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

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Abstract. Soil Water Content (SWC) ~~probes~~sensors are widely used ~~around the Earth~~ for scientific ~~and~~ studies or for the management of agricultural ~~usage. Most of them are~~ practices. The most common sensing techniques provide an estimate of volumetric soil water content based on ~~soil~~sensing of 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),~~ . These techniques include: Frequency Domain Reflectometry (FDR~~)~~), Time Domain Reflectometry (TDR), capacitance, and even remote sensing techniques such as Ground-Penetrating Radar (GPR) and microwave-based techniques ~~are concerned. This~~. Here we will focus on Frequency Domain Reflectometry (FDR) sensors and more specifically on the questioning of their factory calibration, which does not take into account soil specific features and therefore possibly leads to inconsistent SWC estimates. We conducted the present study ~~presents SWC measurements with~~in the south west of France, on two plots that are part of the ICOS ERIC network (Integrated Carbon Observation System, European Research and Infrastructure Consortium), FR-Lam and FR-Aur. We propose a simple protocol for soil-specific calibration, particularly suitable for clayey soil, to improve the accuracy of SWC determination when using commercial FDR ~~probes on clayey soil highlighting the benefit of a meticulous~~sensors. We compared the sensing accuracy after 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~~ versus factory calibration. Our results stress the necessity of performing a thorough soil-specific calibration for very clayey soils. Hence, locally, we found that factory calibration results in 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~~ Indeed, we report relative errors as ~~important~~large as +115% with a factory-calibrated ~~probe~~sensor based on the real part of ~~the~~ dielectric permittivity, and up to +245% with ~~the~~a factory-calibrated ~~probes~~sensor based on the modulus of ~~the~~ dielectric permittivity.

Introduction

~~The~~ In the context of global warming and the disappearance of water resources, the volumetric soil water content (SWC~~) variable~~, also denoted by θ) 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~~SWC, along with other physical and textural ~~soil~~ properties ~~is important to estimate~~ of the soil, is key for the estimation of soil water availability and ~~retention capacity.~~ for the study of related processes.

Several techniques ~~were~~have been developed for SWC ~~measurements~~determination 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.Most SWC sensors rely on soil 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 sensing, (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 (Szyplowska 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 themuch smaller than that of pure water one ((mean values of 4 versus 80; 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 soil sensors, all are based on relative dielectric permittivity determinations. For example, Frequency Domain Reflectometry (FDR) and Time Domain Reflectometry (TDR) SWC sensors rely on a measured signal (frequency or time) that can be related to the dielectric permittivity ε, and hence to the soil water content. These sensors are very widely used and, according to the manufacturers, their accuracy is about 0.03 (m^3m^{-3}) *provided a soil-specific calibration is performed before use*. Sensed relative dielectric permittivity allows to estimate the soil water content, but soil texture and several other soil features should be taken into account for sensor calibration. A brief overview of the used terminology is provided in section 2.

Indeed, as the sample volume is less than 50 cm^3, soil heterogeneity may compromise the measurements' reliability. Crack formation, which is common in vertisol, leads to inconsistent measurements. Also, any pebble, vegetable, or animal between the sensor rods affects measurements. Furthermore, like every alternative current (AC)-derived quantity, dielectric permittivity is a complex value, comprising a real part ε_R, and an imaginary part ε_I (Grimnes and Martinsen, 2015). Ions within the soil greatly affect the dielectric permittivity imaginary part (Campbell, 1990; Szypłowska et al., 2018), especially in the low-frequency range (Skierucha and Wilczek, 2010), that is why the determination of SWC using a sensor based on the dielectric permittivity modulus $|\varepsilon|$ may be less reliable (Sreenivas et al., 1995). Sensing SWC into an ion rich soil can be best performed using a thermally compensated sensor, high-frequencies and SWC calculation solely based on the dielectric permittivity real part ε_R.
Even if the soil type theoretically allows for the use of factory-calibrated sensors, the soil dielectric permittivity may significantly be affected by the soil texture and its organic matter content (Perdoc et al., 1996; Szypłowska et al., 2021). the soil buried sensors, they are all based on relative dielectric permittivity measurements. A soil-specific calibration may thus be required locally to adjust the coefficients of the manufacturer's transfer equation used for the determination of SWC based on the soil's dielectric permittivity. Several studies have shown the benefits of a soil-specific calibration for several soil types, including clayey soil. Different calibration methodologies are described:

- "Soil-suggested" calibration, which is based on an empirical function adapted according to soil texture, granulometry, acidity, organic matter content or even temperature. Such "soil-suggested" calibrations improve accuracy to a limited extent, however (Lukanu, and Savage, 2006).

- "*In situ*" calibration, which establishes the relation between the SWC estimated *in situ* with a factory-calibrated sensor and the actual SWC determined in lab by soil sample weighing, 1 point at a time. For example, Varble and Chávez (2011) show that every individual sensor position requires recalibration.

Furthermore, Dong et al. (2020) report laboratory simulations for *in situ* superficial soil sensor check; Jackisch et al. (2020) present *in situ* cross studies comparing several sensors; De Vos et al. (2021) perform true *in situ* calibration in forest soil and stress that soil samples should be collected periodically over a long period of time to cover the whole range of soil conditions (several years). This method is probably the most accurate, as the sensors are calibrated in real operating conditions. However, in our case, it was not possible to collect relatively dry clayey soil samples from deep layers.

The two cultivated plots where we conducted this study are located in the South West of France and are part of the ICOS ERIC network (Integrated Carbon Observation System, European Research and Infrastructure Consortium), whose member ecosystem stations must continuously monitor SWC at several depths. To this aim, FDR sensors are among the possible instruments and are implemented according to a standardized ICOS protocol on several ICOS ecosystem stations with various soil properties; our plots' soil is mainly clayey. The ICOS mandatory quality standards require sensor accuracy of at least 0.05 (m^3m^{-3}) over the whole expected SWC range. We questioned the relevance and accuracy of the factory-calibrated transfer functions because of the high clay content and the very heterogeneous characteristics of the soil in our plots throughout the year.

The objective of the present study is threefold: (1) to evaluate the accuracy of commercial FDR sensors on a clayey soil, using either the generic calibration constants provided by the manufacturer (raw SWC), or the specific soil calibration constants; (2) to compare SWC estimates based on either the dielectric permittivity modulus or on the dielectric permittivity real part and (3) to propose a FDR sensor soil-specific laboratory calibration process particularly suitable for clayey soils.

2) Theory on dielectric permittivity-based techniques

The dielectric permittivity ε, as expressed in the electromagnetics law, is measured in Faraday per meter (F/m) and formally the term “permittivity” is used only for “absolute permittivity”. It can be expressed as a factor of “relative permittivity”, denoted by “ε_r”, and vacuum absolute permittivity, denoted by “ε_0”: $\varepsilon = \varepsilon_r\varepsilon_0$

Most, if not all, sensors deliver a relative permittivity and most publications, including the present one, refer to “dielectric permittivity” as a unitless number, which is actually the “relative permittivity”.

Another important point is that the sensing of dielectric permittivity is carried out by processing an alternating AC signal which results in complex numbers formalism. Dielectric permittivity is therefore a complex number with a “real part” ε_R (with a capital R, as opposed to the lowercase r of relative permittivity) and an “imaginary part” ε_I. The “modulus” $|\varepsilon|$ is the square root of the sum of squared real and imaginary parts:

$$|\varepsilon| = \sqrt{\varepsilon_R{}^2 + \varepsilon_I{}^2} \qquad \text{(Eq. 1)}$$

Most FDR sensors detect changes in the relative dielectric permittivity modulus.

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, K. Norobio, 1993). Both techniques rely on linking the soil dielectric permittivity measurement ε to the soil water content (Color and Ulaby, 1974). FDR sensors detect the soil's capacitance, which is its ability to store an electric charge, and is 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.sensor’s rods is determined and allows to estimate the water content. In the case of TDR sensors, a high frequency electric pulse is applied to the sensor rods inserted into the soil, travels the rods and is reflected by the rods ends. The measured travel time depends on the dielectric permittivity of the soil. Using a frequency range instead of a single frequency improves accuracy (by mitigating the salinity bias, as discussed below).

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

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

(1Eq. 2)

With *A* and *B* being constantconstants usually depending only on soil composition and soil texture.

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

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

(2Eq. 3)

With A_S and B_S being a constantconstants (A_S = 1/A^{-1}, B_S = - B/ABA^{-1})

As we Since at our study sites, FR-Lam and FR-Aur, soils 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 soiland rich in ions, it is important to work with the real part of dielectric ~~susceptibility~~ permittivity instead of the ~~norm~~modulus of the dielectric permittivity, in order to ~~minimize the possible~~avoid error caused by dielectric dispersion ~~influence~~ and the resulting resistive ~~losses~~loss that mainly ~~affect~~affects the imaginary part. ~~Corresponding commercial probes~~Commercial FDR or other SWC sensors based on the real part of the dielectric permittivity are rare. ~~Special~~Hence, one should pay attention to ~~concerned scientific groups should be paid to choose the right probes for specific soils such as~~the sensors' specifications before installing them on site, especially for clayey soils.

~~Some~~ A transfer equation (Eq. 2) is applied by commercial SWC sensors ~~are using this relationship (Eq. 2)~~, either with factory fixed coefficients that cannot be changed ~~and other SWC sensors can be configured.~~or with resettable coefficients. In both cases, by post-processing correction or by reconfiguring ~~probes~~sensor coefficients, it is possible to recover a more accurate ~~measurement.~~estimate of SWC. Depending on the accuracy ~~of~~required for the SWC measurements ~~sought after~~, it may be necessary to perform a soil-specific calibration, not only for ~~a~~each particular plot but even for ~~a~~each particular pit and ~~particular~~ depth, as on our stations or in the forest (De Vos et al., 2021).

