Using Dielectric Properties to Measure Soil Water Content

Sensors that detect changing dielectric permittivity can be used in soil and other porous media to perform indirect measurements of volumetric water content. Using high-speed logic in an oscillator design makes the measurement simple and inexpensive.

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Reliable and accurate measurement of soil moisture is essential in a broad range of land use applications including agriculture, watershed management, hazardous waste storage, climate modeling, and construction. Many biological, chemical, and physical processes that occur both above and below the soil surface depend on the avail ability of soil moisture. During the past couple of decades, the importance of this information became clear as soil scientists and researchers in related disciplines realized that their models and characterizations of ecosystems were severely limited without detailed and reliable measurements of soil moisture. Motivated by recent advances in both soil science and electronic data acquisition, a new method for measuring this critical parameter has been developed

Soil is a complex system of mineral, organic, liquid, and gaseous components. Its porous structure is the result of numerous interacting forces and is influenced during constant transformation by the par cot material and climate conditions. Soil is an efficient mechanical filter and acts as a substrate for chemical reactions and exchanges. A single gram of soil can have a particle surface area >500 square meters. This large surface area, and the highly reactive nature of the soil solid fraction, explain the critical role soil provides in storing nutrients for plant life as well as purifying our water resources.

A given volume of soil typically consists of ~50% solid material and ~50% void space. Compacted soils have higher density and less pore space than soil acted on by tillage or frost, which has greater pore space. The pore space can be occupied by air and other gases or by liquid, most commonly aqueous solutions. When liquid in the pore space freezes, the result is an impermeable, consolidated structure.

Soil water content is a quantitative description of the amount of water in soil and is expressed on the basis of weight or volume. The most common expression is volumetric since this also accounts for density and is simply the volume of water per volume of soil. The standard method used for direct measurement of soil water content is to calculate the change in weight of a sample before and after oven drying. This method is referred to as a gravimetric determination. Indirect methods include electrical conductivity, neutron thermalization, and gamma attenuation. The gravimetric method provides good results but is destructive and labor intensive. Indirect methods allow in situ monitoring without disturbing the soil, and most can he automated to give frequent and untended measurements. Water has an unusual molecular structure that makes these indirect measurement methods possible. The bond mg of the hydrogen atoms to the highly electronegative oxygen atom makes water a polar molecule. This electrical polarity and the geometry of the structure produce the strong intermolecular bonds responsible for water's unique combination of properties: a high boiling point, a solid phase that is less dense than the liquid phase, high specific heat, and excellent solvent properties.

Water also has a high dielectric permittivity, and this is the basis for a recently developed indirect method for measuring soil water content. Because water's dielectric permittivity is more than an order of magnitude greater than that of other soil constituents, changes in the dielectric permittivity of soil can be attributed to changes in water content. Consequently, the response from a detector sensitive to dielectric permittivity can be calibrated to yield soil water content.

Dielectric Permittivity and Time Domain Reflectometry

Electromagnetic (EM) energy applied to a waveguide will propagate at a velocity that is dependent on the dielectric permittivity of the material surrounding the waveguide elements. Additionally, portions of the traveling wave will be reflected by changes in impedance along the waveguide. This phenomenon of changing velocity and wave reflections is the basis for time domain reflectometry.

The propagation velocity of the energy along the waveguide, v_p, is described by:

$$v_p = \frac{c}{\sqrt{\varepsilon}}$$

where c = speed of light in a vacuum (3×10^8 m/s) and ε = dielectric permittivity.

The dielectric permittivity of soil typically ranges from 2 for very dry soil to around 30 for water-saturated soil. The travel time in one meter of saturated soil is about 4 times longer than in dry soil, or ~ 13.5 ns.

The dielectric permittivity of water is frequency dependent. The water molecule will be polarized when EM energy is applied at frequencies up to a value referred to as the relaxation frequency. Above this frequency, the water molecules do not recover to the lower-state orientation and the energy is dissipated as heat. This is the principle of the microwave oven. The relaxation frequency for liquid water is 17 GHz. At relatively low frequencies, however, the applied signal will be attenuated by ionic conduction and the permittivity cannot be sensed. Therefore, if the response of an applied signal is used to measure dielectric permittivity when water is the principal constituent of the dielectric, the frequency must he near but not beyond 17 GHz.

Time domain reflectometry methods were first applied to soil moisture measurement more than 20 years ago. The original measurement technique used a metallic cable tester that both generated the EM wave applied to the waveguide and captured the reflection. The travel time through soil can be derived from information in the reflection, and this can be interpreted to determine water content. Results from this method are very good, but the required equipment is quite expensive and there are significant limitations on how far away the sensing element can be from the cable tester.

