Original Research

A field experiment was performed in a grassland near Millbrook, NY. Intensive measurements of L-band brightness temperatures, surface temperature, and soil moisture and temperature were collected during three different passes. The research investigates changes in the performance of microwave soil moisture retrieval with diurnal soil temperature variations.

M. Temimi, T. Lakhankar, N. Krakauer, R. Khanbilvardi, and L. Kumassi, NOAA-CREST, City Univ. of New York, New York, NY 10031; M. Temimi, Masdar Institute of Science and Technology, Abu Dhabi, United Arab Emirates; X. Zhan, NOAA-NESDIS Center for Satellite Applications and Research, College Park, MD 20740; M. Cosh, USDA-ARS Hydrology and Remote Sensing Lab., Beltsville, MD 20705; A. Fares, Cooperative Agricultural Research Center, Prairie View A&M Univ., Prairie View, TX 77446; V. Kelly, Cary Institute of Ecosystem Studies, Millbrook, NY 12545. *Corresponding author (mtemimi@ccny.cuny.edu).

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Soil Moisture Retrieval Using Ground-Based L-Band Passive Microwave Observations in Northeastern USA

Marouane Temimi,* Tarendra Lakhankar, Xiwu Zhan, Michael H. Cosh, Nir Krakauer, Ali Fares, Victoria Kelly, Reza Khanbilvardi, and Laetitia Kumassi

A field experiment was performed in a grassland at the NOAA-CREST–Soil Moisture Advanced Radiometric Testbed (CREST-SMART) facility, which includes a mobile L-band dual-polarized radiometer with an in situ soil temperature and soil moisture observation network, located near Millbrook, NY. During the day-long field campaign, intensive spatiotemporal measurements of L-band brightness temperatures, surface temperature, soil moisture, and soil temperature at 3-, 7-, and 12-cm depths were collected during three passes at 0830, 1130, and 1430 h. During the second and third passes, half of the field was irrigated. Soil roughness and water content of the short grass that remained after mowing the study area were measured. The Tau-Omega radiative transfer model was used to assess the performance of the soil moisture retrieval using measured soil temperatures at different depths. In addition, the collected microwave observations at the three different times of the day were used to assess the impact of the diurnal variation of soil temperature on the performance of soil moisture retrieval. Obtained results showed that the root mean square error (RMSE) decreased throughout the day to reach 0.03 m^3/m^3 for the afternoon pass when 12-cm soil temperature values were used in the radiative transfer model. In addition, during the three different passes, the lowest RMSE was consistently obtained when the 12-cm soil temperature was used, which suggests that, for this investigated site, soil temperature at the 12-cm depth can be a surrogate for soil effective temperature when L-band microwave temperatures are used. In ~~term~~ of diurnal variability, observations from the afternoon pass led to the highest agreement between observed and retrieved soil moisture values.

Abbreviations: SMAP, Soil Moisture Active Passive; TDR, time domain reflectometry.

In situ observations are very important to monitor the variability of soil moisture in space and time. They are also very useful to calibrate and validate retrieval algorithms. Several in situ soil moisture observation networks were established across the United States with varying density, extent, and type of sensors. In situ observations from most of the soil moisture networks in the United States and elsewhere in the world can be obtained from the International Soil Moisture Network database (http://ismn.geo.tuwien.ac.at/ismn/) (Dorigo et al., 2011). In the United States, there are mainly three categories of networks, namely, (i) local networks, which usually stretch across a few kilometers like the NOAA-CREST and USDA-ARS networks (Jackson et al., 2010), (ii) regional networks, which cover larger areas like the Oklahoma Mesonet (Illston et al., 2008) and Illinois Climate Network (Hollinger and Isard, 1994) and are very appropriate to study the spatiotemporal variability of soil moisture and the validation or the initialization of hydrologic models (Liu et al., 2011; Manfreda et al., 2007), and (iii) continental networks like SCAN, which covers the entire United States (Schaefer et al., 2007). Among these three categories of networks, local networks, like the NOAA-CREST network that was used in this study, are particularly useful to calibrate and validate active, passive, and active/passive microwave-based soil moisture models and products because they usually cover homogenous terrain with minimal spatial variability.

With respect to microwave-based techniques for soil moisture retrieval, passive microwave observations, in particular, have proven to be sensitive to soil moisture. Airborne and ground-based radiometers were used in several studies to calibrate and verify radiative transfer models and assess their sensitivity to surface parameters, especially those related to surface temperature, soil roughness and texture, and vegetation water content (Jonard et al., 2011; Judge, 2007; Kurum et al., 2011). Wigneron et al. (2011) recently revised the determination of the roughness effect and suggested using a three-parameter roughness model instead of the simplistic models that are currently in use (Choudhury et al., 1979). The vegetation effect was also addressed (Saleh et al., 2007) using ground-based observation of microwave emissions in the L-band.

Compared with soil roughness and vegetation water content, soil temperature requires particular attention as it exhibits the most significant diurnal variability, which impacts the retrieval of soil moisture. Moreover, the soil temperature used in the radiative transfer model, commonly known as *effective temperature*, should correspond to the temperature of the soil layer that corresponds to the penetration depth of the microwave signal, which depends on the frequency and soil parameters. Prigent et al. (1999) noticed a phase lag between brightness temperatures and thermal temperatures in desert areas, which was attributed to the difference in their penetration depths, and proposed a method to account for this difference in the estimation of the effective temperature. Another study corroborated this finding for other land classes and accounted for this difference by the phase and amplitude in the diurnal cycles in the retrieval of emissivity (Norouzi et al., 2011). The impact of these discrepancies between infrared and microwave temperatures varies depending on land cover (Parinussa et al., 2011). Holmes et al. (2006) investigated the seasonal variability of the differences between surface and microwave temperatures and proposed a new regression to estimate the effective temperature that accounts for interannual changes. The ensemble of these findings that were obtained using satellite observations and verified across large-scale areas, needs to be corroborated by results from comprehensive local field-scale experiments.

