Calibration of a Soil Moisture Sensor in Heterogeneous Terrain

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EXTENDED ABSTRACT

Reliable soil moisture measurements over large areas are much needed for both hydrologic modelling and remote sensing applications. For collecting such data, portable electronic sensors offer a practical alternative to gravimetric measurements. The conversion of the measured electrical output to soil moisture is nonetheless a non trivial task as it depends on soil type and temperature. In this study, different calibration approaches of the Stevens Hydraprobe® soil dielectric sensor operating at 50MHz are tested with the National Airborne Field Experiment (NAFE) data. The objective was to evaluate the impact of soil type and temperature on the sensor response and test the applicability of a general calibration equation.

During the NAFE, a spatially enabled platform (Hydraprobe® Data Acquisition System, HDAS) was used to collect extensive measurements of near-surface soil moisture. HDAS is a handheld system integrating the soil dielectric sensor and a PC pocket/GPS receiver allowing for directly storing the measurements onto GIS software. HDAS measurements are composed of the dielectric constant (DC) of the soil/water mixture, soil temperature, soil moisture, salinity and conductivity.

A direct comparison between the factory calibration and gravimetric measurements indicate that the sensor response differs significantly with soil type. It was found that the probe signal is linear in sand but saturates above 20% v/v in clay. On the other hand, the real component of the measured relative DC was found to behave similarly for clay and sand, with a different slope for individual soils. Following these observations, two calibration approaches directly based on the measured DC are tested. The first is derived by averaging the slope obtained with various soil types (general equation). The second uses the ratio of the imaginary to real component of DC (loss tangent) to describe the difference in soil properties (loss-corrected equation). Results indicate that the calculated loss tangent is able to explain most of the variability among soil types. The root mean square error (RMSE) of the predicted soil moisture is decreased from 4.0% v/v with the general equation to 3.3% v/v with the loss-corrected equation. A third-order polynomial regression between the factory equation and observations gave the best overall accuracy with a RMSE of 2.7% v/v. The loss-corrected equation is however more robust as it does not saturate above 20% v/v and is more stable than the polynomial regression with different soil types.

Previous analyses have shown that the sensor is sensitive to temperature. In this study, the temperature effect on the real component of the measured DC was evaluated with sand and clay in different moisture conditions. With sand, the temperature was found to have a negligible effect with the largest effect on real DC for a 15°C temperature increase (relative to 25°C) of about -0.6, corresponding to a soil moisture change of about -1% v/v. With clay, the observed temperature effect of a 15°C increase is about at 30% v/v and 4 near saturation, corresponding to a soil moisture change of about 3% v/v and 4% v/v respectively. It was also found that the manufacturer-supplied temperature correction algorithm increases the observed temperature effect on the measured real DC. A simple correction is then derived based on the loss tangent to account for different effects according to soil types.

The loss-corrected equation including the proposed correction for temperature effect is finally applied to the NAFE data. Images of the calibrated soil moisture at 250m resolution over an area of 27 km^2 are presented for three sampling days following a rainfall event. Such spatial data will be used for calibration/validation of hydrologic models, remote sensing of soil moisture and

understanding controls on spatial patterns in soil moisture.

1. INTRODUCTION

Rapid measurement techniques using electronic sensors such as time domain reflectometers, capacitance, impedance and dielectric sensors offer an alternative to destructive and time consuming gravimetric sampling. They however require a proper calibration to convert the sensor response to soil moisture in different soils and temperature conditions (Cosh *et al.* 2005).

The National Airborne Field Experiment (NAFE) is a series of two soil moisture-dedicated experiments undertaken in South-Eastern Australia (Walker *et al.* 2005, 2006). NAFE'05 was undertaken during 4 weeks in the Goulburn river catchment and NAFE'06 during 3 weeks in the Murrumbidgee catchment, New South Wales. During NAFE, top 5cm soil moisture was measured intensively from paddock to regional scales using a spatially enabled platform (Panciera *et al*. 2006) based on the Hydraprobe® (Vitel, 1994, Mention of manufacturers implies no endorsement on the part of the authors).

