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Discussions

Calculation of soil water content using dielectric permittivity measurements; benefits of soil-specific calibration.

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Abstract. Soil Water Content (SWC) probes are widely used around the Earth for scientific and agricultural usage. Most of them are based on soil dielectric permittivity measurement as the dry soil relative dielectric permittivity ε, typically from 3 to 5, is much smaller than the water relative dielectric permittivity: about 80. The measure of dielectric permittivity in wet soils allows deducing the soil volumetric water content. Capacitance, Time Domain Reflectometry (TDR), Frequency Domain Reflectometry (FDR) and even remote sensing techniques such as Ground-Penetrating Radar (GPR) and microwave-based techniques are concerned. This study presents SWC measurements with commercial FDR probes on clayey soil highlighting the benefit of a meticulous soil-specific calibration although constructors indicate probes calibrated with generic constants as convenient. Locally, the use of the manufacturer's transfer equation can lead to a strong overestimation or underestimation of the actual soil water content.

A simple protocol for clayey soil calibration is proposed. Without soil-specific calibration on clayey soil, we observe errors as important as 115% with a factory-calibrated probe based on the real part of the dielectric permittivity and up to 245% with the factory-calibrated probes based on the modulus of the dielectric permittivity.

1) Introduction

The volumetric soil water content (SWC) variable is one of the most monitored climatic variables as it is a critical interface between all major flows in the water cycle (Wang- Erlandsson et al. 2022). This information, along with other physical and textural soil properties is important to estimate soil water availability and retention capacity. Several techniques were developed for SWC measurements based on direct gravimetric soil sample measurement, or indirect measurements deducing the SWC. A review of all these techniques can be found in Bittelli, 2011. Very widely used are FDR and TDR probes whose accuracy is about 3% *after a soil-specific calibration only* it means after adjusting calibration constants for the concerned soil. As with every measurement technique, several points may induce errors. Therefore, soil homogeneity is crucial and each probe's measurements reflect each specific soil condition. Also, any pebble, vegetable, or animal presence between the probe roods affects measurements. Dielectric permittivity measurement implies an alternative current technique (AC) and as for every AC-derived quantity, measured dielectric permittivity is a complex composed of its real part and imaginary part (Grimnes and Martinsen, 2015). Ionic soils, or soil salinity, greatly affect the dielectric permittivity imaginary part ε_I (Campbell, 1990; Szypłowska et al., 2018) especially for relatively low-frequency measurements (Skierucha and Wilczek, 2010), making it hazardous to base SWC measurements on dielectric permittivity modulus (Sreenivas et al., 1995). The best results are obtained with high-frequency, thermally compensated probes, SWC determined from the real part of the relative dielectric permittivity measurement ε_R. Another important factor is the soil texture that affects dielectric permittivity (Perdoc et al., 1996), and organic matter is usually not signaled in a soil textural triangle representation (Szypłowska et al., 2021). For all these reasons, a soil-specific calibration may be required locally to determine the proper calibration of moisture versus dielectric permittivity constants even if the soil constitution is given as fairly well convenient for the factory-calibrated probes.

2) Capacitance-based volumetric soil water content measurements techniques.

Because dry soil's relative dielectric permittivity is relatively small against the water one (Behari, 2005, Malmberg and Maryott, 1956), most used SWC probes are based on soil capacity measurements. From remote-sensing by ground-penetrating radar (Davis and Annan, 1989) or microwave-based measurements (Hoekstra, A. Delaney 1974) to the soil buried sensors, they are all based on relative dielectric permittivity measurements. Two main techniques have gained widespread acceptance for soil water content measurements: FDR (Skierucha and Wilczek, 2010), and TDR (Ledieu, 1986). While there are some differences in these techniques, both are dependent on accurate soil capacitance against soil water content linking (Cihlor and Ulaby, 1974). In a TDR probe, an electric pulse of a high frequency, up to 1GHz, is applied to the probe rods inserted into the soil. This pulse is traveling the rods and is reflected by the rod end. As the travel time depends on the dielectric soil permittivity, measuring travel time allows us to deduce the soil dielectric permittivity. Using some frequency range and not a unique frequency helps to affine precision and discard the salinity influence. An FDR probe is measuring the soil capacity to store an electric charge directly related to the soil dielectric permittivity. A maximum resonant frequency in the electrical circuit including the soil between the probe's roods is determined and related to the water content.

As a first approximation, a linear relationship between the squared real part of the relative dielectric permittivity and the water content may be used.

$$\sqrt{(\varepsilon_R)} = A\theta + B \tag{1}$$

With *A* and *B* being constant depending on soil composition and soil texture.

And consequently, the volumetric soil moisture linearity with $\sqrt{(\varepsilon_R)}$.

$$\theta = A_S\sqrt{(\varepsilon_R)} + B_S \tag{2}$$

With A_S and B_S being a constant ($A_S = 1/A$, $B_S = -B/A$)

As we are using the FDR probes for SWC estimation in the clayey soils, we will present these soils as an example. For clayey soil, as it is an ionic soil, it is important to work with the real part of dielectric susceptibility instead of the norm of the dielectric permittivity to minimize the possible dielectric dispersion influence and resulting resistive losses that mainly affect the imaginary part. Corresponding commercial probes are rare. Special attention to concerned scientific groups should be paid to choose the right probes for specific soils such as clayey soils.

Some commercial SWC sensors are using this relationship (Eq. 2) with factory fixed coefficients that cannot be changed and other SWC sensors can be configured. In both cases, by post-processing correction or by reconfiguring probes coefficients, it is possible to recover a more accurate measurement. Depending on the accuracy of the SWC measurements sought after, it may be necessary to perform a soil-specific calibration not only for a particular plot but even for a particular pit and particular depth for accurate SWC measurements.

