

A GROUND BASED L BAND RADIOMETER FOR THE MONITORING OF SOIL MOISTURE IN THE REGION OF MILLBROOK, NEW YORK USA

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Abstract

A field experiment was performed in grassland near Millbrook, New York using the NOAA-CREST Microwave Observation Facility, which comprises a network for in situ observation of soil moisture and a mobile dual polarized L band radiometer. During the field campaign, intensive measurements of L band brightness temperatures, surface temperature, and soil moisture and temperature at 3, 7 and 12 cm depth were collected. Observations were collected first early in the morning, starting at 8 AM, then a second pass started at 11 AM and finally a third pass started at 2 PM. During the second and the third pass half of the pixels were irrigated. Soil roughness and vegetation water content of the short grass remaining after mowing were measured.

The Tau-Omega model was then used to assess the potential of using L band microwave observations for the retrieval of soil moisture. A particular focus was placed on investigating the performance of the retrieval when temperature at different depths is used. Also, the collected observations at three different times in the day were used to assess the impact of the diurnal cycle of temperature on the performance of soil moisture retrieval.

Obtained results showed that the RMSE has declined throughout the day to reach $0.03 \text{ m}^3/\text{m}^3$ in the afternoon pass when skin temperature values are used in the Tau-Omega model. In addition, amongst

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the three different passes, the lowest RMSE was consistently obtained when the 12 cm temperature is used. A RMSE of $0.02 \text{ m}^3/\text{m}^3$ was obtained in the afternoon pass when the 12 cm temperatures were used. The reported research contributes to understanding of the performance of microwave soil moisture retrieval algorithms in rocky soils typical of the northeastern US. It is found the tau-omega model may perform acceptably under these conditions but that attention should be paid to the diurnal cycle of the depth-varying soil temperature profile to reduce retrieval errors.

1. Introduction

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 have been established across the U.S. to address this goal. However, their density, extent, and the type of sensors they are using vary. With respect to their extent, there are mainly three categories of networks, namely, a) local networks with a special coverage in the order of several miles like the NOAA-CREST and USDA-ARS networks (Jackson et al., 2010), b) regional networks covering large areas like the Oklahoma Mesonet (Illston et al., 2008) and Illinois Climate Network (Hollinger and Isard, 1994) which are very appropriate to study the spatiotemporal variability of soil moisture and the validation or the initialization of hydrological models (Liu et al., 2011; Manfreda et al., 2007), and c) continental networks like SCAN which covers the entire U.S. (Schaefer et al., 2007). Local and regional networks are very useful to calibrate and validate active-, passive- as well as active/passive-based models and products. Passive microwave observations have been proven to be particularly sensitive to soil moisture. Airborne and ground radiometers have been 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., 2011a; Judge, n.d.; Kurum et al., 2011). (Wigneron et al., 2011) have 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 has been also addressed (Saleh et al., 2007) using ground-based observation of microwave emissions in the L Band. The sensitivity of active and/or passive microwave observations from ground-based tower, aircraft, or spacecraft to changes in vegetation water content and structure has been recently addressed (Vereecken et al., 2012). In their study, Vereecken et al. have highlighted the importance of accounting for vegetation structure and water content to accurately retrieve soil moisture. They have also recommended synergistic approaches that rely on multisensor data to characterize the vegetation effect which is in line with the concept of missions like SMAP (Das et al., 2011) where active microwave observation should accurately determine the vegetation structure.

Amongst soil parameters, it is temperature that should exhibit the more significant diurnal variability, which may impact the retrieval of soil moisture. Moreover, the temperature used in the radiative transfer models should be representative of a soil thickness that is equivalent to the penetration depth of the microwave signal, which depends on the used frequency. Such temperature is commonly known as the effective temperature of the soil. (Prigent et al., 1999) have 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 over other land classes and proposed to account for this difference in phase and amplitude in the diurnal cycles in the retrieval of emissivity (Norouzi et al., 2010). The impact of these discrepancies between infrared and microwave temperatures vary depending on land cover (Parinussa et al., 2011). (Holmes et al., 2006) have investigated the seasonal variability of the differences between surface and microwave temperatures and proposed a new regression to estimate effective temperature that accounts for interannual changes.

These findings, based on large scale studies and obtained using satellite observations, have been corroborated with field experiments. (Chanzy et al., 1997) have estimated effective temperature for the L and C band microwave observations using air and deep soil temperatures as well as microwave temperature at the X band. They have used a ground based radiometer to successfully test their model over smooth bare soil. Burke and Simmonds (Burke and Simmonds, 2001a) have used a track 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 have noticed that soil temperature at 11 cm is very representative of the effective temperature. Schneeberger et al. (Schneeberger et al., 2004) have 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 sun illumination angle throughout the day and its impact on the diurnal variability of soil temperature. (Wigneron et al., 2008) investigated, in preparation for the European L band mission SMOS, the determination of soil effective temperature and demonstrated the importance of including soil temperature of deeper soil layers along with skin temperatures in the used formulas. They have also stated that it is important to account for soil texture, especially for sandy and dry soils.

