY USING TIME DOMAIN REFLECTOMETRY[1]

Steven R. Evett[2]
Member

ABSTRACT

Despite the increased use of time domain reflectometry (TDR) for measurement of soil water content and bulk electrical conductivity (BEC), there are few public releases of software for TDR system control. The TACQ program, under development since the early 1990s, allows control of multiplexed systems supporting up to 256 TDR probes. The program is DOS-based in order to ease creation of low-power, embedded computer systems; and, to eliminate resource conflicts and timing difficulties inherent to multi-tasking, Windows-based operating systems. It runs on IBM[3] PC/XT or AT compatible computing platforms with 640 kbytes of RAM and 1 Mbyte of expanded memory, and with Hercules, ATT, EGA, or VGA graphics. Embedded computer systems based on the PC-104 specification have been implemented using TACQ. Using a parallel port, the program controls multiplexers from both Campbell Scientific, Inc., and Dynamax, Inc.; and it allows reading of probes in any user-defined order if using the latter. The user has complete control over multiplexer address assignments, interconnection of multiplexers, and probe locations on each multiplexer; including individual settings for probe length, window width, averaging, distance to each probe, gain, and kind of data acquired (wave form, travel time, apparent permittivity, water content, BEC, or a combination of these). Interfaces to TDR instruments including Tektronix 1502 (modified), 1502B, and 1502C cable testers are implemented through an RS-232 port. System power control is implemented through the computer's own power management capabilities, and through direct control of power to the TDR instrument and video subsystem where applicable, thus allowing creation of very low-power systems. Wave form interpretation methods are user-controlled, and allow interpretation using various methods reported in the literature or methods available only in TACQ. The default methods allow interpretation of wave forms from a variety of media including loose, air-dry soil, and wet clay.

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[2]Soil Scientist, Conservation and Production Research Laboratory, P.O. Box 10, Bushland, TX 79012, e-mail: srevett@ag.gov, Internet: http://www.cprl.ars.usda.gov

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Time domain reflectometry became known as a useful method for soil water content and bulk electrical conductivity measurement in the 1980s through the publication of a series of papers by Topp, Dalton, Dasberg and others (Topp et al., 1980; Dalton et al., 1984; Dalton and van Genuchten, 1986; Dasberg and Dalton, 1985; Topp et al., 1988; etc.). Automated TDR systems for water content measurement were described by Baker and Allmaras (1990), Heimovaara and Bouten (1990); Herkelrath et al. (1991), and Evett (1993, 1994). Commercial systems became available in the late 1980s and continue to evolve with TDR probes, multiplexers, and instruments available from a few companies, usually with proprietary and fairly rudimentary software interfaces embedded in proprietary data acquisition units. A few papers have been published describing some aspects of wave form interpretation, notably Topp et al. (1982), Baker and Allamaras (1990), and Heimovaara (1993).

In the TDR method a very fast rise time (approx. 200 ps) step voltage increase is injected into a wave guide (usually coaxial cable) that carries the pulse to a probe placed in the soil or other porous medium. In a typical field installation the probe is connected to the instrument through a network of coaxial cables and multiplexers. Part of the TDR instrument (e.g. Tektronix TDR cable tester) provides the voltage step and another part, essentially a fast oscilloscope, captures the reflected wave form. The oscilloscope can capture wave forms that represent all, or any part of, the wave guide (this includes cables, multiplexers and probes), beginning from a location that is actually inside the instrument and ending at the instrument's range (e.g. 500 m or about 5.5 microseconds for a Tektronix cable tester).

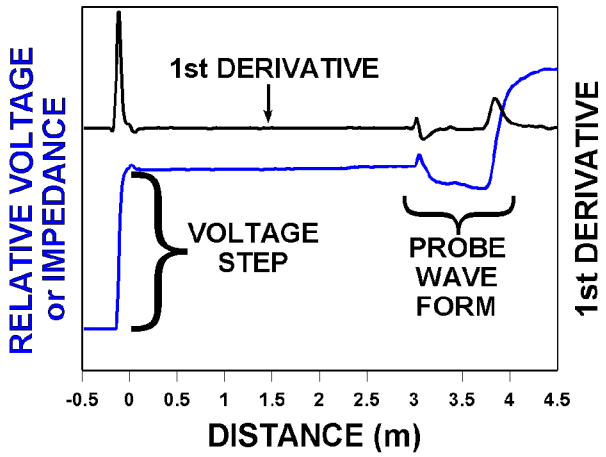

Figure 1. Plot of wave form and its first derivative from a Tektronix 1502C TDR cable tester set to begin at -0.5 m (inside the cable tester). The voltage step is shown to be injected just before the zero point (BNC connector on instrument front panel). The propogation velocity factor, Vp, was set to 0.67. The Vp value multiplied by the speed of light in a vacuum gives the speed of the signal in the coaxial cable connected to the instrument. At 3 m from the instrument a TDR probe is connected to the cable.

For example, Fig. 1 shows a wave form that represents the wave guide from a point inside the cable tester before the step pulse is injected, and extending beyond the pulse injection point to a point along the cable that is 4.5 m from the cable tester. The step nature of the pulse is clear. The relative height of the wave form represents a voltage, which is proportional to the impedance of the wave guide. Although most TDR instruments display the horizontal axis in units of length (a holdover from the primary use of these instruments in detecting the location of cable faults), the horizontal axis is actually measured in units of time. The TDR instrument converts the time measurement to length units by using the relative propagation velocity factor, Vp, which is a fraction of the speed of light in a vacuum. The value of Vp is inversely proportional to the permittivity, ϵ, of the dielectric (insulating plastic) between the inner and outer conductors of the cable

$$Vp = v/c_o = (\epsilon\mu)^{-0.5} \quad [1]$$

where v is the propogation velocity of the pulse along the cable, c_o is the speed of light in a vacuum, and μ is the magnetic permeability of the dielectric material. The amount of the wave form visible on the screen is determined by the distance per division setting, which determines the width of the instrument display in length units.

The TDR method relies on graphical interpretation of the wave form reflected from just that part of the wave guide that is the probe (Fig. 2). Baker and Allmaras (1990) described how the first derivative of the wave form could be used to find some of the important features related to travel time of the step pulse. These and other features are illustrated in Figure 3. An example of graphical intrepration of the wave form for a 20 cm TDR probe in wet sand shows how tangent lines are fitted to several wave form features (Fig. 4). Intersections of the tangent lines define times related to the separation of the outer braid from the coaxial cable so that it can be connected to one of the probe rods, t1.bis; the time when the pulse exits the handle and enters the soil, t1; and the time when the pulse reaches the ends of the probe rods, t2. The time taken for the step voltage pulse to travel along the probe rods, t_t = t2 - t1, is related to the propogation velocity as

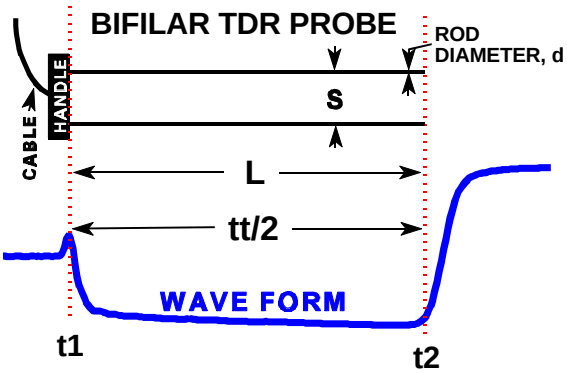

Figure 2. Schematic of a typical bifilar TDR probe and the corresponding wave form, illustrating probe rod length, L; one way travel time, tt/2; rod spacing, S; and rod diameter, d.

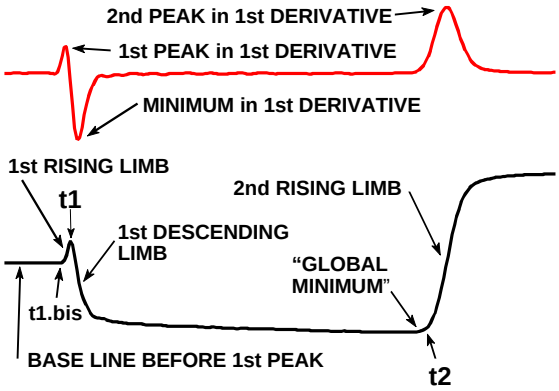

Figure 3. TDR wave form for a wet sand (bottom) and its first derivative (top) showing features useful for graphical interpretation.

$$t_t = 2L/v \qquad [2]$$

where L is the length of the rods (Fig. 2), and the factor 2 is due to the time being for two-way travel. For a TDR probe in a soil the dielectric is a complex mixture of air, water and soil particles that exhibits an apparent permittivity, ϵ_a. Substituting ϵ_a and Eq. 2 into Eq. 1, and assuming μ = 1, we see that ϵ_a may be determined for a probe of known length, L, by measuring t_t

$$\epsilon_a = [c_o t_t/(2L)]^2 \qquad [3]$$

Topp et al. (1980) found that a single polynomial function described the relationship between volumetric water content, θ_v, of four mineral soils and values of ϵ_a determined in this fashion. Since 1980 other researchers have shown that the relationship between t_t and θ_v is linear for all practical purposes (e.g. Ledieu et al., 1986).

