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Calibration of an impedance probe for estimation of surface soil water content over large regions

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Abstract

Large region surface soil moisture estimates are important for both hydrologic modeling and remote sensing applications. For soil moisture monitoring, gravimetric soil moisture sampling is reliable; however, it requires a significant effort to gather and process samples. Portable impedance probes serve as a valuable alternative to destructive gravimetric sampling. These probes measure the dielectric properties of the soil–water–air mixture from which we can infer the volumetric soil moisture. As part of recent large-scale experiments in the summers of 2002 and 2003, three different methods for calibrating impedance probes were investigated with the support of coincident gravimetric samples. Field specific calibration improved the accuracy of the probe from greater than $\pm 5\%$ volumetric soil moisture (using the generalized calibration) to less than $\pm 4\%$. In addition, a significant amount of bias ($\sim 2\%$) was eliminated. It was also determined that field specific calibration removes a bias due to bulk density variations. Based upon these results it was concluded that the generalized calibration is adequate for estimation of diverse conditions. For studies with more stringent accuracy requirements, field specific calibration is necessary because of reduced bias and error.
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1. Introduction

The ground-based estimation of surface soil moisture over large areas is important for areas of hydrology, including climate and land surface modeling as well as satellite validation including the Advanced Microwave Scanning Radiometer (AMSR-E) (Njoku et al., 2003). The most accurate method of estimation is gravimetric sampling, but this is a time intensive procedure. Modern instrumentation has been developed to estimate soil moisture in a quick and easy manner by using the dielectric characteristics of soil and water. However, these instruments require a conversion between dielectric constant and volumetric soil moisture (Topp and Ferre, 2002). There are several factors including soil

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texture that can influence this conversion. Therefore, evaluating various calibration techniques is necessary to determine how to accurately compare field measurements to gravimetric samples in a non-laboratory setting.

One method of efficient soil moisture measurement is the impedance probe. Original investigations into the potential use of this particular technique include Gaskin and Miller (1996) and Miller et al. (1997). These laboratory studies established a benchmark calibration equation for the general category of mineral soils. The authors reported that the calibration yields a root mean square error of $\pm 0.05\ m^3/m^3$ for the probe when compared to gravimetric samples, while developing field specific calibration equations can reduce errors to $\pm 0.02\ m^3/m^3$. There is a need to assess the performance of these calibrations for field experimentation that includes a variety of factors not usually present in laboratory testing. Variations in bulk density, soil properties, and surface conditions all have some impact on calibration equations.

Other methods of soil moisture estimation have distinct advantages and disadvantages compared to the impedance probe method described above. Large-scale (i.e. large area) gravimetric collection is the most accurate method; however, variations in bulk density require additional characterization to compute volumetric soil moisture, which is the parameter being measured by most remote sensing technologies. In addition, there is a prohibitive cost to the collection of gravimetric samples when considering the necessary scale for such monitoring. Other studies have attempted to use soil moisture sensor networks to estimate the soil moisture field (Vachaud et al., 1985; Cosh et al., 2004). The disadvantage of this technique is cost of maintaining a sufficiently large network as well as issues of proper installation and verification that the network is representative. For short term experiments and validation campaigns, impedance probe measurements are a reasonable methodology for large-scale monitoring considering the alternatives.

An assessment of the accuracy of electronic soil moisture estimation needs to be conducted to determine how future sampling schemes can be designed for large-scale estimation (Robinson and Dean, 1993; Famiglietti et al., 1999; Long et al., 2002). One particularly challenging problem is providing field estimates of surface soil moisture over large spatial domains and satellite footprints to calibrate airborne passive radiometers for large-scale soil moisture estimation (Jackson et al., 1999). Other investigators are developing methods of monitoring soil moisture with the goal of implementing irrigation and water management practices to improve crop production (Bell et al., 1987; Starr and Paltineanu, 1998; Fares, 2000).