3) Material and methods.

3.1) SWC measurement sensors and used setup.

FDR SWC measurement probes (analog output 1-5V, operational frequency at 50 MHz): DC200, Beijing Dingtek Technology Co., Ltd. Room A209, Flounder Business Park, Shunbai Road 12, Chaoyang District, Beijing, 100022, China.

FDR SWC reference probe (digital output SDI-12, operational frequency at 50 MHz): HydraProbe, STEVENS, 12067 NE Gleen Wilding Rd, Suite 106 Portland, Oregon 97220, USA.

Scale: EMS 12K0.1, KERN & SOHN GmbH, Ziegelei 1, D-72336 Balingen-Frommern, Germany.

Data logger: CR1000, Campbell Scientific, Logan, Utah, USA.

To collect soil samples of about 100mm height with a minimal disturbance of the soil density, we have used a homemade soil sample extruder apparatus (see Fig. 1) based on stainless-steel short tubes (soil sampler) of 70mm internal diameter sharpened at the bottom, forced into the soil using a pneumatic hammer holding a sampler cloche.

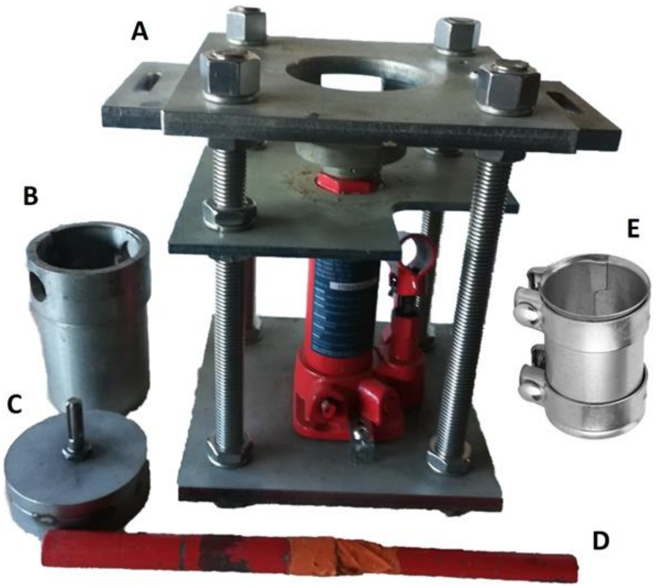

Figure 1. Soil sample extruder: A) Carjack and stainless-steel frame, B) Soil Sampler, C) Sampler cloche for pneumatic hammer, D) Carjack handle, E) Exhaust pipe clamp.

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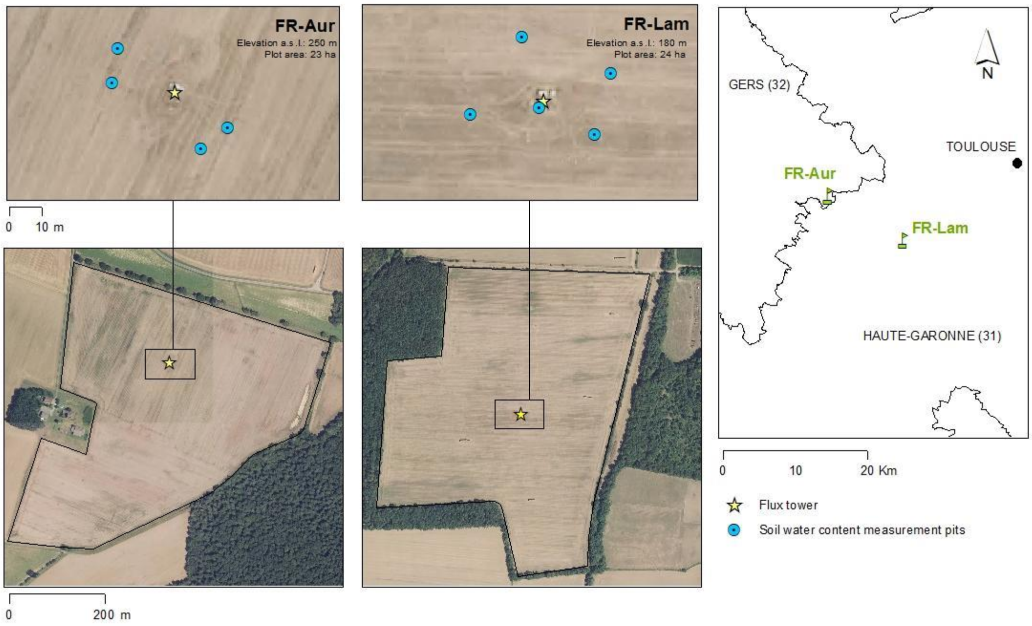

Figure 2. FR-Aur and FR-Lam stations and pit emplacements.

3.2) Soil description and sampling

We have collected soil samples at a different depths (0-10, 5, 10, 30, 50, and 100cm depth) in several pits on two agricultural ICOS stations (Fig. 2) in a very clayey region of south-west France, FR-Lam (43°29’47.21”N, 1°14’16.36”E, silty-clay: 50.3% clay, mainly Kaolinite, 35.8% silt, 11.2% sand, 2.8% organic matter (Malterre and Alabert, 1963)), and FR-Aur (43°32’58.80”N, 1° 6’22.01”E, sandy-clay: 30.8% of clay, mainly Smectite and Montmorillonite, 48.3% silt, 19.2% sands, 1.6% organic matter. Both plots’ soils may be considered as large clay content soils (between 30 and 50 %). However, according to the Steven Hydraprobes’ manual, a priori, there is no need to have a specific soil calibration. With a preliminary check, both plots show an important discrepancy between factory calibrated probes' SWC measurements and the real SWC. A meticulous soil calibration on FR-Lam and FR-Aur was conducted for all the pits and all the depths. As an illustration for this paper, some FR-Aur results are shown.

