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Calibration of a Frequency Domain Reflectometry Sensor for Humid Tropical Soils of Volcanic Origin

Edzo Veldkamp* and Joseph J. O'Brien

ABSTRACT

Recently, a frequency domain reflectometry (FDR) was developed for measuring soil water content. It has a multivibrator that sends electromagnetic waves along its probes, and it measures the frequency of the reflected wave, which varies with water content. This FDR sensor has several advantages over time domain reflectometry (TDR); it is less expensive, has a lower power consumption, and continuous monitoring of soil moisture at several remote locations is easily automated using dataloggers. Our goal was to derive a calibration function for the FDR sensor with the following criteria: it should be applicable to soils with high clay and organic matter contents and with bulk densities between 0.7 and 1.1 g cm⁻³. We used undisturbed soil samples to account for the natural heterogeneity in soils. Our results show that the calibration functions derived from a three-phase mixing model performed better than the manufacturer's empirically derived function for the soil volumetric content (θ) range of 0.45 to 0.70 m³ m⁻³. Separate values of the geometry parameter (α) and of the specific output period for soil matrix (Per_s) were established both for the topsoil (0–0.5 m depth) and for the subsoil (>0.5 m depth). The manufacturer's calibration function underestimated the soil water content by up to 0.15 m³ m⁻³. The three-phase mixing model uses a physical basis for the derivation of the calibration function in that the soil porosity is used for volumetric partitioning among soil components. This physical basis renders the calibration function widely adaptable.

CONTINUOUS MONITORING OF SOIL WATER CONTENT can be a valuable part of environmental and ecological research. As most of these research projects are conducted long-term on multiple sites, the accessibility of sites (including limitation of labor and electric power supply) is the most important consideration when selecting an automated system for measuring soil water con-

tent. Recently, a FDR sensor was developed for continuous measurement of soil water content. This system uses the dielectric properties of water but in a different approach than TDR (Bilskie, 1997). Time domain reflectometry measures the apparent dielectric permittivity of soil (K_a) using a cable tester. As the dielectric permittivity of water is an order of magnitude greater than other soil constituents, changes in K_a can be attributed to changes in soil water content in nonexpanding soils. The FDR sensor, on the other hand, sends an electromagnetic wave along its probes and measures the frequency of the reflected wave, which varies with water content. In contrast to TDR, where K_a is obtained, the output frequency of the FDR sensor has no direct physical meaning. Frequency domain reflectometry has several advantages over TDR: it is inexpensive for multiple site measurements; it has a low power consumption, so batteries can be replaced only monthly; there is no need of an expensive cable tester; the probes can be buried for a long time, because they are designed to withstand harsh environmental conditions; and continuous monitoring of soil moisture at several locations is easily automated using dataloggers. There are, however, also disadvantages to FDR. It has not been widely used yet, and it requires a special calibration for high clay and organic matter content soils (Cambell Scientific, 1998).

For TDR, various calibration functions relating K_a to the volumetric soil water content have been published. Although an empirically derived calibration function is the most widely used (Topp et al., 1980), empirical relations are valid only in the range of soil characteristics covered in the calibration. Special TDR calibration functions derived for high clay content soils (Dasberg and Hopmans 1992; Bridge et al., 1996; and Weitz et

Edzo Veldkamp, Inst. of Soil Sci. and Forest Nutr., Univ. of Göttingen, Büsingenweg 2, 37077 Göttingen, Germany; and Joseph J. O'Brien, Dep. of Biol. Sci., Florida International Univ., Miami, FL 33199. Received 28 May 1999. *Corresponding author (eveldka@gwdg.de).

Abbreviations: FDR, frequency domain reflectometry; Per_a , specific output period for air; Per_s , specific output period for soil matrix; Per_w , specific output period for water; TDR, time domain reflectometry.

al., 1997), resulted in apparent dielectric constant values lower than those obtained and reported by Topp et al. (1980). A promising approach is the use of mixing models, which take soil physical properties into account in the calibration. In mixing models it is assumed that the soil is a mixture of randomly distributed components, each having specific dielectric properties. The measured K_a is assumed to be the result of a volumetric mixing of the different components. A three-phase mixing model developed by Roth et al. (1990) has been successfully applied to calibrating TDR in soils in our study area (Weitz et al., 1997), even though these soils' physical properties were quite different from the soils used in Roth et al.'s (1990) calibration. Our goal was to make a calibration for the FDR sensor, with the following criteria: (i) it should be applicable to soils with high clay and organic matter contents and with bulk densities between 0.7 and 1.1 g cm⁻³, and (ii) the calibration function should be widely adaptable by having a physical basis rather than merely an empirically derived function.

