Estimates of soil moisture using GPR in Cuiarana, Salinópolis, Pará

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This paper was prepared for presentation during the 13th International Congress of the Brazilian Geophysical Society held in Rio de Janeiro, Brazil, August 26-29, 2013.

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Abstract

Soil moisture was estimated using common offset GPR data and a calibration equation developed for an area in Cuiarana, municipality of Salinópolis, northeastern of Pará. The results were compared to moisture obtained using the Time Domain Reflectometry methodology. The proposed calibration equation allows moisture determination as a function of relative electrical permittivity and in terms of electromagnetic wave velocity obtained with GPR. The study successfully showed the feasibility, rapidity, and limitations of estimating water content by GPR.

Introduction

Information about the spatial distribution of soil moisture is of utmost importance to precision farming programs. Even with a plentiful water supply, crop quality can still decline due to adverse effects on vadose zone (the transition zone between the atmosphere and groundwater) such as reduced root transpiration related to the depletion of O_2 and increased toxic ions in the soil from root plant flooding.

Electromagnetic methods (EM) play an important role in this type of vadose zone study because ground electromagnetic properties are controlled by the presence of water (Topp et al., 1980) mainly due to the high value of water's relative electrical permittivity when compared to the geological materials.

One of the most successful EM methods for soil moisture determination is the Time Domain Reflectometry (TDR), which was first used for soil moisture studies in the mid-1980s (Topp et al., 1980) and has become widely used to estimate soil moisture. However, TDR can be ineffective when measuring small volumes of moisture in soil (less than dm^3) due to its extreme sensitivity to macropores and air bubbles caused by the introduction of probes in the soil during the measurements (Huisman et al., 2003).

On the other hand, the use of the EM method Ground Penetrating Radar (GPR) for soil moisture estimation has increased in recent years. Much research on the subject has been performed worldwide (e.g. Weiler et al. 1998; Steelman & Endres, 2011; Lunt et al., 2005; Grote et al., 2010).

In this study soil moisture was estimated through a survey executed with GPR in the Meteorology Department test site of the Institute of Geosciences, Federal University of Pará, localized in the village of Cuiarana, Salinópolis municipality, northeastern of Pará. The site is characterized by the presence of bush vegetation and stunted trees. The geological characteristics of the shallow subsurface includes a homogeneous medium (up to 0.5 m deep) with the presence of yellow latosol (clayed siltstone), very common in this region (Torres, 2011).

The well-known Topp and Roth equations were used for estimating moisture from the GPR data. A new calibration equation was also established from the analysis of reflection hyperbolas detected in radar profiles and moisture obtained in TDR measurements.

Material and methods

The GPR method consists in radiating electromagnetic waves with frequencies ranging from 10 to 2500 MHz via a transmitting antenna placed near the surface. As these waves pass through the soil, they are reflected, refracted, and diffracted by electromagnetic heterogeneities they encounter. In the case of homogeneous soils, the velocity of propagation of the GPR wave (v) is basically controlled by the relative permittivity (ϵ_r) and can be estimated in non magnetic media by:

$$v = \frac{c}{\sqrt{\epsilon_r}}, \tag{1}$$

where c represents the speed of light. Values of ϵ_r are used for moisture determination.

TDR is composed of an electrical pulse generator and an oscilloscope. TDR technology measures wave velocity as it travels along and between probes, while GPR methodology measures waves that travel directly through the soil and reflected at interfaces with different dielectric permittivities (Weiler et al., 1998).

The velocity of the wave traveling through the soil for the TDR is calculated via:

$$v = \frac{2L}{t}, \tag{2}$$

where t represents the two-way travel time for the signal to travel distance L, which represents the length of the probes. The relative permittivity of the soil is then calculated by:

$$\epsilon_r = \left(\frac{ct}{2L}\right)^2 . \quad (3)$$

Various researchers (e.g. Weiler et al., 1998; Huisman et al., 2001; Lunt et al., 2005) have shown that calibration equations based on TDR measurement have been applied very successfully in large-scale studies based on GPR measurements.