The soil sampler was forced horizontally in each pit at the desired depth for all depths except for the soil surface where it was forced vertically. Once the tube is pressed up to its top into the soil and then extracted with the soil sample inside, a hydraulic carjack allows to gently push out from the sampler each soil sample. All samples were withdrawn when the soil was near water-saturated and hermetically sealed in plastic buckets bearing 105°C temperature.

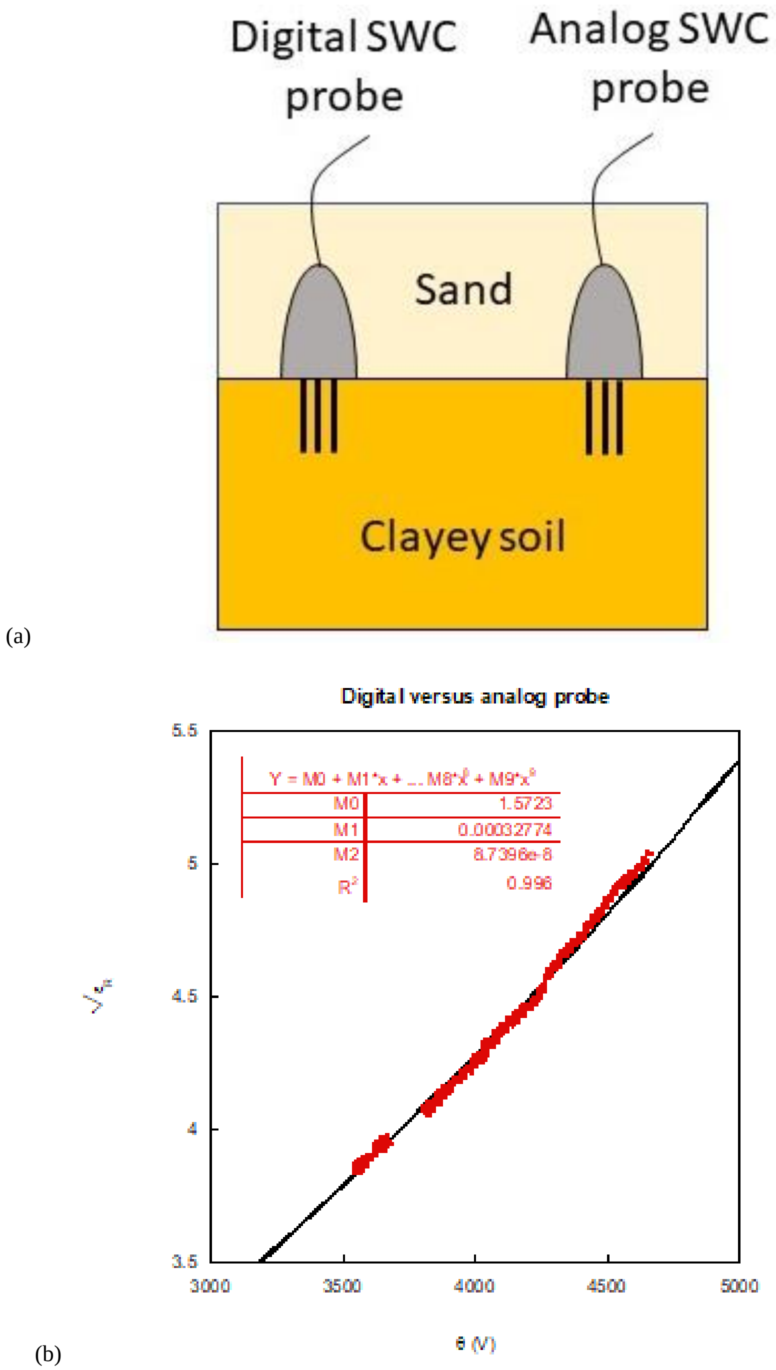

Figure 3. (a) Analog SWC probes calibration configuration. (b) The square root of relative dielectric permittivity real part provided by digital reference probe versus SWC analogic probe tension.

3.3) Soil Calibration

First, the analog soil-calibration FDR probes were checked with one reference digital FDR probe. Indeed, only the digital reference probe is providing the real part of the soil's relative dielectric permittivity ε_R. The analog soil-calibration FDR probes have an analog output proportional to the internally calculated volumetric SWC value calculated using factory fixed constants. The reason for which we used these analogic probes reside in the fact that, contrarily to the digital FDR probes (Hydraprobe), their cable is detachable from the probe's bodies which is necessary for the clayey soil calibration (see appendix A: Specific clayey soil calibration protocol). This way, we know the real part of the soil dielectric constant ε_R using the analog soil-calibration FDR probes. Both types of probes were placed in a large bucket with water-saturated clayey soil from the concerned plot, the bodies of the probe were recovered with sand to slow down the evaporation and thermalize the probes (Fig. 3a). It is important to slow down the evaporation to ensure the SWC homogeneity and prevent cracking. Figure 3b is giving the obtained curve: Digital probe indicated squared real part of $\varepsilon_R$versus analogic probe indicated θ (in mV), adjusted by a second-degree polynomial fit. Obtained coefficients are used for subsequent $\sqrt{(\varepsilon_R)}$ deductions from analogic probes volumetric SWC measurements. The real volumetric SWC was deduced from scale-based gravimetric measurements of the soil drying sample by subtracting oven-dried soil sample, bucket, and probe mass. The soil sample volume was also monitored as the clayey soil volume may change (shrinking in so-called vertisol). Soil calibration lasted seven to eight months. We have proceeded by measurement of all samples from a particular pit at the same time, which means six samples at once using six analogic SWC robes in parallel. As described in appendix A, each working day we weighed and measured sample dimensions.