Data from two Soil Moisture Experiments (SMEX02 and SMEX03) were used in this study. SMEX02 was conducted in the summer of 2002 in Central Iowa, USA, 78 field sites were sampled extensively over a one month period using both gravimetric and impedance probe methods. These samples were taken in both corn and soybean fields, over a variety of soil moisture conditions. SMEX03 was conducted in the summer of 2003 in Oklahoma, USA and 103 field sites were sampled in a similar manner; however, the land cover was mostly bare soil or rangeland. Comparisons between three methods for impedance probe calibration (general calibration, soil classification specific calibration, and field specific calibration) were made and conclusions drawn about the accuracy of the probes and calibrations for large-scale experiments. It should be considered with regards to these experiments that SMEX02 experienced a variety of moisture conditions, but SMEX03 had a limited amount of precipitation, therefore a significantly smaller range of moisture conditions.

2. Study regions

The Soil Moisture Experiment 2002 (SMEX02) (http://hydrolab.arsusda.gov/smex02/) was conducted from June 25th, 2002 to July 12th, 2002 near Ames, Iowa as part of an aircraft and satellite calibration and validation program (Njoku et al., 2003) (http://www.nsidc.org/data/amsr_validation/). This area is predominantly soybean and corn cropland with low topographic relief. The experiment was separated into two study regions, one at the regional scale (IA—Iowa) (50×100 km) and another embedded within it at the watershed scale (WC—Walnut Creek) (10×30 km) (Fig. 1a). Each study region had a different set of sampling protocols, which were designed to

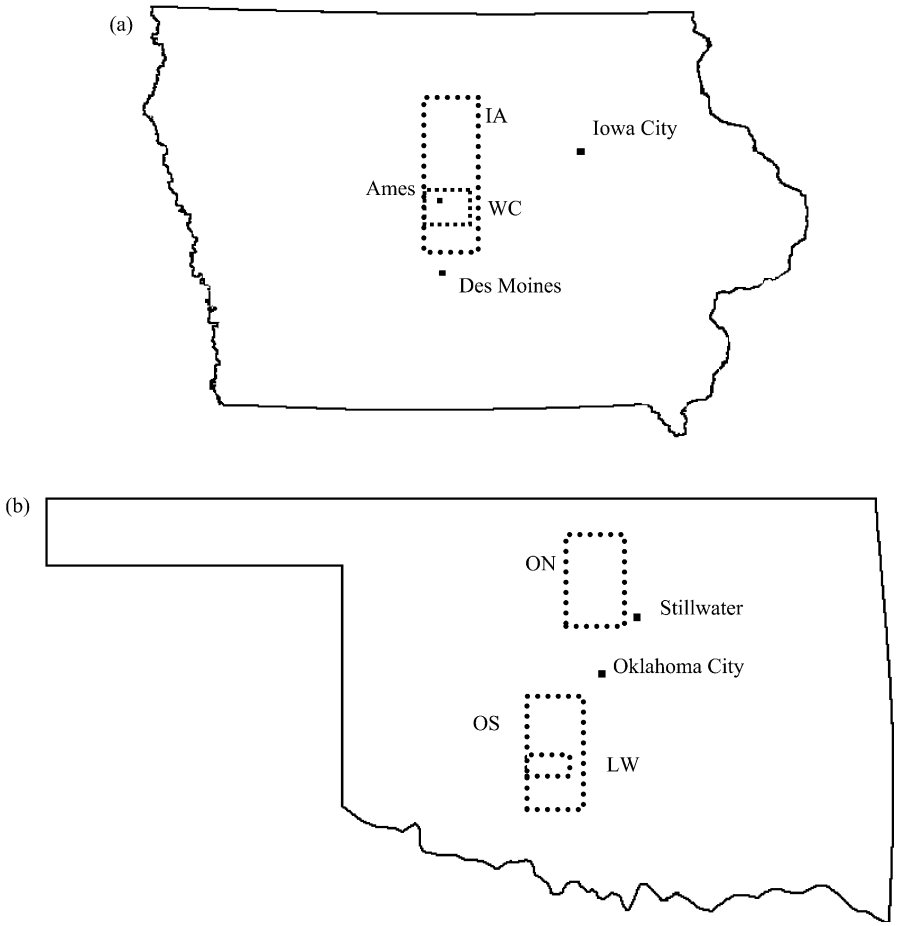

Fig. 1. (a) Map of Iowa with the IA and WC study regions outlined (b) map of Oklahoma with the ON, OS, and LW study regions outlined. Major cities are indicated.

evaluate techniques of estimating large-scale soil moisture averages.

