Development of a Resonant Length Technique for Soil Water Content Measurement

G. C. Starr,* B. Lowery, E. T. Cooley, and G. L. Hart

ABSTRACT

Oven drying a soil sample of known volume is one of the few inexpensive methods for measuring volumetric water content (θ_v). Repetitive application of this technique to field soil sampling is a laborious, time-consuming, and destructive process. Faster and less destructive low-cost methods are needed in all branches of soil science. A technique has been developed that quickly determines θ_v by monitoring the reflected power amplitude with a parallel-rod waveguide probe inserted into soil. Reflected power reaches a distinct minimum when a resonant condition is reached; at this point, the depth of insertion or resonant length (L_{res}) is measured and calibrated against θ_v. An inverse relationship is derived showing that L_{res} increases with decreasing water content. This measurement does not require a microprocessor, as do most time domain reflectometry (TDR) systems. Second-order polynomials adequately describe the calibration curves between L_{res} and θ_v in three soils with coefficients of determination >0.99. Zone of influence varies with θ_v, but the range of L_{res} and θ_v may be tailored to experimental needs by varying the operational frequency or probe length. For a 30-cm probe and 141-MHz operating frequency, L_{res} varies from 1 to 6 cm with a θ_v range from 0.20 to 0.0 $m^3\ m^{-3}$. The need for calibration, water content range, and variable zone of influence could be disadvantages; thus, this technique is not a replacement for more complex and expensive methods, such as TDR.

OVEN DRYING SOIL SAMPLES is a reliable, simple, and accurate means of obtaining gravimetric or volumetric water content (θ_g and θ_v, respectively). Measures of sample volume, wet weight, and oven-dry weight yield not only θ_v, but also the bulk density (ρ_b). However, soil destruction and the time and labor required for this method make it impractical when the required data sets are large or repeated sampling is needed. Many other methods exist that do not have the shortcomings of gravimetric or volumetric sampling, but many of these are expensive. Electromagnetic (EM) or dielectric techniques such as time-domain reflectometry (TDR) (Topp et al., 1980) and frequency-domain reflectometry (Thomas, 1966; Dean et al., 1987; Hilhorst and Dirksen, 1994) utilize EM waves to make very fast measurements from which accurate θ_v may be inferred once a calibration is ascertained. The instrumentation is expensive, but the potential for remote logging and multiplexing (Baker and Allamaras, 1990) are strong advantages of EM techniques. Neutron probes (Belcher et al., 1950; Gardner et al., 1991) work well when profiles of θ_v vs. depth are needed, but these instruments have a radioactive source and require painstaking storage, licensing,

record keeping, calibration, and face increasing use restrictions that prohibit many applications, such as remote, in situ logging. A quick, low-cost, non-destructive, and non-radioactive method would offer many advantages for a wide range of applications.

A relatively simple EM sensor has been developed which may provide an inexpensive alternative to gravimetric sampling with minimal soil disturbance and time requirements. The system exploits a unique resonant condition exhibited by a TDR waveguide when a sine wave excitation is transmitted along the waveguide. There is a characteristic length (L_{res}) of insertion required for the probe to act as a resonator for a fixed-frequency sinusoidal wave. The required resonant condition is identified by monitoring the reflected signal amplitude while the probe is inserted. When the reflected signal amplitude is minimum, a resonant condition has been reached. The objective of this paper is to describe the theory, method, and instrumentation that may be applied to determine θ_v in a wide variety of situations.

There were three phases in the development of this concept into a working prototype. Initially, the principles of electrodynamics and resonance were applied on a waveguide probe to relate L_{res} to dielectric constant and θ_v. Results of the theory were used to determine instrumentation design parameters, such as operating frequency and probe length, and to estimate the effects of changing ρ_b and temperature on measured θ_v. Finally, a reflectometer was designed and constructed for field use. The frequency domain and length domain responses of the probes were studied with a network analyzer to get a better understanding of the measurement method and to elucidate key points of the theory. Although the soil dielectric constant and a probe constant are needed for the theory, in practice only length needs to be recorded, which represents a marked difference between this and other EM θ_v sensors.

THEORY

As water content increases in soil, the apparent dielectric constant (K_a) also increases because of the uncommonly large dielectric constant of water ($K_w = 80$) compared with soil solids ($K_s = 4$) and air ($K_{air} = 1$) (Topp et al., 1980). The ability to relate water content to measurements of soil K_a is the underlying principle behind most EM θ_v methods. Parallel-rod waveguides embedded in soil have wave propagation pa-

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Abbreviations: α, attenuation coefficient; c, velocity of light; C_p, probe constant; δ, phase shift; δ_{air}, air phase shift; δ_b, balun phase shift; EM, electromagnetic; ε_o, permittivity of free space; K_a, apparent dielectric constant; K_{air}, dielectric constant of air; K_s, dielectric constant of soil solids; K_w, dielectric constant of water; L_{res}, resonant length; mU, millivolt · $volt^{-1}$; NA, network analyzer; ω, angular frequency; ϕ, porosity; ρ_b, bulk density; σ, apparent conductivity; T, temperature; TDR, time domain reflectometry; θ_g, soil gravimetric water content; θ_v, soil volumetric water content; v, wave velocity.

rameters that depend on the dielectric properties of the surrounding soil, and this dependence has been evaluated at a theoretical level (Whalley, 1993; Topp et al., 1994) with at least qualitative agreement between theory and experiment. Most theory concerning parallel-rod waveguides in soil science concentrates on TDR applications with considerable emphasis on how observable quantities such as the EM wave attenuation coefficient and propagation velocity depend on the soil properties under investigation, which include K_a, conductivity (σ), salinity, and θ_v. However, little attention has been given to conditions where partially inserted soil waveguides resonate.

