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Dielectric Response of Commercial Capacitance, Impedance and TDR Electromagnetic Sensors in Standard Liquid Media

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ABSTRACT. We investigated the dielectric behaviour of capacitance (ECHO-TE, EC-5, EC-10 and EC-20), impedance (WET Sensor and ML2x) and TDR (Trase, TRIME-P2 and TRIME-EZ) electromagnetic (EM) sensors, in standard liquid media. We derived calibration equations that relate signal of the nine EM sensors studied with the dielectric permittivity of the media (ε). The dielectric response, within the range $1 \leq \varepsilon \leq 68$, of all investigated sensors was satisfactory under dielectric conditions equivalent to those of a non-saline soil of sandy texture. When relaxing conditions show up, such as those that may take place in an organic or clayey soil, the WET Sensor and the EC-10 and EC-20 capacitance probes exhibit a better response than the remaining EM sensors. However, in saline conditions, the EC-10 and EC-20 probes are greatly affected by the electric conductivity of the media, σ, overestimating ε even for $\sigma \leq 0.5$ dS m^{-1}. For moderate electrical conductivities $\sigma \leq 2$ dS m^{-1}, only the TDR Trase and the WET Sensor show an acceptable dielectric behaviour. None of the studied EM sensors is reliable for the whole conductivity interval investigated $0 \leq \sigma \leq 4$ dS m^{-1}.

1. INTRODUCTION

The increasing demand for electromagnetic (EM) sensors in the investigation of flow processes in the soil or for a more efficient irrigation scheduling, raises the need for standards to determine their response reliably. Taking advantage of the marked difference in dielectric permittivity, ε (-), between water ($\varepsilon \approx 80$) and the other phases present in the soil: air ($\varepsilon \approx 1$) and mineral particles ($\varepsilon \approx 2$-15), one can estimate the soil water content,

θ (m^3 m^{-3}), based on the relationship between ε and θ. An example of ε-θ relationship, of "universal" applicability, is the Topp equation (Topp et al., 1980):

$$\theta = -5.37 \cdot 10^{-2} + 2.32 \cdot 10^{-2} \varepsilon - 5.5 \cdot 10^{-4} \varepsilon^2 - 4.3 \cdot 10^{-6} \varepsilon^3 \quad (1)$$

partly responsible for the widespread use of EM sensors in the instrumentation of soil profiles.

EM sensors determine the ε of a (un)-saturated porous medium from far different physical principles: transit time, impedance, capacitance, etc. For example, the TDR (Time Domain Reflectometry) and TDT (Time Domain Transmission) techniques estimate ε from the relationship existing between this and the transit time, t_s (s), of an electromagnetic wave travelling along the rods of length L (m) of a probe inserted into a porous medium, such that (Heimovaara and Bouten, 1990):

$$\varepsilon = (t_s c)^2 / (2L)^2 \quad (2)$$

In equation (2), c (m s^{-1}) is the speed of light in vacuum; the $2L$ term refers to the travelling distance which conducts the electromagnetic wave along the rods. Within the place to discuss the TDR methods, the TRIME system (Imko GmbH, Ettlingen, Germany) performs a particular treatment of the TDR wave not often discussed, and which differs from classical TDR systems. The TRIME system measured the transit time of a pulse, t_1 (ps), relative to a reference time. Different models of TRIME probes (P2, EZ, T3, etc.) are characterized by different relationships t_1 *versus* water content θ (m^3 m^{-3}). To scale the signal from the different types of TRIME probes to the same dynamic range of t_p (not of t_1), a normalized time or "pseudo transit time" t_p (-) is defined, linearly related to t_1 such that

$$t_p = (t_1 + A) / D \quad (3)$$

where A represents a shift towards zero and D is a measure of the sensitivity of the probe. The estimation of θ is then made from a specific calibration which takes the following form (Stacheder, 1996):

$$\theta = C_0 + C_1 t_p + C_2 t_p^2 + C_3 t_p^3 + C_4 t_p^4 + C_5 t_p^5 , \quad 0 < t_p < 900 \quad (4)$$

where C_i are specific parameters determined empirically for each type of TRIME probe (see Figure 1 in Regalado et al., 2006). Regalado et al. (2006) also proposed a logarithmic relation between ε and t_p for TRIME P2 and T3 probes of the form (*Ceff*=0.90; *RMSE*=9.5):

