Microwave Remote Sensing for Soil Moisture Estimation in Tropical Regions – A Review and SMOS L2 Products Validation

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Abstract
The role of soil moisture in the hydrological cycle and climate change monitoring is discussed widely after its designation as an Essential Climate Variable (ECV) by the European Space Agency (ESA). This paper reviews the methods of soil moisture estimation using microwave remote sensing sensors, including the Synthetic Aperture Radar (SAR), Scatterometer, and Radiometer; and the advantages and limitations of using them to estimate soil moisture over tropical regions. The Soil Moisture and Ocean Salinity (SMOS) mission is the first satellite equipped with an L-band radiometer to provide soil moisture products with the best spatio-temporal advantages. Its products have been validated across the world except for the humid tropical regions. An in-situ soil moisture data collection network was set up in Malaysia aimed to provide the first available data to validate SMOS products in the region. This network also aimed to provide data for SMOS retrieval algorithm calibration in the near future. Preliminary result shows unconvincing accuracy between SMOS product and in-situ data.

1. Introduction

Soil moisture generally refers to the amount of water present in the soil pores. The role of soil moisture is important as it is involved in processes such as evaporation, infiltration, and runoff. These processes drive the energy and water fluxes between the surface layer and the atmosphere, thus altering weather conditions. Soil moisture also contributes to the growth of vegetation which is fundamental to food security and national income from agricultural products. It has been designated as one of the Essential Climate Variables (ECVs) and was used to improve climate modeling in the International Panel of Climate Change (IPCC) Fifth Assessment Report (IPCC 2013). Malaysia is located in a humid monsoon tropical region, where the weather is very dynamic which changes the soil moisture. With more than 2500 mm rainfall each year, accurate soil moisture data is very important for prediction of weather, floods and landslides and managing agricultural irrigation, etc. However, accurate soil moisture data are not yet available in Malaysia. *In-situ* soil moisture networks and satellite based remote sensing are both popular methods to acquire soil moisture data. With a long history of equipment development, *in-situ* soil moisture data are normally highly accurate but provide data with limited coverage. A detailed record of available *in-situ* soil moisture networks over the world is shown in Dorigo et al., (2011). Generally, satellite based remote sensing soil moisture estimation has been started since the 1970s (Wang and Qu, 2009). Among different wavelengths, microwave remote sensing shows better capability over optical and thermal wavelengths in estimating soil moisture, especially over tropical regions which have high cloud cover and dense vegetation cover. The launch of the Soil Moisture and Ocean Salinity (SMOS) mission in 2009 by the European Space Agency (ESA) aimed to address the scarcity of global soil moisture data, especially for hydrological research advancement (Kerr et al., 2001). The spatio-temporal advantages of SMOS in providing soil moisture data at a global scale in a routine schedule brings better understanding of soil moisture behaviors especially in areas where soil moisture data are lacking. Since the SMOS product is a good choice to provide soil moisture data in Malaysia, validation of this new satellite product is necessary to ensure its quality. This first part of this paper focuses on reviewing microwave remote sensing methods for soil moisture estimation with an emphasis on the L-band SMOS mission as a suitable product to provide soil moisture data in tropical regions. Secondly, validation activities of SMOS product over different parts of the world are described. Finally, a detailed set-up of the local *in-situ* soil moisture network for the first SMOS product validation within the tropical regions is described and the result is reported.

2. Microwave Remote Sensing for Soil Moisture

Microwave remote sensing detects changes of the dielectric constant with wetter soil having a higher dielectric constant (Seneviratne et al., 2010). The common microwave bands used for remote sensing purposes are X-band (8.0 – 12.5 GHz), C-band (4.0 – 8.0 GHz), and L-band (1.0 – 2.0 GHz) (Lusch, 1999). Microwave remote sensing is classified into two groups, namely active and passive sensing (Martin, 2014). Active microwave sensors radiate a known energy source towards the target and receive the backscattered energy from the target. Synthetic aperture radar (SAR) and scatterometers both work in this active form while passive microwave sensors, i.e. radiometers, records the emitted signal from the target as brightness temperature. Examples of sensors operating in active and passive modes are listed in Table 1.