The objective of this study is to expand these previous analyses to the unique northeastern US environment and to investigate the spatiotemporal variability of soil moisture in a field-scale area, placing a particular focus on analyzing the effect of the diurnal variability of soil temperature on the retrieval of soil moisture. This study makes use of in situ observations of soil moisture obtained from the NOAA CREST network near Millbrook, New York in the northeastern U.S. The observation facility also includes an L band dual polarization radiometer along with a number of surface sensing instruments. The observations were collected during a one-day CREST Soil Moisture Radiometric Testbed experiment. The collocation of soil moisture observation with an L band radiometer makes the network particularly

useful for the verification of retrieval algorithms and their sensitivity to land surface parameters. The site was selected by NASA as a calibration/validation site for the SMAP mission. Moreover, the unique rocky nature of the soil in the region motivates investigating the performances of radiative transfer models and their sensitivity to surface parameters under heterogeneous soil texture.

2. Methodology

2.1. Site description

A field experiment was performed near Millbrook, NY, (Lat: 41 deg 47 min, Long: -73 deg 44 min, elevation 128 m) on May 16th 2012 on the observation site hosted by the Cary Institute of Ecosystem Studies, which includes a) the NOAA-CREST soil moisture network, b) the dual polarized L band radiometer that is part of the NOAA-CREST Microwave Observation Unit, and c) NOAA Climate Reference Network (CRN) station. The soil moisture observation network and the L band radiometer have been deployed in October 2010 and have been providing soil moisture and brightness temperature measurements quasi constantly.

Two long term in situ stations measuring soil water content and temperature are located in the same grassland field as the 2012 experiment, one a NOAA Climate Reference Network (CRN) Station (Palecki and Groisman, 2011) and the other a USDA in situ soil moisture station which is part of the NOAA CREST soil moisture network which was deployed in the region over an area 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. Both stations use the Hydra Probe (Stevens Water, Portland, OR) to estimate soil moisture and soil temperature at the installed depths. CRN has

three profiles installed with sensors at 5, 10, 20, 50, and 100 cm. The USDA station has two profiles of sensors installed at 2.5, 5, and 10 cm. These sensors are installed horizontally with an approximate sensing range of 4 cm, so the 2.5 cm installation is estimating soil moisture from 0.5 to 4.5 cm depth. Sensors at these depths are commonly used to validate satellite remote sensing products as they provide a robust long term time series (Jackson et al., 2010). Soil moisture in this domain typically ranges from 0.05 to 0.35 m³/m³, 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 2.5 cm depth in the study field. The site is part of the NOAA-CREST soil moisture network. The soil moisture at 2.5 cm was shown to be sensitive to precipitation obtained from the adjacent NOAA CRN station. Observation made by the soil moisture probes from April to June 2011 varied between 0.15 and 0.3 m³/m³.

The study site serves as a calibration/validation site for the NASA SMAP mission. The land cover in the region at the kilometer scale is a composite of open field (40%) and forested (60%) terrains and a small urban fraction (the Village of Millbrook). The area is about twelve miles from the Hudson River and includes a few small water bodies (Tyrrel Lake and Dieterich Lake) about 5 miles from the site. The relief in the area is relatively gentle. Soil texture in the region tends to be sandy loam with the following representative percentages of Sand: 60% Silt: 34%, and Clay: 6%. It was also observed that the soil column had a significant amount of rock, specifically shale, with a rock fraction that can reach up to 50%.

The rocky nature of the soil makes the study site unique with respect to other existing sites in the US, which have been largely used to study the interaction of the microwave signal with the soil parameters. It is expected that rocks in the soil impact its dielectric constant and change 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 microwave signal. This motivates studying the modeling of radiative transfer in this unique soil type regions and investigating its variability throughout the day.

2.2. Experiment setup

The one-day field experiment reported here was conducted over an area of 8 pixels of 4x4 m each. Pixels were originally covered with 60 cm tall grass. The grass was mowed twice, first two weeks prior to the experiment and then a day before the experiment. However, litter, short grass, and remaining roots were left at the soil surface. The intention was to alleviate the effect of vegetation and reproduce bare soil conditions in a natural environment like the northeastern U.S.