The Soil Moisture Experiment 2003 (SMEX03) (http://hydrolab.arsusda.gov/smex03/) was conducted from July 2nd 2003 to July 17th, 2003. As part of this experiment, two study regions in Northern and Southern Oklahoma were sampled on the regional scale, and a smaller watershed scale study was located in the Little Washita River watershed near Chickasha, OK (Fig. 1b). The northern study site (ON) (50×75 km) was dominated by harvested winter wheat fields and the southern study site (OS) (50×100 km) was a mixture of harvested winter wheat and rangeland. The Little Washita site (LW) (10×30 km) was embedded in the OS study region and received more intensive field sampling. A summary of the land surface conditions is contained in Table 1 along with the number of study sites per land surface.

3. Instrumentation

Soil moisture impedance probes have been proven to be a valuable means of quickly and efficiently estimating volumetric soil moisture (Gaskin and Miller, 1996; Miller et al., 1997). They rely on the dielectric permittivity of the soil solution phase to infer soil moisture content (Topp et al., 1980; Roth et al., 1992; Whalley, 1993; Topp and Ferre, 2002). The dielectric constant of water is on the order of 80

Table 1
Land surface characteristics of the study sites

Parameter	Category	SMEX02		SMEX03		
		IA	WC	OS	ON	LW
Soil	Clay loam	8	0	0	2	0
	Silt loam/ loam	38	31	37	32	11
	Sandy loam/sand	1	0	14	2	4
Land cover	Soybeans	19	10	0	0	0
	Corn	28	21	0	1	1
	Pasture	0	0	31	6	6
	Winter wheat/ bare soil	0	0	12	29	7
	Grassland	0	0	8	0	1
No. of sites		47	31	51	36	15

Each column lists the number of field sampling sites per category.

and the dielectric constant of soil varies between two and seven. For air, the constant is close to one. In the soil solution phase, a simple mixing formula can be used to estimate the volumetric soil moisture. One commercially available product is the theta probe soil moisture sensor, type ML2 (www.delta-t.co.uk).[1] The probe consists of four metal tines extending 6 cm from a cylindrical instrument head and an effective diameter of ~4.0 cm, as shown in Fig. 2. This device measures a volume of soil 6 cm in depth, which corresponds to the depth of the gravimetric sampling. A data logger records the impedance and volumetric soil moisture can be calculated using a factory set generalized calibration equation for mineral soils. Once inserted into the ground, a simplified voltage standing wave method is used to estimate the relative impedance of the probe. Understanding the dielectric properties of soil and water allow the resulting impedance to be converted to a dielectric constant of the soil and therefore the volumetric soil moisture (Gaskin and Miller, 1996; Miller et al., 1997). The theta probe has been used in several recent remote sensing field experiments (Famiglietti et al., 1999) as a means of collecting regional scale soil moisture estimates quickly and efficiently.

[1] The mention of product names does not constitute an endorsement of this product.

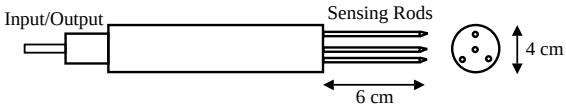

Fig. 2. Soil moisture impedance probe.