The propagation of EM waves is described in simplest terms by the velocity of the waves and the attenuation of their electromotive force. When parallel-rod TDR probes are embedded in soil, the propagation velocity along these rods is strongly influenced by θ_v (Topp et al., 1980; 1994). With TDR, a direct measurement of this propagation velocity may be made and the soil water content determined through calibration. Attenuation of a wave as it travels along the rods is strongly influenced by the salinity of the soil and clay content (Rhoades, 1983; White et al., 1994), but it also has a dependence on water content (Nadler et al., 1991). These effects were expressed mathematically by Topp et al. (1994) using propagation coefficients, which are the attenuation coefficient (α) and the wave velocity (v).

Regarding Eq. [1] through [6], it is not necessary to break the dielectric constant into real and imaginary parts, as in Topp et al. (1994). Using their definition of an apparent dielectric constant (K_a) and defining a conductivity (Jackson, 1975), σ, which includes both the effects of dielectric losses and direct conduction losses, the equations reduce to

$$K_a = (v/c)^2 \qquad [1]$$

and

$$\sigma = K_a^{1/2} \alpha/60\pi \qquad [2]$$

In the above expressions, c is the velocity of light (3×10^8 m s^{-1}). The σ, so defined, has a more intuitive appeal for those who are less familiar with complex electrodynamics and its reliance on imaginary quantities. A typical approach to the analysis of EM sensor data (Topp et al., 1994; Hilhorst and Dirksen, 1994) is to ignore dielectric losses and assume σ equals direct current conductivity. Topp et al. (1994) pointed out that this assumption is not well justified on theoretical grounds, but it is valuable for calibration of TDR probes in solutions where the direct current conductivity is known or independently measured.

In most cases, EM waves may be presumed to travel in transverse electromagnetic mode on parallel-rod waveguides (Whalley, 1993). That is to say, variations in phase and amplitude of sinusoidal waves traveling along the waveguide are the same as those of plane waves with the electric and magnetic fields oriented perpendicularly to the rods. Kim (1985) showed that for plane-wave propagation, the phase shift of a wave that has traveled a given distance can be measured and used to determine θ_v. Kim (1985) evaluated the equation for phase shift, δ,

$$\delta = K_a^{1/2}\omega d/c \qquad [3]$$

of a plane wave of angular frequency (ω) [rad s^{-1}], having traveled a distance (d). The phase shift of a sinusoidal wave that has traveled the length of a probe, been reflected from an open circuit at the end, and returned to its point of departure may be approximated by a generalized equation valid for a parallel-rod waveguide, where an extra term has been added to account for propagation through the balun.

$$\delta = (2K_a^{1/2}\omega L/c) + \delta_b \qquad [4]$$

where L is the length of the waveguide, δ_b (rad) is the phase shift associated with travel through the housing of the balun, and δ is the phase shift between the wave reflected from the balun and the wave reflected from the end of the probe. The factor of two arises because a wave travels the length of the probe twice. In Eq. [4] an assumption is made that propagation through the balun is independent from propagation along the rod: an assumption which is implicit in the analysis of K_a. A resonant condition occurs when the reflection from the balun and from the end of the probe are exactly out of phase. In this condition, superposition of the two major reflections results in destructive interference and a minimum in reflected power. Total destructive interference occurs when the two interfering waves are of equal amplitude. A resonant condition could be reached by attaching a network analyzer to a TDR probe and sweeping frequency. Setting $\delta = \pi + 2\pi n$ rad (where $n = 0$, 1, 2, 3...) in Eq. [4] represents the desired destructive interference. Solving for ω yields the expression for the harmonic resonant frequencies, ω_n, of a probe of length, L:

$$\omega_n = (\pi + 2\pi n - \delta_p)c/2LK_a^{1/2} \qquad [5]$$

Thus, a series of harmonic frequencies of order n is predicted to occur. These frequencies are inversely proportional to (K_a). The phase shift (δ_b) of the balun may be approximated using a probe constant (C_p) approximately equal to the apparent length of the balun:

$$\delta_b = 2\omega C_p/c \qquad [6]$$

The dielectric constant measured at the resonant frequency may be derived by solving Eq. [5] and [6] for K_a which results in

$$K_{a(n)}^{1/2} = [\pi + 2\pi n - (2\omega_n C_p/c)](c/2L\omega_n) \qquad [7]$$

where K_a has been replaced by $K_{a(n)}$ to reflect the fact that K_a may change with resonant frequency (ω_n). Alternatively, the probe can be only partially embedded to a depth, L_{res}, below the soil surface. In this case there will be a reflection from the soil–air interface that has the potential to cause interference and additional resonances at certain frequencies. However, the lowest frequency or fundamental ($n = 0$) harmonic resonance will be associated with reflections from the balun and the end of the probe. Ignoring the reflection from the soil–air interface, a phase shift approximation is

$$\delta = (K_a^{1/2}\omega 2L_{res}/c) + \delta_{air} + \delta_b \qquad [8]$$

Given $K_a = 1$ for air, the phase shift from travel through the air-filled portion of the waveguide, δ_{air}, is

$$\delta_{air} = 2\omega(L - L_{res})/c \qquad [9]$$

and the equation for the nth resonant frequency of a partially embedded probe can be derived from Eq. [6], [8], and [9] by again setting $\delta = \pi + 2\pi n$ and solving the equations:

$$\omega_n = (\pi + 2\pi n)/(2K_{a(n)}^{1/2}2L_{res}/c + 2(L - L_{res})/c + 2C_p/c) \qquad [10]$$