3) Material and methods

3.1) Soil description

We carried out our study on two cropland ICOS stations (Fig. 1) in a very clayey region of south-western France: FR-Lam (43°29'47.21"N, 1°14'16.36"E), whose texture corresponds to silty-clay definition : 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), which is also defined as a silty-clay soil: 30.8% of clay, mainly Smectite and Montmorillonite, 48.3% silt, 19.2% sands, 1.6% organic matter (Table 1). Both sites are certified in the ICOS network which means that their instrumentation and measurement protocols meet the required quality standards. For instance, on both sites, we installed HydraProbe (Stevens water monitoring systems Inc.) which are digital FDR sensors (Table 2). The accuracy required for ICOS sites is specified in the soil-meteorological measurement protocol (Op de Beck et al., 2018). It is recommended to use FDR or TDR sensors with at least 0.05 m^3m^{-3} accuracy over the entire SWC range. According to the manufacturer, the FDR digital sensor HydraProbe meets ICOS quality standards; the purpose of this study is to validate its accuracy on our study sites soil. In a preliminary check, both study plots showed a significant discrepancy between the factory-calibrated sensor SWC estimates and actual SWC (determined by weighing and measuring soil samples to calculate the soil volumetric water content). Therefore, we performed a thorough soil calibration on FR-Lam and FR-Aur, into each pit and each depth. Here, we present only the results from the FR-Aur site as the collection of the samples was carried out later than on FR-Lam, and therefore with the benefit of hindsight and experience of the required delicate handling. So, no sample was damaged during collection or drying.

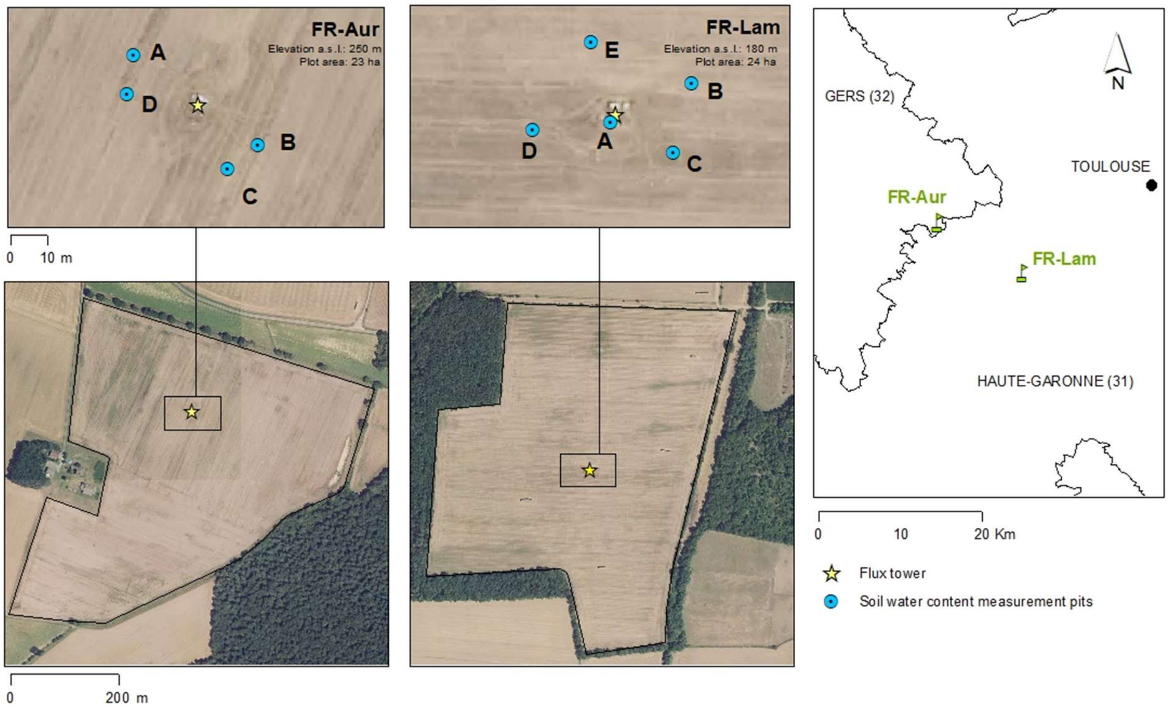


Figure 1. FR-Aur and FR-Lam ICOS stations (https://www.icos-cp.eu/~~accurate~~) and pit emplacements.

Table 1. Pit A FR-Aur soil contents

Depth range (cm)	Sand (% of mineral)	Silt (% of mineral)	Clay (% of mineral)	Organic C content (% of total)
0-15	19.2	50	30.8	9.12
15-30	20.6	47.1	32.3	8.05
30-60	12.7	41.7	45.6	3.16
60-100	11.6	35.2	53.2	2.91

3.2) Soil sampling

On both sites, we collected soil samples at different depths (0-10 or surface, 5, 10, 30, 50, and 100 cm depth) into 4 to 5 pits, depending on the sites, to meet the ICOS requirements for SWC measurements~~.~~

(Op de Beek et al., 2018). When we created the 100 cm deep pits to install the ~~**3) Material and methods.**~~

~~**3.1) SWC measurement sensors and used setup.**~~

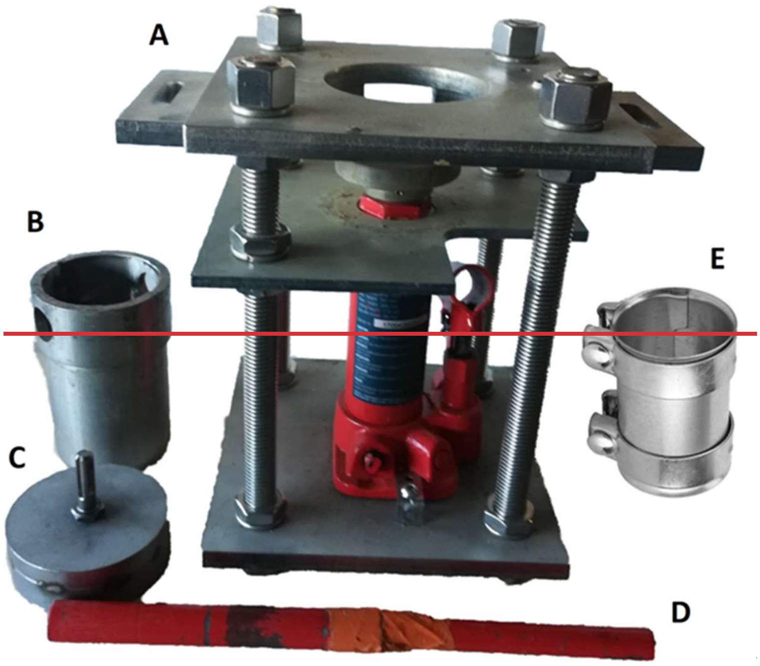
~~FDR SWC measurement probes (analog output 1-5V, operational frequency at 50 MHz): DC200, Beijing Dingtek Technology Co., Ltd. Room A209, Flounder Business Park, Shunbai Road 12, Chaoyang District, Beijing, 100022, China.~~

~~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.~~

sensors, we took the opportunity to collect soil samples at the depths required by the standardized ICOS protocol. Soil samples should be as wet as possible (at filed capacity) when collected from the study site, so that the calibration process performed during in-lab drying covers the whole range of ~~about 100mm height with a minimal~~SWC. Clayey soil is probably one of the most difficult soils to handle. Undisturbed clayey soil sampling is difficult. In case of low SWC, sensor probes insertion or withdrawal into clayey soil may be destructive for the soil samples or the sensor rods. In order to minimize disturbance of the soil density during sample collection, we ~~have used~~designed a homemade ~~soil~~ sample extruder (see Fig. 2). This apparatus ~~(see Fig. 1)~~is based on stainless-steel short tubes (soil sampler) of ~~70mm~~70 mm internal diameter sharpened at the bottom, forced into the soil using a ~~pneumatic hammer~~5J perforator holding a sampler cloche. The collected soil sample volume is about twice as big as the sensed volume, which is less than 50 cm^3. Fig. 2. (b) shows a sectional drawing of the sampler. To minimize soil compaction when the extractor is forced into the ground, this extractor was designed with two particularities. First, its tip is sharpened from the inner diameter to the outer diameter to mainly compact the remaining soil outside the soil sample. Second, the inner diameter at the sharpened edge is slightly smaller than the core sampler inner diameter to minimize the frictions between the soil sample and the inner sampler surface.



The soil sampler was forced horizontally into each pit at each required depth except for the soil surface, where it was forced vertically as the surface SWC sensors are also placed vertically. Once the tube is pushed all the way into the soil and extracted with the soil sample inside, a hydraulic carjack allows the soil sample to be gently pushed out of the sampler. It is important to place a thin round shaped PTFE sheet between the soil sample and the extruder piston to prevent the soil sample from sticking. All samples were hermetically sealed in plastic buckets that can withstand oven drying at 105°C, which is the temperature required to dry soil samples at the end of the calibration process. Soil sample were collected in duplicate, in case of technical problems during the set-up of the experiment (see appendix A for details).