4. Methods of calibration

At the regional scale (IA, OS, and ON), three impedance probe samples were taken within each field site located on a grid at 8 km intervals (http://nsidc.org/data/amsr_validation/soil_moisture/). These three samples were taken across a crop row at 'in row', '1/4 row', and ' 1/2 row' locations or in the case of a non-row crop, along a 1 m distance. Immediately adjacent to the 1/4 row or second sample, a gravimetric sample was taken with a soil coring tool, which has a fixed volume of 137 cm^3 with a 6 cm depth. An oven-dry technique was used to determine the gravimetric soil moisture (Schmugge et al., 1980). The use of a coring tool with a fixed volume allowed the simple and accurate calculation of volumetric surface soil moisture at a particular location. It is this '1/4 row' impedance probe sample that is compared to the gravimetric sample for calibration. These samples are not coincident, but immediately adjacent because there was concern about biasing the bulk density calculations. This introduces some amount of error in the calibration, but it is random error as opposed to systematic error (bias).

Watershed sampling (WC and LW) attempted to characterize within field variability. For each field, 14 sets of three impedance probe samples were taken throughout an 800 by 800 m area at 100 m separation distances (http://nsidc.org/data/amsr_validation/soil_moisture/). Coincident with the 1/4 row sample at four of these locations in each field, a gravimetric soil sample was made with either a scoop tool or a coring tool, designed to obtain approximately 100 cm^3 of soil with a depth of 6 cm. For the scoop tool, used extensively in WC sampling, conversion to volumetric soil moisture was accomplished by using independent estimates of bulk density done explicitly for each field by means of a volume extraction technique (Grossman and Reinsch, 2002). Each field was approximately homogeneous with regard to soil

type and topography. Even minor heterogeneity introduces error into the calculation of volumetric soil moisture; however, there appeared to be no systematic bias in volumetric estimates in the WC data set, for which this was an isolated issue.

Impedance probes record a millivoltage (mV), which is converted to volumetric soil moisture (θ, m^3/m^3) by means of a calibration equation. This generalized equation is

$$\theta = \frac{[1.07 + 6.4V - 6.4V^2 + 4.7V^3] - a_0}{a_1} \quad (1)$$

where a_0 and a_1 are coefficients (Whalley, 1993). For mineral soils, a_0 and a_1 have been suggested to be 1.6 and 8.4, respectively, by the manufacturer, known as the generalized calibration. It is estimated that the error associated with generalized calibration is approximately ± 0.05 m^3/m^3.

Comparisons between the voltage readings of the impedance probes with the volumetric soil moisture readings for the collocated gravimetric sampling point enabled the assessment of two different calibration methods. One is called the soil specific calibration, which requires gravimetric samples to be taken coincident with the probe measurements for each soil type so that soil specific coefficients can be computed. The study sites were organized by soil type (ISPAID 6.0 http://icss.agron.iastate.edu/ for Iowa and STATSGO for Oklahoma) as classified by USDA soil texture protocols. The majority of soils were silt loam/loam, clay loam, and sandy loam/sand. For each of these three soil classes, regression equations were developed to estimate the calibration coefficients of Eq. (1).

The other method of calibration is the more intensive field specific calibration, which requires sampling for each study location, generating field specific coefficients for Eq. (1). This requires a great deal of sampling, which is usually prohibitive for time sensitive studies. The Newton's method for finding a minimum is used to minimize the total rmse by finding the appropriate a_0 and a_1 values for each field. This was done for each field in the IA, WC, OS, ON, and LW study regions, resulting in 180 independent calibration equations.

5. Results of calibration

The performance statistics for the three calibration techniques are contained in Table 2. The primary statistics used in this analysis are the root mean square error and bias. Root mean square error is defined as

$$\text{rmse} = \sqrt{\frac{1}{n}\sum_i (\theta_{\text{probe}} - \theta_{\text{gvsm}})^2} \quad (2)$$

where θ_{probe} is the soil moisture reading from the probe and θ_{gvsm} is the soil moisture measure from gravimetric sampling. This is summed for all paired samples, $i = 1$ to n. The bias is estimated by

$$\text{bias} = \frac{1}{n}\sum_i (\theta_{\text{probe}} - \theta_{\text{gvsm}}) \quad (3)$$

where the difference between the sensor and the gravimetric sample soil moisture is averaged for all sample pairs, $i = 1$–n. The root mean square errors