$$ln(\varepsilon) = 0.00478 t_p + 0.34928 , \quad 100 < t_p < 900 \quad (5)$$

On the other hand, impedance sensors determine the amplitude difference in voltage due to changes in impedance, Z (Ω), between the transmission line of the sensor and the rods that are inserted in the media, so to estimate the value of ε from (Campbell, 1990):

$$\sqrt{\varepsilon} = c \cdot \text{cotanh}^{-1}(Z)/(2\pi L) \quad (6)$$

Finally, the capacitive or capacitance methods, consider the composite media soil-probe as a capacitor whose capacitance, C (F), is proportional to ε (Kelleners et al. 2005):

$$C = g\varepsilon\varepsilon_0 \quad (7)$$

where g (m) is a geometric factor and ε_0=8.54 pF m^{-1} is the value of permittivity of vacuum.

The relation obtained between ε or θ and the signal provided by a given EM sensor is known as calibration equation. In general, the manufacturer of a specific EM sensor provides signal *versus* θ equations or signal *versus* ε, valid for different media or soil textures. However, because the soil is a heterogeneous porous medium of variable composition and since ε depends on other variables such as the electrical conductivity of the medium (Campbell, 2002; Seyfried and Murdock, 2004), or the frequency of the EM wave, f_e (kHz) (Kelleners et al., 2005), it is advisable to establish *ad hoc* calibration equations, especially when a certain level of accuracy in the estimation of θ is demanded. This involves the difficulty of making extensible calibration equations established for a particular soil to others of similar characteristics, given the uncertainties that are generated as a result of the inherent variability of the soil media, its salinity and/or composition, or as a consequence of the sample disturbance e.g. due to probe insertion. That is why Jones et al. (2005) propose to derive such relationships ε *versus* EM signal using fluids of known permittivity, instead of porous media, to reproduce in controlled way soil characteristics, such as its specific surface (texture), salinity and saturation level. It thus manages to reduce the variability of the measurements, reducing the uncertainty in the proposed relationship of ε *versus* the sensor signal. In addition, this procedure permits the independent study of any possible causes or conditions specific to a soil that affect their dielectric behaviour against a specific EM sensor. To this end, Jones et al. (2005) used various fluids and salt solutions as standards to represent soils with certain characteristics or conditions. These liquid media with known dielectric properties are grouped under the title: Non Relaxing-Non Conductive (NR-NC), Non Relaxing-Conductive (NR-C), Relaxing-Non Conductive (R-NC). Thus, the dielectric properties of NR-NC fluids resemble those of a sandy soil, which allows for studying in controlled conditions the response of an EM sensor in a coarse texture media, where ε is independent of f_e. These fluids are non-conductive fluid with a relaxation frequency (f_r) above 2 GHz, such that relaxation is not expected to affect the reading of the majority of EM sensors, which generally operate at frequencies f_e < 2 GHz. Fluids R-NC reproduce the dielectric properties typical of fine-textured and organic soils with low salinity, thus allowing for assessing the effects of dielectric relaxation. Finally, the solutions NR-C represent the conditions of a saline sandy soil, and therefore permit investigation of the dependence of ε on the media electrical conductivity, for a given EM sensor at a specific frequency f_e. Following the proposal by Jones et al. (2005), Blonquist et al. (2005) evaluated the response of several capacitive, impedance and time domain sensors. This work completes Blonquist et al. (2005)

work with additional EM sensors. The objectives of this study are therefore: i) to propose calibration equations ε *versus* the EM sensor signal in a medium NR-NC; ii) to evaluate the accuracy of these calibration equations in the estimation of ε, compared to those proposed by the manufacturer or previous authors for each of the EM sensors studied; iii) to determine the stability of the signal when other factors, such as relaxation or salinity of the media, vary (i.e., conditions represented by R-NC and NR-C media).

2. MATERIALS AND METHODS

2.1. EM sensors investigated

We evaluated the response of nine types of EM sensors, including various TDR systems (3-rods Trase probe, TRIME-P2 and TRIME-EZ), impedance (WET Sensor ML2x) and capacitance (ECHO-TE, EC-5, EC-10 and EC-20) probes (Fig. 1). The main features of these sensors and calibration equations proposed by various authors or by the manufacturer are summarized in Table 1.

