CHAPTER

8

Time Domain Reflectometry

In Chapter 5, we learned how to measure the matric potential energy of water in soil with a tensiometer. Here, we learn how to measure the water content of soil using time domain reflectometry (TDR). This method is the most widely used one, aside from the gravimetric method, to determine soil water content.

TDR makes use of the dielectric constant, ε, of water to determine the volumetric water content of soil. We are going to see how the dielectric constant of a soil sample depends on the amount of water in it. We measure it and then use an empirical relation, which equates the volumetric water content to the dielectric constant.

8.1 DEFINITIONS

The dielectric constant of a medium is defined by ε in the following equation (Weast, 1964, p. F-37):

$$F = \left(QQ'\right)\Big/\left(\varepsilon r^2\right), \tag{8.1}$$

where F is the force of attraction between two charges Q and Q' separated by a distance r in a uniform medium. The dielectric constant of a material is the ratio of the capacitance of a capacitor with the material between the plates to the capacitance with a vacuum between the plates (Shortley and Williams, 1971, p. 519). It is dimensionless. The dielectric constant for a vacuum = 1 exactly. A *capacitor* or *condenser* is a device consisting of two or more conductor plates separated from one another by a dielectric or insulator and used for receiving and storing an electric charge (Websters's New World Dictionary of the American Language, 1959; Schaum, 1961,

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p. 137). The electrical characteristics of a capacitor are determined by its capacitance, which is a measure of the ability of the conductors to store charge when a potential difference is produced between them, whether by a battery, a radio antenna, or any other source of potential difference (Shortley and Williams, 1971, p. 513–514). Capacitance, denoted by C, equals Q/V, in coulombs per volt of potential difference. This unit, 1 coulomb/volt, is given the name "farad," after Faraday. Coulomb's law gives the force between two charges and is $F = (QQ)'/r^2$, where Q and Q' are the two charges and r is the distance between them in a vacuum (Weast, 1964, p. F-42). Note that the force of attraction existing between two masses (Newton's law of universal gravitation) is inversely related to the square of the distance between the masses.

Before we look at the TDR method, let us first review some basic definitions from physics (Shortley and Williams, 1971, p. 243). A "cycle" is one complete execution of a periodic motion. The "period" of a periodic motion is the "time" T required for the completion of a cycle. The "frequency" of a periodic motion is the number f of cycles completed per unit time (unit = cycles/s).

Thus, it is seen that the period T of a periodic motion is the reciprocal of the frequency f, that is, $T = 1/f$ and $f = 1/T$. For example, a pendulum with a period $T = 1/5$ s has a frequency of 5 cycles/s or $f = 5$ /s = 5 Hz.

Frequency is measured in a unit called the hertz (Hz), which corresponds to 1 cycle/s, or 1 Hz = 1 /s. The unit is named after Heinrich Rudolph Hertz (1857–1894), who was a German physicist. (See the Appendix, Section 8.9, for a biography of Hertz.) Hertzian waves are radiowaves or other electromagnetic radiation resulting from the oscillation of electricity in a conductor. Hertz was the first to demonstrate the production and reception of radiowaves.

Mechanical wave motion has a single nonrepeated disturbance, called a "pulse", which is initiated at the source and then travels away from the source through the medium (Shortley and Williams, 1971, p. 415). Another important type of wave motion is the "regular wave train" or "continuous wave". In this type of wave, a regular succession of pulses is initiated at the source and transmitted through the medium. Thus, if a floating block of wood is pushed up and down regularly on a water surface, a regular train of waves will be propagated outward. The simplest type of regular wave train is a sinusoidal wave motion, which is illustrated in Figure 8.1. Part (a) of this figure shows one end of a long stretched string attached to a weight supported by a spring. The weight is arranged so that it can move freely in the vertical "ways" of a frame. If the weight is pulled downward a distance A and then released, the weight will move in the vertical direction with simple harmonic motion

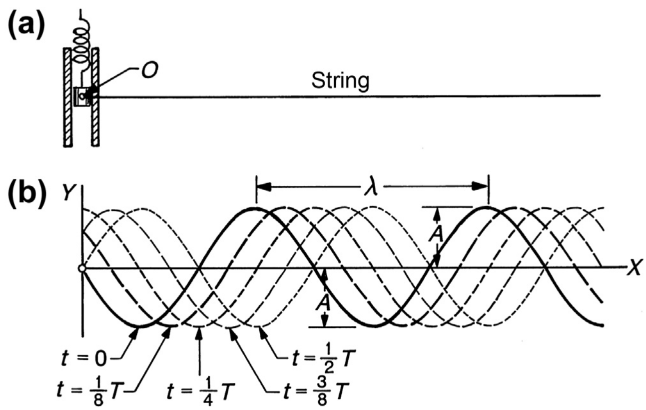

FIGURE 8.1 Production and propagation of a sinusoidal transverse wave in a long string shown in (a). (b) The motion of the string during one half-cycle of oscillation of O, shown in (a), from $Y=0$ to $+A$ and back to 0. *From Shortley and Williams (1971), p. 416. Reprinted by permission of Pearson Education, Inc.: Upper Saddle River, New Jersey.*

