13

Time Domain Reflectometry to Measure Volumetric Soil Water Content

In Chapter 4 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. This method is the most widely used one, aside from the gravimetric method, to determine soil water content.

Time domain reflectometry (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.

I. DEFINITIONS

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

$$F = (QQ')/(\varepsilon r^2) \tag{13.1}$$

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.

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 (units = cycles per second).

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 per second or $f = 5\ \mathrm{s}^{-1} = 5$ Hz.

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

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 Fig. 13.1. 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 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 Fig. 13.1(**B**). These curves show successive "snapshots"

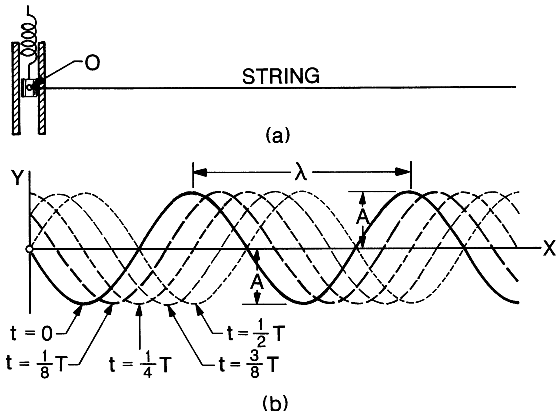

FIG. 13.1 Production and propagation of a sinusoidal transverse wave in a long string shown in part (**A**). Part (**B**) shows the motion of the string during one half-cycle of oscillation of O, shown in part (**A**), from $Y = 0$ to $+A$ and back to 0. (From *Elements of Physics*, 5th ed., by Shortley, G., and Williams, D., p. 416, ©1971. Reprinted by permission of Pearson Education, Inc.: Upper Saddle River, New Jersey.)

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

$$v = \lambda/T, \tag{13.2}$$

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

$$v = f\lambda \tag{13.3}$$

or

$$\lambda = v/f. \tag{13.4}$$

II. 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 is required for 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 time domain reflectometry, a pulse is used that simultaneously contains all the frequencies of interest (Fellner-Feldegg, 1969). In the frequency range of 1 megaHertz (MHz) to 1 gigaHertz (GHz), the dielectric constant is not strongly frequency dependent (mega = 10^6 and giga = 10^9). Figure 13.2 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 radio waves at about the same power as that emitted by today's cellular phones can break down the binding of calcium to the surface of cells. Calcium is essential for virtually all living processes, including enzyme action and cell growth. Data showed that the breakdown occurred at 145 MHz, the frequency at which ham radios operate, and at 450 MHz, the frequency used by security guards' radio phones. European cellular systems operate at 450 MHz (Clark, 1994).

III. THEORY FOR 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 to 7, and that of air is effectively 1 (ε of air = 1.000590). Thus