Figure 1. EM sensors investigated. From left to right: 3-rods Trase probe, TRIME-P2, TRIME-EZ, WET Sensor, ML2x, ECHO-TE, EC-5, EC-10, and EC-20.

Table 1. Characteristics of the EM sensors and calibration equations proposed by the manufacturer or by previous authors ("reference calibration equations").

Technique (f_e)	Model	V_e (cm^3)	L_s (cm)	Reading signal	Reference calibration equation		Reference	Manufacturer
TDR (2-3 GHz)§	3-rods Trase probe	700	20	ε (-)	$\varepsilon = (t_s \cdot c)^2/(2L)^2$	(2)	Heimovaara and Bouten (1990)	Soil Moisture Equipment Corp.
TDR (0.6-1.2 GHz)	TRIME-P2	700	16	t_p (-)	$\ln(\varepsilon) = 0.00478t_p + 0.34928$; $100 < t_p < 900$	(5)	Regalado et al. (2006)	IMKO GmbH
	TRIME-EZ				-	-	-	
Impedance (20 MHz)	WET Sensor	125	6.5	ε (-)	$\sqrt{\varepsilon} = \text{cotanh}^{-1}(Z) \cdot c/(2\pi L)$	(6)	Campbell (1990)	Delta-T Devices Ltd.
Impedance (100 MHz)	ML2x	200	6	S (mV)	$\sqrt{\varepsilon} = 4.7 \cdot 10^{-9}S^3 - 6.40 \cdot 10^{-6}S^2 + 6.40 \cdot 10^{-3}S + 1.07$; $1 < \varepsilon \leq 40$	(8)	Delta-T Devices Ltd. (1999)	
Capacitance (70 MHz)	ECHO-TE	80	5	S_d (-)	$\varepsilon = 7.64 \cdot 10^{-8}S_d^3 - 8.85 \cdot 10^{-5}S_d^2 + 4.85 \cdot 10^{-2}S_d - 10$; $1 < \varepsilon \leq 20$	(9)	Decagon Devices Inc. (2006b)	Decagon Devices Inc.
	EC-5	32	5	S (mV)	$\varepsilon = f(\theta)$; $\theta = 11.9 \cdot 10^{-4}S - 0.401$	(10)	Decagon Devices Inc. (2006a)	
Capacitance (≈10 MHz)	EC-10	93	10	S (mV)	$\varepsilon = f(\theta)$; $\theta = 9.36 \cdot 10^{-4}S - 0.376$	(11)		
	EC-20	140	20	S (mV)	$\varepsilon = f(\theta)$; $\theta = 6.95 \cdot 10^{-4}S - 0.290$	(12)		

§Computed from f_e=0.35/t_r where t_r=125-155 ps (Robinson et al., 2003); V_e is the explored volume and L_s is the probe length; S_d is the digital signal of the Em50 logger (Decagon Devices Inc., Pullman, USA); S is the sensor's signal; $f(\theta)$ is the inverse of Topp equation (1).

