Journal of Hydrology 498 (2013) 335–344

Contents lists available at SciVerse ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Evaluation of several calibration procedures for a portable soil moisture sensor

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ARTICLE INFO

Article history:
Received 12 March 2013
Received in revised form 7 May 2013
Accepted 9 May 2013
Available online 27 May 2013
This manuscript was handled by Corrado Corradini, Editor-in-Chief

Keywords:
Soil moisture
Calibration
Impedance probes

SUMMARY

The calibration and validation of remotely sensed soil moisture products relies upon an accurate source of ground truth data. The primary method of providing this ground truth is to conduct intensive field campaigns with manual surface soil moisture sampling measurements, which utilize gravimetric sampling, soil moisture probes, or both, to estimate the volumetric soil water content. Soil moisture probes eliminate the need for labor-intensive gravimetric sampling. To ensure the accuracy of these probes, several studies have determined these probes need various degrees of localized calibration. This study examines six possible calibration techniques using data collected during a field campaign conducted in 2012, with soil moisture samples being collected over 55 fields in southern Manitoba, as part of the Soil Moisture Active Passive Validation Experiment 2012 (SMAPVEX12). The use of a general equation, applied to all collected data, resulted in the largest error regardless of whether a linear or third order polynomial relationship was established for the calibration of the soil moisture probes. Calibration equations based on soil texture or vegetation land cover reduced the error; however, the individual calibration equations established for each field in the study had the lowest error of all the calibration techniques. Although average bias was low for all of the calibration techniques, the use of the general equation to calibrate individual fields resulted in high biases for some fields.

1. Introduction

The Soil Moisture Active Passive (SMAP) mission was developed by the National Aeronautics and Space Administration (NASA) in response to the report, *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond*, produced by the National Research Council (National Academies Press, 2007). This report highlighted the need for large scale environmental observations, including soil moisture (Entekhabi et al., 2010). One of the SMAP mission prerogatives is to estimate land surface fluxes of water and energy (Entekhabi et al., 2010). Soil moisture is a large reservoir for the storage of water and has high evaporative potential. Understanding of these processes at large scales will enable better weather and hydrological forecasting (Koster et al., 2011; Drewitt et al., 2012).

The SMAP mission has a requirement to be within ±0.04 $m^3\ m^{-3}$ accuracy of the volumetric soil moisture within the first five centimeters of the soil when the vegetation water content is $\leqslant$5 kg m^{-2} (Entekhabi et al., 2010). The SMAP satellite has an anticipated launch date of October, 2014, but prior to the launch, several field calibration and validation campaigns were conducted to ensure that this accuracy is possible. These campaigns, using similar instrumentation aboard aircraft, aim to develop and improve the soil moisture retrieval algorithms. One of the primary validation campaigns for SMAP was the SMAP Validation Experiment 2012 (SMAPVEX12), held in Winnipeg, Manitoba, Canada during June and July, 2012. Prior to SMAPVEX12, several field campaigns were conducted for the calibration and validation of other remote sensing instrumentation and missions, such as the AMSR-E instrument aboard the Aqua satellite and the Soil Moisture and Ocean Salinity (SMOS) mission, developed by the European Space Agency. SMOS, launched in 2009, also has a mission objective of ±0.04 $m^3\ m^{-3}$ accuracy of the volumetric soil moisture within the first five centimeters of the soil (Kerr et al., 2010). Other field campaigns include, but are not limited to: (Soil Moisture Experiment in 2002) SMEX02, SMEX03, SMEX04, SMEX05, National Airborne Field Experiment of

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http://dx.doi.org/10.1016/j.jhydrol.2013.05.021

2006 (NAFE'06) and (the Canadian Experiment for Soil Moisture in 2010) CanEX-SM10. Like SMAPVEX12, these campaigns consisted of intensive soil moisture sampling regimes, where surface soil moisture (0–6 cm) measurements were made manually, typically along established transects within multiple agricultural fields across the study regions. Although the most accurate soil moisture estimates would result from gravimetric sampling (Gardner, 1986), this is extremely labor intensive and impractical, as well as introduces its own variability because of the skill needed to sample volumetric soil moisture. Therefore, in each of the calibration and validation field campaigns listed above, surface soil moisture is measured using electronic-based soil moisture measurement methods.

Impedance type soil moisture probes have distinct advantages over gravimetric sampling in field-based soil measurement campaigns, particularly when a large number of observations are necessary. Studies suggest that impedance probes are precise with little inter-sensor variability (Seyfried and Murdock, 2004); however, several authors suggest that individual soil type calibrations be used for greater accuracies than those calibration equations provided by the manufacturer (e.g. Huang et al., 2004; Seyfried and Murdock, 2004).