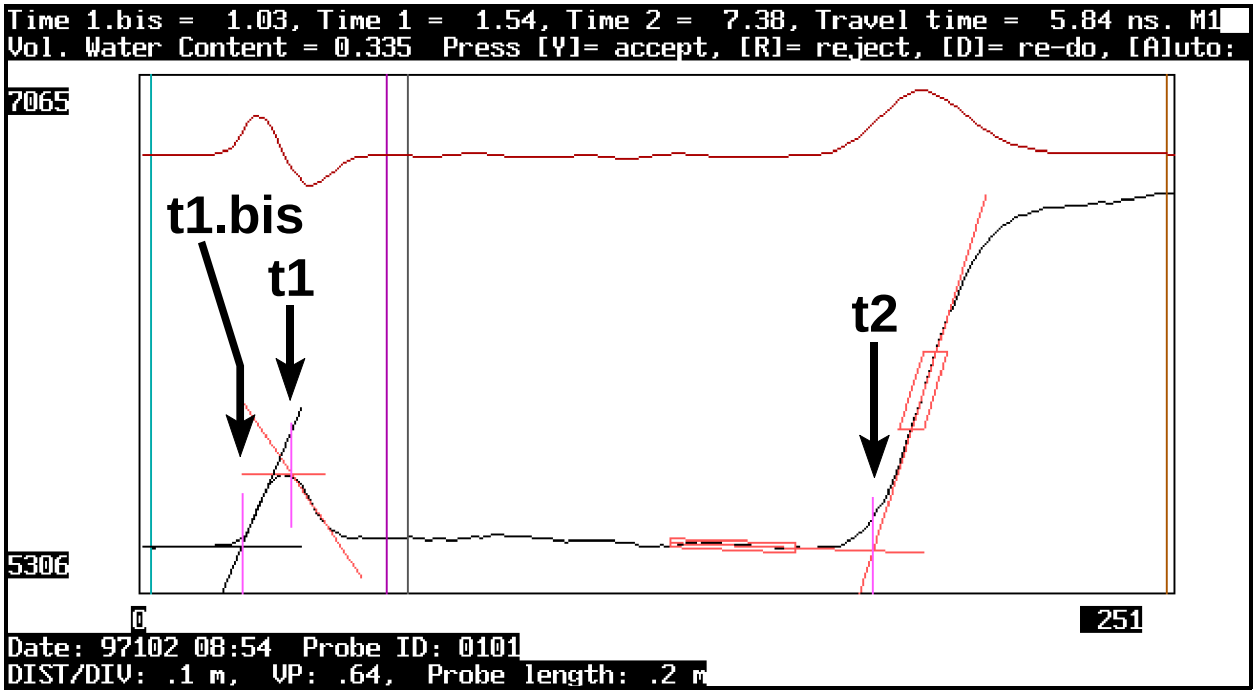

Figure 4. Example from TACQ of graphical interpretation of a wave form from a probe in wet sand. Vertical lines denoting times t1.bis, t1, and t2 have been marked by arrows and labels. The water content is calculated from Eq. 7 of Topp et al (1980).

Graphical interpretation depends on the fact that the probe design itself introduces impedance changes in the wave guide. The impedance, Z (Ω), of a transmission line (i.e. waveguide) is

$$Z = Z_0(\epsilon)^{-0.5} \quad [4]$$

where Z_0 is the characteristic impedance of the line (when air fills the space between conductors) and ϵ is the permittivity of the (homogeneous) medium filling the space between conductors. For our parallel transmission line (the two rods in the soil) the characteristic impedance is a function of the wire diameter, d, and spacing, s (Williams, 1991):

$$Z_0 = 120 \ln\{2s/d + [(s/d)^2 - 1]^{0.5}\} \quad [5]$$

or, if d<<s:

$$Z_0 = 120 \ln(2s/d) \quad [6]$$

For a coaxial transmission line the characteristic impedance is:

$$Z_0 = 60 \ln(D/d) \quad [7]$$

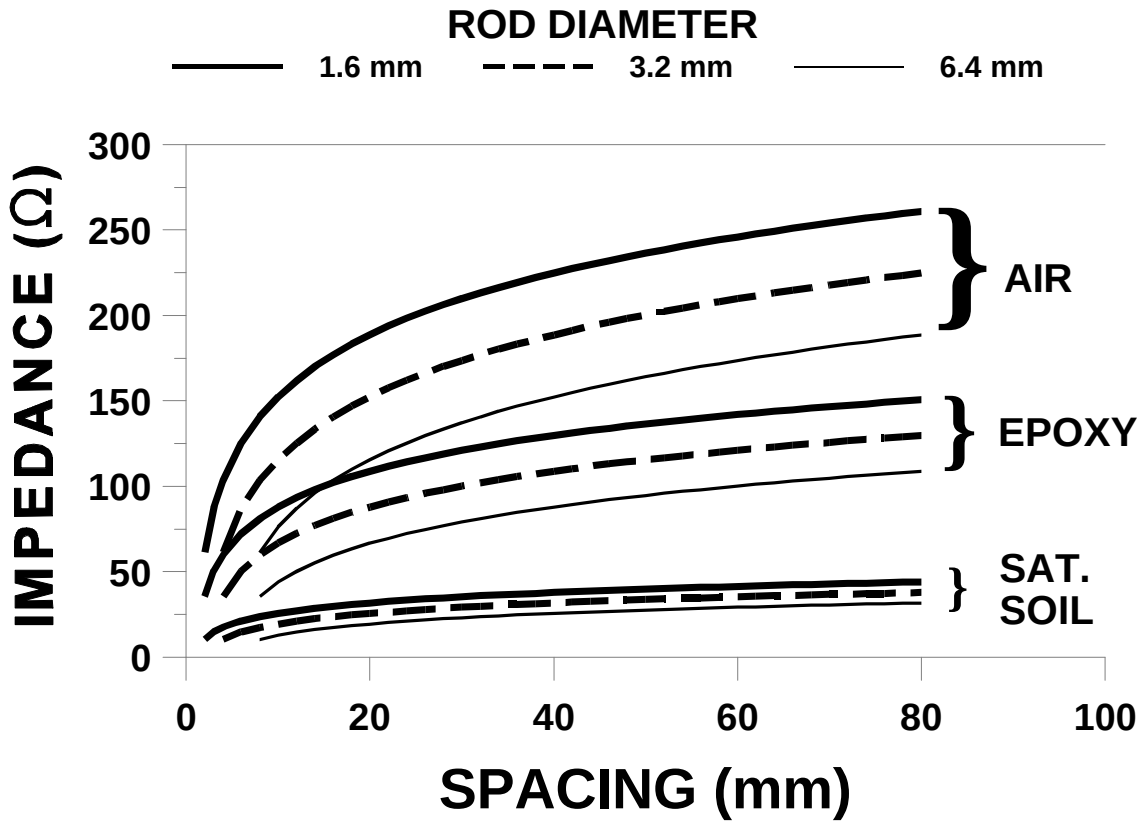

Figure 5. Influence of rod spacing, rod diameter, and permittivity of the medium on impedance of the waveguide according to Eqs. 4 and 5. Permittivities are: AIR, unity; EPOXY, close to 3; and SATurated SOIL, approx. 35.

where D and d are the diameters of the outer and inner conductors, respectively.

From Eqs. 4 through 7 it is apparent that impedance, Z, increases as wire spacing increases and decreases as ϵ (water content) increases for any probe type (Fig. 5). In the probe handle the wire spacing increases from that of the coaxial cable to that of the probe rods. The resulting impedance increase causes the wave form level to rise (first rising limb in Fig. 3). If the porous medium in which the probe rods are embedded is wet then the permittivity of that medium will be higher than that of the epoxy probe handle, causing a decrease in impedance, which results in the descent of the wave form level as the step voltage leaves the handle and enters the rods in the soil (first descending limb, Fig. 3). The combination of impedance increase at the handle and impedance decrease after the handle gives the peak in the wave form. The rod ends are another impedance change in the wave guide, in this case an open circuit. The energy in the voltage step is reflected back at the rod ends, which represent an impedance increase (second rising limb, Fig. 3). As will be discussed later, wave form shapes different from that shown in Figs. 2-4 result from different soil types and conditions (e.g. dry soil, or wet clays). A program for automatic TDR data acquisition must be able to acquire the wave form from the probe and correctly interpret it graphically. It should be able to accomplish this despite different cable lengths to the probes, different probe lengths and rod spacings, and different soil conditions.

The objective of this work was to create a computer program for TDR system control that would work with the most commonly used TDR equipment and meet the following design objectives.

1) Control, and acquire wave forms from, the TDR instrument including setting distance to probe, Vp and DIST/DIV settings, vertical gain setting and vertical position of waveform, and filtering. (Tektronix 1502B or 1502C TDR cable testers, Dynamax modified Tektronix 1502 cable tester).
2) Manage system power consumption including controlling power to the TDR instrument (Tektronix cable tester).
3) Individually control up to 16 Dynamax TR-200 and 16 Campbell Scientific, Inc. SDMX50 coaxial multiplexers (using 6 pins of the computer's parallel port). More than 16 multiplexers of each type may be controlled if multiplexers using the same address are positioned on different branches of the connection tree.
4) Acquire relative voltage data needed for calculation of bulk electrical conductivity (BEC).
5) Interpret wave forms to give travel times, apparent permittivities and water contents.
6) Allow user control of algorithms used for conversion of waveforms to water contents, implementing methods reported in the literature (for backward compatibility) as well as new methods allowing correct conversion of difficult wave forms including those from dry soil.
7) Recommend TDR instrument settings for best wave form window width for any length probe.
8) Save to ASCII files either waveforms alone; travel times, apparent dielectric constants, and water contents alone; or both. Selectively save these data for chosen probes.
9) Selectively (for chosen probes) save data for BEC calculations to a separate ASCII file.
10) Run under DOS to avoid timing conflicts inherent to multitasking operating systems, and to ease application in low-power, embedded computer systems.
11) Run automatically and acquire data at user-set intervals.
12) Be callable by another program for easy integration into larger systems using the TDR data for uses such as automatic irrigation scheduling.
13) Read in ASCII waveform files previously collected; and, under user control or automatically, reduce the waveforms to travel times and water contents.

HARDWARE and OPERATING SYSTEM COMPATIBLITY

The program will run on an IBM PC/XT or AT compatible computer with 640 kbytes of RAM and a floppy disk. However, one megabyte of expanded memory and a hard disk or other mass storage is recommended for better performance, and if wave forms are to be saved to file. Computers with a PC-CARD (PCMCIA) card slot may use an SRAM card, flash RAM card, or hard disk card to store data. Most subnotebook computers are equipped with such a slot and may be configured to boot DOS and run TACQ.EXE from an SRAM PCMCIA card thus eliminating the need for a hard disk or floppy disk and decreasing power usage (see the File Formats section for limitations on data storage). Although it is a DOS program, TACQ will run under Windows in a DOS box. When run under Windows ver. 3.11 (Win3.11) the program will respond more

slowly due to the Windows overhead. For example, the time to acquire a wave form from the 1502B/C and display it increases from about 2.5 s in DOS to 9 s in Win3.11 (TACQ only application running, running in foreground, and priority set to 10000). If other applications are running concurrently in Windows, responsiveness will suffer accordingly. In Windows 95 the program will run in a DOS box and performance does not suffer as it does in Win3.11. However the program will not automatically acquire data when run in the background - it must be in the foreground. The program will run on a Hewlett Packard model 200LX palm top computer if all other programs are terminated, and will correctly acquire data from a Tektronix model 1502B/C; but since the HP200LX does not have a parallel port it cannot be used to control multiplexers.