During the experiment, the field was observed with the L band radiometer three times, beginning at 8:30 AM, 11:30 AM, and 2:30 PM, respectively, Eastern Daylight Time. The starting time of the three passes was determined in order to capture the diurnal variation of soil temperature during daytime. We assumed that the 8:30 AM pass should be close to early morning conditions when dew is still present over the soil surface and soil temperature profile is still uniform. The second pass that started at 11:30 AM is supposed to reproduce conditions close to the daily temperature peak, which corresponds to non-uniform temperature profile, as the surface heats by absorbing solar radiation. The last pass that started around 2:30 PM was supposed to capture conditions after the occurrence of temperature peak. The soil temperature profile is expected to be more uniform at the sensing depths, with respect to the second pass, but with temperature values higher than those recorded during the early morning pass. Moreover, the first pass was performed under natural soil moisture conditions. In the second and third passes, however, half of the field was irrigated, i.e. four out of eight pixels, to create a soil moisture contrast and study the influence of surface temperature in saturated compared to average-wet pixels on the retrieval performance using radiative transfer modeling.

Brightness temperature was measured at the 1.4 GHz frequency (L band) in the vertical and horizontal polarization. The radiometer was mounted on the top of a trailer and towed with a truck parallel to the observed pixels (Figure 2). The instrument was calibrated and inspected right before the experiment. The analysis of prior microwave temperature measurements did not reveal any RFI contamination in the area. Frequent stops were made to stabilize the measured brightness temperature after moving the trailer from one pixel to the next. Each pass took around one hour to complete. Brightness temperatures were measured at 40 degree observing angle, which is similar to the projected angle for the SMAP mission. The trailer was carefully moved to ensure including the full pixel within the footprint of the radiometer while observing the center of the pixel. The same observation path and order was followed during each individual pass.

In addition to the L band brightness temperatures, several other surface parameters were collected at each pass, namely soil moisture, surface temperature, vegetation water content, soil texture, and soil roughness. The last two parameters were collected only once during the experiment as they are not supposed to exhibit a significant temporal variability.

Dielectric and gravimetric soil moisture measurements were made within the field plots to estimate the conditions the radiometer was observing. Several Field Scout 300 TDR sensors (Spectrum Technologies Inc., Plainfield, IL) were used to sample over depths of 3, 7, and 12 cm, in addition to the in situ sensors available on the site as part of the CRN and NOAA CREST observation facilities. Synchronous with these dielectric measurements, gravimetric measurements of the soil moisture were also made at the three observation depths to calibrate the TDR sensor readings. Soil moisture and surface temperature were observed at 5 locations within each 4x4 m pixel at the three sampling depths plus one additional skin temperature reading at the surface for the temperature profile. Four observations were taken around

the corners of the pixel and one additional observation at its center. The average of these observations was considered for each pixel in the verification of the radiative transfer model.

Vegetation water content was determined for the various surface conditions by harvesting all plant material above the surface over a sample area of 0.05 m². Repeated sampling led to a surface vegetation water content estimate of 0.18 kg of water per m² for the mowed short grass pixels compared to 0.78 kg/m² for the unmowed tall grass pixels (results for which will not be reported here). 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.

2.3. Radiative Transfer modeling

Over a perfect smooth surface, the simplified radiative transfer model is written as:

$$T_{bp} = \varepsilon_p T_e \quad T_{bp} = \varepsilon_p T_e \quad (1)$$

where 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.

In the case of this experiment, the measured vegetation content over mowed pixels (0.18 kg of water per m²) was not negligible and therefore assuming that soil surface in natural environment behaves as a smooth surface according to equation 1 was not realistic. So the microwave emission model (Njoku et al., 2003a) commonly known as τ - ω model was used, as it accounts for the vegetation contribution. The model is written as:

$$T_{bp} = \varepsilon_p T_e \exp(-\tau) + (1 - \omega) T_c [1 - \exp(-\tau)] [1 + r_p \exp(-\tau)] \quad (2)$$

where 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 vegetation opacity along the viewing path (known also as the vegetation optical depth), and ω is the vegetation single scattering albedo. The vegetation temperature is assumed to be equal to soil skin temperature.

The parameters of the radiative transfer model, namely the vegetation and soil roughness parameters, were determined in this study from field measurements. The optical depth τ (equation 3) is proportional to the vegetation water content (w_c). The proportionality factor “b” depends on the frequency and vegetation type. In this study we have 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 where the proposed value for “b” was 0.12. This value seems to be consistent with other subsequent studies for short grass (Burke et al., n.d.; Wigneron et al., 1995).

$$\tau = b \cdot w_c / \cos \theta \quad (3)$$

Recall that vegetation water content was measured once during this experiment assuming that its value should not vary significantly on a daily basis. So, the value of (τ) the vegetation optical depth was constant throughout the experiment and was equal to 0.022. This means that the remaining short grass and roots after the mowing does still reduce the signal ($\exp(-\tau) \exp(-\tau)$) 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 near bare soil condition 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 is equal zero ($\omega=0$). Soil roughness was measured as explained above and calculated according

(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 which introduces a roughness parameter h :

$$r_p = r_{0p} * \exp(-h) \quad (4)$$

The roughness parameter h is dimensionless parameter was calculated using measured surface height standard deviation, incidence angle and frequency (Njoku, 1999a), given by: $h = \left(\frac{4\pi\sigma}{\lambda} \cos \theta \right)^2$

A value of $h=0.5$ is usually recommended for rough surfaces. In this study, the roughness height was measured at 8 different locations in the site. The average obtained value of roughness parameter was 0.1.