2.1 Synthetic Aperture Radar (SAR)

Satellite missions using SAR sensors for soil moisture estimation include the ERS series, ENVISAT, and the RADARSAT series. All of these sensors operate at C-band, except for the L-band ALOS PALSAR sensor. The advantage of SAR systems is that they provide fine spatial resolution and these systems are found to perform well with strong correlation (R > 0.70) with *in*-situ data e.g. (Haider et al., 2004, Paloscia et al., 2010, Quesney et al., 2000 and Zribi et al., 2007). However, their major drawbacks are the foreshortening, speckle, and shadow effects in addition to the narrow swath width which prolongs the revisit period. Combining the C-band data from different viewing angles or passing days can improve the temporal issues (Baghdadi et al., 2007). However, the proposed temporal coverage, i.e. two or three times a month is not sufficient to cope with the dynamic changes of soil moisture in tropical regions.

2.2 Scatterometer

The ERS-1 and 2 scatterometer (SCAT) as well as their successor, the MetOp-Advance Scatterometer (ASCAT) are popularly used to estimate soil moisture. A scatterometer provides soil moisture data with wider spatial coverage and without the foreshortening and temporal disadvantages found with SAR. Pulliainen et al., (1998) found soil moisture estimated by SCAT performed better during dry periods than wet periods, where canopy cover is less and precipitation events are fewer. This finding raised a question of the suitability of C-band scatterometry to estimate soil moisture in the tropical region which is often covered with dense vegetation and has a high precipitation rate. C-band scatterometry to estimate soil moisture was continued using MetOp-ASCAT data after both ERS-1 and 2 satellite ended their operation. Equipped with a dual-side viewing sensor, ASCAT collects data at a faster speed. Bartalis et al., (2007) are among the pioneer researchers who demonstrated the relationship of SCAT and ASCAT derived soil moisture data.

Table 1: Details of microwave remote sensing satellite sensors for soil moisture estimation

Group	Type	Satellite mission	Instrument	Operational period	Band[a]	Spatial resolution	Temporal resolution (days)
Active	SAR	ERS 1	AMI	1991 - 1999	C-band	30 m	35
		ERS 2	AMI	1995 - 2011	C-band	30 m	35
		ENVISAT	ASAR	2002 - 2012	C-band	30 m	35
		ALOS	PALSAR	2006 - 2011	L-band	10 m	46
		RADARSAT	SAR	2007 - 2013	C-band	10 – 100 m	24
	Scatterometer	ERS 1	AMI	1991 - 1999	C-band	50 km	3 - 4[b]
		ERS 2	AMI	1995 - 2011	C-band	50 km	3 - 4[b]
		MetOp series	ASCAT	2006 - current	C-band	25 km	1 - 2
Passive	Radiometer	DMSP series	SSM/I	1987 - current	C-band	12.5 km	1[c]
		TRMM	TMI	1997 - current	C-band	5 km	1[c]
		Aqua/Terra	AMSR-E	2002 - 2011	C-band	25 km	1
		SMOS	MIPAS	2009 - current	L-band	40 km	1 - 3
		SMAP	--	Jan 2015	L-band	40 km (3km)	1 - 3

[a]The common band chosen for the respective sensor to map soil moisture
[b]Temporal resolution depends on the sensor operation since both SAR and the Scatterometer on ERS-1 & 2 cannot operate at one time
[c]Frequent temporal resolution with the constellation of satellites

They found positive results at a global scale except for the tropical and snow-covered regions where signal-to-noise ratio (SNR) were less than 10. The low SNR values indicated that the retrieval of soil moisture data using ASCAT signal is impossible.