The Hydraprobe®, hereafter referred to as the soil moisture sensor, is a soil dielectric sensor operating at 50MHz with an embedded thermistor in the probe head. At each measurement point, a volumetric soil moisture value is inferred from the real component of the measured relative dielectric constant (DC). Because the real component of DC (ε_r) may vary with temperature, a temperature correction is proposed by the manufacturer that uses the measured soil temperature (assumed to be the temperature of the probe head). The water content is then calculated based on the temperature-corrected real DC via one of three possible calibration equations for sand, silt and clay.

Independent evaluations of the performance of this sensor were notably made by Seyfried and Murdock (2002, 2004) and Seyfried *et al.* (2005). Seyfried and Murdock (2002) reported that the three calibration curves provided by the manufacturer do not effectively describe observations, and that soil temperature effects may be significant. Seyfried *et al.* (2005) developed two multi-soil calibration equations; a general calibration equation and a calibration equation that incorporates the effects of soil properties.

The objective of the study is to evaluate the impact of soil type and temperature on the sensor response and test the applicability of a general calibration equation to the NAFE data set. In particular, the two calibration equations of Seyfried *et al.* (2005) are tested and compared to a 3rd order polynomial regression in terms of accuracy and robustness. The analysis is based on four distinct data sets, one collected in the field (NAFE'06) and three in the laboratory with both NAFE'05 and NAFE'06 samples including a wide range of soil types from sand to clay.

2. DATA

Among the four datasets used in this study, three were obtained in the laboratory (Temp'05, Lab'05 and Lab'06) and one in the field (NAFE'06). These datasets were all collected in the NAFE framework with the aim of facilitating calibration of the soil moisture sensor.

During NAFE'06, gravimetric measurements were collected at five pre-defined locations within six focus farms (denoted by Y1, Y2, Y7, Y9, Y10 and Y12). These locations were chosen to cover a range of soil type and moisture conditions. The five gravimetric points remained unchanged all along the field experiment so as each gravimetric measurement was associated with a given soil but with time varying moisture conditions. A HDAS reading was taken at each gravimetric point, and a soil sample was collected at the same location. In the case when the probe was modifying the soil surface (e.g. soil stuck on the pins of the probe), the soil sample was collected at the middle of a 10-20cm wide triangle of three successive HDAS measurements. Gravimetric sampling was undertaken as much as possible at the same time on every sampling day, so as to meet similar temperature conditions. Soil samples were processed using the standard thermo gravimetric approach.

Lab'06 complements the field data of NAFE'06 with a set of thirteen soil samples. Soil samples were collected in the same farms as for NAFE'06. Locations were in general different from the gravimetric points of the field experiment. Lab'05 is a laboratory experiment undertaken with soil samples from the NAFE'05 Goulburn river catchment region. Eight soil samples were used, one in each of the eight focus farms. Note that this dataset does not include the output voltages. The infiltration-addition method was applied to all soils of Lab'05 and Lab'06 by pouring water on the top of the containers, and allowing samples to saturate for a minimum of 24 hours. A probe was then inserted into the container and samples were oven dried at 45°C.

Temp'05 is a laboratory experiment specifically designed to quantify the temperature effect on the soil moisture sensor. The infiltration-addition method was applied to the soil samples of Lab'05 by pouring different amounts of water to get different moisture conditions from dry to saturated soil. Samples were then put in the oven at different temperatures 20, 30, 40, 50 and 60°C.

3. TEMPERATURE EFFECT

Seyfried and Murdock (2002) estimated that the temperature effect of a 40°C temperature change was about 4-6% v/v depending on soil type. In this section, the Temp'05 dataset is analysed and a correction for temperature effect on the measured real DC derived.

