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Technical Notes

Core Ideas

- Two commercially available moisture probes were tested on reference solutions.
- Dielectric permittivity was measured across the range from 1 to about 80.
- Uncertainties increased with increasing dielectric permittivity.
- Electric conductivity influenced dielectric permittivity measurements.
- Capability of the probes to measure electric conductivities differed among the probe types.

Evaluating Commercial Moisture Probes in Reference Solutions Covering Mineral to Peat Soil Conditions

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Capacitance and time domain reflectometry (TDR) probes are frequently used for measurements of the volumetric soil water content. The measurement concept is based on the correlation between volumetric water content and dielectric permittivity (ε). While considerable effort has been made to accurately measure ε in the typical range of mineral soils (<40), little attention has been paid to the capability of moisture probes to measure high ε (>40), typical for highly porous media like organic soils. We evaluated the capability of two moisture probe types (TRIME-PICO 64 and GS3) to measure ε across the range from 1 to 80. In the case of the TRIME probes, different equations to calculate ε from transit times were tested. Measuring in a set of reference solutions, the TRIME probes had an RMSE of 18.73 for ε values derived using the manufacturer's calibration. With a new calibration, the RMSE was decreased to 3.55. The GS3 probes had an RMSE of 3.96. For both probes, uncertainties increased with increasing ε. We also tested the performance for different electrical conductivities of the reference solutions. Accuracy of ε values was unaffected by increasing conductivities for the TRIME probes but decreased for the GS3 probes. The GS3 probes, however, were able to determine electric conductivities accurately, while TRIME probes failed for electrical conductivity although indicated differently by the manufacturer.

Abbreviations: EC, bulk electric conductivity; i-C_3E_1, 2-isopropoxyethanol; PVC, polyvinyl chloride; TDR, time domain reflectometry; TRIME, Time Domain Reflectometry with Intelligent Micromodule Element.

Electromagnetic-based sensors have been used for decades for measurements of volumetric water contents (θ) in porous media. The measurement principle takes advantage of the strong correlation between θ and the dielectric permittivity (ε) (in this study, ε is always expressed as dielectric permittivity relative to vacuum permittivity). A variety of empirical (Malicki et al., 1996; Pepin et al., 1992; Topp et al., 1980) and physically based mixing models (Roth et al., 1990; Whalley, 1993) have been published to derive θ from ε measurements in porous media. Applying these models to high-porosity media requires an accurate determination of ε across the entire range from air (ε = 1) to water (ε = ∼80).

Capacitance and time domain reflectometry (TDR) measurements have been proven to be appropriate methods for determining ε (Robinson et al., 2008). Capacitance probes, such as the GS3 probe (Decagon Devices, 2016), polarize the surrounding medium with an electromagnetic field. The measured capacitance depends on the imposed frequency, the electrode configuration, and the ε of the porous medium (Topp and Ferré, 2002). Capacitance probes operate, in contrast to TDR probes, at relatively low frequencies between 20 and 300 MHz (Bircher et al., 2016). This makes them cost effective on the one hand, but more susceptible to energy losses due to absorption and electrical conductivity on the other hand (Kizito et al., 2008; Vaz et al., 2013).

Time domain reflectometry probes use a voltage step pulse to generate a high-frequency electromagnetic wave that propagates along a transmission line. From the elapsed transit time (t) (ps) that the wave needs to travel forth and back along the transmission line, ε can be calculated with

$$\varepsilon=\left(\frac{ct}{2L}\right)^2 \quad [1]$$

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where L is the length (m) of the transmission line and c is the velocity of light (3×10^8 m s^{-1}). Details can be found in Robinson et al. (2003) or Topp and Ferré (2002) and are not repeated here.

