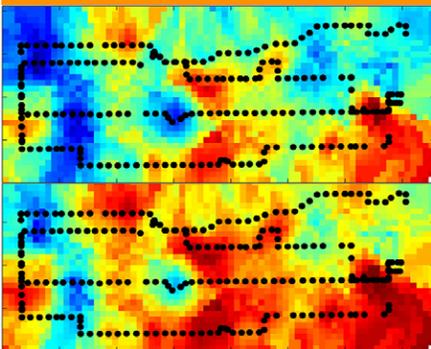


Original Research



The COsmic-ray Soil Moisture Observing System (COSMOS) rover was used to map soil moisture for two regions in Oklahoma: a 16- by 10-km and a 34- by 14-km region. The 0- to 5-cm soil moisture determined by the rover was within $\pm 0.03 \text{ cm}^3 \text{ cm}^{-3}$ of the best available independent estimates for each region. This study demonstrates the excellent potential of the COSMOS rover for calibration and validation of soil moisture satellites.

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Calibration and Validation of the COSMOS Rover for Surface Soil Moisture Measurement

Jingnuo Dong, Tyson E. Ochsner,* Marek Zreda, Michael H. Cosh, and Chris B. Zou

The COsmic-ray Soil Moisture Observing System (COSMOS) rover may be useful for validating satellite-based estimates of near-surface soil moisture, but the accuracy with which the rover can measure 0- to 5-cm soil moisture has not been previously determined. Our objectives were to calibrate and validate a COSMOS rover for mapping 0- to 5-cm soil moisture at spatial scales suitable for evaluating satellite-based soil moisture estimates. Region-specific calibrations for the COSMOS rover were developed using field-average soil moisture measured using impedance probes and the oven-drying method on volumetric samples. The resulting calibrations were applied to map soil moisture on two dates in a 16- by 10-km region around the Marena, Oklahoma, In Situ Sensor Testbed (MOISST) in north central Oklahoma and one date in a 34- by 14-km region in the Little Washita River watershed in southwestern Oklahoma. The mapped soil moisture patterns were consistent with the regional spatial variability in surface soil texture and with soil wetting by an intervening rainfall. The rover measured field-average soil moisture with a root mean squared difference (RMSD) of $0.03 \text{ cm}^3 \text{ cm}^{-3}$ relative to impedance probes. Likewise, the regional-average 0- to 5-cm soil moisture determined by the rover was within $\pm 0.03 \text{ cm}^3 \text{ cm}^{-3}$ of the best available independent estimates for each region. These results demonstrate that a COSMOS rover can be used effectively for 0- to 5-cm soil moisture mapping and for determining the average soil moisture at spatial scales suitable for satellite calibration and validation.

Soil moisture is a key variable influencing a wide range of agricultural, ecological, hydrological, and meteorological processes. Understanding and predicting soil moisture patterns at a range of spatial scales is important but challenging (Western and Bloschl, 1999). In particular, there is a gap in understanding soil moisture spatial variability at intermediate scales (one to hundreds of kilometers) due to a scarcity of data (Western et al., 2002). To bridge this gap, the development of new techniques for soil moisture measurement at intermediate scales is needed (Robinson et al., 2008). The cosmic-ray neutron method is a relatively new soil moisture measurement technique that has shown promise for measuring area-average soil moisture at an intermediate scale (Zreda et al., 2008).

Cosmic rays are high-energy subatomic particles that originate in outer space (Hess et al., 1959). When the cosmic rays penetrate the atmosphere, fast neutrons are generated by the interactions of the cosmic rays with the atmospheric nuclei. Additional fast neutrons are generated as the cosmic rays interact with the land surface. As the fast neutrons travel through the air and the soil, they are moderated greatly by H. Since a neutron and a H atom have similar mass, the kinetic energy loss of a fast neutron in a collision with a H atom is much greater than in collisions with other atoms. Because H at the land surface is mostly in the form of soil water, the fast neutron intensity above the land surface is inversely correlated with soil moisture (Zreda et al., 2008). This provides the theoretical basis for measuring soil moisture by fast neutron detection. The method has been implemented in the COsmic-ray Soil Moisture Observing System (COSMOS), a U.S. network of stationary neutron probes designed for long-term soil moisture monitoring (Zreda et al., 2012).

A typical stationary COSMOS probe consists of two neutron detectors having different energy sensitivities (Desilets et al., 2010; Zreda et al., 2012). The detectors are gas filled (^3He or BF_3). One is shielded by low-density polyethylene, which makes the detector sensitive to fast neutrons; the other is unshielded and is sensitive mainly to thermal neutrons. The neutron detectors and the associated electronics are mounted on a pole approximately 1 m above the soil surface. The horizontal footprint of a COSMOS probe is a circle with a diameter of ~ 600 m at sea level (Desilets and Zreda, 2013). The footprint diameter decreases with increasing atmospheric pressure and with increasing atmospheric water vapor (Zreda et al., 2012; Desilets and Zreda, 2013; Rosolem et al., 2013). The effective measurement depth of COSMOS probes has a strong dependence on the soil moisture and theoretically ranges from ~ 76 cm (completely dry soil and no other H present) to ~ 12 cm (saturated soil) (Zreda et al., 2008). In practice, the maximum effective measurement depth is shallower than 76 cm because all soils contain some H in the mineral lattice and soil organic matter (Zreda et al., 2012). The COSMOS measurement precision depends on the measured neutron count, which is a proxy for the neutron intensity. The uncertainty of the neutron count, as indicated by the coefficient of variation, is inversely proportional to the square root of the neutron counts (Knoll, 2000). Thus, the measurement precision increases as the neutron count rate increases but decreases as the soil water content increases.