In this perspective, ground-based instruments were used in several investigations to calibrate and validate proposed models and products. In addition to active microwave sensors like the ground-penetrating radar, which showed good potential for the retrieval of soil moisture at the field scale (Minet et al., 2011, 2012), other studies that focused on the use of passive microwave instruments can be mentioned. Chanzy et al. (1997) estimated effective temperature using air and deep soil temperatures as well as microwave temperature in the X-band for the retrieval of soil moisture using L- and C-band microwave observations. They used a ground-based radiometer to successfully test their model over smooth bare soil. Burke and Simmonds (2001) used a truck-based radiometer to develop a model to retrieve near-surface soil moisture and determine the effective temperature that should reflect the temperature of the soil layer that is contributing to the microwave signal. They noted that soil temperature at the 11-cm depth can be a proxy for the effective temperature. Schneeberger et al. (2004) used two truck-based radiometers and collected brightness temperature observations in the L- and C-bands. They stated that L-band passive microwave observations were particularly sensitive to changes in the sun illumination angle throughout the day and its impact on the diurnal variability in soil temperature. Wigneron et al. (2008) investigated, in preparation for the European L-band Soil Moisture and Ocean Salinity (SMOS) mission, the determination of the soil effective temperature and demonstrated the importance of including the temperature of deeper soil layers along with skin temperatures in the retrieval. Recently, Jonard et al. (2011) chose to use the soil temperature at the 5-cm depth as an approximation for the soil effective temperature to retrieve soil moisture from L-band observations.

The objective of this study was to investigate the spatiotemporal variability of soil moisture in a field-scale area with a particular focus on the analysis of the effect of the diurnal variability in soil temperature on the retrieval of soil moisture from L-band passive microwave observations. Specifically, this study addressed the sensitivity of the radiative transfer model to changes in the soil temperature profile throughout the day and its impact on the retrieval of soil moisture and builds on previous studies by, among others, Wigneron et al. (2008) and Schneeberger et al. (2004). The diurnal cycle of soil temperature depends on the latitude (i.e., location) and the season (i.e., time period) in addition to soil and surface characteristics. Its impact on the retrieval of soil moisture is therefore site specific. This study expands the geographic domain of the previous studies by conducting a comprehensive field campaign in the northeastern United States. To our knowledge, this study constitutes the first attempt to study, in the northeastern region, the performance of soil moisture retrieval throughout the day using passive microwave observations from a ground-based L-band radiometer that mimics the future NASA Soil Moisture Active Passive (SMAP) sensor that will be launched in 2014.

This study used radiometric and in situ soil moisture data obtained from the NOAA-CREST–Soil Moisture Advanced Radiometric Test Bed (CREST-SMART) facility that includes an L-band dual-polarized radiometer, soil temperature, and an in situ soil moisture network. The site of the facility was selected by NASA to be one of the calibration/validation sites for the future SMAP mission. The field campaign was part of a rehearsal program to increase the readiness of the community during the prelaunch phase and issue appropriate recommendations that should be addressed during the post-launch phase. The facility is located near Millbrook, NY, in the northeastern United States. In addition to its geographic location, the high rock fraction of the soil adds to the particularity of the study site. The existence of rocks in the soil impacts its dielectric constant and changes the interaction with the microwave signal. In addition, the existence of rocks in the soil should affect the thermal inertia and radiative properties of the soil profile and therefore the effective temperature and its diurnal variability with respect to the microwave signal. This motivated the analysis of the radiative transfer under the particular soil conditions of this region and investigation of its variability throughout the day.

Methodology

Site Description

The field experiment was performed on 16 May 2012 at the CREST-SMART facility near Millbrook, NY, (41°47′ lat., −73°44′ long., elevation 128 m asl) hosted by the Cary Institute of Ecosystem Studies, which includes (i) the NOAA-CREST soil moisture network, (ii) a dual polarized L-band radiometer that is part of the NOAA-CREST Microwave Observation Unit, and (iii) a NOAA Climate Reference Network (CRN) station. The soil moisture observation network and the L-band radiometer were deployed in October 2010. They have been providing soil moisture and brightness temperature measurements regularly since their deployment.

Two long-term in situ stations measuring soil moisture and soil temperature profiles are located in the same grassland field where the experiment was conducted, namely, a NOAA CRN station (Palecki and Groisman, 2011) and a USDA in situ soil moisture station. Both sites are part of the soil moisture observation network that covers nested pixels of the prospective grids of future SMAP soil moisture products, namely, the 3-km active product, the 9-km active/passive product, and the 36-km passive product. The network is equipped with Hydra Probe sensors (Stevens Water) to measure soil moisture and soil temperature at the installed depths. The CRN station has three profiles installed, with sensors at the 5-, 10-, 20-, 50-, and 100-cm depths. The rest of the sites in the network have two observation profiles with sensors installed at 2.5, 5, and 10 cm. All sensors are installed horizontally with an approximate sensing range of 4 cm, so the 2.5-cm installation estimates soil moisture in the 0.5- to 4.5-cm depth. Sensors at these different depths are commonly used to validate satellite remote sensing products because they provide useful long-term observations of soil moisture at depths close to the penetration depth of the microwave signal in the L-band (Jackson et al., 2010). An analysis of observations from the permanent sites has shown that soil moisture at the study site typically ranges from 0.05 to 0.35 m^3/m^3, which is common for this temperate climate. ~~Figure 1~~ shows a typical time series of soil moisture measured in 2011 by the Hydra Probe sensors at the 2.5-cm depth in the study field. The soil moisture at 2.5 cm was shown to be in qualitative agreement with precipitation obtained from the adjacent NOAA CRN station. Observations made by the soil moisture probes from April to June 2011 varied between 0.15 and 0.3 m^3/m^3.

The land cover in the region at the kilometer scale is a composite of open field (40%) and forested (60%) terrain, with a small urban fraction (the village of Millbrook). The area is about 19 km (12 miles) from the Hudson River and includes a few small water bodies (Tyrrel Lake and Dieterich Lake) about 8 km (5 miles) from the site. The relief in the area is relatively gentle. Soil texture in the region tends to be sandy loam, with representative percentages of 60% sand, 34% silt, and 6% clay. It was also observed that the soil column had a significant amount of rock, specifically shale, with a rock fraction that can reach 50%.

