77

BARD

FINAL REPORT

PROJECT NO. US-868-84

**Time Domain Reflectometry: Simultaneous
In-Situ Measurement of Soil Water Content
and Salinity**

F.N. Dalton, S. Dasberg, J.D. Rhoades, A. Nadler

1990

Standard BARD Cover Page for Scientific Reports

Date: 12-6-89

BARD
P.O. BOX 6
Bet Dagan, ISRAEL

BARD project No. US - 868 - 84

Title

Time Domain Reflectometry: Simultaneous In-Situ Measurement
of Soil Water Content and Salinity.

Investigators' Names (Principal listed first)

F. N. Dalton

S. Dasberg

J. D. Rhoades

A. Nadler

Investigators' Institutions

USDA- ARS-U. S. Salinity Lab.

A. R. D. Volcani Center

USDA - ARS-U. S. Salinity Lab.

A. R. D. Volcani Center

Project's starting date: October 1985

Type of Report: 1st Annual 2nd Annual Final x

F. N. Dalton

Signature
Principal Investigator

W. G. Chace
Signature
Institution's Authorizing Official

FORWARD

Optimum use of available water resources, especially in arid and semi-arid regions, is the goal of local and regional governments, farm managers and various other special interest groups. Basic research on the physics of plant water use and its relation to water resource management and crop yield is of critical importance. Methods and resources available to research installations for monitoring the components of the agricultural production system often exceed those of the producing farm. However, it is just such research efforts that produce the innovative and accepted methods of the future. The research presented in this report and supported by BARD falls into this category. Instrumentation using state of the art technology is developed to make in-situ measurements of soil water content and salinity over identical sampling volumes. This measurement is fundamental to all phases of water management and research. While the techniques require sophisticated electronic equipment, a broad base of use is developing in the United States. We can expect a continuing decrease in cost and an increase in adaptability making the technique as common as neutron scattering and as accurate as gravimetric sampling.

The able and enthusiastic assistance of J. A. Poss, T. J. Heimovaara, R. Austin, W. Alves, and W. Russell during the course of this investigation is gratefully acknowledged.

F. N. Dalton

Principal Investigator

ABSTRACT

This report develops the principles and applications of time-domain reflectometry (TDR) as a new technique for simultaneously monitoring both soil water content and soil water salinity over identical sampling volumes using a single probe. An electromagnetic pulse is launched into this probe by way of a co-axial cable and electronic circuitry measures the transit time and energy of the pulse after it has completed a round trip along the path formed by the two metallic rods. Design criteria for the construction and use of the TDR probe is given. The velocity or transit time of the the electromagnetic pulse is a measure of the soil water content and the energy dissipation is a measure of the electrical conductivity. Soil water salinity is then calculated by a knowledge of the soil water content, electrical conductivity and soil type. Water content and bulk soil electrical conductivity measurements are reported for six water contents each at ten different salinities and two temperatures. The low frequency component of the electrical conductivity measured by conventional methods is shown to be equivalent to the electrical conductivities obtained by two different analysis of wave propagation in loaded and unloaded transmission lines. TDR water content measurements correlate well with gravimetric samples and show only a small temperature dependence. At high bulk soil electrical conductivities the TDR technique overestimates the water content. Theoretical analysis explains the overestimation in terms of a velocity retardation due to dispersion phenomena of the TDR pulse. The TDR technique lends itself nicely to field scale sampling of water and salinity since the equipment with data acquisition systems are also suitable for long time monitoring of agricultural land and water sheds. TDR offers many advantages over conventional methods for soil water measurements and should become an effective tool for irrigation scheduling both in saline and non-saline environments.

TABLE OF CONTENTS

Forward	ii
Abstract	iii
1. INTRODUCTION	
1.1 Objectives Of The Original Research	1
1.2 Preliminaries	2
2. TIME-DOMAIN REFLECTOMETRY PRINCIPLES	
2.1 Basic Concepts	3
2.2 Measurement Of Transit Time And Dielectric Constant	5
2.3 Measurement Of Bulk Soil Electrical Conductivity	8
3. DESIGN CRITERIA FOR CONSTRUCTING TDR PROBES	
3.1 Wave Guide Separation And Diameter	14
3.2 TDR Wave Guide Probe Lengths	15
3.3 TDR Probe Interface With Cable Tester	17
4. TIME-DOMAIN REFLECTOMETRY APPLICATIONS	
4.1 Use Of TDR For Column Lysimeter Measurements	25
4.2 Use Of TDR For Surface Measurements	26
4.3 Use Of TDR For Vadose Zone Measurements	27
4.4 Summary	27
5. DATA ACQUISITION AND WAVE FORM ANALYSIS	
5.1 Introduction	30
5.2 Method For Obtaining A Digital Waveform	30
5.3 Method For Obtaining The Right Data Format	31
5.4 The TDR Program	32
5.5 Summary	36
6. FURTHER RESEARCH ON THE EFFECT OF SALINITY AND TEMPERATURE ON TDR MEASUREMENTS	
6.1 Introduction	38
6.2 Materials And Methods	38
6.3 TDR Measurements	40
6.3.1 Water Content	40
6.3.2 Bulk Soil Electrical Conductivity	41
6.4 Results: TDR Measured Water Content	41
6.5 Results: TDR Measured Bulk Soil Electrical Conductivity	42
6.6 Summary	43

7. TDR WATER CONTENT INTEGRATION	
7.1 Introduction	54
7.2 Methods	54
7.3 Results	54
8. ALTERNATIVE TECHNIQUES FOR TDR MEASUREMENT OF BULK SOIL ELECTRICAL CONDUCTIVITY AND SALINITY	
8.1 Introduction	57
8.2 The Loaded Transmission Line	57
8.3 Calibration Of Sampling Head	59
8.4 Results	60
8.5 Summary	62
9. THEORETICAL ANALYSIS OF THE EFFECT OF SALINITY ON TDR WATER CONTENT MEASUREMENTS	71
9.1 Introduction	71
9.2 Experimental Observations	71
9.3 Effect Of Ionic Strength On Dielectric Constant	72
9.4 Dispersion And Its Effects On Electromagnetic Propagation	72
9.5 Summary	76
10. APPENDIX A	
10.1 How To Use The Micrologger For Obtaining TDR Waveforms	92
11. APPENDIX B	
11.1 Program Used To Add Data Point Numbers To The Input File	94
11.3 Example Of An Input File	95
11.3 Example Of An Output File	95
11.4 Example Of CALC.CAL	96
11.5 Example Of TDRRHO1.PRN	96
12. APPENDIX C	
12.1 Code For The TDR Program	98
13. REFERENCES	106
14. DESCRIPTION OF COOPERATION	108
15. EVALUATION OF RESEARCH ACHIEVEMENTS WITH RESPECT TO AIMS OF ORIGINAL RESEARCH PROPOSAL	109
16. LIST OF PUBLICATIONS	111

1. INTRODUCTION

1.1 Objectives Of The Original Research

The objective of this research was to develop the use of time-domain reflectometry techniques for the simultaneous measurement of soil water content and soil water salinity and to make theoretical and experimental investigations on the physical properties of soil and water which affect the accuracy of the measurements. Field applications were to be developed for characterizing root zone salinity and water content for the purpose of irrigation management and predicting plant stress

1.2 Preliminaries

Time-domain reflectometry (TDR) is a relatively new method used to measure soil water content and bulk soil electrical conductivity. Topp et al.(1980) measured the effective dielectric constant of soil in a specially designed coaxial container and showed that it was uniquely related to the water content of a large class of soils. In laboratory and field experiments, Dalton et al. (1984), Dasberg and Dalton (1985), Dalton and van Genuchten (1986), and Dalton (1987), Dasberg and Nadler (1987) showed that in addition to the effective dielectric constant, the TDR waveform contained sufficient information to deduce the bulk soil electrical conductivity. These measurements can be made simultaneously and over identical sampling volumes using a single probe. The bulk soil electrical conductivity and dielectric constant can then be used to calculate soil water salinity according to Rhoades (1976).

This report focuses on the principles, design and use of TDR techniques for inferring soil water content and salinity from the fundamental measurements of soil

dielectric constant and electrical conductivity. TDR measurements are suited to situations where neutron tube installation is too bulky and destructive and where gravimetric sampling is not feasible. In addition the TDR method does not have any radiation hazards and for most situations does not need to be calibrated.

The main body of this report consists of the unpublished portion of the work completed during the course of our investigations. The report provides a detailed discussion of the construction, installation, data acquisition, and analysis for the simultaneous measurement of soil water content and salinity using the techniques of time-domain reflectometry.

2. TIME-DOMAIN REFLECTOMETRY PRINCIPLES

2.1 Basic Concepts

A simplified diagram depicting the physical principle of the TDR method used to measure soil water content, and bulk soil electrical conductivity is shown in Figure 2.1.. Two parallel metallic electrodes of length l are used as a transmission line or wave guide for the propagation of an applied electromagnetic pulse. At time $t = 0$, a voltage V_0 is applied to the rods at points A by closing switch S. The voltage at points B is precisely measured as a function of time from time $t = 0$ by the voltage and timing meter (V-T). The applied voltage (V_0) is not immediately detected at the ends of the parallel probe wave guide (points B) because a finite time is required for the voltage pulse to travel the length of the rods and register on the V-T meter. As will be discussed later, this finite time interval is directly correlated to the soil water content

In practice, the V-T meter is connected at points A. The voltage pulse travels along the rods and upon reaching point B is reflected with a 180 phase change and returns to point A. The time interval for this round-trip is determined by the transmission line length, l , and dielectric constant, ϵ , of the medium. The voltage at point A is precisely measured as a function of time from $t = t_0$, and thereby senses the superposition of the reflected voltage, V_r , and the initial voltage, V_0 . The cable tester repeats this scenario over 16,000 times per second and the results are sampled and stored visually on a cathode ray tube (CRT) for inspection and analysis.

According to electromagnetic theory, the pulse velocity along electrodes imbedded in a soil with an effective dielectric constant ϵ , is a fraction of the pulse velocity in free space, c , and to a first approximation is given by

$$v = \frac{c}{\sqrt{\epsilon}} \quad (2.1)$$

The velocity of the pulse is also obtained from the ratio of the path length, $2l$, to the transit time, t

$$v = \frac{2l}{t} \quad (2.2)$$

Equations 1 and 2 yield an expression for the effective dielectric constant of the soil

$$\epsilon = \left[\frac{ct}{2l} \right]^{1/2} \quad (2.3)$$

These relationships are strictly true only when the electrical conductivity between the parallel transmission line is zero. In a saline soil this is not true, especially at high water contents where these equations are only first approximations. We exploit this condition, however, to simultaneously determine the bulk soil electrical conductivity by using the same waveform used to determine the dielectric constant. Referring back to Figure 1, the initially applied voltage, V_0 , is attenuated in a saline soil and the detected signal, V , at points B is less than V_0 . The diminished voltage V is then related to V_0 based on electromagnetic theory where $V = V_0[-2\alpha l]$ where α is the attenuation coefficient proportional to salinity and l is the path length, $l=2l$.

2.2 Measurement Of Transit Time And Dielectric Constant

A general relationship between the soil dielectric constant, ϵ , and the volumetric soil water content, θ , has been determined by Topp (1980) and is given by

$$\theta = -5.3 \times 10^{-2} + 2.92 \times 10^{-2} \epsilon - 5.5 \times 10^{-2} \epsilon^2 + 4.3 \times 10^{-6} \epsilon^3. \quad (2.4)$$

This relation has been shown to be good for a wide class of soils. Most likely this equation will require adjustment for peat and heavy clay soils

According to equation 2.3, the water content determination is reduced to the measurement of a voltage pulse transit time over a known path length.

A typical pulse transit time for a path length of 30 cm in a wet soil is about two nano-seconds. This extremely small time interval can be accurately measured with commercially available equipment. Depending on the specific TDR cable tester design, the dielectric constant can be obtained by a direct measure of the pulse transit time or by the more common method of converting a distance measurement to the pulse transit time. When using the Tektronix¹ S52 pulse generator, 7S12 sampling unit, S-6 sampling head and 7603 oscilloscope, the pulse transit time can be measured directly in nano-seconds. Equations 3 and 4 are then used to calculate the effective dielectric constant and water content of the soil respectively.

However, the instrument most commonly used for soil moisture determination is the Tektronix 1502 cable tester. With this instrument the procedure is less direct since the cable tester is calibrated to the "path length" of the signal rather than the "transit time" of the signal. The procedure for using the cable tester as a soil moisture gauge is explained with reference to a typical waveform obtained with this

¹Names of products are included for the benefit of the reader and do not imply endorsement or preferential treatment by USDA

instrument.

Figure 2.2 shows the cable tester interfaced with parallel metallic probes embedded in a moist soil with expanded wave forms and corresponding settings for the function switches to measure soil moisture. The TDR wave form contains characteristic pick off points which are used measure the soil dielectric constant. Point A is where the probe enters the soil, and B corresponds to where the pulse, having made a round trip over the probe length, is sensed and added to the initial pulse. This distance between points A and B is thus twice the probe length, (Fig. 2.2a). The cable tester is designed to render the distance to a line discontinuity or break (in this case the probe length) and consequently, the instrument read-out is in "length" units. The length or distance is easily read directly from the cathode ray tube (CRT), where each vertical division represents some unit of distance determined by the chosen scale setting (S2) (Fig. 2.2b). Alternatively, the distance is obtained by using the "horizontal adjust" (D1) to align point A to a vertical reference line and then displacing the entire wave form to the left with the calibrated "Distance" dial (D2) until point B lies on the same reference line. The distance is then read directly from the calibrated dial D2[XX.XX].(Fig. 2.2c).