The commercial TRIME (Time Domain Reflectometry with Intelligent Micromodule Element) TDR system (IMKO Micromodultechnik GmbH) is an adaption of conventional TDR systems. In contrast to conventional TDR systems, transit time is not determined across the entire waveform. TRIME systems determine transit time from the time of the reflection at a given (threshold) voltage level (amplitude), and this transit time is thus further referred to as t_{TRIME}. This requires that the amplitude after the reflection remains high. TRIME systems achieve this primarily by coating the metallic probe rods with polyvinyl chloride (PVC) (IMKO, 1996, technical data sheet, https://www.dropbox.com/s/8hz4jdwin5jcdsj/TRIME-theory.pdf?dl=1; accessed 23 Jan. 2018). The coating of the TDR rods (i) minimizes transmission losses and thus extend the working range in high-conductivity media, like saline soils (Vaz et al., 2013), but also (ii) influences measured transit times (Ferré et al., 1996). Thus, measured t_{TRIME} cannot be directly used in Eq. [1] for obtaining ε. Reliable ε values are, however, necessary to make TRIME measurements comparable with values obtained from other moisture probe types and to apply the various soil-specific ε–θ relationships that are available in the literature.

TRIME probes internally convert t_{TRIME} values to a "pseudo transit time" (t_{p}) accounting for the thickness of the rod coating, cable length, variations in initial amplitude, and bias in timing-control circuits. Thereby, measured t_{TRIME} values are rescaled to t_{p} by the manufacturer based on measurements in dry and wet glass beads. It is emphasized here that t_{p} is still (similar to t_{TRIME}) not applicable to Eq. [1] to obtain ε.

Inside the TRIME electronics, an empirical t_{p}–ε relationship is stored, which, however, has no documentation on how it has been derived. Regalado et al. (2006) proposed an alternative empirical t_{p}–ε relationship. Dielectric permittivities calculated with the two available equations show high discrepancies for ε >30. For most mineral soils, these differences are negligible because most ε values are <30 (Topp et al., 1980) and t_{p}–ε relationships do not differ considerable in that range. However, for highly porous media like organic soils and mosses with water-filled porosities up to 97% (Paavilainen and Päivänen, 1995), the different t_{p}–ε relationships would lead to substantially different ε measurements. Users have to choose one equation, and to our knowledge it is not clear which equation should be used for accurate ε measurements >30.

Electromagnetic response in soils does not depend only on ε but also on the bulk soil electric conductivity (EC) (Topp and Ferré, 2002). It is common practice to simultaneously determine ε and EC (Robinson et al., 2003), and most commercially available capacitance and TDR probes combine ε and EC measurements. Measurements of ε, however, can be interfered by high EC values. Usually TDR probes are less susceptible to interference by EC because they work at higher frequencies than capacitance probes (Robinson et al., 2008).

In this study, we evaluated the capability of two commercial moisture probes to measure ε across the whole ε range from approximately 1 to 80. The two systems were the TDR TRIME-PICO 64 (IMKO Micromodultechnik GmbH) and the capacitance-type probe GS3 (Decagon Devices). In the case of the TRIME-PICO 64 probes, different t_{p}–ε relationships were applied and tested. Based on our measurements, a new empirical t_{p}–ε relationship was derived to improve measurements with TRIME-PICO 64 probes. We also tested the influence of increased EC values on the accuracy of ε measurements and the capability of the probes to measure EC.

Materials and Methods

Probes

The measurements in this study were conducted with TRIME-PICO 64 TDR (IMKO Micromodultechnik GmbH) and GS3 (Decagon Devices) capacitance probes. TRIME-PICO 64 probes are referred to as TRIME in the following. Both probe types determine the ε-dependent variable (t_{TRIME} or capacitance) and EC simultaneously. As a reference probe for ε measurements, we used a conventional TDR probe designed and constructed at the Agrosphere Institute (Research Center Jülich), which also was used by Bechtold et al. (2010), connected to a Campbell TDR100 time-domain reflectometer (Campbell Scientific).

IMKO TRIME-PICO 64

TRIME-PICO 64 probes measure θ and EC at a frequency of 1 GHz. The probes have two 160-mm-long coated rods. According to IMKO (2017), the measurement volume is 1.25 L (height: 160, diameter: 100 mm). The TRIME probes have a probe internal, linear conversion of measured t_{TRIME} values into t_{p} (ps) ($t_{\mathrm{p}} = at_{\mathrm{TRIME}} + b$), which compensates for differences in the thickness of the rod coating, cable length, variations in initial amplitude, and bias in timing-control circuits and is supposed to bring different TRIME probe designs to similar measurement ranges of t_{p}. All probes are calibrated by the manufacturer, with values for the parameters a and b stored inside the TRIME electronics. Parameters can be modified for probe-specific calibrations. In the TRIME settings, the relationship between t_{TRIME} and t_{p} can also be described by polynomial equations up to the degree of 5. Please note that t_{TRIME} measured with TRIME probes differs from t in Eq. [1] that is measured with conventional TDR systems using the entire waveform for analysis.