This study is based on the following three equations:

(a) Topp equation (Topp et al., 1980):

$$\theta_{TOPP}(\epsilon_r) = -5.3\times10^{-2} + 2.92\times10^{-2}\epsilon_r -5.5\times10^{-4}\epsilon_r^2 + 4.3\times10^{-6}\epsilon_r^3 . \quad (4)$$

(b) Roth equation (Roth et al., 1992):

$$\theta_{ROTH}(\epsilon_r) = -7.8\times10^{-2} + 4.48\times10^{-2}\epsilon_r -1.95\times10^{-3}\epsilon_r^2 + 3.61\times10^{-5}\epsilon_r^3 . \quad (5)$$

(c) Three-phase model equation (Dobson et al., 1985; Roth et al., 1990). In this model, the permittivity of the soil-water-air (ϵ_r) is expressed with the Complex Refractive Index Model (CRIM):

$$\theta_{TPM} = \frac{\epsilon_b^\alpha - (1-n)\epsilon_s^\alpha - n\epsilon_a^\alpha}{\epsilon_w^\alpha - \epsilon_a^\alpha} . \quad (6)$$

where *n* (m^3 m^{-3}) represents the porosity of the medium; ϵ_w, ϵ_s and ϵ_a represent the respective relative permittivity of water, soil, and air; and *α* represents the orientation factor related to the electric field over the geometry of the medium (*α* = 1 for the electric field parallel in soil layers,*α* = - 1 for an electric field perpendicular to the layers of soil, and *α* = 0.5 for an isotropic medium). Substituting the values $\epsilon_a = 1$ and *α* = 0.5, results in the simple physical interpretation relating electrical permittivity and soil moisture (Ledieu et al., 1986; Herkelrath et al., 1991):

$$\theta_{TPM}(\epsilon_b) = a\sqrt{\epsilon_b} - b, \quad (7)$$

where a and b are designated as calibration parameters; while ϵ_b can be considered as the relative permittivity of the medium.

GPR and TDR data acquisition

The site is characterized by the presence of bush vegetation and stunted trees. The geological characteristics of the shallow site included a homogeneous medium (we considered up to 0.5 m deep) with the presence of yellow latosol (clayey siltstone), very common in this region (Torres, 2011).

GPR profiles were executed with a GSSI model SIR-3000 equipment using the common-offset configuration with 400 MHz antennas and a recording time window of 50 ns.

Profile 1 - Extension of 12 m in the direction N80E (Figure 1A). This profile is approximately 0.3 m west of a trench (located at the 8 m position).

Profile 2 - Extension of 10 m, nearly perpendicular to profile 1 and under a tree located at the 6 m position (Figure 1B).

Trench profile – Profile executed parallel and with the same extension of profile 1, adjacent to the trench Profile executed nearby to profile 1. Only the region around the trench is considered in this study, since it includes TDR measurements in three depths taken along a period of time.

The TDR measurements were performed with a Hydrosense Soil Water Measurement System (CS655L) manufactured by Campbell Scientific, Inc, with a display unit and two parallel sensor probes of 0.12 m. Its accuracy is within 3 % of soil moisture content in environments with electrical conductivity less than 2 dS/m. This system determines the total volume of 3600 cm³ (approximately 7.5 cm radius around each probe rod and 4.5 cm beyond the end of the rods). The volume water content range from 5 % to 50 % and the measurement parameters are based on the Topp Equation (Campbell Scientific, 2012). Table 1 shows the TDR soil moisture values collected at 2 m intervals along the GPR profiles 1 and 2.

Table 1. Soil moisture values obtained through by TDR measurements in profiles 1 and 2.

	Profile 1	Profile 2
Position (m)	Moisture (%)	Moisture (%)
0	30	23
2	28	25
4	25	27
6	20	32
8	25	29
10	30	30
12	22	-

Results

GPR data were processed using the software ReflexW (Sandmeier, 2011). The hyperboles of reflection were identified in the radargrams and then were obtained reflected wave velocities in "packages" located above the levels of the reflectors.