Results of the Temp'05 experiment are presented in Fig 1. For each soil sample analysed, the effect of a 15°C increase relative to 25°C on the measured DC is evaluated from the DC constants measured at 20°C and 40°C. It is computed as the ratio of the difference between the DC measured at 40°C and that estimated at 25°C, divided by the temperature change (15°C). The DC at 25°C is interpolated by assuming a linear temperature effect between 20°C and 40°C (Seyfried and Murdock, 2004). In Fig. 1, the temperature effect on the real and imaginary DC is plotted as a function of soil moisture. Both the measured DC and the DC corrected for temperature effect by the manufacturer's algorithm are presented for comparison.

Temperature has a different effect on the real and imaginary components of the measured DC. Concerning the imaginary component, the temperature effect is always positive and generally increases with soil moisture (Seyfried and Murdock, 2004). It is however efficiently corrected by the manufacturer's algorithm, which reduces the temperature effect on the imaginary DC down to 20% on average (see Fig. 1a).

The temperature effect on the real component of the measured DC differs with soil type. With sand, the effect is slightly negative near saturation (Seyfried and Murdock, 2004). This can be explained by the fact that soil water in sand has dielectric properties similar to those of pure water. In that case, the temperature correction proposed by the manufacturer is in good agreement with observations. With clay, the temperature effect is positive and increases with soil moisture. The observed change in real DC over the 15°C temperature increase is about 2 at 30% v/v and 4 at 40% v/v, corresponding to an estimated soil moisture change of about 3% v/v and 4% v/v respectively. It is found that the correction proposed by the manufacturer is not satisfactory with clay as the error on the measured real component of DC is increased for all soil samples (see Fig. 1b).

A correction for temperature effect on the measured real DC is then proposed. The correction equation is based on the observations that (i) the temperature effect differs largely with soil types; (ii) the temperature effect is significant with clay and increases with soil moisture. As the manufacturer's temperature correction amounts to calculating the correct dielectric constants at 25°C, our correction equation is also relative to 25°C, and can be written as

$$\varepsilon_r^{corr} = \varepsilon_r \left[1 - K\left(T - 25\right)\right], \tag{1}$$

with ε_r^{corr} the temperature-corrected real DC, T the sensor temperature and K a constant. As the temperature effect differs with soil types (negative with sand and positive with clay), parameter K was correlated to loss tangent to integrate the effects of soil dielectric properties. The loss tangent is defined as

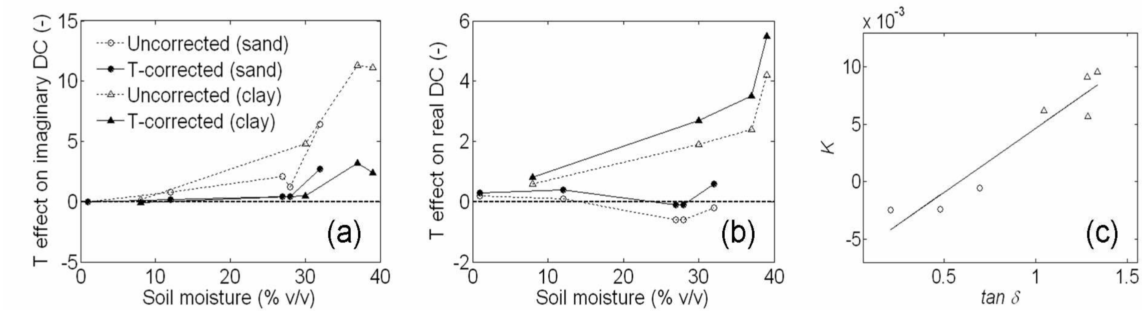

Figure 1. Temperature effect on the uncorrected DC and the DC corrected for temperature effect by the manufacturer's algorithm: a) the imaginary component of DC; b) the real component of DC. With clay, the observed temperature effect on real DC is increased by the manufacturer's correction. In (c), the temperature effect (K) for a 15°C increase is shown as a function of loss tangent.

$$\tan\delta = \frac{\varepsilon_i}{\varepsilon_r}, \tag{2}$$

This quantity is proportional to the energy dissipation experienced by the input voltage. Fig. 1c illustrates the relationship existing between the estimated *K* and the loss tangent computed with the Temp'05 data set. A linear regression gives $K = 0.011 \tan\delta - 0.0065$ with a correlation coefficient of 0.95.