According to IMKO (2017), θ can be measured in the range from 1 to 100% with an accuracy of $\pm$1% for θ between 0 and 40% and $\pm$2% for θ between 40 and 70% in solutions with EC values between 0 and 6000 μS cm^{-1}. Repeating accuracy (= precision) is reported by IMKO at $\pm$0.2%. They also indicate that TRIME probes are able to measure EC up to 20,000 μS cm^{-1}.

To obtain ε values, a conversion from t_{p} to ε is needed. The default calibration of the TRIME probes provided by the manufacturer is given as

$$\varepsilon = -14.459 + 0.32424 t_p - 2.1837\times10^{-3} t_p^2 + 6.8626\times10^{-6} t_p^3 - 9.7552\times10^{-9} t_p^4 + 5.3155\times10^{-12} t_p^5 \quad [2]$$

Regalado et al. (2006) proposed a logarithmic relationship between ε and t_p based on (i) measurements of Laurent et al. (2005) (TRIME-T3 access tube) on reference media, (ii) measurements of Stacheder (1996) (TRIME-P2 probe) in two-phase mixtures of water and dioxin, and (iii) their own measurements (TRIME-P2 probe) in 10 reference media with known ε. Measurements of t_p ranged from 100 to 900 ps:

$$\varepsilon = \exp\left(0.00478 t_p + 0.34928\right) \quad [3]$$

Laurent et al. (2005) also proposed an empirical relationship between ε and t_p. The equation of Laurent et al. (2005) was not considered in this study because it is based solely on the TRIME-T3 access tubes, which have a different probe geometry. Their proposed relationship is very different from those of Regalado et al. (2006) and ours, indicating that t_p measured with the different probe geometries are hardly comparable.

Table 1. Reference solutions, mix ratios, calculated dielectric permittivity ($\varepsilon_{calculated}$), mean of ε measurements with the reference system ($\varepsilon_{reference}$), and standard derivation (σ) of $\varepsilon_{reference}$ measured at a temperature of 22 ± 1°C.

Solution number	Solution†	Mix ratio	$\varepsilon_{calculated}$	Mean $\varepsilon_{reference}$	σ $\varepsilon_{reference}$
1	air	–	1	–	–
2	oil	100	3	2.4	0.04
3	i-C_3E_1	100	10.75	10.54	0.11
4	i-C_3E_1–water	92:8	16.24	15.80	0.32
5‡	i-C_3E_1–water	76:24	27.22	25.68	0.29
6	i-C_3E_1–water	68:32	32.71	31.05	0.84
7	i-C_3E_1–water	58:42	39.57	38.51	0.36
8	i-C_3E_1–water	48:52	46.44	44.93	0.53
9	i-C_3E_1–water	38:62	53.30	53.12	0.47
10	i-C_3E_1–water	28:72	60.16	61.53	0.44
11‡	i-C_3E_1–water	18:82	67.03	67.28	0.26
12	i-C_3E_1–water	12:88	71.14	71.87	0.81
13	water	100	79.38	–	–

† i-C_3E_1 = 2-isopropoxyethanol.
‡ Additional measurements at different electrical conductivities.

Decagon GS3

The GS3 probes polarize the surrounding medium with a 70-MHz oscillating wave that charges in proportion to ε (Decagon Devices, 2016). The derived ε values are based on a calibration in liquid standards. The probes have three 55-mm-long stainless steel rods and a measurement volume of 0.16 L.