The distance axis is related to the fundamental time measurement by the expression

$$\text{Distance} = \text{pulse velocity} \times \text{travel time} \quad (2.5)$$

According to Equation 2.1, the pulse velocity is given in terms of the medium dielectric constant as, $v=c/\sqrt{\epsilon}$. For telephone cables and other wire pairs, the dielectric constant of the insulating material is known. Therefore, the distance is a simple product of a constant factor ($c/\sqrt{\epsilon}$) and travel time. The operator sets the cable tester for the appropriate dielectric constant, (Figure 2.2, B1, B2), and reads

the horizontal axis directly as one half the actual path length.

In contrast, soil water measurements require an inverse procedure. The effective dielectric constant of the soil is sought while the path length ($2l$) is known. The dielectric constant is determined in the following way when using the Tektronix 1502 cable tester.

The dielectric constant for the cable tester is set to $\epsilon=1$ (all "cable dielectric" buttons out). Let S represent the cable tester reading for the distance between points A and B. Then $2S$ is the path length for the TDR pulse, and according to Equations 2.5 and 2.1.

$$S = (c / \sqrt{\epsilon}) \times T \quad (2.6)$$

where T is the travel time. However, the true path length between points A and B is just twice the probe length $2L$. This true path length is given in terms of the effective dielectric constant of the soil and travel time according to Equation 2.1

$$2l = (c / \sqrt{\epsilon}) \times T \quad (2.7)$$

Taking the ratio of equations (2.6) and (2.7) gives

$$\sqrt{\epsilon} = \frac{S}{l} \quad (2.8)$$

and

$$\epsilon = \left[\frac{S}{l} \right]^2 \quad (2.9)$$

The effective dielectric constant of the soil is therefore determined by squaring the ratio of the distance between points A and B and the probe length.

This explains an apparent discrepancy for path length in other formulations of the theory (Topp et al., 1982 and Dalton et al., 1984), when the cable tester was being used.

Alternative procedures for obtaining S using the 1502 cable tester are:

1. Reading the value of S directly from the CRT for the distance between points A and B, taking into account division scale (Figure 2.2,b).
2. Using the "distance dial" reading after displacing point B to point A independent of the division scale (Figure 2.2,c).
3. Recording the wave form on x-y recorder for later analysis.
4. Digitizing the wave form and transferring to a PC for later analysis.

It should be noted that direct measurements may introduce subjectivity into determining points of inflection.

2.3. Measurement Of Bulk Soil Electrical Conductivity

As previously shown (Dalton et al., (1984), Dasberg and Dalton (1985), Dalton and van Genuchten (1986)), the bulk soil electrical conductivity (σ) is given in terms of a transmitted voltage (V_T), a reflected voltage (V_R), and the dielectric constant, (ϵ) of the medium as:

$$\sigma = \frac{\sqrt{\epsilon}}{120 \cdot \pi} \ln (V_T / V_R) \quad (2.10)$$

Figures 2.3a and 2.3b show to scale the complete TDR wave form depicted on the CRT used to simultaneously determine water content and salinity.

The vertical axis on the Tektronix 1502 cable tester is not calibrated in voltage units but is calibrated in terms of a reflection coefficient ρ . The reflection coefficient, at some position x , along the wave guide, is the ratio of the amplitudes of the positive traveling wave to the negatively traveling wave. The superposition of the amplitudes of the waves at x is the voltage at x . Since the fundamental measurement made by the cable tester is the time varying voltage at the instrument input; the ratio of the cable tester reflection coefficient is equivalent to the ratio of the voltage.

The transmitted voltage, V_T is most easily obtained by first using the meters/div switch (S2) to horizontally compress the wave form thus facilitating the location of the TDR pulse base line voltage, V_0 (Figure 3a). The base line is then aligned with a bottom horizontal line of the CRT using the vertical and horizontal positioning dials D3 and D1, respectively. Second, the horizontal adjust (D1) is then used to position point B on the vertical grid in the center of the CRT. The transmitted voltage (V_T) can now be read directly from the screen as the number of divisions from the base to point B, (Figure 2.3a).

The reflected voltage (V_R) is now obtained by first using the vertical adjust dial (D3) to position point B on the CRT base line and, second, moving point B to the left with the distance dial the same amount as determined for the dielectric constant measurement (Figure 3b). The reflected voltage (V_R) is then read where the TDR trace intersects the center vertical graduated grid on the CRT, (Figure 2.3b).

These procedures extract the necessary information from the TDR wave form to

simultaneously calculate soil water content and bulk soil electrical conductivity over identical sampling volumes. This information can , of course , be obtained from a signal trace reproduced on a X-Y recorder or from a data acquisition system.

Figure 2.1. Conceptual diagram of physical principle of TDR method for simultaneous soil water and salinity measurements.

Figure 2.2(a). Expanded TDR waveform on CRT used to measure moisture content. Point A results from pulse entering soil. Point B results from reflected voltage returning to source. S1 and S2 settings are 100 m/div and 0.1 m/div respectively.

Figure 2.2(b). Expanded TDR waveform on CRT moved with vertical adjust (D3) to measure time/distance with aid of graduations on CRT. S1 and S2 settings same as in Figure 2a.

Figure 2.2(c). Expanded TDR waveform on CRT after displacement using distance dial (D2) to measure path length/time.

(a)

(b)

Figure 2.3(a). Compressed and aligned waveform with point B positioned on vertical grid to measure V_T using gradations on CRT.

Figure 2.3(b). Point B now positioned on Baseline and waveform displaced distance determined previously by dielectric constant determination procedure, then V_R is read using gradations on CRT.

3. DESIGN CRITERIA FOR CONSTRUCTING TDR PROBES

3.1 Wave Guide Separation And Diameter

In principle, the electrode pair can be constructed of any material with an electrical conductivity much greater than the medium they are immersed in. The connection of the electrode pair to the cable tester is governed by the experimental constraints of the soil measurement. If the probe is buried in a soil profile, the electrode pair must be connected to a transmission line that can be connected to the cable tester input at the soil surface. If the electrode pair is directly accessible, as with column studies or near surface measurements, the transmission line does not need to be permanently affixed to the electrode pairs.

For optimum efficiency in each of these cases, the characteristic impedance of the electrode pair should be matched to the impedance of the transmission line connecting the TDR unit to the electrode pair. To a first approximation, the characteristic impedance, Z_o , of the parallel electrode geometry is dependent on the dielectric constant of the soil, the separation (s), and diameter, (d), of the electrode pair (Ramo and Whinnery, 1959).

$$Z_o = \frac{120}{\sqrt{\epsilon}} \left[\frac{2s}{d} \right] \quad (3.1)$$

Equations 3.1 and 2.4 can be used to obtain the characteristic probe impedance as a function of water content. Figure 3.1 shows the results of such calculations for a variety of ratios of electrode separation to diameter (s/d). The electrode impedance varies considerably with water content, electrode diameter, and separation. It is also useful to calculate an optimum ratio of electrode separation to diameter, s/d , as

a function of soil water content. Let Z_0 in Equation 3.1 represent the characteristic impedance of the connecting transmission line, then the optimum value, s/d , is given by

$$\frac{s}{d} = \frac{1}{2} e^{\left[\frac{Z_0 \sqrt{\epsilon}}{120} \right]} \quad (3.2)$$

The optimum electrode geometrical factor, s/d , is calculated as a function of water content by using Equation 2.3 to express the dielectric constant, ϵ , in terms of the water content, θ . Figure 3.2 shows these functions for transmission lines with characteristic impedances of 50 and 256 ohm.

In practice, one electrode separation and diameter are chosen and used over the entire water content range. Thus the optimum probe separation is often determined by the particular experimental constraints such as the required sampling volume. In the following application, the separation is 5 cm and the diameter is 0.32 cm.

3.2 TDR Wave Guide Probe Lengths

An essential requirement for a water content measurement using the TDR method is the ability to identify points A and B on the wave form trace (Figure 2.2a). Point A is always identifiable and unaffected by water content or salinity. However point B can disappear (e.g., $V_R=0$) for some combinations of electrode length and bulk soil electrical conductivity. Conceptually, this occurs when the voltage pulse is completely attenuated due to the high electrical conductance of the medium. Since the energy of the pulse is fixed, the efficacy of the TDR method is dependent upon the bulk soil electrical conductivity and path length.

This dependency can also be described quantitatively. The reflected voltage decays exponentially in proportion to an attenuation coefficient, α , and path length,

2l,

$$V_R = V_T e^{(-2\alpha l)} \quad (3.3)$$

To a first approximation (Dalton et al. (1984))

$$= \frac{60\pi\sigma}{\sqrt{\epsilon}} \quad (3.4)$$

Solving Equations 3.3 and 3.4 for L yields,

$$L = \frac{\ln (V_T / V_R) \sqrt{\epsilon}}{120 \pi \sigma} \quad (3.5)$$

Using the arbitrary criteria that point B can be defined when the reflected voltage is at least 10% of the transmitted voltage, then equation 3.5 represents the maximum probe length for any given values of σ and ϵ .

Furthermore, the bulk soil electrical conductivity (σ), is defined in terms of the the water content (θ), the pore water conductivity (σ), the mineral phase surface conductance σ_s , and a tortuosity factor $T(\theta)$ by Rhoades et al. (1976) as

$$\sigma = \sigma_w \theta T(\theta) + \sigma_s \quad (3.6)$$

Equation 3.5, in conjunction with equations 3.6 and 2.4 is then used to obtain an approximation for the maximum TDR probe length for any combination of water content, pore water conductivity and soil type.

Figures 3.3a and 3.3b show such relationships using $T(\theta)$ for a fine sandy loam soil. Similar curves can be generated for a loam or clay soil using its appropriate

$T(\theta)$ relationship (Rhoades, 1976). This information provides additional design criteria for various experimental conditions.

When salinity is not a concern, the maximum probe length for the Tektronix 1502 cable tester is dependent only on water content and soil texture. Table 3.1 shows approximate probe lengths for three different soil textures over given water content ranges assuming an upper limit of pore water electrical conductivity (σ_w) of 3ds/m.

3.3 TDR Probe Interface With Cable Tester

Once the electrode is fabricated, a method for attaching the cable tester to the probe must be devised. Ultimately the parallel electrode probe must be connected to the cable tester through its 50 ohm coaxial input cable. This is accomplished in different ways depending on the constraints of each particular application. As previously discussed, the electrode impedance cannot be matched to varying soil conditions. It has been demonstrated that a 50–200 ohm impedance matching pulse transformer such as the Anzac TP103 is suitable for variations in electrode impedance encountered when making water content measurements. In this case the impedance matching transformer can be coupled directly to the TDR electrode pair by means of a "quick disconnect" type interface so as to facilitate the rapid reading of a large number of probes. Further developments in this area may reduce the need for an impedance matching transformer.

Figure 3.4 shows the design of such an interface system under test. A 3.2 mm diameter slot, 3 mm deep and 5 cm wide is milled into the solid PVC block as shown. Two thin metal strips (printed circuit) are glued to the bottom of the slot and provide electrical contact to the parallel rod electrodes by a press fit. The transformer coupling the coaxial lead wire to the metal strips is held in a 1/2 inch

PVC tube which serves as a handle. The coaxial line is constrained to the handle with a simple swagelock fitting. Elastic stays provide pressure to maintain electrical contact during measurement.

For any soil column experiment or soil surface requiring water content measurements, this method of electrode fabrication, electrode insertion and electrode interface connection is an efficient and simple solution to a host of potential problems encountered with most other methods.

Figure 3.1 TDR probe characteristic impedance as a function of water content for various s/d ratios.

Figure 3.2 TDR electrode separation to diameter (s/d) ratios as a function of water content for characteristic probe impedances of 50 ohm and 256 ohm.

Figure 3.3a. Maximum TDR probe length as a function of salinity at various water contents.

Figure 3.3b. Maximum TDR probe length as a function of water content over a wide range of soil water salinities (σ_w).

θ	SANDY LOAM	LOAM	CLAY
	----- TDR ELECTRODE LENGTH -----		
0.10	58.2	34.9	33.5
0.20	59.3	37.6	35.6
0.30	50.4	34.6	30.9
0.40	41.8	30.6	25.9
0.50	36.2	27.9	22.5

Table 1. Approximate TDR electrode lengths (cm) for three soil textures over a range of water contents assuming an upper limit of pore water electrical conductivity.

Figure 3.4 Detailed diagram of quick connect interface used for surface and lysimeter installed TDR probes. (A) one inch square PVC plastic bar with milled slot 5 cm long, 3.2 mm wide, and 3 mm deep and 1/2 inch hole to hold the handle; (B) silver metal contact strips glued to bottom of slot; (C) Handle 1/2 inch PVC plastic bar bored out to house (D) the impedance matching transformer (Adams Russell part no. TP-103); (E) tube fitting used as a cable clamp, male connector, 1/4 inch tube O.D. to 1/8 inch pipe (Swagelock cat. no. 400-1-2 or equivalent). Note fitting was back-drilled out so as to accept cable and ferrule was replaced with (F) a small piece of plastic or rubber tubing; (G) coaxial cable, 50 ohm (Belden no. 8219); (H) set screw to hold handle in place.