2.3 Radiometer

Apart from active SAR and scatterometry systems, passive radiometry is another source of data for soil moisture estimation. Among the systems listed in Table 1, products from SMM/I and AMSR-E are more frequently assessed. Basist et al., (2001) used more than 44,000 ground collected temperature data with brightness temperature from the SSM/I radiometer over 6 years to generate the Basist Wetness Index (BWI). The data covered six different land types and it can be considered as the first available radiometer-derived soil moisture data at a global scale. Unfortunately, the detection of soil moisture in desert and densely vegetated area are found to be unconvincing due to BWI tending to show zero values in these two land types. By knowing the potential of microwave radiometry to estimate soil moisture, the launch of AMSR-E onboard the Aqua/Terra satellite presented a new and more compatible dataset for soil moisture estimation. Validation of AMSR-E soil moisture data was performed extensively in various regions (Al-Jassar and Rao, 2010, Bindlish et al., 2006, Draper et al., 2009 and Rao et al., 2006). As the studies use different validation approaches, it produced diverse and inconclusive outcomes which put the reliability of AMSR-E derived soil moisture products under question. Meanwhile, to verify the accuracy of AMSR-E soil moisture data over tropical forest, Kang and Kanniah (2013) validated the product using soil moisture data measured at a flux tower site equipped with a soil moisture sensor at 5 cm depth for a period of 2 years in Malaysia. The result shows a low correlation ($R^2 < 0.01$). Moreover, AMSR-E was found unable to capture the daily pattern of soil moisture over the study period. This again shows that soil moisture products derived from AMSR-E are not representative of the tropical region. This also agreed with the general theory that C-band has low penetration in densely vegetated areas, causing the data received by the sensor to be mainly from canopy rather than the soil surface. However, it should be noted that Kang and Kanniah (2013) validated the AMSR-E product of 25 km with a single point in the forested area which may not representative of the soil moisture variation over 25 km. A more compatible design of *in-situ* - soil moisture network is needed to improve further validation activities. Rather than applying only one data point to estimate soil moisture, Romshoo and Musiake (2004), De Jeu et al., (2008) and Liu et al., (2011) combined C-band data collected by various sensors to map soil moisture. Liu et al., (2012) presented a global soil moisture map based on products acquired by SMMR, SSM/I, TMI, AMSR-E (passive sensors), SCAT and ACSAT (active sensors). The time-series of the data span from January 1979 to December 2008, which covers nearly 30-year period. Despite merging of various soil moisture products, the study still showed scarcity of soil moisture data over the tropical region [see figure 14 in Liu et al., (2012)]. This is due to the fact that the available data products are collected using wavelengths shorter than or equal to C-band, which produce significant noise (from scattering, penetration depth problems, etc.) in tropical regions. Therefore, high quality soil moisture estimation over tropical regions is still unavailable.

2.3.1 L-Band radiometer for soil moisture estimation

L-band radiometer has become recent trend for soil moisture estimation as it is capable of providing high penetration and high temporal revisit. ESA is among the first to initiate the L-band radiometer mission for soil moisture estimation by selecting Soil Moisture and Ocean Salinity (SMOS) as the second Earth Explorer Opportunity mission (Kerr et al., 2000). SMOS was launched on 2nd November 2009 into a sun-synchronous polar orbit at an altitude of 758 km above earth surface. The main objectives of SMOS are global surface soil moisture estimation with an accuracy of ±0.04 $m^3 m^{-3}$ at <50 km spatial resolution in 3 days interval and estimation of global ocean salinity with accuracy of 0.1 – 0.2 practical salinity unit (psu) at 100 – 200 km spatial resolution within 30 days (Kerr et al., 2010). The MIRAS instrument, a 2D interferometric radiometer operating at L-band (wavelength ~21 cm), applied the technique of very large baseline interferometers (VLBI). A Y-shaped array with 69 elementary antennas which was folded in three folds during launching, was deployed right after the satellite was fit into the orbit (Drinkwater et al., 2009). This design has made the launch of L-band radiometer mimic the sensor carried by Skylab-1. Further details of the mission can be found at ESA webpage (https://earth.esa.int).

3. Validation of SMOS Soil Moisture Products

Validation studies of the SMOS Level 2 Soil Moisture Product are listed in Table 2. They were generally conducted over areas with latitude higher than 30^0 N or S, while study within the tropical regions is yet to be available. Results from statistical analysis for the respective studies are summarized in Table 2 and the lowest and highest bias found among them are -0.021 m^3m^{-3} and -0.23 m^3m^{-3} respectively. It is noticeable that SMOS L2 soil moisture product always underestimates soil moisture when compared to the ground measurements. Another remark that can be made here is that only the results from Jackson et al., (2012) and Al Bitar et al., (2012) (for the REPv4 product) met the SMOS objective, which is to produce soil moisture within a bias of 0.04 m^3m^{-3}. In the case of correlation or coefficient of determination (R/R^2), statistical plots showed high variance of these variables regardless of the study area, suggesting that the stability of SMOS L2 Soil Moisture Product is yet to be clarified.