According to Decagon Devices (2016), the accuracy of ε measurements is ±1 for ε from 1 to 40 and ±15% from 40 to 80. Measurements of EC can be conducted in a range between 0 and 25,000 μS cm^{-1} with an accuracy of ±5% from 0 to 5000 μS cm^{-1} and ±10% from 5000 to 23,000 μS cm^{-1}.

Reference System: Campbell TDR100 and Three-Rod TDR Probe

Classical TDR with uncoated probe rods was used as a reference system. The reference TDR probe (probe characteristics: three wires, 0.11 m long, 0.02-m spacing, 0.002-m radius, spacing/radius = 10) (Bechtold et al., 2010) was connected via an RG58 C/U cable to a Campbell TDR100 time-domain reflectometer (Campbell Scientific, 2007). The full waveform was recorded for air and water, and a waveform analysis was conducted in MATLAB to calibrate the probe parameters (offset and length), which allows accurate determination of ε across the whole range from air to water (Robinson et al., 2003).

Experimental Setup

The measurements in this study were conducted in air, oil (Wartungsöl Multi), 2-isopropoxyethanol (i-C_3E_1), i-C_3E_1–water mixtures, and deionized water (Table 1). Following Jones et al. (2005), we chose i-C_3E_1–water mixtures because they are non-relaxing for a wide range of frequencies and permit comparisons of sensors working with different frequencies. Mixture ratios were based on Bogena et al. (2007) and calculated with an ε of ~10.75 for i-C_3E_1 (Kaatze et al., 1996) and 79.38 for deionized water at 22°C. For the calculated ε, we assumed a linear relationship because Jones et al. (2005) found a relationship that was nearly linear. Deionized water was also used for the mixtures. Measurements were performed at a temperature of approximately 22°C (±1°C).

Solutions 5 and 11 were mixed four times, and different amounts of $CaCl_2$ were added to get solutions with EC values between 0 and 1000 μs cm^{-1}. The electric conductivity was measured with a WTW TetraCon 325. All reference solutions except air were measured three times with the reference probe to obtain $\varepsilon_{reference}$ and the corresponding standard deviation (σ) of $\varepsilon_{reference}$. Measurements of $\varepsilon_{reference}$ were close to the calculated ε values (±6%), except for the measurements in oil (±25%), which can have permittivity variations from different sources and lots (Jones et al., 2005).

All measurements were performed in PVC containers (height: 220 mm; diameter: 152 mm). The volume of the containers was larger than the measurement volume of all probe types, and the distance between container wall and rods was large enough to avoid disturbance by boundary effects.

Each solution was measured 30 times with 13 TRIME and 14 GS3 probes. For the TRIME probes, a SM-USB IMP-Bus/RS485 Level-Converter Module (IMKO) was used for the PC connection. The measurements were performed using TrimeTool software (IMKO). The GS3 measurements were performed with a UP SDI-LOG datalogger (Umweltanalytische Produkte GmbH) using the SDI-12 communication protocol.

Results and Discussion

Dielectric Permittivity

In the following, $\varepsilon_{reference}$ refers to the ε values measured with the reference TDR probe and correspond to $\varepsilon_{reference}$ in Table 1.

Based on our measurements with 13 different TRIME probes, we derived the following fifth-order polynomial expression to describe the relationship between ε and t_p:

$$\varepsilon = 1.981 + 0.01071 t_p - 3.083\times10^{-5} t_p^2 + 4.095\times10^{-7} t_p^3 - 1.107\times10^{-9} t_p^4 + 1.015\times10^{-12} t_p^5 \quad [4]$$

Figure 1 shows (i) the measured t_p values of the TRIME probes vs. the $\sqrt{\varepsilon_{reference}}$ values measured with the reference probe and (ii) t_p–$\sqrt{\varepsilon}$ relationships derived from Eq. [2], [3], and [4]. The measured t_p values ranged from −73 to 823 ps. Negative values are based on the probe internal calibration from t_{TRIME} to t_p. Figure 1 shows that the slope of the t_p–$\sqrt{\varepsilon}$ relationship is increasing with increasing t_p and $\sqrt{\varepsilon}$ values. This is an effect of the coated TDR rods. For the uncoated TDR rods of conventional TDR systems, the relationship between transit times and $\sqrt{\varepsilon}$ is linear. Measurements of transit times with coated probes, however, are influenced by the comparatively low ε of the coating material compared with most of the reference solutions (Ferré et al., 1996; Nichol et al., 2002). This influence increases for high ε values, which leads to the increasing slope depicted in Fig. 1.