4. TIME-DOMAIN REFLECTOMETRY APPLICATIONS

4.1 Use Of TDR For Column Lysimeter Measurements

The TDR method for making soil water measurements is well suited for column studies where both neutron and gamma ray methods become inappropriate. In addition, there is the advantage of obtaining both water content and salinity over the same sampling volume. The fabrication of TDR probes used in column studies is unique from TDR probes designed for use in a soil profile, the later requiring considerable fabrication time. The following system was designed for an experiment using PVC lysimeters, 45 cm in diameter and 1.5 m high.

Stainless steel rods, with a specific resistance to salt corrosion (# 316), .32 cm (1/8 inch) diameter, were cut to specified lengths depending on the expected electrical conductivity of soil water in each column. Where salinity is of no concern, a 30 cm length was used. One inch square pvc bars were cut to length and then drilled to accommodate two stainless steel rods with a 5 cm separation. A curvature corresponding to the outer circumference of the lysimeters was cut into each PVC block with a band saw. The blocks were then glued to the lysimeters at specified vertical intervals. Using the holes in each pvc block as a template, holes were drilled through the PVC lysimeter itself, making it possible to simply press each electrode into the soil profile. An insertion gauge was fashioned from a solid aluminum rod with a 3 mm recess milled into one end and used to position the end of each electrode to an exact and uniform protrusion from the PVC block. A few drops of "super glue" applied to the metal electrode where it finally intersects with the PVC block provides excellent adhesion and prevents any electrode movement. Figure 4.1 shows a cross section of the final assembly.

The electrodes must be absolutely constrained from any movement or flex during

the course of the measurement as it can introduce serious errors due to air gaps (Annan, 1977). This aspect can not be over emphasized especially when using the small diameter electrodes because they are so flexible.

Insertion of the electrodes in this manner is simple and precise. It requires the least fabrication time of any known permanent installation and is easily installed after a column has been packed with soil.

Time dependent water content distribution for a large number of columns can now be easily monitored by connecting the electrode interface system to an electrode pair at any depth. Data can then be collected as discussed earlier.

4.2 Use Of TDR For Surface Measurements

The system of electrode insertion and the use of the quick disconnect head described for the lysimeter application is also ideal for rapid sampling of water content and salinity in the top soil layer (0–30 cm). When large variation of soil conditions are encountered, this technique of electrode insertion is far superior to attempting to insert a pre-assemble electrode pair. When the soil surface is hard and dry, small diameter electrodes can be inserted individually by hand where as inserting them as an assembled pair usually results in bent and broken probes. This method is also preferable when large variations in soil salinity occur and require electrode length adjustment.

The insertion technique requires a template which is placed on the soil surface and firmly constrained from any movement. The thickness is critical and five times the electrode diameter has been found to be satisfactory. The individual electrode is forced into the ground with the aid of an insertion tool machined from aluminum. A series of insertion tools are made for a variety of electrode lengths and insertion depths. Final electrode insertion is obtained exactly as described for the lysimeters, with the exception of a friction fit used in place of glue, leaving a 3 mm protrusion

for each electrode. The quick disconnect head is then used for the measurement. The electrodes are removed and the procedure repeated at the next site.

4.3 The Use Of TDR For Vadose Zone Measurements

When the electrode pairs are buried, a commercially available 256 ohm TV two inch transmission line is attached directly to the electrode pair embedded at the end of a PVC pipe of desired length (Figure 4.2). The TV cable is brought to the surface through the pipe where it is interfaced to the 50 ohm coaxial input cable. In this case the impedance matching transformer interfaces the 50 ohm and 256 ohm transmission lines and the quick disconnect becomes a banana-plug connector.

4.4 Summary

The principle of a time-domain reflectometry measurement and the use of a Tektronix 1502 cable tester as a moisture and conductivity gauge has been explained. Constraints on the separation, diameters, and lengths of TDR probes are given as a function of water content and pore water electrical conductivity. A TDR electrode insertion and cable tester quick disconnect system is described for column and field studies.

These techniques can be utilized to make rapid measurements in the field where there is a large variation in soil conditions. Temporary or permanent installations are possible with surface accessible electrodes. The ability to insert the electrodes one at a time and to select an electrode length, reduces insertion problems encountered in the field due to very hard soils or high salinities.

This method is ideally suited for studies designed to model the space and time distribution of water and salt. Since the TDR method of soil water measurements is over identical sample volumes, it eliminates uncertainties caused by spatially variable properties of soils.

Figure 4.1 Top view cross section of PVC lysimeter equipped with TDR electrode. Probes can be placed at a series of depths to characterize soil water and salinity distributions.

Figure 4.2 (A) stainless steel TDR rods; (B) metal strips soldered to TDR rods; (C) solid PVC plastic plug with milled slot and two holes to hold the TDR rods; (D) shielded transmission line; (E) epoxy poured in slot to hold assembly in place; (F) 2 inch schedule 125 PCV pipe; (G) soldered joints; Note 1: Rods A were soldered onto metal strips B and stripped leads of shield transmission line D soldered to strips B. Then rods A were placed through the holes in plug C and the slot filled with epoxy. The assembled plug was glued into the end of the PVC pipe C as shown.

5. DATA ACQUISITION AND WAVE FORM ANALYSIS

5.1 Introduction

Time-domain reflectometry waveforms are analyzed to obtain simultaneous measurements of the dielectric constant and electrical conductivity of soils. The conventional method of obtaining TDR data is to directly read data from the cable tester or to record the waveforms with an analog X-Y recorder. Waveforms recorded this way require subjectivity in reading the points needed to calculate the volumetric water content and the bulk soil conductivity. Also, at least two plots using different scales are needed to get the resolution necessary for accurate calculations with the x-y recorder. In order to increase speed and accuracy of measurements we developed a method of sampling TDR waveforms with a portable data acquisition system. Recording the data digitally for analysis with a computer program is timesaving and increases the accuracy of the measurements. An extra benefit of digitally recorded waveforms is the potential for numerical analysis of individual waveforms.

This report contains a complete method for obtaining digital TDR waveform data using a Tektronix 1502 Time Domain Reflectometry Cable Tester and a Campbell Scientific, Inc. 21X Micrologger¹. A program that analyses the waveforms and the assumptions made in order to write the program is also provided.

5.2 A Method For Obtaining A Digital Waveform

The data is recorded using a Campbell Scientific Inc. 21X micrologger in combination with the Tektronix 1502 cable tester. The micrologger utilizes burst

¹Names of products are included for the benefit of the reader and do not imply endorsement or preferential treatment by USDA.

mode software that samples an analog signal and stores the results digitally. This data is then stored on a cassette tape and later dumped to a floppy diskette through a modem.

The 21X micrologger samples the waveform at regular intervals when the 1502 cable tester is triggered. The data is then recorded in internal memory. After the burst is completed the micrologger dumps the data to tape. The micrologger is programmed to start the burst measurement as soon as the toggle switch on the cable tester is triggered. The measurement ends when the cable tester has completed one waveform. The time that the cable tester needs to complete one waveform is about 22 seconds. The 21X micrologger samples the waveform on an internal time interval. Initially this interval was set to 27.5 milliseconds, but after looking at the waveforms on the computer it was decided that a more accurate measurement was needed, 27.5 milliseconds corresponds to about 800 ($22/0.027$) data points. The internal time interval was decreased to 7.5 milliseconds which increased the number of data points to about 2900. It was found that this was the maximum number of data points possible due to the limited internal memory of the 21X micrologger.

For the detailed information on how to program the micrologger and how to connect the micrologger to the cable tester see section 10.

5.3 Method For Obtaining The Right Data Format

The data is dumped on to a cassette recorder. By using a Campbell Scientific, Inc. C20 modem and a IBM compatible personal computer it is possible to dump the data from the cassette to IBM formatted floppy diskettes. One 360 kB floppy diskette can store 5 TDR waveforms each consisting of about 2900 data points. The micrologger dumps the data in the following format:

01+0105 02-333.3

01+0105 02-310.1

All the numbers in the first column and until the 2 in the second are used by the micrologger to specify memory locations used to store the data in internal storage. This part of the data was deleted using an ASCII editor called PMATE. After cleaning up this set of numbers the five waveforms had to be separated from each other. While doing this it appeared that the micrologger started the burst measurement by measuring a series of numbers with a value between -1 and $+1$. A TDR wave form starts with a value of about -350 depending how the waveform was located on the cable tester screen. After deleting all the data which did not belong to the wave form, each wave form is stored in a separate file. Then each of the data points is numbered, this is done by using a simple Fortran program called TDRED.FOR (see section 11). This program adds the data point numbers and writes the data to a file that the TDR program uses as an input file, the data is in (x,y) coordinates in the following FORTRAN 77 format (F9.0,F12.3). First the number of the data point (x), an integer, and then the vertical amplitude value (y) of the data point.

5.4 The TDR Program

The program is written to perform two functions. (1) To generate an output file in which the points of a TDR waveform are stored as reflection coefficient (ρ) versus time and (2) to calculate the volumetric water content and the bulk conductivity of the soil medium.

To do the first step one must understand how the 21X micrologger digitizes the analog waveform generated by the TDR cabletester. The micrologger samples the analog waveform at regular internal time intervals. At each of these time intervals the micrologger samples the relative vertical amplitude of the dot on the TDR screen. The value it records corresponds to the relative position on the screen in

comparison to the divisions on the screen. The micrologger sees each division as about 100 mV. Figure 5.1. shows an example of how the waveform is recorded.

In figure 5.1, seven points are shown which are located by the program, points A to G. These are the points on the waveform used by the program for calculating the volumetric soil water content and the bulk soil conductivity:

Point A represents the lowest value on the base value line on which all reflections are superimposed.

Point B is the transformer maximum, this point is a common point on all the waveforms, it is part of the measuring device and it is not influenced by the soil. This makes the transformer maximum a convenient point to use in locating where the voltage pulse enters the soil.

Point C is the point where the voltage pulse enters the soil, the program sets the time value of this point to zero ($t = 0$).

Point D is where the voltage pulse has reached the end of the wave guide and where the pulse is reflected back towards the cable tester. Here the time is equal to t ($t = t$).

Point E is the point of the wave form where the reflected voltage is measured. This point is taken to be $2t$. This measurement is used for calculating the attenuation coefficient used to calculate the bulk soil conductivity.

Point F is the start of the rise step of the voltage.

Point G is the end of the step rise of the voltage. The peak after G is due to a poor connection adapter for the 50 Ω precision cable to the cable tester.

Each time the program is run it uses four files. It reads a waveform in from the previously prepared INPUT FILE in which the waveform is stored as (x,y) coordinates. This INPUT FILE is specified by the user. It writes the rescaled waveform in (ρ, t) coordinates to an OUTPUT FILE also to be specified by the user. The values of the dielectric constant (ϵ), the soil water content (θ_v) and the bulk

soil electrical conductivity (σ_b) are written to a file named TDRRHO1.PRN. Each time it is run the program adds the calculated values to this file. The program also writes the values it uses to locate points A to G and some other values used to check for input errors to a file called CALC.CAL. See section 11.. for examples of these files.

The program has 17 steps. Each step is briefly explained in the program which is given in section 12. The following is a brief explanation of the assumptions made in the program to calculate the required values.

Before the program starts to look for the points A to E, it first finds the position of the step rise of the voltage, from points F to G. This is a convenient starting point for the search for the other points. MINFLX is the x coordinate of the first point of the waveform which has a slope larger than 2 (point F). This is considered to be the beginning of the step rise of the waveform. MAXFLX is the x coordinate of the first point after MINFLX with a slope smaller than 2 (point G). This is considered the beginning of the flat part of the waveform which is the reflection of the 50 Ω impedance cable connecting the sampling head to the cable tester. This part of the curve will be called the baseline as opposed to the basevalue line (points A to G) which is the part of the waveform on which all the reflections are superimposed. The slope of the waveform is calculated by using the forward difference formula:

$$f'(x) = \frac{f(x+h) - f(x)}{h} \quad (5.1)$$

The rest of the points are found by using the waveform analysis of Dalton and van Genuchten (1986).

The timescale is calculated by first calculating the distance that the voltage pulse has travelled using the datapoint number and then calculating the time needed to travel this distance. The micrologger sampled the waveform at a regular time

interval (27.5 or 7.5 milliseconds). Each 27.5 or 7.5 millisecond interval corresponds to a distance interval on the cable tester scale. This distance interval was calculated by measuring the known length of a test cable and counting the number of measurements made on the cable. The distance factor is calculated as the length of the cable divided by the number of measurements (points). For the 27.5 milliseconds interval the factor was measured to be 1.4286 cm per interval and for the 7.5 milliseconds interval it was 0.3940 cm per interval.