Profile 1 - Figure 2a shows TDR soil moisture values for points of the GPR image illustrated in Figure 2b. The TDR data (values in black) were collected every 2 m in the profile (Figure 2a). Due to the presence of many reflection hyperbolas between each pair of points, the values for soil moisture were determined by the average of adjacent values (values in red). Values of GPR reflected wave velocity, reflector depth, relative permittivity, moisture values with TDR, and soil moisture values obtained using Topp and Roth equations estimated from GPR reflected wave velocity are shown in Table 2.

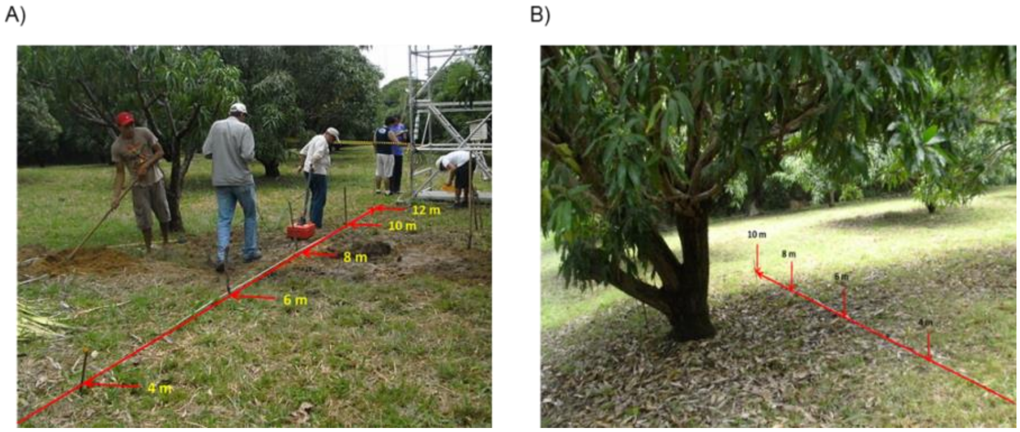

Figure 1. Photos showing the GPR profiles. A) Profile 1. B) Profile 2.

Profile 2 - Figure 3a shows soil moisture values obtained with TDR, while Figure 3b shows the GPR image. Several reflection hyperbolas were likely caused by the presence of the roots of a tree at 6 m. Results are shown in Table 3.

Trench profile – For this profile (Figure 4), soil moisture values measured by TDR in the trench located from 6 m to 10 m were considered. Table 4 shows the soil moisture values on the day of the study from 11:00 AM to 11:00 PM using TDR at three depths: 0.2, 0.5 and 1.0 m. Soil moisture values decreased slightly during the day at depths of 0.2 and 0.5 m and their daily average stayed on 0.2464 m^3 m^{-3} and 0.2103 m^3 m^{-3} respectively. The soil moisture measured at 1 m stayed on 0.1914 m^3 m^{-3} without a substantial variation. The adjusted velocity at the 0.3 m depth hyperbole results in $\epsilon_r = 14.06$, $\theta_{TOPP} = 0.2608$ m^3 m^{-3} and $\theta_{ROTH} = 0.2668$ m^3 m^{-3}.

Proposal of a calibration equation

As illustrated in Tables 2 and 3, some moisture values got from GPR velocity are different of TDR moisture values. For these cases, we posted in Table 5 the arithmetic mean of θ_{TDR} for each velocity. We observe in Tables 2 and 3, however, that in general the equations of Topp and Roth used to estimate soil moisture showed accurate results and on the average, values based on the Roth equation showed more accurate results.

The results shown in Table 5 were used to create a calibration equation using the method of least squares by fitting a curve relating the relative permittivity of the medium obtained through GPR and TDR volumetric moisture content. For this procedure, the simplied three-phase model equation, as illustrated in equation 7, was utilized. The calibration equation relating the permittivity is then given by:

$$\theta_{CE}(\epsilon_r) = 0.0308\sqrt{\epsilon_r} + 0.1488\,, \qquad (8)$$

which can also be expressed in terms of the velocity of the GPR wave by:

$$\theta_{CE}(v) = \frac{9.24 \times 10^{-3}}{v} + 0.1488\,. \qquad (9)$$

Figure 5 shows the GPR site-specific calibration curve (equation 8) fitted to the measured TDR soil moisture. In Figure 6 is shown a comparison between values obtained with TDR, Topp, Roth, and the proposed calibration equation.