Figure 2 shows the median and the 2.5 to 97.5% quantiles of the ε measurements vs. the reference ε values ($\varepsilon_{reference}$) for the TRIME (Fig. 2a) and GS3 probes (Fig. 2b). The variability expressed by the shown quantiles includes the variability among the different probes and the 30 repeated measurements of every probe. The variability can also be seen in Fig. 1 by the range of all measured t_p values at specific $\sqrt{\varepsilon_{reference}}$ values.

The ε values for the TRIME probes (Fig. 2a) were calculated with Eq. [2], [3], and [4]. Equation [4] was fitted to the measured data and therefore had the best performance, with an RMSE of 3.55. Although the median is in good agreement with $\varepsilon_{reference}$, the 95% variability indicates high uncertainties for increasing ε values. This is caused by the increasing slope of the ε–t_p relationships with increasing ε (shown in Fig. 1). This leads to higher ε changes for varying t_p measurements and, thus, also increases the effect of variability among different TRIME probes. Uncertainties between different TRIME probes for ε measurements are further increased for t_p >625 ps as the manufacturer rescales t_{TRIME} to t_p ($t_p = at_{TRIME} + b$) with measurements on dry and wet glass beads (moisture ~2.8 and ~43.9) with reference values of 145 and 625 ps, respectively (IMKO, 2017). We think this linear relationship is not sufficient to harmonize different probes across the whole ε range from air to water and to account for differences in probe electronics and geometries like variations in coating thickness of the TDR rods, which have an increasing influence on measured t_p values with increasing ε values. Additionally, it was observed that the variability of the 30 repeated t_p measurements per probe increased with increasing ε (not shown).

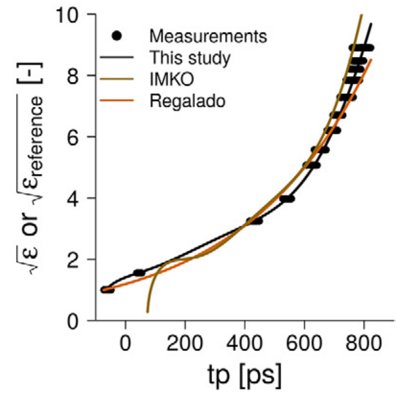

Fig. 1. Square root of the (i) reference dielectric permittivity $\sqrt{\varepsilon_{reference}}$ vs. measured “pseudo transit times” (t_p) and (ii) relationship of t_p and square root of the dielectric permittivity ($\sqrt{\varepsilon}$) derived from Eq. [2], [3], and [4].

Besides Eq. [4], the equation of Regalado et al. (2006) had the best performance, with an RMSE of 7.08. The IMKO manufacturer’s equation (RMSE 18.73) showed the highest discrepancy to the reference ε values, especially for ε values higher than ~40. We could only speculate about the bad performance of the IMKO equation because it is not documented how their measurements were performed. Their calibration might have not included ε values >40. The equation of Regalado et al. (2006) might be biased by the measurements of Laurent et al. (2005) on reference solutions, which were included in their calibration. Laurent et al. (2005) used probes with a different geometry, and measurements might not be comparable.

The measurements with the GS3 probes (Fig. 2b) match the reference ε values with an RMSE of 3.96. The discrepancy between