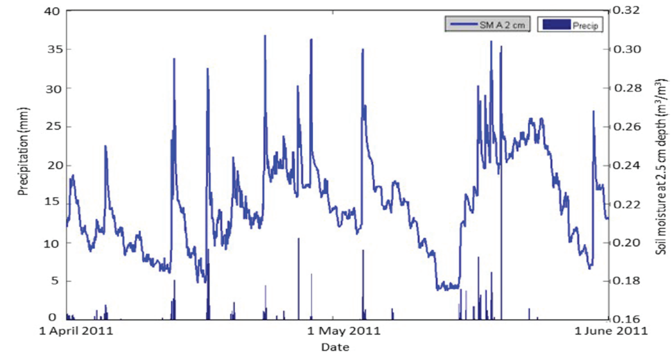

Fig. 1. Time series of precipitation and soil moisture observed at the study site during April to June 2011.

Experiment Setup

The field experiment reported here was conducted across an area of eight pixels of 4 by 4 m each. These pixels were originally covered with 60-cm-tall grass. The grass was mowed twice: 2 wk before the experiment and then a day before the experiment. The intention was to alleviate the effect of vegetation and reproduce bare soil conditions in a natural environment like the northeastern United States; however, litter, short 1- to 2-cm-tall grass, and roots remained at the soil surface after mowing the field. The mowing alleviated the effect of vegetation and created conditions close to bare soil conditions.

During the experiment, the field was observed with the L-band radiometer three times, at 0830, 1130, and 1430 h. The start time of the three passes was chosen to capture the diurnal variation in soil temperature during the daytime, knowing that each pass should last around 1.5 h. We assumed that the 0830 h pass should be close to early morning conditions when dew is still present on the soil surface and the soil temperature profile is still uniform. The second pass that started at 1130 h was meant to reproduce conditions close to the daily temperature peak, which corresponds to a nonuniform temperature profile where the topsoil layer is warmer than deeper layers. The last pass that started around 1430 h was meant to capture conditions after the occurrence of the temperature peak. The soil temperature profile was expected to be more uniform at the sensing depths than during the second pass but with temperature values higher than those recorded during the early morning pass.

Moreover, we intentionally introduced a heterogeneous irrigation pattern by irrigating half of the field, i.e., four out of eight pixels, during Passes 2 and 3. Irrigation lasted long enough to ensure close to saturated conditions in each pixel. We believe that there were losses through infiltration and evaporation, which might happen after the irrigation, during the passes and the reading with the radiometer (during 1.5 h) that could not be avoided. The first pass was performed under natural, undisturbed soil moisture conditions.

Brightness temperature was measured at the 1.4 GHz frequency (L-band) in the vertical and horizontal polarizations. The radiometer was mounted on the top of a trailer and towed with a truck parallel to the observed pixels (Fig. 2). A potter horn antenna was used to achieve a 30° half-power beam width antenna pattern. The antenna was positioned at around 4 m above the ground. The instrument has a typical 20-min warm-up time and 0.5 K resolution for a 200-ms integration time. The instrument was inspected right before the experiment for calibration purposes. The analysis of prior microwave temperature measurements did not reveal any radio frequency interference contamination in the area. Frequent stops were made to stabilize the measured brightness temperature after moving the trailer from one pixel to the next. Brightness temperatures were measured at a 40° observing angle, which is similar to the angle of the future SMAP mission. The radiometer's potter horn antenna was designed with an integrated mounting plate. The elevation-over-azimuth rotator is a fully weatherized pan-tilt rotator designed for harsh environments and a large payload. It is powered and steered via a remote-control head located inside the trailer. The rotator provides 360° horizontal and 180° elevation (zenith to nadir) tilt capability. The trailer was carefully moved to maintain the same incidence angle and positioned to ensure that the entire observed pixel was included within the footprint of the radiometer. The same path and order of observation were followed during each individual pass.

In addition to the L-band brightness temperatures, several other surface parameters were collected during each pass, namely, soil moisture and surface temperature profiles. Vegetation water content, soil texture, and soil roughness were collected only once during the experiment because they are not considered to exhibit a significant temporal variability. Several Field Scout 300 time domain reflectometry (TDR) sensors (Spectrum Technologies) were used to sample at depths of 3, 7, and 12 cm. Soil moisture and soil temperature profiles were observed at five locations within each 4- by 4-m pixel at the three sampling depths with vertically installed TDR sensors. For each parameter, four observations were made at the corners of the pixel and one additional observation at its center. Also, one additional skin temperature reading was taken with an infrared sensor at the center of each pixel. The average of these observations was considered for each pixel in the verification of the radiative transfer model. Table 1 provides a summary of the averages and the standard deviations of the collected soil moisture measurements at the three sensing depths during the three passes. The soil moisture value reported in Table 1 is the mean of the five observations collected within each individual pixel, i.e., the four corner observations plus the fifth observation taken at the center of each pixel.