4) Results and discussion

4.1) Vertisol issues

FDR and TDR probes provide volumetric measurements, not gravimetric ones, which is not the most adapted representation for vertisol (Zawilski, 2022). Indeed, vertisols' shrinkage causes at least two problems. The first one is to accurately monitor drying soil sample volume and the second problem is the micro and macro cracks. To monitor the sample soil volume, height measurement may not be enough. Indeed, vertisol shrinkage may be anisotropic (Mishra et al., 2020). However, because of accurate diameter measurement difficulty with the sample inside a bucket, we have assumed the shrinkage in the studied soil moisture range as isotropic. Our simplification is close to reality since the sample is not diametrically constrained and, except soil sample bottom, air-surrounded. The apparent squared dielectric permittivity versus volumetric soil moisture linearity confirms this point at least before the crack's apparition (Fig. 4). Also, the two different volume determination influences were checked and are limited to about 10% of the calculated volume difference.

The second problem concerns the cracks apparitions. Formally, there is a leak in the soil volumetric water definition. Water volume is well defined by the water mass (water density is 1liter by 1kg of the water) but soil volume is difficult to delimit when the crack forms and deforms the sample shape. Are the cack volume parts of the sample volume? If not, there is a challenge to subtract crack volume from the soil sample volume as it is very difficult to measure it.

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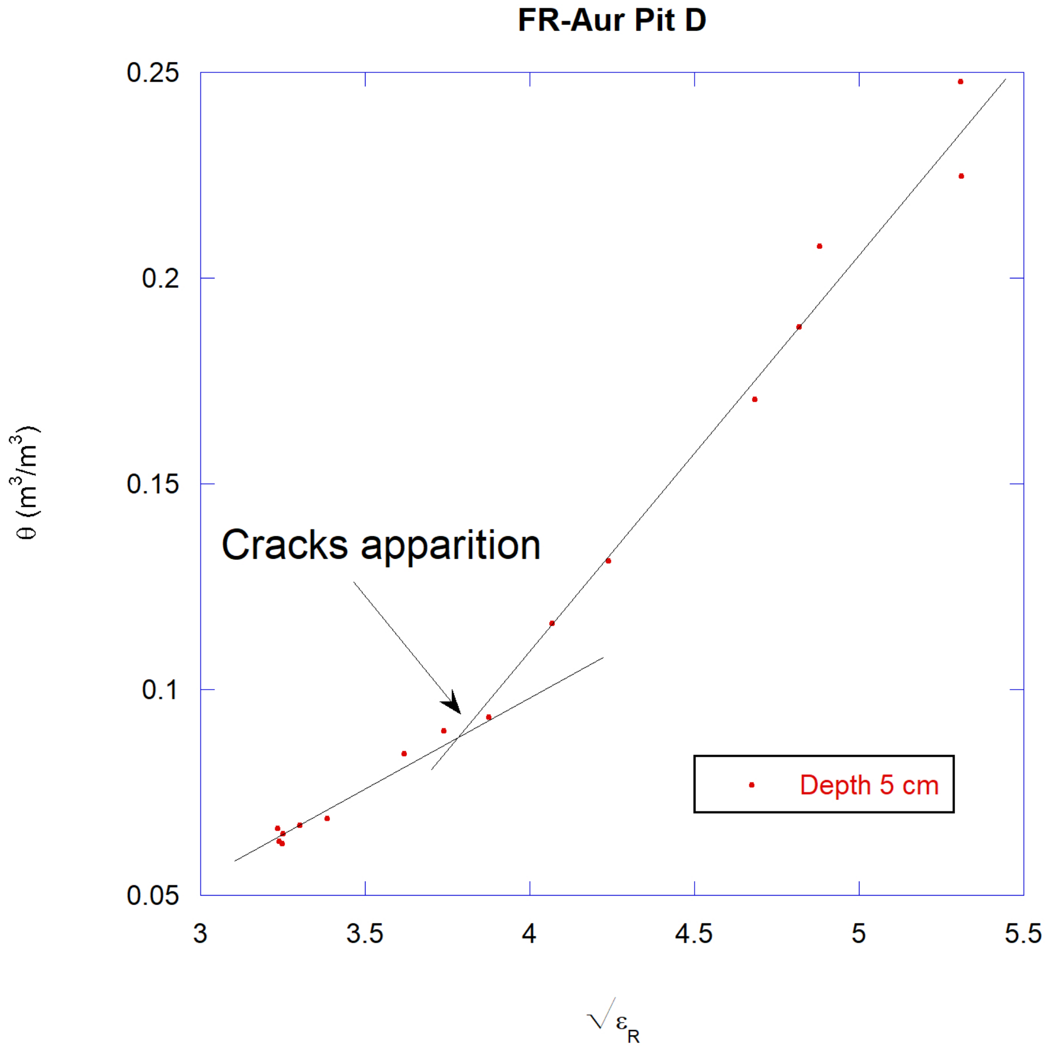


Figure 4. Typical curve of real SWC versus square root of relative dielectric permittivity real part.

4.2) Real part of the dielectric relative permittivity versus volumetric soil water content.

Figure 4, shows the typical behavior of the real dielectric relative permittivity part. When soil samples are progressively drying, the measurement curves are well linear up to the crack formations where the slope changes abruptly becoming sensibly smallest.

For calibration, a simple linear fit does not correctly cover the whole SWC range. For closer modulization, second-order polynomial fits of squared relative dielectric permittivity real part were used.

Disparities in the observed coefficients are important between each pit and each depth of the soil sample origins. In general, near the surface (from 0 to 10 cm) the homogeneity of the calculated coefficients is better than in-depth and closer to the factory calibrated FDR probe indications. This fact may be tied to lower soil density and lower clay content at the surface than in-depth.