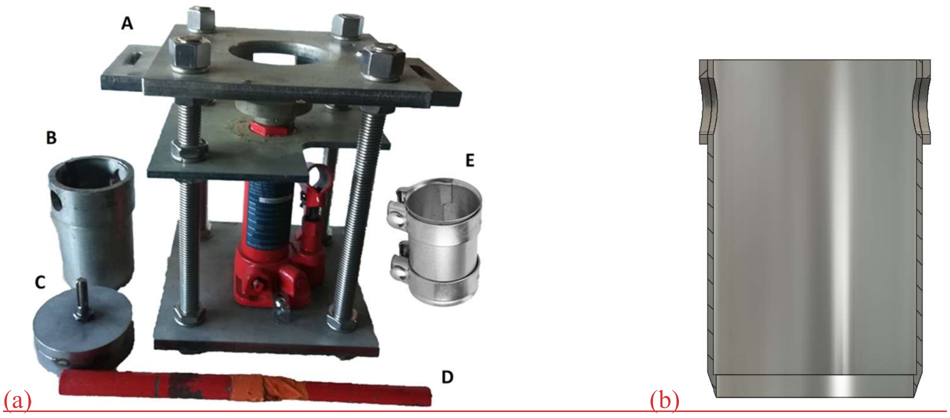
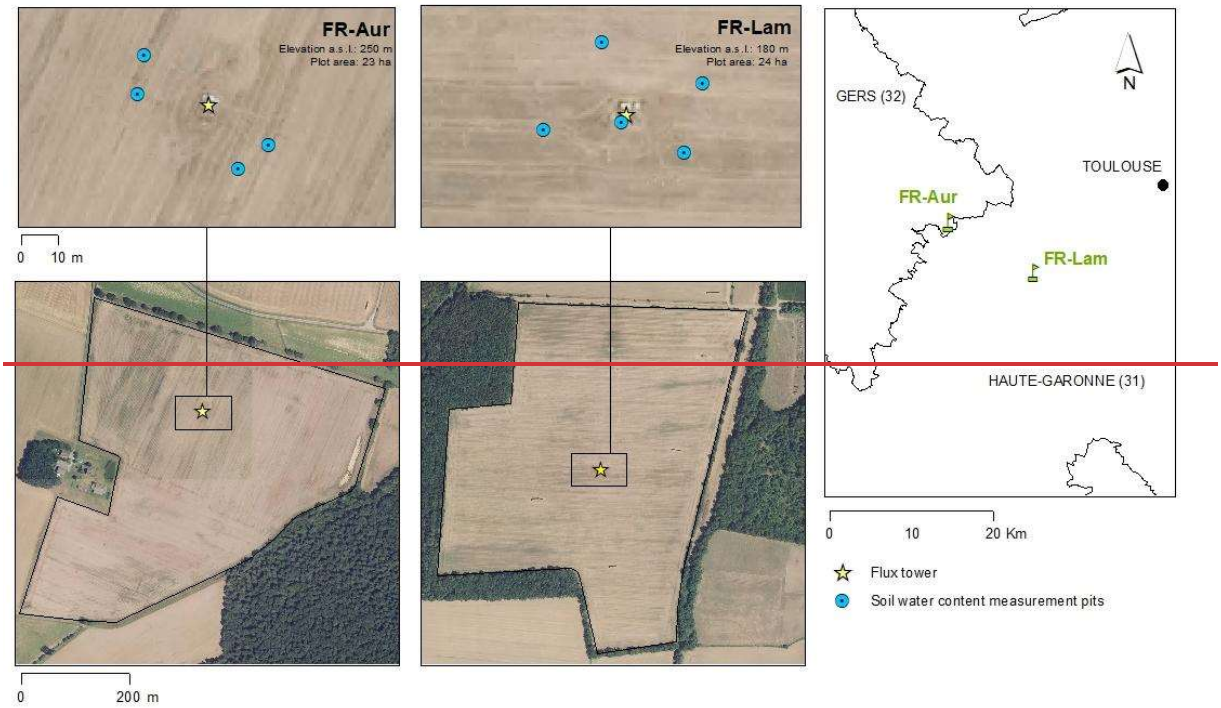


Figure ~~1.~~2. (a) Soil sample extruder: A) Carjack and stainless-steel frame, B) Soil sampler, C) Sampler cloche for pneumatic hammer, D) Carjack handle, E) Exhaust pipe clamp. (b) Sectional drawing of the sampler.

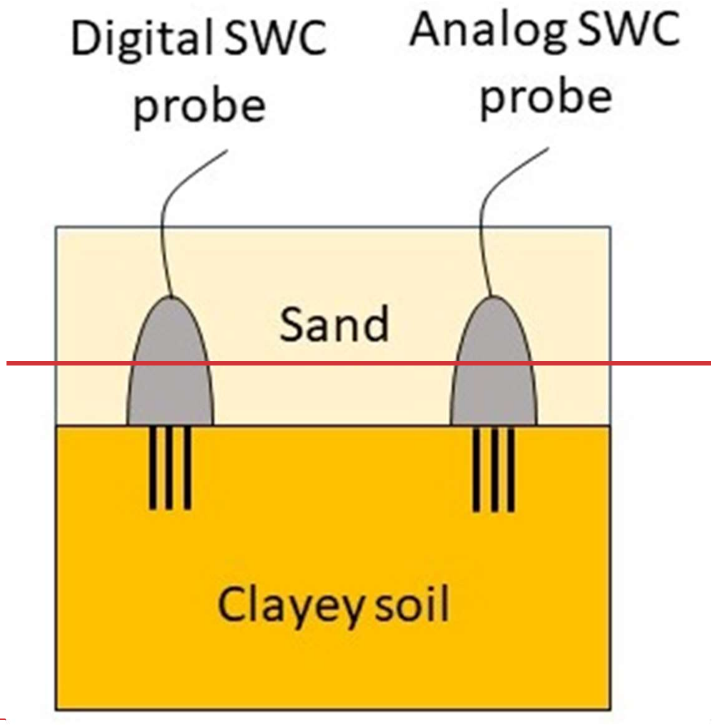


~~**Figure 2. FR-Aur and FR-Lam stations and pit emplacements.**~~

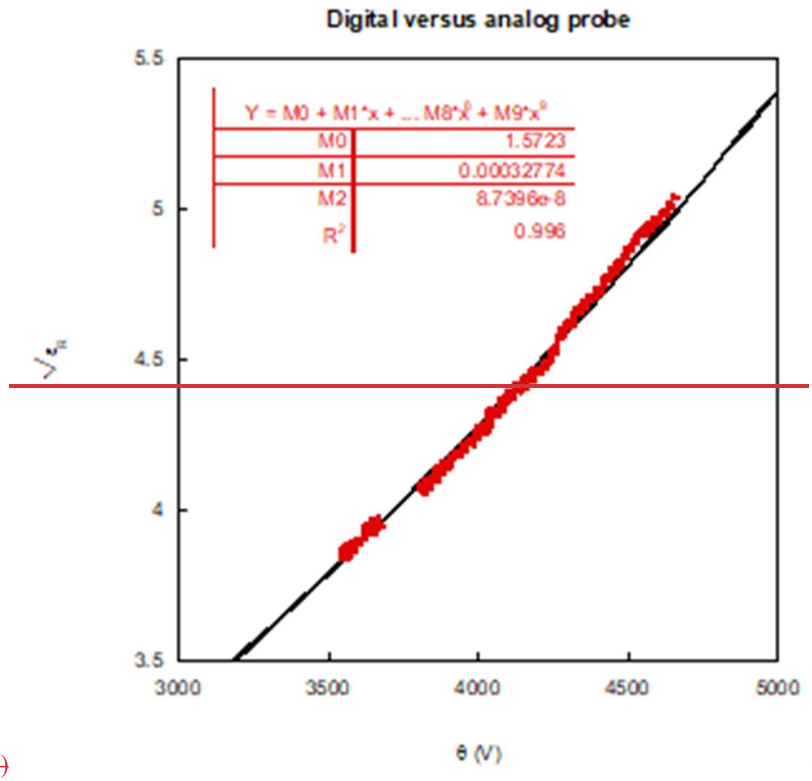
3.23) Soil description and sampling

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.



(a)



(b)

3.3.1 Analog and Digital FDR sensors cross-calibrations

For the purpose of this study, we used several sensors and we assume that sensors of the same model are identical to each other. For practical reasons, we used an analog FDR sensor type with a cable that could be removed from the sensor's body for the weighing process, in order not to disturb the clayey sample by removing the sensor rods (Lukanu and Savage, 2006; see appendix A for details on soil calibration protocol and the different process steps). The analog FDR sensors were first cross-calibrated with the reference digital FDR HydraProbe sensor (SWC sensors' specifications are reported in Table 2). Indeed, only the reference digital FDR sensor provides**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

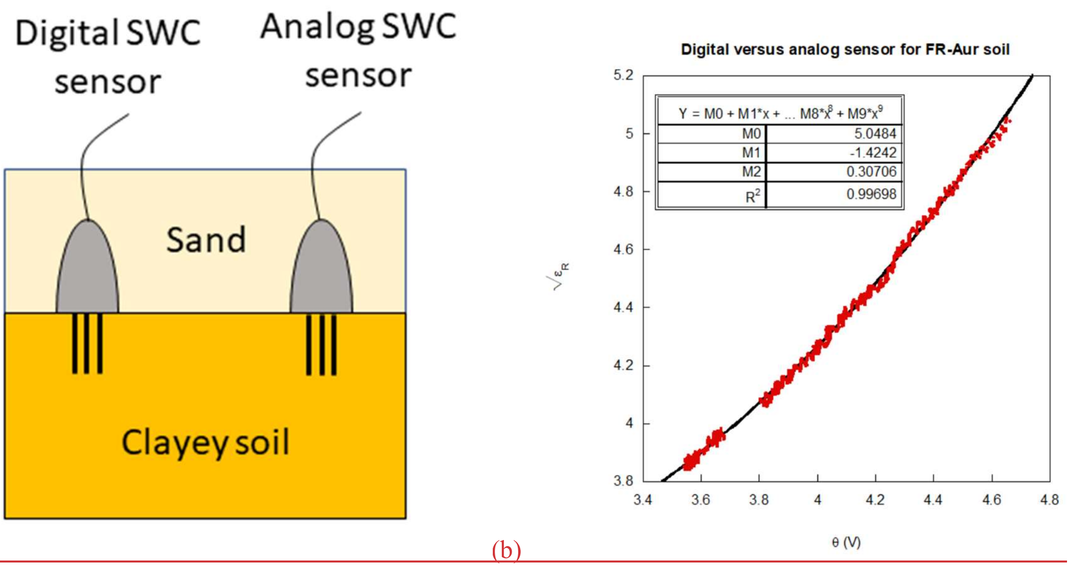
First, the analog soil-calibration FDR probes were checked with one reference digital FDR probe. Indeed, only the digital reference probe is providing the real part of the soil's relative dielectric permittivity ε_R. The analog soil-calibration FDR probessensors have an analog output which is proportional 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).deduced from factory fixed coefficients. This way, we knowcan also access the real part of the soil dielectric constant ε_R using the analog soilFDR sensors.

During the cross-calibration FDR probes. Both types of probesstep, both sensors were first placed in a large bucket with their rods into water-saturated clayey soil from the concerned plot, theour study site. The sensor bodies of the probe were recoveredcovered with sand to slow down the evaporation, in order to limit crack formation and thermalize the probessensors (Fig. 3a). It is important to slow down the evaporation to ensure the SWC homogeneity and prevent cracking.We repeated this manipulation using sand as a substrate instead of clay to compare the intercalibration results.