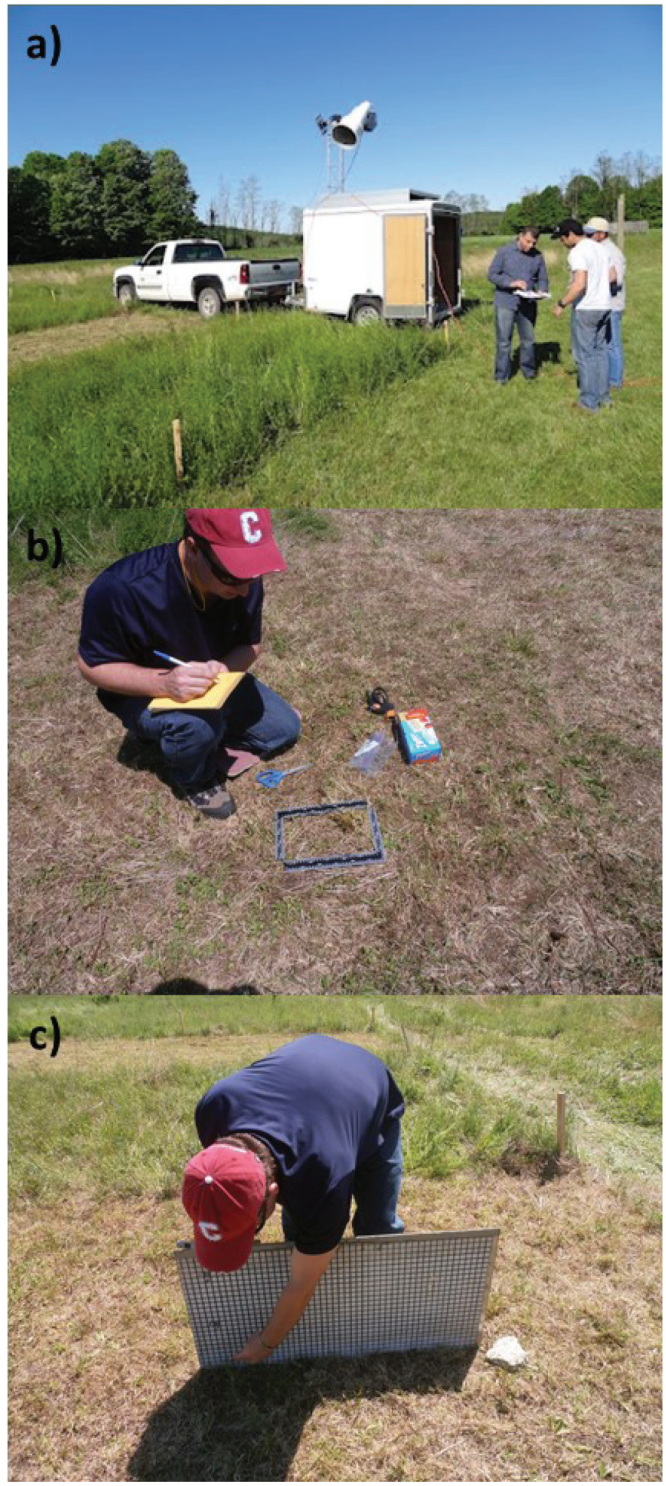

Fig. 2. (a) The setting and equipment for the field experiment performed on 16 May 2012; (b) measuring vegetation water content; and (c) measuring board to photograph soil roughness.

A total of 21 co-located dielectric and volumetric soil moisture measurements were made in the study area to assess the reliability of the measurements made by the TDR sensors. First, dielectric measurements with the TDR sensors were made at three sampling depths. Then, soil samples were collected for the gravimetric measurements at the same location where TDR readings had been

Table 1. Summary of the average and standard deviation of soil moisture measurements collected during the three passes. Irrigated pixels during Passes 2 and 3 are in bold type.

Pass	Depth	Soil moisture							
		Average				Standard deviation			
	cm	m^3/m^3							
1	3	0.25	0.23	0.19	0.24	0.04	0.04	0.02	0.01
		0.23	0.21	0.23	0.22	0.05	0.03	0.03	0.03
	7	0.25	0.3	0.19	0.24	0.03	0.05	0.05	0.03
		0.26	0.28	0.23	0.22	0.04	0.02	0.04	0.02
	12	0.15	0.14	0.13	0.13	0.02	0.03	0.02	0.02
		0.15	0.17	0.15	0.13	0.01	0.01	0.03	0.01
2	3	0.14	0.13	0.11	0.11	0.01	0.01	0.01	0.01
		0.24	**0.26**	**0.2**	**0.2**	**0.02**	**0.04**	**0.02**	**0.07**
	7	0.25	0.21	0.22	0.25	0.03	0.02	0.04	0.03
		0.34	**0.43**	**0.31**	**0.27**	**0.03**	**0.03**	**0.02**	**0.03**
	12	0.14	0.13	0.14	0.14	0.02	0.01	0.02	0.01
		0.2	**0.21**	**0.19**	**0.17**	**0.02**	**0.02**	**0.02**	**0.01**
3	3	0.12	0.13	0.12	0.1	0.02	0.01	0.01	0.02
		0.14	**0.22**	**0.21**	**0.16**	**0.01**	**0.02**	**0.07**	**0.02**
	7	0.27	0.21	0.22	0.2	0.02	0.02	0.01	0.01
		0.29	**0.37**	**0.3**	**0.24**	**0.02**	**0.01**	**0.02**	**0.02**
	12	0.14	0.14	0.13	0.12	0.02	0.01	0.02	0.01
		0.14	**0.22**	**0.18**	**0.16**	**0.02**	**0.02**	**0.02**	**0.01**

taken. The analysis of the dielectric and volumetric measurements revealed that the highest agreement between them was obtained at the 12-cm depth, where the correlation coefficient was 0.7. The rest of the gravimetric samples, taken at the 7- and 3-cm depths, did not show significant variability and strong agreement with the TDR measurements; the agreement between both measurements was 0.1 and 0.4, respectively. This can be attributed to the existence of roots in the top layer of the soil, which may have affected the agreement between both measurements. We can also attribute the disparity to the existence of rocks in the soil where the samples were collected, which may have introduced a bias between both readings as well.

Vegetation water content was determined for the various surface conditions by harvesting all plant material above the surface across a sample area of 0.05 m^2. Repeated sampling led to a surface vegetation water content estimate of 0.18 kg/m^2 for the mowed short grass pixels compared with 0.78 kg/m^2 for the unmowed tall grass pixels (results not presented). Surface roughness was estimated by using a grid board hammered into the surface and photographed. After perspective correction, the soil surface photo was digitized and surface roughness calculated.