2.2. Experiments with standard liquids of known permittivity

Following Jones et al. (2005), aqueous solutions of 2-iso-propoxyethanol were used as NR-NC media. In addition, we used dry ($\theta \approx 0.03$ m^{3}m^{-3}) glass beads of 500 mm in diameter (Imko GmbH), which provide a value ε =3.8 intermediate between ε = 1 (air) and ε = 12.70 for the 2-iso-propoxyethanol, necessary for the adjustment of calibration equations in the low range of permittivity. As R-NC the following liquids were used: glycerol (ε = 46.5; f_r= 0.127 GHz), 1-propanol (ε = 22.75; f_r= 0.475 GHz), polyethylene glycol 300 (Carbowax) (ε = 16.75; f_r = 1.27 GHz) and castor oil (ε = 3.75; f_r= 1.06 GHz). Finally, as NR-C media were prepared salt solutions of NaCl and 2-iso-propoxyethanol to 60% with electrical conductivities of σ=0, 0.5, 1.1, 2 and 4.1 dS m^{-1}. For each of these media, measurements were carried out with the nine EM sensors in PVC containers, which were bigger than the volume explored by the probes (see Table 1) to avoid the influence of the container walls. We carried out eight replications for each EM sensor and media, presenting the results as the arithmetic mean of these. ε readings with the probe Trase were obtained from the TDR wave analysis carried out internally by the Trase system I 6050X1 (Soil Moisture Equipment Corp., Santa Barbara, USA). The TRIME-P2 measurements were performed using the software SMCAL (Imko GmbH) as an interface, with an excitation pulse provided by the reader TRIME-FM (Imko GmbH). In the case of the TRIM-EZ probe, this was externally fed with a battery of 12 V and the t_p readings were made from a PC via the RS232 port using the software TRIME WinCal (Imko GmbH). For the impedance probes, ε (WET Sensor) and voltage (ML2x) readings were performed with the HH2 Moisture Meter handheld (Delta-T Devices Ltd.). All capacitance probes were read with the EM50 logger (Decagon Devices Inc.) managed from the ECH2O utility 1.10 (Decagon Devices Inc.). The EC-5 probe was completely immersed in the solutions, since differences were observed when comparing readings where the head encapsulation was fully submerged in the fluids *versus* those where it remained outside the standard liquids (also acknowledged by the manufacturer; personal communication).

2.3. Goodness-of-fit evaluation

The goodness-of-fit between the fluids permittivity, ε, and the permittivity estimated from the sensors signal, ε_{est}, was quantified by means of the coefficient of efficiency ($-\infty \leq Ceff \leq 1$) and the root mean square error (*RMSE*) defined, respectively, as:

$$Ceff = 1 - \sum_{i=1}^{N}\left(\varepsilon_{est,i} - \varepsilon_i\right)^2 \Big/ \sum_{i=1}^{N}\left(\bar{\varepsilon} - \varepsilon_i\right)^2 \quad ; \qquad RMSE = \sqrt{\sum_{i=1}^{N}\left(\varepsilon_{est,i} - \varepsilon_i\right)^2 \Big/ N} \tag{13}$$

where $\bar{\varepsilon}$ is the permittivity values mean and *N* is the number of measurements carried out. The subscript "*est*" denotes a permittivity value computed with a calibration equation.

3. RESULTS AND DISCUSSION

3.1. Calibration of the EM sensors in Non Relaxing-Non Conductive media (NR-NC)

Table 2 summarizes the calibration equations of the EM sensors studied resulting in NR-NC media. In the case of the Trase TDR and WET Sensor, ε readings are taken directly and therefore calibration equations are not proposed for these two EM sensors. In general the fit is satisfactory (*Ceff* >0.94 and *RMSE* ≤5.3), except for the ML2x impedance probe, where we used the equation previously proposed by Blonquist et al. (2005), with *Ceff*=0.698 and *RMSE*=7.0 in the range $43 < \varepsilon \leq 80$.

Table 2. Calibration equations of the EM sensors derived in NR-NC media.

Model	Calibration equation	*Ceff*	*RMSE*
Trase probe	-	0.982	2.9
TRIME-P2	$ln(\varepsilon) = 0.4259+0.0047 \cdot t_p$	0.993	2.0
TRIME-EZ	$ln(\varepsilon) = 0.4714+0.0049 \cdot t_p$	0.995	1.4
WET Sensor	-	0.993	1.9
ML2x	$1/\varepsilon = (-0.105+0.134/\sqrt{S})$; $1 \leq \varepsilon \leq 43$	0.985	1.4
	$1/\varepsilon = 0.0279-0.767 \cdot \ln^2(S)$; $43 < \varepsilon \leq 80$	0.698	7.0
ECHO-TE	$1/\varepsilon = 1.3281-0.0032\, S_d + 2.6741 \cdot 10^{-6}\, S_d^2 - 7.6082 \cdot 10^{-10}\, S_d^3$	0.947	5.3
EC-5	$\ln(\varepsilon) = -11.5075+54.0203 \cdot S-70.4199 \cdot S^2+32.3594 \cdot S^3$	0.991	2.2
EC-10	$1/\varepsilon = -0.0455+0.0589/S^2$	0.996	1.4
EC-20	$1/\varepsilon = -0.2581 + 0.0607 \cdot S + 0.2331/S$	0.999	0.7