MATERIALS AND METHODS

Sites

Our study sites are located at La Selva Biological Station (10°20' N, 83°50' W) in the Atlantic zone of Costa Rica. The mean annual temperature and rainfall are 25.8°C and 3962 mm, respectively (Sanford et al., 1993). We selected two soil types: an Inceptisol of moderate fertility formed on river terraces, and an Ultisol of low fertility formed on in situ, weathered, underlying lava flows. These are the dominant soils in the old-growth forest at La Selva. On each soil type we established three 4-m-deep pits. Both soils have clay texture (60–80% clay), low bulk densities (0.6–0.7 g cm⁻³ in the topsoil, increasing to ≈1.1 g cm⁻³ below 2 m depth) and high organic C content (4%–6% in the topsoil decreasing to ≈0.5% below 2 m depth). The main clay mineral in the topsoil is kaolinite, while gibbsite is dominating in the subsoil (M. Kleber, personal communication, 2000). The frequent and abundant rainfall combined with the high organic matter and clay content means that the volumetric water content only very rarely reaches values <0.45. On the other hand, even during rain storms, the volumetric soil water content never reaches values >0.70 m³ m⁻³, which is attributable to the high soil porosity.

Frequency Domain Reflectometry Sensor

We used a commercially available FDR sensor (Model CS615, Campbell Scientific, Logan, UT). This sensor is based on simple transmission line oscillators, which were developed and tested by Campbell and Anderson (1998). The FDR sensor consists of two stainless steel rods (0.3 m long, 0.0032 m in diam., 0.032-m spacing) that are connected to a printed circuit board and are protected by an epoxy block. On the circuit board high speed electronic components are configured as a bistable multivibrator. The output of the multivibrator is connected to the probe rods, which act as wave guides. When the multivibrator switches states, the transition travels the length of the rods and is reflected by the rod ends. The travel time to the end of the rods and back is dependent on the dielectric constant of the material surrounding the rods. The reflected wave is detected by a threshold circuit and, in turn, triggers the multivibrator into the alternate state. This sequence repeats as long as the sensor is enabled. A scaling circuit adapts the multivibrator frequency to a value compati-

ble with a data acquisition device, such as a datalogger or a multimeter. The sensor output is a square wave with a frequency that varies with water content and has an approximate range of 700 to 1500 Hz (Bilskie, 1997; Campbell Scientific, 1998).

The propagation of electromagnetic waves is not only affected by soil water content but also by electrical conductivity, temperature, and clay content. If electrical conductivity is >1 dSm⁻¹, the slope of the sensor output (ms) against volumetric water content decreases. This response of the sensor is well behaved up to ≈5 dSm⁻¹ and can be compensated for. High clay content has a similar effect on the calibration, but the magnitude is dependent on the clay type. The temperature dependence of the FDR sensor varies with water content (Campbell Scientific, 1998) and can be easily corrected for.

Calibration Procedure

For the calibration procedure we largely followed that described by Weitz et al. (1997) with a few simplifications. We prepared undisturbed soil samples of 0.305 by 0.17 by 0.08 m using plastic boxes as molds. Soil samples at 0.05-, 0.20-, 0.75- and 2.5-m depths were taken horizontally in the soil pits, while soil samples at the surface (0–0.3 m depth) were taken vertically. The soil samples remained in the plastic boxes and were transported to the laboratory. Two small holes were drilled in one of the short sides of the boxes to facilitate insertion of the FDR sensors. The sensors were inserted horizontally in the center of each block, leaving ≈0.04 m between the rods and the top and bottom of the soil block. As the sensitive region extending radially from the rods is approximately 0.02 m (Bilskie, 1997), the size of our soil blocks was more than sufficient to ensure that measurements were limited to the soil sample. Small holes were drilled in the bottom of each box and the samples were saturated with water from the bottom up in a basin with ≈0.01-m water level. The basin had to be refilled several times by hand.