The transformer maximum, TRAMAX is identified as the highest point of the waveform between the baseline and the minimum of the waveform, MIPULX where the reflection occurs. This minimum is the lowest value of the waveform between the transformer maximum and the tail end. XTRA, the actual x-coordinate measured as a real number, is the interpolated transformer maximum determined by using a cubic spline interpolation of the integer points in the vicinity of the observed maximum. The point where the voltage pulse enters the soil, XNUL, for this particular head, was found by comparing the divergence of several waveforms, to be 13.0694 cm from the transformer maximum, XTRA. XNUL is calculated using XTRA, the distance from XTRA and the distance factor. To go from distance to time values, the relation $t=2l/c$ is used where l is the electrode length and c is the velocity of light and that the dielectric constant on the cable tester is set to be equal to 1.

The volumetric soil water content (θ_v) and the bulk soil conductivity (σ_b) are calculated as outlined in section 1 using the following equations:

$$\epsilon = \left[\frac{ct}{2L} \right]^2 \quad (5.2)$$

$$\theta_v = \frac{(-530 + 292\epsilon - 5.5\epsilon^2 + 0.043\epsilon^3)}{10000} \quad (5.3)$$

$$\sigma_b = \frac{\sqrt{\epsilon}}{120 \pi L} \ln \left[\frac{V_t}{V_r} \right] \quad (5.4)$$

where:

- ϵ : The real dielectric conductivity of the soil.
- c : The speed of light in vacuum, $c = 3 \times 10^8 \text{ ms}^{-1}$.
- t : The time it takes for the pulse to reach the end of the wave guide. (This is the minimum of the waveform after the transformer maximum.)
- L : The length of the electrodes used (m).
- θ_v : The volumetric soil water content.
- σ_b : The bulk soil conductivity (dSm^{-1}).
- V_t : The transmitted voltage (V).
- V_r : The reflected voltage (V).

In the program the ratio $\frac{V_t}{V_r}$ is take to be equal to $\frac{\rho_t}{\rho_r}$ because ρ is linearly dependent on the voltage.

5.5 SUMMARY

This section gives details for obtaining a digitized TDR waveform. A computer program is developed to identify critical parameters in the wave form which are necessary calculating water content and electrical conductivity. The advantage of obtaining the data in this fashion is that measurements are standardized and therefore more accurate due to the higher resolution of the obtained waveforms. The data is in a form which is easier to manipulate so the speed of interpreting the waveforms is increased.

Figure 5.1. TDR waveform in Input format. Points A to G are the points the program uses to calculate the soil water content and electrical conductivity.

6. FURTHER RESEARCH ON THE EFFECTS OF SALINITY AND TEMPERATURE ON TDR MEASUREMENTS

6.1. Introduction

Time Domain Reflectometry is a technique that is being developed for measuring soil water content and bulk soil electrical conductivity simultaneously. The TDR-method uses a single probe and measures the volumetric water content and bulk electrical conductivity in the same soil volume. In the past, in-situ measurements of water content and salinity have utilized different principles and different instrumentation for each measurement.

This report contains results of an extensive laboratory experiment designed to understand those principles important in obtaining accurate TDR measurements.

6.2. Materials And Methods.

Sixty PVC columns hand packed with a Pachappa sandy loam soil were used for this experiment. The preparation of these columns is explained by Dalton (1987). The current study used electrodes of 24 cm in length instead of 30 cm and the height of the soil column is 35 cm instead of 30 cm.

Time Domain Reflectometry (TDR) measurements were made on these columns at 5 different temperatures (8, 15, 25, 28 and 35° Celsius). The TDR waveforms were recorded using a setup similar to the one shown in Figure 6.1.

Initially the waveforms were recorded by using a Tektronix S-52 pulse generator, 7S12 sampling unit, S-6 sampling head and a 7603 oscilloscope together with a Gould ComputagraphTM II analog x-y recorder¹. In addition the waveforms

¹Names of products are included for the benefit of the reader and do not imply

were digitized and analyzed with computer aided techniques (Sections 10, 11, 12).

To obtain the digital waveforms a Tektronix 1502 TDR cable tester was used together with a Campbell Scientific Inc. 21X micrologger. Only three of the five temperature measurements were taken digitally (28, 15, 25° Celsius), however, each of the five measurements at different temperatures were also taken in the original manner. The digitally recorded data from the 28°C measurement was discarded because of insufficient resolution for accurate measurements (800 data points per waveform). For the other two temperatures the resolution was increased to 2700 data points per waveform which improved the waveform analysis significantly. Before recording a waveform the temperature of the soil in the column was measured, in order to obtain the temperature dependence of the TDR measurements of water content and bulk soil electrical conductivity.

In addition to the TDR measurements a low frequency resistance measurement was made on each column. The cell constant of a TDR electrode pair was determined, and then the resistance was measured using a standard one kilohertz impedance bridge.

After all the waveforms were recorded, each column was intensively sampled for gravimetric soil water content and electrical conductivity of the soil water extract. The moisture content and the soil water electrical conductivity were sampled at 4 depths: 0–8 cm, 8–16 cm, 16–24 cm and 24–35 cm. The bulk density was measured as the average of the total column.

A 2 cm diameter core sample was taken from the center of each column exactly between the two electrodes. This sample was divided into the different depths and for each depth the gravimetric soil water content was determined. After the core sample was taken, another larger bulk sample of each depth was taken by

endorsement or preferential treatment by USDA.

digging it out of the column to each depth and then mixing to obtain a homogeneous sample. From this sample the gravimetric water content and the electrical conductivity of the soil water extract was measured.

The electrical conductivity of the soil water was measured on an extract obtained by centrifuging the moist soil for 45 minutes at 3500 rpm. The EC of this extract was measured by using a salinity drop tester. Because no extract could be obtained from the columns which were brought to a volumetric moisture content of 10%, the electrical conductivities of the soil water was determined by using saturation extracts.

6.3 TDR Measurements

6.3.1 Water Content

Water content measurements were made using the standard TDR techniques discussed in detail in sections 1 and 4. The travel time of an electromagnetic pulse is measured and related to the dielectric constant by,

$$\epsilon = \left[\frac{ct}{L} \right]^2 \quad (6.1)$$

where c is the velocity of light in vacuum, t is the travel time of the electromagnetic pulse over a path length L . L is twice the TDR probe length l , $L=2l$. We use the empirical relationship between ϵ and the volumetric soil water content θ_v obtained by Topp et al. (1980),

$$\theta_v = \frac{(-530 + 292\epsilon - 5.5\epsilon^2 + 0.043\epsilon^3)}{10000} \quad (6.2)$$

6.3.2 Bulk Soil Electrical Conductivity

The bulk soil electrical conductivity was measured with a standard impedance bridge at one kilohertz and compared to the TDR method using the method proposed by Dalton et. al where the bulk soil electrical conductivity, σ_b , is given by,

$$\sigma_b = \frac{\sqrt{\epsilon}}{120 \pi L} \ln \left[\frac{V_t}{V_r} \right] \quad (6.3)$$

Where:

σ_b is the bulk soil conductivity in dSm^{-1} .

L is the length of the electrodes in m.

ϵ is the real part of the complex dielectric constant.

V_t is the transmitted voltage in V.

V_r is the reflected voltage in V. (see figure 3.1)

6.4 Results: TDR Measured Water Content

The digital waveforms which are used are those recorded from the sixty columns at 15 and 25°C. The waveforms recorded at 28°C were not used because the resolution of these waveforms (800 data points per waveform) was insufficient. A computer program was used to analyze the waveforms to obtain the volumetric water content, θ_v and the bulk electrical conductivity, σ_b of the soil (Section 12).

The TDR measured volumetric soil water content in each column is compared to the volumetric water content of the same column calculated from the measured gravimetric water content and bulk density. This comparison is made with the core samples and the bulk samples. In figure 6.2 the relationship between θ_v of both the bulk samples and the core samples is shown. θ_v of the bulk sample

appears to be consistently lower than θ_v of the core sample. This might have been caused by the sampling method where there was a possibility of evaporation.

In figures 6.3 and 6.4 the TDR-measured θ_v is compared to the gravimetrically measured θ_v determined on the bulk(average) samples and core samples. The comparison of the TDR measured θ_v with the gravimetric measured θ_v of the bulk sample also indicates that there has been a larger source of error in the sampling technique of the bulk sample than the core sample.

A very good correlation between the TDR measured θ_v and the gravimetric measured θ_v is found for the core samples, however substantial scatter exists in the data of the TDR-measured θ_v . This scatter increases with increasing water content and with increasing bulk electrical conductivity. The origin of this scatter will be discussed in more detail in section 8. However we can note here that the waveform minimum used to determine water content becomes less well defined as the water content or electrical conductivity increases (Figure 6.5). For low water contents and low bulk soil electrical conductivities the minimum is clearly defined. These differences will be attributed to the effects of electrical conductivity on the propagation velocity of the electromagnetic pulse, (dispersion).

As the figures show, the measurements of the dielectric constant and thus of the volumetric water content are better for the data obtained from waveforms recorded at 15°C than data from the waveforms recorded at 25°C. The conductivity of the soil decreases as the temperature decreases resulting in reduced dispersion. This holds true for all the temperatures which were included in this experiment, the recordings at 8°C had the most pronounced reflections. The ones recorded at 35°C had the least pronounced reflections and thus the highest amounts of dispersion.

6.5 Results: TDR Measured Bulk Soil Electrical Conductivity

The TDR measured bulk soil electrical conductivity is compared to the

electrical conductivity determined using a standard 1kHz impedance bridge.

Conductivities were calculated using the measured electrode resistance and a cell constant for the electrode pair of 57.3 m^{-1} .

The conductivity has a known temperature dependence of about 2% per degree, and can be factored into the TDR measured electrical conductivity as,

$$\sigma_b = T_c \sigma \quad (6.4)$$

where σ is the uncorrected measurement of electrical conductivity and T_c is the temperature correction factor;

$$T_c = 1 + 0.02(25-T) \quad (6.5)$$

where T is the soil temperature in degrees Celsius.

In figure 6.6a and 6.6b the relationship between the TDR determined σ_b and the 1 kHz bridge is shown for both temperatures. For low conductivities the correlation is very good but as the conductivity increases so does the scatter. The best linear fit of the data obtained from the waveforms recorded at 25°C shows a large deviation from the 1:1 relationship.

6.6 Summary

TDR measurements of both water content and bulk soil electrical conductivity give good correlations with the standard and independent measurements (eg. gravimetric and conductivity bridge measurements respectively). Comparing TDR water content measurements at 15°C and 25°C shows a negligible temperature effect on the effective dielectric constant. The bulk soil electrical conductivities are normalized to 25°C but using the known temperature dependence

of the liquid phase component of the soil media. Comparison of the temperature normalized data shows a good 1:1 correlation at 15°C and 25°C. The anomalous data points in figure 6.6b should be discarded because of uncertainty in wave form interpretation but are included for the sake of completeness.

The tendency for increased scatter in the TDR water content measurements at high salinities is discussed in section 9.

Figure 6.1. Example of a TDR-measurement setup. The TDR-unit contains the pulse generator, the pulse sampler and and a display. The impedance matching transformer is built in the sampling head. From Dalton et al. 1986.

Figure 6.2. Volumetric water contents of the average samples plotted against the core samples.

Standard errors:

intercept: $\pm 1.276E-02$

slope: $\pm 5.350E-02$

estimate: $\pm 3.588E-02$

15 degrees Celsius

Figure 6.3a: Volumetric water content determined with the TDR-method (equation 5.3) for the wave forms recorded at 15°C, compared to the gravimetric determined volumetric water content of the average samples..

Standard errors:

intercept: $\pm 1.398E-02$ slope: $\pm 6.001E-02$ estimate: $\pm 4.063E-02$

Figure 6.3b: Volumetric water content determined with the TDR-method (equation 5.3) for the wave forms recorded at 25°C, compared to the gravimetrically determined water content of the average samples.

Standard errors:

intercept: $\pm 1.960E-02$

slope: $\pm 8.489E-02$

estimate: $\pm 5.665E-02$

15 degrees Celsius

Figure 6.4a: Volumetric water content determined with the TDR-method (equation 5.3) for the wave forms recorded at 15°C, compared to the gravimetrically measured volumetric water content of the core samples.

Standard errors:

intercept: $\pm 8.955E-03$ slope: $\pm 3.756E-02$ estimate: $\pm 2.519E-02$

25 degrees Celsius

Figure 6.4b: Volumetric water content determined with the TDR-method (equation 5.3) for the wave forms recorded at 25°C, compared with the gravimetrically measured volumetric water content of the core samples.

Standard errors:

intercept: $\pm 1.619E-02$ slope: $\pm 6.852E-02$ estimate: ± 0.0452

Figure 6.5: Examples of TDR-waveform attenuation due to differences in water content and electrical conductivities.

15 degrees celsius

Figure 6.6a: Bulk electrical conductivity determined with TDR and the attenuation model (equation 5.4) measured at 15°C, versus the bulk electrical conductivity determined with the standard 1 kHz impedance bridge.

Standard errors:

intercept: $\pm 4.005E-02$ slope: $\pm 4.854E-02$ estimate: ± 0.169

25 degrees celsius

Figure 6.6b: Bulk electrical conductivity determined with TDR and the attenuation model (equation 5.4) measured at 25°C, versus the bulk electrical conductivity determined with the standard 1kHz impedance bridge.

Standard errors:

intercept: ± 0.404 slope: ± 0.489 estimate: ± 1.702

7. TDR WATER CONTENT INTEGRATION

7.1 Introduction

Previous laboratory work with time-domain reflectometry (TDR) has been in soil columns of uniform water content distribution. To evaluate how volumetric moisture content is integrated over the length of a TDR electrode, an experiment was conducted with a soil moisture profile that varied with depth. Comparisons between waveforms from uniform and non-uniform soil moisture profiles may prove useful in determining moisture content distribution using TDR.