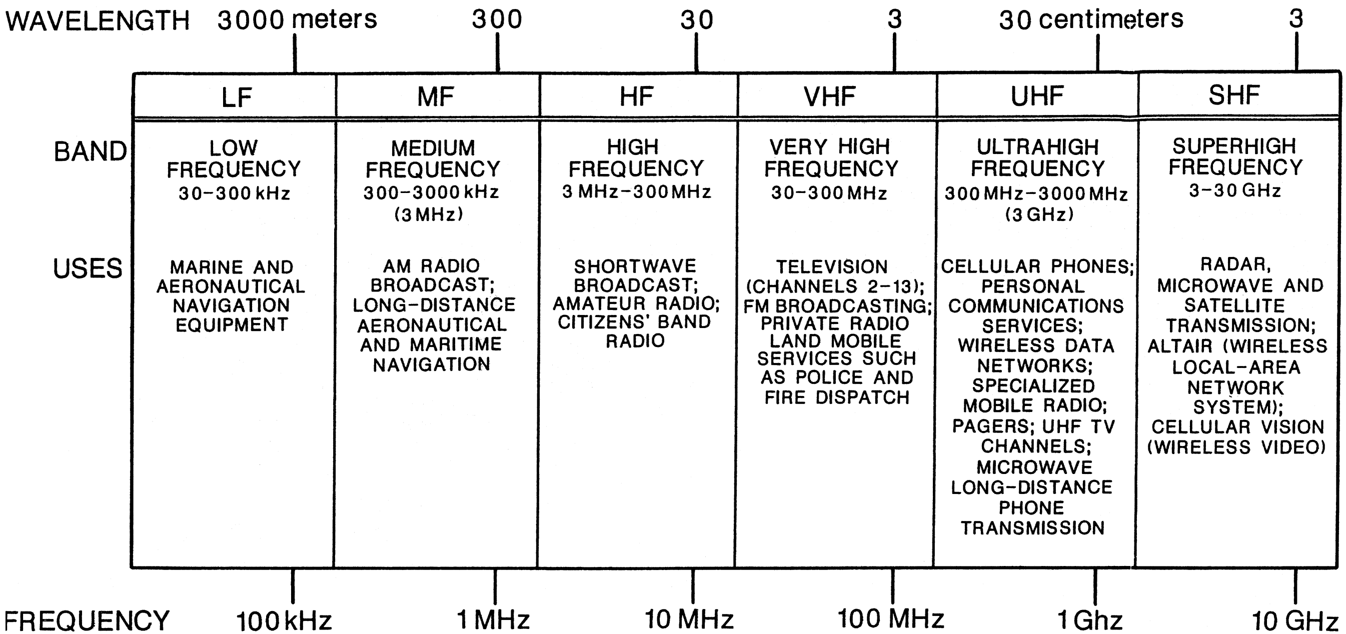

FIG. 13.2 Wavelengths, frequencies, and their uses. (From Clark, D., 1994. Reprinted by permission of The Wall Street Journal, ©1994, Dow Jones & Company, Inc. All Rights Reserved Worldwide.)

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. And 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 to 1 GHz). The velocity of propagation is as follows:

$$V = c/(K')^{1/2}, \tag{13.5}$$

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' = dielectric constant of the soil.

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

Equation 13.5 can be rearranged to give the apparent dielectric constant as

$$K_a = [(ct)/L]^2 \tag{13.6}$$

where K_a is the apparent dielectric constant. However, we need to add a "2" to the denominator in Equation 13.6, 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 two times the line length. So we have

$$K_a = [(ct)/2L]^2. \tag{13.7}$$

The relationship in Equation 13.5 is approximate, so in Equations 13.6 and 13.7 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 (Fig. 13.3 from Clothier et al., 1994), so that

$$K_a = [(ct)/2L]^2 = (l_a/Lv_p)^2 \tag{13.8}$$

where v_p is the relative velocity setting of the instrument (Vogeler et al., 1996; see their Equation 10). It is relative so it is unitless (v = the Greek letter nu.) The reason the 2 appears in the first equation of Equation 13.8 is that the echo must travel down and back along the rods of

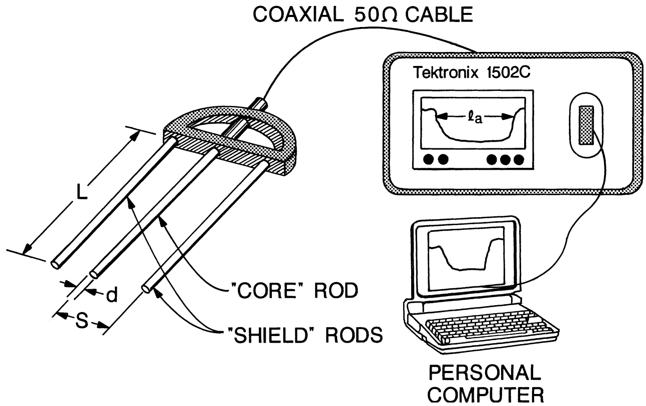

FIG. 13.3 Schematic diagram of the TDR system with the three-rod probe, the cable tester, and the computer that controls, acquires, and analyzes the data. (From Clothier et al., 1994. Reprinted by permission of Brent E. Clothier.)

length L, as noted above. On the right-hand side of Equation 13.8, 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, Oregon) 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 2 times the length, and saves the operator the hassle by dividing by two before it puts the trace on the screen (Fig. 13.3).