of a certain period T. Because the end of the string is attached to the weight, the oscillating weight acts as a source of a sinusoidal transverse wave that travels to the right along the string in the manner indicated by the curves of Figure 8.1(b). These curves show successive "snapshots" of the shape of the string during one half-cycle, after the motion has been well established. The distance between adjacent crests or adjacent troughs in such a wave is called the "wavelength"; in the figure, the wavelength is denoted by λ. Each time the particle O attached to the weight makes a complete oscillation, the wave moves a distance λ in the X-direction. Hence, the wave speed, v, and the wavelength are related by the equation

$$v = \lambda/T, \tag{8.2}$$

where T is the period of oscillation and λ is the wavelength. In terms of the frequency $f = 1/T$, this equation can be written as

$$v = f\lambda \tag{8.3}$$

or

$$\lambda = v/f. \tag{8.4}$$

8.2 DIELECTRIC CONSTANT, FREQUENCY DOMAIN, AND TIME DOMAIN

We recall the physical properties of water and remember that the dielectric constant varies with temperature (Weast, 1964, p. E-36):

Temperature °C	ε
0	88.00
10	84.11
20	80.36
30	76.75
40	73.28
50	69.94
100	55.33

One can obtain information about a dielectric in either the frequency domain or the time domain. In the frequency domain, a number of measurements over a wide frequency range are required for the complete characterization of the dielectric, which is time consuming and requires a considerable investment in instrumentation. However, one can obtain the same information over a wide frequency range in only a fraction of a second by making the measurement not in the frequency domain but in the time domain. In TDR, a pulse is used that simultaneously contains all the frequencies of interest (Fellner-Feldegg, 1969). In the frequency range of 1 MHz (megahertz)−1 GHz (gigahertz), the dielectric constant is not strongly frequency dependent (mega $= 10^6$ and giga $= 10^9$). Figure 8.2 shows the wavelength and frequency of commonly used devices, such as radios, televisions, and cellular phones (Clark, 1994).

In passing, we note that the safety of electromagnetic waves, especially those associated with cellular telephones, is still in doubt. A link between brain cancer and electromagnetic fields has been found in some studies (Bishop, 1995). Experiments have shown that radiowaves at about the same power as that emitted by today's cellular phones can breakdown the binding of calcium to the surface of cells. Calcium is essential for virtually all living processes, including enzyme action and cell growth. Data have shown that the breakdown occurs at 145 MHz, the frequency at which ham radios operate, and at 450 MHz, the frequency used by security guards' radiophones. European cellular systems operate at 450 MHz

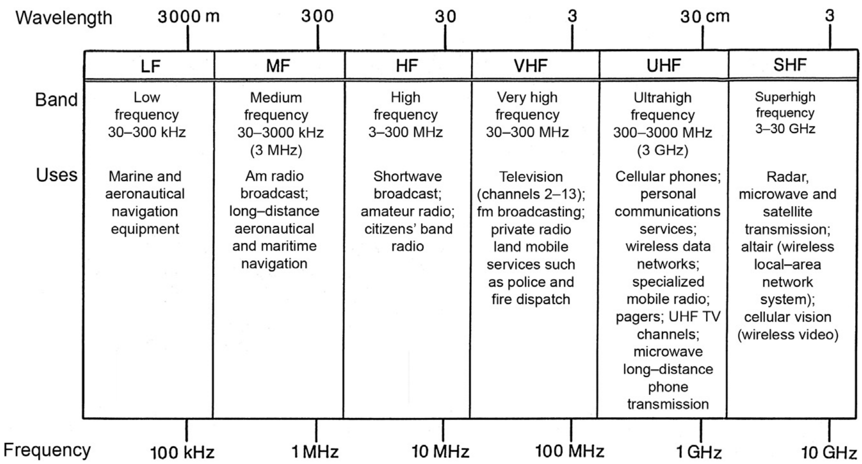

FIGURE 8.2 Wavelengths, frequencies, and their uses. *From Clark (1994). Reprinted by permission of Dow Jones & Company, Inc. All rights reserved worldwide.*

(Clark, 1994). Cell phone use appears to increase brain activity (glucose consumption) in regions close to where the phone antenna is held against the head (Park, 2011; Wang, 2011). After studying the results from a large number of available studies, the International Agency for Research on Cancer panel, made of up 31 scientists from 14 countries, concluded that cell phone radiowaves possibly increase the risk of brain cancer (Martin and Hobson, 2011). In May 2011, a World Health Organization panel added cell phones to a list of things that are possibly carcinogenic (Mukherjee, 2011). In 2010, San Francisco became the first city in the USA to pass legislation making cell phone retailers display radiation levels (Dowd, 2010).

8.3 THEORY FOR THE USE OF THE DIELECTRIC CONSTANT TO MEASURE SOIL WATER CONTENT

Most of the solid components of soil have dielectric constants in the range of 2–7, and that of air is effectively 1 (ε of air = 1.000590). Thus, a measure of the dielectric constant of soil is a good measure of the water content of the soil.