Recently a COSMOS rover was developed to conduct large-area soil moisture field campaigns. While individual stationary COSMOS probes enable the temporal variability of soil moisture in the 600-m-diameter footprint to be measured and studied, the COSMOS rover enables the spatial variability of soil moisture across larger areas to be measured and studied. The COSMOS rover consists of an array of fast neutron detectors that are mounted in a vehicle (Desilets et al., 2010). In previous studies using the COSMOS rover, soil moisture was measured along a 35-km west–east transect in Hawaii (Desilets et al., 2010), mapped in a 37- by 42-km region around the MOISST site in Oklahoma (Zreda et al., 2011), and mapped repeatedly during 1 yr in a 25- by 40-km area in Arizona (Chrisman and Zreda, 2013). However, field measurements for the validation of soil moisture estimates from the rover were limited in these prior studies.

The COSMOS rover may be useful for the calibration and validation of satellite microwave remote sensing approaches for measuring soil moisture, such as the ongoing Soil Moisture Ocean Salinity (SMOS; Kerr et al., 2010) mission or the upcoming Soil Moisture Active Passive (SMAP; Entekhabi et al., 2010) mission. However, no studies have determined the accuracy with which the rover can measure the 0- to 5-cm soil moisture, which is the target variable for these microwave remote sensing approaches. This is shallower than the theoretically predicted effective measurement depth range for the cosmic-ray neutron method. Therefore, the objectives of this study were to calibrate and validate a COSMOS

rover for mapping the 0- to 5-cm soil moisture at spatial scales suitable for evaluating satellite-based soil moisture estimates.

To calibrate in this context means to establish a relationship, for the conditions of this study, between neutron intensity indicated by the COSMOS rover and the average 0- to 5-cm soil moisture in the rover's footprint as determined using impedance probes (i.e., intermediate standard), which were themselves calibrated to volumetric soil samples (i.e., ultimate standard). *To validate* in this context means to use additional independent soil moisture data (i.e., not including the calibration data) to evaluate the accuracy of the 0- to 5-cm soil moisture estimates derived from the calibrated COSMOS rover. The scope of this study and the data used were limited. The intent was to demonstrate the process of calibrating and validating a particular rover in two specific regions, not to produce a universal rover calibration.

Materials and Methods

Field Surveys

Field campaigns were conducted around the Marena, Oklahoma, In Situ Sensor Testbed (MOISST) site on 3, 6, and 13 June 2011. The MOISST site is located ~ 13 km southwest of Stillwater, OK, at 36.06°N , 97.22°W . The field containing the MOISST site and four other nearby target fields distributed across ~ 6 km in the east–west direction were selected for rover calibration and validation. The locations of the five target fields are shown in Fig. 1. The easternmost target field was predominantly covered by eastern red-cedar (*Juniperus virginiana* L.), while the other four fields were primarily grassland.

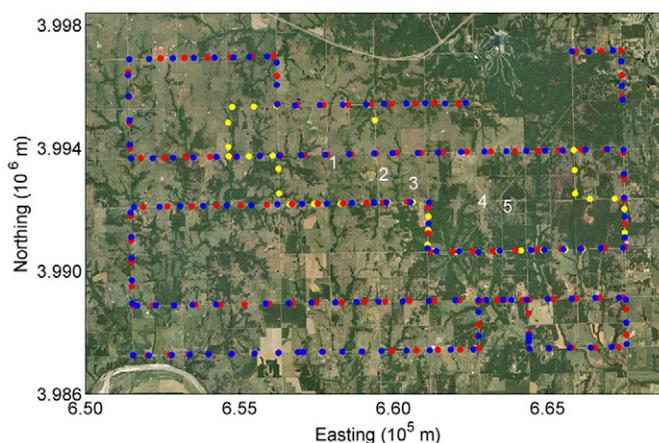


Fig. 1. Aerial photo of the Marena, Oklahoma, In Situ Sensor Testbed (MOISST) study region near Stillwater, OK. The yellow dots show the small survey on 3 June 2011, and the red and blue dots show the large surveys on 6 and 13 June, respectively. The white numerals indicate the locations of the five target fields. Field 3 is the MOISST site. The projection is UTM Zone 14N. (Photo by the National Agriculture Imagery Program, USDA Farm Service Administration.)

To determine the field-average soil moisture, 14 measurements (Bindlish et al., 2009) were made of the 0- to 6-cm soil layer using impedance probes (ML2x, Theta Probe, Delta-T Devices) along two transects in each field on each of the three survey days (i.e., 210 total Theta Probe soil moisture measurements in the five MOISST region target fields). The neutron flux at the center of a ring source decreases exponentially with the radius of the ring (Desilets and Zreda, 2013); therefore, it may be inferred that the spatial weighting function for the rover will decrease exponentially with distance from the rover. For this reason, a radial sampling scheme has been used for stationary COSMOS probe calibration (Zreda et al., 2012). However, our objective was to calibrate the COSMOS rover to the field-average 0- to 5-cm soil moisture, so we designed our sampling strategy to efficiently determine that field-average value. To calibrate the Theta Probes, three volumetric soil samples (5-cm diameter, 0–5-cm depth) were taken per field per day, collocated with three of the Theta Probe measurements, to determine soil moisture by the thermo-gravimetric method (i.e., 45 total volumetric samples). Volumetric sampling points were unique each day so that volumetric samples were obtained for nine out of the 14 transect locations in each field during the course of the study.