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

$$\theta_v = -0.053 + 0.0292\, K_a - 5.5 \times 10^{-4}\, K_a^{\,2} + 4.3 \times 10^{-6}\, K_a^{\,3} \quad (13.9)$$

Equation 13.9 has been shown to hold for many different types of soil. 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, Equation 13.9 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., Equation (13.9), predicted 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.

IV. 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) (Fig. 13.4). S.A. Schelkunoff was a developer of the coaxial cable. (See the Appendix, Section X, 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 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^{-1}, and f is the frequency) (Lorrain and Corson, 1979, p. 304). At these frequencies, of the order of 10^{10} Hertz, 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 (Fig. 13.5), 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 Fig. 13.4. 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

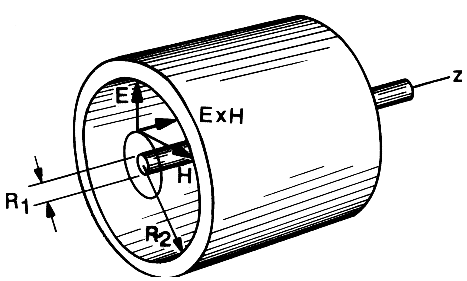

FIG. 13.4 Coaxial line. We assume that the wave propagates in the positive direction of the z-axis. E = electric field intensity; H = magnetic field intensity; R_1 and R_2 = radii of the inner and outer conductors, respectively. (From Lorrain, P., and Corson, D.R., *Electromagnetism: Principles and Applications* p. 488, ©1979 by W.H. Freeman and Company: San Francisco. Used with permission.)

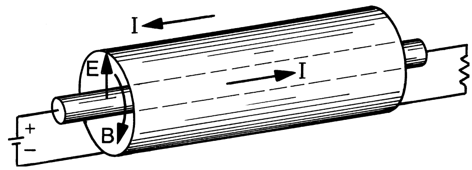

FIG. 13.5 Coaxial line. E = electric field intensity; B = magnetic induction; I = electric current. (From Lorrain, P., and Corson, D.R., *Electromagnetism: Principles and Applications* p. 304, ©1979 by W.H. Freeman and Company: San Francisco. Used with permission.)

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}).

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.

V. 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 (Fig. 13.6). 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 high frequency (in the GHz 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 (Fig. 13.7).

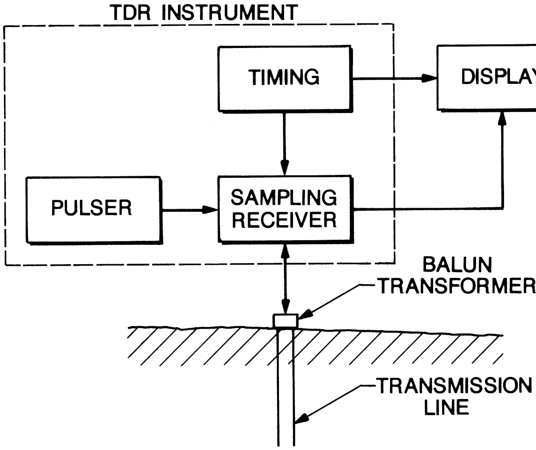

FIG. 13.6 A block diagram of a TDR instrument and its display units. (From Topp, G.C., Soil water content. In *Soil Sampling and Methods of Analysis*, (M.R. Carter, Ed.), p. 545, ©1993, CRC Press: Boca Raton, Florida.)