7.2 Methods

Air dried Pachappa Sandy Loam soil was packed in four PVC columns (35cm high X 10cm diameter) to a bulk density of 1.4 gcm^{-3} . Water was then added to the surface in an amount equivalent to 15% volumetric water content (θ_v), and the columns were left to equilibrate for 3 days. On day three, an additional 5% θ_v equivalent of water was added at the surface. At specified time intervals after surface water had disappeared, TDR measurements were made with 30 cm length TDR probes. Immediately after a TDR measurement, the column was cored and sampled at 2 cm increments over the length of the electrodes. The time intervals were 00:26, 1:00, 2:00 and 3:22 hours after ponding ceased. Gravimetric water content measurements of the soil core increments were converted to θ_v and compared with θ_v values obtained from the TDR waveform.

7.3 Results

Figure 7.1 shows the water content distribution at each TDR measurement. Water contents are somewhat uniform up to the wetting front and varies between

about 33% and 38%. A steep gradient develops near the end of the electrodes where the water content becomes again uniform at about 3%. Thus, water contents over the length of the electrodes varied from 38% at the top to 2% at the bottom. The 2-cm incremental soil moisture samples were averaged over the 30-cm length of the electrodes to obtain a profile average θ_v . Table 7.1 shows the gravimetric determined average water content and the TDR determined water content. TDR appears to average accurately despite very large gradients in water content.

Table 7.1 Average volumetric water contents measured gravimetrically and with TDR probes

Column	Mean Volumetric Water Content (θ_v)		Standard Error
	gravimetric (%)	TDR (%)	
1	22.9	21.8	0.55
2	24.7	23.4	0.80
3	23.5	23.4	0.05
4	22.8	22.8	0.00

Figure 7.1. Water content distributions of the four columns with depth

8. ALTERNATIVE TECHNIQUE FOR TDR MEASUREMENT OF BULK SOIL ELECTRICAL CONDUCTIVITY AND SALINITY

8.1 Introduction

The TDR technique used for determining the bulk soil electrical conductivity is based on the analysis of wave propagation along an unloaded transmission line as indicated in Figure 8.1. The cable tester is schematically represented by the voltage source V and cable impedance Z_0 . The TDR wave guide probe is shown as an unloaded wave guide of impedance Z_1 . Concepts of wave velocity and dissipation along the wave guide were used to infer the bulk soil electrical conductivity, (Dalton et. al 1984). While it has been recently pointed out by Yanuka et al(1988), that the value for reflected voltage used in this calculation is not the true value because of multiple internal reflections, the correction must be a small one since Daltons method gives an excellent correlation with independent measurements of the bulk soil electrical conductivity.

In this section a transmission line analysis is given that allows for an alternative method of using a TDR wave form to calculate the bulk soil electrical conductivity. This analysis approaches the probleming from the point of view of a loaded transission line as depicted in Figure 8.1.

8.2 The Loaded Transmission Line

Figure 8.1 shows both loaded and unloaded transmission lines. Previous analyses were based on the unloaded transmission line where the effect of the dielectric constant on the electromagnetic transit time is emphasized. When the TDR probe is analysed as a load impedance at the end of a coaxial cable, transit times are not considered. We are only interested in the reflection coefficient, ρ ,

after all possible multiple reflections. As discussed previously, the cable tester gives a direct readout of the reflection coefficient and is ideally suited for this measurement. The soil system is assumed to be a simple load resistance at the end of the cable tester input cable. A reflection coefficient ρ , is given in terms of the cable impedance Z_0 and the load impedance Z_1 ,

$$\rho = \frac{Z_1 - Z_0}{Z_1 + Z_0} \quad (8.1)$$

Rewriting equation 8.1 gives the load impedance in terms of the measured reflection coefficient and the known impedance of the TDR input cable,

$$Z_1 = Z_0 \left[\frac{1 + \rho}{1 - \rho} \right] \quad (8.2)$$

The bulk soil electrical conductivity, σ , is related to the load impedance by,

$$\sigma = \frac{K}{Z_1}, \quad (8.3)$$

where K is the cell constant for the TDR probe. Rewriting equations 8.3 and 8.2 yields,

$$\sigma = \frac{K}{Z_0} \left[\frac{1 - \rho}{1 + \rho} \right] \quad (8.4)$$

The bulk soil electrical conductivity is now defined in terms of a known cell constant, and input cable impedance. The reflection, ρ , can now be approximated with the cable tester and correlated with in-situ measurement. As before the

temperature dependence of the electrical conductivity can be corrected for by the 2% per degree increase according to the compensating factor T_c ,

$$\sigma_c = T_c \sigma \quad (8.5)$$

where T_c is given by equation 6.5 is the uncompensated measurement of the bulk soil electrical conductivity.

8.3 Calibration Of Sampling Head

The sampling head which connects the cable—tester's coaxial cable to the parallel wire TDR probe is shown in Figure 8.2. There is a large difference between the 50 ohm impedance of the coaxial cable connecting the sampling head to the cable tester (50 Ω) and the impedance of the parallel rod wave guide in the soil. When the pulse reaches the interface between the cable and the wave guide, much of the energy in the pulse would be lost due the large impedance difference between the cable and soil, making the measurements more difficult. To solve this problem a low loss impedance matching transformer is connected to the end of the coaxial cable just before the interface of the cable and the wave guide inside the sampling head (see figure 8.2). This tends to balance the coaxial cable with the TDR wave guide, but since the impedance of the soil will change with water content and salinity it is nearly impossible to have an exact match.

Using the impedance matching transformer reduces the energy loss but changes the value of the reflection coefficients in the transmission line after the transformer. In order to correct for known and unknown artifacts of the system, all measured reflection coefficients are made relative to the reflection coefficients for the two extremes of possible load impedances. That is, by equation 8.1, for an open transmission line, the load impedance is much greater than Z_0 , and $\rho = 1$. For a

shorted transmission line, the load impedance approaches zero and $\rho = -1$. When the line impedance matches the load impedance $Z_0 = Z_1$ and $\rho = 0$. Figure 8.3 shows the results of such a head calibration and is used in subsequent measurements of ρ for soils at various water content and salinities. In practice a long time value of ρ is used (average value between 20 and 45 ns) and scaled according to the upper and lower limits of ρ shown in Figure 8.3.

8.4 Results

Figure 8.4 show the results of plotting the quantity $(1-\rho)/(1+\rho)$ as a function of bulk soil electrical conductivity measured with a 1 kHz impedance bridge. ρ was measured at the tail end of the waveform at the average between 20ns and 45 ns. By assuming that the intercept can be neglected, and using equations 8.4 and 8.5, the the inverse of the slope is equal to $\frac{K}{Z_0} T_c$. Solving for K gave 58.829 m^{-1} for 15°C waveforms and 54.469 m^{-1} for 25°C waveforms. The average, 56.649 m^{-1} was close to 57.3 m^{-1} which was the cell constant used for the 1 kHz bridge measurements. Because these values are similar and only one electrode pair was used to measure the cell constant it was assumed reasonable to use the same cell constant for both measurements. This also seems logical because the same electrodes were used for both the 1 kHz bridge and the TDR measurements.

Figure 8.5a and 8.5b show the comparison between σ with equation 8.5 and σ measured with the 1 kHz bridge at 15 and 25°C . Both figures show a very good correlation. The best line fit on the data obtained from the 15°C waveforms varies only slightly from the 1:1 line.

Since the salinity of the soil water is of more interest than the bulk soil electrical conductivity, the electrical conductivity of the soil water extract is calculated according to a method proposed by Rhoades et al. (1988). The proposed method is

based on a multiple pathway model for the electrical conductance. This model results in the following formula:

$$\sigma_b = \left[\frac{(\theta_s + \theta_{ws})^2 \sigma_s \sigma_{ws}}{\theta_s \sigma_{ws} + \theta_{ws} \sigma_s} \right] + (\theta_w - \theta_{ws}) \sigma_{wc} \quad (8.6)$$

where:

σ_s is the electrical conductance of the solid phase of the soil.

σ_{ws} is the electrical conductance of a series coupled pathway of the soil and water in a "immobile phase" (not the same as the immobile phase for flow problems).

σ_{wc} is the conductivity of the continuous current pathway in the soil water, similar to a "mobile phase".

θ_s is the solid fraction of the soil.

θ_{ws} is the fraction of the water in the series coupled pathway.

θ_w is the fraction of the total water in the soil.

Rhoades et al. fitted this model to data obtained from very precise measurements to get the parameters needed for the equation 8.6. For undisturbed Pachappa soil samples these empirically determined parameters are:

$$\sigma_s = 0.22 \text{ dSm}^{-1}$$

$$\theta_s = 0.574$$

$$\theta_{ws} = 0.45082 \theta_w^{0.64763}$$

Since the columns were allowed to equilibriate for more than a week it is a safe to assume that $\sigma_{ws} = \sigma_{wc}$ which is equal to the electrical conductivity of the soil water extract σ_w .

In figure 8.6 the relationship between the TDR determined σ_b and the σ_b

according to equation 8.6 is shown. Even though there is some scatter, there is a definite correlation between the two methods. The reason for the difference of the best fitted line from the 1:1 relationship could be due to the fact that the parameters fitted for the Pachappa soil were obtained from undisturbed field samples. In this experiment hand packed screened Pachappa soil is used. For better results the parameters for equation 4.1 need to be determined more accurately for the column system.

8.5 Summary

The results presented thus far show that Time Domain Reflectometry is a very promising method for the simultaneous measurement of water content and salinity in soils. The data show that there is a good correlation between water content and the effective dielectric constant of the media. However, difficulty in interpreting waveforms from measurements made in conductive media still needs attention and is addressed in the next section. The methods proposed in this report for measuring the electrical conductivity of soils is equivalent to those measured by standard low frequency bridges. The method described in this section is appealing because it is independent of a dielectric constant measurement as is required in the previous method.

CONDUCTIVITY MEASUREMENTS BY LOADED TRANSMISSION LINE ANALOGY

Figure 8.1 Schematic of an unloaded and loaded transmission line used for the analysis of the response of TDR probes to water and salinity.

Figure 8.2 Schematic of sampling head used to connect cable tester to TDR probes.

Figure 8.3: Plots of wave forms recorded from the sampling head with transformer not connected to a waveguide.

Figure 8.5a: Bulk electrical conductance determined with TDR and the resistance model (equation 8.5) from wave forms recorded at 15°C versus bulk electrical conductance measured with the standard 1 kHz impedance bridge.

Standard errors:

intercept: $\pm 2.271\text{E-}02$

slope: $\pm 2.752\text{E-}02$

estimate: $\pm 9.572\text{E-}02$

15 degrees celsius

Figure 8.4a: $\frac{1-\rho}{1+\rho}$ obtained from the wave forms recorded at 15°C versus the bulk electrical conductivity measured with the standard 1 kHz impedance bridge.

Standard errors:

intercept: $\pm 2.361\text{E-}02$

slope: $\pm 1.034\text{E-}02$

estimate: $\pm 9.942\text{E-}02$

25 degrees celsius

Figure 8.4b: $\frac{1-\rho}{1+\rho}$ obtained from the wave forms recorded at 25°C versus the bulk electrical conductivity measured with the standard 1 kHz impedance bridge.

Standard errors:

intercept: $\pm 2.364\text{E-}02$

slope: $\pm 7.978\text{E-}02$

estimate: $\pm 9.938\text{E-}02$

Figure 8.5b: Bulk electrical conductance determined with TDR and the resistance model (equation 8.5) for wave forms recorded at 25°C versus bulk electrical conductance measured with the standard 1 kHz impedance bridge.

Standard errors:

intercept: $\pm 2.473E-02$

slope: $\pm 2.998E-02$

estimate: ± 0.104

TDR versus lab results (+ dry soils!)

Figure 8.6: Bulk electrical conductivity with TDR versus bulk electrical conductivity calculated with equation 8.6.

Standard errors:	15°C	25°C
intercept:	$\pm 3.165E-02$	$\pm 3.768E-02$
slope:	$\pm 4.564E-02$	$\pm 5.435E-02$
estimate:	± 0.1237	± 0.1473

9. THEORETICAL ANALYSIS OF THE EFFECT OF SALINITY ON TDR WATER CONTENT MEASUREMENTS

9.1 Introduction

Extensive laboratory investigations reported on thus far indicate that at moderate salinities there appears to be a significant affect on TDR water content determinations. This section attempts to explain these observations on the basis of dispersion phenomena of electromagnetic propagation in a conductive media.