The program will use CGA, EGA, VGA (in EGA mode), ATT, or Hercules graphics. To use Hercules graphics, the memory resident program MSHERC.COM should be run before TACQ.EXE. A parallel port is required for control of multiplexers or control of power to the cable tester. A serial port is required to acquire data from either the digital Tektronix 1502B or 1502C cable testers, or the Dynamax modified Tektronix 1502 cable tester. The program can automatically scan serial ports COM1 through COM4; and will find the 1502B/C cable tester if it is connected to the serial port, powered on, and selected in TACQ's Software Setup. The program will then set the cable tester to the maximum baud rate of 19,200 for the 1502B/C or 9,600 for the modified 1502. If there are multiple serial and parallel ports, the user may specify which to use. The program has been used on IBM compatible computers with CPUs ranging from 8088 to Pentium including laptop and notebook computers and embedded systems using the PC-104 specification for IBM PC/AT compatible embedded computers. TACQ will run with no cable tester connected, but the user should indicate that there is no cable tester in Software Setup.

The TACQ program, and complete TDR system documentation in Adobe PDF file format, may be freely downloaded from (http://www.cprl.ars.usda.gov/programs/). Install the program by copying files TACQ.EXE, TACQ_TDR.INI, and TACQ.INI to the desired directory on the computer's hard disk. If you do not have the initialization files TACQ_TDR.INI and TACQ.INI you can still run the program and create them in Software Setup.

RUNNING TACQ

Run TACQ from the DOS command line by typing TACQ and pressing the Enter key. If automatic start-up of the program is desired (e.g. in case of a power failure you might want the program to re-start automatically when the power comes back on and the computer reboots) make the following lines the last 2 lines in the computer's AUTOEXEC.BAT file:

```
CD  \path
TACQ  AUTO
```

where "path" is the path to the subdirectory where TACQ.EXE and the *.INI files reside. If the program is installed on the root directory of the boot drive (usually C:) then only the following line is necessary:

```
TACQ  AUTO
```

Note that a space should separate the words 'TACQ' and 'AUTO'.

The program also may be run from a batch file so that control is returned to the batch file after all TDR probes are read. This is done by using the line:

TACQ AUTOSTOP

This is useful when other programs will be using the data output by TACQ. It is also useful for allowing TACQ to run in the forground in a Windows 95 system. A supervisory program (written, for example, in Visual BASIC) can run TACQ in the foreground and resume control after TACQ has finished. For an example of this use of TACQ in an automatic irrigation system see Lascano et al. (1996).

FILE FORMATS

There are four output file formats used by TACQ. Three of these are shared by files that are written during automatic data collection, and files that are created manually. The fourth is only created during manual operation of TACQ. File naming conventions differ between automatically collected files and manually collected files.

Automatically Collected Files

Data files created automatically by TACQ are of three kinds; files containing wave forms and associated data needed for proper interpretation of the wave forms (e.g. Vp, distance per division, distance units, probe length); files containing water contents, travel times and apparent permittivities; and files containing relative wave form voltages useful for calculation of bulk electrical conductivity. Each file type is designated by a one letter code in its file name: T for wave forms, W for water contents, and E for bulk electrical conductivity. The water content files also contain the travel times and apparent permittivities; either of which could be used in a spreadsheet to compute water contents using a calibration equation of the user's own choosing. New files are created each day. This prevents data loss of more than a day's data if there is a power failure or system crash for some reason during file I/O. File names have the format yyyydddX.SUF where yyyy is the current year, ddd is the day of year, X is the code identifying the file type, and SUF is a file name suffix of up to 3 characters specified by the user in the Setup part of the program. Thus for a water content file containing data for day 206 of year 1994, the file name would be "1994206W.TAC" if the user had chosen "TAC" for the file name suffix. A file containing wave forms for the same day and file suffix would be named "1994206T.TAC". The user supplied file name suffix serves as an identifier to distinguish files from one TDR system from those written by another system.

Wave form files contain data for one wave form on each line. From left to right on the line the numbers are: an integer formed from the year and the day of year (e.g. 1994206 for our example); the hour, minute and seconds separated by colons (e.g. 19:01:51 for one minute, 51 seconds after 7 pm); an integer formed from the multiplexer number and probe number on that multiplexer (e.g. for multiplexer number 7 and probe 4 the number would be 0704, for probe number 16 the number would be 0716, for multiplexer number 12 and probe number 3 the number would be 1203); the propagation velocity factor; the distance per division; the units code for the

distance per division (1 for feet, 2 for meters); the probe length in meters; the number of data points in the wave form; and finally, the sequential data representing the wave form from left to right on the cable tester screen. An example for 7:01:51 pm on day 206 of 1994 is:

1994206, 19:01:51, 1101 0.99 1 1 .2 251 ....

For this example the multiplexer number was 11, the probe was connected to input number 1 on that multiplexer, the propagation velocity factor was 0.99, the distance per division was 1 foot, the probe length was 0.2 m and there were 251 data points in the wave form (data not shown). The wave form data are Y-values (related to voltage) only. The X-values are not needed since the number of points in the wave form and the Vp and distance per division settings can be used to calculate the time interval between data points along the X-axis. For the Tektronix 1502B/C cable testers one wave form and associated data will take about 1546 bytes of hard disk space (251 data points in the wave form). Thus, a 120 Mbyte hard disk can store about 77,000 wave forms.

Water content files are formatted for easy input to a spread sheet so some numbers are in double quote marks. Each line contains data for one measurement. For the same probe used in the previous example the first line of data might look like:

1994206 19:01:47 "1101" 1.690451 2.197025 6.161919 3.964894 0.1649 8.8306

where the year and day of the year are given as one number, the time is given to seconds in 24 hour format, and the multiplexer number and probe number are in the double quoted string; followed by the time from the left hand side of the screen to t1.bis, the time to t1, the time to t2, the travel time, the water content and finally the apparent permittivity. The travel times are two-way. Each line takes about 79 bytes so a 120 Mbyte hard disk can store over 1.5 million readings. A 1 Mbyte PCMCIA SRAM card with DOS and TACQ.EXE installed has about 530 kbytes free RAM and can hold over 6700 readings. Larger SRAM cards are also available. Our subnotebook computer can boot from these PCMCIA cards. Thus, the hard disk can be removed to make the computer data logging system completely solid state with very low power consumption (about 290 mA at 12 VDC).

BEC data files contain 9 values on each line. For example:

1994206, 20:32:12, 0101 5459.562 5655.086 5457.88 6865.02 3910.72 5440.692

The first value is a combination of the year (first 4 digits) and the sequential day of the year; the second value is the hour, minute, and second; and the third value is the multiplexer number and channel on that multiplexer. For this example the data were taken on the 206th day of 1994 at 8:32:12 pm (20:32:12 in 24 hour format) from channel 1 of multiplexer 1. The six data values are the cable tester's digital representations of the wave form voltage at various points along the wave guide. These are called Vo, Vmin, Vo, Vf, Vi, and Vr, which are defined as follows:

V_O The voltage of the wave form before the first peak, i.e. the pre-incident pulse height. This is taken from the regular wave form that the user sets up for determination of water content. If the first peak is set to occur just at or after the first vertical division on the screen, then this value of V_O will be the average of about 15 to 25 points. The actual number of points depends on what the program

determines to be the flat part of the wave form before the first peak. This value is determined by the program for the use of some who might want to use a particular method cited in a paper. This value is somewhat noisier than the second value of V_O (see below). The second value of V_O is preferred for BEC calculations.

V_{MIN} Again, this value is taken from the regular wave form that the user set up for determination of water content. It is the voltage of the minimum of the wave form between the first peak caused by the probe handle and the final reflection caused by the ends of the rods. Some persons have used this value for BEC calculations, but there are better methods now. It is output by TACQ for compatibility with older techniques. The value of V_{MIN} is more noisy than the others because it is a single point value, not an average. Applying more wave form smoothing will reduce the noise somewhat; but the extra smoothing may cause problems with wave form interpretation for water content. This is the only value that is taken from the smoothed wave form.

V_O The second value of V_O is acquired by first moving the 'regular' wave form view one tenth of its length to the left (one DIST/DIV to the left), and then taking the average of the first 25 data points. These data are the first 25 data to the left of the beginning of the regular wave form that the user set up for determination of water content. Normally the two values of V_O should be the same, but the first value is slightly more noisy because of the possibility that some data from the initial part of the rise of the first peak may inadvertently be included in the averaging.

V_F The voltage of the wave form at great distance (final voltage). To find this, the program sets DIST/DIV to 1 m or 2 feet, sets the wave form to start at 599 m or 1980 feet, and then takes the mean of the last 50 data points.

V_I The initial voltage of the wave form before the voltage pulse is injected. This is virtual zero for the TDR system and all other voltages may be normalized by subtracting V_I from them. The program sets DIST/DIV to 0.1 m or 0.5 foot, sets the start of the wave form to -0.51 m or -2 feet, and takes the mean of the first 25 data points. The negative distance setting means that the wave form that we are looking at here is inside the cable tester, before the BNC connector on the front panel and before the pulse is injected.

V_R This is called the relative voltage and is used in the paper by Baker et al. (1996). It is determined from the same wave form as for V_I but is the mean of the last 25 data points of the wave form. This is in the cable outside the cable tester and after the pulse is injected. Note that the values of V_R, the first V_O, and the second V_O are all about the same, differing only due to changes in impedance due to cable resistance, cable type before and after the multiplexer (if there is one), noise, etc. In general Vr tends to be slightly smaller than either V_O value.

Manually Collected Files

Three of the files created manually (e.g. by pressing F, A, S; or B; at the Main Menu) are identical in format to those created automatically; only the names differ. Wave forms are saved to a file with the WAV suffix and a user supplied prefix of up to 8 characters. For example if the user entered TEST_ONE as the prefix, the file name would be TEST_ONE.WAV. Water content files have the suffix WAT. For the TEST_ONE prefix a water content file name would be TEST_ONE.WAT. Data for bulk electrical conductivity would be in file TEST_ONE.BEC where the BEC is assigned by TACQ.

There is a fourth file type created by TACQ during manual data collection. The file name suffix is DIG and the prefix is the same as for the first 3 file types. This file contains the same wave form as in the *.WAV file. But, it is in the format used by the Tektronix program SP.EXE. It is created for compatiblity with programs that use that file format. The format contains some data not saved in TACQ's other file formats, including gain and vertical offset data, and a user-supplied comment.. TACQ can read this file type.