Solving Eq. [10] for L_{res} gives a theoretical equation for resonant length as a function of K_a:

$$L_{res} = [(\pi + 2\pi n)c/2\omega_n - C_p - L]/(K_{a(n)}^{1/2} - 1)$$
$$0 < L_{res} < L \qquad [11]$$

As shown in Eq. [11], an inverse relationship is predicted between $K_{a(n)}$ and L_{res} for each resonant frequency. The numer-

ator of Eq. [11] is a constant when probe length, probe constant, and frequency are fixed, so it is predicted that L_{res} will follow an inverse relationship with θ_v, which could be determined by direct calibration of length vs. θ_v. In order to understand the effects of varying soil and instrument parameters, an empirical relationship relating K_a to θ_v and ρ_b (Malicki et al., 1994) was combined with Eq. [11] to extend the theory for predictions of L_{res} vs. θ_v (see following section on ρ_b effects). Figures 1 and 2 show the effects of varying probe length and frequency, respectively, on the fundamental resonance of L_{res} for a wide range of θ_v.

It is clear that L_{res} is much more sensitive to θ_v changes in dry soil. The maximum sensitivity range (steep portions of Fig. 1 and 2) is shifted by varying probe length or frequency. In wetter soil, flatter, almost linear curves are predicted. With a fixed frequency device, multiple harmonic lengths are possible (at values of $n = 0, 1, 2 ...$). At some values of the variables, Eq. [11] gives a negative value for L_{res} or a value of L_{res} that is greater than L. Although mathematically possible, neither of these results is physically possible. This places practical restrictions on the design parameters of a system.

A field instrument described in more detail in a later section has an operating frequency of 141.4 MHz (888.4 rad s^{-1}), and probe parameters are $L = 30$ cm and $C_p = 18$ cm. The requirement $L_{res} > 0$ implies that $L < 35$ cm for $n = 0$ harmonic resonance. Requiring $L_{res} < L$ for the given probe length and the $n = 0$ harmonic places a lower boundary on the measurable value of $K_{a(n)}$. For example, $L = 30$ cm and $n = 0$ places the restriction that $K_{a(0)} > 1.2$. This restriction is met even for the driest desert soil, but if shorter probes are used, two things happen; L_{res} becomes larger for all θ_v, and the minimum $K_{a(0)}$ for the $n = 0$ resonance gets larger, resulting in a minimum θ_v at which the probe will work. The minimum θ_v that can be measured for a given probe length may be calculated theoretically using the resonant condition of a fully embedded probe (Eq. [7]), or by setting $L_{res} = L$ in Eq. [11] and inserting the measured or empirical relation for θ_v as a function of $K_{a(n)}$. For the $n = 1$ harmonic and a 30-cm probe, the minimum $K_{a(n)}$ is 4.75. A second ($n = 1$) harmonic has never been observed in soil experiments with the field instrument that will be presented later. Three harmonics have been observed in water,

which is in accordance with the predicted minimum $K_{a(2)} > 8.3$ for $n = 2$ and $L = 30$ cm. This theory was used in the design of a field instrument that has the desired characteristic of having only one resonance ($n = 0$) for all but the wettest soils. For use in wet soil, it may be desirable to shorten the probe length or lower the operating frequency so that both the sensitivity to soil water content and the magnitude of L_{res} may be appropriate.

Bulk Density Effects

Bulk density variations cause significant changes in the K_a that introduce errors in θ_v estimations, particularly in dry soil. Essentially, the increased density of soil particles in higher ρ_b soil is mistaken for higher θ_v. Therefore, knowledge of the mean field ρ_b of the soil under study is necessary for the most accurate calibrations. Using TDR and a variety of mineral and organic soils, Malicki et al. (1994) found a strong dependence of K_a on ρ_b. Their empirical result relates θ_v to measured K_a by the following formula:

$$\theta_v = (K_a^{1/2} - 0.819 - 0.186\rho_b - 0.159\rho_b^2)/$$
$$(7.17 + 1.18\rho_b) \qquad [12]$$

The ρ_b correction indicates that in a compacted area with a ρ_b of 1.7 g cm^{-3} and a θ_v of 0.10 m^3 m^{-3}, a TDR unit calibrated in soil with a ρ_b of 1.5 g cm^{-3} will read a θ_v of 0.12 m^3 m^{-3}, representing a small, but significant loss in accuracy. Combining Eq. [11] and [12] yields the theoretical effect of varying ρ_b and θ_v on L_{res}:

$$L_{res} = [(\pi + 2\pi n)c/2\omega_n - C_p - L]/$$
$$[-0.181 + 0.168\rho_b + 0.159\rho_b^2$$
$$+ (7.17 + 1.18\rho_b)\theta_v] \qquad [13]$$

Figure 3 shows the ρ_b effect for a range of θ_v. Lower ρ_b will cause larger L_{res} for a given water content. The ρ_b error in going from $\rho_b = 1.5$ to $\rho_b = 1.7$ g cm^{-3} at a θ_v of 0.10 m^3 m^{-3} is very similar to the TDR example discussed above. Both methods will overstate θ_v by ≈ 0.02 m^3 m^{-3}.
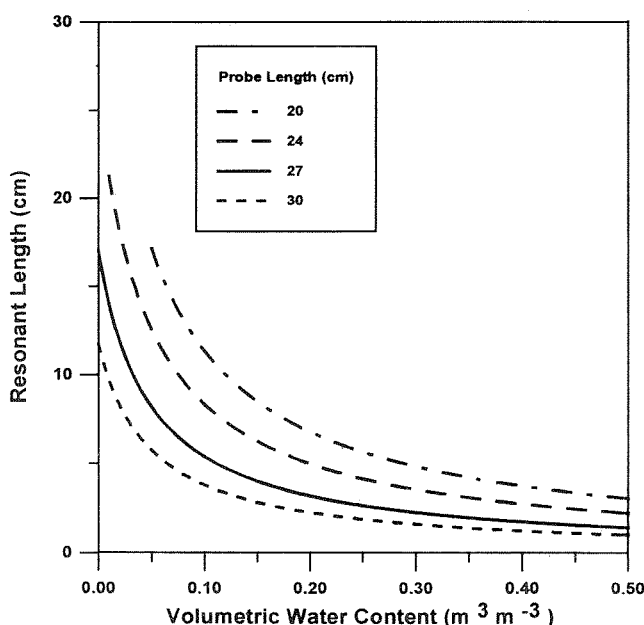