The problem is then reduced to a system with a single equation and one unknown, soil moisture. An iterative approach was adopted that adjusted soil moisture values to minimize (F) the sum of the squared difference between the measured and the simulated brightness temperatures with the radiative transfer model (Equation 2):

$$F = \sum (T_{bp}(\text{measured}) - T_{bp}(\text{simulated}))^2 \quad (5)$$

Appropriate initial condition 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).

3. Results and discussions

Figure 3 shows the observed surface soil moisture values at 3 cm depth and the measured brightness temperatures at the vertical and horizontal polarization during the three passes of the experiment. Recall that soil moisture as well as soil temperature were observed at deeper layers as well. The first column of pixels in the obtained maps corresponds to the area that was irrigated in second and third passes. The impact of the irrigation on brightness temperature is clear. Lower brightness temperatures were observed in the second and the third passes in the irrigated area for the horizontal and vertical polarizations. The first pass, where no irrigation was performed, exhibits a quasi-homogenous distribution of brightness temperatures across the field. Overall, the microwave temperatures at the horizontal polarization are systematically lower than those at the vertical polarization in both irrigated and non-irrigated areas. The second column of pixels which was not irrigated showed consistent brightness temperature values at the vertical polarization as the areal average was 280 K in the first and the second pass before it increases 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 non-irrigated region of the field (i.e. the second column) showed a more significant decrease in their values throughout the day 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 measured soil moisture at the 3 cm depth did not exhibit a pattern that is similar to the one observed with the microwave temperatures. The areal average of soil moisture has decreased from $0.25 \text{ m}^3/\text{m}^3$ in pass 1 to $0.23 \text{ m}^3/\text{m}^3$ in pass 2 to finally reach $0.22 \text{ m}^3/\text{m}^3$ in the last pass, despite irrigating half of the field before the second pass. It is worth noting that after mowing the pixels, the remaining roots and grass could have intercepted the irrigation water and impacted the agreement between microwave temperature and soil moisture at the surface. In addition, the presence of grass roots at the 3 cm depth may significantly affect the TDR readings.

Table 1 summarizes the correlations between observed microwave temperature at the vertical and horizontal polarization 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 different depths. This can be explained by the difference in sensitivity to surface roughness between brightness temperatures at the vertical and horizontal polarizations. In addition, the existence of rocks in the soil, especially near the surface, could have augmented the difference between the polarizations. The lowest agreement between both variables was noticed at the 7 cm depth. At the vertical polarization the agreement between soil moisture at the 12 cm and 3 cm depths and microwave temperature was similar. Although the horizontal polarization brightness temperatures have shown lower agreement with the observed soil moisture, their spatial patterns (figure 3) were similar. The weak sensitivity of horizontal polarization brightness temperatures to soil moisture in this case can be attributed to the horizontal orientation of the cut grass that remained over the soil surface after the mowing. Microwave signal at the vertical polarization seems to penetrate deeper into the soil layers, which explains the higher agreement with observed soil moisture at the three sampling depths.

The determined soil roughness and vegetation parameters were integrated into the radiative transfer model to determine soil moisture values using the radiative transfer model. The determined soil moisture is the result of the minimization of the function in equation 5. Equation 5 can be minimized using, vertical polarization, horizontal polarization or both vertical and horizontal polarization microwave temperature measures. The performed simulations have shown that the best agreement between observed and simulated soil moisture was obtained when only vertical polarization brightness temperatures are used in the minimization process. This is in line with the correlation coefficients in table 1, which were lower between observed soil moisture and measured horizontal polarization

microwave temperature. Therefore, the retrieval of soil moisture shown below was based on microwave observations at the vertical polarization.

As well, the radiative transfer model was run with the effective temperature corresponding to that measured at one of four levels, 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 to the observed soil moisture at the three different depths. Figure 4 shows an example of the agreement between observed soil moisture at 3 cm depth and simulated values when the four temperatures were used. According to Figure 4, the use of 3 and 7 cm soil temperatures led to an underestimation of soil moisture during the three passes. The best performances were noticed when the 12 cm soil temperatures were used. Table 2 shows the obtained RMSE values when the simulated soil moisture values were compared to the measured ones. First, when the 3 cm soil moisture observations are considered in the assessment of the performance of the radiative transfer model, the agreement between observed and simulated soil moisture seems to be systematically higher when 12 cm surface temperatures are used. During the second and third pass, the obtained RMSE with the 12 cm surface temperature were close to RMSE values obtained with skin temperatures. The agreement was the lowest when the 3 cm temperatures were used. This can be attributed to the effect of existing roots of the mowed grass on the observed temperature and soil moisture, which makes the observation at this depth less relevant for the retrieval of soil moisture.