FILE HANDLING

A file directory facility allows the user to specify the path for output files. It is also used to find and specify files for input when TACQ is used to interpret previously acquired wave forms. Thus, the program can read wave form files archived, for instance, on a CDROM and write the output file of travel times, apparent permittivities, and water contents on a writeable drive somewhere else in the system. When specifying input data files the user can tag one or many files and sort the files in the order in which they should be interpreted. Interpretation can be done automatically, but the user may intervene at any time or interpret wave forms one at a time, as desired. Water content output files are sequential, but the user may take advantage of a transposition feature if the input data were in regularly repeated form such as would be created during automatic data acquisition with a system of multiplexers and TDR probes. Using the transposition feature the user may create a file of parallel output with all water contents for each data acquisition interval output on a single line. The transposed data are easily read into a spreadsheet for graphing of water content vs. time for each probe.

The facility for specifying the path for output files is also useful for redirecting output in embedded computer systems in which TACQ is run from a small Flash or SRAM solid state disk. In these cases the solid state disk is normally too small to store much more than the operating system, TACQ, and its initialization files; so, output is redirected to outboard data storage such as a PC-CARD hard disk or larger FLASH disk.

HANDLING MULTIPLEXERS and PROBES

Up to sixteen Dynamax TR-200 multiplexers and 16 CSI SDMX-50 multiplexers may be individually controlled using six output lines of the parallel port. By default the program assigns parallel port pins 2, 3, and 4 to the TR-200, and pins 6, 7, and 8 to the SDMX-50. But, any combination of the eight output pins (numbers 2 through 9) may be chosen by the user. For more that sixteen probes (more than 8 for the SDMX-50) multiplexers are usually connected in a tree configuration with a single primary level multiplexer connected to the TDR instrument, and two or more secondary level multiplexers connected to input channels of the primary one. The TR-200 and SDMX-50 multiplexers are addressable with the address of a multiplexer set by moving jumpers on the circuit board (see, for example, Evett (1998). Up to 256 probes may be connected to a multiplexer system if two of the secondary multiplexers share an address (both secondary multiplexers will switch at the same time but only one will be connected to the active input channel of the primary multiplexer).

By default, TACQ enables a primary multiplexer, with input channel number one of that mux assigned to a TDR probe. Via the Software Setup menu the user creates a virtual network of mux and probe connections that mimics the actual network that is or will be put in place for making measurements. During automatic or manual data acquisition this virtual network guides the software in controlling the multiplexers so that they switch the correct probe into connection with the TDR instrument before a reading is acquired. The user specifies which channels of each multiplexer are connected to other multiplexers or to probes, and which are not used. Multiplexer addresses and model are specified as well. Despite the fact that the TR-200 and SDMX-50 muxes are controlled via different sets of parallel port output lines, the two models of mux may be used

together in the same virtual and actual data acquisition system. Figures 6 and 7 illustrate the Multiplexer Setup screen for a five multiplexer system installed at Ismailia, Egypt in May 1998; and the Channel Setup screen for multiplexer 1.

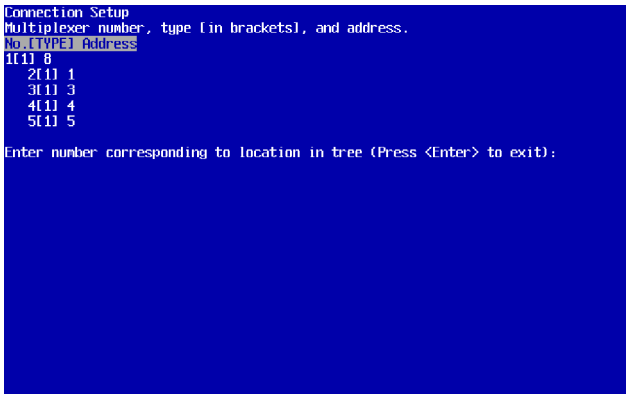

Figure 6. Connection Setup screen showing a primary multiplexer with four secondary multiplexers.

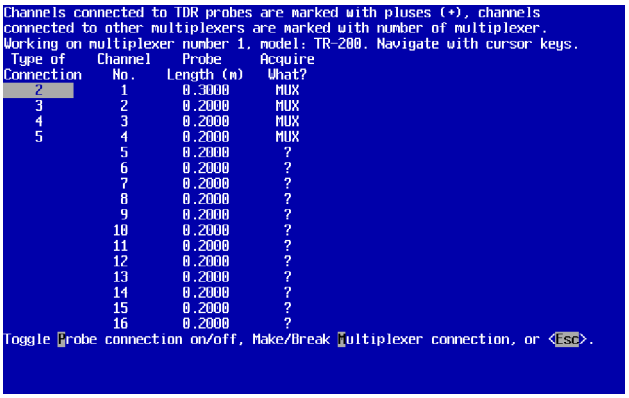

Figure 7. Channel Setup screen for the primary mulitplexer showing the four secondary multiplexers connected to channels 1 through 4.

When specifying that a probe is attached to a particular input channel, the user specifies the probe length, and the type of data to be acquired as well. Two types of data are possible, 1) travel times, apparent permittivities, and water contents, and/or 2) wave form level data for bulk electrical conductivity calculations. Either type or both types may be chosen. The purpose of allowing these choices is to provide an opportunity to save file space and to eliminate unneeded data. Because probe length may be specified, probes of different lengths may be used in the same system. This is often desirable where different layers of soil with differing properties are to be probed, or where mixtures of horizontally and vertically installed probes are used. Figure 8 shows the Channel Setup screen for a multiplexer with 16 probes attached. For this installation in a deep sand probe lengths varied from 1.5 to 0.3 m.

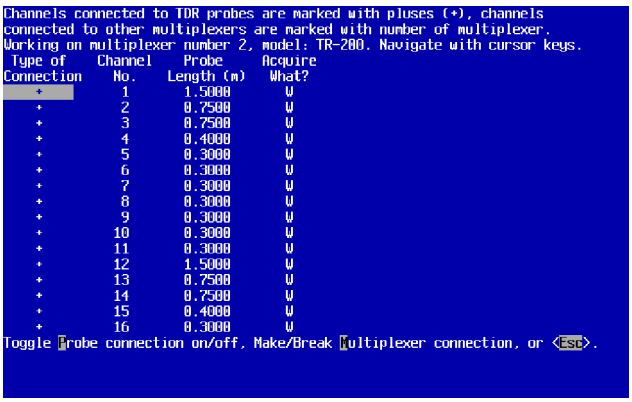

Figure 8. Multiplexer 2 in the system illustrated in Figures 6 and 7. Sixteen probes with lengths varying from 1.5 to 0.3 m are attached. Only water content is being measured.

The TDR method relies on graphical interpretation of the wave form reflected from a probe in the soil or other porous medium. Instruments such as the Tektronix TDR cable testers can return wave forms that represent all, or any part of, the wave guide (this includes cables, multiplexers and probes) beginning from a location that is actually inside the cable tester and ending at the cable tester's range of 500 m. In order to correctly interpret the wave form reflected from the probe we want the screen to display only the part of the wave guide that includes the probe. For this reason the TDR instrument must be directed to acquire the wave form that represents the probe, not some part of the cabling or multiplexers. Setting the "distance" or apparent cable length to each probe, and setting the wave form window width for probes of different lengths is accomplished using the Wave Form Manipulation screen (Fig. 9).

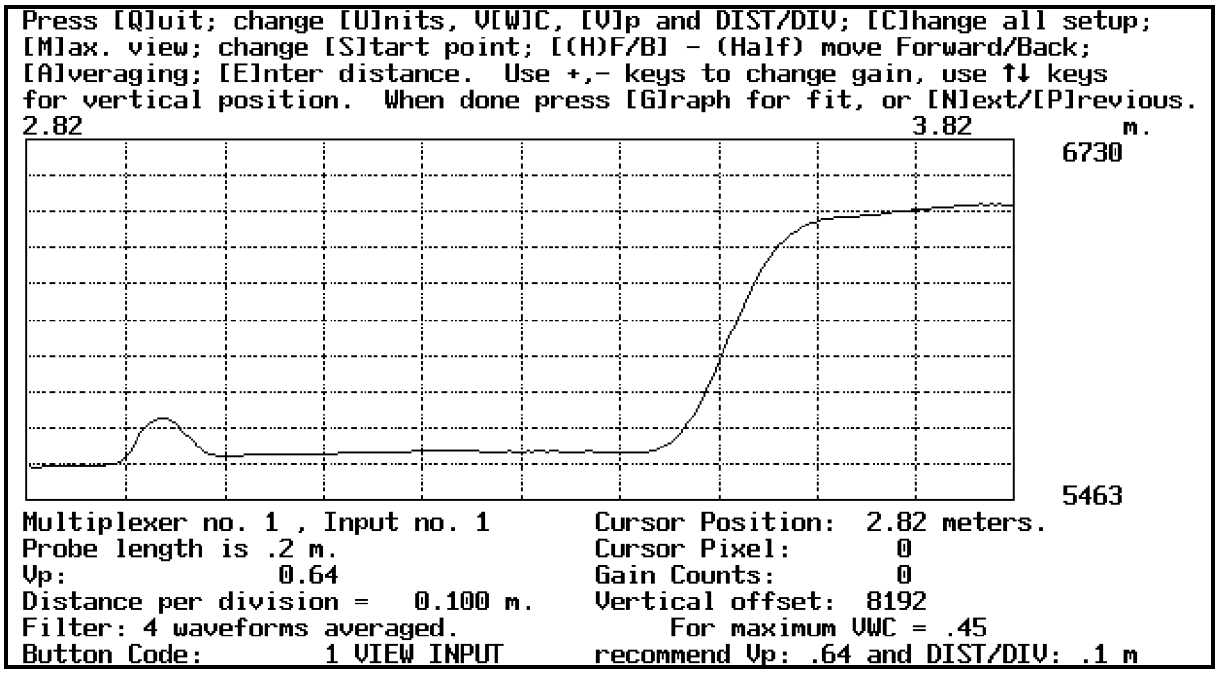

Figure 9. Wave form manipulation screen for probe on 2.5 m cable after adjusting the left hand border by pressing the S key and using the cursor keys. The wave form is well positioned for correct interpretation, and the window width is set according to the recommended Vp of 0.64 and distance per division of 0.1 m. Probe is in saturated sand.