Here is a brief outline of what we are going to do to use TDR to get the volumetric water content of soil. We are going to measure a travel time, and by knowing the length of the rods (waveguides) in the soil, we are going to get a velocity (velocity = length/time). We are going to relate this velocity to the dielectric constant. Then, we will relate the dielectric constant to volumetric water content.

The TDR technique measures the velocity of propagation of a high-frequency signal (1 MHz−1 GHz). The velocity of propagation is as follows:

$$V = c\Big/\left(K'\right)^{1/2}, \tag{8.5}$$

where

V is the velocity of propagation in the soil;
c is the propagation velocity of light in free space; $c = 3 \times 10^8$ m/s;
K' is the dielectric constant of the soil.

By determining the travel time, t, of the pulse traveling in the transmission line or waveguide of length L, one can get the velocity as L/t.

Equation (8.5) can be rearranged to give the apparent dielectric constant as

$$K_a = [(ct)/L]^2, \tag{8.6}$$

where K_a is the apparent dielectric constant. However, we need to add a "2" to the denominator in Eqn (8.6), because the line length is the distance *traveled*, but commercial cable testers measure the length down and the echo (reflection). Hence, the distance *measured* is twice the line length. So we have

$$K_a = [(ct)/2L]^2. \tag{8.7}$$

The relationship in Eqn (8.5) is approximate, so in Eqns (8.6) and (8.7), we use K_a, the apparent dielectric constant, instead of K' (Topp and Davis, 1982).

Commercial TDR cable testers reduce the transfer time to an apparent probe length, l_a (Figure 8.3 from Clothier et al., 1994), so that

$$K_a = [(ct)/2L]^2 = \left(l_a/L\nu_p\right)^2, \tag{8.8}$$

where ν_p is the relative velocity setting of the instrument (Vogeler et al., 1996; see their Eqn (8.10)). It is relative, so it is unitless (ν = the Greek letter nu.) The reason the two appears in the first equation of Eqn (8.8) is that the echo must travel down and back along the rods of length L, as noted above. On the right-hand side of Eqn (8.8), the travel time is normalized to the length that is found relative to the true length. The length is $2l_a$ over $2L$, so the 2's cancel (B.E. Clothier, personal communication, March 6, 1997). The commercial cable tester made by Tektronix (Model 1502C, Wilsonville, OR) does not display $2l_a$ because it is used as a cable tester to find breaks in a cable. So it knows it is measuring twice the length, and saves the operator the hassle by dividing by two before it puts the trace on the screen (Figure 8.3).

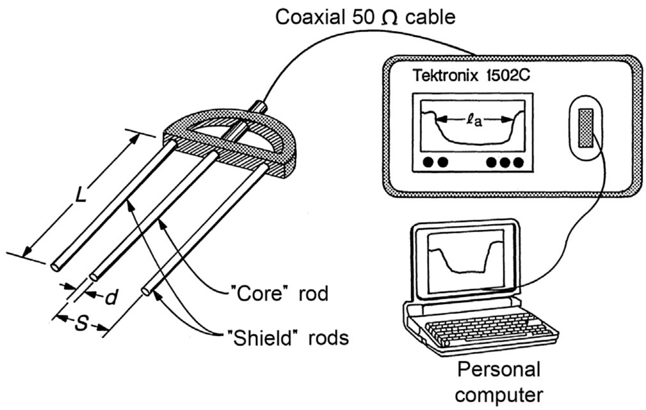

FIGURE 8.3 Schematic diagram of the time domain reflectometry system with the three-rod probe, the cable tester, and the computer that controls, acquires, and analyzes the data. *From Clothier et al. (1994). Reprinted by permission of Brent E. Clothier.*

Experimental results (Topp et al., 1980) have given the following relation between volumetric water content and the dielectric constant:

$$\theta_v = -0.053 + 0.0292K_a - 5.5 \times 10^{-4}K_a^2 + 4.3 \times 10^{-6}K_a^3. \tag{8.9}$$

Equation (8.9) has been shown to hold for many different types of soils. The relationship between volumetric water content (θ) and the dielectric constant (K_a) is essentially independent of soil texture, porosity, and salt content. However, if a soil is high in organic matter, Eqn (8.9) does not hold and a separate calibration equation needs to be determined. Herkelrath et al. (1991), who studied organic soil, found that the equation of Topp et al. (Eqn (8.9)) predicted the values of soil water content that were 30% too low. Topp et al. (1980) also reported a similar shift in their calibration for an organic soil. The soil cores of Herkelrath et al. (1991) had a large fraction of organics: 12.6% carbon.