During the saturation period of ≈48 h the samples were loosely covered with lids to reduce evaporation. Excess water was drained following saturation and the lid was removed to allow evaporation. Average temperature in the laboratory was 24°C, which is close to the average temperature measured in the field. We took daily measurements of the frequency output of the sensor (Hz) using a multimeter and converted these to output period (ms) by calculating the reciprocal. We also weighed the soil samples including the box and sensor for gravimetric measurement of the soil water content. After 1 to 2 wk, as the soil samples became dry, the multimeter readings were out of the range measured in the field. The soil samples were then dried for 48 h at 105°C and weighed. The gravimetric water content was converted to volumetric water content (θ) using dry bulk density values that were measured from the same soil pits. Porosity was calculated assuming a density of mineral particles of 2.65 g m⁻³. Bulk density was measured at each soil depth on six undisturbed soil samples, using sample rings with volume of 300 cm³. Bulk density rings were carefully inserted by hand without a hammer in order to prevent compaction during sampling. We did not use the bulk density of the soil samples used for calibration because the plastic mold was easily deformed and had no fixed volume.

Theory and Calculations

The standard empirical calibration function for the FDR established by the manufacturer for soils with an electrical conductivity ≈1.0 dS m⁻¹ is

$$\theta = 0.037x + 0.335x^2 - 0.187 \quad [1]$$

Table 1. Results of frequency domain sensor measurements in water and air.

Phase†	Sensor output period (m s ⁻¹)					
	<i>n</i>	Mean	SD	CV	Minimum	Maximum
Water (Per _w)	24	1.7970	0.0137	1.0%	1.7599	1.8238
Air (Per _a)	24	0.7410	0.0168	1.9%	0.6868	0.7583

† Per_w is specific output period for water; Per_a is the specific output period for air.

where x is the sensor output period in ms and θ is the volumetric water content in m³ m⁻³ (Campbell Scientific, 1998). This function does not contain any soil physical information and according to Campbell Scientific (1998) is not suitable for soil with a high clay and organic matter content. As mixing models have been successfully used for TDR calibrations in a wide range of soils, we decided to develop a mixing model for the tested sensor. Following the approach used for three-phase mixing models in TDR calibrations (Roth et al., 1990; Dasberg and Hopmans, 1992; Weitz et al., 1997), we assume that the FDR probe output is the result of a mixing of the independent components in the soil: soil matrix, air, and water. We use soil porosity to partition between the soil matrix and the soil pores that are filled with air and/or water. A geometry parameter (α) is used to define the shape of the calibration function between very low and very high output periods. α is supposed to be a soil specific geometry parameter that accounts for the soil structure. The resulting three-phase mixing model reads

$$\theta = \frac{[x^\alpha - (1 - \phi)Per_s^\alpha - \phi Per_a^\alpha]}{(Per_w^\alpha - Per_a^\alpha)} \quad [2]$$

where

- θ is volumetric water content
- x is FDR sensor output period (ms)
- α is geometry parameter

f is soil porosity

Per_s is specific output period for soil matrix (ms)

Per_a is specific output period for air (ms)

Per_w is specific output period for water (ms)

The frequency or period of the multivibrator is related to the dielectric constant of the medium in which the sensor is placed. However, the output period of the FDR sensor is not equal to the period of the multivibrator but has been scaled by digital circuitry to an appropriate frequency for measurements with a datalogger (Campbell Scientific, 1998). Therefore, the output period of the sensor as such does not have a soil physical meaning, and in contrast to TDR mixing models we cannot derive a theoretical value for the three different phases: water, air, and soil matrix. Nevertheless, this problem can be solved by measurement of the sensor output in air and in water, which gives the specific output period for air (Per_a) and water (Per_w). Per_a and Per_w were measured by taking the mean of five 1-min averages of 12 measurements both in air and in water. The water temperature was 24°C and the electrical conductivity was <1.0 dS m⁻¹. Per_s and α can be derived empirically from the best fit of the three-phase model to the observations. It should be kept in mind that Per_s and α vary spatially within a soil as the soil density and structure vary spatially. We used the least square method to fit the model to the observations. Root mean square error (RMSE) was