Different brands of cable may pass the TDR pulse at different speeds even though they are nominally the same type of cable. Most coaxial cables used for TDR have a propogation velocity factor of 0.66 or 0.67 of the speed of light in air. Because the TDR instrument really measures time, not distance, the "distance" between the TDR instrument and a given probe in the system is only an apparent distance. For these reasons setting the distance is not as simple as, say, entering the cable length. In the TACQ wave form manipulation window the user may change distance by entering a number in feet or meters, or by moving the window forward or backward one or one-half window width at a time. The user may also change the propogation velocity factor used by the TDR instrument to calculate the apparent distances that are displayed above the window. Knowing the Vp for the cable used in the system, the user may enter a propogation velocity factor (Vp) of 0.67 and the actual physical length of cable to a particular probe; and the wave form for that probe will appear in the manipulation window fairly close to its correct position (usually not exactly due to temperature-dependent variation in cable dielectric permittivity, and additional distance due to multiplexers in the system). From this position it is an easy task to position the wave form correctly using the cursor provided or by entering a distance directly. The program recommends the best combination of Vp and distance per division (DIST/DIV) for a probe of any particular length. Once the wave form is placed in the window the user may enter these Vp and DIST/DIV values and then fine tune the wave form position. Once the wave form is correctly positioned the user proceeds to the next probe in the system or may return to a previous probe. How TACQ determines the best Vp and DIST/DIV values will be discussed later.

WAVE FORM INTERPRETATION

Topp et al. (1982) described a method of interpreting wave forms captured on paper using a chart recorder or by photographing an oscilloscope screen. This analysis consisted of two graphical algorithms. Algorithm 1 consisted of drawing a horizontal line across the top of the first peak, and drawing a line tangent to the descending limb of the first peak (Fig. 3). The intersection of these lines defined t1 as illustrated in Fig. 4. Algorithm 2 consisted of drawing a horizontal line tangent to the base line between the first peak and second inflection, and drawing a line tangent to the second inflection. The intersection of the latter two lines defined t2. The travel time of the pulse in the part of the wave guide that was buried in the soil was t_t = t2 - t1. Peaks and inflections were identified by eye and no computer code or algorithms were presented.

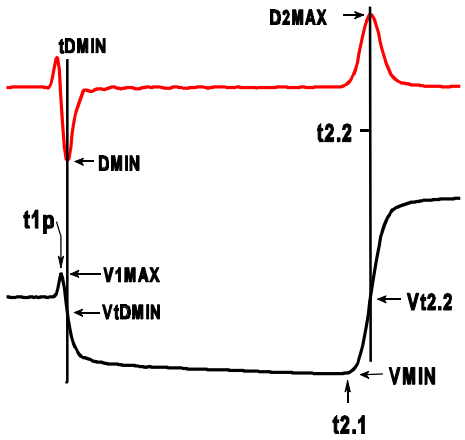

Figure 10. The TDR wave form (bottom) and its first derivative (top) with features identified by Baker and Allmaras (1990) (our nomenclature).

Later, Baker and Allmaras (1990) discussed a computer program for interpretation of wave forms following the ideas of Topp et al. (1982). The program, which was not published, included the following steps applied to a wave form consisting of 200 data points (Fig. 10):

1) Smooth and differentiate the data (Savitsky and Golay, 1964).
2) Use a loop to search the wave form data for the global minimum, VMIN, and associated time, t2.1.
3) Find the local maximum, V1MAX, and associated time, t1p, in the data between the first point and t2.1. This is the time, t1p, of the first peak.
4) Find the most negative derivative, DMIN, the corresponding time, tDMIN and wave form value, VtDMIN, in a region of 25 points following t1p. The slope of the first descending limb is DMIN.
5) Define a line with intercept V1MAX and slope of zero that is horizontal and tangent to the first peak. Define a second line with slope DMIN and intercept such that it passes through VtDMIN at tDMIN. Solve the two lines for their intersection point and associated time, t1, that corresponds to the point where the rods exit the handle.
6) Find the maximum derivative, D2MAX, in a region of 25 points following VMIN, and associated time t2.2 and wave form value Vt2.2.
7) Define a line tangent to the second inflection with slope D2MAX and passing through Vt2.2 at t2.2. Define a horizontal line tangent to VMIN. Solve for the intersection of these lines to find t2, the time corresponding to the ends of the rods.

The travel time of the pulse through the exposed length of the rods was t_t = t2-t1. While these algorithms worked well for relatively moist soils, there were problems with the absence of DMIN

and absence or movement of VMIN and associated times in wave forms for dry, low bulk density soils (see later section on wave forms from dry soils).

Heimovaara and Bouten (1990) described a computer program that involved fitting lines to the second inflection and to the base line between t1 and t2. The regions of data points to which these lines were fit were determined empirically for a given probe. Also, they recognized that the wave form might not always descend at t1 and so introduced the concept of fitting lines to the rising limb of the first inflection and to the base line before the first inflection, and using the intersection of these lines to define a time, termed t1.bis in this paper, corresponding to the point of separation of the cable conductors (illustrated in Fig. 4). A correction time was added to t1.bis to get t1. This correction time was determined by performing a single measurement in air before probe installation.

Factors Influencing Wave Form Shape

Many conditions may alter the wave form from the classical forms displayed in Figures 2-4 and 10. It is perhaps an accident of location, climate, and soil type that many of the early computer algorithms emphasized finding the minimum, VMIN, and its time, t2.1; the second maximum in the first derivative, D2MAX, and its time, t2.2; and the minimum of the first derivative, DMIN, and its time, tDMIN (see Fig. 10). In humid environments where soils are seldom dry, and are well leached so that bulk electrical conductivity is low, these features are found in almost all wave forms and can be reliably used as keys for computer analysis. However, in dry soils DMIN and the descending limb of the first peak may disappear. Also in dry soils, the position of VMIN may change dramatically, moving from the right side to the left side of the wave form. In soils with high bulk electrical conductivity the wave form may rise only slowly at the point corresponding to the ends of the rods; making the value of D2MAX so low as to be lost in the noise level of the first derivative. These and other factors influencing wave form shape are discussed here. Later, a suite of algorithms for interpreting wave forms despite these changes in shape will be presented.

Influence of Dry Soil on Wave Form Shape

As the soil drys, the first descending limb (Fig. 3) becomes less steep. Since dry soil has about the same permittivity as the plastic materials used in most probe handles there may be little or no impedance change between the wave guide in the handle and in the soil. Indeed, if the soil is both dry and of low bulk density the impedance of the wave guide may actually increase in the soil compared to the handle. Both conditions cause the first descending limb to be almost absent (Fig. 11) and render ineffective both algorithm 1 of Topp et al. (1982) and the corresponding methods of Baker and Allmaras (1990). Dry soils of low bulk density are usually found close to the

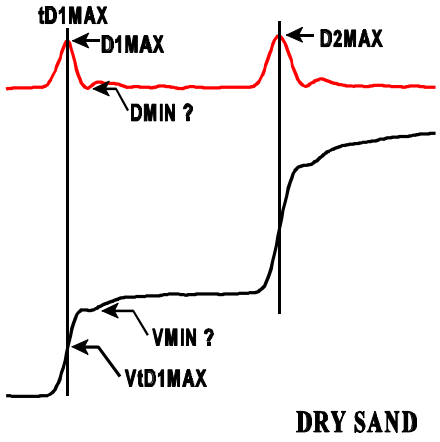

Figure 11. Influence of dry soil on wave form shape illustrating difficulty of finding DMIN and VMIN.

surface. Because this is where the TDR method enjoys its greatest advantage compared to its nearest competitor, neutron scattering, it is imperative that the method be usable in such soils. For dry soil the second inflection, caused by the distal ends of the rods, is invariably steep and high, making it easy to find by searching for D2MAX. However, at the same time the global minimum may not occur after t1 or the position of the local minimum may shift from just before the second inflection to a point just after the first peak, or to any intermediate position. This causes variations in the intersection of the two lines (horizontal tangent to global minimum and tangent to second inflection) that have no relation to the travel time, t_t.

Another phenomenon sometimes found in low bulk density soils is the double peak. This may be due to compression of a thin layer of soil next to the handle as the probe was inserted into the soil at installation time. This higher bulk density soil will exhibit a lower impedance due to lower porosity (air has a permittivity of 1, soil minerals have permittivities of 3 to 5, so denser soils have higher permittivities) and correspondingly higher water content (at equilibrium with surrounding soil), and will cause the dip in the wave form after the handle. As the pulse enters less compressed soil it encounters a higher impedance and the reflected wave form rises, only to lower again as the pulse travels further down the rods (due to the impedance decline associated with the lowering of total resistance with rod length). It is important to have an algorithm to discriminate between these peaks.

Influence of Probe Design on Wave Form Shape

The height of the first peak increases with the separation distance of the rods because the impedance at this point in the wave guide increases with the separation distance (Eq. 5; Fig. 5). The impedance and peak height are inversely proportional to the diameter of the rods. The height is also influenced by the permittivity of the material separating the proximal ends of the probes (Eq. 4). For a handle made of epoxy (ϵ_a approx. 3), rod diameter of 3.2 mm and spacing of 30 mm the characteristic impedance increases from 50 ohms in the cable to 152 ohms in the part of the stainless steel wave guide embedded in the handle (Fig. 5). The pulse travel time between t1.bis and t1 increases with the permittivity of the material between the point of splitting the antenna cable and the connections to the rods. It also increases with the separation distance of the rods. Finally, this travel time increases with the distance between the split in the cable and the point of connection to the rods.

Consider an early type of TDR probe consisting of two stainless steel rods buried parallel to one another in the soil with the proximal ends connected to bifilar antenna cable. Connections were sometimes made using alligator clips, sometimes soldered, and sometimes made by clamping the wire to the rod with a screw. The perpendicular distance between the rods was the separation distance. Typically the antenna cable would have a characteristic impedance of 300 ohms. In order to match impedances (thus lowering signal loss and distortion) between the antenna cable and the 50 ohm wave guide of the cable tester a balun would usually be used to connect the antenna cable to the cable tester. In the case of our probe made with antenna cable and two rods, the connections are separated by the soil between the distal ends of the rods. In this case the height of the peak is influenced not only by the separation distance but by the water content of the intervening soil (assuming the probe is buried). For dry soil the impedance may be nearly the same as for epoxy but for wet soil the value of ϵ_a may approach 35 and the impedance may be 30 ohms or lower (Fig. 5).

Using our probe made with antenna cable and two rods we can see several reasons why

the height of the first peak and the time between t1.bis and t1 might not be reproducible between probes in the field. The length of cable split may vary, the separation distance at the proximal rod ends may vary (over time even if controlled at installation), and the permittivity of the porous medium separating the two wires of the wave guide may vary in time and space between the cable split and the point of connection to the rods. If the rods are installed vertically and the point of connection is at the soil surface the split cable may be separated by air, whereas if the probe is installed deeper in the soil the split cable will be separated (along at least some of its length) by soil that varies in permittivity as it wets and drys.