On the other hand, when soil moisture observations at 7 cm depth are used in the assessment, it was noticed that the RMSE are significantly higher for the three passes, regardless of the depth of the used temperature value. It is important to note that these observations were also subjected to gravimetric correction like the rest of soil moisture observations. However, when 12 cm-depth soil moisture observations are used the agreement between simulated and observed soil moisture improves

significantly and reaches its best RMSE values. The obtained RMSE were also consistent with those obtained with the 3 cm-depth soil moisture values as the lowest values were also obtained when the 12 cm-depth temperatures are observed. Moreover, the RMSE obtained in the third pass tend to be the lowest amongst the values obtained during the experiment with the exception of the values obtained when the 7 and 12 cm temperature were used in pass 1. So, one can conclude that the 12 cm temperatures seem to be representative of the effective temperature of the soil layer that is affecting the microwave signal. These findings are in line with those by (Burke and Simmonds, 2001b) where temperature depth at 11 cm was found to be representative of the effective temperature of the soil layer. This may also suggest that L band microwave signal in the conditions of this experiment provides information on the soil moisture at depths greater than 5 cm.

In addition, three versions of the radiative transfer model were run. First, a version that assumes perfect smooth bare soil conditions as expressed in equation 1 was run. In a second version, only soil roughness was accounted for (equation 4). Finally, both roughness and vegetation parameters were introduced in a third run. Simulations showed that the third scenario that includes both vegetation and roughness parameters gave the lowest RMSE values and therefore the best agreement between the observed and simulated soil moisture. For instance, in the third pass, the RMSE for retrieved soil moisture declined from $0.045 \text{ m}^3/\text{m}^3$ which was obtained when ideal smooth bare soil conditions were assumed to $0.03 \text{ m}^3/\text{m}^3$ obtained with the second scenario to finally reach $0.02 \text{ m}^3/\text{m}^3$ with the third scenario. This implies that it is important to account for both roughness and vegetation, even if it is only short grass remaining on the surface after the mowing.

One of the reasons of the difference between the performances of the retrieval when vertical polarization versus horizontal polarization microwave temperatures is used can be related to the roughness factor. In the model, the same polarization factor “h” was used for both polarizations, which

is a common assumption (Choudhury et al., 1979; Njoku, 1999b). However, recent studies (Jonard et al., 2011b) suggested that using different roughness parameters for the vertical and horizontal microwave temperature can lead to an improved retrieval of soil moisture with respect to using a common roughness parameter for both polarizations.

Despite the quasi bare soil condition, it was demonstrated that the remaining grass after the mowing still has an impact on the performance of the retrieval. Its impact seems to be more significant during the early morning passes where dew is still present with respect to subsequent passes later on in 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) is the same for the vertical and horizontal polarizations.

The prevalence of rocks in the soil of the study field would also have an impact on the radiative transfer and the interaction of the microwave signal with the soil. As well, the rocky nature of the soil in the region should also impact the permeability of the soil and the readings of soil moisture. In this study, soil moisture from TDR and gravimetric observations were used. Gravimetric observations were necessary to calibrate the TDR readings. When collecting the gravimetric samples rocks were excluded, which may introduce a discrepancy between the in situ TDR measures, which is sensitive to rocks, and the gravimetric observations made using rock-free samples.

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., 2003b), and for the upcoming SMAP mission as well, data from early morning passes have been considered for the retrieval of soil moisture, this study in the northeastern US region suggests that the later the microwave observation during the day, the better is

the retrieval of soil moisture. This may suggest that the suitability of microwave observations with respect of their overpass times for soil moisture retrieval may vary in space according to land surface conditions and soil texture. 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 as it is typically obtained from one polar orbiting sensors (Zhan, X. , J. Liu, X. Wang, L. Zhao, K. Jensen, F. Weng, 2012), should account for the difference in overpass time and its impact on the performance of the retrieval.

4. Conclusions

This study places a particular focus on investigating the impact of the diurnal variation of soil temperature on the performance of the retrieval of soil moisture. In addition, the performance of the retrieval has been assessed using soil temperature observed at different depths which is expected to lead to the determination of the effective depth that is contribution to the microwave emission.

The largest discrepancies between soil moisture measurements at lower depth and simulated soil moisture were seen during the pass 2 and pass 3. This is due to instability in daytime surface soil temperature. Further investigation is required to understand the effects of changing soil temperature on the microwave measurements. This is important for accurate retrievals of ground soil moisture conditions from satellite microwave measurements. Although effort was made to develop bare soil conditions by mowing the grass twice, the effect of remaining roots on microwave emission as well as measuring soil moisture using hydra probe need to be understand. Future research using enhanced suite of instruments will include quantifying the vegetation characteristics at the surface and their effect on microwave emissivity.