Radiative Transfer Modeling

In this study, the microwave emission model (Njoku et al., 2003) commonly known as the Tau-Omega model was used. The model is written as

$$T_{bp} = \varepsilon_p T_e \exp(-\tau) + (1-\omega) T_c [1-\exp(-\tau)][1+r_p \exp(-\tau)] \quad [1]$$

where T_{bp} is the brightness temperature at polarization p, T_c is the mean temperature of the vegetation, T_e is the effective mean soil temperature, ε_p is the soil surface emissivity at polarization p, which depends on soil moisture and roughness, τ is the vegetation opacity along the viewing path (also known as the vegetation optical depth), r_p is the surface roughness at polarization p, and ω is the vegetation single scattering albedo. The vegetation temperature was assumed to be equal to the soil skin temperature. Surface emissivity depends on the soil dielectric constant, which is correlated to the soil moisture. In this study, the dielectric mixing model proposed by Dobson et al. (1985) was used. The vegetation optical depth (Njoku and Entekhabi, 1996) was calculated according to

$$\tau = \frac{b w_c}{\cos\theta} \quad [2]$$

where θ is the incidence angle, τ is the optical depth, w_c is the vegetation water content, and b is a proportionality factor. According to Eq. [2], τ is proportional to the vegetation water content (w_c). The proportionality factor b depends on the frequency and vegetation type. In this study, we adopted the typical value of b that was recommended by Njoku and Entekhabi (1996) for the retrieval of soil moisture using brightness temperatures measured in the L-band, which was 0.12. This value seems to be consistent with other subsequent studies for short grass (Burke et al., 1999; Wigneron et al., 1995).

Vegetation water content in the grass remaining after mowing was measured only once during this experiment, assuming that its value should not vary significantly on a daily basis. Hence, we assumed that because of the nonsignificant density of the remaining grass over the surface of the soil, any change in brightness temperature was due to variation in soil moisture and not to vegetation water content, even after the irrigation. The value of the vegetation optical depth (τ) was therefore constant throughout the experiment and was equal to 0.022. This means that the remaining short grass and roots after the mowing still reduced the signal [exp(τ)] by around 3%. The vegetation single scattering albedo (ω) describes the scattering by the vegetation of the energy emitted at the soil surface. In the case of the near bare soil conditions that we observed using an L-band radiometer (i.e., a long wavelength of around 21 cm), it is very reasonable to assume that this parameter was equal to zero ($\omega = 0$).

Soil roughness, r_p, was measured as explained above and calculated according to Choudhury et al. (1979), where the reflectivity (reflectivity = 1 − emissivity) of a rough surface is related to that of an equivalent smooth surface, r_{0p}, using an empirical expression that introduces a roughness parameter h:

$$r_p = r_{0p} \exp(-h) \quad [3]$$

The roughness parameter h is dimensionless and was determined using the measured surface height standard deviation, incidence angle, and frequency (Njoku, 1999). A value of $h = 0.5$ is usually recommended for rough surfaces. In this study, the roughness height was measured at eight different locations randomly selected around the site. The average value obtained for the roughness parameter was 0.1.

The parameters of the radiative transfer model, namely, the vegetation and soil roughness parameters, were determined from field measurements and then used in the retrieval of soil moisture. The problem is then reduced to a system with a single equation and one unknown, soil moisture:

$$F = \sum \left[T_{bp}\left(\text{measured}\right) - T_{bp}\left(\text{simulated}\right) \right]^2 \qquad 4]$$

Appropriate initial conditions and variation range ([0 0.45]) of the inferred parameter were imposed in the optimization procedure as proposed in previous studies (Njoku et al., 2003). An iterative approach was adopted that adjusted soil moisture values to minimize the sum of the squared difference between the measured and the simulated brightness temperatures (F) with the radiative transfer model. The algorithm of the minimization procedure is based on a golden section search and parabolic interpolation (Brent, 1973).

Results and Discussion

Figure 3 shows the observed surface soil moisture values at the 3-cm depth and the measured brightness temperatures at the vertical and horizontal polarizations during the three passes of the experiment. The first column of pixels in the obtained maps corresponds to the area that was irrigated in the second and third passes. The impact of the irrigation on the brightness temperature is clear. Lower brightness temperatures were observed in the second and third passes in the irrigated areas for the horizontal and vertical polarizations. Observations from the first pass, where no irrigation was performed, showed a quasi-homogenous distribution of brightness temperatures across the field, unlike observations from Passes 2 and 3, where the difference between the irrigated (lower brightness temperature) and unirrigated (higher brightness temperature) columns is obvious. The microwave temperatures in the horizontal polarization were, as expected, systematically lower than those in the vertical polarization in both irrigated and unirrigated areas. The second column of pixels, which was not irrigated, showed persistent brightness temperature values in the vertical polarization, as the areal average was 280 K in the first and second passes before it increased in the third pass to 283 K, perhaps because of the warming surface temperature in the afternoon pass. The horizontal polarization microwave temperatures in the unirrigated region of the field (i.e., the second column) showed a more significant decrease in their values throughout the day, especially between Passes 1 and 2, as their average declined from 248 K in the first pass, to 241 K in the second pass, and then to 240 K in the third pass. The decrease was less significant between Passes 2 and 3 despite irrigation before both passes, perhaps because of the higher surface and air temperatures during Pass 3, which caused more losses through evaporation. In the irrigated portion of the field, the average brightness temperatures in the horizontal polarization were 238, 231, and 221 K in the first, second, and third pass, respectively. The vertical polarization brightness temperature averages varied from 275 K in the first pass to 268 K in the second and third passes. The measured soil moisture at the 3-cm depth exhibited a pattern that is similar to the one observed with the microwave temperatures, especially in the unirrigated right column (Fig. 3) where soil moisture values dropped to <0.25 m^3/m^3. The areal average