4. CALIBRATION APPROACHES

Fig. 2 shows the variations of the sensor response with datasets Lab'05 and Lab'06. The soil moisture simulated by the manufacturer's algorithm (option silt) and the real DC measured by the sensor are both plotted against gravimetric measurements. Note that the recommendation of the manufacturer for when the soil type is unknown is to set the programming option for silt. The real DC could not be computed with data set Lab'05 as the input data of the algorithm (voltages) were not stored. Fig. 2a indicates that with sand the sensor soil moisture is linearly correlated with observations, while with other soils, the sensor soil moisture saturates above 20-25% v/v. However, as shown in Fig. 2b the measured DC keeps increasing until saturation, and the relationship is similar with different soil types.

These results are consistent with Seyfried et al. (2005), who developed a calibration equation of the probe directly from the dielectric constant. They use a linear relationship between θ and $\sqrt{\varepsilon_r}$ given by

$$\theta = A\sqrt{\varepsilon_r} + B, \tag{3}$$

with *A* and *B* two soil-dependent parameters. In that study, a general equation was derived by averaging the parameters obtained with measurements made on 20 different soil types. This calibration equation (*A*=11.0; *B*=-18.0 % v/v) was found to be superior to any of the three equations provided by the manufacturer. Seyfried et al. (2005) then correlated the difference between the measured and predicted soil moisture with the loss tangent at saturation $\tan\delta_s$. The loss tangent was used for correcting the observed differences between individual soil calibrations. Since most of the variation in soil calibrations was due to variations in *A*, the loss-corrected *A* parameter value A_{lc} is based on the regression between *A* and $\tan\delta_s$. The new calibration equation was written

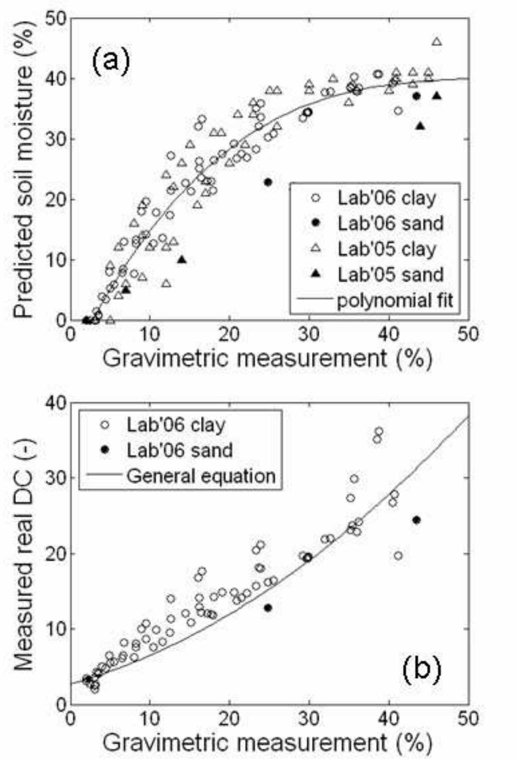

Figure 2. Sensor response as function of soil moisture: a) soil moisture predicted by the manufacturer's calibration equation (option silt); b) real DC measured by the sensor.

$$\theta = A_{lc}\left(\sqrt{\varepsilon_r} - \sqrt{\varepsilon_r(\theta = 0)}\right), \tag{4}$$

with A_{lc} = -1.53 $\tan\delta_s$ + 12.02 (% v/v) and ε_r = 2.7 at θ = 0. Note that *B* was replaced by - $A_{lc}\sqrt{2.7}$.