Figure 3b is ~~giving the obtained curve: Digital probe~~a graphic comparison of the square root of the real part of ε_R, indicated ~~squared real part of $\varepsilon_R$versus analogic probe~~by the digital FDR sensor, with the θ value (in V) indicated ~~θ (in mV), adjusted by~~ by the analog sensor. Experimental points can be best fitted to a second-degree polynomial ~~fit. Obtained coefficients are~~ regression. The second-degree polynomial equations were similar whatever the substrate, clayey or sandy soil, showing a relatively low sensitivity of the cross-calibration to the soil texture in our case (data not shown). The obtained equation was used for subsequent ~~$\sqrt{(\varepsilon_R)}$~~$\sqrt{\varepsilon_R}$ deductions from analog sensors volumetric SWC sensing. Note that for future potential application by the scientific community, the cross-calibration should be carried out on soil from the study plot as the analog and digital sensors may behave differently in other soils types.

Table 2. SWC sensors specifications

SWC sensor Model	Manufacturer	Output	Sensing base	Sensing range (m^3m^{-3})	Rod length (cm)	Sampling volume (cm^3)	Temperature sensing-compensation
HydraProbe, referred to as “digital” sensor	Stevens, 12067 NE Gleen Wilding Rd, Suite 106 Portland, Oregon 97220, USA	Digital (SDI 12)	The real part of the permittivity at 50 MHz	0 - 1	4.5	≈40	yes
DC2300, referred to as “analog” sensor	Beijing Dingtek Technology Co., Ltd. Room A209, Flounder Business Park, Shunbai Road 12, Chaoyang District, Beijing, 100022, China.	Analog (1-5V)	The modulus of the permittivity at 50 MHz	0 - 0.6	6	≈45	yes



(a) (b)

Figure 3. ~~analogic probes~~**(a) Analog and digital FDR sensors cross-calibration configuration (b) Graphic comparison of the square root of the real part of relative dielectric permittivity, indicated by the digital FDR sensor, versus the SWC θ value (in V) indicated by the analog FDR sensor. The table indicates the second-degree polynomial regression and the corresponding determination coefficient R^2.**

3.3.2 Volumetric SWC ~~measurements. The real volumetric~~ *estimation and associated error*

In this section, we detail our protocol for SWC ~~was deduced from~~ estimation during sample drying. We calculated the actual volumetric soil water content (referred to as "real SWC") by weighing and measuring the soil samples, while simultaneously monitoring SWC obtained with the sensors, in order to compare the respective errors on SWC estimates, depending on sensor calibration strategy.

To determine the "real SWC", on a daily basis, on working days, we performed scale-based gravimetric measurements ~~of the soil drying~~ (EMS 12K0.1 scale, KERN & SOHN GmbH, Ziegelei 1, D-72336 Balingen-Frommern, Germany) of the slowly drying soil sample by subtracting the masses of the oven-dried soil sample, of the bucket, and ~~probe mass.~~of the sensor. The soil sample volume was also monitored using a generic digital caliper as the clayey soil volume may change (shrinking in so-called vertisol~~). Soil calibration lasted seven to eight months. We have~~) (See appendix A for more details). Simultaneously, SWC values indicated by the analog FDR sensor were recorded by a data logger (CR1000, Campbell Scientific, Logan, Utah, USA). We proceeded by measurement of all samples from a particular pit at the same time, which means 6 samples (six ~~samples~~depths) at once using ~~six analogic SWC robes in parallel. As described in appendix A,~~6 analog FDR sensors, until all of the 6 samples were completely dry, ensuring the whole SWC range was covered. Then, we repeated the operations for each of the 9 pits of our two study sites. In our case, the total soil calibration took 8 months.

For each ~~working day we weighed and~~sample, a second-order polynomial fit provides us with the transfer function between the sensor determined $\sqrt{\varepsilon_R}$ and the real volumetric SWC. It should be noted that a second-order polynomial fit (R^2=0.997) was used instead of a linear regression (R^2=0.989) to improve the accuracy of the modeling (see section 4.1).

Next, the relative errors on SWC estimate using factory calibration parameters of the FDR sensors were calculated using Eq. 4, where *FDR measured* ~~sample dimensions~~*SWC* is the SWC estimated with the analog FDR sensor with its factory settings (transfer function to convert voltage signal into SWC) and *Real Volumetric SWC* is the SWC estimated with the gravimetric measurements.

$$Relative\ SWC\ Error = \frac{FDR\ measured\ SWC - Real\ Volumetric\ SWC}{Real\ Volumetric\ SWC} \quad (4)$$

We used the determination coefficient (R^2, Eq. 5.) to compare the respective accuracies of calibration strategies.

$$R^2 = \frac{sum\ of\ squared\ regression\ (SSR)}{total\ sum\ of\ squares\ (SST)} \quad (5)$$

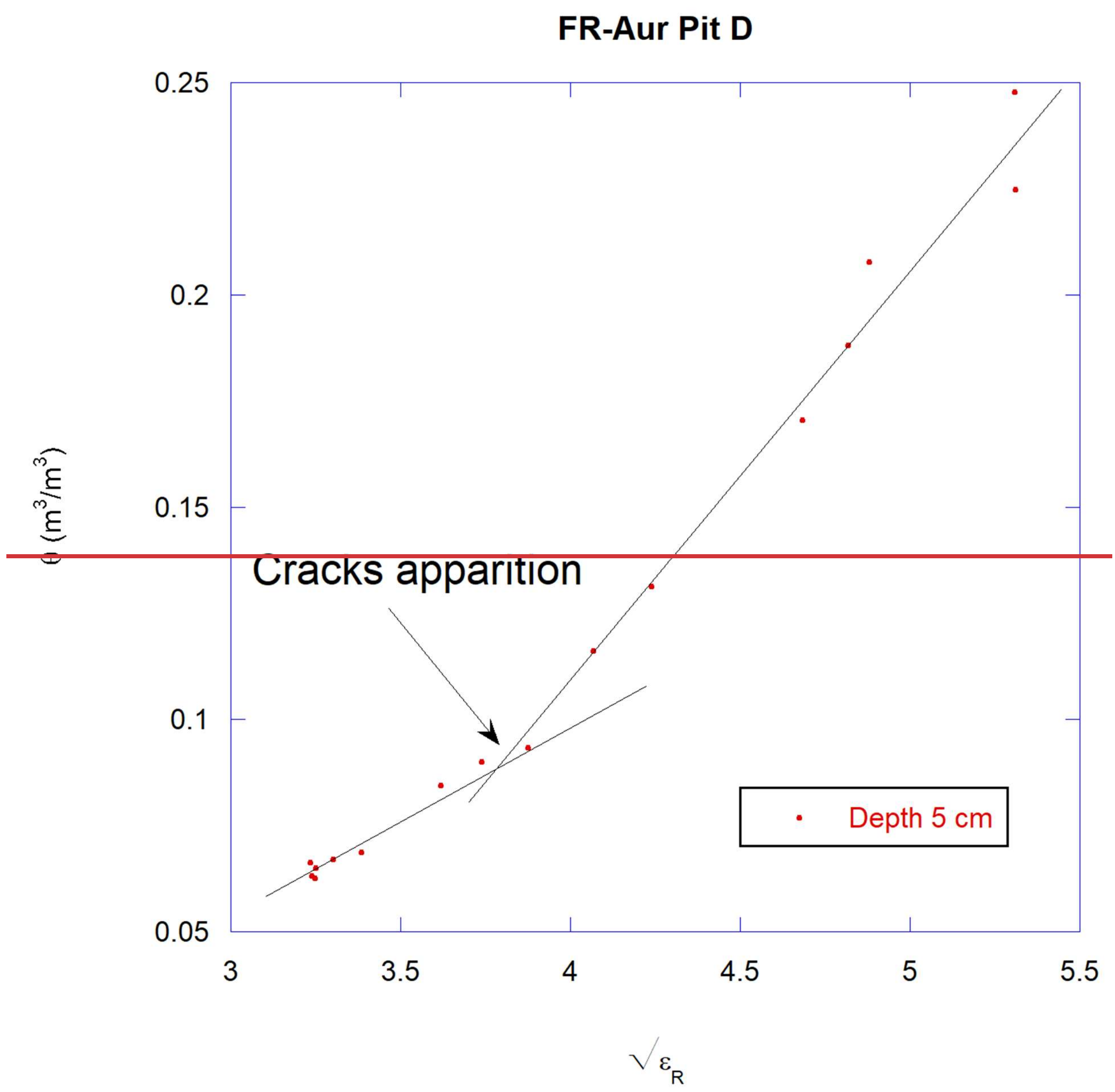
4) Results and discussion

4.1) Vertisol issues

The FDR and TDR ~~probes~~sensors provide volumetric ~~measurements~~sensing of the soil water content, not gravimetric ~~ones~~water content, which is not the most adapted ~~representation~~technique to estimate soil water content for vertisol (Zawilski, 2022). Indeed, ~~vertisols'~~vertisol specific shrinkage ~~causes at least two problems. The first one is~~makes it difficult 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~~ crack formation induce local errors. Vertisol shrinkage may be anisotropic (Mishra et al., ~~2020).~~2020), so that measuring the height of the samples may not exactly reflect volume changes. However, ~~because of accurate diameter~~

~~measurement difficulty with~~as it is difficult to accurately measure the soil sample diameter inside ~~a~~the bucket, we ~~have assumed the~~ considered shrinkage ~~in~~to be isotropic over the studied soil moisture range ~~as isotropic. Our simplification~~. This approximation is close to reality since the sample is not diametrically constrained and, ~~except soil sample~~ with the exception of the bottom, air-surrounded. ~~The apparent squared dielectric permittivity versus volumetric soil moisture linearity confirms this point at least before the crack's apparition (~~Concerning the issue~~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.~~