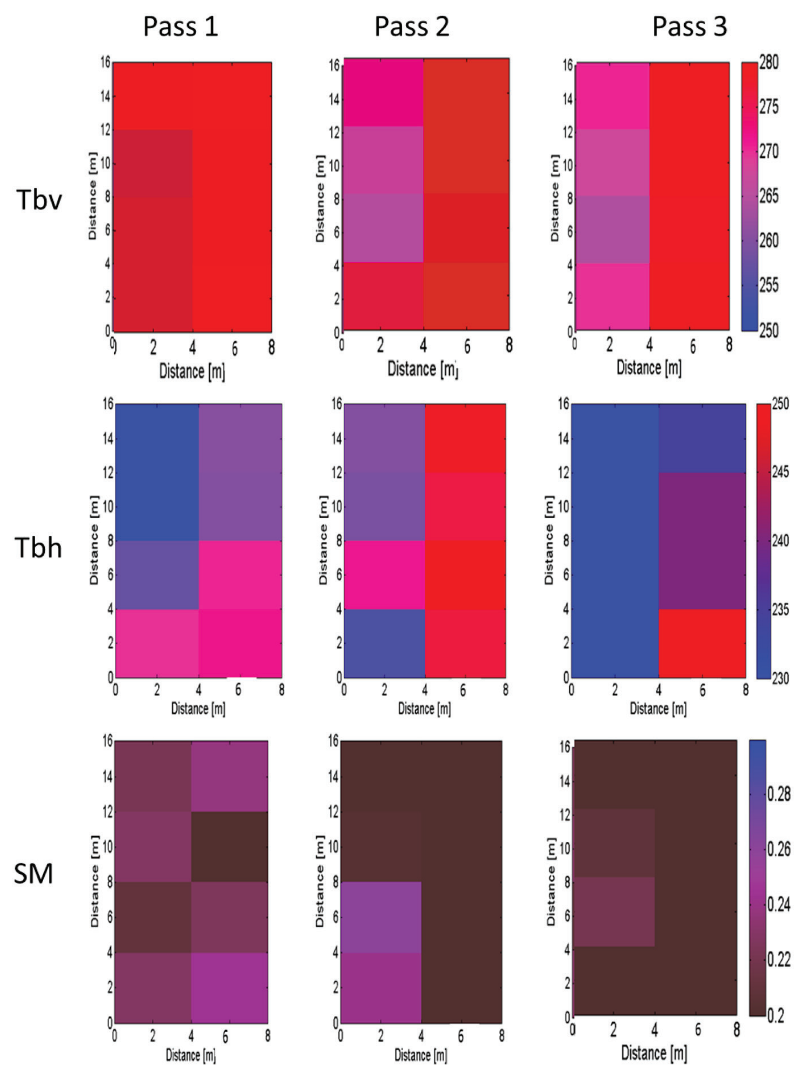

Fig. 3. Observations of microwave temperature at vertical and horizontal polarizations (Tbv and Tbh, respectively, in K) and 3-cm-depth soil moisture (SM, in m^3/m^3) during the three passes. In Passes 2 and 3, the left column was irrigated.

of soil moisture across the entire study area decreased from 0.25 m^3/m^3 in Pass 1 to 0.23 m^3/m^3 in Pass 2 to finally reach 0.22 m^3/m^3 in the last pass, despite irrigating half of the field before the second pass. After mowing the pixels, the remaining roots and grass could have intercepted part of the water used in the irrigation and impacted the average soil moisture values across the field. In addition, the areal soil moisture averages reported here include the unirrigated part of the field, which showed a decrease in soil moisture throughout the day that counterbalanced the increase caused by the irrigation.

Table 2 summarizes the correlations between the observed microwave temperature at the vertical and horizontal polarizations and the measured soil moisture at the three different observation depths, namely, 3, 7, and 12 cm, during the second and third passes coincident with the irrigation events. First, it is clear that the vertical polarization microwave temperatures have a stronger agreement with the measured soil moisture for the three depths. This can be explained by the difference in sensitivity to surface roughness between brightness temperatures at the vertical and horizontal polarizations. In the model, the same polarization factor h was used for both polarizations, which is a common assumption (Choudhury et al., 1979; Njoku, 1999). However, recent studies (Jonard et al., 2011) have suggested that using different roughness parameters for the vertical and horizontal microwave temperatures can lead to an improved retrieval of soil moisture with respect to using a common roughness parameter for both polarizations.

In addition, the remaining roots and grass at the soil surface could have affected the difference between the polarizations. The lowest agreement between both variables was noticed at the 7-cm depth. At the vertical polarization, the agreements between soil moisture at the 12- and 3-cm depths and microwave temperature were similar. Although the horizontal polarization brightness temperatures showed lower agreement with the observed soil moisture, their spatial patterns (Fig. 3) were similar to the irrigation pattern introduced in Passes 2 and 3 because the left unirrigated columns exhibit higher brightness temperatures with respect to the right irrigated columns. The weaker sensitivity of the horizontal polarization brightness temperatures to soil moisture in this case can be attributed to the orientation of the cut grass that remained over the soil surface after mowing. The microwave signal at the vertical polarization seemed to be more sensitive to deeper soil layers, which explains the higher agreement with observed soil moisture at the three sampling depths. Indeed, the performed simulations showed that the best agreement between observed and retrieved soil moisture was obtained when only vertical polarization brightness temperatures were used in the minimization process (Eq. [4]). This is in line with the correlation coefficients in Table 2, which were lower between observed soil moisture and measured microwave temperature in the horizontal polarization.

Table 2. Correlation between observed brightness temperatures and measured soil moisture at 3, 7, and 12 cm during the second and third passes.

Observation depth	Polarization	Pass 2	Pass 3
cm			
3	vertical	0.65	0.76
	horizontal	0.10	0.48
7	vertical	0.58	0.51
	horizontal	0.05	0.15
12	vertical	0.71	0.61
	horizontal	0.15	0.28

In addition, the radiative transfer model was run separately with each measured soil temperature depth, namely, the surface skin temperature, the 3-cm temperature, the 7-cm temperature, and the 12-cm temperature. The observed soil moisture values, which were corrected using the gravimetric sampling, were compared with the simulated soil moisture at the three depths. Figure 4 shows an example of the agreement between observed soil moisture values at the 3-cm depth and their corresponding simulated values when the four soil temperatures were used in the retrieval algorithm. According to Fig. 4, the use of 3- and 7-cm soil temperatures led to an underestimation of soil moisture during the three passes, particularly at low soil moisture values. The best performances were noted when the 12-cm soil temperatures were used.