Using Dielectric Properties in a Different Approach

The high-frequency requirement for polarization of water molecules in soil can be satisfied by using high-speed components in the electronic design of the water content sensor. Figure 1 is a block diagram of a circuit used to drive a waveguide buried in soil and to detect the return of the reflection from the open end of the waveguide. The line driver is configured as a bistable multivibrator that controls the output at one of two discrete values. A control line is used to enable the circuit.

When the output transitions from one state to the other, the band of frequencies associated with the rise or fall time of this transition travels from the line driver circuit to the probe rods, which are surrounded by soil. The EM wave propagates along the 30 cm rods at a velocity dependent on the amount of water in the soil. The ends of the rods appear as an open in the waveguide, causing a reflection back to the linedriver circuit. The return signal is detected by the threshold circuit, which triggers the line driver into the alternate state. This sequence repeats as long as the probe is enabled.

Changes in soil water content affect the transit time of the EM wave along the rods.

The sum of the rod transit time and the inherent delay of the electronic components determines the oscillation frequency of the multivibrator, represented by:

$$\left[2\bullet\left(\tau_{circuit}\right)+\frac{2\bullet L\bullet\sqrt{\varepsilon}}{c}\right]^{-1}$$

which is simply the inverse of the period.

$\tau_{circuit}$ = delay of the circuit components
L = length of the probe rods

The first factor of 2 is necessary since two transitions occur during each complete cycle. The rod length must be multiplied by 2 since the EM wave travels a round trip path along the rods. A scaling circuit connected to the line river circuit divides the line driver frequency to a value compatible with data acquisition devices such as data loggers. The final probe output is a square wave with a frequency that varies with water content and as an approximate range of 700-1500 Hz. The circuit board and electronic components are encapsulated in epoxy. A 4-conductor cable electrically connects the probe a data logger and 12 V power. The data logger controls when the probe is enabled, measures the probe output frequency, and applies the conversion to give water content. Total power consumption is <1 W when enabled.

Making the Measurement

Determining soil water content is a matter installing the probe in the site to be monitored and making the electrical connections to power and a readout device. Probe performance is not sensitive to rod orientation with respect to the surface. Because the probe is designed to withstand harsh environmental conditions, it can be buried. Results from a probe with rods inserted vertically into the soil surface are the average water content in the top 30 cm of soil. A probe inserted at a 30° angle to the surface will give average water content in the top 15 cm. If the probe is buried with the rods oriented horizontally, the movement of soil moisture in the vertical direction can be monitored. Vertical water fluxes are the result of precipitation events or evapotranspiration.

The measurement provides the average water content over the length of the rods because this method is effectively an integrator. Sensitivity to the presence of water in the soil does not vary with position along the rod. The sensitive region in the direction extending radially from the rods is 2 cm. This gives a total sampled volume of ~700 cm^3.

Calibration

Because the propagation time of the signal along the probe rods depends on dielectric permittivity, and water in the soil is the predominant source of permittivity, a calibration can be used to translate the sensor output directly to a value of water content (see Figure 2). As indicated by the equation for EM wave propagation velocity, the curve has an inverse square root shape. This well-behaved response can be described with simple algebraic functions to give a value for water content as a function of probe output frequency or period. The laboratory calibration data used in development of this sensor are described using a quadratic relationship with volumetric water content expressed as a function of the probe output period.

A single calibration provides a volumetric water content accuracy of ±2.5% for the majority of soil types. This compares well with other water content measurement methods. Soil moisture monitoring at several locations is easily automated using data loggers. Soil composition can vary significantly under some conditions and some applications require that the calibration be modified. Soils high in sand content, for example, may require a small calibration adjustment because the dielectric permittivity of quartz is higher than that of most other soil solid constituents. Also, some clays and organic material such as peat are structures of polar molecules. This results in a force being exerted on the water molecule that can affect the degree of polarization by the applied EM energy. The calibration may need to be adjusted when used in soils with very high amounts of clay or organic material.

As previously noted, electrically conductive dielectric material will attenuate the signal traveling along the waveguide. Soils with high salt content will have significant electrical conductivity as the salt dissolves with increasing water content, and the concentration of free ions in the soil solution increases. The effect of soil electrical conductivity on the soil moisture probe calibration is shown in Figure 3. These values are relatively high and are present in only a small fraction of soils around the world.