3.2. Response of the EM sensors in Non Relaxing-Non Conductive (NR-NC) and Relaxing-Non

Conductive (R-NC) media

Figure 2 presents, for each EM sensor, the comparison between the values of ε versus ε_{est} (using the calibration equations derived in NR-NC media; Table 2) for conditions of both NR-NC and R-NC. It is also included the value of ε obtained from calibration equations proposed by the manufacturer or previous authors, called here "reference calibration equation" (Table 1). In both cases the sensor's ability to estimate the value of ε is quantified by the *Ceff* and the *RMSE* (13), distinguishing with an asterisk (*Ceff** and *RMSE**) when calculated with the corresponding reference calibration equation. The TDR sensors (Trase, TRIME-P2 and TRIME-EZ) showed values of *Ceff* ≥0.846 y *RMSE* ≤8.6 (Fig. 2a-c). Although the TDR Trase shows a good fit (*Ceff*=0.985; *RMSE*=2.8) in NR-NC media (Table 2), its reliability worsens when considering also R-NC liquids (*Ceff*=0.840; *RMSE*=8.6), and especially with glycerol (ε=46.5; f_r=0.127GHz). In fact, the value of permittivity of glycerol (ε=46.5) appears as an outlier in Figure 2 for those EM sensors working at $f_e \geq 7 \cdot 10^4$ Hz: Trase, TRIME, ML2x, ECHO-TE and EC-5, possibly because they measure in a range close to the relaxation frequency of glycerol (f_r=1.27 10^5 Hz). The TRIME-P2 probe exhibits a good fit both when using equation (5), which relates the pseudo transit time t_p *versus* ε (*Ceff**=0.944; *RMSE**=5.3), such as when using an equation similar to that obtained in this work (*Ceff*=0.951; *RMSE*=4.9) (Fig. 2b). However for the TRIME-EZ probe, it follows that equation (5), proposed previously by Regalado et al. (2006) for probes TRIME-P2 and TRIME-T3, cannot be applied, because the sensor t_p output values are lower than those rendered by the TRIME-P2 probe for the same ε (*Ceff**=0.746; *RMSE**=11.2). An alternative equation, that achieves a good fit either in NR-NC and R-NC (*Ceff*=0.983; *RMSE*=2.9), is therefore proposed (Fig. 2c). In general, impedance probes (WET Sensor and ML2x) determine correctly the values of ε in both media NR-NC and R-NC. The WET sensor exhibits a satisfactory performance close to the 1:1 line (*Ceff*=0.992; *RMSE*=2.0) (Fig. 2d).