A study by Cosh et al. (2005) examined the calibration of the soil moisture probes used in the SMEX02 (conducted in Iowa) and SMEX03 (using data from the Oklahoma sites) field campaigns. In this study, four different calibration techniques were compared to gravimetrically based volumetric water content samples, collected with co-located soil moisture probe measurements, specifically the Theta probe (Delta-T, Cambridge, UK). The calibration approaches included: a general calibration equation established for each region in the campaign and then applied to all fields individually within that region; a calibration equation based on three soil textural classes, clay loam, silt loam/loam, and sandy-loam/sand; a calibration equation based on land-cover type; and finally, calibration equations were established for individual fields. In this study, the root mean square error (RMSE) values for the application of a general equation to all fields were the highest, and the bias over some fields was also high. There was some improvement (reduction) in RMSE when using soil texture based calibration equations; however, values were still >0.04 $m^3 m^{-3}$. The calibration based on land-cover yielded similar results. Calibration of the soil moisture probes using field-specific equations resulted in RMSE $\leqslant$ 0.04 $m^3 m^{-3}$ for four of the five regions. The use of individual field calibration equations also resulted in little to no bias.

Over the aforementioned field campaigns there is significant variation in the calibration efforts of the impedance-based soil moisture measurement probes. For the NAFE'06 (Merlin et al., 2008), SMEX02 (Bindlish et al., 2006) and SMEX03 field campaigns, all soil moisture measurements for the Georgia (Bosch et al., 2006) and Oklahoma (Cosh et al., 2005) regions were calibrated using field-specific calibration equations, whereas the fields measured in the Alabama region were calibrated using the general Theta probe calibration equation as provided by the manufacturer (Jackson et al., 2005). The SMEX04 data from the Arizona region was calibrated using a site-specific calibration (Bindlish et al., 2008), whereas the measurements in the Sonora region were calibrated using the manufacturer suggested calibration equation because of a lack of infrastructure to process soil samples. Finally, the soil moisture data collected during SMEX05, conducted in Iowa, was calibrated using a site-specific calibration, using the same methodology as Cosh et al., 2005. During the CanEX-SM10 field campaign a general calibration equation was established from co-located gravimetric soil moisture samples and probe readings, and applied that equation to all manual soil moisture measurements taken over 60 fields during the experiment (Magagi et al., 2013).

The SMAPVEX12 field campaign was one of the longest satellite calibration campaigns conducted, with soil moisture measurements occurring over a 6-week period. Measurements were taken over a large range of soil textures, vegetation growth stages and soil moisture conditions. This study examines calibration techniques used in previous campaigns (Cosh et al., 2005; Famiglietti et al., 2008; Magagi et al., 2013), in addition to alternatives, in an attempt to obtain RMSE values that reflect of the accuracy goals of the SMOS and SMAP missions.

In this study, we investigate six different impedance probe calibration approaches using data from the SMAPVEX12 field campaign. The calibration approaches are divided into four categories, one technique which investigates the development of a general equation, two techniques which take into account soil texture, one which considers the vegetation land cover, and finally, the development of unique calibration equations for individual fields. The calibration techniques are described in detail in Section 3.2. During this campaign, over 700 core samples were taken from 55 fields, upon which calibration of the field data was based. These samples had a range of soil textures, from high sand content to clay, including some samples from fields with high organic matter content.

2. SMAPVEX12 field campaign

The SMAPVEX12 campaign was conducted approximately 70 km southwest of Winnipeg, Manitoba, in the Red River watershed as part of a pre-launch validation campaign for the NASA SMAP mission (Fig. 1). The experimental region was approximately 15 × 70 km in size and had minimal changes in topography. Intensive soil moisture measurements were taken on 55 fields within the experimental region, where field size ranged from approximately 20–60 ha. The land-use in this region is dominated by annual crops with some grassland and pasture. Of the fields used in the campaign, 16 fields were cereals (wheat, winter wheat, oats),

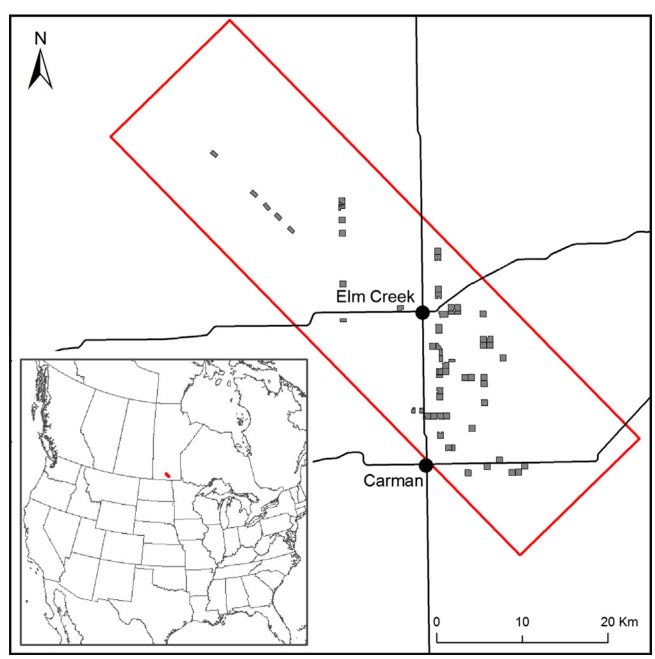

Fig. 1. Map of the SMAPVEX12 field campaign. The red box defines the campaign limits, with the study fields indicated by the gray boxes. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)