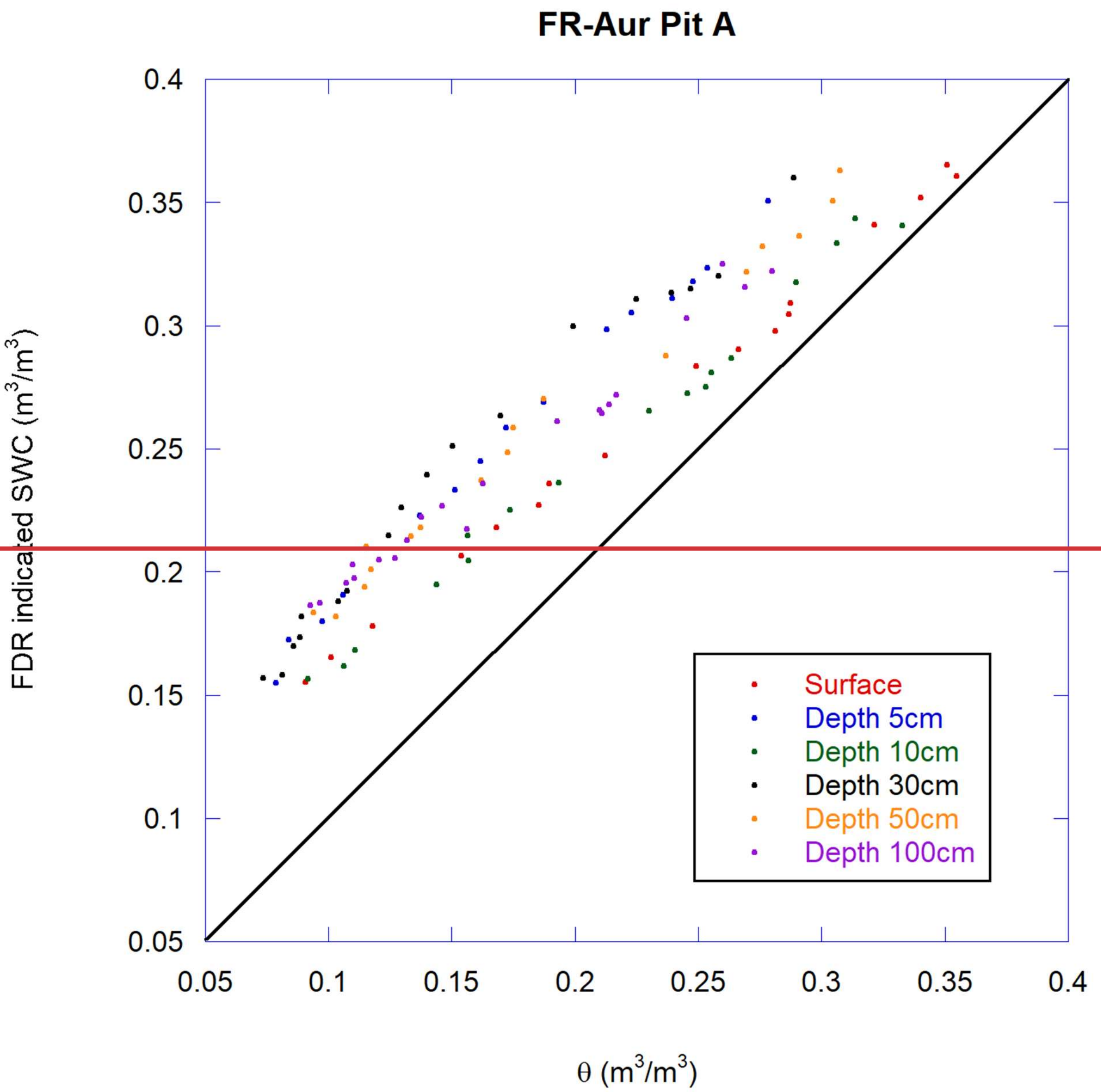
~~**Figure 4. Typical curve of real SWC versus square root of relative dielectric permittivity real part.**~~

~~**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~~formation, it should be noted that the volumetric water content is the volume of the water contained in a soil sample divided by the total soil volume, including cracks. Hence, any SWC sensing technique is extremely dependent on soil spatial heterogeneity. On a shrinking soil (like clayey soil), cracks are often larger than the SWC sensor diameter, possibly introducing biases. Using multiple sensors may help mitigate errors, but crack formation is clearly a limitation to the use of FDR and TDR sensors in vertisol. Figure 4 shows the typical behavior of $\sqrt{\varepsilon_R}$ versus θ ("real volumetric SWC", determined by weighing and measuring soil samples). When the soil samples are progressively drying, the measurement curves are ~~well~~quite linear up to the ~~crack formations~~ point where crack formation begins. Then, the slope changes abruptly, becoming ~~sensibly smallest.~~

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

~~Disparities in the observed coefficients are important between each pit~~ for each depth 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~~profile. The linearity, at least before the crack's apparition, confirms isotopic shrinking assumption validity for the soil sample volume calculations.



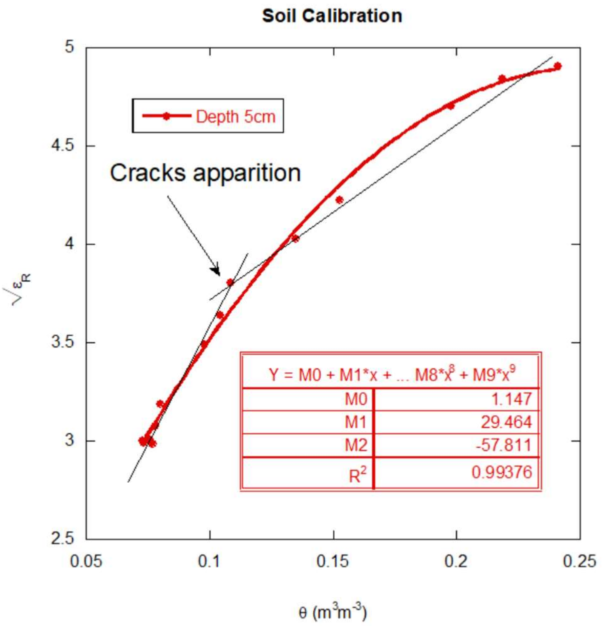
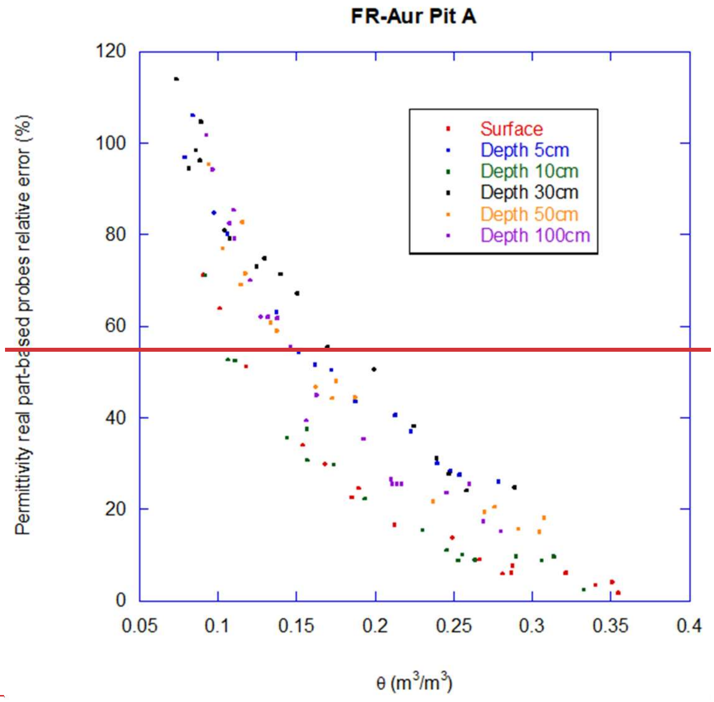
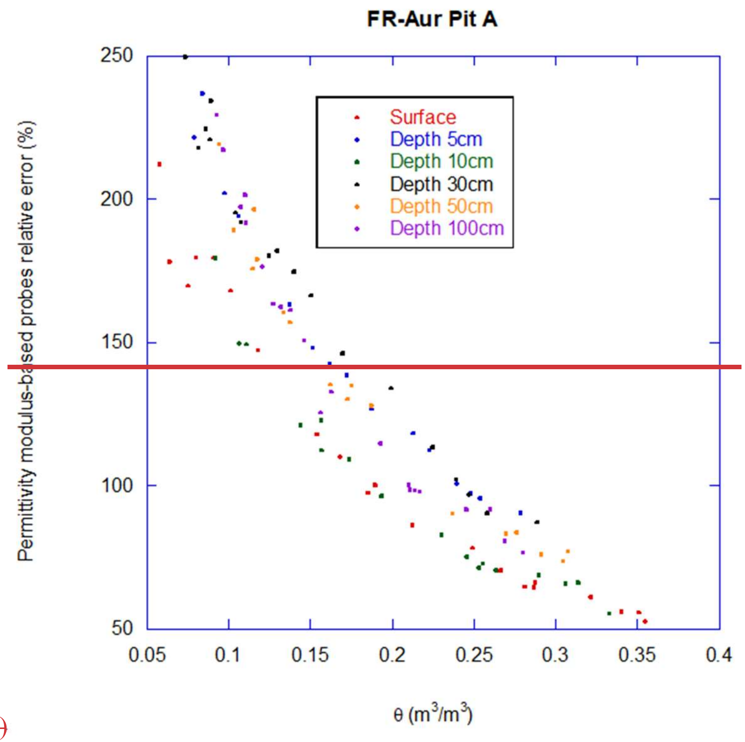


Figure ~~5. SWC provided by a digital reference factory calibrated FDR probe versus real SWC for several depths inside Pit A.~~