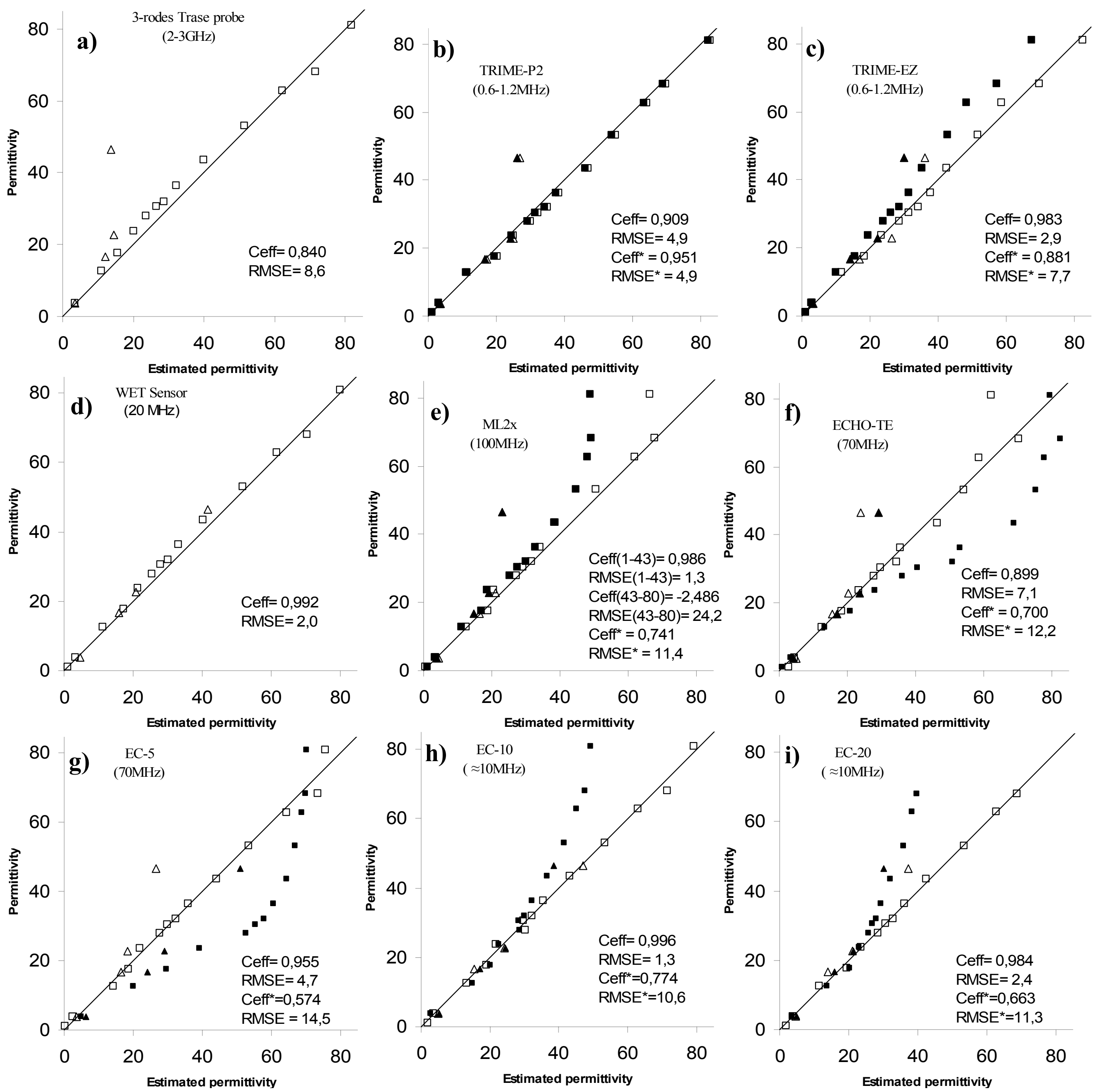

Figure 2. Comparison between values of ε *versus* ε_{est} for each EM sensor under NR-NC and R-NC conditions. Filled symbols represent permittivity values computed from the calibration equations included in Table 1, which were proposed by previous authors, or by the manufacturer. Empty symbols represent permittivity values estimated with the equations proposed in this work and included in Table 2. The *Ceff* and *RMSE* for the reference equation are denoted by an asterisk. □: NR-NC; ■: NR-NC*; Δ: R-NC; ▲: R-NC*; — 1:1 line.

The probe ML2x estimated permittivity correctly with both the calibration equation previously proposed by

Blonquist et al. (2005) (*Ceff*=0.986; *RMSE*=1.3), as with the manufacturer proposed equation in the range 1 ≤ ε ≤ 43 (Fig. 2e). The glycerol distorts the overall response of this sensor, which impacts on the goodness-of-fit indices (*Ceff*=-2.486; *RMSE*=24.2; *Ceff**=0.760; *RMSE**=11.2). Finally, capacitance sensors (EC-5, EC-10, EC-20 and ECHO-TE) show generally similar behaviour to other sensors, except the probe ECHO-TE, whose response with the equation proposed by the manufacturer deviates from the 1:1 line (*Ceff**=0.700; *RMSE**=12.2) for values of ε above the range for which this was obtained (ε > 20). That is why we propose an alternative calibration equation valid in the permittivity range 1 <ε ≤ 68 (*Ceff*=0.899; *RMSE*=7.1) (Fig. 2f). The probes EC-5, EC-10 and EC-20 show similar behaviour (Fig. 2g-i).