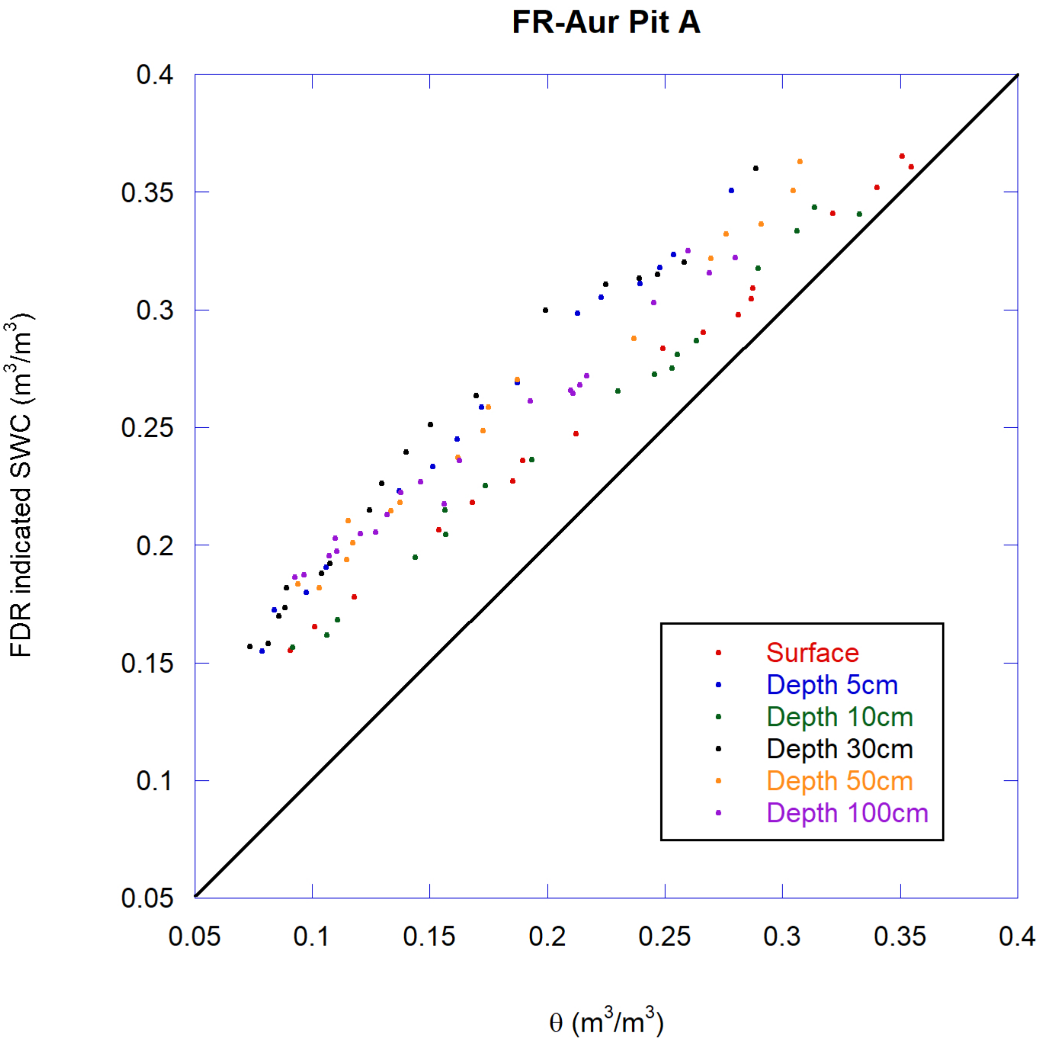
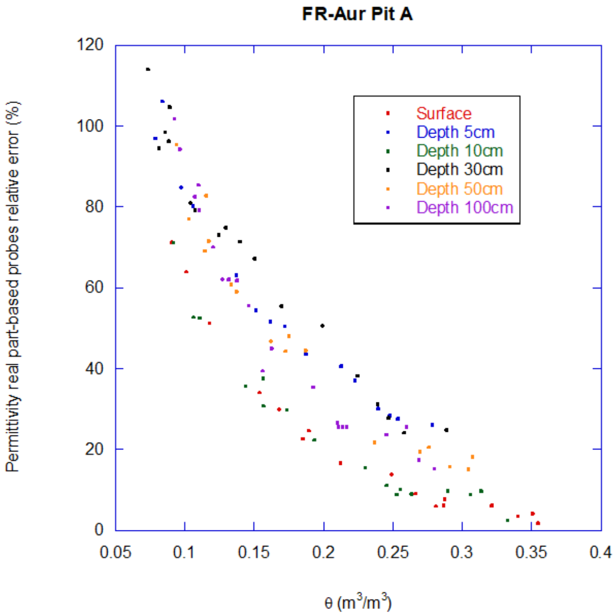
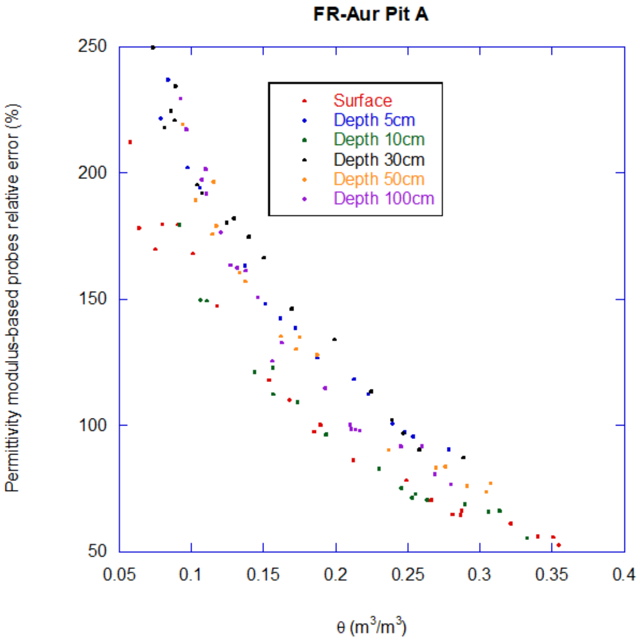


Figure 5. SWC provided by a digital reference factory calibrated FDR probe versus real SWC for several depths inside Pit A.



