Soil Moisture Measurement in Heterogeneous Terrain

Merlin, O.[1], J.P. Walker[1], R. Panciera[1], R. Young[1], J.D. Kalma[2] and E.J. Kim[3]

[1] Department of Civil and Environmental Engineering, The University of Melbourne, Australia
[2] School of Engineering, The University of Newcastle, Australia
[3] NASA Goddard Space Flight Center, Greenbelt, USA
Email: omerlin@unimelb.edu.au

Keywords: *soil moisture sensor, calibration, uncertainty assessment, soil moisture patterns.*

EXTENDED ABSTRACT

Reliable soil moisture measurement over large areas is 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 National Airborne Field Experiment (NAFE) data. The objective is to evaluate the impact of soil type and temperature on the sensor response and test the applicability of a general calibration equation.

During 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 pocket PC with GPS receiver allowing for direct storage of location and measurement with GIS software. HDAS measurements are composed of the dielectric constant (DC) of the soil-water mixture, soil temperature, soil moisture content, salinity and conductivity.

A direct comparison between the factory calibration and gravimetric soil moisture measurements indicates that the sensor response has a loss of sensitivity at soil moisture over 25 % v/v in clay. On the other hand, the real component of the measured relative DC is found to be more strongly correlated to gravimetric observations than the predicted soil moisture. Following these observations, two calibration approaches based on the measured DC were 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 gives the best overall accuracy with a RMSE of 2.7% v/v. However, the loss-corrected equation is more robust as it does not loose sensitivity above 25% v/v and is more reliable than the soil type dependent polynomial regression.

Previous analyses have shown that the Hydraprobe sensor is also sensitive to soil temperature. In this study, the temperature effect on the real component of the measured DC is evaluated with sand and clay in different moisture conditions. With sand, temperature is 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 on DC for a 15°C increase is about 2 at 30% v/v and 4 near saturation, corresponding to a soil moisture increase of about 3% v/v and 5% v/v respectively. It is also found that the factory temperature correction algorithm increases the temperature effect on the measured real DC. Consequently, a new correction is derived based on the loss tangent, to account for different temperature effects according to soil type.

The loss-corrected equation, including the proposed correction for temperature, is finally applied to the data from the National Airborne Field Experiment. Maps of soil moisture at 250m resolution over an area of 27km^2 are presented for three sampling days following a rainfall event. Such spatial data will be available 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. However they require careful 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 a 4 week intensive period in the Goulburn River catchment and NAFE'06 during a 3 week intensive period in the Murrumbidgee catchment, New South Wales. During NAFE, top 5cm soil moisture was measured extensively from paddock to regional scales using a spatially enabled platform (Panciera *et al.* 2006) based on the Hydraprobe® (Vitel[1], 1994).

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) and the conductivity (linked to salinity) from the imaginary component. 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 from the temperature-corrected real DC via one of three possible manufacturer's calibration equations (for sand, silt and clay).

Independent evaluations of the performance of this sensor were 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 present 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 using NAFE'05 and NAFE'06 samples that include a wide range of soil types ranging 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, volumetric samples were collected at five pre-defined locations within each of six focus farms (denoted by Y1, Y2, Y7, Y9, Y10 and Y12) – see Walker et al., this issue. These locations were chosen to cover a range of soil type and moisture conditions. The five gravimetric points remained unchanged throughout the field experiment so that each thermogravimetric measurement was associated with a given soil but with time varying moisture conditions. A Hydraprobe reading was taken at each thermogravimetric point, and a soil sample was collected at exactly 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 Hydraprobe 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 thermogravimetric approach.

Lab'06 complements the field data of NAFE'06 with a set of thirteen soil samples. Soil samples were collected on the same farms as for NAFE'06, but locations were in general different from the gravimetric points of the field experiment. Lab'05 is an identical laboratory experiment except that soil samples were from the NAFE'05 Goulburn River catchment region. Eight soil samples were used, one on each of the eight focus farms. [Note that this dataset does not store 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 sensor was then inserted into the container and samples were

---

[1] Mention of manufacturers implies no endorsement on the part of the authors

oven dried at 45°C, with soil moisture measurements made periodically until dry.