Fig. 1. Predicted resonant length for various probes as a function of soil water content.
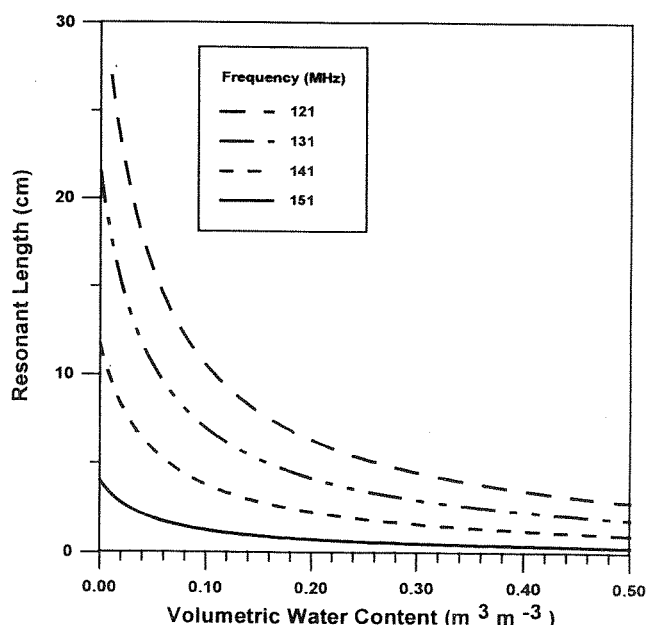

Fig. 2. Predicted resonant length for various frequencies as a function of soil water content.

Zone of Influence

Zone of influence, or sampling volume, is not an accurately known quantity in most θ_v measurement techniques. Approximate volumes are derived theoretically, or they are determined experimentally. If sampling volume changes with θ_v, this must be viewed as a disadvantage of the method. Theoretical approximations of the zone of influence are available for TDR (Whalley, 1993; Knight et al., 1994). A "cylinder of influence" with a radius of ≈ 3 cm is appropriate for a parallel-rod TDR probe with rods separated by 3 cm (Knight et al., 1994). With the L_{res} method, the same cylinder of influence as that for TDR is appropriate, but the length of the cylinder (L_{res}) varies with water content.

Temperature Effects

Dielectric constant depends upon temperature (T), which may be a source of error in θ_v measurements. The effects of T can be estimated by assuming that T dependence of the water phase is primarily responsible for changes in K_a (Hook and Livingston, 1996). The dependence of K_a in pure water on T may be estimated by

$$K_w = 78.54[1 - 4.579 \times 10^{-3}(T - 25) + 1.19$$
$$\times 10^{-5}(T - 25)^2 - 2.8 \times 10^{-8}(T - 25)^3] \qquad [15]$$

Here, K_w is the dielectric constant of water and T is in °C (Weast, 1986). In a physical model that closely resembles sandy soils with low salt contents, Roth et al. (1990) give a simple mixing law:

$$K_a^{1/2} = \theta_v K_w^{1/2} + (1 - \phi)K_s^{1/2} + (\phi - \theta_v)K_{air}^{1/2} \qquad [16]$$

This model treats the soil as a composite dielectric with the index of refraction (K_a) set equal to the sum of the refractive indices of water (K_w), air (K_{air}), and soil solids (K_s) weighted by the respective volumetric fractions of water (θ_v), solids ($1 - \phi$), and air ($\phi - \theta_v$), where ϕ is porosity. Substituting the properties of sand at a bulk density of 1.5 g cm^{-3} ($\phi = 0.43$, $K_s = 4$, $K_{air} = 1$) yields

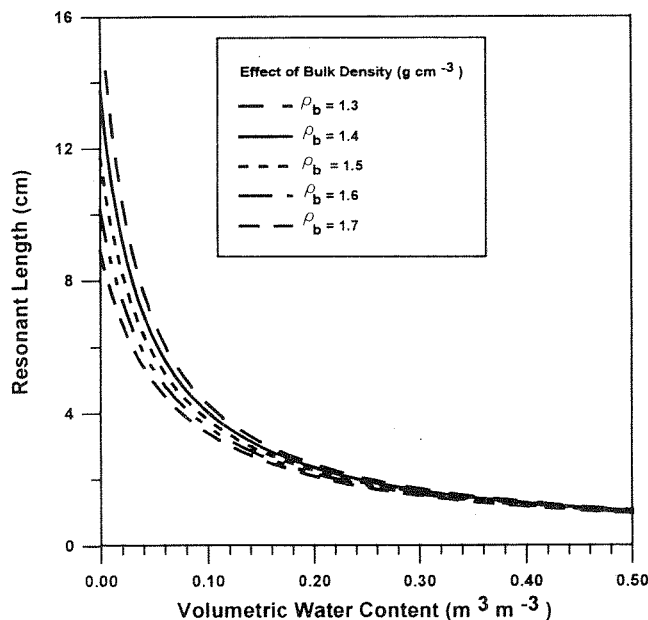$$K_a^{1/2} = \theta_v(K_w^{1/2} - 1) + 1.56 \qquad [17]$$