8.4 COAXIAL CABLE AND WAVEGUIDES

Before we go further, let us define a coaxial cable or a coaxial line. A coaxial line is composed of an internal conductor of radius R_1 and an external conductor of radius R_2 separated by a dielectric (Lorrain and Corson, 1979, p. 172) (Figure 8.4). S.A. Schelkunoff was a developer of the coaxial cable. (See Section 8.10, for a biography of Schelkunoff.) Coaxial lines are widely used for the interconnection of electronic equipment and for long-distance telephony. They can be used with either direct or alternating currents, up to very high frequencies, where the wavelength

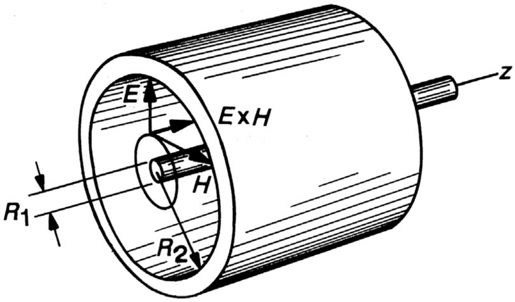

FIGURE 8.4 Coaxial line. We assume that the wave propagates in the positive direction of the Z-axis. E = electric field intensity; H = magnetic field intensity; R_1 and R_2 = radii of the inner and outer conductors, respectively. *From Lorrain and Corson (1979), p. 488. Used with permission.*

c/f is of the same order of magnitude as the diameter of the line. (Remember c is the speed of light in a vacuum, 2.99792458×10^8 m/s, and f is the frequency in reciprocal seconds) (Lorrain and Corson, 1979, p. 304). At these frequencies, of the order of 10^{10} Hz, the field inside the line becomes much more complicated than that shown in the figure and quite unmanageable (Lorrain and Corson, 1979, p. 304). There is zero electric field outside the line. Because the outer conductor carries the same current as the inner one does (Figure 8.5), there is also zero magnetic field. A structure designed to guide a wave along a prescribed path is called a "waveguide" (Lorrain and Corson, 1979, p. 487). The simplest type is the coaxial line illustrated in Figure 8.4. An electromagnetic wave propagates in the annular region between the two coaxial conductors, and there is zero field outside. The medium of propagation is a dielectric.

If one were using a coaxial cable (as is used in cable testing), one would put the soil sample in the coaxial cable and send a voltage pulse through the cable. When the pulse reached the sample (it would have been traveling through air up to this point), part of the pulse would be reflected (the rest would travel on or we could terminate the cable, so that the pulse would travel no further). The time dependence of the reflection of the pulse from the interface between air and the dielectric medium (soil sample) in the coaxial line is measured. (We measure a "time", which is reduced to an "apparent probe length" by the cable tester.) The reflection from a dielectric sample in a coaxial line is recorded on the oscilloscope of the cable tester. (Y-axis = pulse height; X-axis = time or apparent probe length.) The time is on the order of nanoseconds (nano = 10^{-9}).

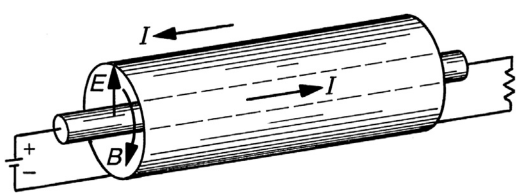

FIGURE 8.5 Coaxial line. E = electric field intensity; B = magnetic induction; I = electric current. *From Lorrain and Corson (1979), p. 304. Used with permission.*

However, it is impractical to put a soil sample in a coaxial cable to determine soil moisture. Therefore, parallel transmission lines (rods or waveguides) have been developed to determine soil water content by using TDR. The soil between and surrounding the rods serves as the dielectric of the transmission lines (Topp and Davis, 1982). The voltage pulse is propagated down and reflected back from the end of the waveguides in the soil.

8.5 MEASUREMENT OF SOIL WATER CONTENT USING TDR

Now let us look at the procedure, when we use TDR (Topp, 1993, pp. 544−549). First, we need the TDR equipment proper (Figure 8.6). This includes the pulser of voltage; a sampling receiver that receives both the pulse and the reflected pulse from the soil; a timing device that synchronizes the timing for pulser, receiver, and data display; and a data display that shows the time and voltage magnitude. (As noted above, commercial cable testers display an apparent length rather than a time.) The TDR cable tester sends square-wave pulses of voltage down the waveguides at a high frequency (in the gigahertz range) and stores on the screen their superpositions so that a single "form" is observed, whereas in fact it is the result of overlaying many forms (B.E. Clothier, personal communication, February 21, 1994).

Second, we need rods (also called probes or waveguides). They can be either two pronged or three pronged. If they are two pronged, we need a balun, which is an impedance matching transformer (Figure 8.7). The

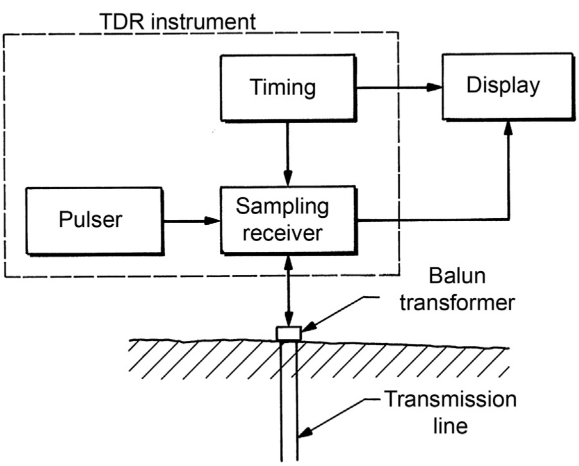

FIGURE 8.6 A block diagram of a time domain reflectometry instrument and its display units. *From Topp (1993), p. 545, CRC Press.*

coaxial cable in Figure 8.7 is 50 Ω. The coaxial cable is connected to an 185 Ω shielded television cable and a balun to provide a "balanced line" (Herkelrath et al., 1991). "Impedance" is the apparent resistance in an alternating electrical current corresponding to the true resistance in a direct current (Webster's New World Dictionary of the American Language, 1959). If one is using three pronged probes, they simulate the coaxial line and require no impedance matching transformer (Clothier et al., 1994).