9.2 Experimental Observations

Experimental results show a good correlation between TDR determined water content and gravimetric water content over a wide rage of pore water salinities. Figure 9.1 shows the composite results of TDR water contents determined in soil columns using waters at ten different salinities for each targeted water content. However, the deviations of the data from the regressed line is seen to increase as the water content and pore water salinity increases. Figures 9.2 –9.11 show individual regressions for TDR water content determinations for each of the ten saline waters used. While the regressions are quite good, the deviation from the one-to-one correlation line is seen to increase with increasing pore water salinity. The deviation in measured water content appears to increase with an increase in both the water content and pore water salinity. We can emphasize the dependency by creating a scatter graph of the standard error, (measured θ – true θ) as a function of the bulk soil electrical conductivity. Figure 9.12 shows such a graph and it becomes immediately apparent that an overestimation of water content is

likely when the bulk soil electrical conductivity is greater than 0.6 dS/m.¹

9.3 Effect Of Ionic Strength On Dielectric Constant

The apparent overestimation of water content by TDR measurements at high salinities means that the effective dielectric constant of the soil is greater than expected. However, it is known that the presence of ions in liquid water tends to decrease the polarization of the of the medium under the applied field and should result in a lower effective dielectric constant. The smaller polarization and lower dielectric constant would be equivalent to a lower water content. Therefore on the basis of this physical reasoning one would expect an underestimation of water content with increasing electrolyte concentration. The observations shown in Figure 9.12 indicate that some other phenomena is dominant over the known ionic effects on the dielectric constant since the exact opposite is observed.

9.4 Dispersion And Its Effect On Electromagnetic Propagation

As a possible explanation of the overestimation of the effective dielectric constant at elevated bulk media electrical conductivity, it will be instructive to analyze the propagation of electromagnetic waves in a conductive media. A differential element of the wave guide is shown in Figure 9.13. The governing equations in the frequency domain (using complex notation) describing the time and position relationships of the voltage and current in this circuit are:

$$V(z,t) = Re V(z)\exp(j\omega t) \quad (9.1)$$

¹From this scatter graph one might argue that below 0.6dS/m TDR underestimates soil water content. It is more likely that the line indicating zero error is biased upward by about one percentage unit due to the regression model used to calculate water content coupled with the subjectivity of picking the appropriate wave form parameters.

$$I(z,t) = \text{Re } I(z) \exp(j\omega t) \quad (9.2)$$

$$\frac{\partial V}{\partial z} = -(R + j\omega L) I(z) \quad (9.3)$$

$$\frac{\partial I}{\partial z} = -(G + j\omega C) V(z) \quad (9.4)$$

then,

$$\frac{\partial^2 V}{\partial z^2} = \gamma^2 V \quad (9.5)$$

where,

$$\gamma = \sqrt{(R + jL\omega)(G + jC\omega)} = \alpha + j\beta \quad (9.6)$$

γ is a complex function consisting of real and imaginary components. α and β are the attenuation and phase functions respectively. For the set of equations 9.1 to 9.6, V and I are the voltage and currents respectively. R is the electrode skin resistance, L , the inductance, G , the conductance and C , the capacitance. ω is the frequency and $j = \sqrt{-1}$. γ is the propagation constant composed of a real and imaginary component. For a TDR electrode system R is generally negligibly small. L , G and C are determined for a parallel rod array and the attenuation coefficient, α , is determined (chapter x). The imaginary component is used to describe the phase velocity, which in general is frequency dependent. We now consider the lossless and dissipative cases for the TDR parallel rod wave guide. The phase velocity, v_p , is given in terms of the frequency and phase factor as,

$$v_p = \frac{\omega}{\beta} \quad (9.7)$$

For the lossless line case, the skin resistance and conductance between the TDR

probes is zero, in which case,

$$\beta = \omega(LC)^{1/2} \quad (9.8)$$

and the phase velocity becomes,

$$v_p = \frac{1}{(LC)^{1/2}} \quad (9.9)$$

For non magnetic material equation 9.9 reduces to the familiar $v_p = c/\sqrt{\epsilon}$, used in the previous sections. It is noted that for the lossless case the phase velocity is indeed independent of frequency. For the more general case of a dissipative line, where the conductance between the TDR electrodes increases with salinity and water content, $G \neq 0$, then,

$$\beta_D = \omega(LC)^{1/2} \cosh \left[\frac{-q}{2} \right] \quad (9.10)$$

where

$$\sinh q = \frac{G}{C\omega} \quad (9.11)$$

Then the phase velocity becomes

$$v_p = \frac{1}{(LC)^{1/2} \cosh \left[\frac{-q}{2} \right]} \quad (9.12)$$

Equations 9.11 and 9.12 show that for a dissipative media, the phase velocity is frequency dependent and affected by the conductivity and capacitance of the media. The effect of frequency on the phase velocity relative to the phase velocity in the

lossless line is obtained by defining a phase velocity retardation factor, Γ , in terms of the ratio of phase factors for the lossless and dissipative conditions;

$$\Gamma = \frac{\beta}{\beta_D} \quad (9.13)$$

The general phase velocity is then given as,

$$v_p = \Gamma(c/\sqrt{\epsilon}) \quad (9.14)$$

The retardation factor is given in terms of the bulk soil electrical conductivity, the effective dielectric constant, and the frequency of the electromagnetic radiation. Figure 9.14 gives the calculated relationship between the retardation factor, Γ , and frequency for three values of the ratio of the bulk soil electrical conductivity and dielectric constant, σ/ϵ . It is seen that the higher the ratio σ/ϵ , the higher is the frequency at which the velocity becomes retarded with respect to the lossless transmission line. That is to say that the fourier components of the TDR pulse are affected differently depending on the ratio σ/ϵ . The higher the electrical conductivity the larger is the fraction of the frequency spectrum making up the TDR pulse that has its velocity of propagation retarded with respect to ideal conditions. When the velocity of propagation is retarded, the transit time along the TDR probe is decreased. This decrease in transit time is interpreted as a higher effective dielectric constant which is equivalent to a higher water content. This physical explanation of the apparent overestimation of TDR measured water contents at moderate salinities is further verified by replotting the standard error of the TDR water content measurement (Figure 9.12) as a function of the ratio the bulk soil electrical conductivity and the effective dielectric constant (as suggested

from Figure 9.14). The results of this relationship are shown in Figure 9.15 and a critical value for the ratio of σ/ϵ (similar to Figure 9.14) is observed above which an overestimation of water content occurs. This observation is a strong indication that the phase velocity used to calculate the effective dielectric constant is in fact retarded, not only at high salinities but also at low water contents.

9.5 Summary

Time-domain reflectometry overestimates soil water content at moderate to high salinities. The pulse transit time is a measure of the effective dielectric constant of the soil is directly proportional to water content. The known effects of salinity on the dielectric constant predicts a lower dielectric constant and therefore an underestimate of water content. An analysis of electromagnetic propagation in a conductive medium shows that the velocity of the TDR pulse is retarded. The lower velocity means a longer transit time in the TDR probe and is interpreted as a higher dielectric constant and bulk soil electrical conductivity. Combining information on bulk soil electrical conductivity with water content determinations should allow one to correct for the phase velocity retardation, dielectric constant, and finally the measured water content.

Figure 9.1. Volumetric water content determined gravimetrically ($\theta_g \times \rho_b$) related to TDR measured volumetric water content for soils having six different target water contents and ten different target bulk soil salinities.

Figure 9.2. Volumetric water content determined gravimetrically ($\theta_g \times \rho_b$) related to TDR measured volumetric water content for soils brought to six different target water contents with irrigation water of 1 dS/m.

Figure 9.3. Volumetric water content determined gravimetrically ($\theta_g \times \rho_b$) related to TDR measured volumetric water content for soils brought to six different target water contents with irrigation water of 2 dS/m.

Figure 9.4. Volumetric water content determined gravimetrically ($\theta_g \times \rho_b$) related to TDR measured volumetric water content for soils brought to six different target water contents with irrigation water of 3 dS/m.

Figure 9.5. Volumetric water content determined gravimetrically ($\theta_g \times \rho_b$) related to TDR measured volumetric water content for soils brought to six different target water contents with irrigation water of 4 dS/m.

Figure 9.6. Volumetric water content determined gravimetrically ($\theta_g \times \rho_b$) related to TDR measured volumetric water content for soils brought to six different target water contents with irrigation water of 5 dS/m.

Figure 9.7. Volumetric water content determined gravimetrically ($\theta_g \times \rho_b$) related to TDR measured volumetric water content for soils brought to six different target water contents with irrigation water of 6 dS/m.

Figure 9.8. Volumetric water content determined gravimetrically ($\theta_g \times \rho_b$) related to TDR measured volumetric water content for soils brought to six different target water contents with irrigation water of 7 dS/m.

Figure 9.9. Volumetric water content determined gravimetrically ($\theta_g \times \rho_b$) related to TDR measured volumetric water content for soils brought to six different target water contents with irrigation water of 8 dS/m.

Figure 9.10. Volumetric water content determined gravimetrically ($\theta_g \times \rho_b$) related to TDR measured volumetric water content for soils brought to six different target water contents with irrigation water of 9 dS/m.

Figure 9.11. Volumetric water content determined gravimetrically ($\theta_g \times \rho_b$) related to TDR measured volumetric water content for soils brought to six different target water contents with irrigation water of 10 dS/m.

Figure 9.12. Deviations from the actual measured water contents and those determined with TDR as related to the bulk soil electrical conductivity.

DISTRIBUTED CIRCUIT MODEL OF TDR PROBE USED TO MEASURE DIELECTRIC
CONSTANT AND ELECTRICAL CONDUCTIVITY

L: INDUCTANCE
R: SKIN RESISTANCE
G: CONDUCTANCE
C: CAPACITANCE

Figure 9.13 Differential element and equivalent circuit for TDR transmission line.

Effect Of Frequency On Phase Velocity

Figure 9.14. The effect of frequency on the phase velocity at three different ratios of bulk soil salinity and effective dielectric constant of the medium.

DIFFERENCES IN WATER CONTENT ESTIMATES VS. σ/ϵ

Figure 9.15. Deviations from the actual measured water contents and those determined with TDR as related to the ratio of bulk soil salinity and effective dielectric constant of the medium.

10. APPENDIX A

10.1 How To Use The 21X Micrologger For Obtaining TDR Waveforms

The micrologger is wired to the cable tester in the following way:

The red jack of the penlift on the tdr scope is wired to the high side of channel 1 on the micrologger. The black jack of the penlift is wired to the ground of channel 1.

The Y-output jacks on the TDR scope are wired for a single ended analog measurement to channel 2. The red jack of the output module is wired to the high side of channel 2 and the black jack is wired to the low end of channel 2.

To program the micrologger a key sequence must be entered. The key sequence is given in table A1.. To store each command an A must be typed after each command.

After the program has been entered it must be compiled. This is done by typing *0. The initial memory partitioning of the micrologger is not sufficient to compile and run this program, if this is the case the display will show E60. The memory is repartitioned by typing *A,6200 A and then compile the program again by typing *0. Before the measurements are started, the micrologger must know where to dump the data. To set it in tape mode type : *4A,10A,01A,*0. Now the micrologger is ready to start a burst measurement. The micrologger will be ready to start a burst measurement only after flag 1 is reset. So to prepare the micrologger to accept a waveform type *6AD1*0. As soon as the colon disappears hit the toggle switch and the micrologger will sample a waveform. The micrologger will dump the data to the tape as soon as it has completed the measurement.

Table A1.

Key	Code	Comments
*1	01:00	Enter table 1.
30	01:30	30 second interval.
91	01:P91	If flag command.
21	01:21	Execute if flag 1 is clear (set to 0)
30	02:30	Then do the following.
23	02:P23	Enter the program step for the Burst measure- ment.
1	01:1	Use 1 analog channel for measurement.
14	02:14	Range code. Specifies a 250 μ s integration time and a 500 mV range.
2	03:2	Channel 2 is the first analog channel used for the measurement.
1200	04:1200	4 digit code specifying trigger and output 1: Digital trigger on channel 1. 2: Trigger if below limit. 0: Destination of the data is input storage. 0: Differential measurement.
7D5	05:7.5	7.5 millisecond time interval.
2D934	06:2.934	2934 points to be measured (22 s/7.5 ms)
0	07:0	0 samples to be saved before trigger.
0	08:0	0 mV trigger limit.
0	09:0	0 mV trigger excitation.
1	10:1	First location to store the data is loca- tion 1.
1	11:1	Multiplier is 1.
0	12:0	0 offset.
86	03:P86	Program step 3: Do.
11	01:11	Set flag 1 to 1.
87	04:P87	Program step 4: Start loop.
0	01:0	0 delay.
2934	02:2934	Iteration count of 2934.
86	05:86	Program step 5: Do.
10	01:10	Set flag 0 to 1.
70	06:P70	Sample.
1	01:1	Increase sequentially with 1.
1C	02:1—	Start at memory location 1.
95	06:P95	End (sample).
95	07:P95	end (loop).

11. APPENDIX B

11.1 Program Used To Add Datapoint Numbers To The Inputfile.

The following program code is in FORTRAN 77 and can be compiled with a MS fortran 77 compiler.

```
-C234567
PROGRAM TDRED

C*** THIS PROGRAM READS A DATA FILE AND ADDS THE LINE NUMBER AND SENDS
C*** THE DATA TO AN OUTPUT FILE.

CHARACTER*13 IN,OUT

WRITE (*,20)
20 FORMAT (' ENTER INPUTFILE :',\ )
READ (*,21) IN
WRITE (*,22)
22 FORMAT (' ENTER OUTPUTFILE :',\ )
READ (*,21) OUT
21 FORMAT (A)

OPEN (1,FILE=IN)
OPEN (2,FILE=OUT , STATUS = 'NEW')

NX=0

30 READ (1,23,END=31) Y
NX=NX+1
WRITE (2,24) NX,Y
GOTO 30
23 FORMAT (F9.2)
24 FORMAT (2X,16,3X,F9.3)

31 STOP
END
```

11.2 Example Of An Input File.

The following series of numbers is part of an input file which the program is able to read. The first column represents the data point numbers or the x values and the second column represents the relative amplitude or the y values.