Table 2
Summary statistics for the SMEX02 impedance probe calibration methods

Data set	Generalized calibration	Soil specific calibration	Field specific calibration
WC region			
R^2	0.698	0.698	0.787
Bias (m^3/m^3)	0.022	0.001	0.000
rmse (m^3/m^3)	0.061	0.049	0.041
IA region			
R^2	0.744	0.742	0.803
Bias (m^3/m^3)	0.009	−0.014	0.000
rmse (m^3/m^3)	0.053	0.054	0.040
Little Washita (LW)			
R^2	0.367	0.370	0.612
Bias (m^3/m^3)	−0.010	−0.006	0.001
rmse (m^3/m^3)	0.057	0.051	0.039
OS region			
R^2	0.713	0.722	0.844
Bias (m^3/m^3)	0.013	0.014	0.000
rmse (m^3/m^3)	0.039	0.040	0.027
ON region			
R^2	0.571	0.571	0.760
Bias (m^3/m^3)	0.003	0.007	−0.001
rmse (m^3/m^3)	0.048	0.040	0.028
Total			
R^2	0.716	0.716	0.821
Bias (m^3/m^3)	0.001	−0.006	0.000
rmse (m^3/m^3)	0.053	0.050	0.037

Table 3
Coefficients for soil specific calibration equations and the associated statistics

Soil Type	Sand Range (%)	Clay Range (%)	No. of fields	a_0	a_1	R^2	Bias (m^3/m^3)	rmse (m^3/m^3)
Clay loam	20–45	30–40	10	0.802	12.625	0.671	<0.001	0.048
Silt loam/loam	0–30	0–50	149	1.291	11.377	0.717	<0.001	0.048
Sandy loam/sand	0–25	50–70	21	1.417	9.858	0.644	<0.001	0.043

(rmse) are slightly greater than 0.05 m^3/m^3 (0.053 m^3/m^3 for all the sites) for the generalized calibration, which is the estimated error according to Miller et al. (1997). The use of the generalized calibration can result in a considerable bias for a particular field. As the calibration is fine tuned to soil specific and then field specific conditions, the errors decrease to less than 0.04 m^3/m^3 for rmse and the bias is negligible. This establishes that some specific type of calibration is desirable for any type of field investigation where bias less than ± 0.02 m^3/m^3 is critical.

The soil specific calibration coefficients for each study area are shown in Table 3 along with the approximate soil definitions. There was a relatively small difference in rmse values for the three soil categories. There was a negligible difference in a_0 and a_1 values across soil types, when considering how the coefficients affect the final soil moisture. A similar analysis was conducted by land cover type and there was no improvement in the rmse. Fig. 3 is a plot of the calibration curves for each of these soil specific calibrations. Also plotted are the manufacturer's generalized and Topp and Reynolds (1998) relationships. The three soil curves all report lower soil moisture values for high dielectric constants. This may be a result the salinity of these soils. Another theory would be that the overestimation of the generalized calibration is a result of laboratory calibration versus field calibration involving soil with roots, stones, and small scale variations in density and composition. Fig. 4 contains plots of gravimetrically based soil moisture versus impedance probe based soil moisture for the generalized calibration equation and the field specific calibration equations. There is an apparent difference between the generalized calibration plot and the field specific plot. The number of outliers decreases, and the errors are reduced by using a field specific calibration. It appears generalized calibration results in a higher θ and bias (also evident in Fig. 3).

There appears to be only a minor improvement in performance (as measured by rmse) of the theta probe when a field specific calibration is used; however, other statistics are greatly improved as shown in Table 2. Fig. 5 shows the histograms of the biases for each of the study regions for the general calibration equation. There is a negligible amount of bias for a field specific calibration, but significant bias when using the general calibration. For studies that do not focus on large-scale estimates, there can be considerable bias for a single field.