Combining Eq. [15] and [17] gives an equation for the T effect on K_a in sand:

$$K_a^{1/2} = \theta_v\{(78.54[1 - 4.579 \times 10^{-3}(T - 25)$$
$$+ 1.19 \times 10^{-5}(T - 25)^2 - 2.8$$
$$\times 10^{-8}(T - 25)^3])^{1/2} - 1\} + 1.56 \qquad [18]$$

This model indicates that if a TDR calibration is done at a θ_v of 0.10 m^3 m^{-3} and a T of 25°C, then a K_a of 5.82 will be measured. At a T of 30°C, the K_a decreases to 5.79. This causes a very small and acceptable error of only ≈ 0.001 m^3 m^{-3} in θ_v. Combining Eq. [18] and [11] gives a formula to estimate the effects of T and θ_v on L_{res} in a sand:

$$L_{res} = [(\pi + 2\pi n)c/2\omega_n - C_p - L]/[\theta_v\{(78.54[1$$
$$- 4.579 \times 10^{-3}(T - 25) + 1.19$$
$$\times 10^{-5}(T - 25)^2 - 2.8 \times 10^{-8}(T - 25)^3])^{1/2}$$
$$- 1\} + 0.56] \qquad [19]$$

Figure 4 depicts the effect of widely varying T on a measurement of L_{res} at a variety of θ_v. Unlike ρ_b, which shows the greatest effect in dry soil, T has the greatest effect in wet soil. Care must be exercised in the application of this model to soils high in peat, clay, or salinity in which the dielectric properties are more complex and greater temperature effects have been observed (Pepin et al., 1995). Temperature effects are typically neglected in the analysis of TDR and many other EM θ_v sensors (Hook and Livingston, 1996).

Laboratory Test of the Resonant Length Technique

To detect L_{res} a relatively simple field instrument was constructed operating at a radio frequency of 141.4 MHz. Important components of this system are a crystal oscillator that generates a sine wave, an amplifier that increases the transmitted power and absorbs part of the reflected power, a directional coupler that diverts part of the reflected power for measurement, and a power meter on which reflected power amplitude may be read. A schematic diagram is shown in Fig. 5. A fixed frequency sine wave excitation is generated in a
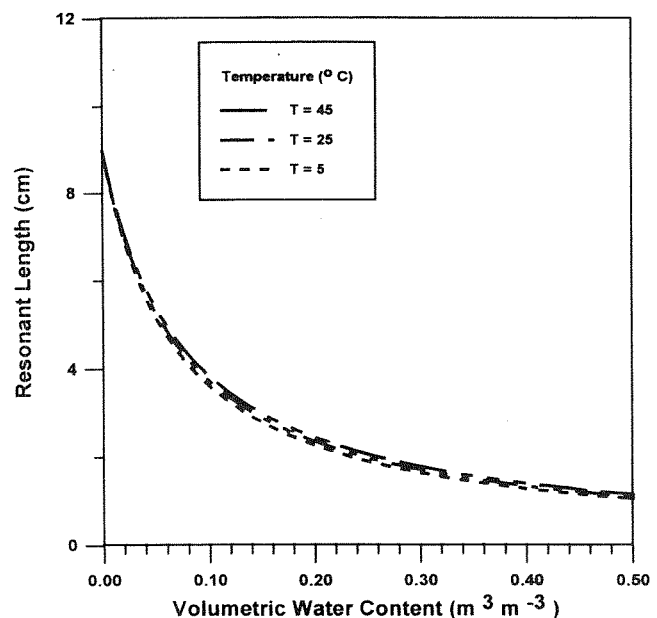
Fig. 3. Predicted resonant length for various soil bulk densities (ρ_b) as a function of water content.

Fig. 4. Predicted resonant length for various temperatures (T) as a function of water content.
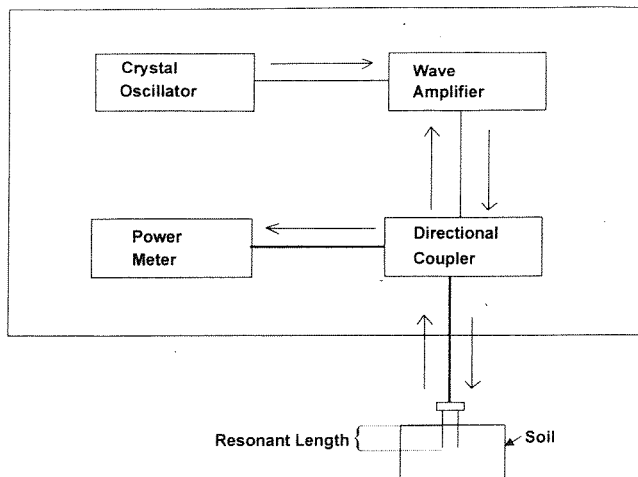
Fig. 5. Schematic of wavelength domain electronic components.

crystal oscillator and is sent through an amplifier. The amplified wave passes unimpeded through a directional coupler, then through coaxial cable to a 30-cm parallel-rod TDR probe (Midwest Specialty Supply, Minneapolis, MN)[1]. The reflected wave returns along the coaxial cable. A portion of the reflected power is sent to a power meter through the directional coupler. The remainder of the reflected wave returns to the amplifier where its energy is dissipated as heat.