5. Acknowledgment

We would also like to thank the Cary Institute of Ecosystem studies for hosting the experiment and for their valuable logistic support. Also, we would like to thank Dr. Francois Jonard for his assistance. This study was supported by the National Oceanic and Atmospheric Administration (NOAA) under grants number NA06OAR4810162 and NA11SEC4810004. The statements contained in this article are not the opinions of the funding agency or government, but reflect the views of the authors.

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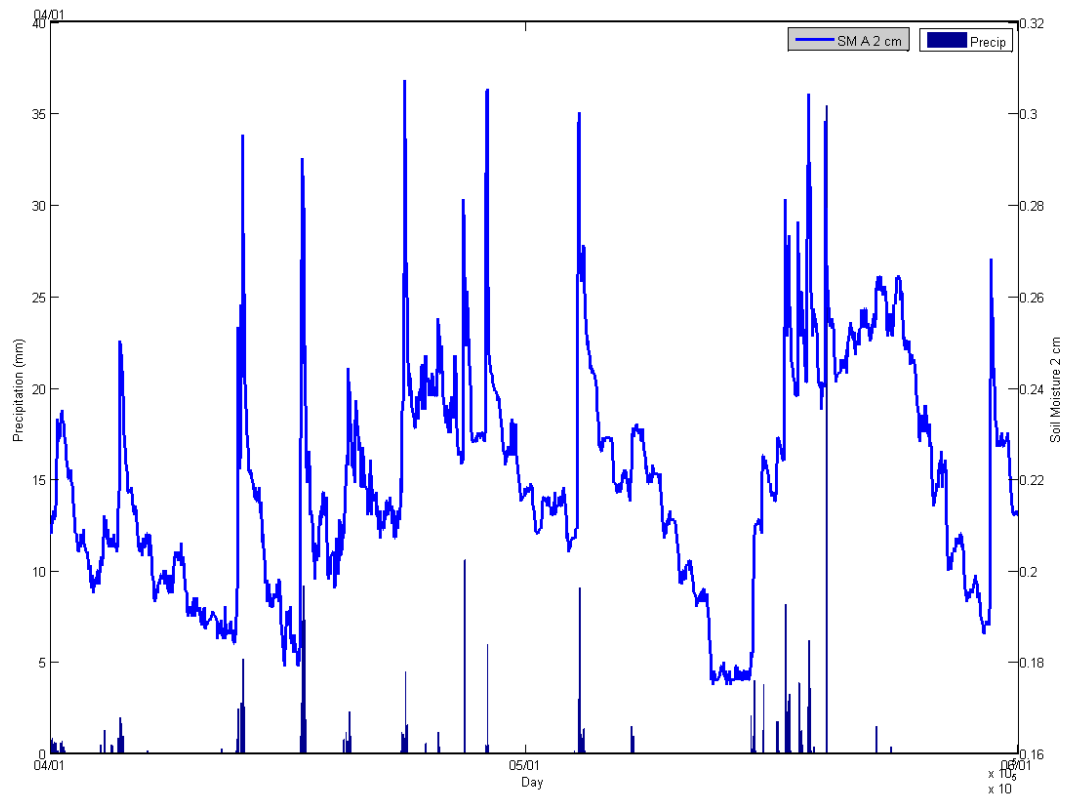


Figure 1 Time series of precipitation and soil moisture observed at study site during April to June 2011