3.3. Response of the EM sensors in Non Relaxing-Conductive (NR-C) media

To study the effect of σ on the reading of permittivity obtained by each EM sensor and the calibration equations proposed in Table 2, we took as reference the value of ε corresponding to a 60% aqueous solution of 2-isopropoxyethanol (ε = 40 from Table 1 in Jones et al., 2005). Figure 3 shows the results of this experiment for each of the EM sensors studied. The TDR-Trase did not render readings for σ = 4 dS m^{-1} (due to an attenuation of the TDR waveform which does not allow its analysis), but for σ ≤ 2 dS m^{-1} the response is acceptable (*RMSE*=1.37) showing little effect of salinity. The TRIME-P2 probe exhibits a relatively linear response throughout the σ range studied (*RMSE*=8.71). This is not the case with the TRIME-EZ probe, which shows a clear overestimation of ε with respect to the reference value ε = 40, even for σ <1 dS m^{-1}, which is inconsistent with the applicable range of this probe indicated by the manufacturer (0≤σ≤10 dS m^{-1}). As this deviation is closely linear, it may be possible to correct ε readings with TRIME-EZ in saline media to include the effect of σ on ε.

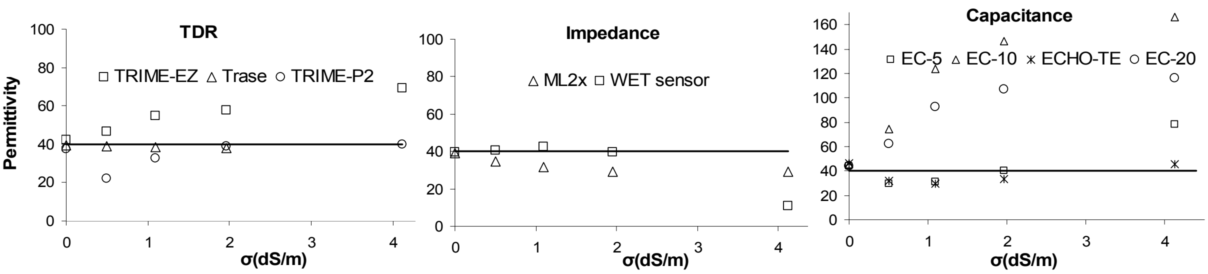

Figure 3. Response of the EM sensors in saline media (NR-C).

In the case of the impedance sensors, both were affected by high salinity values around σ=4 dS m^{-1} (*RMSE*=13.02 for the WET Sensor and *RMSE* = 7.94 for the probe ML2x). Below σ ≤ 2 dS m^{-1} measurements with the WET Sensor remain relatively constant. However, the ML2x probe is affected by salinity over the whole range of σ. Finally, capacitance sensors showed disparity in their behavior. EC-10 probes (*RMSE*=84.30) and EC-20 (*RMSE*=52.09) were greatly affected by σ. This is expected, because these EM sensors work at low f_e frequencies (of the order of 10 MHz) where ε is greatly affected by f_e. However, these sensors show a monotonic response against σ which in principle would allow a simple correction of the effect of salinity on the reading of the EC-10 and EC-20. By contrast ECHO-TE (*RMSE* = 7.61) and EC-5 (*RMSE* = 18.29) sensors, working at f_e = 70 MHz, are less affected by salinity for σ ≤ 2 dS m^{-1} but overestimated ε for σ = 4 dS m^{-1}.