Another test of the goodness of fit of the calibration equations was conducted on the residuals. Fig. 6 contains a plot of the bias versus the gravimetrically based volumetric soil moisture for each of the calibration techniques. The large majority of bias is focused around 0.0 m^3/m^3. It must be

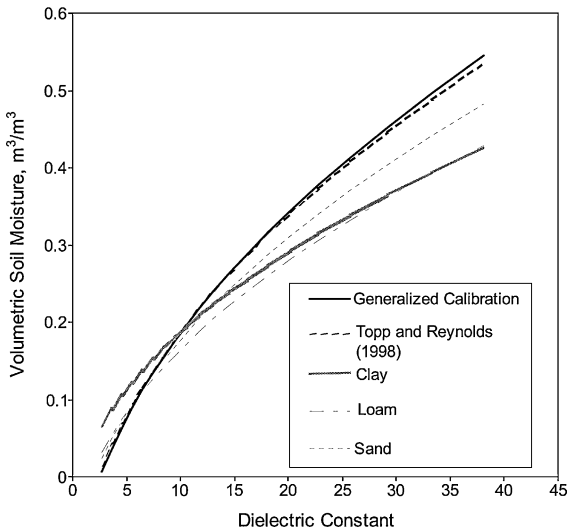

Fig. 3. Plot of volumetric soil moisture as a function of dielectric constant for various models and calibrations.

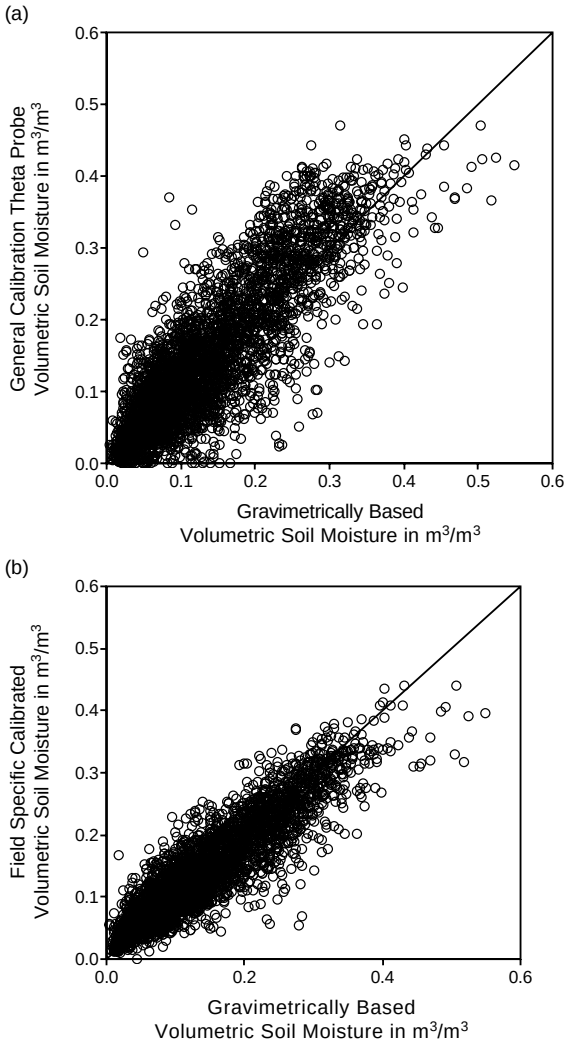

Fig. 4. (a) General calibration versus gravimetrically based volumetric soil moisture; (b) field specific calibration versus gravimetrically based volumetric soil moisture.

considered that there is a restriction at the lower soil moisture values because soil moisture is limited to non-negative values, therefore the bias has a limitation as indicated by the boundary lines in Fig. 6. Also, there is a subtle consistently negative bias at high moisture contents ($\theta > 0.4\ m^3/m^3$). For these values, the calibrated equation is unable to correct the bias, as described in the manual for the instrument.