The COSMOS rover consisted of four ^3He -filled proportional counters, two from LND, Inc. and the other two from General Electric. All counters were shielded by 2.5-cm-thick polyethylene. Neutron pulse modules (Q-NPM-1000, Questa Instruments) connected to the counters monitored the neutron counts and sent the number of counts to a datalogger (Q-DL-2100, Questa Instruments). A barometric pressure sensor and a GPS receiver were integrated with the rover. Data were stored in the datalogger on a removable SD card. The COSMOS rover measurements were collected at each target field, with the rover sitting stationary in the field while the soil moisture samples were being taken. This resulted in an average stationary measurement time of 36 min in each field. After the target field measurements on each survey day, a roving survey was completed for the surrounding region. The roving paths are shown in Fig. 1. The yellow dots showed the path of the small survey (13 by 5 km) conducted on 3 June and the red and blue dots show the paths of the larger surveys (10 by 16 km) on 6 and June, respectively.

Another field campaign was conducted on 7 June 2011 in the Little Washita River watershed located in southwestern Oklahoma. This watershed was chosen due to the presence of a distributed network of soil moisture sensors (USDA–ARS Micronet; Cosh et al., 2006) that allowed direct comparison between soil moisture measured by sensors (Hydra Probe II) and the COSMOS rover data. The study area and the path for the roving survey, along with the locations of the Micronet stations, are shown in Fig. 2. The land use of the study area is mainly rangeland and winter wheat (*Triticum aestivum* L.) cropland. The study area (34 by 14 km, $\sim 455 \text{ km}^2$) covers more than 70% of the Little Washita River watershed (610 km^2) (Cosh et al., 2006).

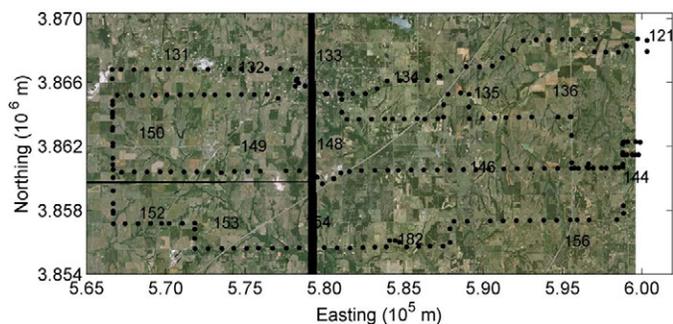


Fig. 2. Aerial photo of the study region in the Little Washita River watershed. The black dots show roving paths; the black numerals show USDA–ARS Micronet station locations. The thick vertical black line is a region where the aerial images are lacking. (Photo by the National Agriculture Imagery Program, USDA Farm Service Administration.)

For all rover measurements, the fast neutron counts were totaled every minute, and the GPS coordinates and barometric pressure were recorded at the end of each 1-min interval. The average driving speed was 48 km h^{-1} . In our roving measurements, two of the four detectors malfunctioned, and the neutron counts collected from those two detectors were not taken into consideration. The rover surveys reported here required from 1 to 5 h to complete.

COSMOS Rover Calibration, Validation, and Spatial Estimation

For the MOISST region, the rover was calibrated to the 0- to 5-cm soil moisture using data from the five target fields. The Theta Probe soil moisture measurements were first calibrated using the volumetric soil samples. A linear regression model was established with 45 collocated volumetric soil samples and Theta Probe measurements from all five fields across the three survey days. The data from the first survey day in the MOISST region were used to calibrate neutron count rates recorded with the rover stationary inside each target field to the average calibrated Theta Probe soil moisture for each field. This calibration used the shape-defining function, which characterizes the relationship between neutron intensity and soil water content:

$$\theta = \left(\frac{a_0}{\phi/\phi_0 - a_1} - a_2 - w_{\text{lat}} \right) \rho_b \quad [1]$$

where θ is the soil volumetric water content, w_{lat} is the soil lattice water content (g g^{-1}), ϕ (counts per minute, cpm) is the observed fast neutron intensity normalized for variations in atmospheric pressure, ϕ_0 (cpm) is the neutron intensity over dry soil, ρ_b is the soil bulk density (g cm^{-3}), and a_0 , a_1 , and a_2 are fitting parameters (Desilets et al., 2010). Lattice water is here defined as the amount of water released when soil that has been dried at 105°C is heated to 1000°C (Franz et al., 2012b). In this research, the parameter values were $a_0 = 0.0808$, $a_1 = 0.372$, $a_2 = 0.115$ (Desilets et al., 2010), and $w_{\text{lat}} = 0.052 \text{ g g}^{-1}$, a value previously measured at the MOISST site (Zreda et al., 2012). The average bulk density for

the 0- to 5-cm layer in the MOISST region was 1.23 g cm^{-3} , as determined by the volumetric sampling. The ϕ_0 parameter was adjusted to produce the best fit between the field-average Theta Probe measurements and the soil moisture values predicted by Eq. [1] for the first MOISST survey day.