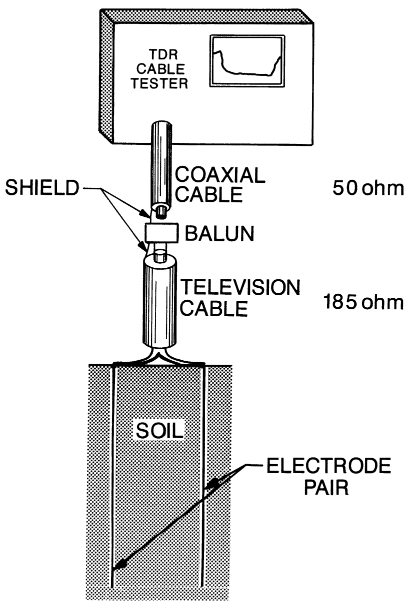

FIG. 13.7 The basic TDR circuit for use in determining soil moisture. (From Herkelrath, W.H., Hamburg, S.P, and Murphy, F. Automatic, real-time monitoring of soil moisture in a remote field area with time domain reflectometry. *Water Resources Research* 27(5); 857, 864, 1991. Copyright ©1991, American Geophysical Union. Reproduced by permission of the American Geophysical Union.)

The coaxial cable in Fig. 13.7 is 50 ohm. The coaxial cable is connected to an 185-ohm 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 or more 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. This way we can easily take many readings and quickly get a "feel" for spatial variability. Second, for longer probes, it is necessary to make "pre-holes" with a dummy probe. 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).

And, fifth, if we are automating measurements, we need a multiplexer. Baker and Allmaras (1990) describe a system for automated measurements using a multiplexer.

VI. PRACTICAL INFORMATION WHEN USING TDR TO MEASURE SOIL WATER CONTENT

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 shorter than 50 mm do not give good traces (B.E. Clothier and M.B Kirkham, personal observations, January–April, 1991). Probes longer than 1 m are difficult to insert into the soil without them bending. 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 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 meters or more. 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 deep depths. In semi-arid regions like Kansas, it is important to measure 2 to 3 m below the surface of the soil, to determine 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 with 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 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 electrical conductivity of the soil (Topp, 1993). The exact relation has yet to be established. 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).

6. Simultaneous measurements of soil water content and electrical conductivity by using TDR have been done (Dalton et al., 1984; Dasberg and Dalton, 1985; Zegelin et al., 1989; Nadler et al., 1991), and the method is being used to determine solute transport (Lundin and Johnsson, 1994; Ward et al., 1994; Vogeler et al., 1996; Duwig et al., 1997).

VII. 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 (Fig. 13.8, 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 (Fig. 13.8, 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 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 greater depth. Such observations are made possible by using TDR.

VIII. HYDROSENSE™

Campbell Scientific, Inc. sells the HydroSense™ to measure soil water content (Tanner, 1999). It consists of a sensor with two parallel rods. The HydroSense™ is often referred to as a quasi-TDR device. Its frequency is