If we have a reliable algorithm for finding t1 we need not worry about the time between t1.bis and t1. However, as we have seen, there are soil conditions that make finding t1 alone practically impossible. Also, the varying permittivity of the material separating the rods makes the height of the first peak variable (the first rising limb may cease to exist under some conditions), further complicating the search for t1. If t1 is difficult to find we may search for an algorithm that finds t1.bis reliably. But, since the travel time we ultimately need is t_t = t2 - t1 not t2 - t1.bis, we would need to have a consistent time (t1 - t1.bis) in order to use t1.bis to find t_t. With our probe made of antenna cable and two rods it is virtually impossible to guarantee consistent conditions that would allow reliable determination of either t1 or t1.bis, or that would quarantee that t1 = t1.bis + t_C where t_C is a constant.

For these reasons the TDR probes commercially available today are invariably made with the split in the cable (usually coaxial cable) and the connections to the rods fixed in some sort of rigid configuration, usually called the handle; and enclosed in a material of consistent and constant permittivity. The handle may be made of epoxy resin, delrin, polymethyl methacrylate (acrylic), RTV silicone or some other plastic and may contain metal for shielding or connection of rods. These handles share the properties of a fixed separation distance, fixed permittivity of the material separating the conductors of the wave guide in the handle (with some minor temperature variations), fixed distance between the cable split and the point of connection to the rods, and fixed distance between the point of connection at the proximal ends of the rods and the point at which the rods exit the handle and enter the soil. Such handles provide optimal conditions for reliable algorithms determining t1.bis and t1, and the rest of this discussion will assume such a handle.

It has been argued (Spaans and Baker, 1993), that in order to match impedances (thus lowering signal loss and distortion) between the coaxial cable and the two rods in a bifilar probe, a balun should be used at the point of connection. Also, the balun should serve to convert the unbalanced signal in the coaxial cable (where the inner conductor carries the wave form and the outer conductor remains at virtual ground) to a balanced signal in the two rods (where both conductors carry the wave form. The argument states that, absent a balun, the unbalanced signal will tend to balance as it travels down the rods, eventually becoming closely balanced at some point along the rods. But, between the handle and that point the signal reflections will be distorted due to the partial imbalance. If the rods are very short the distorted part of the wave form may interfere with the second inflection. The trifilar probe responds to this concern by providing a waveguide that is geometrically more similar to a coaxial waveguide (Zegelin et al., 1989). Measurements by Zegelin et al. (1989) show only minor differences in wave form shape between trifilar and coaxial waveguides.

Influence of Bulk Electrical Conductivity on Wave Form Shape

As the bulk electrical conductivity (BEC) of the soil increases the impedance of the wave guide in the soil decreases due to the lowering of the resistance component of impedance. In addition there is a lowering of signal voltage along the length of the rods due to conduction through the soil. This causes the wave form level after the first peak to decline relative to that for a soil of lower BEC. It also lowers the slope, D2MAX, of the second rising limb (Hook and Livingston, 1995) and the final height to which the wave form rises after the second inflection. This latter fact has been used successfully to find the BEC of soils (e.g. Dalton et al., 1984; Topp et al., 1988; Wraith, 1993).

However, these effects can make it difficult to reliably find the second rising limb by searching for D2MAX. Smoothing of the wave form and its first derivative can make the determination of D2MAX more reliable by reducing the relative height of peaks in the first derivative that are caused by random noise in the wave form. However, in case of a very weak second rising limb the peak in the first derivative can be so spread out that the apparent position of the second rising limb, deduced from the position of D2MAX, is not consistent (Fig. 12). Fortunately, in these cases the high BEC guarantees that the wave form will slope downward between t1 and t2, in turn guaranteeing that the position of VMIN is always just before the second rising limb. In this situation, VMIN can be used reliably as the key to an algorithm used to find t2 (see below).

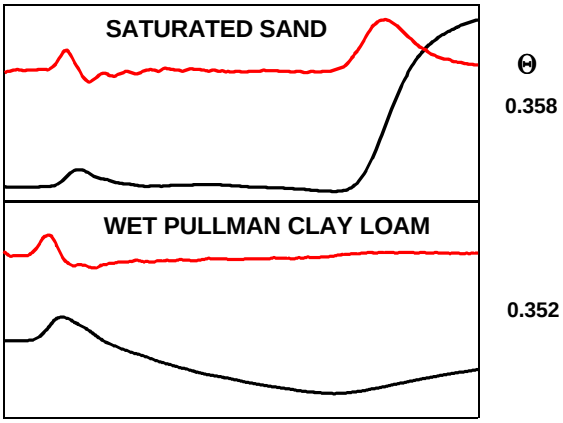

Figure 12. Wave forms and their first derivatives (top line in each plot) for two soils showing the lack of a distinct peak in the first derivative corresponding to the second rising limb of the wave form for the wet clay loam. Although the sand is slightly wetter there is a distinct peak in the derivative useful for finding t2.

Unfortunately, increased soil salinity is only one source of increase in BEC. Another source of BEC is the conductivity arising from certain clays, especially clays with high CEC. These are often expanding lattice clays containing cations entrapped between clay layers. When such soils are dry they exhibit low BEC, probably due to the contracted nature of the clay micelles and discontinuous water films on soil particles and the resulting low mobility of cations. As these soils wet their BEC increases as shown in Fig. 13 for an expansive Pullman clay loam with mixed minerology at Bushland, TX. The effects are apparent as a lowering of the second inflection and final wave form height as these soils wet. Although the problems posed by this phenomenon vis-a-vis the finding of t2 can usually be solved, the implications for relating TDR wave forms to soil salinity cannot be ignored.

Furthermore, this phenomenon has implications for the application of frequency domain (FD) probes to water content determination in these soils, similar to the implications and reported problems related to salinity effects on water content determination by FD probes. A frequency domain probe relies upon the change in frequency of an oscillator circuit caused by the change in permittivity of the soil around the probe. For the oscillator to change states the reflected voltage must reach the set point voltage of the oscillator at which time the oscillator changes states and drives the wave guide to the opposite polarity. The time it takes for the reflected voltage to reach

the set point is determined not only by the travel time to t2 but by the additional time between t2 and the time at which the second rising limb rises to the set point. Thus, the frequency of oscillation is dependent not only on t2 or t2-t1 but on the BEC of the medium. Since the BEC may be changed by salinity changes, clay content changes and/or water content changes in a clayey or saline soil it is obvious that calibration of an FD probe for routine field use, where these factors may change in time and space, is problematic.

Figure 13 illustrates the fact that as the soil becomes wetter the width of the wave form increases. This has implications for correct positioning of the wave form in the window and choice of window width settings Vp and DIST/DIV as will be discussed later. Not all clay soils show increases in BEC with water content as shown in Fig. 14 for a Cecil clay of kaolinitic minerology from Watkinsville, GA. Figures 13 and 14 illustrate the loss of the first descending limb and VMIN as the soil dries.

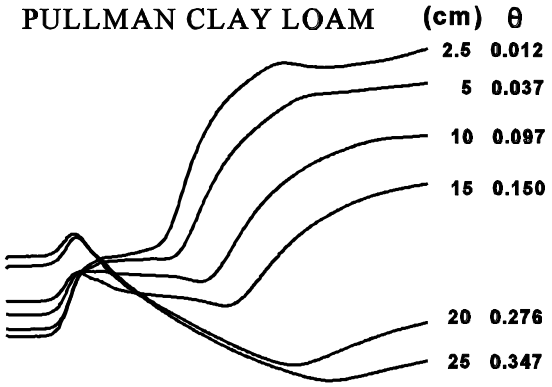

Figure 13. Effect of soil water content (θ, $m^3\ m^{-3}$) on the bulk electrical conductivity of a non-saline soil at several depths (cm) in the silty clay loam A horizon (2.5 to 15 cm) and the clay B horizon (20 and 25 cm).

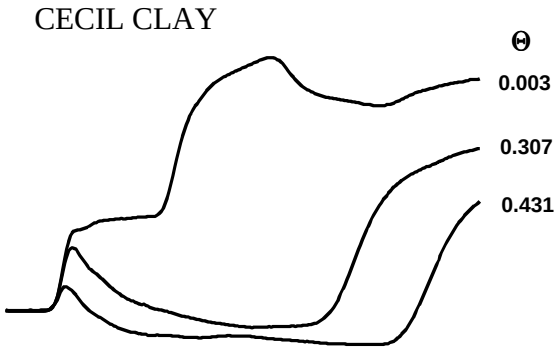

Figure 14. Effect of soil water content (θ, $m^3\ m^{-3}$) on the bulk electrical conductivity of a non-saline Cecil clay (kaolinitic).

Influence of Cable Length on Wave Form Shape

As the pulse moves down the cable to the probe its higher frequency components are selectively attenuated. The cable acts as a low pass filter. This means that the longer the cable, the slower the rise time of the pulse at the probe, and the less steep the rising and descending limbs of the inflections caused by probe handle and end of rods, i.e. transition time increases (Hook et al., 1992; Hook and Livingston, 1995). If the wave form is correctly interpreted then the travel time, t_t, should be constant despite cable length. However, if the probe is short enough, the descending limb of the first peak will intersect the rising limb of the second inflection causing the travel time to be incorrect. The longer the cable, the lower the slope of the descending limb and the longer the probe must be to avoid this problem. Since the slope of the descending limb also decreases with increasing BEC of the soil a probe length adequate for a given cable length is difficult to predict. Another problem associated with long cable lengths is the loss of the first peak altogether.

SETTING WINDOW WIDTH

We are aware of no reports that describe a method for setting the TDR window width that allows for reproducible and consistent computerized finding of t_t. Yet positioning has a direct affect on whether enough data are present to reliably fit lines to various portions of the wave form. Consider wave forms similar to those in Figs. 2-4 and 11. Because the data are digital representations of an analog phenomenon there are only a fixed number of data pairs of voltage and time representing a screen of data. For instance for the Tektronix model 1502B/C cable testers there are 251 data pairs. For Fig. 2 there were only 4 data pairs in the first rising limb, 12 data pairs in the first descending limb, and about 25 data pairs in the second rising limb. For Fig. 11 there were 18 data pairs in the first rising limb, only three data pairs in the first descending limb, and 24 data pairs in the second rising limb. If the wave forms were compressed horizontally even by 50% it would be difficult to find enough data points to reliably fit tangent lines to key parts of the wave forms. Thus, it is best to have the wave form occupy as much of the screen as possible. This is easily accomplished using the distance per division, DIST/DIV, and relative velocity of propogation, V_{pr}, settings of the cable tester. However, the width of the wave form increases with soil water content, and unless the cable tester is set when the water content is at saturation the wave form may widen enough with increasing water content that the second rising limb can no longer be seen on the screen. Figures 13 and 14 illustrate this. If the wave form width had been set to occupy the full screen for dry soil, the wave form for wet soil would be too wide for the second rising limb to appear on the screen.