(a)



(b)

175 **Figure 6. (a) Relative error of SWC indicated by factory-calibrated digital reference probe based on the real part of the dielectric permittivity measurement versus real SWC inside Pit A at six depths. (b) Relative error of SWC indicated by factory-calibrated analog soil-calibration probe based on the modulus of dielectric permittivity measurement versus real SWC inside Pit A at six depths.**

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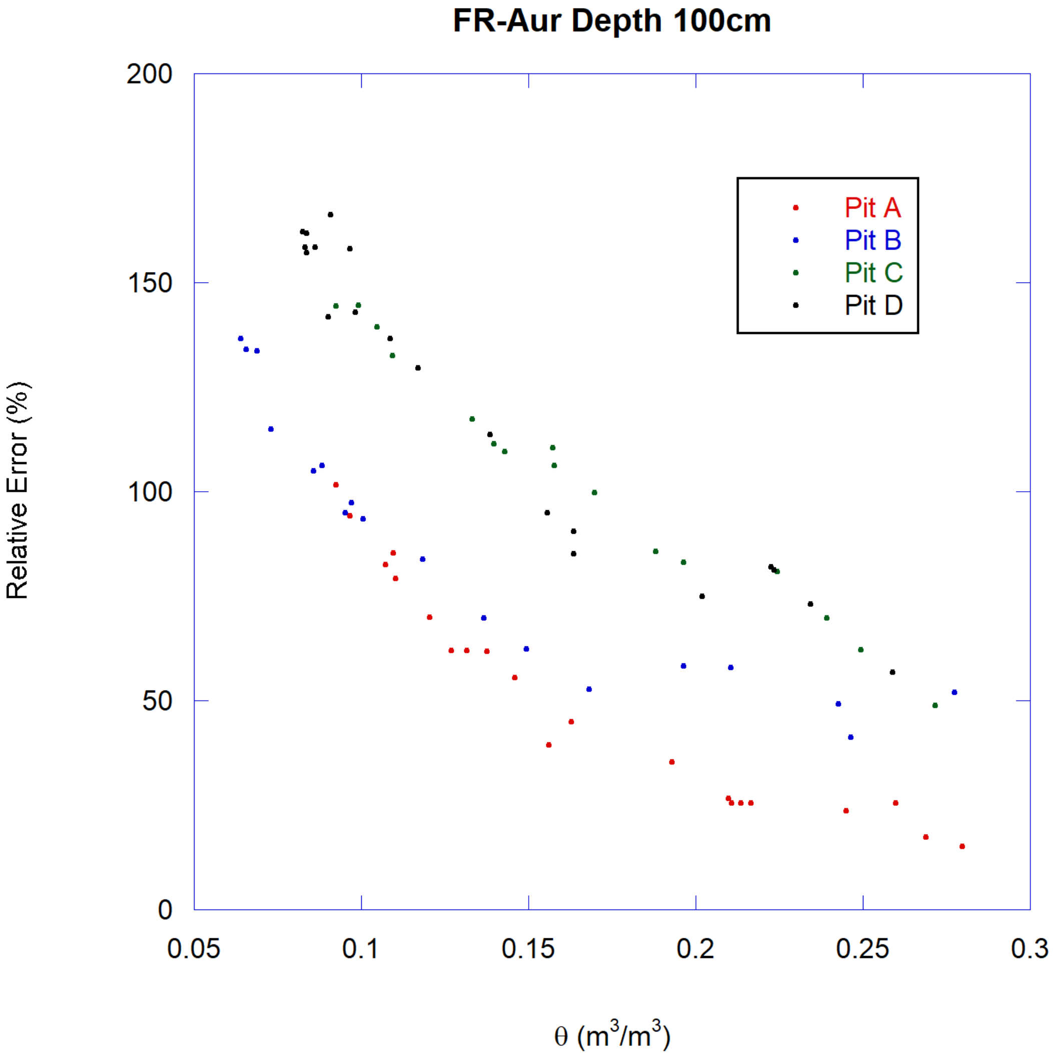
We compared the real SWC and the indirectly measured SWC with the reference digital FDR probes either by using factory calibrated coefficients or by using the specific soil calibrated coefficient. Figure 5 displays FDR factory calibrated SWC measurements based on the real part of the dielectric permittivity versus real SWC for several depths inside pit A at FR-Aur station. No one SWC value estimated with the factory-calibrated coefficient accurately represented the real SWC. The remarkable offset in all measurements resulted in an overestimation of soil water content. Figure 6 shows the dynamics of the relative error (see equation 3 for definition) of the SWC estimated with the factory-calibrated FDR probes (Fig 6a for the digital reference probe and Fig 6b for analog soil-calibration probe) versus the real SWC measured at the six depths, from surface to 100cm, in the pit A (see Fig. 2 for this pit location). The important difference in the relative error for digital and analog SWC probes comes from the fundamental difference between the analog and the digital probes' operational modes. Indeed, the digital probes we use are based on the relative part of the dielectric permittivity while the analog probes we use are based on the modulus part of the dielectric permittivity. As mentioned previously, the ionic soil characteristic affects mainly the imaginary part of the dielectric permittivity which is a component of the modulus of the dielectric permittivity. For the digital FDR probes, the relative error decreased with an increasing real SWC from 115 % to 1% with SWC (in m^3/m^3) increasing from 7% to 35%. The relative error of the analog soil-calibration FDR probes based on permittivity modulus is much larger than the relative error of the permittivity real part-based probes whatever the SWC is for concerned clayey soil. Moreover, the analog probes' raw measurements are 50% overestimated for nearly saturated soil and up to 245% overestimated for dry soil.