The measured neutron intensities were normalized to a reference pressure of 97.2 kPa, the average atmospheric pressure for the first MOISST survey day, using an exponential model (Desilets and Zreda, 2003) in which the atmospheric attenuation coefficient was set to 0.077 kPa^{-1} . Neutron intensities for the 6 and 13 June MOISST region surveys were also normalized, relative to the 3 June survey, for changes in incoming high-energy neutrons associated with variations in solar activity (Zreda et al., 2012) using the Newark neutron monitor data (pressure and efficiency corrected; available at www.nmdb.eu). Finally, the measured neutron intensities for the 6 and 13 June surveys were normalized, relative to the 3 June survey, for changes in atmospheric water vapor (Rosolem et al., 2013) using air temperature and relative humidity data from the Marena station of the Oklahoma Mesonet (McPherson et al., 2007).

The optimized ϕ_0 value and normalized neutron counts were then used in Eq. [1] to estimate the 0- to 5-cm soil moisture from the rover for the subsequent MOISST region surveys so that the calibration results could be validated. For the Little Washita River watershed, the rover was calibrated using soil moisture determined by oven drying volumetric soil samples collected in two fields, one on the west side of the region and one on the east side. The measured neutron intensities were again normalized to the measured atmospheric pressure at the start of the survey. Lattice water for the Little Washita River watershed was assumed to be the same as for the MOISST region. The average bulk density for the 0- to 5-cm layer in the Little Washita region was estimated to be 1.28 g cm^{-3} based on the volumetric samples.

The ordinary kriging method was used to map fast neutron intensity and soil moisture to allow visualization of the soil moisture spatial patterns (Bárdossy and Lehmann, 1998). Experimental variograms for fast neutron counts were first estimated then fitted with variogram models. The fitted variogram models were then used to create maps of fast neutron counts by ordinary kriging. The neutron count maps were converted to soil moisture maps using Eq. [1]. Given the minimum distance ($\sim 1600 \text{ m}$) between the rover paths and the effective diameter (600 m) of the rover footprint, the pixel size of the kriging output was set to 533 by 533 m.

Soil data were obtained from the Soil Survey Geographic (SSURGO) database and used to create soil surface horizon sand content maps (Soil Survey Staff, 2013). As shown below, patterns in soil surface horizon sand content were reflected in the soil moisture maps produced using the rover. Latitude and longitude coordinates were converted to the Universal Transverse Mercator (Zone 14) coordinate system for accurate horizontal distance

calculations and for mapping purposes. All the analyses in this study were conducted using Matlab R2012a with the Matlab Mapping Toolbox and the BMElib version 2.0b (Christakos et al., 2001).

Results and Discussion

Calibration and Validation

The Theta Probe measurements using the manufacturer's calibration in the MOISST region were linearly related to the volumetric water content determined by soil sampling with $r^2 = 0.88$ across the range from 0.062 to $0.38 \text{ cm}^3 \text{ cm}^{-3}$ (Fig. 3). After calibration, the RMSD between the Theta Probe soil moisture values and those from volumetric sampling was $0.031 \text{ cm}^3 \text{ cm}^{-3}$. The quality of this Theta Probe calibration is similar to that of prior field-specific calibrations ($r^2 = 0.76$, RMSD = 0.028) in this region (Cosh et al., 2005).

The calibration of the neutron intensity with the field-average Theta Probe soil water content for the five target fields on 3 June is shown in Fig. 4. Equation [1] with $\phi_0 = 176 \text{ cpm}$ ($\pm 1.5 \text{ cpm}$, 95% confidence interval) provided soil moisture estimates that closely matched the Theta Probe data with $r^2 = 0.966$ and RMSD = $0.0063 \text{ cm}^3 \text{ cm}^{-3}$. The data in Fig. 4 demonstrate that a cosmic-ray neutron probe, in general, and the COSMOS rover, in particular, can be effectively calibrated to the 0- to 5-cm soil moisture even though the typical calibration depth is 0 to 30 cm (Franz et al., 2012b). The quality of the calibration data in Fig. 4 is similar to that reported by Franz et al. (2012b) for a stationary cosmic-ray neutron probe in Arizona ($r^2 = 0.927$ and RMSE = $0.0095 \text{ cm}^3 \text{ cm}^{-3}$). For the Little Washita River watershed, the calibration process resulted in $\phi_0 = 184 \text{ cpm}$ ($\pm 92.6 \text{ cpm}$).