Table 3 shows the obtained RMSE values when the simulated soil moisture values were compared with the measured values for the three sensing depths. First, when the 3-cm soil moisture observations were considered in an assessment of the performance of the radiative transfer model, the best agreement between observed and retrieved soil moisture was obtained when the 12-cm soil temperature values were used. The agreement was the lowest when the 3-cm soil temperatures were used. This can be attributed to the effect of existing roots on soil temperature and soil moisture readings, which makes the observation at this depth less reliable for the verification of soil moisture retrieval models. When soil moisture observations at the 7-cm depth were used in the assessment, it was noted that overall the agreement between observed and retrieved values was not strong because RMSE values were higher for the three passes regardless of the depth of the soil temperature used in the retrieval (Table 3) and despite the fact that the best agreement was also observed when the 12-cm soil temperatures were observed. This can be attributed to the quality of the 7-cm soil moisture readings themselves, as it was reported above that the agreement between the dielectric (from TDR) and volumetric (from gravimetric sampling) soil moisture values was the lowest at the 7-cm depth. However, when 12-cm-depth soil moisture observations were used, the agreement between simulated and observed soil moisture improved significantly and reached RMSE values higher than those obtained with the 3- and 7-cm sensing depths. Again, it was noted that the best agreement

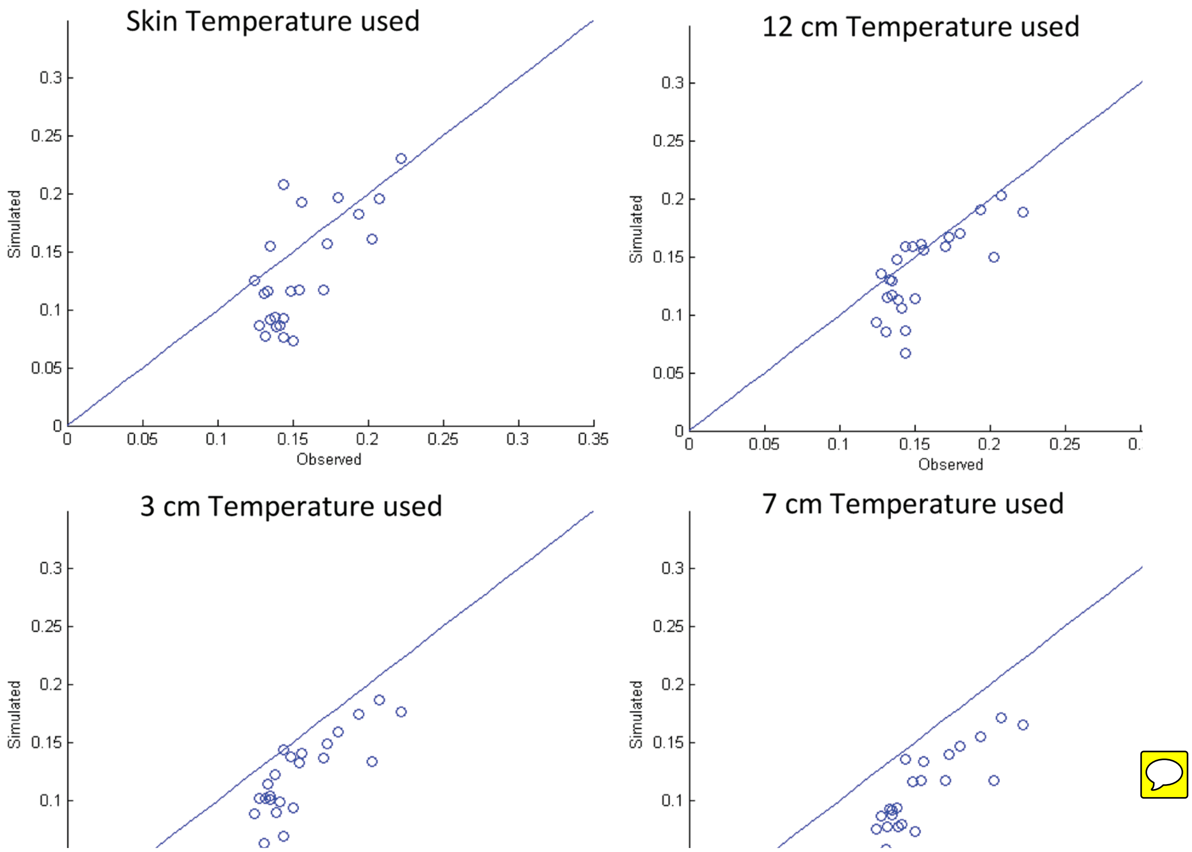

Fig. 4. Comparison of observed soil moisture (m^3/m^3) to simulated soil moisture using skin temperature and 3-, 7-, and 12-cm soil temperatures.

was obtained when the 12-cm-depth soil temperature was used. It was noticed based on the obtained RMSE values that the retrieval performance was better when the 12-cm-depth soil temperatures were used in the radiative transfer model. The strong agreement at the 12-cm soil moisture sensing depth can be explained by the fact that, at this range of depths, soil moisture spatial variability decreases with depth, which may naturally lead to better agreement between observed and retrieved soil moisture values. However, the persistently higher retrieval performance for the 12-cm-depth soil temperature with all soil moisture sensing depths suggests that the 12-cm soil temperature can be a surrogate for the soil effective temperature. These findings are in line with those stated by Burke and Simmonds, (2001), where soil temperature at the 11-cm depth was found to be representative of the effective temperature of the soil layer when the same L-band microwave frequency was used. This may suggest that the penetration depth of the L-band microwave signal under the conditions of this experiment is deeper that the generally assumed 5-cm penetration (Jonard et al., 2011) and can penetrate, under specific circumstances, deeper.

With respect to the temporal variability, RMSE values obtained in the third pass tended to be the lowest amongst the values obtained during the entire experiment with the exception of the values obtained when the 7- and 12-cm temperatures were used in Pass 1. There was a gradual improvement in the RMSE values throughout the day as the RMSE values maintained their decrease from Pass 1 to Pass 2 and from Pass 2 to Pass 3. Recall that the field was irrigated in Passes 2 and 3. The irrigation, which introduced an artificial soil moisture heterogeneity, did not affect the gradual improvement in retrieval performances. During the second and third passes, the RMSE obtained with the 12-cm soil temperatures were close to RMSE values obtained with skin temperatures. This can be explained by the fact that in the second and third passes, the soil temperature profiles could be uniform in the 12-cm-depth soil layer, which means that skin temperature can be a good approximation of the 12-cm-depth temperature. We should expect the soil temperature profile to exhibit a decrease at levels deeper than 12 cm (Holmes et al., 2008), but we did not have soil temperatures at deeper layers in this study.