Fortunately, if we have a good idea of what the saturated water content would be for a given soil, we can compute the desired screen width in nanoseconds as follows. First, compute the apparent permittivity from Eq. 8 (Topp et al., 1980):

$$\epsilon_a = 3.03 + 9.3\theta_s + 146\theta_s^2 - 76.7\theta_s^3 \qquad [8]$$

where θ_s is the saturated water content. The saturated water content can be estimated from the soil dry bulk density, ρ_b. Simply calculate the total soil porosity, $f = 1 - \rho_b/\rho_p$, where ρ_p is the particle density (assumed equal to 2.65); and assume that all air is displaced when the soil is saturated so that $\theta_s = f$.

Second, re-arrange Eq. 1 to calculate the velocity, v, of the signal in the wave guide

$$v = c_o(\epsilon_a \mu)^{-0.5} \qquad [9]$$

Then calculate the travel time over the length of the probe from

$$t = L/v \qquad [10]$$

where L is the probe length. Adding additional time for the base line before the first peak and for the second rising limb after t2 we have the time that we wish to have represented by the full screen width. Then we have only to find a combination of distance per division (DIST/DIV) and relative propagation velocity (V_{pr}) settings that results in a full scale horizontal axis at least equal to this time. Experience shows that it is best to have at least one tenth of the screen width (one

division) between the left had side of the screen and the first peak in order to reliably fit the base line. Also it is best to have at least 0.2 of the screen width between t2 and the right hand side of the screen to reliably fit the tangent to the second rising limb. A computer algorithm for finding appropriate combinations of DIST/DIV and V_{pr}, given the soil's saturated water content and the probe length, is given in Appendix A. Example results for several probe lengths and saturated water contents are given in Table 1. These are for the Tektronix 1502B or 1502C cable testers which allow variation of Vp settings in hundreths.

Table 1. Optimum relative propagation velocity (V_{pr}) and distance per division (Dist/Div) settings and resulting screen widths in ns for several combinations of probe length and saturated water content. Settings give screen widths within 2% of those calculated using the assumptions in the preceding paragraph.

	$\theta_s = 0.5$			$\theta_s = 0.4$			$\theta_s = 0.3$		
Probe Length (m)	V_{pr}	Dist/Div (m)	screen width (ns)	V_{pr}	Dist/Div (m)	screen width (ns)	V_{pr}	Dist/Div (m)	screen width (ns)
0.05	0.59	0.025	1.40	0.69	0.025	1.20	0.85	0.025	0.98
0.10	0.59	0.05	2.80	0.69	0.05	2.39	0.42	0.025	1.96
0.15	0.39	0.05	4.20	0.46	0.05	3.59	0.56	0.05	2.94
0.20	0.59	0.10	5.61	0.69	0.10	4.78	0.42	0.05	3.92
0.30	0.39	0.10	8.41	0.46	0.10	7.18	0.56	0.10	5.87

For the older Tektronix model 1502 cable tester, the V_{pr} setting has much less flexibility. There are three buttons for V_{pr}. Pressing Solid PTFE gives a V_{pr} of 0.70; pressing Solid POLY gives a V_{pr} of 0.66; and pressing OTHER allows the V_{pr} to be adjusted from 0.55 to 0.99 by turning the VAR screw. When all three buttons are out the V_{pr} is 0.99; or, when the VAR button is pressed in and the VAR screw is turned all the way clockwise, the V_{pr} is 0.99. Unfortunately, there is no simple way to know the exact V_{pr} value that is set with the VAR screw, so the user is left with just three usable V_{pr} settings, 0.66, 0.70, and 0.99. If the Tektronix 1502 is selected in Software Setup in TACQ then pressing D for defaults will, in addition to allowing the user to set the V_{pr} and Dist/Div settings, give two recommendations for Dist/Div (using the V_{pr} value chosen by the user). The first recommendation will show a negative percent error, and the second will show a positive percent error. These are the percentages difference from the optimum screen width in ns. If the negative percent error is small, then the user may be able to use the corresponding Dist/Div recommendation. Otherwise, the user should use the Dist/Div recommendation that gives a positive percent error. This will result in a screen width in ns that is wider than absolutely necessary, but that will ensure that the second rising limb of the wave form is not lost off the right side of the screen when the soil becomes saturated. The user should use Vp values of 0.66, 0.70, and 0.99 and see which gives the smallest percent error. Tables 2 and 3 give some possible combinations of probe length and Dist/Div and associated errors as a

percentage of the optimum screen width in ns for V_{pr} values of 0.99 and 0.70, respectively.

Table 2. Distance per division (Dist/Div) settings, and associated errors compared with optimum screen width, for V_{pr} of 0.99 and for a range of saturated water contents and probe lengths. For a cable tester set for units of feet.

	$\theta_s = 0.5$		$\theta_s = 0.4$		$\theta_s = 0.3$	
Probe Length (m)	Dist/Div (ft)	Percent Error	Dist/Div (ft)	Percent Error	Dist/Div (ft)	Percent Error
0.05	0.1	-27	0.1	-14	---	---
	0.2	47	0.2	72	0.1	5
0.10	0.2	-27	0.2	-14	0.1	-48
	0.5	83	0.5	115	0.2	5
0.15	0.2	-51	0.2	-43	0.2	-30
	0.5	22	0.5	43	0.5	75
0.20	0.5	-8	0.2	-57	0.2	-48
	1.0	83	0.5	7	0.5	31
0.30	0.5	-39	0.5	-28	0.5	-13
	1.0	22	1.0	43	1.0	75

Table 3. Distance per division (Dist/Div) settings, and associated errors compared with optimum screen width, for V_{pr} of 0.70 and for a range of saturated water contents and probe lengths. For a cable tester set for units of feet.

	$\theta_s = 0.5$		$\theta_s = 0.4$		$\theta_s = 0.3$	
Probe Length (m)	Dist/Div (ft)	Percent Error	Dist/Div (ft)	Percent Error	Dist/Div (ft)	Percent Error
0.05	---	---	---	---	---	---
	0.1	4	0.1	21	0.1	48
0.10	0.1	-48	0.1	-39	0.1	-26
	0.2	4	0.2	21	0.2	48
0.15	0.2	-31	0.2	-19	0.2	-1
	0.5	73	0.5	102	0.5	147
0.20	0.2	-48	0.2	-39	0.2	-26
	0.5	30	0.5	52	0.5	85
0.30	0.5	-14	0.2	-60	0.2	-51
	1.0	73	0.5	1	0.5	24

It is obvious that for some combinations of probe length and saturated water content there is no combination of Dist/Div, and the Vp settings possible with the push buttons on the Tektronix 1502 cable tester, that comes close to providing an optimum screen width. This doesn't necessarily mean that good data can't be obtained, but it does mean that the user may want to choose probe lengths that lend themselves more easily to optimization of this sort.

ALGORITHMS for WAVE FORM INTERPRETATION

This section briefly describes algorithms used by TACQ for automatic graphical interpretation of a wide variety of wave forms. The user may choose from several methods described in the literature or use methods available only in TACQ. These methods assume wave forms positioned in the instrument window as described in the preceding section. Features of the wave form and its first derivative discussed below are defined in Figures 3, 10, and 11.

Wave Form Smoothing

Following the method of Baker and Allmaras (1990) wave forms are smoothed using the Savitsky-Golay procedure (Gorry, 1990). The user may choose any degree of smoothing from none to a 21 point smooth. To provide a symmetrical smooth only odd numbers of points are allowed. Derivative smoothing may vary from none to a 19 point smooth. Derivative smoothing must be over a number of points at least two lower than the number chosen for wave form smoothing. The user should specify only enough smoothing to reduce extraneous peaks in the first derivative. Excessive smoothing can cause errors, most particularly loss of sharp wave form features such as the first peak. The default setting for smoothing is 9 points on the wave form and 3 points on the first derivative.

Circumscribing Wave Form Interpretation

In order to avoid dealing with sudden drops or rises in level that may occur at the beginning or end of the wave form (usually only seen with the 1502 cable tester) the user may set any number of points not to be used in wave form interpretation at either end of the wave form. Vertical lines on the screen show the parts of the wave form thus excluded. The number of excluded points for either end may be set by entering a number or by moving the lines interactively using the cursor keys.

Also, the user may define a limit excluding data in the right hand side of the wave form from being used to find the first peaks in the wave form and first derivative. This excludes the second peak in the first derivative from consideration for finding time 1and eliminates confusion between the first and second rising limbs. Correspondingly, the user may exclude a portion of the left hand side of the wave form from consideration when determining the location of the second rising limb. Again, these limits may be set by entering a number or by using the cursor keys to move the vertical lines that represent the limits on the computer screen. Table 4 summarizes the user-set limits.

Table 4. User Set Limits on Data Searched for Wave Form Features

StartPt	Time before which to exclude data from examination.
EndPt	Time after which to exclude data from examination.
D2Lim	Time at which to begin search for second maximum in the first derivative. Search ends at EndPt.
D1Lim	The data between StartPt and D1Lim are searched for the first peak in the first derivative, D1MAX.
SafetyLim	If t1 is less than this time then zeros are written to the output.
t1Swath	Number of data points after tD1MAX to use when searching for V1MAX.

Choosing Wave Form Interpretation Methods:

For finding the center of the second rising limb (t2.2) the user may choose to use only a global minimum method (i.e. find VMIN and t2.1), only a method that finds D2MAX and associated time t2.2, or an automatic method that uses the global minimum method if the value of D2MAX is below a user set threshold, D2Thresh, and that uses the time of D2MAX otherwise. The global minimum method for t2 is similar to that of Baker and Allmaras (1990) except that the search for VMIN is conducted in the data between t1p and EndPt rather than over all the data. Regardless of the method for finding t2.2 the line tangent to the second rising limb is found by linear regression on a swath of points around t2.2 (user chosen swath width).

The user may choose how to fit the "horizontal" intersecting line that partially defines t2. The line is either a horizontal line passing through the wave form at t2.1 or a line fit by regression to a swath of points just prior to t2.1 (user chosen swath width). If the horizontal tangent method is chosen the program will examine the slope of a line fitted to the swath of points, and if the slope is positive the program will use the fitted line rather than the horizontal tangent. This avoids improper interpretation of wave forms from dry soils for which VMIN may be located closer to t1 than t2.