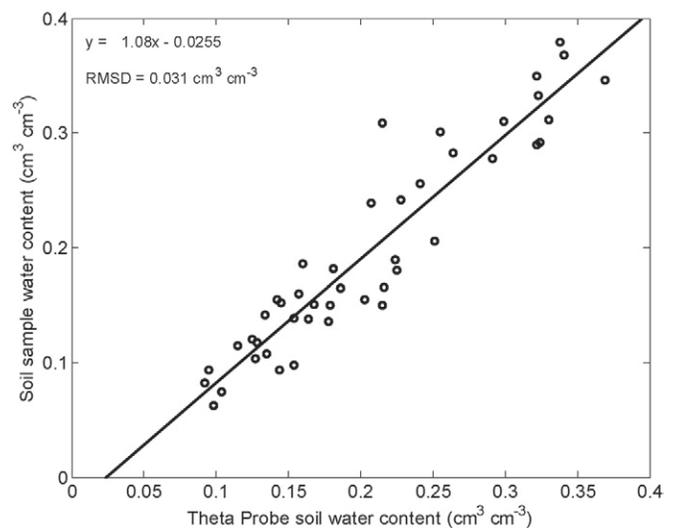


Fig. 3. Volumetric soil sample water content (0–5 cm) vs. Theta Probe soil water content using the manufacturer's calibration for five target fields in the MOISST region on 3, 6, and 13 June 2011.

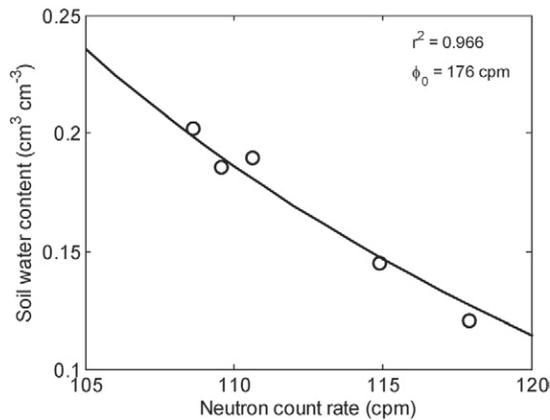


Fig. 4. Calibrated shape-defining function (Eq. [1]) for the first MOISST survey (3 June) data. Circles are the averages of 14 calibrated Theta Probe soil moisture measurements in each of the five target fields. The solid line is the calibrated shape-defining function; ϕ_0 is the neutron intensity over dry soil.

The calibrations developed here are specific to the particular COSMOS rover used and the particular regions studied. The calibration process would need to be repeated for studies in any other region or studies using any other rover. The a_0 , a_1 , and a_2 parameters in Eq. [1] may also be slightly affected by H pools other than soil moisture, a possibility that may warrant further investigation.

The shape-defining function with the calibrated ϕ_0 for the MOISST region was validated using field-average Theta Probe measurements from the second and third MOISST surveys, and the results are shown in Fig. 5. The calibrated soil moisture values from the first MOISST survey are also plotted in this figure. A 37-mm rainfall event occurred approximately 24 h before the third survey (13 June), providing a substantial increase in the

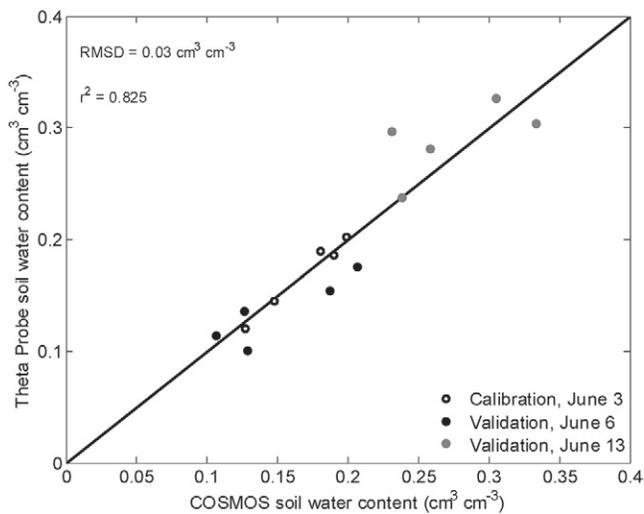


Fig. 5. Field-average calibrated Theta Probe soil water content vs. COSMOS rover field-average soil water content (stationary) for all three MOISST region surveys. The r^2 and root mean squared difference (RMSD) were computed using only the validation data (6 and 13 June).

0- to 5-cm soil moisture. The validation data indicate a linear 1:1 relationship between the field-average 0- to 5-cm soil moisture measured with the calibrated Theta Probes and that estimated with the rover across a water content range of approximately 0.10 to 0.35 $\text{cm}^3 \text{cm}^{-3}$. The $\text{RMSD} = 0.03 \text{ cm}^3 \text{cm}^{-3}$ is larger than that reported for validation of a stationary COSMOS probe, 0.0165 $\text{cm}^3 \text{cm}^{-3}$ (Franz et al., 2012b). Note that the uncertainty in the rover field averages ($\text{RMSD} = 0.03$) is comparable to the uncertainty in the Theta Probe measurements themselves ($\text{RMSE} = 0.031$, Fig. 3). The largest discrepancy was a 0.066 $\text{cm}^3 \text{cm}^{-3}$ underestimate of the 0- to 5-cm soil water content by the rover in Field 4 on 13 June. If a wetting front from the previous day's rainfall had penetrated only the top few centimeters of soil, the Theta Probes would have measured wetter conditions than the COSMOS rover, which would have also sensed the drier soil underneath. The time since the last rainfall, or the depth of the wetting front, may be important variables to consider in future evaluations of the error in using COSMOS rover data for estimating the 0- to 5-cm soil moisture (Franz et al., 2012a).