Third, we need cables for connecting the TDR instrument and soil probes (Topp, 1993). Cable combinations between the TDR instrument and soil probes are determined by the type of probes used (two pronged, three pronged, or more).

Fourth, we need tools for installation of soil probes. Three procedures can be used for insertion. First, for short probes (in most soils, except the most resistant), we can insert the probes by hand, take a reading, and remove them and move on to the next spot. In this way, we can easily take many readings and quickly get a "feel" of the spatial variability. Second, for longer probes, it is necessary to make "preholes" with a dummy probe.

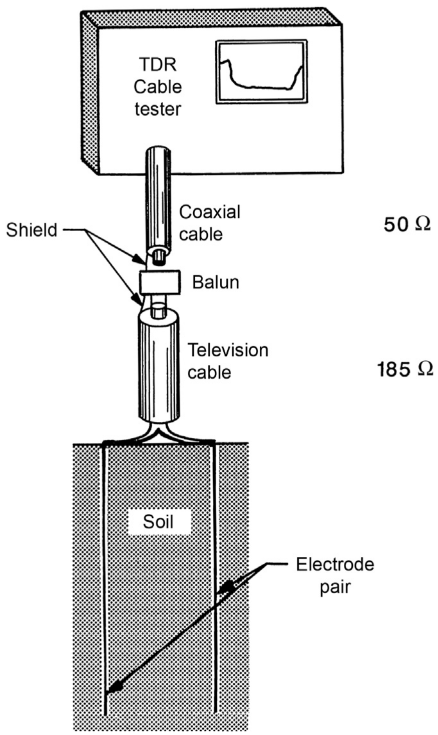

FIGURE 8.7 The basic TDR circuit for use in determining soil moisture. *From Herkelrath et al. (1991). Reproduced by permission of the American Geophysical Union.*

This could also be done to obtain repeated measurements in space, although once the longer probes are inserted, we tend to leave them in place connected to a multiplexer, or with caps on the coaxial connector if single measurements are to be made. Third, B.E. Clothier and S.R. Green in New Zealand have made “direct-wired” probes that they insert horizontally into a face of a pit that they have dug. The probes are inserted horizontally, the hole backfilled, and the probes remain in place underneath undisturbed soil during the summer. One has to be careful when removing them at the end of the experiment, for it is easy to put a spade right through the connector cable when exhuming them (B.E. Clothier, personal communication, February 23, 1994).

Fifth, if we are automating measurements, we need a multiplexer. Baker and Allmaras (1990) describe a system for automated measurements using a multiplexer. Multiplexers are available commercially from Campbell Scientific Corporation (Logan, UT) (Buckley et al., 2010).

8.6 PRACTICAL INFORMATION WHEN USING TDR TO MEASURE SOIL WATER CONTENT

The following are some notes on the use of the TDR technique.

1. Rods normally range in length from 100 mm to 1 m. The shortest depth that I have seen documented in the literature is 50 mm (Mallants et al., 1996). Probes <50 mm do not give good traces (B.E. Clothier and M.B. Kirkham, personal observations, January−April, 1991). Probes >1 m are difficult to insert into the soil without bending them. Sometimes, it is difficult even to insert the probes to this depth (e.g., in the caliche soils of Texas; Todd A. Vagts, personal communication, February 11, 2000). Miller and Buchan (1996) in New Zealand describe the challenges of inserting rods at a depth in a silt loam soil overlying unweathered greywacke gravels and stones with a sand matrix.

   However, the fact that TDR probes measure soil water content only to 1 m does not mean that we do not need to measure deeper than 1 m. Neutron probes can measure to a depth of ≥3 m. Even though TDR is replacing the use of neutron probes, because no danger from radioactivity is involved with TDR, we cannot abandon neutron probes. They provide the only method that can be used to get soil water content at great depths. In semiarid regions such as in Kansas, it is important to measure 2−3 m below the surface of the soil, to determine the maximum depth of water depletion by roots. Miller and Buchan (1996) report the widespread use of neutron probes in Australia and South Africa to schedule irrigations.