~~(a)~~

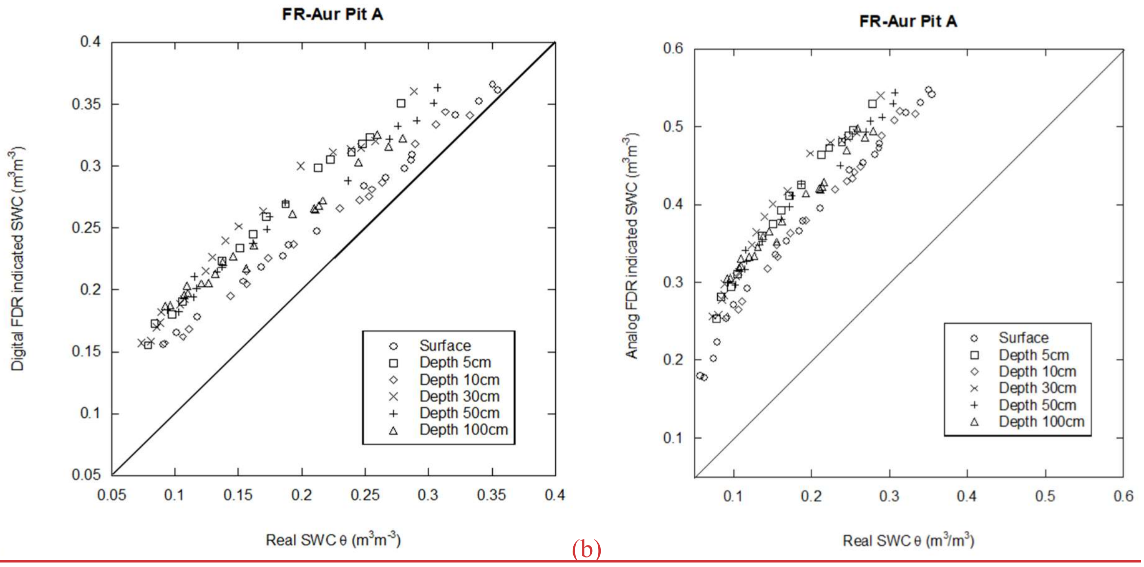


~~(b)~~

4. Typical calibration relating~~Figure 6. (a) Relative error of SWC indicated by factory-calibrated digital reference probe based on~~ the square root of the real part of ~~the~~relative 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.~~to the “real volumetric SWC” (FR-Aur, pit D, depth 5 cm). For the purpose of this study, second-order polynomial regression was used for calibration (in red).

4.2) FDR sensor SWC estimation with factory-calibration and associated error

Estimated SWC versus “real volumetric SWC” - We compared the real SWC ~~and~~ (determined by weighing and measuring soil samples) with the ~~indirectly measured SWC~~ SWC estimated using digital and analog FDR sensors, with the ~~reference digital FDR probes~~application of either ~~by using~~ factory calibrated coefficients or ~~by using the~~soil specific ~~soil calibrated coefficient~~coefficients. Figure 5 displays ~~FDR~~ the SWC estimated with the factory-calibrated ~~SWC measurements based on the real part of the dielectric permittivity~~FDR sensors versus real SWC ~~for several~~measured at six depths ~~inside~~, from surface to 100 cm, into 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.~~site (see Fig. 1). For both FDR sensors, we found a large discrepancy between both methodologies of SWC measurements with a significant positive offset whatever the real SWC. This results in a significant overestimation of SWC using factory-calibrated FDR sensors. The overestimation was on average the highest (0.10 m^3 m^{-3}) for real SWC lower than 0.2 m^3 m^{-3}.



(a) (b)

Figure 5. SWC estimated with a factory-calibrated digital (a) or analog (b) FDR sensor, versus real SWC, at several depths into Pit A at FR-Aur site.

Relative error of estimated SWC versus real SWC - Figure 6 shows the dynamics of the relative error (see equation 3 for definition) of the SWC estimated with the factory-calibrated FDR probesdigital (Fig. 6a for the digital reference probe) and Fig 6b for analog soil-calibration probe)(Fig. 6b) FDR sensors 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. 6 depths into pit A at FR-Aur site. For the digitalboth FDR probessensors, 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 (from dry, 0.07 $m^3 m^{-3}$, to nearly water-saturated soil and up to , 0.35 $m^3 m^{-3}$): from 115% to 1% with the digital FDR sensor and from 245% overestimated for dry soil.

The relative error was calculated using Eq. 3:

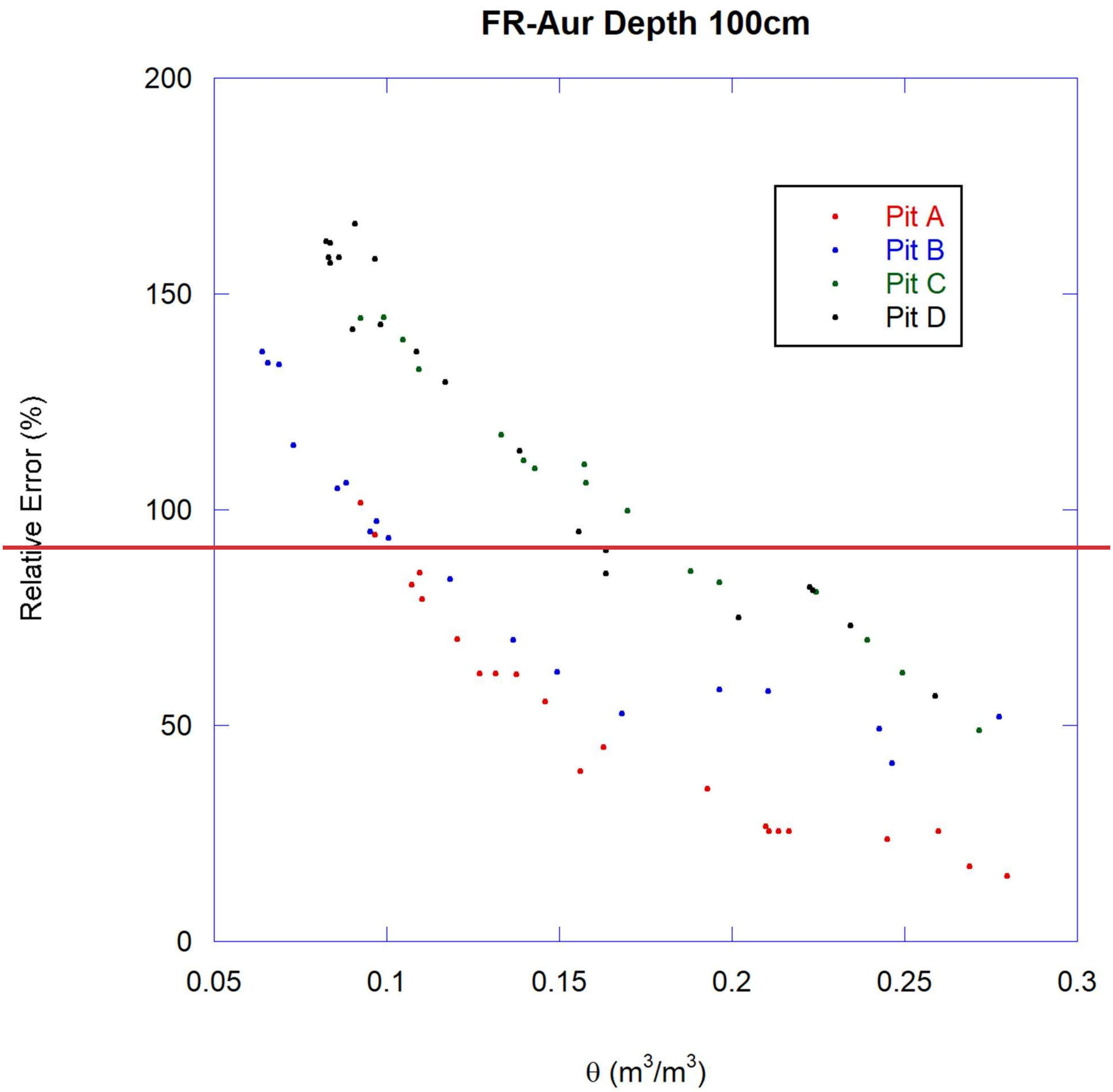
to 50 % with the analog FDR sensor. $Relative\ SWC\ Error = \frac{FDR\ measured\ SWC - Real\ Volumetric\ SWC}{Real\ Volumetric\ SWC}$

(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 iswas also a large error

~~disparity~~scatter 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%.~~ and the pit. Figure 7 displays relative SWC ~~error for a~~errors at depth of ~~100cm measured in~~100 cm into all four pits (~~please~~ see Fig. ~~2 for pit emplacements~~1). 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. For both FDR sensors and whatever the pit or the depth, errors were significant and positive, which means the soil was actually drier than the factory-calibrated FDR sensors would indicate. The drier the soil, the greater the relative error. The accuracy is way lower than required by the ICOS quality standards (0.05 $m^3 m^{-3}$). It should be noted that the SWC derived from manufacturer's calibrations were so erroneous that the corresponding coefficient of determinations may be negative (Table 3).



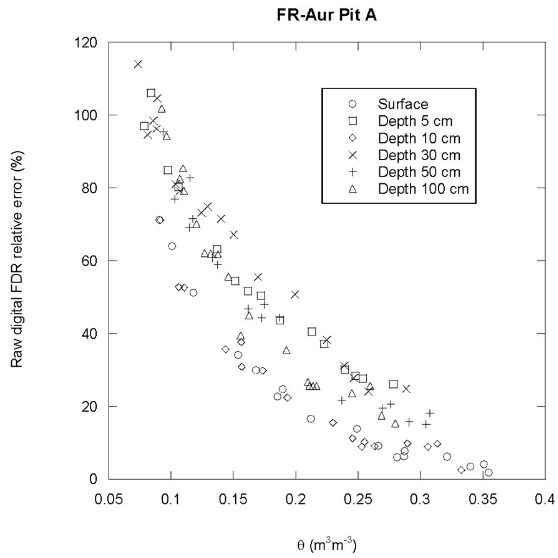


Figure 7. (a) (b)

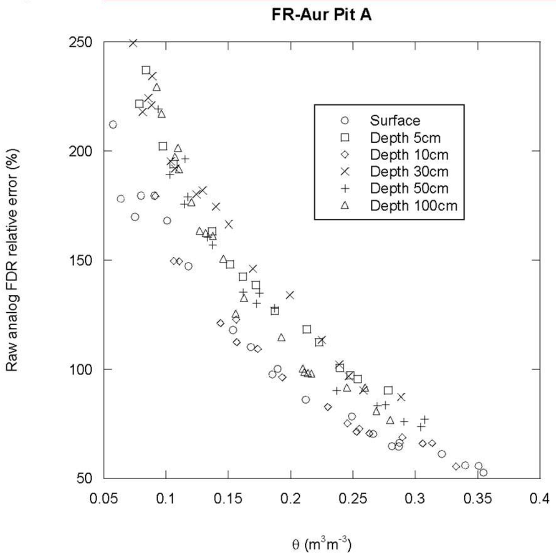


Figure 6. **Relative error ~~on~~of SWC estimated (a) with a factory-calibrated digital sensor based on the real part of the dielectric permittivity or (b) with a factory-calibrated analog sensor based on the modulus of the dielectric permittivity, versus real SWC into pit A at six depths.**