Temp'05 was 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. Sealed samples were allowed to equilibrate in the oven at temperatures of 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 to confirm this assertion and a correction for temperature effect on the measured real DC is derived.

Results of the Temp'05 experiment are presented in Fig 1. As the manufacturer's temperature correction amounts to calculating the correct DC at 25°C, the temperature effect on the real and imaginary component of DC is evaluated relative to 25°C. As no measurement was made at that temperature, the DC at 25°C is linearly interpolated from the DC measured at 20°C and 30°C. Fig. 1a and 1b show the change in DC for a 15°C increase relative to 25°C 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. For the imaginary component, the temperature effect is always positive and generally increases with soil moisture (Seyfried and Murdock, 2004). The manufacturer's algorithm was able to efficiently correct for this effect (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. This can be explained by the fact that soil water in sand has dielectric properties similar to those of pure water (Seyfried and Murdock, 2004). 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 5% v/v respectively. In this case, it is found that the correction proposed by the manufacturer is not satisfactory as the error on the measured real component of DC is increased for all soil samples (see Fig. 1b).

As the factory temperature correction for real DC was found to be unsatisfactory, a new formula is 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 for 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

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

with ε_r^{corr} the temperature-corrected real DC, ε_r the measured real DC, T (°C) the sensor temperature and K (°C^{-1}) a constant. As the temperature effect differs with soil types (negative with sand and positive with clay), parameter K was correlated with the loss tangent to integrate the effects of soil dielectric properties. Parameter K is computed as the difference between DC at 40°C and 25°C divided by the temperature change (15°C) and the loss tangent $\tan\delta$ is computed as

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

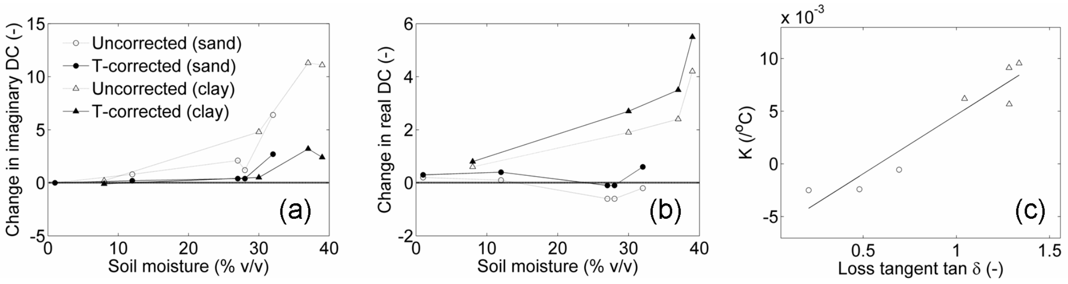

Figure 1. Effect on the uncorrected and manufacturer corrected DC for a 15°C increase in soil temperature: a) the imaginary component of DC; and b) the real component of DC. In (c), the temperature effect per degree (*K*) on the real DC is shown as a function of loss tangent.

where ε_i is the measured imaginary DC. This quantity is proportional to the energy dissipation experienced by the input voltage. Fig. 1c illustrates the relationship 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 temperature-corrected sensor response with laboratory datasets Lab'05 and Lab'06. The soil moisture calculated by the manufacturer's algorithm (option silt) and the real DC measured by the sensor are both plotted against gravimetric measurements. Note that the manufacturer's recommendation is to set the programming option for silt when the soil type is unknown. The real DC could not be computed with data set Lab'05 as the input data of the algorithm (voltages) are not stored. Fig. 2a indicates that there is a loss of sensitivity of the predicted soil moisture θ_{silt} at soil moisture over approximately 25% v/v. However, Fig. 2b shows that there is good relationship with DC until saturation. The correlation coefficient is increased from 0.90 in Fig. 2a to 0.94 in Fig. 2b.