Fig. 7 shows a plot of the general versus field specific calibration rmse values of each field for each

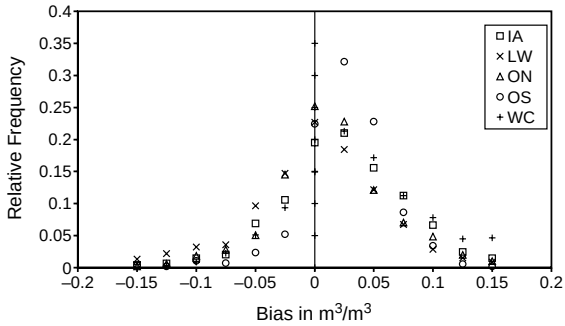

Fig. 5. Histograms of bias values for each study region for the general calibration equation volumetric soil moisture.

study. In all cases the rmse value decreases with the field specific calibration, as is expected. However, for individual fields, the improvement can be dramatic. For example, a field in IA (IA24) improved from an rmse of 0.071 to 0.025 m^3/m^3. This field was a typical corn field in the southern portion of this study region. It had low relief and silt loam soil, like the majority of the region.

It was speculated that there is a relationship between the impedance probe readings and some physical soil quantity, most likely bulk density. However, an investigation using the soil-specific calibration revealed no conclusive relationship between the bulk density of the soil being measured and the errors of prediction (Fig. 8).

6. Conclusions

Results presented here have shown that impedance probes require calibration in order to achieve small errors, but more importantly, this calibration removes significant bias as well. Comparing the general calibration (Miller et al., 1997) with soil specific and field specific calibrations revealed an improvement in both rmse and bias. For most soil moisture investigations, errors and variability are unavoidable, but bias can be alleviated. By investing in gravimetric sampling, the impedance probe estimates were validated to within $\pm 0.04\ m^3/m^3$ volumetric soil moisture with a bias less than $\pm 0.001\ m^3/m^3$, which is the error of the probe measurement.