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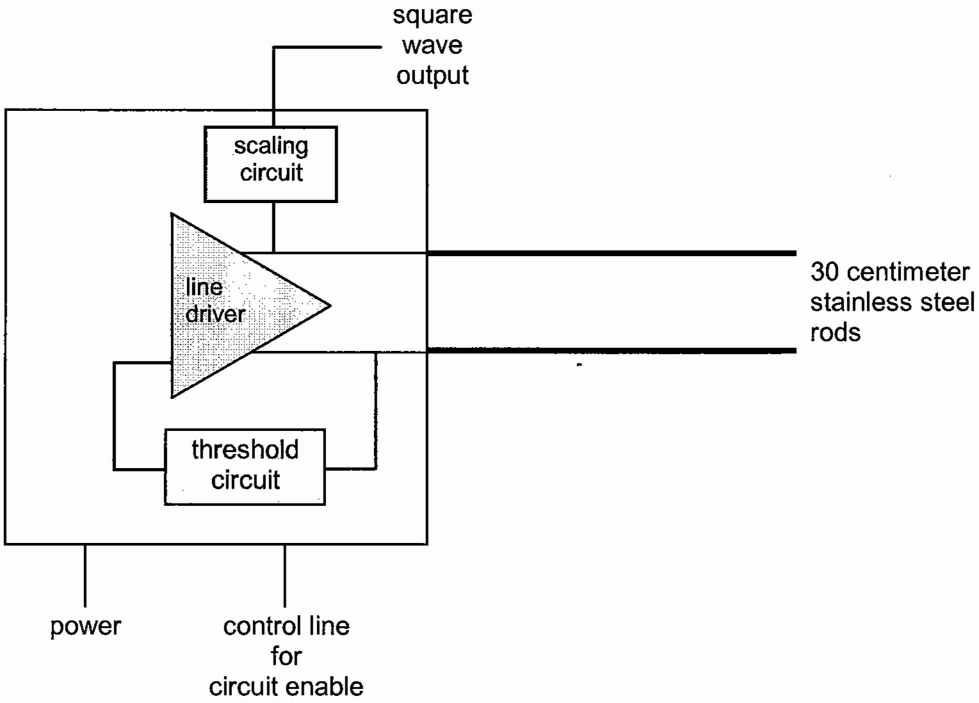
Figure 1


square
wave
output
scaling
circuit
line
driver
threshold
circuit
30 centimeter
stainless steel
rods
power
control line
for
circuit enable