In addition, three versions of the radiative transfer model were run. First, a version was run that assumes perfect, smooth, bare soil conditions, where vegetation and roughness parameters were assumed to be equal to zero. Then, in a second version, only soil roughness was accounted for, neglecting therefore the effect of the remaining debris after the mowing operation. Finally, both roughness and vegetation parameters were introduced in a third run. Simulations showed that the third scenario that included both vegetation and roughness parameters gave the lowest RMSE values and therefore the best agreement between the observed

Table 3. Summary of the RMSEs obtained when observed soil moisture at 3, 7, and 12 cm was compared with the simulated values.

Pass	RMSE			
	Skin temperature	3-cm temperature	7-cm temperature	12-cm temperature
	3-cm soil moisture			
1	0.12	0.12	0.11	0.08
2	0.04	0.07	0.05	0.04
3	0.03	0.04	0.04	0.02
	7-cm soil moisture			
1	0.15	0.15	0.13	0.10
2	0.15	0.18	0.16	0.14
3	0.10	0.16	0.15	0.13
	12-cm soil moisture			
1	0.05	0.05	0.03	0.01
2	0.04	0.06	0.04	0.03
3	0.04	0.04	0.04	0.03

and retrieved soil moisture. For instance, in the third pass, the RMSE for retrieved soil moisture declined from 0.045 m^3/m^3, which was obtained when ideal smooth bare soil conditions were assumed, to 0.03 m^3/m^3 obtained with the second scenario, to finally reach 0.02 m^3/m^3 with the third scenario. The impact of short grass seems to be more significant during the early morning passes, when dew is still present, than in subsequent passes during the day when the surface temperature is higher. Note that the assumption was made in the radiative transfer modeling that the effect of vegetation optical depth (i.e., b factor) was the same for the vertical and horizontal polarizations. It is also worth noting that adding parameters to the model may naturally lead to higher agreement because it offers more flexibility for the optimization process to fit the observations.

The examination of the change in the sensitivity of the microwave signal to soil moisture throughout the day and the impact of the diurnal cycle of surface temperature on the soil moisture retrieval is very relevant for the retrieval of soil moisture from multiple sensors that have different overpass times. While in previous studies (Njoku et al., 2003), and for the upcoming SMAP mission as well, data from early morning passes were considered for the retrieval of soil moisture, this study suggests that the performance of the retrievals improves with time during the day. This may suggest that the suitability of microwave observations with respect to their overpass time to retrieve soil moisture may vary in space according to land surface conditions, soil texture, and also the characteristics of the diurnal cycle of soil temperature. Early morning overpasses may be appropriate for bare soil conditions, as the soil temperature profile tends to be uniform at that time of the day. This aspect should be investigated further and carefully addressed, especially when blended soil moisture products that use data from multiple satellites with different overpass times are in use. Attempts to merge multi-satellite data to retrieve soil moisture at higher temporal frequency, more than twice a day (Zhan et al., 2012), should account for the difference in overpass time and its impact on the performance of the retrieval.

The investigation of the effect of the diurnal cycle of soil temperature and the effective temperature on the retrieval of soil moisture from microwave observations, which was at the heart of this study, should be complemented in future studies by a thorough assessment of the impact of rocks on the retrieval of soil moisture. The prevalence of rocks in the soil of the study field can impact the interaction of the microwave signal with the soil and therefore the performance of the used version of the radiative transfer model. As well, the high rock fraction in the soil in the region should also impact the readings of both dielectric and volumetric soil moisture values. Samples for the volumetric soil moisture determination were collected in this study at locations with fewer surface rocks. The correction for the effects of rocks on the soil moisture values can be done according to Cosh et al. (2008) using the volumetric rock fraction of the sample at the surface, a parameter that was not measured during the field campaign. Future work should address incorporating the volumetric rock fraction in the radiative transfer modeling through the adjustment of the dielectric mixing model.

Conclusions

This study placed a particular focus on investigating the impact of the diurnal variation of soil temperature on the performance of the retrieval of soil moisture in the context of the specific high-rock-fraction soils in the northeastern United States. In addition, the performance of the retrieval was assessed using soil temperature observed at different depths, which was expected to lead to the determination of the effective soil depth that contributes to the microwave emission. The best agreement between measured and simulated soil moisture values was obtained when the 12-cm-depth soil temperature was used, which suggests that soil temperature at that depth can be a proxy for the soil effective temperature. An accurate understanding of the effect of the diurnal change in soil temperature on the retrieval of soil moisture from satellite microwave measurements is important.

In addition, we noticed that the highest agreement between observed and retrieved soil moisture values was obtained during the 1430 h pass. The performances were lower when observations from earlier passes were used. The 1430 h pass is closer to the overpass time of missions like the operational AMSR2 onboard the GCOM-W1 satellite or the past AMSR-E mission, which have an overpass time at 0130/1330 h. The soil moisture dedicated missions like SMAP and SMOS have an 0600/1800 h crossing time. Early morning 0600 h observations will be used in the case of the NASA SMAP mission for the retrieval of soil moisture.

Although an effort was made during the field experiment to reproduce bare soil conditions by mowing the grass twice, the effect of the remaining roots on the microwave signal persisted in both horizontal and vertical polarizations. A lower agreement between observed and retrieved soil moisture values was observed with brightness temperatures in the horizontal polarization, possibly because of the remaining grass and roots at the soil surface. We noticed a degradation of the quality of soil temperature and soil moisture in situ observations at the 3- and 7-cm depths because of the presence of roots and possibly rocks. Future research using an enhanced suite of instruments will address the determination of the effect of the existence of roots in the topsoil layer on the microwave signal and its impact on soil moisture retrieval, especially in cultivated fields where the accuracy of the retrieval is important.

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