These results are consistent with Seyfried *et al.* (2005), who developed a calibration equation of the probe directly from the dielectric constant [note: they used the manufacturer's temperature correction]. They derived a linear relationship between θ and $\sqrt{\varepsilon_r}$ given by

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

with A and B soil-dependent parameters. In that study, a general equation was derived by averaging the parameters obtained with measurements made on 20 different soil types. Their general 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 the slope A, the loss-corrected A parameter value A_{lc} was based on a regression between A and $\tan\delta_s$. The new loss-corrected calibration equation was written

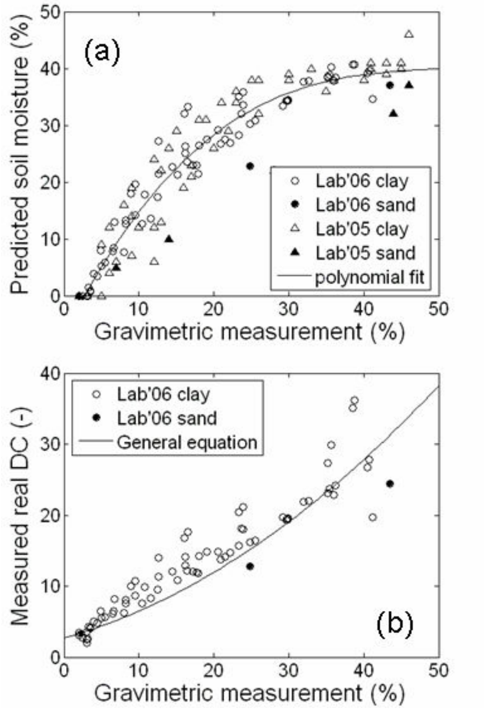

Figure 2. Sensor response as function of soil moisture: a) soil moisture predicted by the factory calibration equation (option silt); b) real DC measured by the sensor.

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

with $A_{lc} = -1.53\tan\delta_s + 12.02$ (% v/v) and $\varepsilon_r = 2.7$ at $\theta = 0$ (Seyfried *et al.*, 2005). Note that B was replaced in (4) by $-A_{lc}\sqrt{2.7}$.

A third 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 fitting parameters.

As an illustration of the three calibration approaches, the polynomial equation (5) and the general equation (3) are plotted in Fig 2a and 2b respectively. 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 (4) cannot be plotted in Fig 2 as the predicted soil moisture is also a function of the imaginary component of DC.

5. MULTI-SOIL CALIBRATION

In this section the general equation (3), the loss-corrected 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-corrected equation to the roving measurements made during NAFE'06, which uses the loss tangent measured at saturation, one needs to assume that the loss tangent is constant (i.e. does not depend on soil moisture). Fig. 3 shows the variation of $\tan\delta$ as a function of soil moisture at six permanent sites in the NAFE'06 area. The loss tangent at saturation varies from 0.4 (Y1) to 1.5 (Y12) with a variability attributed to soil moisture ranging from 0.2 to 0.8. 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 reliably applied for soil moisture values above 15% v/v. Note that below 15% v/v, the difference between soil types is still greater than the difference by soil moisture.

A second assumption is that the temperature measured by the sensor located in the head of the probe represents the top 5cm soil temperature. Fig. 4 plots the sensor temperature measured in the field by the roving measurements as function of the 2.5cm 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 much smaller than the range covered by temperature values (15 to 35°C). In the worst 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 within 2°C of the 0-5cm soil temperature, yielding a soil moisture error less than 1% v/v.

The temperature correction of equation (1) is applied to the measured real DC of the NAFE'06 dataset. To do so, we assumed a linear temperature effect in the temperature range experienced during the experiment (15 to 45°C). Results obtained with the general equation and the loss-corrected equation of Seyfried *et al.* (2005) are then compared in Fig. 5a and 5b respectively. The use of the loss tangent reduces the RMSE of the predicted soil moisture from 4.0% to 3.3% v/v.