Table 2: Results of conducted SMOS Level 2 products validation activities

Reference	Location	Accuracy			Field data network density
		Bias	RMSE	r	
dall'Amico et al., (2012)	Danube catchment, Germany	-0. 23	-	-	60 stations / 101 km^2
Jackson et al., (2012)	4 watersheds over The U.S	-0.023 - 0.026	0.038 - 0.051	0.152 - 0.809	WZ : 21 stations / 148 km^2 LW: 16 stations / 610 km^2 LR : 29 stations / 334 km^2 RC : 19 stations / 238 km^2
Bircher et al., (2012)	Western Denmark	-	0.092	0.700	30 stations / 30 km^2 *30 stations were divided into 3 clusters within 10 km^2 area.
Al Bitar et al., (2012)	SCAN/SNOTEL networks, The U.S.	REPv4: -0.021 DPGS: -0.069	REPv4: 0.057 DPGS: 0.044	-	335 stations over the U.S. continent
Sanchez et al., (2012)	Duero Basin, Spain	-	0.069	0.73	20 stations / 35 km^2
(Lacava et al., (2012))	2 areas in Italy (SPC, CER) Luxembourg (BIB)	CER:-0.065 SPC: 0.058 BIB: -0.107	CER: 0.108 SPC: 0.100 BIB: 0.127	CER: 0.345 SPC: 0.582 BIB: 0.537	Information not available

*Accuracy values shown in the table is regardless the version of SMOS L2 Product used unless specified
**Bias and RMSE units are reported in m^3 m^{-3}

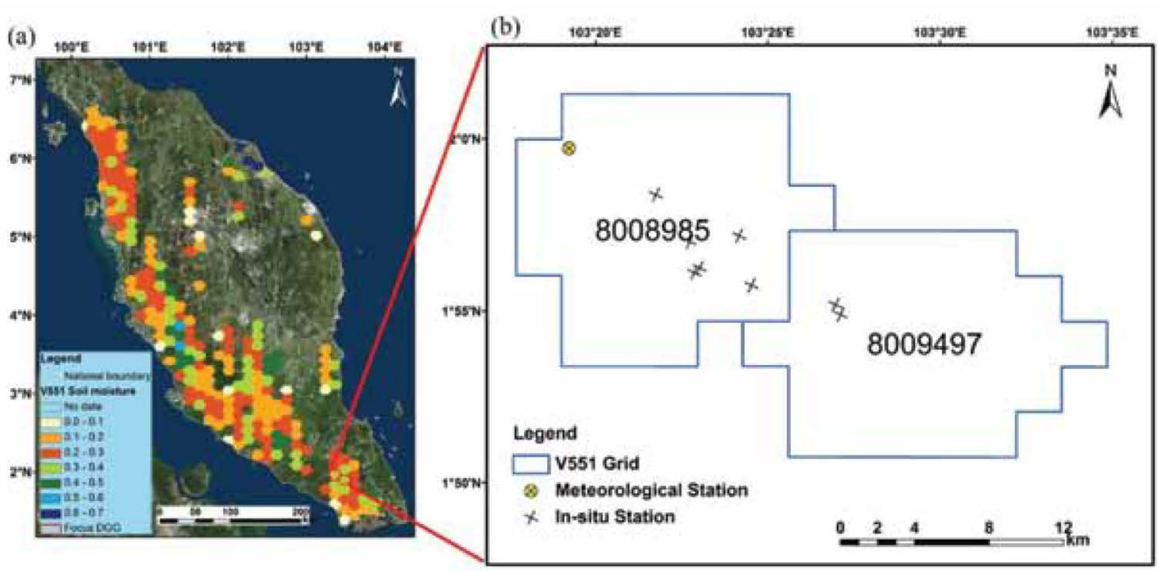

Figure 1: (a) Sample of SMOS Soil Moisture Product over Peninsular Malaysia on 2nd August 2014; (b) Map of the selected DGGs and the location of *in-situ* soil moisture stations and the meteorological station which collecting data for SMOS Soil Moisture Products Validation