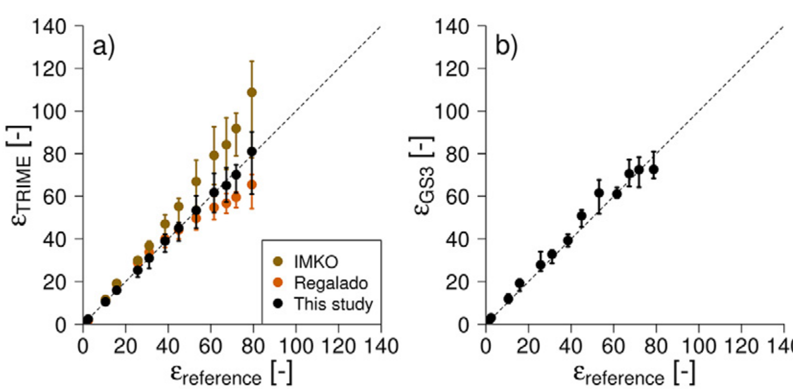

Fig. 2. Median and the 2.5 to 97.5% quantiles of all measured dielectric permittivities (ε) with (a) TRIME (ε_{TRIME}) or (b) GS3 (ε_{GS3}) probes vs. the reference dielectric permittivity ($\varepsilon_{reference}$). Dashed line is the 1:1 line.

measurements and reference increases for ε values >40. The comparison between the TRIME and GS3 probes (Fig. 2) shows that the GS3 probes have a lower variability among different probes and repeated measurements for ε values >40.

Electric Conductivity

Influence of Electric Conductivity on Measured Dielectric Permittivity

Figure 3 shows the median and the 2.5 to 97.5% quantiles of the ε measurements vs. $\varepsilon_{reference}$ for the TRIME (Fig. 3a) and GS3 probes (Fig. 3b) for EC between 0 and 1000 μS cm^{-1}. No systematic influence of increasing EC values on ε measurements could be observed for the TRIME probes. For Solution 5, the RMSE of the ε measurements increased from 1.22 to 4.87. For Solution 11, RMSE values varied from 4.58 to 5.91 without any dependence on the EC values. The ε measurements of the GS3 probes showed a tendency to decrease with increasing EC. With increasing EC values, the RMSE of the ε measurements increased from 2.92 to 6.57 for Solution 5 and from 4.71 to 9.70 for Solution 11. This clearly shows that the TRIME probe measurements are less affected by EC. The lower sensitivity to EC is well explained by the coated TDR rods and the higher measurement frequency compared with the GS3 probes. Please note that the effect of EC on the imaginary component of ε is strongly frequency dependent for the i-C_3E_1–water mixtures (Jones et al., 2005). Following this, the effects of increased EC on ε measurements found in this study can differ from measurements in natural soils.

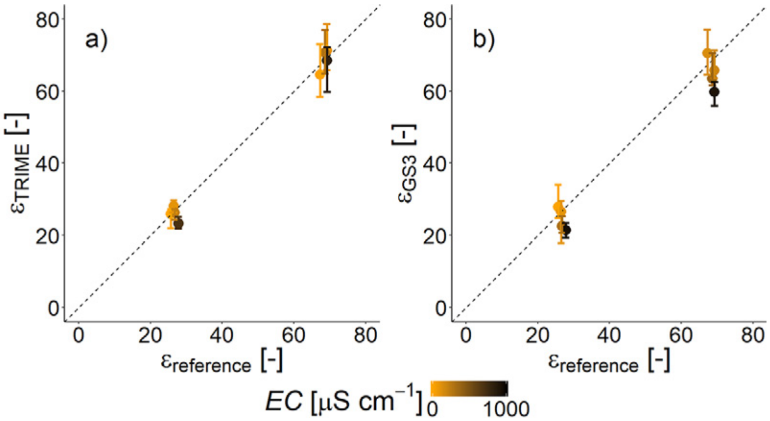

Fig. 3. Median and the 95% variability of measured dielectric permittivities (ε) with (a) TRIME (ε_{TRIME}) or (b) GS3 (ε_{GS3}) probes vs. the reference dielectric permittivity ($\varepsilon_{reference}$) under different electrical conductivities (EC) (μS cm^{-1}) with Solutions 5 and 11. Dashed line is the 1:1 line.

Measurement of Electric Conductivity

Figure 4 shows the measured EC vs. $EC_{reference}$ for the TRIME (Fig. 4a) and GS3 (Fig. 4b) probes.