The relative error was calculated using Eq. 3:

$$Relative\ SWC\ Error = \frac{FDR\ measured\ SWC - Real\ Volumetric\ SWC}{Real\ Volumetric\ SWC} \tag{3}$$

Where the real volumetric SWC measured with the scale is subtracted from the raw FDR measured SWC using the factory settings and scaled by the real volumetric SWC.

In Fig. 6 we can see that errors are important and positive, which means the soil is dryer than the factory-calibrated FDR probes would indicate. The dryer is the soil and the biggest is the relative error. There is a large error disparity depending on the depth. In the best case, it means for the real part of the permittivity-based probes, the maximum error is about 115%, depending on the real soil volumetric water content and depth. It means, for example, that when the FDR probe is indicating a SWC value of 20%, the real SWC is only 10%. Figure 7 displays relative SWC error for a depth of 100cm measured in all four pits (please see Fig. 2 for pit emplacements). We may note that pit A and pit B or pit C and pit D show similar relative error behaviors. However, between these two groups, the relative error gap is about 20% at the depth of 100 cm.



210 **Figure 7. Relative error on SWC with factory calibrated digital preference probe versus real SWC for depth of 100cm inside all four pits.**

4.3) FDR probe SWC measurements after soil specific calibration

Once soil calibration is done, new calibration constants can be injected into the relations between SWC and the real part of dielectric permittivity. Figure 8 displays the same curves as Fig. 5 after post-processing corrections with new 215 soil-specific calibration coefficients for the concerned Pit and depth. The corrected measurements are much closer to the real SWC.

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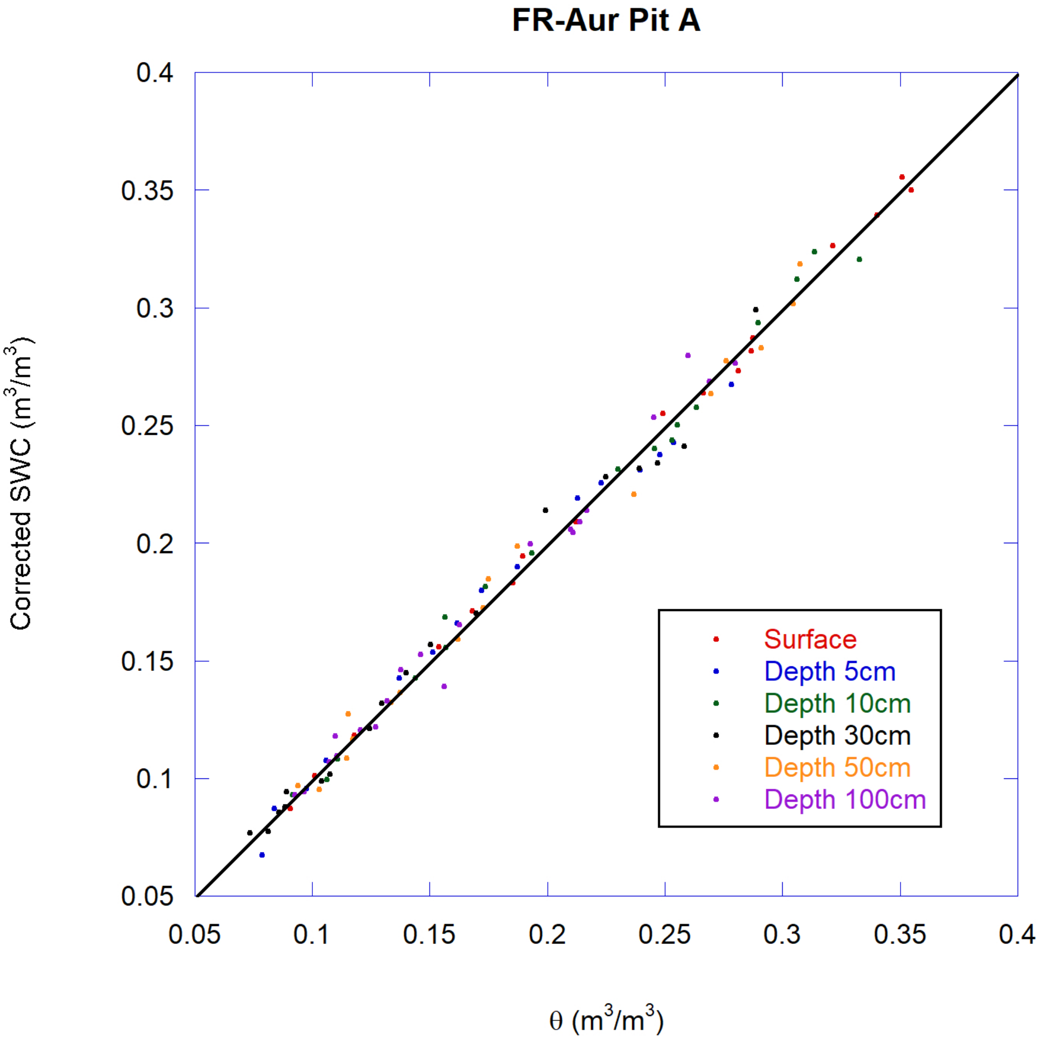

220 **Figure 8. SWC measurements deduced from soil-calibration analog probe measures using soil-specific calibration coefficients for the same pit and depths as the Fig. 6.**

5) Conclusion.