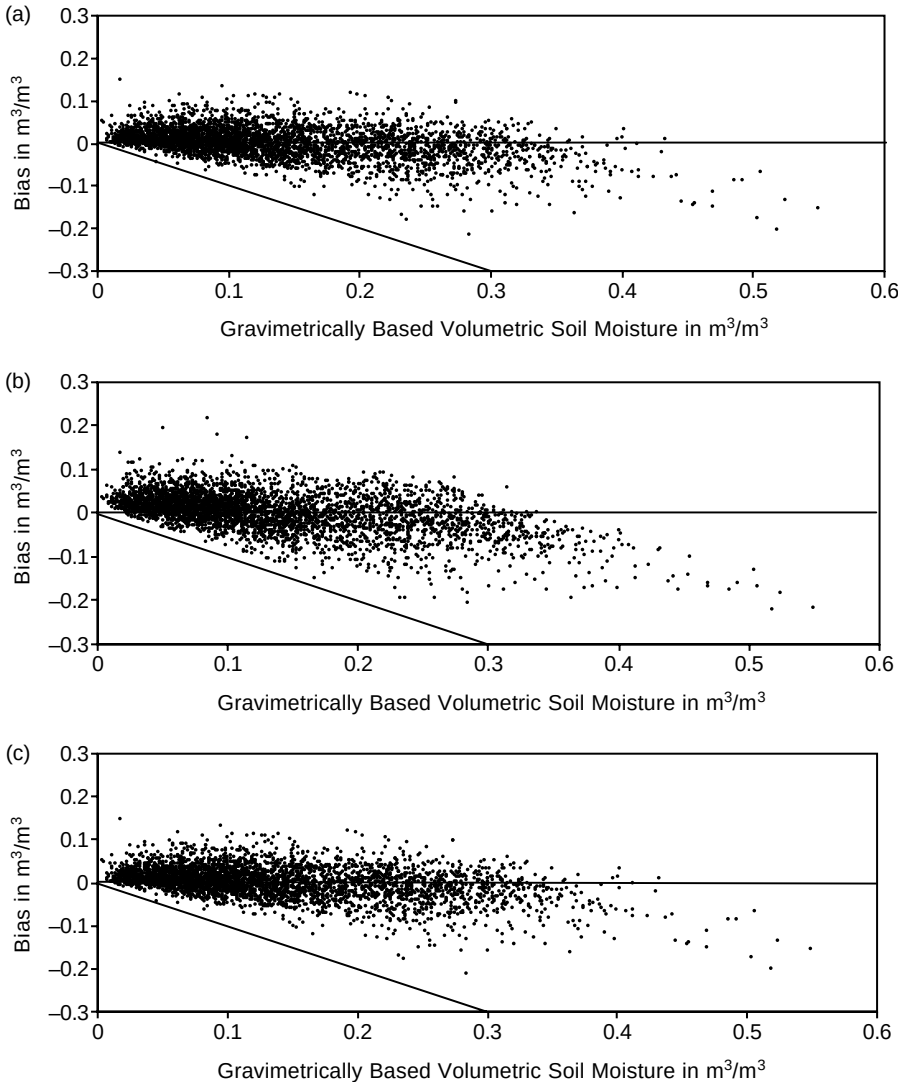

Fig. 6. Bias versus gravimetrically based volumetric soil moisture for each of the calibration techniques: (a) Generalized calibration, (b) soil specific calibration, and (c) field specific calibration. The diagonal line to the left indicates the boundary for possible values of bias considering that volumetric soil moisture is non-negative.

In future field campaigns, due to the time involved with gravimetric sampling, the emphasis will be placed on electronic methods of soil moisture estimation. However, this study demonstrates that considerable bias can be introduced without proper calibration. When implementing such schemes it is important to consider that each field and even within a single field, that the interaction between an impedance probe and the soil is complex. The use of the theta probe requires a good contact between the probe and the soil. The presence of soil pores, especially in porous soil and harvested fields may result in some errors in measurement. Variability in the comparison of gravimetric and impedance samples is unavoidable, but bias is removable by field (site) specific calibration equations for most soil moisture values.

The results of this study have an impact on the future of field and regional scale estimation of soil

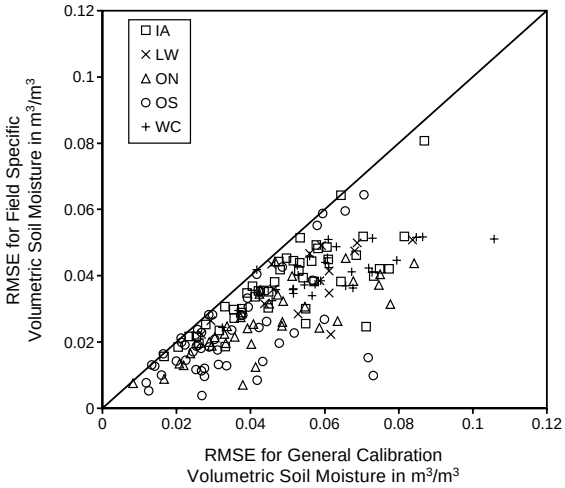

Fig. 7. RMSE values for each site in the study for the general calibration versus the field specific calibration. Different study areas are indicated by symbols.

moisture. For large-scale estimation, the impedance probe provides a reasonable estimate of soil moisture with a small error. However, this generalized calibration can result in a large bias at small scales. For purposes of specific soil moisture monitoring, it is important to recognize that a significant bias can be introduced as the soil deviates from the generalized calibration. With simple gravimetric calibration, this bias as well as error can be reduced, though for high soil moisture values there is still some bias.

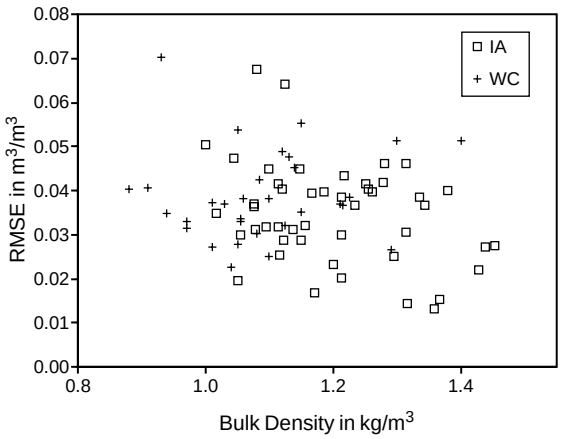

Fig. 8. Root mean square error in m^3/m^3 as a function of the average bulk density of each field in SMEX02.

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