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Sensor-to-sensor variability of ECH2O EC-5, TE and 5TE sensors used for wireless sensor networks

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Introduction

Towards a continuous, automated, high temporal resolution and spatial covering measurement of soil water content at the catchment scale, the wireless sensor network SoilNet (Bogena et al., 2008) is a successful novel technique. Low-budget soil water content sensors used for sensor networks typically show variations between sensors (Sakaki et al., 2008) which may reduce the measurement accuracy if not appropriately accounted for.
Thus, we aimed to determine the sensor-to-sensor variability for ECH_2O sensors and the improvement of measurement accuracy when the sensor-to-sensor variability is considered via a sensor-specific calibration compared to a \`universal\` calibration.

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Sensor-to-sensor variability, ECH_2O sensors, Wireless sensor networks

Materials and Methods

In this study, multiple ECH_2O EC-5, TE and 5TE sensors (Decagon Devices, Inc.) were investigated. The EC-5 sensor measures solely soil water content via dielectric permittivity via sensor response. The sensor response of the EC-5 sensor is analogue and depends on supply voltage (here fixed at 3V). The TE and its successor, the 5TE sensor, measure also soil water content (sensor response in digital output format) and in addition also temperature and soil bulk electrical conductivity.

To circumvent the dilemma that the direct calibration for a large number of soil water content sensors (e.g. 900 for a SoilNet application in the forest catchment Wuestebach) is labour intensive and time consuming, we used an alternative calibration method based on dielectric liquids. This two-step method consists first, of the sensor response-permittivity relationship (unique for every sensor type) and second, the soil-dependent permittivity-soil water content relationship. This calibration procedure was proposed e.g. by Robinson et al. [1998), standardized by Jones et al. (2005) and applied e.g. by Bogena et al. (2007) for the older ECH_2O-20 and the EC-5 sensor. We concentrated here solely on the sensor response-permittivity relationship and approximate an equivalent soil water content θ_{eq} (just for a better hydrological understanding) via the empirical equation of Topp et al. (1980).

We used a set of five standard liquids (Table 1) to provide an even distributed permittivity range from nearly 2 to 35. These standard liquids are mixtures of 1,4 Dioxane (D)/water and 2-isopropoxyethanol (i-C_3E_1)/water mixtures), with a defined reference permittivity ε_{ref} obtained by fitting the Cole-Cole model to complex dielectric permittivity measurements via Network Analyzer and a Slim probe.

Table 1 Set of calibration standard liquids

Standard liquid	εref [-]	θeq [cm³ cm⁻³]
Dioxane 1.00	2.2	0.009
Dioxane 0.92	6.65	0.113
i-C3E1 0.92	18.14	0.321
i-C3E1 0.80	26.26	0.412
i-C3E1 0.68	34.82	0.478

The sensor response measurements of 105 EC-5 and 55 TE sensors were performed in five standard liquids, for 105 5TE sensors solely in two standard liquids (D1.0 and i-C_3E_1 0.68) as presented in Fig.1 (data set 1).

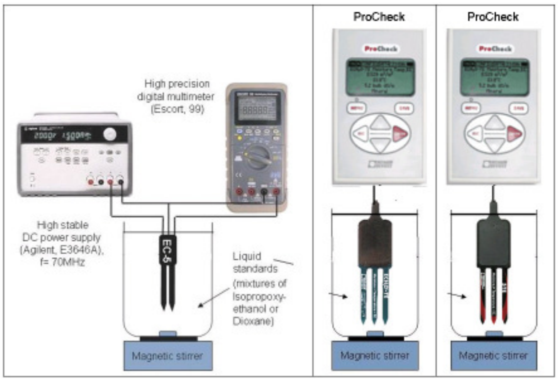

Figure 1 Calibration procedure for ECH2O sensors

Five replication sensor response measurements with five different EC-5, TE and 5TE sensors, respectively, were performed in i-C_3E_1 0.68 (data set 2). Based on that data set, the Analysis of Variance (ANOVA) leads to the separation of the total variance caused by the actual difference between the sensors (sensor-to-sensor variability) and the measurement noise.

Empirical sensor response-permittivity relationships (SRP models) were used to relate the sensor response (v) to the apparent sensor permittivity (K_a) of the EC-5 ([1]), TE ([2]) and 5TE ([3]) sensor according to:

$$\sqrt{K_a} = a_1 v^{b_1} + c_1 \qquad [1]$$

$$K_a = c_2 + \frac{1}{[a_2 + b_2 /(v/1000)^2]} \qquad [2]$$

$$K_a = a_3 v + b_3 \qquad [3]$$

with the fitting parameters a_i, b_i, and c_i.

Results

We observed largest scattering in sensor response (data set 1) using the standard liquid with highest permittivity for all three sensor types. The Coefficient of Variation is nearly constant for the EC-5 sensor, and is higher and increases for both the TE and the 5TE sensor with increasing permittivity.

The ANOVA test (data set 2) demonstrated (not shown here) that the sensor-to-sensor variability is significantly larger than the measurement noise for all three sensor types.

Therefore, applying an individual calibration for each sensor of each sensor type (sensor-specific calibration curves, not shown here) leads to a low root mean squared error (RMSE) between apparent sensor permittivity K_a and reference permittivity ε_{ref}. We found that the RMSE is quite low (<1) over the whole permittivity range, e.g. for the EC-5 sensor.

Compared to that, the fit of the SRP models to data set 1 leads to the sensor type-specific universal calibration curves (UCC) (Fig. 2) and the associated universal fitting parameters (see Rosenbaum et al., 2009).

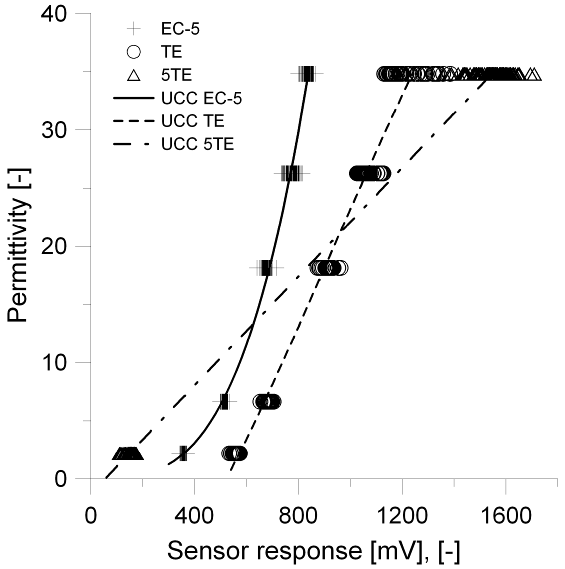

Figure 2: Universal Calibration Curve (UCC) for the EC-5, TE and 5TE sensor fitted to data set 1.

The estimated RMSE between K_a and ε_{ref} rises with increasing permittivity (see Fig. 2). E.g., we determined a RMSE of 0.7 in i-C_3E_1 0.68 using the SSC compared to 3.5 applying the UC for the TE sensor. Therefore, the comparison of these RMSE indicates that the accuracy is higher in the high permittivity range (from nearly 18 to 35) when each sensor is calibrated individually.

Conclusion

We can conclude that an improvement of approximately 0.01 to 0.015 $cm^3\ cm^{-3}$ can be achieved in high soil water content range through a sensor-specific calibration of EC-5, TE and 5TE sensors considering the observed variability between sensors of one sensor type. We further conclude that the calibration method using dielectric standard liquids is suited as an efficient calibration method for large numbers of sensors as needed for sensor network applications.

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