A third calibration approach consists of fitting the sensor soil moisture to observations using a polynomial regression

$$\theta = a\theta_{silt}^3 + b\theta_{silt}^2 + c\theta_{silt} + d, \tag{5}$$

with θ_{silt} the soil moisture predicted by the manufacturer's calibration equation (option silt) and *a*, *b*, *c* and *d* four parameters.

As an illustration of the three calibration approaches, the polynomial equation and the general equation are plotted respectively in Fig 2a and 2b. It is apparent that the general equation is more linear than the polynomial equation and fits relatively better the sensor response with the range of soil types of NAFE. Note that the loss-corrected equation cannot be plotted in the same figures as the predicted soil moisture is also a function of the imaginary component of DC.

5. MULTI-SOIL CALIBRATION

The general equation (3), the loss-correlation equation (4) and the polynomial regression (5) are successively applied to the NAFE'06 datasets. The different approaches are then assessed in terms of accuracy and robustness.

To apply the loss-correlation equation to the roving measurements made during NAFE'06, which uses the loss tangent measured at saturation, one needs to assume that loss tangent is constant (i.e. does not depend on soil moisture). Fig. 3 shows the variation of tan δ as a function of soil moisture at six permanent sites in the NAFE'06 area. At most sites, the value at saturation appears to be reached at about 15% v/v, which means that the loss-corrected equation can be applied for soil moisture values above 15% v/v. Note that the difference between soil types is expected to be small below 15% v/v. One can therefore assume that the difference due to the use of tan δ instead of tan δ_s in the loss-corrected equation is relatively small over the full range of soil moisture.

A second assumption is about the temperature measured by the sensor. To correct for temperature effect in the field, one needs to make sure that the temperature measured by the sensor, which is located in the head of the sensor, is consistent with the top 5cm soil temperature. Fig. 4 plots the sensor temperature measured in the field by the roving HDAS as function of the 0-5cm temperature measured continuously at the permanent sites in the sampling area. The standard deviation between roving and station-based measurements is about 2°C, which is smaller than the range covered by temperature values (15 to 35°C). In the less favourable case where the difference in temperature is maximum (10°C), and with a high loss tangent (1.5), the predicted maximum error on the measured real DC is about 10% of its value, corresponding to an error in soil moisture of about 4% v/v at 30% v/v and 5% v/v at 40% v/v. In general, the temperature measured by the soil moisture sensor is a good estimate of the 0-5cm soil temperature that can be used for the temperature correction.

The temperature correction of equation (1) is applied to the measured real DC of the NAFE'06 dataset. Results obtained with the general and loss-corrected equation of Seyfried *et al.* (2005) are then compared in Fig. 5a and 5b. The use of the loss tangent reduces the root mean square error of the predicted soil moisture from 4.0% to 3.3% v/v. This improvement confirms the existing correlation between the loss tangent and the change in the measured real DC among soil types

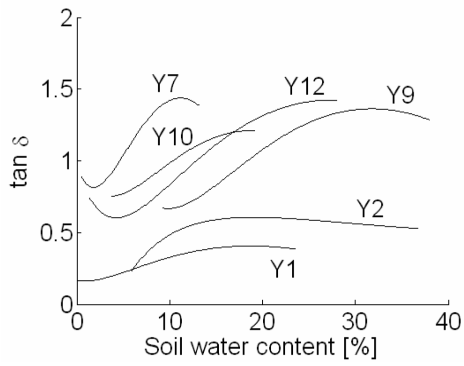

Figure 3. Loss tangent (tan δ) versus soil moisture at six stations of the Murrumbidgee network in Spring 2006. Curves were generated from best-fit polynomial equations for each soil.