The instrument's circuit box was mounted on a frame with a carrying strap. An external digital volt meter provides the readout as DC voltage. The majority of the system mass ($\approx$6 kg) is in the battery (Panasonic LCR12v6.5, Secaucus, NJ), which has a mass of 2.4 kg, and in the frame (designed for carrying or mounting), which has a mass of $\approx$3 kg. The combined cost of materials used to construct the field instrument was approximately $800, which may be compared with the cost of a cable tester (Tektronix 1502C, Redmond, OR) of about $7000 and the cost of the network analyzer used in this study of about $12 000 (HP8712B Hewlett Packard, Santa Rosa, CA). The system was constructed from packaged integrated circuits (widely sold for radio applications) with subminiature coaxial connections between components. If a printed circuit board was designed, cost of producing the field instrument would be around $300.

The system was calibrated for reflected power measurement with a Thruline model 43 directional power meter (Bird Electronic, Cleveland, OH). Operational frequency and signal integrity were verified with a 2230 oscilloscope (Tektronix, Redmond OR). A network analyzer (HP8712B, Hewlett Packard, Santa Rosa, CA) provided an alternative measure of L_{res} and generated data on the frequency domain response of partially embedded probes.

For testing the L_{res} method, known amounts of water were mixed with oven-dry soil and packed into 1-L samples in a 2-L plastic beaker. Amplitude, monitored by the operator while the probe was inserted, drops dramatically near the resonant length and reaches a minimum. Reflected power drops from $\approx$150 mW when the probe is in air to <10 mW when inserted to the resonant length in soil. At the first detected increase of amplitude, the operator stops. At this point, a clamp, consisting of two pieces of wood and a hinge, is placed on the waveguide at the soil–air interface, the probe pulled from the soil, and length of probe below the soil surface (L_{res}) measured. A length accuracy of about ±1 mm was ob-

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[1] Mention of company and/or product does not constitute endorsement by the Univ. of Wisconsin, Madison.

tained provided the soil surface was flattened. A jig, consisting of an 8 × 8 cm square piece of 2.2-cm thick plywood coated with polyurethane and having two, 0.32-cm diam. holes separated by 0.03 m, was sometimes used to guide the probe into soil. Although we have not found the jig and clamp to be necessary in laboratory studies where the surface of soil was flat, it may be useful in field applications (such as in turfgrass) to flatten the soil surface. With practice the measurement process can take place within 30 s, but the time required is longer in very dry soil because the probe must be inserted further. Once a calibration of L_{res} vs. θ_v is ascertained, a calibrated measuring scale is made that allows for a direct readout in units of soil water content (m^3 m^{-3}). When L_{res} is less than $\approx$1 cm, it was difficult to measure accurately, and when L_{res} exceeded about 25 to 30 cm, it became difficult to insert the probe by hand.

The instrument was calibrated for L_{res} vs. θ_v in three very different soils: a coarse textured (Sparta, uncoated mesic, Typic, Quartzipsamments), a fine textured (Griswold, fine-loamy, mixed, mesic Typic Hapludalfs), and high organic matter soil (a standard mixture used to construct golf course greens). The C horizon of Sparta sand, which is >99% sand and <1% organic matter, was used. The B horizon of Griswold silty clay loam, a fine textured soil with 30% clay, 60% silt, and 10% sand was used. Golf course greens use a high organic matter mix of 80% sand and 20% peat, referred to as 80–20 mix, which was the third test soil. Measurements of L_{res} were made in Sparta sand that was oven dried and then mixed with 3000 mg L^{-1} KBr solution and with deionized water to determine what effect, if any, should be attributed to soil salts. For the evaluation of significant differences between L_{res} measured in saline and non-saline soil, the linear regression method of dummy variables outlined in Draper and Smith (1981) was used.

A calibration obtained by measuring L_{res} at known values of θ_v was all that was needed to apply the method; however, for comparing theory with experiment, several additional tests were conducted. The apparent length (C_p) of the balun was measured with the probe in air using the NA and the synthesized TDR method (Starr, 1997; Starr et al., 1999b) at a center frequency of 650 MHz. For the balun and probe (Spaans and Baker, 1993) used in this study, a probe constant of 19 cm was measured. A C_p of 18 cm resulted in a better match between L_{res} predicted from Eq. [13] and L_{res} measured at known water content in soil. An additional test involved measuring L_{res} in three solvents (acetone, methanol, and water) with known K_a (taken from Kaya et al., 1994).

RESULTS AND DISCUSSION

To begin our discussion of results we present data for comparison of measurements of L_{res} with a network analyzer (NA), theoretical approach (Eq. [11]), and the field instrument described above. The resonant frequency can be measured at various insertion lengths with a NA. In this study 141.4 MHz was used for NA measurements of L_{res} for comparison with the field instrument. Deviations between the NA-measured L_{res}, and field instrument-measured L_{res} (Table 1) were <0.2 cm in water, methanol, and acetone. As predicted (by Eq. [11]), three ($n = 0, 1, 2$) resonances were observed in water, two ($n = 0, 1$) in methanol, and one ($n = 0$) in acetone. The predicted L_{res} exceeded measured values by $\approx$0.4 cm for $n = 0$, $\approx$2 cm for $n = 1$, and $\approx$2 cm for $n = 2$, possibly because of an imperfect theory or a small error in the value of C_p (18 cm) used in the prediction.

Table 1. Predicted (Eq. [15]) and measured resonant lengths (L_{res}) in various solvents with known dielectric constants (K_a).

Solvent	Harmonic resonance	Network analyzer measured	Field instrument measured	Predicted L_{res}
		cm		
Water	$n = 0$	0.2	0.1	0.5
($K_a = 80.6$)	$n = 1$	12.5	12.5	13.8
	$n = 2$	25.5	25.6	27.0
Acetone	$n = 0$	0.9	0.9	1.1
($K_a = 20.7$)	$n = 1$	−†	−	−
	$n = 2$	−	−	−
Methanol	$n = 0$	0.5	0.5	0.8
($K_a = 33.0$)	$n = 1$	20.7	20.5	23.1
	$n = 2$	−	−	−

† − = no resonance.