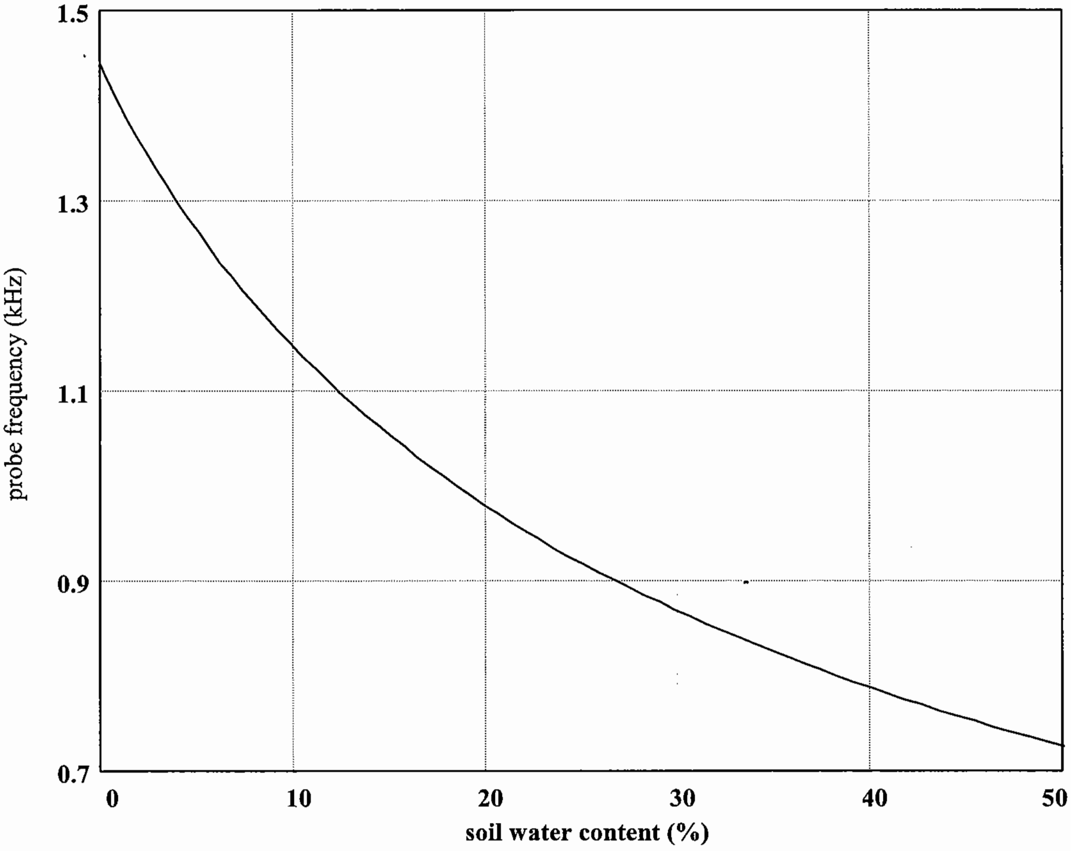

1.5
1.3
1.1
0.9
0.7
probe frequency (kHz)
0
10
20
30
40
50
soil water content (%)

figure 2

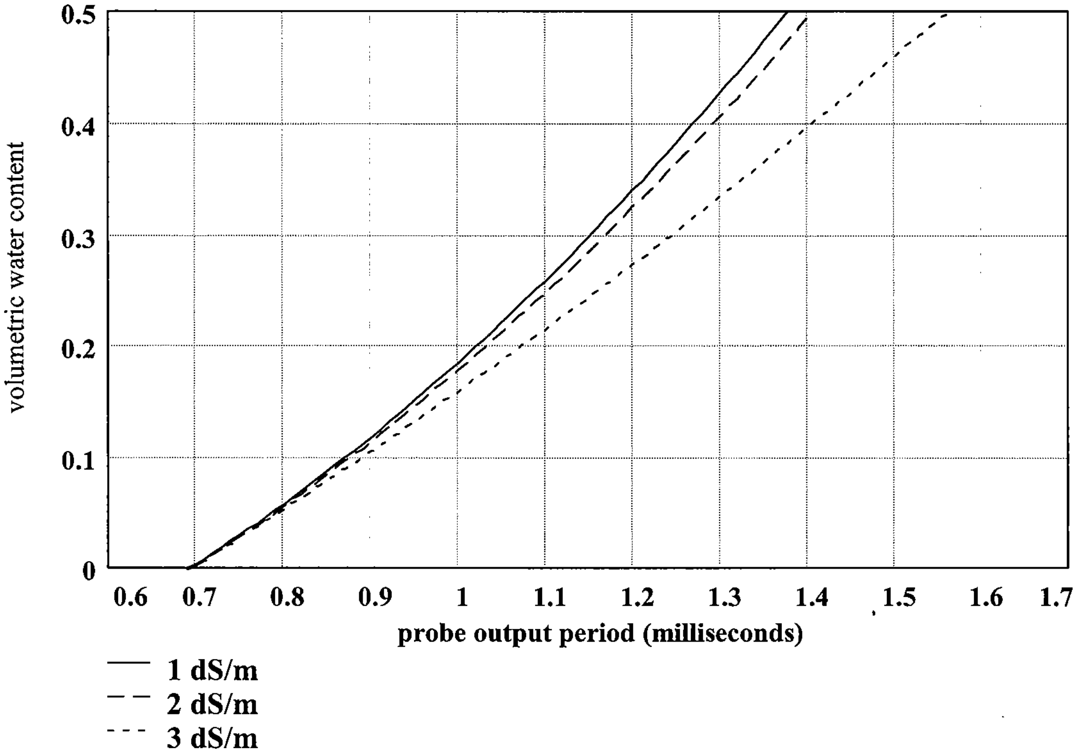

0.5
0.4
0.3
0.2
0.1
0
volumetric water content
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
1.4
1.5
1.6
1.7
probe output period (milliseconds)
1 dS/m
2 dS/m
3 dS/m

figure 3

Figure 1. High-speed logic electronic components are used to drive parallel rods which function as a waveguide. The propagation time for the electromagnetic energy along the rods is dependent on the amount of water in the surrounding soil.

Figure 2. The frequency of the probe output changes nonlinearly with water content in the soil. An algebraic description of this relationship provides a calibration yielding soil water content.

Figure 3. Soils with solution electrical conductivity up to about 2 decisiemen/meter (dS/m) have the same probe output response to changes in water content. Value above 2 dS/m require an adjustment in the calibration because of signal attenuation.