A polynomial form for the proposed calibration equation was also established:

$$\theta_{CE}(\epsilon_r) = 0.1108 + 0.1367 \times 10^{-1}\epsilon_r$$
$$-0.2625 \times 10^{-3}\epsilon_r^2 + 0.3025 \times 10^{-5}\epsilon_r^3\,. \qquad (10)$$

The proposed calibration equation (9) was tested by estimating the moisture in the trench at the 0.3 m depth, being obtained the value $\theta_{CE} = 0.2643$ m^3 m^{-3}.

The standard error for soil moisture estimates is around 0.0196 m^3 m^{-3}. In like fashion for the equations of Topp and Roth, the respective standard errors are 0.061 m^3 m^{-3} and 0.041 m^3 m^{-3}. The coefficient of determination showed a value for $r^2 \cong 0.514$.

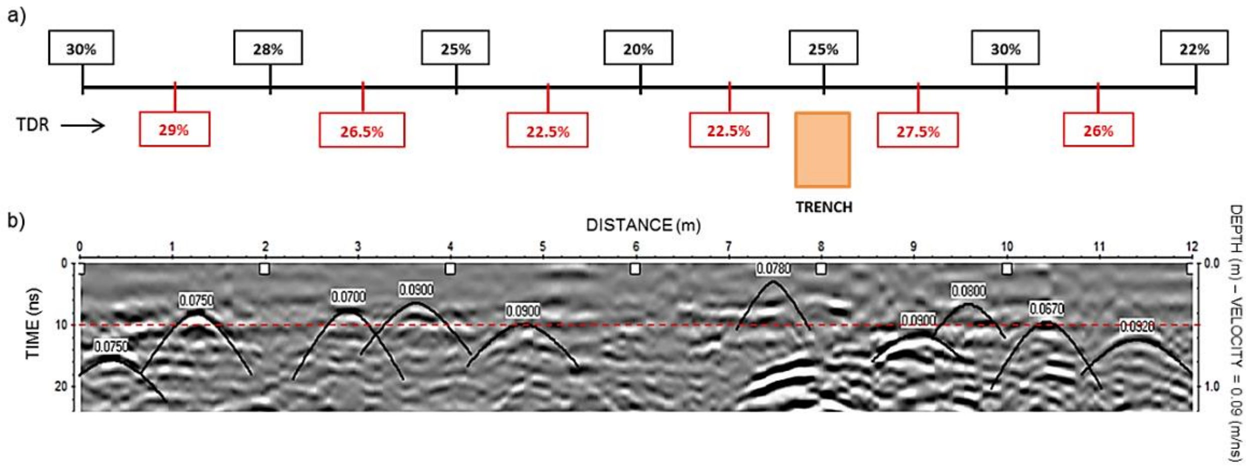

Figure 2. A) Moisture values obtained using TDR in profile 1 (values in black). Values in red represent the arithmetic mean of the values measured by TDR (in black). B) GPR image for profile 1 showing the hyperboles used in velocity determination. The dashed line represents the depth limit at which the reflection hyperbolas were considered.

Table 2. Soil moisture obtained from GPR velocity and TDR in profile 1.

GPR Velocity (m/ns)	Reflector Depth (m)	ϵ_r	θ_{TDR} (m^3 m^{-3})	θ_{TOPP} (m^3 m^{-3})	θ_{ROTH} (m^3 m^{-3})
0.090	0.5	11.11	0.225	0.2094	0.2286
0.080	0.3	14.06	0.300	0.2608	0.2668
0.080	0.3	14.06	0.250	0.2608	0.2668
0.078	0.2	14.79	0.250	0.2725	0.2749
0.075	0.4	16.00	0.290	0.2910	0.2875
0.070	0.4	18.37	0.265	0.3244	0.3107
0.067	0.5	20.05	0.260	0.3460	0.3273