It is not possible, with the existing data, to directly validate the regional-average soil water content determined with the rover because the target fields constitute only a fraction of the region of interest. However, if the target fields are representative of the region of interest, then it is useful to compare the regional-average soil water content measured by the rover with that calculated from the target fields. We can strengthen the comparison by considering only the subset of rover data collected nearest to the target fields (within ~ 4 km). That subset is labeled as the small rover survey in Fig. 6, while the complete surveys are labeled as the large rover survey. The regional-average soil moisture from the roving surveys agreed well with the Theta Probe measurements. The differences between the average soil moisture for the small survey region measured using the rover and the average soil moisture for

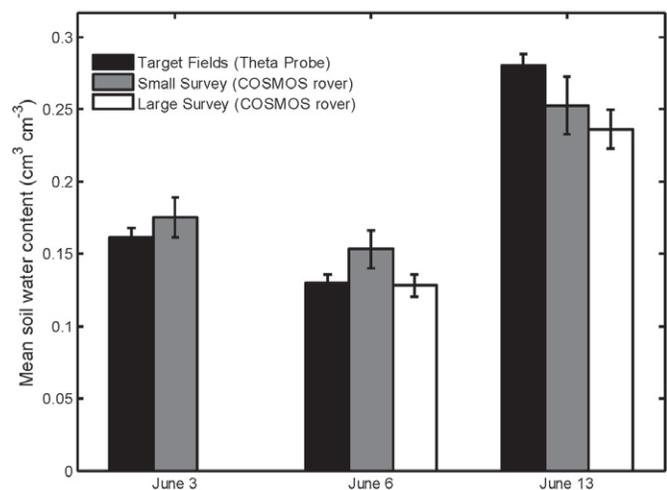


Fig. 6. Comparisons of mean soil water content and standard error of the mean between Theta Probe data from the target fields and calibrated COSMOS rover data from MOISST region surveys.

the target fields measured using the Theta Probes were 0.014, 0.023, and $-0.028 \text{ cm}^3 \text{ cm}^{-3}$ for the three MOISST survey dates. Similar to the field-average data, the largest discrepancy occurred for the third survey, which was conducted 1 d after a rainfall event. Soil moisture may still have been moving downward, and the water may have been more concentrated near the surface. During the surveys, Theta Probes were sensitive only to soil moisture from 0 to 6 cm, which was shallower than the effective depth of the COSMOS rover. The standard errors (Fig. 6) of the rover surveys for the wet condition (June 13) were larger than for the drier conditions (3 and 6 June). This was probably due to the fact that fewer fast neutrons were detected under wet conditions, which increases the uncertainties of the measurements.

The COSMOS rover survey in the Little Washita River watershed agreed well with the Micronet station data. Using Eq. [1] calibrated for the 0- to 5-cm depth, the COSMOS rover regional-average soil moisture was $0.062 \text{ cm}^3 \text{ cm}^{-3}$ with a standard error of $0.004 \text{ cm}^3 \text{ cm}^{-3}$, and the average soil water content at the 5-cm depth measured at the 20 Micronet stations in the Little Washita watershed was $0.080 \text{ cm}^3 \text{ cm}^{-3}$ with a standard error of $0.018 \text{ cm}^3 \text{ cm}^{-3}$. Drying conditions prevailed, and the average soil moisture for the 0- to 5-cm depth was probably lower than the soil moisture at 5 cm.

Spatial Estimation

The neutron intensity and 0- to 5-cm soil moisture maps were made for the 6 June (before rainfall, Fig. 7) and 13 June (after rainfall, Fig. 8) surveys in the MOISST region. Fast neutron counts were lower and the estimated soil moisture was higher following the rainfall event than before it, as expected. These maps clearly demonstrate that the rover responds to temporal changes in soil moisture. The surface horizon soil sand content map for the study area, created

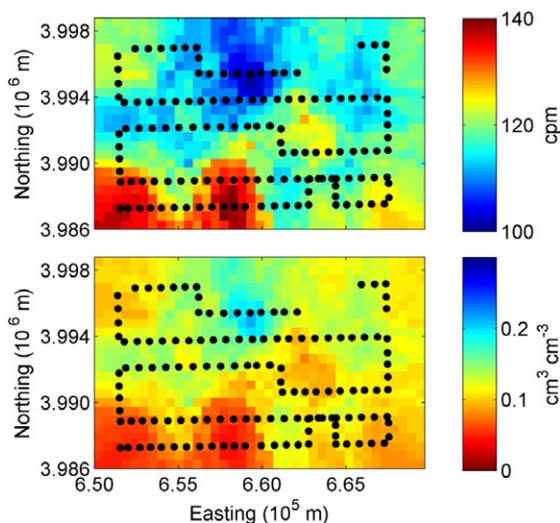


Fig. 7. The COSMOS rover neutron intensity (upper panel) and 0- to 5-cm soil water content (lower panel) for the 6 June 2011 survey of the MOISST region.