860.	152.700
861.	150.500
862.	148.900
863.	146.400
864.	144.800
865.	142.700
866.	141.100
867.	139.700
868.	138.600
869.	137.700
870.	137.400
871.	137.400
872.	137.000
873.	137.000
874.	135.800
875.	134.700
876.	133.200
877.	131.700

11.3 Example Of An Output File.

The following series of numbers is part of an output file that the program generates. The first column are the time coordinates, the second the ρ coordinates and the third are the derivatives of the points calculated with the input data, these are the same data points as above.

-.4904E-09	191.4401	-2.3000
-.4642E-09	185.9334	-2.2000
-.4379E-09	180.6661	-1.6000
-.4116E-09	176.8354	-2.5000
-.3854E-09	170.8498	-1.6000
-.3591E-09	167.0191	-2.1000
-.3328E-09	161.9912	-1.6000
-.3066E-09	158.1605	-1.4000
-.2803E-09	154.8086	-1.1000
-.2540E-09	152.1750	-.9000
-.2278E-09	150.0201	-.3000
-.2015E-09	149.3019	.0000
-.1752E-09	149.3019	-.4000
-.1490E-09	148.3442	.0000

11.4 Example Of CALC.CAL.

First CALC.CAL confirms that the subroutines have been entered. The input file is given and the number of errors encountered. Then the values of the variables used in the program: The name, the row number of the array location, the values in the row of the array.

```

In DERIV
In MAXFIND
col2SA01.dat
INPUT ERRORS      0
  MAXTRA 846      845.0000    240.5000    -.5000
REAL MAXTRA      845.4000    240.7485
  MINFLX 120      119.0000   -383.1000    3.1000
  MAXFLX 133      132.0000    101.4000   -1.1000
  MAXPUX 879      878.0000    132.9000   -.4000
  MIPULX 1005     1004.0000    41.3400    .1400
  2T      1131     1130.0000    277.8000    .4000

In DERIV
In MAXFIND
col2SA02.dat
INPUT ERRORS      0
  MAXTRA 843      842.0000    240.8000   -.7000
REAL MAXTRA      842.4000    240.9770
  MINFLX 118      117.0000   -381.5000    3.5000
  MAXFLX 130      129.0000    100.6000   -.4000
  MAXPUX 876      875.0000    131.9000   -1.2000
  MIPULX 1030     1029.0000   -13.7000    .2700
  2T      1184     1183.0000    172.7000    .2000

```

11.5 Example Of TDRRHO1.PRN.

This file contains the final results of the program. The sequence in which the results are written is: outputfile name, EPSILON, THETA, V_t , V_r , V_{QUO} , SIGMA, R_{QUO} , RHO. These variables are explained in the program in Section 12.

col3st01.out	4.3283	.0634	988.0712	481.5795	2.0517	.1653	4.1004	.6079
col3st02.out	6.2701	.1095	848.7606	356.9229	2.3780	.2397	2.2297	.3807
col3st03.out	11.9225	.2242	582.4270	72.7852	8.0020	.7937	.4036	-.4249
col3st04.out	13.3218	.2486	635.5944	201.6382	3.1522	.4631	.6289	-.2278
col3st05.out	14.7230	.2714	602.7059	199.4964	3.0211	.4689	.5837	-.2629
col3st06.out	11.2520	.2120	671.1168	244.5686	2.7441	.3742	.7891	-.1179
col3st07.out	5.0163	.0802	914.6210	376.2283	2.4310	.2199	2.4688	.4234
col3st08.out	6.8932	.1236	807.9374	303.3853	2.6631	.2842	1.4173	.1726
col3st09.out	10.3882	.1958	673.2706	209.7521	3.2098	.4154	.7212	-.1620
col3st10.out	11.2851	.2127	675.9512	243.4364	2.7767	.3792	.8571	-.0770
col3st11.out	14.1738	.2626	562.1385	96.3943	5.8317	.7337	.3849	-.4441
col3st12.out	17.7908	.3166	529.7537	117.7230	4.5000	.7012	.3772	-.4522
col3st13.out	4.8775	.0768	959.8974	434.2634	2.2104	.1936	3.2079	.5247
col3st14.out	8.5995	.1602	700.3187	152.7348	4.5852	.4936	.6511	-.2113
col3st15.out	10.6009	.1999	659.6499	180.1737	3.6612	.4670	.6519	-.2107
col3st16.out	12.0818	.2271	602.8535	156.0981	3.8620	.5191	.5312	-.3062
col3st17.out	15.4756	.2831	525.9570	118.4676	4.4397	.6481	.3974	-.4312
col3st18.out	17.3094	.3099	511.9476	93.3237	5.4857	.7827	.3336	-.4997
col3st19.out	5.3299	.0877	892.1743	346.6486	2.5737	.2412	1.7138	.2630
col3st20.out	7.6636	.1404	743.3605	213.9040	3.4752	.3811	.8505	-.0808

12. APPENDIX C

12.1 Code For The TDR Program

The following is the code for the TDR program. This program can be used for rescaling and analyzing TDR waveforms obtained with a micrologger. The program is written in FORTRAN 77 code and can be compiled using a M.S. Fortran Compiler.

```
C234567
      PROGRAM TDRR27
C*** By T.J. Heimoaara 10/87
C   Program reads a TDR waveform inputfile, selects the appropriate points
C   of the waveform: the baseline, transformer peak, point where the voltage
C   pulse enters the soil, the minimum of the wave form between the trans-
C   former maximum (time = t) and the reflected voltage at time= 2t.
C   Then the program recalculates the x-values to the proper distance
C   and it recalculates the y-values to the proper rho-values.
C   Finally the program gives Epsilon (the relative dielectric constant),
C   theta (the soil volumetric water content) and Sigma (the bulk
C   electrical conductivity).
C   Modification date: 11/11/87

C*** Input Arguments:      FNAME: variable in which the input and output
C                           file names are read into.
C                           COL(NX,NY): array into which the input file is read
C                           into.
C                           FN2: variable for the string values of the read
C                           statements.
C                           IAR: integer variable in read statements.
C                           AR: real variable in read statements.
C
C*** Output Arguments: COL(NX,NY): array in which the output file is created.
C                           KC: number of errors found in the inputfile.
C                           XTRA: real point number of where the trans-
C                           former maximum is.
C                           TRAMAX: transformer maximum at XTRA.
C                           MAXTRA: Integer value of XTRA.
C                           MINFLX: first point of step rise.
C                           MAXFLX: last point of step rise.
C                           MAXPUX: point where the pulse enters the wave-
C                           form. t=0
```



```

C      MIPULX: point where pulse gets reflected, the
C      end of the waveguide. t=t
C      MIPUL2: point where reflected voltage is measured.
C      t=2t.
C      FNAME: variable which contains the filename of
C      file where the modified input file is stored.
C      EPSIL: the dielectric constant epsilon.
C      THETA: the volumetric watercontent theta.
C      VT: the transmitted voltage.
C      VR: the reflected voltage.
C      VQUO: VT/VR
C      SIGMA: the bulk soil salinity sigma.
C      RQUO: (1+rho)/(1-rho).
C      RHO: the average value of the last 100 points.
C      RHOT: the transmitted rho on the rescaled axis.
C      RHOR: the reflected rho.
C
C*** Local Declarations:
C      A: slope of the linear transformation used to
C      to calculate the rho-values.
C      B: intercept of the linear transformation.
C      BASAVG: lowest point on the basevalue line.
C      BASLNE: average value of the baseline amplitude
C      between IBAS1 and IBAS2.
C      FACTOR: factor used to convert point number to distance.
C      IBAS1: point number of the point at d=-250.
C      IBAS2: point number of the point at d=-50.
C      MINBAS: point number of the lowest value of the baseline.
C      NX: counter used for the array (rows).
C      NY: counter used for the array (columns).
C      SUM: sum value of certain sum routines.
C      XNUL: real point number where the pulse enters the
C      soil.
C      XT: extra variable used in the time calculation
C      to break down the equation.
C
C
C*** Subroutines used:      DERIV: subroutine used for calculating the slope
C      in each point of the waveform.
C      MAXFIND: subroutine for finding the interpolated
C      maximum of a set of points.
C      CLMPCUBE: external subroutine from the mathlibrary
C      uses the clamped cubic spline method for
C      interpolating between the points.
C
C
C*****

```

```

      CHARACTER*13 FNAME,FN2

      DIMENSION COL(2800,3)

C*** Step 1: Read in the data from an input file.
C   Read Inputfile name in from the keyboard

      WRITE (*,20)
20  FORMAT (' Enter inputfilename :',\ )
      READ (*,21) FNAME
21  FORMAT (A)
      OPEN (7,FILE = FNAME )

C*** Read the inputfile into array COL(x,y)
      NX=0
      KC=0
22  NX=NX+1
28  READ (7,100, END=26, ERR=27) (COL (NX+KC,NY),NY=1,2)
      GOTO 22
27  KC=KC+1
      GOTO 22
100 FORMAT (F9.0,F12.3)
26  CLOSE (7, STATUS = 'KEEP')

C*** Find out how many points are in the input array

      MAXNUM = NX+KC-1

C*** Step 2: Get to last record in CALC.CAL.

24  OPEN (11,FILE='CALC.CAL')
16  READ (11,130,END=18)
      GOTO 16
18  BACKSPACE (11)

C*** Step 3: Calculate the slope of the waveform at each point.
C   Call the subroutine that calculates the first derivative.

      CALL DERIV (COL,MAXNUM)

C*** Step 4: Find the rise from the base value to the baseline
C   of the waveform.

      NX = 10
40  IF (COL(NX,3) .GT. 2) THEN
      MINFLX = NX
      GOTO 44
    ELSE
      NX = NX + 1
      GOTO 40
    ENDIF

```

```

44 IF ( ABS(COL(NX,3)) .LT. 2 ) THEN
    MAXFLX = NX
    GOTO 43
ELSE
    NX=NX + 1
    GOTO 44
43 ENDIF
333 FORMAT (A,16)

```

C*** Step 5: Find the minimum of the waveform between the
C end of the file and the beginning of the plateau.

```

MIPULX = MAXFLX
DO 41 NX = MAXFLX,MAXNUM
    IF (COL(NX,2) .LE. COL(MIPULX,2)) MIPULX = NX
41 CONTINUE

```

C*** Step 6: Find the transformer maximum between MIPULX and MAXFLX + 150.

```

MAXTRA = MIPULX
DO 42 NX = MAXFLX+150,MIPULX
    IF (COL(NX,2) .GE. COL(MAXTRA,2)) MAXTRA = NX
42 CONTINUE

```

C*** Find the transformer maximum, TRAMAX, using CLMPCUBE.

```

CALL MAXFIND (COL,MAXTRA,XTRA,TRAMAX)

```

C*** Step 7: Calculate the point where the voltage enters the soil.
C The distance factor was defined by counting the points between a known
C distance on 60 waveforms and deviding the distance by the number of
C points, for the 2700 waveforms the factor was 0.3940.

```

FACTOR = .3940
XNUL = (XTRA + 13.0694/FACTOR)
MAXPUX = NINT(XNUL)

```

C*** Step 8: Check to see that MIPULX is not more than 600 data points from
C MAXPUX.

```

MIN = MAXPUX
DO 45 NX = MAXPUX, MAXPUX + 600
    IF (COL(NX,2) .LT. COL(MIN,2)) MIN = NX
45 CONTINUE
IF (MIN .LT. MIPULX) MIPULX = MIN

```

C*** Step 9: Write the found values to CALC.CAL

```

WRITE (11,131) FNAME
WRITE (11,133) 'INPUT ERRORS ',KC
WRITE (11,130) '    MAXTRA ',MAXTRA,(COL(MAXTRA,NY),NY=1,3)
WRITE (11,132) 'REAL MAXTRA ',XTRA,TRAMAX
WRITE (11,130) '    MINFLX ',MINFLX,(COL(MINFLX,NY),NY=1,3)
WRITE (11,130) '    MAXFLX ',MAXFLX,(COL(MAXFLX,NY),NY=1,3)
WRITE (11,130) '    MAXPUX ',MAXPUX,(COL(MAXPUX,NY),NY=1,3)
WRITE (11,130) '    MIPULX ',MIPULX,(COL(MIPULX,NY),NY=1,3)
MIPUL2 = MAXPUX + 2*(MIPULX-MAXPUX)
WRITE (11,130) '    2T    ',MIPUL2,(COL(MIPUL2,NY),NY=1,3)

```

```

130 FORMAT (A,14,3(2X,F10.4))
131 FORMAT (A)
132 FORMAT (A,2(2X,F10.4))
133 FORMAT (A,16)

```

```

C*** Step 10: Find the lowest point of the baseline and then calculate
C the parameters for the linear transformation of the y-values
C according to the following equations:

```

```

C
C          Yfinal = A* Yoriginal + B
C knowing :   -1100 = A* MINBAS   + B
C              120  = A* BASLNE   + B

```

```

MINBAS=1
DO 32 NX = 1,MINFLX
  IF (COL(NX,2) .LT. COL(MINBAS,2)) MINBAS = NX
32 CONTINUE

```

```

C*** Step 11: Calculate the average y-value of the waveform between
C d=-250 and d=50.