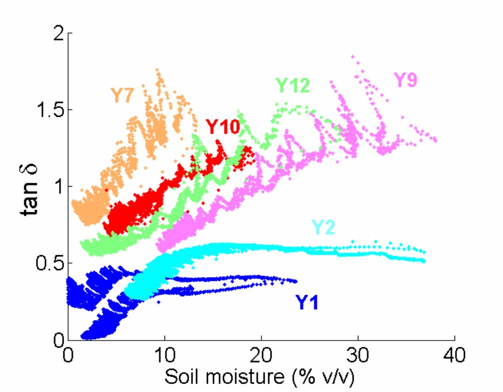

Figure 3. Loss tangent ($\tan\delta$) versus soil moisture at six stations of the Murrumbidgee network .

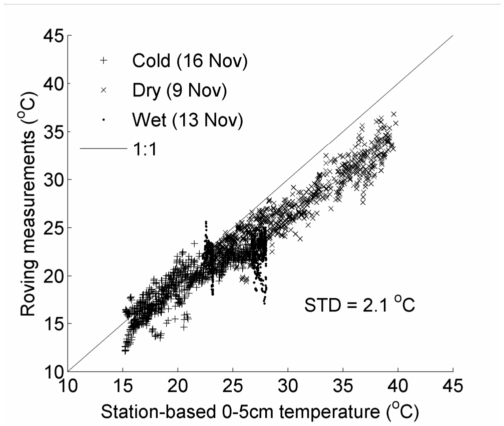

Figure 4. Roving versus station-based soil temperature measurements for three different days during NAFE'06: a typically cold (16 Nov), dry (9Nov) and wet (13 Nov) day.

This improvement confirms the existing relationship between the loss tangent and the change in measured real DC among soil types, including the assumption that the measured loss tangent is $\tan\delta_s$. The loss-correlated parameter A_{lc} is then fitted to the NAFE'06 data set. A linear regression between the measured A and $\tan\delta$ gives $A_{lc} = -4.3\tan\delta + 14.4$ (% v/v). With the new slope, the RMSE 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 $\theta = (-0.0078\theta_{silt}^3 + 0.183\theta_{silt}^2 + 69.9\theta_{silt} + 210)/100$ and results are plotted in Fig. 5c. The RMSE of the predicted soil moisture is 2.7% v/v, which represents the best fit among the four calibration equations proposed. However, when using the whole NAFE'06 data set to compare the polynomial and the loss-corrected equations (see Fig 5d), one observes that there is a loss of sensitivity of the soil moisture predicted by the polynomial regression at about 25% v/v. This finding is consistent with the results obtained in the laboratory (Fig. 2) showing the saturation of the factory-predicted soil moisture at gravimetric measurement over 25% v/v.. In fact, the apparently better results obtained with the polynomial equation is an artefact of the NAFE'06 soil and moisture conditions, with the soil in the study area being relatively homogeneous (mainly clay), and the range of soil moisture values measured 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 regard, 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 temperature correction 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 the loss tangent on calibrated data, the loss tangent is computed on the wettest day of the field campaign (13 November). Only the 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 maximum (2.2) loss tangent is about 8% and 10% v/v at 30% at 40% v/v soil moisture respectively.

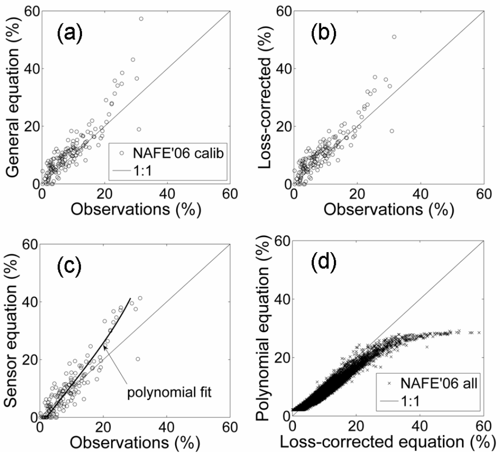

Figure 5. Different calibration equations: the general (a); the loss-corrected (b) and the polynomial fit (c) equation. The loss of sensitivity of the polynomial fit at soil moisture over 25% v/v is illustrated in d) with the whole NAFE'06 data set.