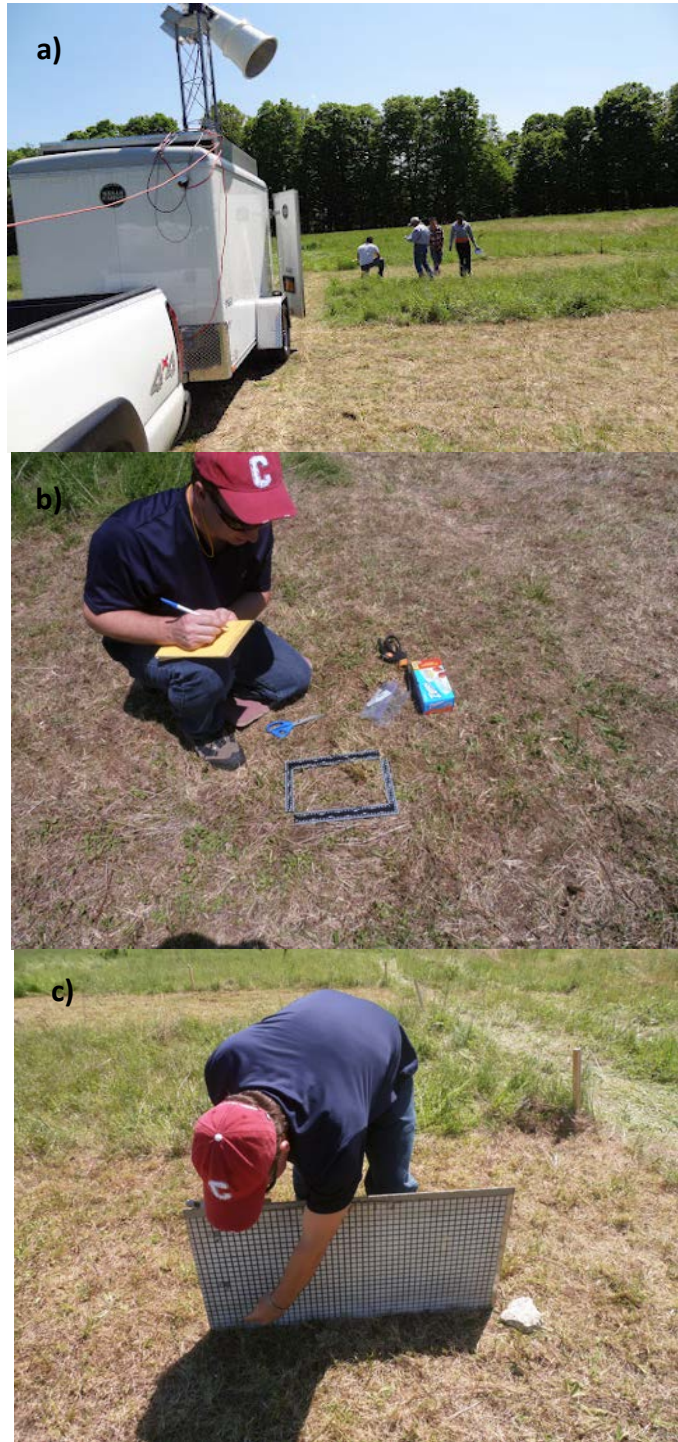


Figure 2: a) The setting and equipment for the field experiment performed on May 16th 2012; b) measuring vegetation water content; c) measuring soil roughness