These short studies show clearly that factory calibrated SWC probes, when based on dielectric permittivity measurement (FDR, TDR, Capacitance, radar, or microwave techniques), would not be accurate enough on every soil and A specific soil calibration should be performed even if the soil composition does not predict this necessity 225 according to the probes' manual recommendation. Clayey soils are often concerned and their properties may significantly change not only according to the geographic position but also according to the concerned depth due to their physicochemical properties and especially the density (Namdar-Khojasteh et al., 2012). Without soil-specific calibration, the drier is the soil and bigger is the relative error up to 160% on our stations for the probes based on the real part of the dielectric permittivity and 245% for the probes based on the modulus of the dielectric permittivity. Once soil-specific calibration is done, FDR probes, and certainly other dielectric permittivity measurement-based probes, are accurate and may serve for SWC measurement. For the precision required by scientific studies, i.e., the need to access precise absolute values of SWC for the estimation of the useful reserve, the study of soil microbial processes, soil water flows, and/or characterization of their spatial variability, we are suggesting to always check if the SWC is accurately measured by commercial probes in the concerned soils. If there is a sensible discrepancy, calibrate the soil. Soil calibration is long and manpower-consuming but may be necessary. The same problem concerns remote measurement techniques which have the advantage to assess SWC without physical contact. However, on some soil, an important error may also occur biasing results and requiring soil-specific calibration for more accuracy.

Appendix A: Specific clayey soil calibration protocol

Used Setup

- Withdrawn cylindrical soil samples should be large enough for the used soil moisture probes and withdrawn as wet as possible as the calibration process is made during sample drying.

- Data logger, such as Campbell’s CR1000, programmed for soil moisture probe monitoring. Wired with labeled cables for each labeled probe.

- Scale with sufficient weighting range capacity and resolution.

- Buckets big enough for the soil samples, bearing 105°C temperature (Polypropylene buckets are OK).

- Caliper for soil sample dimensions measurements.

-Stainless steel exhaust pipe clamp of internal diameter and height fitting soil samples external diameter and height.

Preliminary measurements.

Measuring the weight of each soil moisture probe without its cables: W_P.

Measuring the weight of the buckets: W_B. Note: It is not necessary but may be used for uncertainty determination.

During each measurement cycle.

Probes are inserted into the soil samples and placed individually inside a bucket.

Note: during probe insertion into the soil sample, it can be placed in an exhaust pipe clamp of fitted dimensions to prevent sample altering.

Three points are marked on each soil sample around its circumference every 120° (this will be necessary to determine the sample dimensions during the measurement cycle by averaging).

Probes connected with their cables to a logger are surrounded by tissue paper to slow down the evaporation from the soil samples.

Routine measurement.

Every day:

- dielectric permittivity (ε_r) values (or directly the square root of) measured by the logger for each probe is noted.
- Paper surrounding the probes disposed of and their cable disconnected, each sample is weighted (including bucked and inserted probe) W_{SBP}.
- The height of three points around the circumference of each soil sample is measured with the caliper H_{S1}, H_{S2}, and H_{S3}, and the sample diameter D_S (if possible) in dekameters (dm).
- It is welcome to take a clear picture of the samples to track any crack apparition.
- Pater is applied back around each connected back probe.

Once the soil samples are considered dried:

- When the measurement cycle is considered finished It may be necessary to wet the soil sample again to withdraw the moisture probes.
- Each sample into its bucket but without the SWC probe is dried in an oven at 105°C for two days.
- After two days, each completely dried soil sample, including the buckets, is weighted: W_{SB}.

Data processing

Using all acquired data, from each daily soil sample weighting including bucket and inserted SWC probe, subtracting the weight of completely dried soil sample (including bucket) and the probe weight, the soil water content weight in kg is obtained:

$$W_W=W_{SBP}-W_{SB}-W_P. \tag{A1}$$

Note: We can take the water density constant and equal to 1 kg/liter. With this density the water volume V_W (in liters), present in the soil samples during the measurements, is numerically equal to the water mass:

$$V_W=W_W$$

With the samples height (and diameter if available) measurements, the soil samples volume is calculated: in liters:

$$\Theta = V_W/V_S \tag{A2}$$

Note: if the sample diameter is not measured during the measurement campaign, for example, due to the bucket presence and inaccessibility of the sample, as an approximation, we can suppose that this diameter will change in the same way as the height (isotropic shrinkage).

$$V_S = \frac{(H_{S1}+H_{S2}+H_{S3})}{3}\pi\left(\frac{D_S}{2}\right)^2 \tag{A3}$$

With previously determining water volume, the samples' volumetric soil water content (SWC or θ) in m^3/m^3 (or in liters/liters which is the same) can be calculated:

$$\Theta = A_S\ \sqrt{}(\varepsilon_R)+B_S.\ \text{or, in the case of second-order polynomial fit: } \Theta = C_S(\varepsilon_R)+A_S\ \sqrt{}(\varepsilon_R)+B_S \tag{A4}$$

A graph: SWC versus square root along with a linear regression (or second-degree polynomial regression) provides the calibration constants A_S and B_S (and C_S).

Author contributions

This study was conceptualized by BZ, who carried out a preliminary investigation showing the benefits of soil-specific calibration, developed the soil calibration methodology protocol, designed and built the soil sample extruder apparatus, participated in the: soil samples extraction, measurements, and formal analysis, and wrote the first draft. FG was involved in the soil sample extraction. NC was involved in the measurements. AB reviewed the draft and participated in the measurements. TT was involved in the soil sample collection, the measurement, the formal analysis, and the writing and reviewing of the original manuscript.

Code and data availability.

The data and source code used for these studies can be obtained by contacting the author.

Competing interests.

The author declares that he has no conflict of interest.

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