Figure 6 shows the frequency domain response, measured with the NA, using a 30-cm probe inserted to the resonant length for the 141.4 MHz, $n = 0$ resonance for a Griswold soil at 0.10 m^3 m^{-3} water content. Amplitude of the reflection coefficient, the ratio of reflected to transmitted signal amplitude, is plotted in milliunits (mV V^{-1}, or mU) vs. frequency in MHz from 100 to 200 MHz. The reflection coefficient drops from ≈500 to ≈100 mU in the vicinity of resonance. The marker indicates the operational frequency of our field instrument at 141.4 MHz.

Calibration curves of the field instrument (Fig. 7, solid lines) were not independent of soil type as shown by data on L_{res} (measured with the field instrument) vs. θ_v for a 30-cm probe in Sparta sand, Griswold, and 80–20 mix. Each point is a single measurement of L_{res} at a known θ_v. Solid calibration curves represent second-order polynomial fits to data and dashed lines are predictions of L_{res} for $\rho_b = 1.5$ g cm^{-3} (lower dashed line) and $\rho_b = 1.05$ g cm^{-3} (upper dashed line). In the cases of Sparta and 80–20 mix, both of which have a ρ_b of 1.5 g cm^{-3}, the calibration curves were within 0.004 m in L_{res}, or 0.008 m^3 m^{-3} in θ_v, of one another. But, the Griswold at a ρ_b of 1.05 g cm^{-3} deviated from Sparta by ≈0.02 m in L_{res} or ≈0.05 m^3 m^{-3} in θ_v. What this means in practice is that when the system is calibrated in Sparta

Fig. 7. Calibration curves of wavelength domain reflectometer. Solid lines are polynomial fits to laboratory data and dashed lines are theoretically calculated for bulk density (ρ_b) of 1.5 (lower dashed line) and 1.05 (upper dashed line).

and that calibration is used for measurements in Griswold, the measured θ_v will be lower than actual by ≈0.05 m^3 m^{-3}. These deviations may be caused by the ρ_b effect, as evidenced by the predicted curves showing roughly the same magnitude of separation between the two ρ_b, as well as the same trend of larger L_{res} for lower ρ_b at a given θ_v. The chosen soils represent fairly extreme cases of ρ_b variation; most soils used for agriculture are in the range of 1.2 to 1.6 g cm^{-3}.

Predicted curves are seen to deviate rather widely from experimental measurements, particularly at high θ_v where the deviation is ≈0.01 m in L_{res}. The Malicki
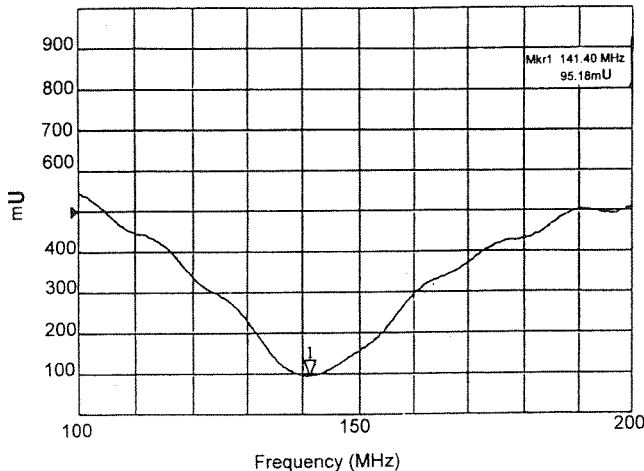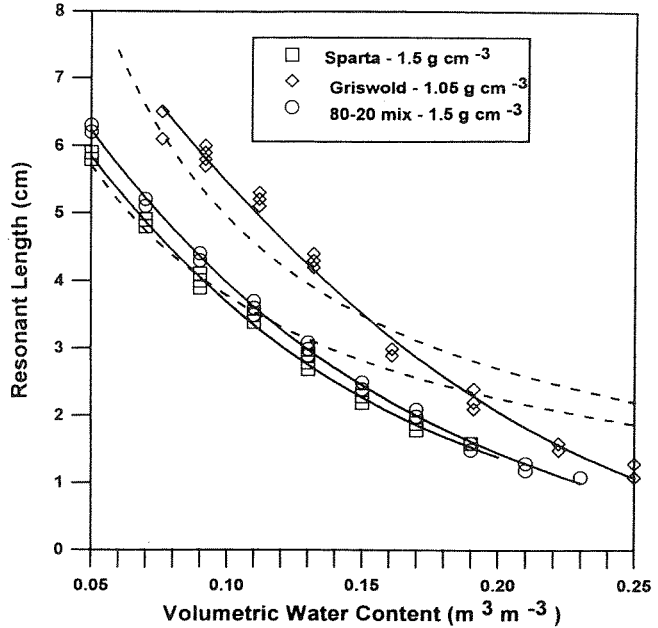