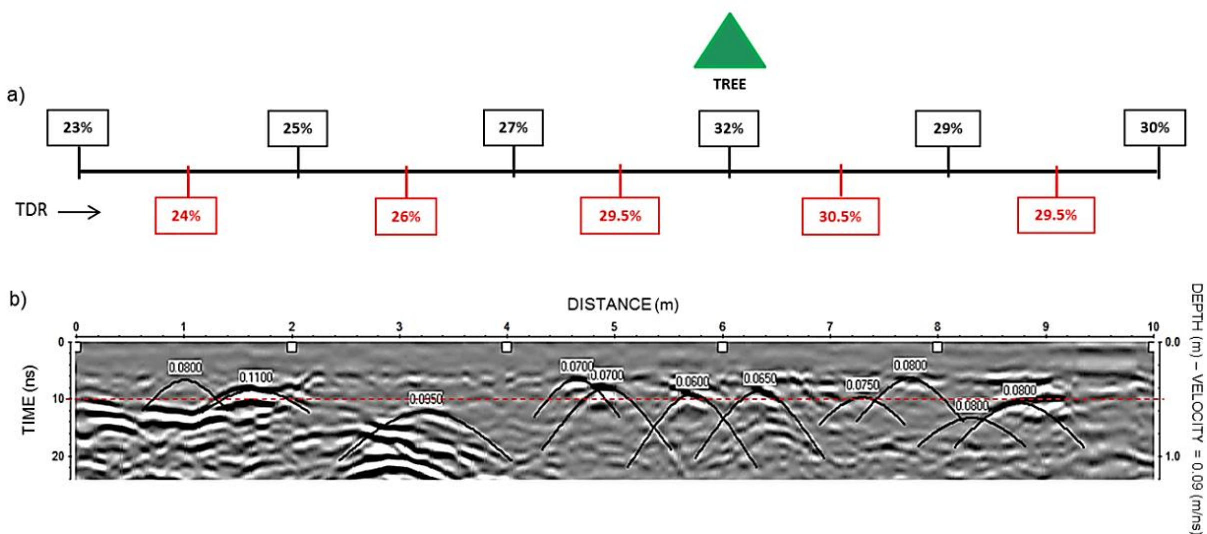

Figure 3. A) TDR moisture measurements obtained in Profile 2. Values in gray represent the arithmetic mean of the values measured by TDR (in black). B) GPR image for profile 2 showing the hyperboles used in velocity determination. The dashed line represents the depth limit at which the reflection hyperbolas were considered.

Table 3. Soil moisture obtained from GPR velocity and TDR in profile 2.

GPR Velocity (m/ns)	Reflector Depth (m)	ϵ_r	θ_{TDR} (m^3 m^{-3})	θ_{TOPP} (m^3 m^{-3})	θ_{ROTH} (m^3 m^{-3})
0.110	0.4	7.440	0.250	0.1355	0.1622
0.080	0.3	14.06	0.240	0.2608	0.2668
0.080	0.3	14.06	0.290	0.2608	0.2668
0.080	0.5	14.06	0.295	0.2608	0.2668
0.075	0.5	16.00	0.305	0.2910	0.2875
0.070	0.3	18.37	0.295	0.3244	0.3107
0.060	0.5	25.00	0.320	0.4004	0.3873

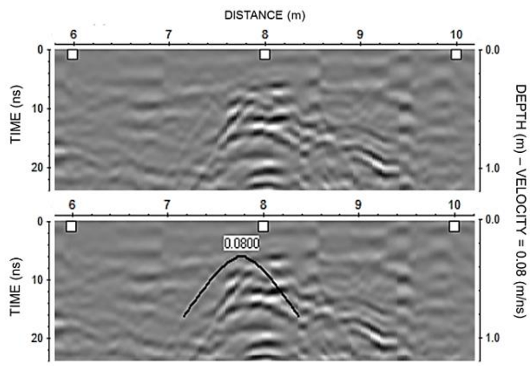

Figure 4. Profile over the trench. The hyperbole used to estimate the velocity is detached.