2. The rods allow flexibility in determining water content. The spacing and geometry can be changed. Probes can be inserted horizontally or vertically. The ability to insert probes horizontally allows calculation of the velocities of both the wet front and solute front in a soil (Duwig et al., 1997).
3. There is some heating involved while using the TDR method, but given the power levels involved, it is minuscule (B.E. Clothier, personal communication, February 22, 1994).
4. The accuracy of the method is $\pm 0.01\ m^3/m^3$ (Topp, 1993). For comparison, Song et al. (1998) found that the dual-probe, heat-pulse technique (described in Chapter 9) monitored soil water content within $0.03\ m^3/m^3$ and changes in soil water content within $0.01\ m^3/m^3$.
5. The magnitude of reflected signals, after the first one for soil water content, can be used to determine the electrical conductivity of the soil (Topp, 1993). The degree to which the signal is "lost" (attenuated) after all the multiple reflections have died away is due to the soil's electrical conductivity, which is, in some large part, due to the salt content of the solution (B.E. Clothier, personal communication, January 20, 1994). Dalton et al. (1984) were the first to show how the attenuation of the TDR trace can be used to calculate the soil bulk electrical conductivity. Since then, numerous papers have been published using TDR to measure electrical conductivity or solute transport as well as water content (Dasberg and Dalton, 1985; Zegelin et al., 1989; Nadler et al., 1991; Lundin and Johnsson, 1994; Ward et al., 1994; Vogeler et al., 1996; Duwig et al., 1997; Persson et al., 2000; Moret-Fernandez et al., 2012). However, TDR measures solutes in the soil only when they are at a low concentration. TDR cannot measure solutes in saline soil. Vogeler et al. (1996) measured up to 4 mmhos/cm (4 dS/m) electrical conductivity using TDR (see their Figure 6). This shows a low level of salts in the soil. Bernstein (1964) gives the following information about crop response to salinity. From 0 to 2 mmhos/cm, salinity effects are mostly negligible; from 2 to 4 mmhos/cm, yields of very sensitive crops may be restricted; from 4 to 8 mmhos/cm, the yields of many crops are restricted; from 8 to 16 mmhos/cm, only tolerant crops yield satisfactorily; and >16 mmhos/cm, only a few very tolerant crops yield satisfactorily. Wraith (2002) gives the principles of using TDR to determine solute transport. Evett (2003) points out that the TDR method has even been extended to measure atmospheric CO_2 based on the solution electrical conductivity increase caused by its dissolution in water (Baker et al., 1996).

8.7 EXAMPLE OF USING TDR TO DETERMINE ROOT WATER UPTAKE

Many papers have been published that analyze the TDR technique (e.g., Heimovaara and Bouten, 1990) and its use for routine measurements of soil water content (e.g., Grantz et al., 1990), and the literature is growing rapidly. TDR permits observations of the changing pattern of water content in the soil that occurs as a result of root water uptake. Here, we present only one example in which a kiwifruit vine was studied (Clothier and Green, 1994). After an initial irrigation, the soil water content was uniform across the root zone of the kiwifruit vine; also, the water uptake was quite uniform (Figure 8.8, top). Beginning in the tenth week of 1992, just one half of the vine's root zone, the southern half, was wetted by a sprinkler irrigation. Following this differential irrigation of the root zone, the flow of water in the "wet" southern root increased, but the flux in the "dry" northern root was about halved. Thus, the vine quickly switched its pattern of uptake away from the drier parts of its root zone.

Of greater interest, however, was the depthwise pattern of root uptake observed on the wet side. The preference for near-surface water uptake can be seen (Figure 8.8, bottom). The vine continued to extract water in the densely rooted region surrounding its base, but the shift in uptake to the surface roots on the wet southern side was remarkable.

The results show that a greater efficiency in irrigation water might be obtained by applying small amounts of water, more frequently. A small amount of irrigation water would be rapidly used by active, near-surface roots. This would then eliminate drainage of irrigation water into the lower regions of the root zone, where draining water passes by inactive roots and goes to a greater depth. Such observations are made possible by using TDR.

8.7.1 Sample Problem

Like Clothier and Green (1994), Clothier and Kirkham (1991) also measured water extraction by roots at different depths in the same kiwifruit orchard (TDR data not published, but data on kiwifruit growth are published in Clothier and Kirkham (1991)). They used TDR equipment supplied by the Soilmoisture Equipment Corporation (Santa Barbara, CA) and waveguides of three different lengths: 20, 40, and 60 cm. Here, are actual data observed on the readout:

20 cm waveguide: 38.0%
40 cm waveguide: 32.3%
60 cm waveguide: 28.0%

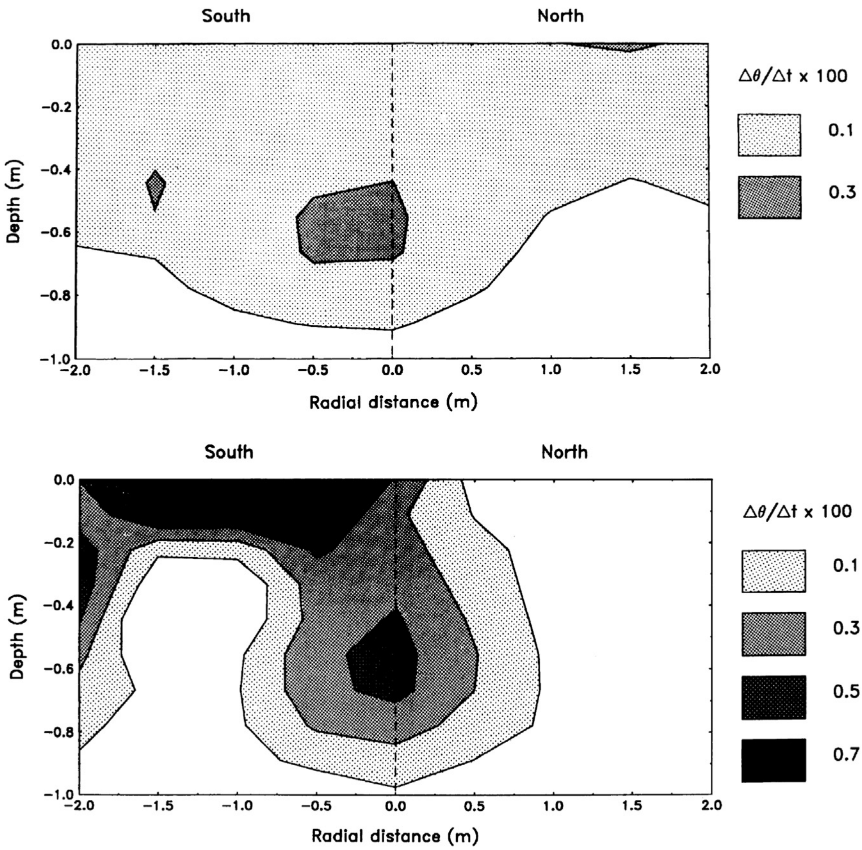

FIGURE 8.8 Measurement by time domain reflectometry of the changing spatial pattern of soil water content in the root zone of a kiwifruit vine growing near Palmerston North, New Zealand. The upper figure depicts the average rate of water content change over the four-week period, February 11–March 9, 1992. The lower figure shows the change that occurred over the two weeks following irrigation of just the south side on March 10. Rate of water extraction $\Delta\theta/\Delta t$ is given in units of cubic meter per cubic meter per second. The vine is located at the center. *From Clothier and Green (1994). Reprinted by permission of Elsevier, Amsterdam.*

Problem: What are the water contents (percent by volume) at the 0–20 cm depth, the 20–40 cm depth, and the 40–60 cm depths? We use θ to symbolize the volumetric water content and L to symbolize the length of the waveguide.

Answers:

0–20 cm depth: The value observed on the readout is the answer (38.0%).

20−40 cm depth: $\theta_{20-40\text{cm}} = [(L_{40}\theta_{40})-(L_{20}\theta_{20})]/(L_{40}-L_{20}) =$
$[(40\text{ cm})(0.323)-(20\text{ cm})(0.380)]/(40-20\text{ cm}) = 5.32\text{ cm}/$
$20\text{ cm} = 0.266$ or 26.6%
40−60 cm depth: $\theta_{40-60\text{cm}} = [(L_{60}\theta_{60})-(L_{40}\theta_{40})]/(L_{60}-L_{40}) =$
$[(60\text{ cm})(0.280)-(40\text{ cm})\ (0.323)]/(60-40\text{ cm}) = 3.88\text{ cm}/$
$20\text{ cm} = 0.194$ or 19.4%.

The answers are as follows:

0−20 cm depth: 38.0%
20−40 cm depth: 26.6%
40−60 cm depth: 19.4%

Note that a waveguide determines the soil moisture over its entire length. To obtain water extraction by roots at specific depths, one must do the above calculations.

8.8 COMMERCIALLY AVAILABLE EQUIPMENT

The Soilmoisture Equipment Corporation (Santa Barabara, CA) sells TRASE, which measures soil moisture using TDR. Clarke Topp worked with the Soilmoisture Equipment Corporation to develop the equipment. It comes with two-pronged probes and a balun. The equipment allows one to see the trace of the wave on a screen (see Figure 8.3 for an example of a wave trace). An earlier model sold by the Soilmoisture Equipment Corporation, called Instrument for Reflectometry Analysis of Moisture in Soil (IRAMS), also was developed by Clarke Topp, but the IRAMS did not display the wave trace. As we shall note in Chapter 9, one can also measure soil moisture accurately by using the dual-probe, heat-pulse technique. Many soil moisture sensors are on the market, but, as described in Chapter 9, Section 9.16, their principles of operation are not known. They need to be calibrated with a standard method, such as neutron probes. True TDR (TDR that is calibrated and detects the trace of the electromagnetic signal on an oscilloscope) is a reliable way to measure soil moisture. Buckley et al. (2010) used true TDR in studying the effect of tillage on the hydrology of a claypan soil. They built their own TDR equipment using supplies from Campbell Scientific (Logan, UT). In their experiment, the trace is not seen on an oscilloscope but is detected digitally using the Campbell Scientific equipment. One can save the traces and review them after measurement. Setting up the equipment takes much effort and a knowledge of software. Reproducible results with TDR in different soils are hard to obtain (G.J. Kluitenberg, personal communication, July 17, 2013). Each TDR instrument needs to be calibrated. Results with TDR depend on pH, what is in the soil solution, the type of soil, and the wavelength.