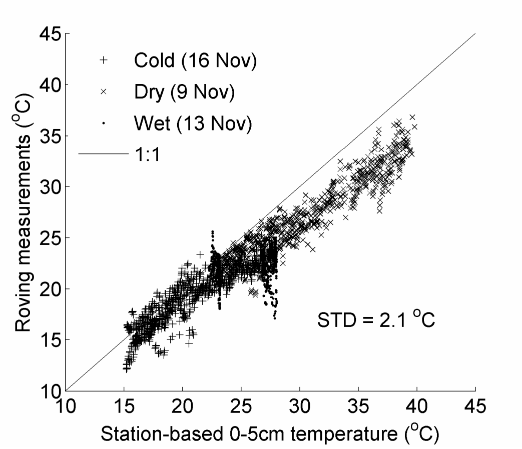

Figure 4. Roving versus station-based soil temperature measurements for three different days during NAFE'06: a typically cold (16 Nov), dry (9Nov) and wet (13 Nov) day.

and entails the assumption that the loss tangent can be approximated to the loss tangent at saturation for the calibration. The loss-correlated parameter A_{lc} is then fitted to the NAFE'06 data set. A linear regression between the measured A and tan δ gives A_{lc} = -4.3 tan δ + 14.4. With the new slope, the root mean square error of the loss-corrected equation is slightly decreased to 3.1% v/v.

A third order polynomial regression between the soil moisture computed by the manufacturer's calibration equation and observations is derived (-0.0078 θ^3 + 0.183 θ^2 + 69.9θ + 210)/100 and results are plotted in Fig. 5c. The root mean square error of the predicted soil moisture is 2.7% v/v, which represents the best fit among the four calibration equations proposed. However, when suing the whole NAFE'06 data set to compare the polynomial and the loss-corrected equations (see Fig 5c), one observes that the soil moisture predicted by the polynomial regression strongly saturates at about 25% v/v. This finding is consistent with the results obtained in the laboratory, and presented in Fig. 2. In fact, the best fit obtained with the polynomial fit is an artefact of the NAFE'06 soil and moisture conditions. The soil in the NAFE'06 study area is relatively homogeneous (mainly clayey), and the range of soil moisture values measured during the experiment was relatively low. It is expected that the polynomial equation (or any equation fit to the sensor measured soil moisture) would induce systematic errors with soils that are non-representative of whole area (in particular sand for NAFE) and for soil moisture values above 25% v/v. In this regards, the multi-soil calibration equation of Seyfried *et al.* (2005) with the temperature correction developed here is a more robust approach for an operational application.

6. APPLICATION

The calibration equation of Seyfried *et al.* (2005) including the correction for temperature effect derived in this paper is applied to the NAFE data with the assumption of a constant loss tangent. As the calibration of the slope with the NAFE'06 data did not significantly improve the accuracy of the predicted soil moisture (error of 3.1% instead of 3.3%), the slope of Seyfried *et al.* (2005) is used instead of the calibrated one.

An illustration of the calibrated data is provided in Fig. 6. The soil moisture maps obtained on 13, 14 and 16 November 2006 at three farms Y2, Y9 and Y12 are presented. A rainfall of about 15mm occurred in the sampling area on 12-13 November. The general drying of the study area is clearly visible from an average of about 25% v/v on 13 November down to 15% v/v on 16 November. Over the drying period, the spatial variability within farms Y9 and Y12 is mainly due to irrigated crops; Y2 is dry land pasture while Y9 and Y12 are cropping farms with some irrigated crops (maize and wheat). Saturated soils are apparent in the irrigated areas at the south-west corner of Y9 and the middle of Y12.

To assess the impact of loss tangent on calibrated data, loss tangent is computed on the wettest day of the field campaign (13 November). Only the HDAS measurement points with a soil moisture value higher than 30% v/v are used, giving an average of soil moisture of about 35% v/v for Y2, Y9 and Y12. The computed loss tangent varies from 0.7 to 2.2 in Y12 (mean 1.2), from 0.3 to 1.8 in Y9 mean (1.0) and from 0.4 to 1.1 in Y2 (mean 0.9). The predicted maximum difference in soil moisture between the minimum (0.3) and