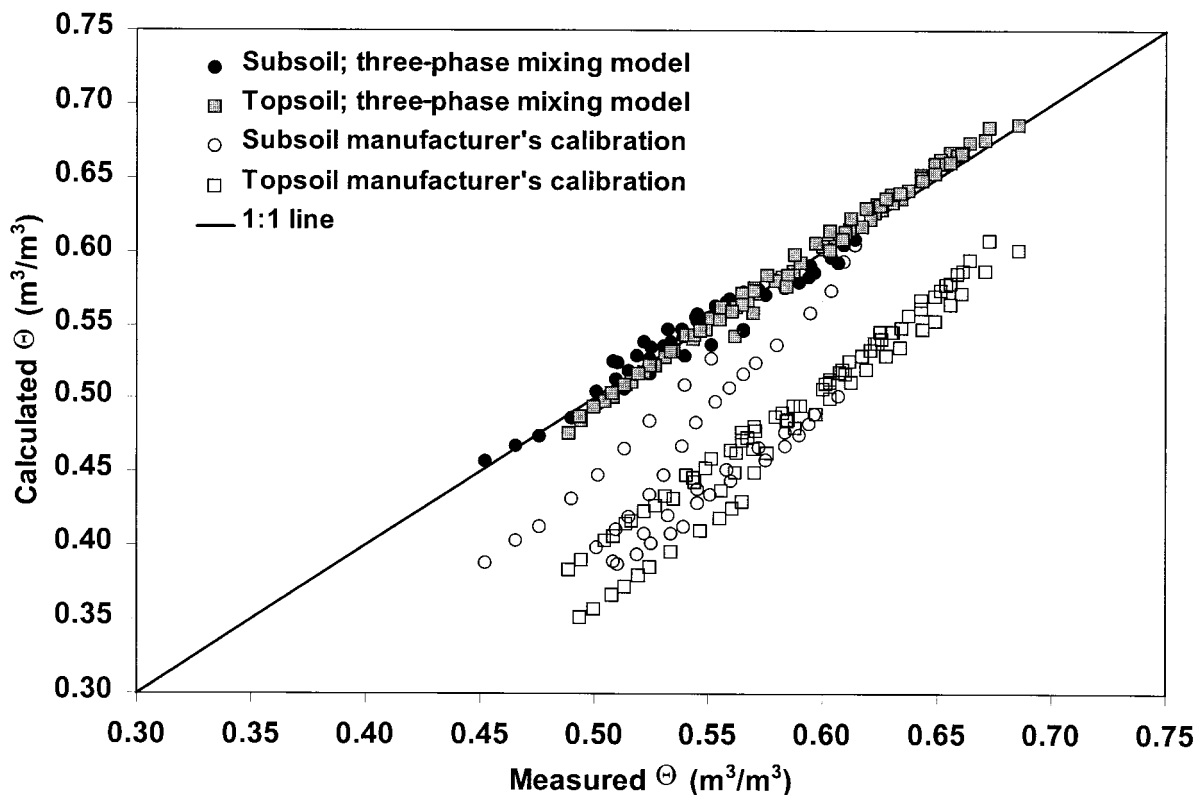


Fig. 1. Measured volumetric water content compared to the three-phase mixing model with $\alpha = 0.5$ and $Per_s = 0.918$ for samples of the topsoil and $\alpha = -2.2$ and $Per_s = 1.307$ for samples of the subsoil. The manufacturer's calibration is added for comparison.

Table 2. Characterization of soil samples and root mean square error (RMSE) for manufacturer's calibration and mixing model.