```

```

IBAS1= NINT(-250./FACTOR*XNUL)
IBAS2= NINT(50. /FACTOR*XNUL)
SUM = 0.
DO 33, NX = IBAS1,IBAS2
  SUM = SUM + COL(NX,2)
33 CONTINUE
BASLNE = SUM/(IBAS2-IBAS1)

A = 1220./((BASLNE-COL(MINBAS,2))
B = 120 - (A*BASLNE)

```

```

C*** Step 12: Redefine the x and the y variables to the time and the
C reflection variables using the parameters A and B.

```

```

NY = MAXNUM -1
DO 50 NX = 0,MAXNUM
  XT =(COL(NX,1)-XNUL)*FACTOR
  COL (NX,1) = (2.*XT)/3.0E+10
  COL (NX,2) = A*COL(NX,2)+B
50 CONTINUE

```

```

C*** Step 13: Recalculate the derivative using new x-values.

```

```

C*** Step 14: Write COL(x,y) to an outputfile.

```

```

WRITE (*,25)
25 FORMAT (' Enter outputfilename :',\ )
READ (*,21) FNAME

OPEN (8,FILE = FNAME , STATUS= 'NEW' )

```

```

DO 31 NX = 0 ,NY
  WRITE (8,110) (COL(NX, NY), NY=1,3)
31 CONTINUE
110 FORMAT (2X,E12.4,2(3X,F10.4))
CLOSE (8, STATUS = 'KEEP')

```

C*** Step 15: Calculate epsilon, theta, Vt/Vr, and sigma.

```

BASAVG=-1100.
EPSIL = ((3E+08*COL(MIPULX,1))/0.48)**2
THETA = (((0.043*EPSIL-5.5)*EPSIL+292)*EPSIL -530)/10000
VT= COL(MIPULX,2)-BASAVG
VR= COL(MAXPULX + 2*(MIPULX-MAXPULX),2)-COL(MIPULX,2)
VQUO= VT/VR

IF (VQUO .LE. 0.) THEN
  WRITE (11,131) ' VQUO < 0'
  SIGMA = 9.9999
  GOTO 90
ENDIF
CLOSE (11, STATUS = 'KEEP')

SIGMA = 10.0* ((SORT(EPSIL)/(120.*3.14159*.24))*ALOG (VQUO))

```

C*** Step 16: Calculate the value of $1+\text{Rho}/1-\text{Rho}$ at a large time.

```

90 SUM = 0
DO 34 NX = MAXNUM-100,MAXNUM
  SUM = SUM + COL(NX,2)
34 CONTINUE
RHO = (SUM / 100.)/1000.
RQUO = (1.+RHO)/(1.-RHO)
RHOT = (COL(MIPULX,2)+1000.)/1000.
RHOR = RHO - RHOT
RHOTR = RHOT/RHOR

```

C*** Step 17: Write calculated values to a file where all the results
C are stored.

```

OPEN (9,FILE = 'TDRRHO1.PRN')
15 READ (9,200,END=17)
GOTO 15
17 BACKSPACE 9

```

```

WRITE (9,200) FNAME, EPSIL, THETA, VT, VR, VQUO, SIGMA, RQUO, RHO, RHOTR
200 FORMAT (A,9(3XF10.4))
CLOSE (9)

```

```

STOP
END

```

```

SUBROUTINE DERIV (COL, MAXNUM)
C*** Calculate the first derivative (f') of all the points of the
C*** waveform (using the forward difference-formula:
C***  $f'(x) = (f(x+h) - f(x))/h$ .

      DIMENSION COL(2800,3)
      WRITE (11,150)
150  FORMAT (' In DERIV')
      DO 30 NX = 1, MAXNUM-1
          COL (NX,3) = (COL(NX+1,2)-COL(NX,2))/(COL(NX+1,1)-COL(NX,1))
30  CONTINUE
      RETURN

END

SUBROUTINE MAXFIND (COL,MAXX,XMAX,YMAX)

C*** This subroutine calls a subroutine that uses an algorithm that
C finds the the real transformer maximum using a cubic spline interpolation
C of the data points. The algorithm is a subroutine from Bill's Math-
C library and is called clmpcube. This will have to be linked to this
C program.

C*** Arguments:      X: array containing the x-values of the points to
C                     be interpolated.
C                     A: array containing the functional values of the
C                     points to be interpolated.
C                     F0: the derivative of the function at X0
C                     F1: the derivative of the function at X1
C                     YMAX: maximum value of interpolated curve.
C                     NX: counter
C                     NXX: counter
C                     XX: NXX*.01 so that the increment is 0.1.
C                     S: interpolation function using results from
C                     clmpcube.for.
C                     XMAX: X-value that goes along with YMAX.
C
C
C*****

```

```

      DIMENSION COL(2800,3)
      DIMENSION X(20), A(20), B(20), C(20), D(20)
      WRITE (11,151)
151  FORMAT (' In MAXFIND')

C*** Step 1: Load the X and Y values around the max in to arrays X and A.

      DO 71 NX = -9,10
          X(NX+10)=COL(MAXX+NX,1)
          A(NX+10)=COL(MAXX+NX,2)
71  CONTINUE

C*** Step 2: Load the boudary derivatives in F0 and F1.

```

```

F0 = COL(MAXX-9,3)
F1 = COL(MAXX+10,3)

```

C*** Step 3: Use the Clamped Cubic Spline Subroutine.

```

CALL CLMPCUBE (20,X,A,B,C,D,F0,F1)

```

C*** Step 4: Find the interpolated maximum using the results from the Clamped
C Cubic Spline Method.

```

YMAX = 0

```

```

DO 69 NX = 8,12
  DO 70 NXX = -50,50,10
    XX=NXX*0.01

```

```

    S = A(NX)+B(NX)*XX+C(NX)*(XX**2)+D(NX)*(XX**3)

```

```

    IF (S .GT. YMAX) THEN

```

```

      YMAX = S

```

```

      XMAX = X(NX)+XX

```

```

    ENDIF

```

```

70 CONTINUE

```

```

69 CONTINUE

```

```

RETURN

```

```

END

```

13. REFERENCES

Annan, A.O. 1977. Time-domain reflectometry air-gap problem for parallel wire transmission lines. Report of activities, Part B: pages 77-1B: 59-62. Geol. Surv. of Canada, Ohara.

Dalton, F.N., W.N. Herkelrath, D.S. Rawlins, and J.D. Rhoades. 1984. Time Domain Reflectometry: Simultaneous measurement of soil water content and electrical conductivity with a single probe. *Science*. 224: 989-990.

Dasberg, S. and F.N. Dalton. 1985. Field measurement of soil water content and bulk electrical conductivity with time-domain reflectometry. *Soil Sci. Soc. Am. J.* 49: 293-297.

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

Dalton, F.N. 1987. Measurement of soil water content and electrical conductivity using time-domain reflectometry. International conference on measurement of soil and plant water status. 1: 95-98.

Rhoades, J. D., P.A.C. Raats, and R.J. Prather. 1976. Effects of liquid-phase electrical conductivity, water content, and surface conductivity on bulk soil electrical conductivity. *Soil Sci. Soc. Am. J.* 40: 651-655.

Rhoades, J.D., Manteghi, N.A., Shouse, P.J., Alves, W.J., 1988. Soil Electrical

Conductivity and Soil Salinity: New Formulations and Calibrations. In review.

Ramo, S. and J.R. Whinnery. 1959. Fields and waves in modern radio. Wiley, New York, N.Y.

Topp, G.C., J.L. Davis, and A.P. Annan. 1980. Electromagnetic determination of soil water content: measurement in coaxial transmission lines. Water Res. Research. 16: 574–582.

Topp, G. C., J. L. Davis, and A.P. Annan. 1982. Electromagnetic determination of soil water content using TDR:I. Applications to wetting fronts and steep gradients.

Topp G. I., W. D. Zebchuk and S. Zegelin, 1988. Determination of electrical conductivity using time–domain reflectometry: soil and water experiments in coaxial lines. Water Res. Research, 24:945–952.

Yanuka, M., G. C. Topp, S. Zegelin and W. D. Zebchuk 1988. Multiple reflections and attenuation of time–domain reflectometry pulses: theoretical considerations for applications to soil and water. Water Res. Research 24:934–944.

14. DESCRIPTION OF COOPERATION

The basis of cooperation on the project was laid during two sabbatical periods of Dr. A. Nadler with Dr. J. Rhoades in 1981–1982 and Dr. S. Dasberg with Dr. F. N. Dalton in 1983–1984 at the U. S. Salinity Laboratory in Riverside. During this period Dr. Dasberg worked with Dr. Dalton on the continued development of TDR based on preliminary research of Dr. Dalton, published in Science, 1984, 224:989–990. The results of their cooperation were published in SSSAJ 49: (1984) and the proposal was prepared based on these initial results.

In November 1985 S. Dasberg paid a short visit to Riverside (not within the framework of BARD) during which the final plans for the initiation of the project were made. In the beginning of 1987 Dr. Dalton visited Israel. The first results of the Israeli team were reviewed, details of technique or measurements were worked out and the work for the next year was planned.

In July 1987 a conference on the measurements of soil and plant water status was held in Logan, Utah where TDR was one of the main subjects. Both S. Dasberg and A. Nadler were able to attend (funded by the project), as well as F. N. Dalton. Fruitful discussions during the conference with other experts on TDR, were of further help to generate ideas for the completion of the project. Immediately after this conference S. Dasberg and A. Nadler visited the Salinity Laboratory for further discussions, planning, and reviewing of obtained results. After these mutual visits information was exchanged by electronic and regular mail during the final stage of the project.

15. EVALUATION OF RESEARCH ACHIEVEMENTS WITH RESPECT TO AIMS OF ORIGINAL RESEARCH PROPOSAL

15.1 Development Of TDR Concept For Water And Salinity Measurement And Determination Of The Sensitivity And Accuracy Of The Measurement As Affected By The Distribution Of Water And Salt.

This project was successful in the application of time-domain reflectometry (TDR) techniques for the in-situ measurement of the effective dielectric constant and bulk soil electrical conductivity of a moist soil. These two physical properties were measured in the laboratory and under field conditions and were shown to be directly correlated with soil water content and soil water salinity. Design criteria, construction techniques and installation practices were developed for the use of TDR probes in experimental applications. A theoretical analysis was successful in 1) characterizing the effects of media electrical conductivity on the propagation of the TDR electromagnetic pulse and its subsequent interpretation and 2) developing an alternative technique for measuring the bulk soil electrical conductivity independent of a dielectric measurement. The TDR measurement is also shown to integrate over the spatial distribution of water content which exists over the length of the TDR sensing probe. It has been shown that the TDR determination of bulk soil electrical conductivity is essentially identical to the low frequency measurements made with either the four-probe or standard conductivity bridge. The problem of translating from bulk soil electrical conductivity to soil salinity is a problem of a general nature, not specific to the TDR method and solutions to this problem are available. The ability to determine both water content and conductivity with a single probe over identical sampling volumes using TDR is a

significant advance in our ability to access and monitor soil salinity.

15.2 Development And Use Of TDR In The Field For Characterizing Root Zone Salinity And Water Content In Order To Predict Plant Stress For Irrigation Management

TDR measurements have been carried out in several field experiments on varying soil types in conjunction with neutron and gravimetric water content determinations and 4 electrode and saturation extracts for conductivity determinations. These measurements have shown the feasibility of using TDR in the field for measurements. These measurements are an important tool in irrigation management. The technology for interfacing TDR techniques with actual irrigation control were beyond the budget and time constraints of this investigation. However the principles are proven and simply await the the next phase of development.

16. LIST OF PUBLICATIONS

Dalton, F.N. 1987. Measurement of soil water content and electrical conductivity using time-domain reflectometry. *Proceedings of the International Conference on Measurement of Soil and Plant Water Status, Logan, Utah*. 1: 95-98.

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

Dasberg, S. and A. Nadler 1987. Field sampling of soil water content and bulk electrical conductivity with time-domain reflectometry, *Proceedings of the International Conference on Measurement of Soil and Plant Water Status, Logan, Utah*. 1:99-103

Dasberg, S. and A. Nadler. 1988. Soil salinity measurements. *Soil Use And Management*.4:127-133.

Manuscripts Submitted Or In preparation (*Intended Journal*)

Dalton, F. N., J. A. Poss and R. S. Austin 1989. Methods for measuring soil water content and salinity with time-domain reflectometry. (*ASAE*)

Dalton F. N. and J. A. Poss. 1988. Time-domain reflectometry: water content and bulk soil electrical conductivity measurements in a saline environment. Agron. Abst. p.181.(SSSAJ)

Dalton F. N. and J. A. Poss 1989. Soil water content and salinity assessment for irrigation scheduling using time-domain reflectometry: principles and applications. *Int. Symposium On Scheduling of Irrigation for Vegetable Crops Under Field Condition, Maretea, Italy.* p.80.(Acta Horticulturae)

Dalton, F. N., J. A. Poss, T. Heimovara, R. Austin, W. Alves and W. Russel, 1990. Time-domain reflectometry. (*U. S. Salinity Laboratory Research Report*)