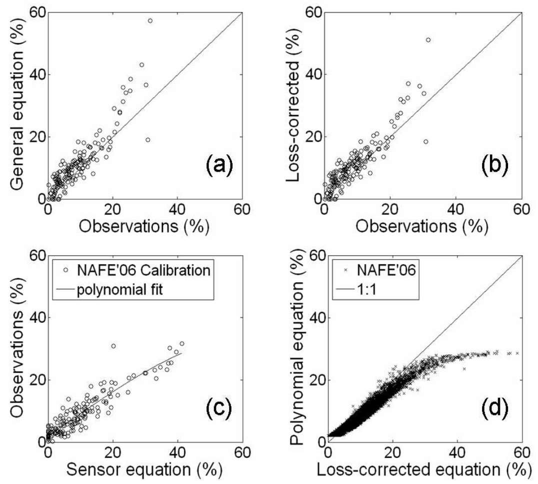

Figure 5. Different calibration equations: in a) the general equation; in b) the loss-corrected equation; in c) the polynomial equation. In d), the polynomial equation is plotted against the loss-corrected equation with the whole NAFE'06 data set.

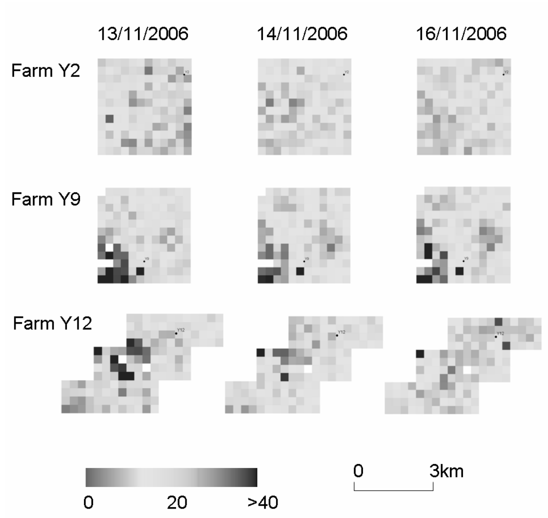

Figure 6. Example of near-surface soil moisture maps using the calibration equations presented in this paper.

maximum (2.2) loss tangent is evaluated to be about 8% and 10% v/v at 30% at 40% v/v soil moisture respectively.

7. CONCLUSION

The objective of this study was to evaluate the impact of soil type and temperature on the sensor response and test the applicability of a general calibration equation to the NAFE data set. The analysis is based on four distinct data sets, one collected in the field (NAFE'06) and three in the laboratory with both NAFE'05 and NAFE'06 soil samples.

The temperature effect on the soil water sensor response was evaluated with sand and clay in a range of moisture conditions. With sand, the temperature appears to have a negligible effect with the largest temperature difference (15°C) estimated to have only about 1% v/v impact on the soil moisture value. With clay, the observed temperature effect is more significant with a soil moisture change up to 4% v/v. It is found that with our data set the manufacturer's algorithm increases the observed temperature effect on the measured real DC. A simple correction was then derived based on the observed relationship between the relative effect on the real DC and loss tangent.

The general and loss-corrected calibration equations of Seyfried *et al.* (2005) were applied to the temperature-corrected dielectric constant, and compared to observations. Results indicated that the computed loss tangent is able to explain most of the variability among soil types. The RMSE of the predicted soil moisture is reduced from 4.0% to 3.3% v/v. A third-order polynomial regression between the manufacturer-simulated and the observed soil water content gives the best overall accuracy with a RMSE of 2.7%. The loss-corrected equation is however more robust than the polynomial regression for different soil types, and soil moisture values above 25% v/v.

The temperature correction and the loss-corrected equation have been applied to the NAFE data set. As an illustration of the calibrated data, a time series of soil moisture maps at 250m resolution are presented. The temporal and spatial variability is high with near-surface soil moisture values covering the full range from near 0 to 40%. Such spatial data will provide the "ground truth" that can be used for calibration/validation of hydrologic models and remote sensing techniques.

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