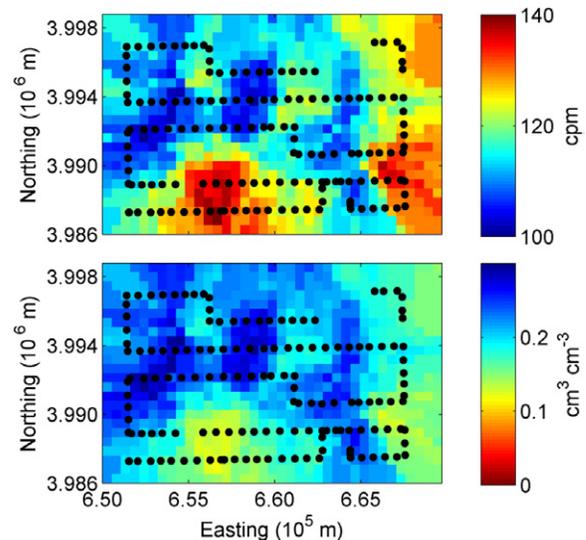


Fig. 8. The COSMOS rover neutron intensity (upper panel) and 0- to 5-cm soil water content (lower panel) for the 13 June 2011 survey of the MOISST region.

using SSURGO data, is shown in Fig. 9. A comparison with Fig. 7 and 8 shows that low soil moisture correlates with high sand content, for example in the vicinity of easting $\sim 6.58 \times 10^5 \text{ m}$. Sandy soil typically retains less water than finer textured soil, so this correspondence between soil moisture and soil texture patterns supports the validity of the soil moisture patterns recorded with the rover.

Figure 10 shows the variogram of neutron intensity for the roving survey in the Little Washita River watershed. The empirical variogram was well described by a spherical variogram model having a range of 2900 m, a sill of 225 cpm^2 , and a nugget of 160 cpm^2 . The range is an important parameter because it is related to the spatial scale of the variability in neutron intensity. The range represents the maximum separation distance across which individual values of the neutron intensity, and presumably soil moisture, were correlated in the Little Washita River watershed on the day of the

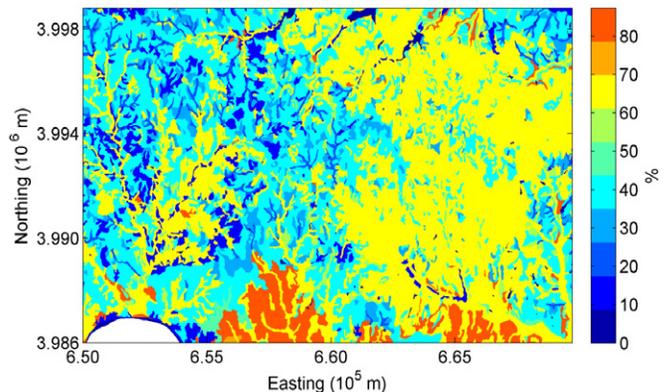


Fig. 9. The SSURGO estimated sand content for the surface horizon based on the predominant soil series in each mapping unit in the MOISST region.

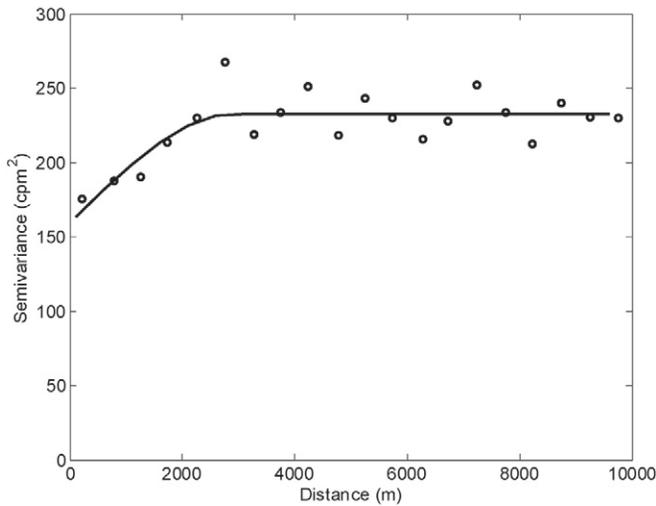


Fig. 10. Neutron intensity semivariogram for the rover survey in the Little Washita River watershed on 7 June 2011.

survey. Similarly, Joshi and Mohanty (2010) found variogram ranges between 2000 and 12,000 m for soil moisture estimates in the Walnut Creek watershed (Iowa) derived from an airborne polarimetric scanning radiometer with 800- by 800-m resolution. The plausible variogram structure observed in the present study is additional evidence for the utility of the COSMOS rover as a tool for understanding the spatial variability of soil moisture.

Figure 11 contains the neutron intensity map (top) and the soil moisture map (bottom) for the Little Washita survey, and Fig. 12 shows the surface horizon sand content map of the study area. As in the MOISST surveys, similarities exist between the soil moisture patterns and the soil texture patterns. The areas with highest surface sand contents, in the center of the domain and in the south-east quadrant, correspond to the areas with the lowest soil water

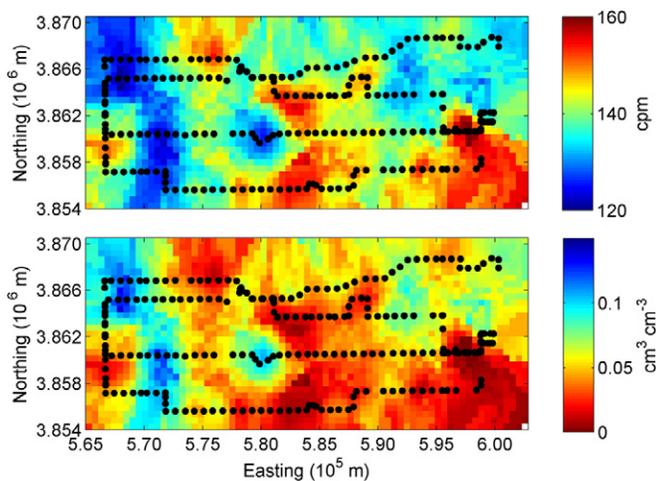


Fig. 11. The COSMOS rover neutron intensity (upper panel) and 0- to 5-cm soil water content (lower panel) for the rover survey in the Little Washita River watershed on 7 June 2011.