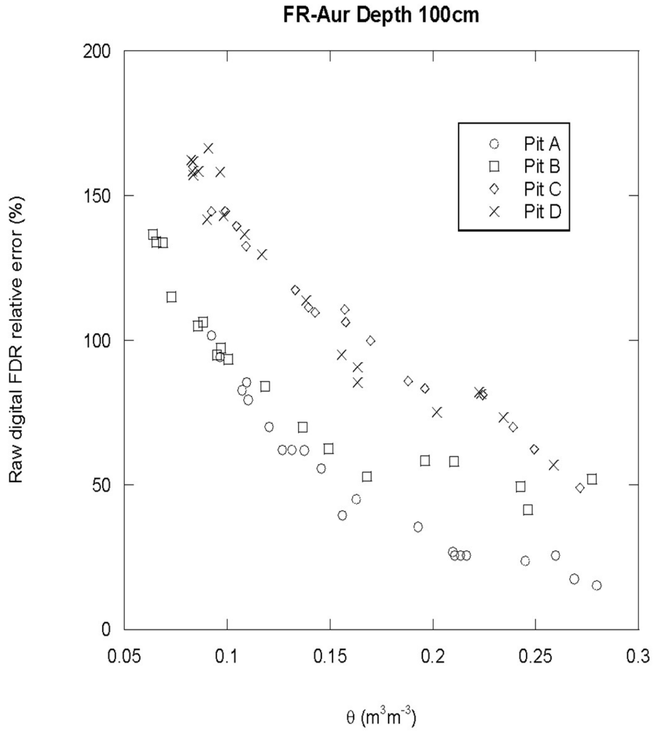


Figure 7. ~~preference probe~~Relative error on SWC estimated with factory-calibrated digital sensor versus real SWC for depth of ~~100cm~~100 cm inside all four pits.

~~4.~~

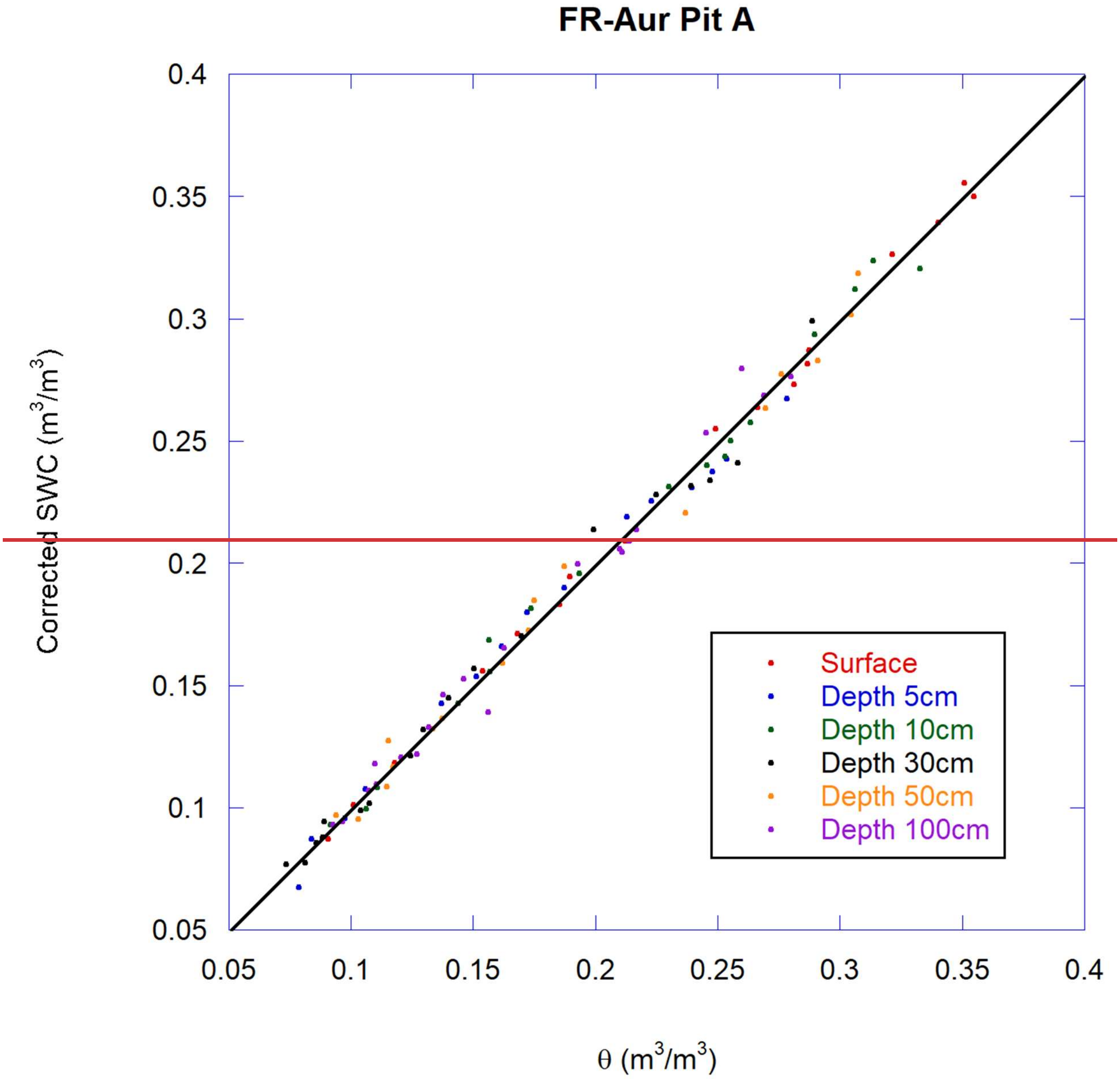
Table 3~~)~~. Fr-Aur, pit A: relative errors and coefficient of determination before and after calibration

Depth (cm)	Digital sensor						Analog sensor	
	Factory calibration		Soil-specific ε_R based calibration		Soil-specific $\lvert\varepsilon\rvert$ based calibration		Factory calibration	
	Relative error (%) at $\theta = 0.25\,(m^3m^{-3})$	R^2	Relative error (%) at $\theta = 0.25(m^3m^{-3})$	R^2	Relative error (%) at $\theta = 0.25(m^3m^{-3})$	R^2	Relative error (%) at $\theta = 0.25(m^3m^{-3})$	R^2
Surface	21	0.80	1.7	0.996	0.9	0.996	78	-2.1
5	42	-0.19	-4.2	0.991	-2.0	0.995	96	-11
10	21	0.70	-3.3	0.985	-3.2	0.992	73	-5.0
30	48	-0.60	-5.6	0.987	-5.5	0.987	94	-10
50	37	0.02	-4.8	0.989	-4.6	0.989	88	-7.8
100	30	-0.53	2.4	0.985	1.0	0.986	87	-12

Modulus versus real part of the dielectric permittivity - The relative error of SWC estimated with factory-calibration is around twice greater when using analog FDR ~~probe~~sensors than when using digital FDR sensors (Fig. 6). This may be explained by their different operational modes. Indeed, the estimation of SWC with the digital FDR sensors is based solely on the real part of the dielectric permittivity, while the estimation of SWC with the analog sensors used for the in-lab calibration relies on the modulus of the dielectric permittivity. Soil ions affect mainly the imaginary part of the dielectric permittivity, which is in turn reflected in the modulus of the dielectric permittivity. Thus, the important shift observed in our study may not only result from the inadequate factory embedded calibration factors, but also from the high electric conductivity of the FR-Aur clayey soil. However, even if SWC estimate based on modulus was significantly improved after soil-specific calibration (Table 3), it should be noted that soil conductivity modifications, due to fertilization or liming for example, affect mainly the imaginary part of the dielectric permittivity and therefore the modulus of dielectric permittivity. Therefore, we found that the dielectric permittivity modulus-based sensors may be less accurate than the dielectric permittivity real part-based sensors. Soil conductivity changes with SWC; however, this variation was taken into account during the calibration. We would thus recommend the use of FDR sensors based on the real part of the permittivity for soils subject to large changes of electrical conductivity, such as cropland soils often submitted to fertilization operations.

4.3) FDR sensor SWC measurements after soil-specific calibration

Once soil calibration is ~~done, new calibration constants~~ performed, accurate coefficients can be ~~injected into the relations between~~ applied to determine SWC ~~and~~based on the real part of dielectric permittivity. Figure 8 displays the same ~~curves~~results as ~~Fig. 5~~figure 5a after post-processing corrections with new soil-specific calibration coefficients for ~~the concerned~~each pit and depth. ~~The corrected measurements~~Corrected digital FDR signals are much closer to the real SWC.



~~**Figure 8. SWC measurements deduced from**~~ After specific soil-calibration, relative error drastically decreases and the coefficient of determination is greater than $R^2 = 0.9$ (Table 3). For example, for a real SWC value of 0.25 $m^3 m^{-3}$ at 30 cm depth, the *relative* error decreases to -5.6 and -5.5 % for estimated SWC with digital and analog FDR sensors respectively, with R^2 values of 0.987. Our experiment shows that soil-specific calibration in clayey soil allows for a dramatic improvement of the accuracy of SWC determination. Hence, soil calibration ensures compliance with ICOS quality standards. The new calculated coefficient values after calibration vary significantly between pits for the same depth and between depths into the same pit, as shown in Fig. 6 and Fig. 7. In general, near the surface (from 0 to 10 cm) the calibration coefficients were more homogeneous and closer to the factory calibration coefficients than in deeper soil layers. This may be explained by soil homogenization by surface tillage, lower soil density (Namdar-Khojasteh et al., 2012) and lower clay content at the surface than in-depth.