For finding t1 the user may choose to use a method (M1), similar to that of Baker and Allmaras, that finds t1p by searching for V1MAX and DMIN but that starts the search from the time of D1MAX; and that, failing to find V1MAX and D1MAX assigns values as explained below. Or, the user can choose method M2 that finds D1MAX and fits a line tangent to the first rising limb and a horizontal line tangent to the baseline before the first rising limb and solves the intersection for t1.bis. Method M2 then adds a user set time, t_C, to t1.bis to get t1. The time t_C = t1 - t1.bis is found by measurements on probes installed in wet soil using method M1. This is different from the method proposed by Heimovaara and Bouten (1990) involving a single measurement in air.

Finding Travel Times

Times t1 and t2 are reliably found by a combination of searches and decisions based on the results of those searches. In this discussion the wave form is assumed to consist of NP digitized data pairs of voltage and time with equal increments of time between consecutive data pairs.

1. Smooth data and first derivative using the Savitsky-Golay method and user set number of points, and find the maximum and minimum first derivative, maxDeriv and minDeriv.

2. Scan the wave form data from D2Lim to EndPt to find the lowest value, VMIN, and corresponding time, t2.1.

3. Scan the first derivative in a loop from StartPt to D1Lim to find the first maximum value, D1MAX, and associated time tD1MAX. If tD1MAX is greater than t2.1 then reduce D1Lim by NP/40 and try again. If D1Lim reaches 0 then write zeros to output.

4. Scan wave form data from tD1MAX+30 to EndPt for the lowest value, VMIN, and associated time, t2.1.

5. Scan wave form data from tD1MAX to tD1MAX + NP/8 to find the highest value, V1MAX, and associated time, t1p. Update V1MAX whenever the wave form value is higher than V1MAX and accumulate a count whenever the wave form value is lower. If count is greater than t1Swath then stop the search. This avoids finding the second peak if double peaks exist. If the wave form is continuously rising then t1p may be greater than tD1MAX + NP/20. If so then set t1p equal to tD1MAX + NP/20 and set V1MAX to the wave form value at that time.

6. Unless the global minimum method for finding t2 is forced, scan the derivative data from D2Lim to EndPt for the maximum derivative, D2MAX, and corresponding time, t2.2.

7. If the t2 derivative peak method is forced or if the t2 method is automatic and D2MAX is larger than D2Thresh then scan the data from t2.2 to t2.1 to find the zero derivative nearest to t2.2. Redefine t2.1 at this point and take the value of the wave form at this point as VMIN. If no zero derivative is found in this range of data then set t2.1 equal to t1p plus tatVMINFrac times the quantity (t2.2 - t1p) and set VMIN equal to the corresponding value of the wave form.

8. If the method for t2 is automatic and D2MAX is less than D2Thresh then set t2.2 equal to t2.1 plus the offset (RiseLimbOffset) specified by the user and set D2MAX equal to the corresponding value of the first derivative. Then set t2.1 equal to t1p plus tatVMINFrac times the quantity (t2.2 - t1p) and set VMIN equal to the corresponding value of the wave form.

9. If the local minimum method for t2 is forced then set t2.2 to t2.1 plus RiseLimbOffset (limited to less than or equal to NP) and set D2MAX to the corresponding value of the first derivative.

10. Regardless of how t2.2 is determined set Vt2.2 equal to the wave form value at t2.2.

11. Fit by linear regression a line to the base line between t2.1 and t2.1-BaseSwathWidth where BaseSwathWidth is a user chosen number of data points. If the slope of this line is positive then force a regression fit to the base line rather than a horizontal line tangent to VMIN.

12. Scan the derivative data from t1p to t1p plus t1Swath to find the lowest derivative value, DMIN, and corresponding time, tDMIN, which are associated with the descending limb of the first peak.

13. If DMIN is greater than -0.01 then set DMIN=(yll-yuu)/(xuu-xll), and set tDMIN equal to t1p + 1. The values of yll and yuu are the minimum and maximum of the wave form, respectively, and the values of xll and xuu are the minimum and maximum of the x-axis. Thus, the slope is scaled to the wave form amplitude.

14. Set VtDMIN equal to the wave form value at tDMIN, and if this value is greater than V1MAX then set VtDMIN to V1MAX.

15. Calculate the time of the intersection of tangent lines for t1 and if this time is less than t1p then increase the value of tDMIN and the magnitude of the slope, DMIN, until the intersection is at t1p or greater.

16. If t1 is less than the safety limit, SafetyLim, then write zeros to the file.

17. Set up limits on data used to fit tangent line to second rising limb as t2.2-Xinc and t2.2+Xinc where Xinc is user chosen. If these limits are out of range then write zeros to file.

19. If actual point to point slope near tD1MAX is greater than smoothed slope, D1MAX, then set D1MAX to actual maximum slope.

20. Examine derivative before first rising limb for slope close to zero (slope lesser in magnitude than [maxDeriv-minDeriv]/100). If such points are found then use the average wave form value for those points as the intercept for a line tangent to the baseline with slope of zero. If such points are not found then set the intercept of the horizontal line to the minimum wave form value to the left of tD1MAX.

SUMMARY

The TACQ computer program was developed to automatically control a stand-alone TDR system consisting of a TDR instrument, up to seventeen multiplexers, and up to 256 probes. It is easily used in an embedded computer system and allows storage of data in removable media while running from a read-only solid state disk. It can control system power to allow low-power TDR systems including solar powered ones. The program will run under DOS, OS/2, and Windows (3.11 and 95) and can be run by a supervisory program (e.g. under Windows) as part of a larger data acquisition and control system; for example, an automated irrigation control system. Automatic graphical interpretation of wave forms includes methods given in the TDR literature as well as methods unique to TACQ that allow the program to correctly interpret wave forms from soils of many different properties. The user has complete control over the interpretation methods used, the acquisition interval, the kind of data acquired for each probe, and the interconnection of probes and multiplexers. Different cable lengths to probes and different probe lengths are accomodated easily in the same system. Data for both water content and bulk electrical conductivity measurments may be collected.

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Appendix A.

```
SUB BestDistDv.Vp (ProbeLen, FtMtrs, Theta)
'Routine for choosing the best combination of Dist/Div and Vp for a given
'probe length based on inversion of Topp's equation for permittivity, Ka,
'as a function of water content.  Written in Microsoft BASIC 7.1 by Steven R. Evett
'ProbeLen is probe length in meters.
'FtMtrs 'If 1 then units are feet else units are m.
'Theta is volumetric water content (m^3/m^3).

SHARED Vp
SHARED Dist
SHARED DistDv
SHARED CardType%
i% = 10
DIM TimeErr(i%)
DIM DistVal(i%)

'Limit values of water content:
IF Theta < 0 THEN Theta = 0
IF Theta > .6 THEN Theta = .6
'Calculate the apparent permittivity (Ka) (Topp et al., 1980):
Ka = 3.03 + 9.3 * Theta + 146! * Theta * Theta - 76.7 * Theta * Theta * Theta
'The velocity of propogation is a function of Ka:
v = .299792 * 1E+09 / SQR(Ka)
'The travel time is a function of v and probe length:
tt = ProbeLen / v

'Assume that the travel time should occupy 70% of the screen max.
NewTtFull = (tt / .7) * 1E+09   'in ns

row% = CSRLIN
col% = POS(0)

TryAgain% = 0
SELECT CASE CardType%
CASE 5
Start.Search:
   'Try smallest Dist first, then next biggest, etc.
   'Get Dist for i=1 to 10:
   FOR i% = 0 TO 10
      DistDv = i%
      ReturnDistDv 'This returns one of the 11 possible Dist/Div settings.
      'Make sure DistM is in meters:  DistM is the distance per division.
      IF FtMtrs = 1 THEN
         'was in feet, convert to meters
         DistM = Dist * .3048
      ELSE
         'was in meters
         DistM = Dist
      END IF
      'Try biggest Vp first, then go to smallest
      FOR Vp = .99 TO .39 STEP -.01
         TtFull = DistM * 10 / (Vp * .2997925)
         IF TtFull >= NewTtFull THEN EXIT FOR
      NEXT Vp
      IF TtFull >= NewTtFull THEN EXIT FOR
   NEXT i%
   TimeError = (TtFull - NewTtFull) / NewTtFull
```

```
    BestDist = Dist
    IF ABS(TimeError) > .02 THEN
       PRINT "Best DIST/DIV and Vp not found."
       PRINT "Error was"; TimeError * 100; "%"
       PressAKey (5)  'Wait for a key press before continuing.
    END IF
    'One combination of Vp and Dist/Div is known.
    'The Dist/Div value is in BestDist.  Print both Vp and Dist/Div:
    PRINT "        For VWC ="; Theta;
    LOCATE row% + 1, col%
    PRINT USING "recommend Vp: .## "; Vp;
    PRINT "and DIST/DIV:"; BestDist;
    IF FtMtrs = 1 THEN
       PRINT "ft";
    ELSE
       PRINT "m";
    END IF

CASE ELSE
'For Tektronix 1502 cable tester, not 1502B/C.
'Provide two closest Dist/Div values for given Vp.
Start.Search2:
    'Get Dist for i=1 to 10:
    FOR i% = 0 TO 10
      DistDv = i%
      ReturnDistDv
      'Make sure DistM is in meters:
      IF FtMtrs = 1 THEN
         'feet
         DistM = Dist * .3048
      ELSE
         'meters
         DistM = Dist
      END IF
      'Use actual Vp first, and return error if TimeErr is too great
      TtFull = DistM * 10 / (Vp * .2997925)
      TimeErr(i% + 1) = (TtFull - NewTtFull) / NewTtFull
      DistVal(i% + 1) = Dist
      IF TimeErr(i% + 1) > 0 THEN EXIT FOR
    NEXT i%

    LOCATE 22, col%
    PRINT "For VWC ="; Theta;
    PRINT USING " and for Vp: .## "; Vp;
    FOR j% = i% TO i% + 1
       LOCATE 22 + 1 + j% - i%, col%
       PRINT "could use DIST/DIV:"; DistVal(j%);
       IF FtMtrs = 1 THEN
          PRINT "ft";
       ELSE
          PRINT "m";
       END IF
       PRINT USING ". Error: ###"; TimeErr(j%) * 100;
       PRINT "%";
    NEXT j%
END SELECT
REDIM TimeErr(0)
REDIM DistVal(0)
END SUB
```