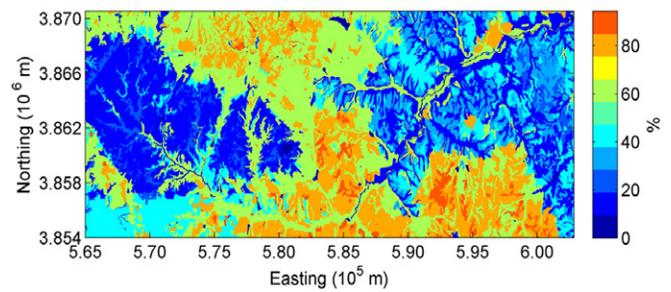


Fig. 12. The SSURGO estimated sand content for the surface horizon based on the predominant soil series in each mapping unit in the Little Washita River watershed.

contents. This result is consistent with the expectation that sandier soils dry faster and retain less water than finer textured soils.

Cosmic-ray neutrons are moderated not only by soil moisture but also by other pools of H such as lattice water and vegetation water content (Franz et al., 2013). Fast neutrons can also be moderated by the C and H present in soil organic matter. Thus, spatial patterns in neutron counts measured by the rover may be impacted by the spatial variability in these other pools of H and not simply by the spatial variability in soil moisture. The rover calibrations implicitly included the spatial variability of these other pools, so the regional average soil moisture estimates are probably unbiased. However, the soil moisture estimate for any specific pixel in the survey region may be biased due to local variations in H pools other than soil moisture.

Currently, only a first-order analysis of these uncertainties is possible. The standard deviation of the lattice water content measured at the MOISST site was 0.014 g g^{-1} . Two times this standard deviation multiplied by a bulk density of 1.23 g cm^{-3} results in an estimated uncertainty of $\pm 0.034 \text{ cm}^3 \text{ cm}^{-3}$ arising from the spatial variability in the lattice water content. Spatial patterns in lattice water content may be linked to patterns in clay content because previous research has shown a positive correlation between these variables (Greacen, 1981). The standard deviation of the organic C content of the surface layer of grassland soils in Oklahoma is 0.0077 g g^{-1} (Ochsner, unpublished data, 2013). Assuming that the water equivalent of soil organic matter is equal to the mass percent of organic carbon (Zreda et al., 2012), the uncertainty associated with spatial variability in soil organic matter would be $\pm 0.018 \text{ cm}^3 \text{ cm}^{-3}$. The spatial standard deviation of vegetation water content measured at the MOISST site averages 0.33 mm (Ochsner, unpublished data, 2013). Two times this standard deviation distributed throughout a soil layer 50 mm thick (i.e., 0–5 cm) results in an estimated uncertainty of $\pm 0.0066 \text{ cm}^3 \text{ cm}^{-3}$ arising from the spatial variability in vegetation water content. Thus, spatial variations in lattice water and soil organic matter probably contribute larger uncertainties than does the spatial variability in vegetation water content to the soil moisture maps generated with the rover in this study. Further efforts are needed to develop

accurate maps of lattice water and soil organic matter that would permit a spatially variable calibration function for the rover.

Conclusion

The COSMOS rover was calibrated to the 0- to 5-cm soil moisture using 1 d of in situ data and subsequently validated, demonstrating that the COSMOS rover can be used effectively for measuring surface soil moisture. Our intent was not to conduct comprehensive calibrations across the full range of possible soil types, vegetation covers, and climates but rather to demonstrate the feasibility of accurate field calibration and the efficacy of spatial mapping with the rover. Although the calibration and validation data were collected in a limited period of time, they covered a relatively large range of soil moisture values, from 0.08 to 0.32 cm³ cm⁻³. For the conditions of this study, the calibrated COSMOS rover determined the regional-average 0- to 5-cm soil moisture with an accuracy of approximately ±0.03 cm³ cm⁻³. The largest discrepancy occurred on the day following a sizable rainfall event when the rover underestimated the surface water content.

The results of this study provide evidence that the COSMOS rover will be a valuable tool for calibration and validation of satellite microwave remote sensing missions like SMOS and SMAP. Larger neutron detectors or slower driving speeds could be used to further increase the precision of the soil moisture estimates from the rover, although the accuracy may not be affected by these variables. The COSMOS rover is a unique tool for measuring soil moisture at intermediate scales (one to hundreds of kilometers), a scale at which data and effective measurement techniques are scarce. Thus, it creates intriguing new possibilities to advance scientific understanding of the spatial variability of soil moisture and its impacts on agricultural, ecological, hydrological, and meteorological processes.

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