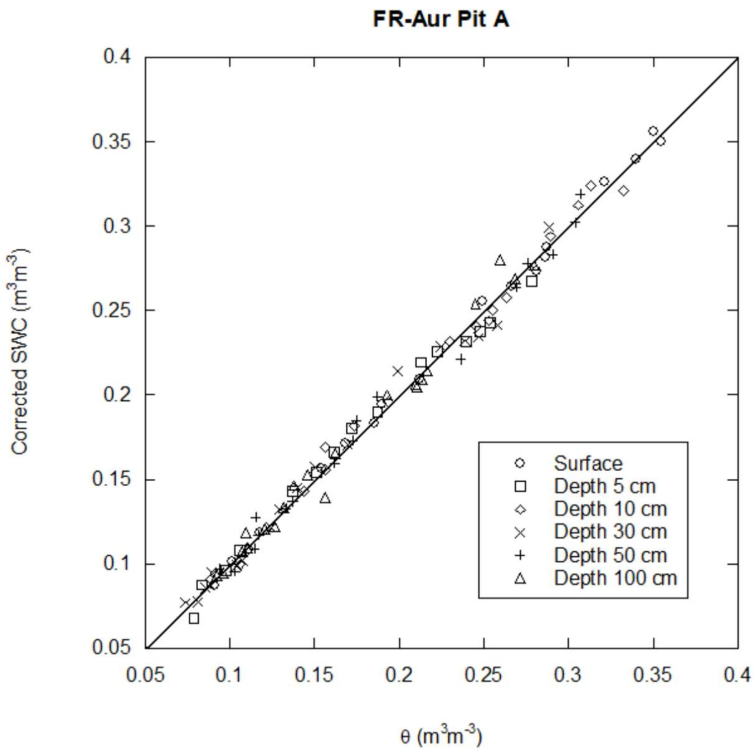


Figure 8. ~~probe measures~~SWC provided by digital FDR recalibrated sensor using soil-specific calibration coefficients for the same pit and depths as ~~the Fig. 6~~in figure 5a.

5) Conclusion~~.~~

~~These short studies show clearly~~ This study highlights that using factory ~~calibrated~~ generic calibrations for SWC ~~probes,~~ sensors with the same transfer function between permittivity constant and SWC, especially when they are based on dielectric permittivity ~~measurement~~sensing (FDR, TDR, Capacitance, radar, or microwave techniques), would not ~~be~~provide accurate ~~enough~~ estimates of SWC on every kind of soils. First, we demonstrated that the SWC relative error was clearly higher when using FDR sensors based on the modulus of the dielectric permittivity than on the real part of the dielectric permittivity. This was partly due to the high electric conductivity of our study site soils. Depending on the site soil and ~~A specific soil~~the field operations which in turn may affect the imaginary part of the dielectric permittivity and thus bias the estimated SWC, it is highly recommended to use FDR sensors based on the real part of the permittivity for cropland soils often subject to major fertilization operations. Secondly, we show that in the case of clayey soils, a laboratory calibration ~~should be performed even if the soil composition does not predict this necessity 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~~ is needed to ensure accuracy of the soil water content determination. Indeed, we found that the sensing of dielectric permittivity to determine SWC in clayey soils is highly influenced by spatial heterogeneity in terms of texture, density and physicochemical properties ~~and especially the density (Namdar-Khojasteh et al., 2012).~~. Without soil-specific calibration, ~~the drier is the soil and bigger is~~we observed an increase of the relative error when the soil turns very dry. This relative error can reach up to ~~160% on our stations for the probes~~115% on cropland soils when using sensors based on the real part of the dielectric permittivity and up to 245% ~~for~~when using the ~~probes~~sensors based on the modulus of the dielectric permittivity. ~~Once~~We show that performing 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~~at a specific sensor location allows to adjust the constants of the transfer equation, ensuring very accurate SWC estimates at that specific location with FDR sensors based on the real part of the permittivity. We recommend to always check if the SWC is accurately determined with the factory-calibrated commercial sensors in the soil of interest before conducting studies such as the estimation of the ~~useful~~extractable soil water and water reserve, the study of soil microbial processes, soil water ~~flows~~and greenhouse gas fluxes, 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~~accuracy is ~~a sensible discrepancy, calibrate the soil.~~not sufficient, perform soil calibration at each specific location. Soil calibration is long and manpower-consuming but may be necessary. ~~The same problem concerns~~It would be interesting to test our soil-calibration process with remote ~~measurement techniques~~sensors, using satellites, 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~~when collected from the study site, so that the calibration process ~~is made~~performed during ~~sample~~in-lab drying covers the whole range of SWC. They should be large enough to accommodate the sensor rods. Soil sample should be collected in duplicate, in case of technical problems during the set-up of the experiment.

- Use a data logger, such as Campbell's CR1000, programmed for soil moisture ~~probe~~sensor monitoring~~.~~ and wired with labeled cables for each labeled ~~probe~~sensor.

- Use a scale with sufficient ~~weighting range~~ weighing capacity and resolution.

- ~~Buckets~~Use buckets that are big enough for the soil samples~~, bearing 105°C~~ and that can withstand a temperature of 105°C (polypropylene buckets are ~~OK~~suitable).

- Use a caliper for measuring soil ~~sample~~samples' dimensions ~~measurements~~.

~~-Stainless~~ - Use a stainless-steel exhaust pipe clamp, to hold the sample and prevent it from being altered during sensor rods' insertion of internal diameter and height fitting soil samples external diameter and height, to hold the sample and prevent it from being altered during sensor rods' insertion.

Preliminary measurements~~.~~

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

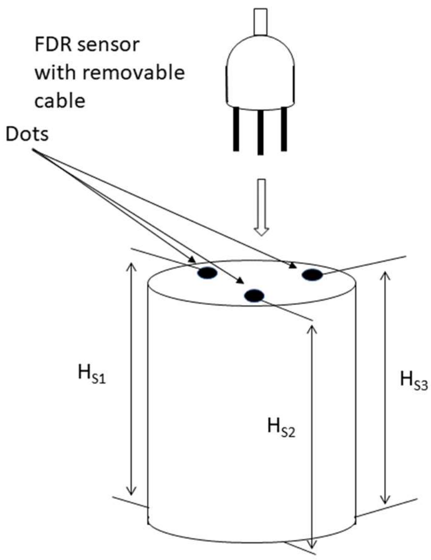
~~Measuring the weight of~~Weigh the buckets: W_B~~. Note: It is not necessary but~~ (may be used for uncertainty determination~~.~~).

During each measurement cycle~~.~~:

~~Probes~~Sensors 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~~ Note: an exhaust pipe clamp of fitted dimensions can be used to ~~prevent~~hold the sample ~~altering~~and prevent it from being altered during sensor rods' insertion.

Three points are marked on each soil sample around its circumference, every 120° (See Fig. A1, this will be necessary to determine the sample dimensions during the measurement cycle, by averaging).



~~Probes~~

Figure A1. Calibration setup

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

Routine measurement~~.~~

~~Every day:~~

~~-~~ On a daily basis, on working days:

- Relative dielectric permittivity (~~ε_r~~ε_R) values ~~(or directly the square root of) measured by~~are reported from the logger for each ~~probe is noted~~sensor.

- The tissue paper surrounding the ~~probes disposed of and their cable~~sensors is set aside and the sensor cables are disconnected~~,~~ before each sample is ~~weighted~~weighed (including ~~bucked~~bucket and inserted ~~probe)~~sensor): W_{SBP}.

- The height of three points around the circumference of each soil sample ~~is~~are measured with ~~the~~a caliper: H_{S1}, H_{S2}, and H_{S3}, ~~and~~along with the sample diameter D_S (if possible~~)~~), in dekameters (~~dm~~dam).

- It is welcome to take a clear picture of the samples to track any apparent crack ~~apparition~~formation.

- ~~Pater~~Sensors are reconnected and the tissue paper is ~~applied~~put back ~~around each connected back probe~~in place.

Once the soil samples are considered ~~dried:~~completely dry:

- When the measurement cycle is considered finished, it may be necessary to ~~wet~~rewet the soil sample ~~again~~ to withdraw the ~~moisture probes~~sensor rods.

- 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,~~ , into its bucket but without the SWC sensor, before final weighing (including the ~~buckets, is weighted:~~bucket): W_{SB}.

Data processing

~~Using all acquired data, from each daily soil sample weighting including bucket and inserted SWC probe,~~The soil water content weight (W_w = water weight, in kg) is calculated by subtracting the weight of completely dried soil sample (including bucket) (W_{SB}) and the sensor probe weight~~, the soil water content weight in kg is obtained:~~ (W_P) to each daily soil sample weighing including the bucket and the inserted SWC sensor probe (W_{SBP}):

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

Note: ~~We can take the~~With water density being 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~~:~~ (in kg):

$$V_W = W_W$$

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

~~$\Theta = V_W/V_S$~~

$$V_S = \frac{(H_{S1} + H_{S2} + H_{S3})}{3} \pi (\frac{D_S}{2})^2 \tag{A2}$$

Note: As an approximation, if the sample diameter ~~is~~(D_S) was not measured ~~during the measurement campaign, for example~~, due to the ~~bucket presence and~~ inaccessibility of the sample~~, as an approximation, we can suppose~~ into the bucket, it should be estimated by assuming that ~~this diameter will change in~~ it varies along with the ~~same way as~~mean of the three measured height (isotropic shrinkage).

We can then determine ~~$V_S = \frac{(H_{S1}+H_{S2}+H_{S3})}{3}\pi(\frac{D_S}{2})^2$ (A3)~~

~~With previously determining water volume,~~ the samples' volumetric soil water content (SWC or θ) in m^3/m^3 (or in liters/liters)

$$\theta = V_W V_S^{-1} \tag{A3}$$

which isLastly, plotting these values of the same) can be calculated:samples' volumetric soil water content (SWC or θ), based on sample weighing, on a graph versus the square root of the real part of ε_R, as indicated by the FDR sensor, enables us to infer the calibration constants of the sensor (A_S, B_S and C_S), using the following regressions (whichever fits best):

$\Theta = A_S \sqrt{(\varepsilon_R)} + B_S$. or, in the case of $\theta = A_S\sqrt{\varepsilon_R} + B_S$ (linear fit)

$\theta = C_S\varepsilon_R + A_S\sqrt{\varepsilon_R} + B_S$ (second-order polynomial fit: $\Theta = C_S(\varepsilon_R) + A_S \sqrt{(\varepsilon_R)} + B_S$)

(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).

AuthorAuthors' 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, themeasurements, 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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