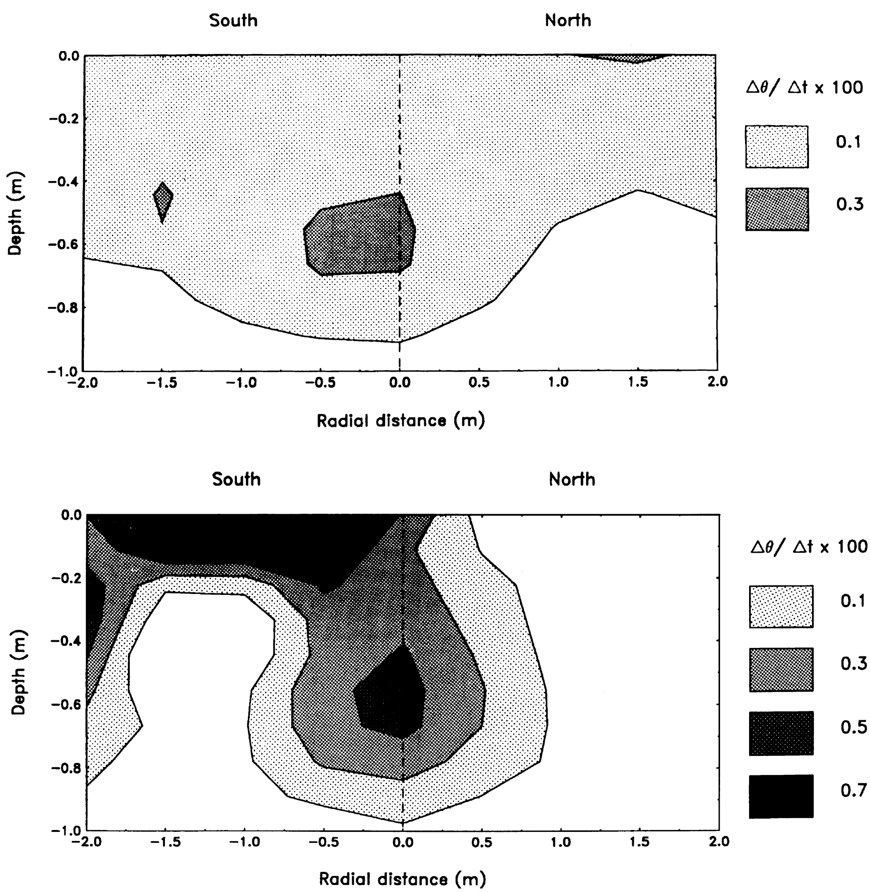

FIG. 13.8 Measurement by time domain reflectometry of the changing spatial pattern of soil water content in the root zone of a kiwifruit vine growing near Palmerston North, New Zealand. The upper figure depicts the average rate of water content change over the four-week period 11 February–9 March 1992. The lower figure shows the change that occurred over the two weeks following irrigation of just the south side on 10 March. Rate of water extraction $\Delta\theta/\theta t$ is given in units of $m^3\ m^{-3}\ s^{-1}$. The vine is located at the center. (From Clothier, B.E., and Green, S.R., Rootzone processes and the efficient use of irrigation water, *Agricultural Water Management* 25; 1–12, ©1994, Elsevier Science: Amsterdam. Reprinted by permission of Elsevier, Amsterdam.)

not in the GHz range of true TDR, but it is a good instrument once an electrical conductivity has been calibrated (B.E. Clothier, personal communication, March 6, 2000). The HydroSense™ has the advantages of being easily portable (hand-held) and cheap. Because it measures both water and solute concentration, one can track tracers with it.

The product brochure describes the instrument as follows (Tanner, 1999): The HydroSense™ "consists of an electronic circuit encapsulated in epoxy. Replaceable rods are 5 mm in diameter and are available in 12- and 20-cm lengths. A measurement is made by fully inserting the rods into the soil and pressing the READ button." The display gives volumetric water content in percent. The instrument also can be set in the water deficit mode in which the user sets "lower and upper water content references by taking measurements under those conditions and storing the values in memory. Once reference values are stored, subsequent measurements provide a display of the relative water content and the water deficit."

To calibrate the probe, mix up some soil of known water content in the laboratory and insert the probes into it. If one chooses 2-3 water contents, one can get a feel as to which electrical conductivity setting to use in the Hydrosense™ to get the right water content result (B.E. Clothier, personal communication, March 3, 2000).

IX. 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 professor of physics in the Polytechnic in Karlsruhe, Germany (Preece, 1971)—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 (Fig. 13.9). 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

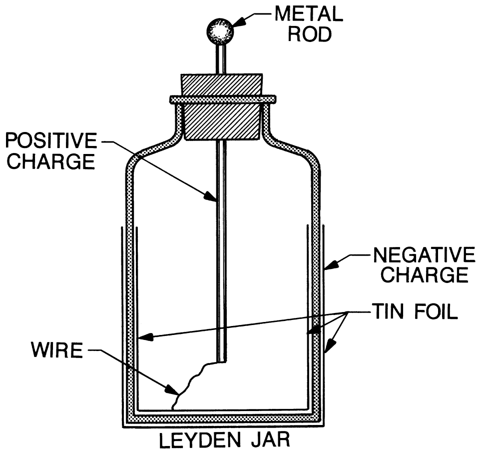

FIG. 13.9 Leyden jar. (From *Webster's New World Dictionary of the American Language: College Edition*. Copyright ©1959, The World Publishing Company: Cleveland and New York. All rights reserved. Rights now owned by Wiley. Reproduced here by permission of Wiley Publishing, Inc., Indianapolis, Indiana.)

wave and a magnetic wave. Hertz was able to observe each 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 professor of physics at the Univeristy 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 researches 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).

X. 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's 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 radio wave 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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