Fig. 6. Reflection coefficient in mU (mV V^{-1}) vs. frequency (MHz) printed from a network analyzer.
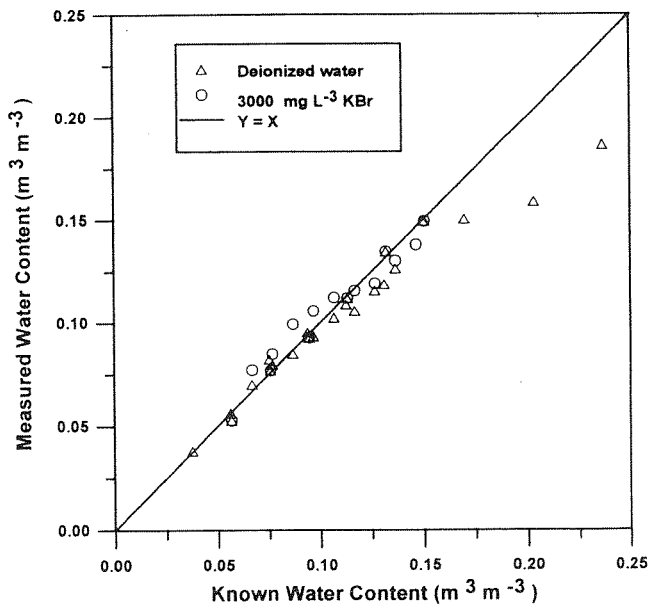

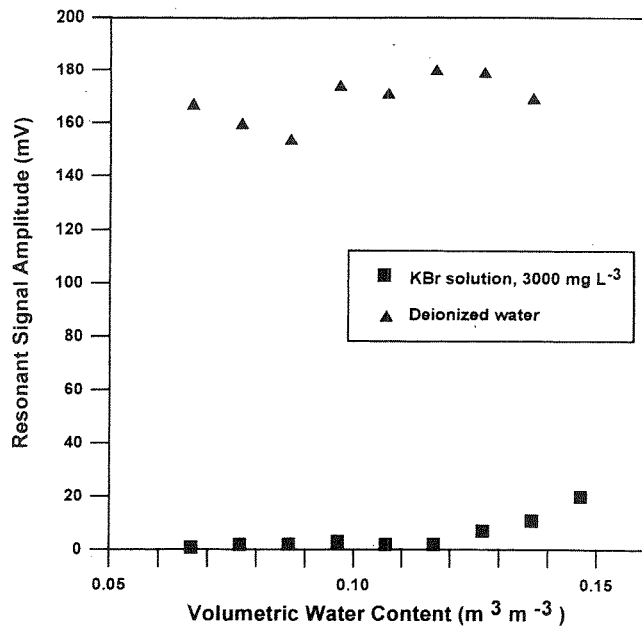Fig. 8. Salinity effect on water content measurement in Sparta sand.

Fig. 9. Salinity effect on resonant signal amplitude in Sparta sand.

et al. (1994) equation relating K_a to θ_v and ρ_b, a result obtained with TDR, is not exactly representative of soil dielectric properties at a fixed frequency of 141.4 MHz. Therefore, its use in the predictions (Eq. [13]) could cause significant error. It is clear that predicted curves cannot be used for calibration; however, in calculating the design parameters of this system, the prediction errors seen in Fig. 7 were not problematic.

A comparison of data measured in Sparta sand (Fig. 8), where known water contents were established with distilled water and with 3000 mg L^{-1} KBr solution and measurements of θ_v were made using the previously described calibration, indicated substantial independence of measured θ_v on soil salts. A linear regression test was conducted from which it was determined that there was no significant difference at the $P = 0.05$ level between measured θ_v in Sparta sand mixed with deionized water and the same soil mixed with 3000 mg L^{-1} KBr solution. Deviations of measured from known θ_v, seen as scatter around the line $Y = X$ in Fig. 8, are typically less than ≈ 0.01 m^3 m^{-3}. However, at θ_v above ≈ 0.15 m^3 m^{-3} the deviations are larger because of inadequacies in the calibration method and the very short lengths measured in wet soils. The theory predicts that using a shorter probe (Fig. 1) or a lower frequency (Fig. 2) will improve performance at higher θ_v by extending the measurement depth, L_{res}.

Although L_{res} is not greatly affected by salt content, reflected signal amplitude (mV) at resonance (Fig. 9) shows a dramatic response to salts in all θ_v tested. Reflected signal amplitude drops from ≈ 160 to ≈ 180 mV in Sparta mixed with deionized water to ≈ 0 to ≈ 20 mV in Sparta mixed with 3000 mg L^{-1} KBr. It is known that to increase salt concentrations increases the conductivity and the attenuation coefficient, thereby reducing the amplitude of the wave reflected from the end of the probe. Because the resonant condition requires destruc-

tive interference between the reflection from the end of the probe and from the balun, it follows that the salt concentrations will affect the reflected signal amplitude at resonance. The resonant condition seen in Sparta with 3000 mg L^{-1} KBr solution was similar to that observed in the Griswold (Fig. 6), which has moderate to high attenuation because of high (30%) clay content.

CONCLUSIONS

Development and evaluation of a resonant length method have confirmed theoretical predictions of an inverse relation between the $n = 0$ harmonic resonant length and the θ_v that is caused by variation in K_a when θ_v changes. Use of a 30-cm probe and an operational frequency of 141.4 MHz gave best results for water contents of <0.20 m^3 m^{-3}. As expected, not all soils follow exactly the same calibration curve; both theory and experimental data suggest this is primarily caused by variations in bulk density. The L_{res} technique is a simple, speedy, non-radioactive, inexpensive, and non-destructive method for determination of θ_v and may find application as an alternative to gravimetric sampling. In experiments and tests using a prototype instrument, limitations in the range of θ_v, the variable zone of influence, and the requirement of a calibration for very accurate measurements were seen as disadvantages with respect to gravimetric sampling. It was clear that the prototype instrument is not a replacement for the more complex and expensive systems such as TDR, which have multiplexing and remote logging capabilities. Although water content measurements were not affected by soil salt concentrations ≤ 3000 mg L^{-1} KBr, reflected signal amplitude showed a dramatic response to soil salts. The theory suggests that the θ_v range and the L_{res} range may be tailored to fit experimental needs by adjusting probe length or operational frequency.

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