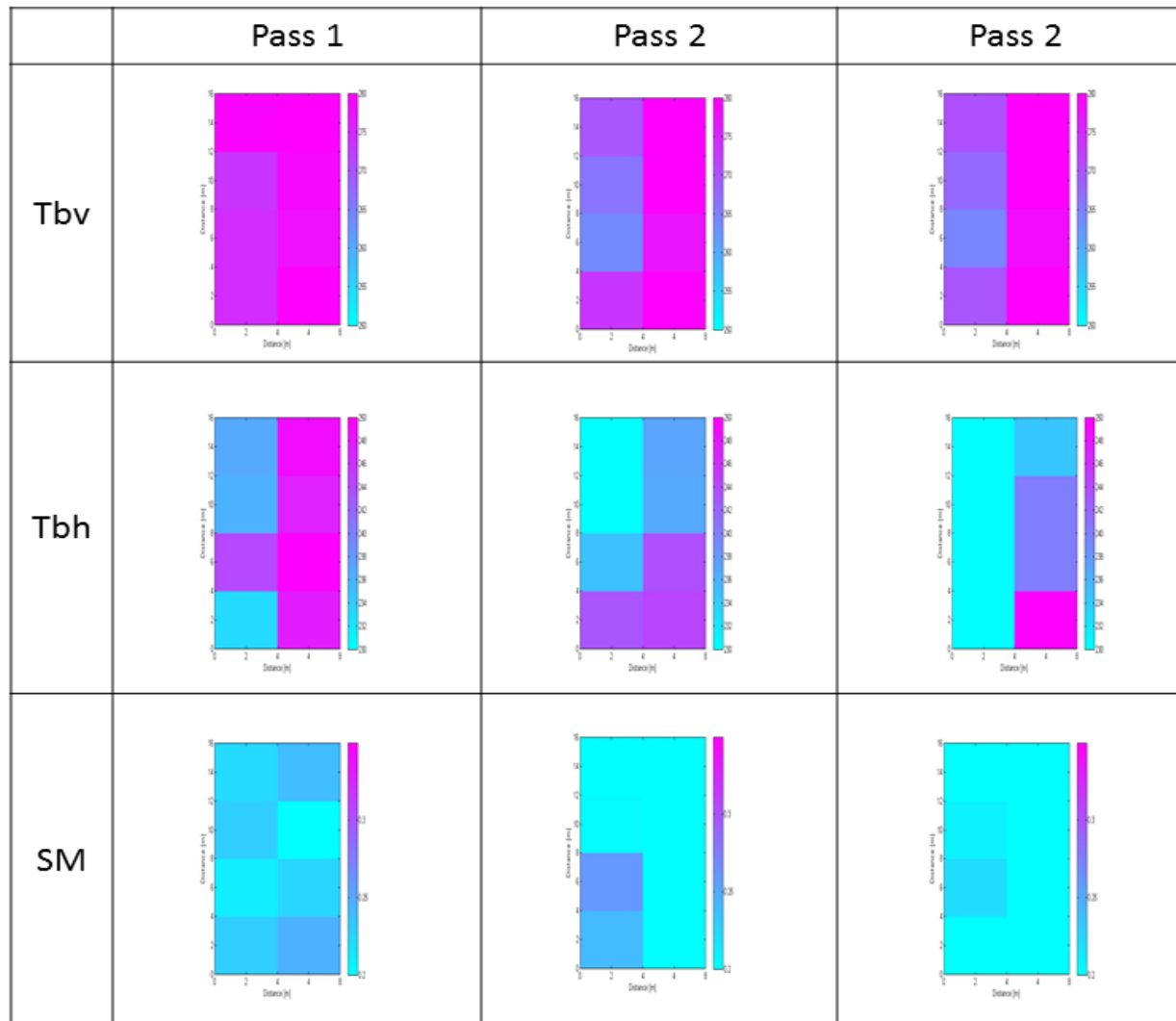


Figure 3 observations of microwave temperature at vertical and horizontal polarization (Tbv and Tbh respectively) and 3 cm depth soil moisture (SM) during the three passes

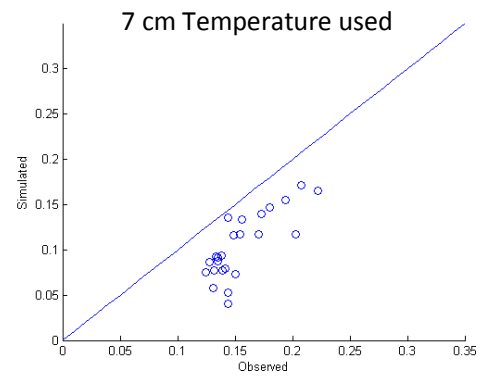
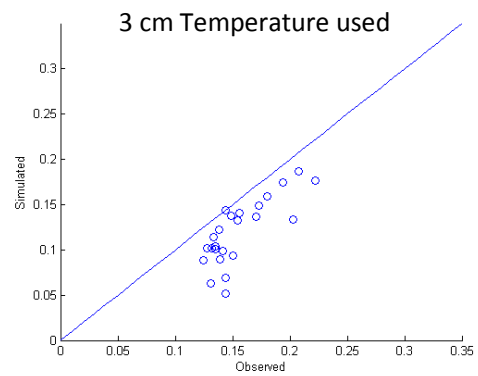
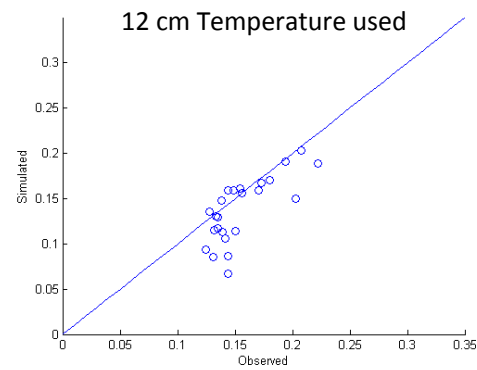
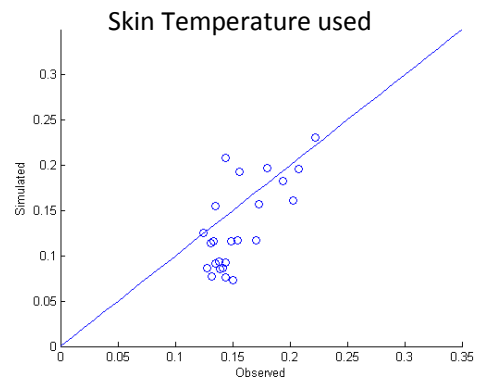


Figure 4 Comparison of observed soil moisture to simulated soil moisture using skin temperature, 3 cm, 7 cm, and 12 cm soil temperatures

Table 1: 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
3 cm	V	0.65	0.76
	H	0.10	0.48
7 cm	V	0.58	0.51
	H	0.05	0.15
12 cm	V	0.71	0.61
	H	0.15	0.28

Table 2 summary of the obtained RMSEs when observed soil moisture at 3, 7 and 12 cm were compared to the simulated values

Pass	RMSE (3 cm soil moisture)			
	Skin Temperature	3 cm temperature	7 cm Temperature	12 cm temperature
Pass 1	0.12	0.12	0.11	0.08
Pass 2	0.048	0.071	0.057	0.04
Pass 3	0.03	0.049	0.04	0.02

Pass	RMSE (7 cm soil moisture)			
	Skin Temperature	3 cm temperature	7 cm Temperature	12 cm temperature
Pass 1	0.15	0.15	0.13	0.10
Pass 2	0.15	0.18	0.16	0.14
Pass 3	0.10	0.16	0.15	0.13

Pass	RMSE (12 cm soil moisture)			
	Skin Temperature	3 cm temperature	7 cm Temperature	12 cm temperature
Pass 1	0.05	0.05	0.03	0.01
Pass 2	0.04	0.06	0.04	0.03
Pass 3	0.04	0.04	0.04	0.03