Soil type, sampling depth	Dry bulk density	Porosity	SOC %	Clay %	RMSE 3-phase mixing model	RMSE manufacturer's calibration function
Topsoil: $\alpha = 0.5$ and $Per_s = 0.918^\dagger$						
Inceptisol, 0.05–0.35 m	0.790	0.702	2.3	76	0.004	0.094
Inceptisol, 0–0.3 m	0.780	0.706	2.1	68	0.006	0.096
Inceptisol, 0.05 m	0.719	0.729	3.1	67	0.006	0.091
Inceptisol, 0.20 m	0.807	0.696	1.5	69	0.008	0.086
Ultisol, 0.05 m	0.750	0.728	6.6	78	0.006	0.102
Ultisol, 0.2 m	0.749	0.717	3.5	81	0.003	0.140
Subsoil: $\alpha = -2.2$ and $Per_s = 1.307^\dagger$						
Inceptisol, 0.75 m	0.881	0.667	0.7	76	0.012	0.110
Inceptisol, 2.5 m	1.097	0.586	0.6	33	0.010	0.050
Ultisol, 0.75 m	0.916	0.654	1.0	79	0.008	0.120
Ultisol, 2.50 m	0.942	0.645	0.9	86	0.006	0.066

† α is a geometry parameter; Per_s is specific output period for soil matrix (ms).

calculated to evaluate the performance of the calibration models.

RESULTS AND DISCUSSION

Measurements in Water, Air, and Undisturbed Soil Samples

Sensor output in air and in water were 0.741 and 1.797 ms, respectively (Table 1). The small variation of measurements in air and water can be attributed to random variation between probes (J. Greene, personal communication, 1997). Compared to spatial variation of soil water content, the error introduced by probe variation is negligible. However, for high precision measurements it is also possible to calibrate individual probes and to use the specific sensor output for water and air. Comparison of the measured volumetric water contents of the soil samples with those calculated from

the manufacturer's calibration function showed that the latter underestimates the volumetric water contents for the whole range measured (Fig. 1). This was especially true for the topsoil. The order of magnitude of this underestimation ($0.05\text{--}0.15\text{ m}^3\text{ m}^{-3}$) was of the same order as was measured for the calibration function of Topp et al. (1980) for TDR measurements in similar soils (Weitz et al., 1997). Also, the offset from the standard calibration was not linear, which confirms that the manufacturer's calibration function cannot be applied to the soils in this study.

Three-Phase Mixing Model

We adapted Per_s and α in such a way that the sum of squares of the differences between the measured and calculated soil moisture content from the three-phase mixing model was minimized. Best results were obtained