Table 4. Soil moisture values obtained on the day of the study, using TDR in three depths: 0.2, 0.5 and 1 m.

Hour	θ_{TDR} (m^3 m^{-3}) Depth 0.2 m	θ_{TDR} (m^3 m^{-3}) Depth 0.5 m	θ_{TDR} (m^3 m^{-3}) Depth 1 m
11:00	0.243	0.211	0.192
13:00	0.241	0.211	0.191
15:00	0.239	0.211	0.192
17:00	0.238	0.210	0.191
19:00	0.237	0.210	0.191
21:00	0.237	0.210	0.191
23:00	0.236	0.209	0.192
Arithmetic mean	*0.2464*	*0.2103*	*0.1914*

Table 5. Results obtained after analysis of GPR profiles 1 and 2 to create a calibration equation relating relative permittivity and water content.

GPR Velocity (m/ns)	ϵ_r	θ_{TDR}(m^3 m^{-3}) *(Arithmetic mean)*
0.110	7.440	0.2500
0.090	11.11	0.2250
0.080	14.06	0.2750
0.078	14.79	0.2500
0.075	16.00	0.2975
0.070	18.37	0.2800
0.067	20.05	0.2600
0.060	25.00	0.3200

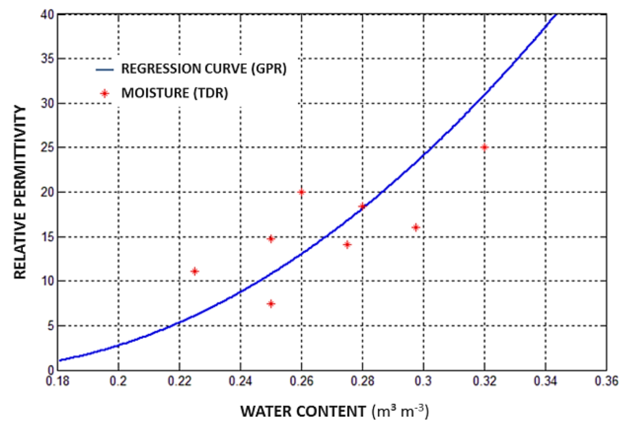

Figure 5. GPR site-specific calibration curve fitted to the estimated soil moisture.

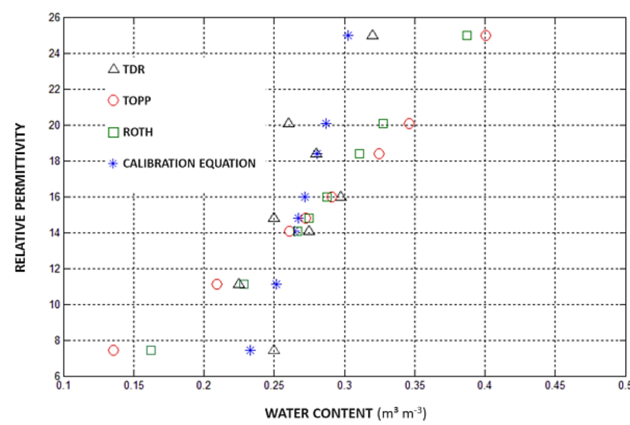

Figure 6. Relative permittivity versus water content for TDR, Topp, Roth and the proposed GPR calibration equation.

Conclusions

1. The study allowed for the establishment of a equation for the specific type of soil that occurs in the investigated area at the UFPA test site. The estimated soil moisture obtained with this equation was similar to moisture measured with TDR.

2. In general, the GPR wave velocity for soil moisture determination is obtained using CMP or WARR configurations for the measurements. However, the common-offset GPR configuration proved to be efficient,

giving accurate moisture with rapidity and facility for taking the measurements. A drawback for this configuration is that the environment must include hyperbolic reflection patterns in the GPR images in order to provide velocity determinations.

Acknowledgments

Marcelo Jorge Luz Mesquita deeply thanks the members of the Postgraduate Course in Institute of Geophysics at UFPA and the National Council for Scientific and Technological Development (CNPq).

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