8.9 APPENDIX: BIOGRAPHY OF HEINRICH HERTZ

Heinrich Rudolf Hertz (1857–1894), a German physicist, was born on February 22, 1857, at Hamburg. After leaving the gymnasium, he studied civil engineering, but at the age of 20, he came to a turning point in his career (Cajori, 1929, p. 258) and abandoned engineering in favor of physics. He went to Berlin, and worked under Hermann Ludwig Ferdinand von Helmholtz (German physiologist and physicist, 1821–1894), advancing rapidly to become his assistant by 1880. In 1883, he became a private docent (official but unpaid lecturer) at Kiel. There he began the studies of Maxwell's electromagnetic theory (James C. Maxwell, Scottish physicist, 1831–1879), which resulted in the discoveries—between 1885 and 1889, while he was the professor of physics in the Polytechnic in Karlsruhe, Germany (Preece, 1971; cited under Hertz)—that made Hertz's name famous. It was there that he performed his memorable experiments on electromagnetic waves.

In 1888, Hertz found means of detecting the presence of electromagnetic waves arising from a Leyden jar (Cajori, 1929, p. 259). A Leyden jar, named after the Dutch city of Leiden in The Netherlands, where it was invented, is a glass jar coated outside and inside with tin foil and having a metallic rod connecting with the inner lining and passing through the lid (Webster's New World Dictionary of the American Language, 1959). It acts as a condenser for static electricity (Figure 8.9). During the oscillatory discharge of a Leyden jar, electromagnetic waves radiate into space. Such a wave is called "electromagnetic", because it has two components: an electric wave and a magnetic wave. Hertz was able to observe each

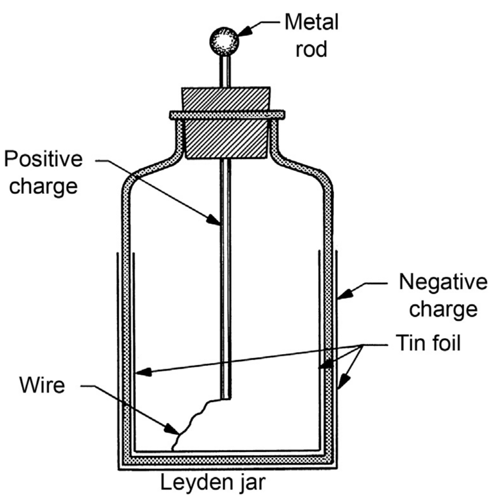

FIGURE 8.9 Leyden jar. *From Webster's New World Dictionary of the American Language: College Edition (1959). All rights reserved. Rights now owned by Wiley. Reproduced here by permission of Wiley Publishing, Inc., Indianapolis, IN.*

separately, an accomplishment that Maxwell had feared would never be realized (Cajori, 1929, p. 259).

In 1889, Hertz was appointed to succeed Rudolf Julius Emanuel Clausius (German physicist, who made important contributions to molecular physics; 1822−1888) as the professor of physics at the University of Bonn. Thus, at the age of 32, he occupied a position attained much later in life by most men of his time. There he continued his research on the discharge of electricity in rarefied gases, only just missing the discovery of the X-rays described by Wilhelm Konrad Röntgen (German physicist, 1845−1923, who received the Nobel Prize in physics in 1901) a few years later. There Hertz wrote his treatise *Principles of Mechanics*. In 1892, a chronic blood poisoning began to undermine his health, and, after a long illness, he died in the prime of life on January 1, 1894, in Bonn. By his premature death, science lost one of its most promising disciples (Preece, 1971). For a book that describes Hertz's experiments and production of electromagnetic waves, see Buchwald (1994).

8.10 APPENDIX: BIOGRAPHY OF SERGEI SCHELKUNOFF

Sergei A. Schelkunoff, inventor and expert on electromagnetism, was born in Samara, Russia. He researched the coaxial cable now widely used for television transmission (Lambert, 1992). He was a student at the University of Moscow when he was caught up in the tumult of World War I and the Bolshevik Revolution. Drafted and trained as a Russian Army officer in 1917, he fought and worked his way across Siberia into Manchuria and on to Japan before landing in Seattle in 1921. He learned English and worked his way through school, earning both bachelor's and master's degrees in mathematics from the State College of Washington, now the University of Washington, and a doctorate from Columbia University in New York City in 1928.

He went to work for Western Electric's laboratories and its successor, Bell Labs, and in his 35 years there, he became assistant director of mathematical research and assistant vice president for university relations. The government granted him 15 patents for radio antennas, resonators, and wavelength guides. In 1935, he and three colleagues reported that the newly developed coaxial cable could transmit television or up to 200 telephone circuits. He specialized in coaxial frequency, impedance, attenuation, coupling, shielding, circuit, and field characteristics. He published four books and dozens of papers in scientific journals, and also taught for five years at Columbia University, where he retired in 1965. The Institute of Radio Engineers awarded him a prize for his contributions to radiowave transmission theory, and the Franklin Institute awarded him a medal for his communication and reconnaissance research. He died of a heart ailment at age 95 on May 2, 1992. He had no immediate survivors. His wife of 51 years, the former Jean Kennedy, died in 1979.

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