4. CONCLUSIONS

Following the methodology proposed by Jones et al. (2005), we evaluated the dielectric response of nine EM sensors in standard liquid, simulating certain features or soil conditions such as specific surface (texture), salinity and saturation level. Calibration equations were derived for each of the EM sensors that allow relationships between permittivity (1 ≤ ε ≤ 68) and the sensor signal in a medium NR-NC and were compared to those proposed by the manufacturer or previous authors. These equations were obtained in reproducible conditions and same range of permittivity for all EM sensors, which facilitates that their responses are comparable. In general, all sensors studied behaved correctly under conditions equivalent to those of a non saline soil with sandy texture, i.e. in a medium NR-NC. Since the studied nine sensors are reliable over the entire range of water content, its suitability for a particular application should be decided according to other specific criteria: volume explored, robust probes, possibility of automation of the readings, the versatility of the registration signal, cost, etc. When relaxation conditions show up in the media, such as those that might appear in clayey soils, sensors working at frequencies f_e≤ 20 MHz (WET sensor and EC-10 and EC-20 capacitance probes) exhibit a better performance than other EM sensors. As a counterpoint, are precisely the probes EC-10 and EC-20, with f_e ≈ 10 MHz frequencies, which are more affected by salinity in NR-C media, overestimating ε even for low salinities σ ≤ 0.5 dS m^{-1}. The possibility of correcting the signal taking into account σ, is however a potential option to be explored. For electrical conductivity σ ≤ 2 dS m^{-1}, only the TDR-Trase (f_e = 2-3 GHz) and the WET Sensor (f_e = 20 MHz) exhibit an acceptable behaviour. None of the studied sensors are reliable over the whole range of conductivity investigated 0 ≤ σ ≤ 4 dS m^{-1}. From a practical standpoint, given their good performance in the range of permittivity 1 <ε ≤ 68, both in NR-NC media as R-NC, their low cost, and the possibility of automation of registration with economical loggers, the EC capacitance probes are optimal candidates to be considered in studies of soil flow and transport processes, or irrigation scheduling. If concomitant readings of the electrical conductivity of soil solution were available and the corresponding correction of ε=*f*(σ) too, the probes EC-10 and EC-20 may prove useful also in soils and substrates with moderate/high salinity.

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REFERENCES

Blonquist, J.M. Jr., S.B. Jones and D.A. Robinson, 2005. Standardizing characterization of electromagnetic water content sensors: Part2. Evaluation of seven sensing systems. *Vadose Zone J. 4*, 1059-1069.

Campbell, J.E., 1990. Dielectric properties and influence of conductivity in soils at one to fifty megahertz. *Soil Sci. Soc. Am. J. 54*, 332-341.

Campbell, J.E., 2002. Salinity effects in capacitive soil moisture measurement. 12 p. *En* I.C. Paltineau (ed.) *Transactions first international symposium on soil water measurement using capacitance and impedance*, volume 1. Baltimore, USA.

Decagon Devices Inc., 2006a. ECH2O Soil moisture sensor operator's manual version 5. Decagon Devices Inc., Pullman, USA.

Decagon Devices Inc., 2006b. ECH2O TE. Water content, EC and temperature sensor operator's manual version 2. Decagon Devices Inc., Pullman, USA.

Delta-T Devices Ltd., 1999. Theta probe soil moisture sensor. User manual ML2x-UM-1.21. Delta-T Devices Ltd., Cambridge, UK.

Jones, S.B., J.M. Blonquist Jr., D.A. Robinson, V.P. Rasmussen and D. Or, 2005. Standardizing characterization of electromagnetic water content sensors: Part1. Methodology. *Vadose Zone J. 4*, 1048-1058.

Kelleners, T.J., D.A. Robinson, P.J. Shouse, J.E. Ayars and T.H. Skaggs, 2005. Frequency dependence of the complex permittivity and its impact on dielectric sensor calibration in soils. *Soil Sci. Soc. Am. J. 69*, 67-76.

Regalado, C.M., A. Ritter and R. Becker, 2006. Comments on "Monitoring soil water content profiles with a commercial TDR system: Comparative field tests and laboratory calibration". *Vadose Zone J. 5*, 1067-1068.

Robinson, D.A., S.B. Jones, J.M. Wraith, D. Or and S.P. Friedman, 2003. A review of advances in dielectric and electrical conductivity measurement in soils using time domain reflectometry. *Vadose Zone Journal 2*, 444–475.

Seyfried, M.S. and M.D. Murdock, 2004. Measurement of soil water content with a 50-MHz soil dielectric sensor. *Soil Sci. Soc. Am. J. 68*, 394-403.

Stacheder, M., 1996. Die Time Domain Reflectometry in der Geotechnik. Messung von Wassergehalt, elektrischer Leitfähigkeit und Stofftransport. PhD thesis, Schriftenreihe angewandte Geologie, Karlsruhe, Germany.

Soil Moisture Equipment Corp., 2000. Trase System I 6050X1 operating instructions. Soil Moisture, Santa Barbara, USA.

Topp, G.C., J.L. Davis and A.P. Annan, 1980. Electromagnetic determination of soil water content:

Measurements in coaxial transmission lines. *Water Resour. Res. 16*, 574-582.