Five of the 13 TRIME probes measured decreasing EC with increasing $EC_{reference}$. These probes were excluded from Fig. 4a. Even after exclusion of the apparently poorly performing probes, all remaining TRIME probes failed to measure $EC_{reference}$ accurately, and all EC_{TRIME} measurements showed a high uncertainty. This clearly shows the difficulty of measuring EC with coated TDR rods (Jones et al., 2002). For Solution 5, a weak linear relationship between EC_{TRIME} and $EC_{reference}$ does exist. However, for Solution 11, no clear linear relationship can be found between EC_{TRIME} and $EC_{reference}$. Our results for EC_{TRIME} clearly contradict what IMKO advertises on their homepage (https://imko.de/en/products/industrial-moisture/pico64; accessed 23 Jan. 2018) and in the probe manual that "TRIME probes measure moisture and conductivity very precisely at a frequency of 1GHz." All GS3 probes accurately measured EC with a low uncertainty (Fig. 4b). The accuracy of the EC values was independent of ε.

Summary and Conclusions

Both tested commercial soil moisture probes fulfilled the expectation of accurate ε measurements in the typical permittivity range of mineral soils (<40). For ε values >40, which occur in organic soils, the uncertainties increased for both probe types. The GS3 probes measured ε with acceptable accuracy and within the indicated accuracy of ±15%. With the TRIME probes, in contrast, it was not possible to measure ε >40 with acceptable accuracy without an extensive calibration on reference solutions. Despite a newly calibrated t_p–ε relationship for our set of probes, the measurement variability was up to 28% for water and up to 16% for the measurements in i-C_3E_1–water mixtures. It would only be possible to reduce the uncertainty with a probe-specific calibration that goes beyond the linear harmonization of t by $t_p = at_{TRIME} + b$. In fact, our results indicate that the original linear probe-specific calibration on two reference media with t_p ranging from 145 and 625 ps is not sufficient to obtain comparable t_p values that cover the whole ε range with t_p ranging from −73 to 823 ps. Therefore, our suggestion is to substitute the two-step empirical approach, going from

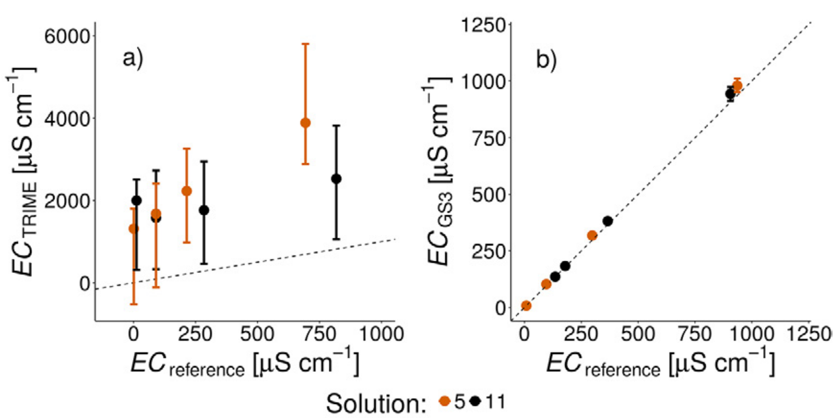

Fig. 4. Median and the 2.5 to 97.5% quantiles of all measured electrical conductivities with (a) the TRIME probes (EC_{TRIME}) and (b) the GS3 probes (EC_{GS3}) vs. the reference electric conductivities ($EC_{reference}$). Dashed line is the 1:1 line.

t_{TRIME} to t_p and from t_p to ε used in this study and proposed by IMKO, with a one-step approach going directly from t_{TRIME} to a transit time t that is applicable to Eq. [1]. More specifically, our suggestion is to improve the probe-specific calibration with a higher order polynomial transformation from t_{TRIME} directly to transit times comparable to t of Eq. [1] using data across the whole permittivity range from 1 to 80. This can be achieved by fitting transformed transit times to theoretical transit times calculated from known ε values of reference solutions using Eq. [1]. This calibration should be performed routinely by the manufacturer, as users of most applications will not be able to afford a probe-specific calibration with many reference solutions.

In solutions with different EC values, the TRIME probes performed better than the GS3 probes. Measurements in soils with high EC values will benefit from this property. In contrast, the GS3 probes determined EC values with high accuracy, while the TRIME probes failed to measure EC.

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