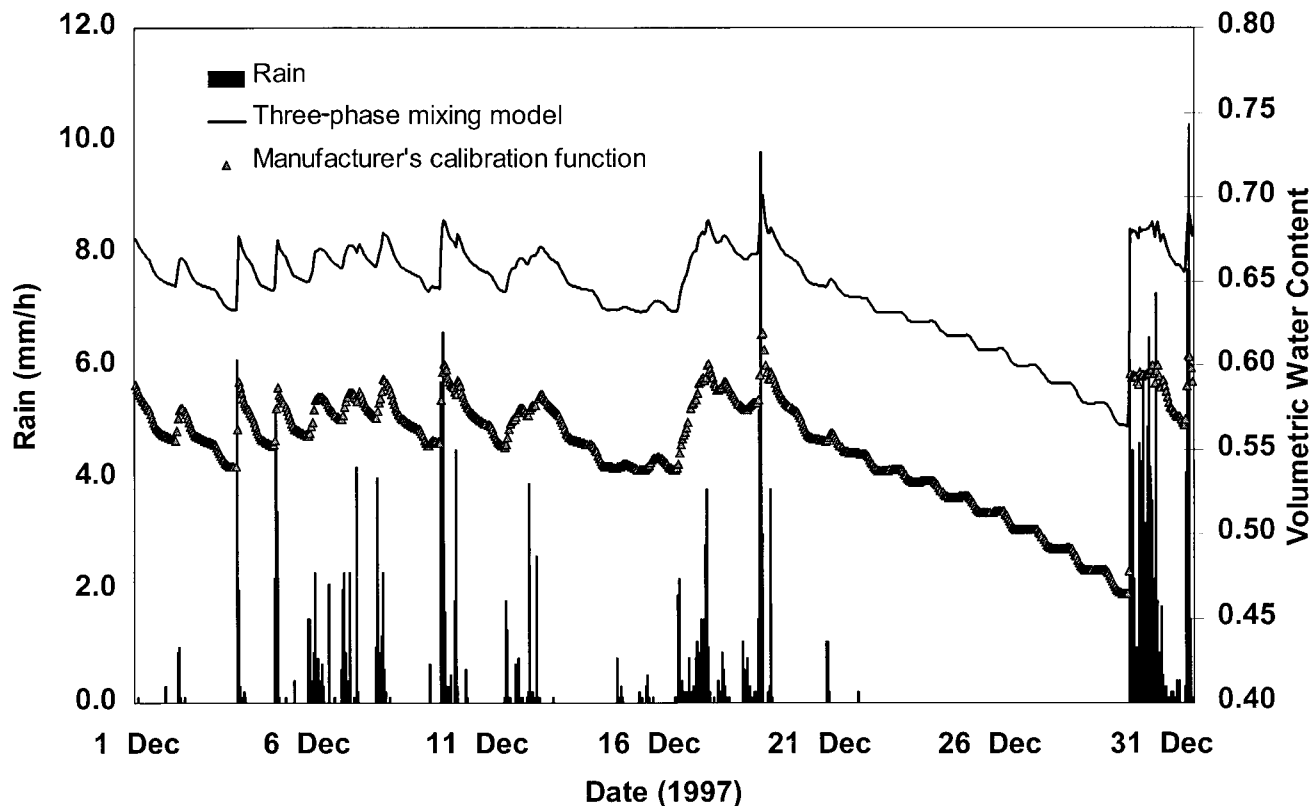


Fig. 2. Soil water content estimates in the 0–0.1 m layer using the manufacturer's calibration function and the three-phase mixing model with $\alpha = -0.5$ and $Per_s = 0.918$ on field-measured frequency domain reflectometry output.

when we made a separate calibration for samples of the topsoil and subsoil. The best fit was found for $\alpha = 0.5$ and $Per_s = 0.918$ for the topsoil (0–0.5 m), and $\alpha = -2.2$ and $Per_s = 1.307$ for the subsoil (>0.5 m depth). The negative value of α in the subsoil is different from values found in mixing models for TDR application. We explain this by pointing out the different shape of the FDR probe response compared that of the TDR. Values of Per_s were different between topsoil and subsoil, which we explain via the relatively large difference in soil organic C content (Table 2). As porosity is already included in the calibration through the partition between soil matrix and the soil pores, this is probably not the cause of the different values of Per_s . The RMSE of our three-phase mixing model for FDR calibration (Table 2) were lower than the RMSE of the TDR calibration (between 0.044 and 0.045) in similar soils (Weitz et al., 1997). A comparison of measured volumetric water contents of the soils with those calculated from the three-phase mixing model showed that the values are scattered around the 1:1 line with an r^2 of 0.99 for the topsoil and an r^2 of 0.95 for the subsoil (Fig. 1). Mixing models have an inherent advantage compared to empirical calibration functions in that the former include soil porosity for volumetric partitioning among soil components. This physical basis of mixing models allows its calibration function to be more widely adaptable. This is demonstrated by the RMSE, which is small for soils with high and low bulk densities (Table 2). We encourage anybody who uses FDR or similar sensors for measuring soil water content to calibrate it using a three-phase mixing model instead of relying solely on the manufacturer's empirical calibration function. The importance of a good calibration is illustrated by a comparison of the volumetric water contents calculated from the manufacturer's calibration function and the three-phase mixing model calibration on field-measured FDR output (Fig. 2). This figure shows hourly rain and soil moisture data in the topsoil during December 1997. The results with the three-phase mixing model are consistently higher than the standard calibration.

CONCLUSIONS

The main disadvantage of the FDR, which is the limited applicability of its manufacturers' empirical calibration function on high clay and high organic matter con-

tent soils, can be solved by using a three-phase mixing model to generate a more robust calibration function that takes into account soil physical properties. Our results show that the calibration functions (for the topsoil and subsoil) derived from a three-phase mixing model performed better on the above-specified conditions than the manufacturer's empirically derived function. So far, the performance of the FDR probes has been good. We have run >40 sensors under harsh environmental conditions for more than two years without significant problems. Frequency domain reflectometry is a reliable, precise, and relatively cheap alternative to TDR, especially for continuous measurements of soil water contents in multiple sites with accessibility and power supply limitations.

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