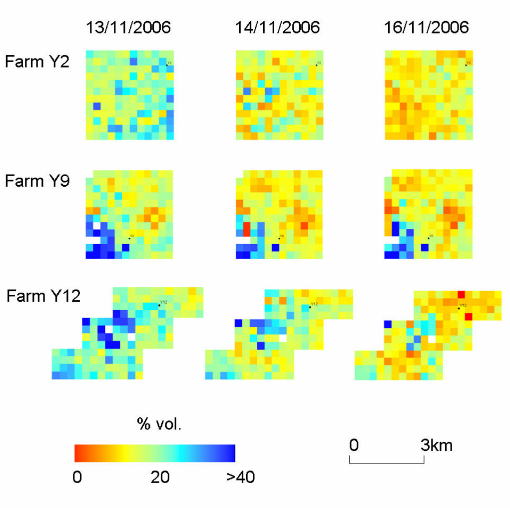

Figure 6. Examples of near-surface soil moisture maps using the calibration equations presented in this paper.

7. CONCLUSION

The objective of this 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.

The temperature effect on the soil water sensor response is evaluated with sand and clay over 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 5% v/v. With our data set the manufacturer's algorithm increases the temperature effect on real DC. A simple correction is derived based on the observed relationship between the relative effect on real DC and loss tangent.

The general and loss-corrected calibration equations of Seyfried *et al.* (2005) are applied to the temperature-corrected dielectric constant, and compared to observations. Results indicate 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 at soil moisture over 25% v/v.

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

8. ACKNOWLEDGEMENT

We wish to thank Daniele Biasioni and Hannah Meade for their laboratory work, and all the NAFE participants for field calibration and data collection. The National Airborne Field Experiments have been made possible through recent infrastructure (LE0453434 and LE0560930) and research (DP0557543) funding from the Australian Research Council, and the collaboration of a large number of scientists from throughout Australia, the United States and Europe. Initial setup and maintenance of the study catchments was funded by research grants (DP0209724, DP0343778 and DP0556941) from the Australian Research Council, the CRC for Catchment Hydrology, and NASA.

9. REFERENCES

Cosh, M.H., Jackson, T.J., Bindlish, R., Famiglietti, J.S., and Ryu, D., 2005. Calibration of an impedance probe for estimation of surface soil water content over large regions. *Journal of Hydrology*, **311**: 49-58.

Panciera, R., Merlin, O., Young, R., and Walker, J.P, 2006. The Hydraprobe Data Acquisition System (HDAS): User guide". *Report, University of Melbourne*.

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

Seyfried, M.S., and Murdock, M.D., 2002. Effects of soil type and temperature on soil water content measurements using a soil dielectric sensor. P1-13. In I.C. Paltineanu (ed.) First international symposium on soil water measurement using capacitance and impedance, Beltsville, MD. 6-8 Nov. 2002.

Seyfried, M.S., Grant, L.E., Du, E. and Kumes, K., 2005. Dielectric Loss and Calibration of the Hydra Probe Soil Water Sensor. *Vadose Zone J.*, **4**:1070-1079.

Vitel, Inc. 1994. Hydra soil moisture probe user's manual. Version1.2. Vitel Inc., Chantilly, VA.

Walker, J.P., Hacker, J.M., Kalma, J.D., Kim, E.J. and Panciera, R., 2005. National Airborne Field Experiments for Prediction in Ungauged Basins. In A. Zerger and R. M. Argent (Eds), *MODSIM 2005 International Congress on Modelling and Simulation*. Modelling and Simulation Society of Australia and New Zealand, December 2005, 2974-2980.

Walker, J.P., Merlin, O., Panciera, R. and Kalma, J.D., 2006. National Airborne Field Experiments for Soil Moisture Remote Sensing, *30th Hydrology and Water Resources Symposium [CD-ROM]*. The Institute of Engineers Australia, Launceston, Australia, 4-8 December, 2006.