These studies concluded that further validation activities are required to investigate and to build a better retrieval model that can provide compatible soil moisture data over the world. The last column of Table 2 reports the density of *in-situ* soil moisture data collection station used in these validation studies. This analysis aims to provide an insight on the number of stations needed in a single SMOS pixel for the validation. We noticed that there is no consistent method applied or rule of thumb to follow during the building of these networks. A conclusive remark on the best density of stations within a SMOS pixel is unavailable. Therefore, the design of the local *in-situ* soil moisture network strongly relies on the budget and the accessibility of the sites among other factors. Figure 1 (a) shows the samples of soil moisture data derived from SMOS Soil Moisture Product acquired on 2nd August 2014 over Peninsular Malaysia. This product is retrieved from the SMOS Version 551 algorithm and downloaded from the Earth Observation Link (EOLi) supported by the ESA. From the map shown, we can observe that most of the estimated soil moisture falls within 0.01 – 0.03 m^3m^{-3}. The forest area located mainly in the center part of Peninsular Malaysia shows no successful retrievals. This is due to the nature of the SMOS retrieval algorithm which is unable to perform retrieval when vegetation water content is found to be higher than 5 kgm^{-2}. Due to the lack of *in-situ* soil moisture data collection system in the tropical region, we took the initiative to set up a data collection network in Kluang District, Johor, Malaysia. A total of 8 systems were installed, where half of them are placed in an oil palm plantation and another half in pasture lands. Malaysia Palm Oil Board (MPOB) and Malaysia Agricultural Research and Development Institute (MARDI) are both parties who provided us access to their lands for sensor installation and subsequent data collection. All of these stations are located within the selected focus Discrete Global Grid (DGG) and their specific location is shown in Figure 1 (b). Since the size of each DGG is around 15 km^2, it is quite impossible to find an area which is homogeneous throughout the grid. However, the selection of these two sites where over 80% of the lands are covered with oil palm plantation with minimal urban and water surface, are optimum for validation activities over densely vegetated area. Each station consists of three soil moisture sensors collecting readings at different depths (5 cm, 50 cm and 100 cm depths), soil temperature sensor at the surface, and a data logger equipped with temperature and relative humidity sensors. All the equipment is produced by Spectrum Technologies Inc., manufactured in the USA. The data collection interval is set at an hourly basis. The installation of the *in-situ* soil moisture data collection network was completed and data have been collected continuously since June 2014. The *in- situ* soil moisture data measured at 5 cm depth is being used for SMOS Soil Moisture Products validation. The accuracy assessment of SMOS L2 Soil Moisture Products against the *in-situ* data was conducted by measuring the bias, root mean square error (RMSE) and the correlation (*r*) between the two datasets, using the following equations:

$$\text{Bias} = \frac{\sum(\text{SM}_{Sat} - \text{SM}_{in-situ})}{\text{n}}$$

Equation 1

$$\text{RMSE} = \sqrt{\frac{\sum(\text{SM}_{Sat} - SM_{in-situ})^2}{n}}$$

Equation 2

Where SM_{Sat} and $SM_{in\text{-}situ}$ refers to the soil moisture estimated by SMOS and collected at the field, respectively, *n* is the number of retrievals.

$$r = \frac{n\sum xy - (\sum x)(\sum y)}{\sqrt{n(\sum x^2) - (\sum x)^2}\sqrt{n(\sum y^2) - (\sum y)^2}}$$

Equation 3

Where *x* refers to SM_{Sat} and *y* refers to $SM_{in\text{-}situ}$, respectively.

4. Validation Results and Discussions

Validation on one year of SMOS L2 Soil Moisture Products (Version 5.51) spanning from 1st June 2014 to 31st May 2015 is conducted. Table 1 listed the computed bias, RMSE and r for both DGGs, including the retrievals from ascending and descending nodes. High biases and RMSE values were found in all the assessments, which do not achieve the target of SMOS mission to retrieve soil moisture with an accuracy below 0.04 m^3 m^{-3}. The positive signed bias values can be explained as the overestimation of SMOS product retrievals, assuming that the *in-situ* data is providing the correct soil moisture. The reasons of the overestimation could be the presence of dense vegetation cover at the study area which influence the emitted signal received by the instrument and lead to retrieval errors. Correlation coefficient (*r*) between the two datasets was computed and low *r* values was found for DGG 8008985 while moderate *r* values were found for DGG 8009497. Based on Figure 1 (b), six out of eight *in-situ* stations are installed in DGG 8008985, while the remaining two stations are installed in DGG 8009497. All these stations are not well distributed within each DGG. In DGG 8008985, four stations are installed on the pasture land and another two are on oil palm land. The difference of land cover type within a DGG might be one of the reasons for the low *r* values. For DGG 8009497, the two stations were installed on oil palm land. Despite there is only two stations available, the *r* values are higher than the other DGG selected in this study (Table 3).

Table 3: Accuracy assessment results of the selected DGGs for ascending and descending pass (superscript A and D, respectively)

DGG	Bias	RMSE	*R*
8008985^A	0.112	0.149	0.006
8008985^D	0.095	0.114	0.196
8009497^A	0.119	0.145	0.550
8009497^D	0.067	0.094	0.540

5. Conclusion

The review of the remote sensing based soil moisture estimation methods concludes that the recent launched SMOS mission with its L-band radiometer is the most suitable sensor for global soil moisture estimation due to its spatio-temporal and vegetation penetration advantages, especially in the tropical regions. Previously reported SMOS validation activities conducted at different regions showed inconsistent results, where most of them do not fulfill the accuracy set by the SMOS mission (± 0.04 m^3m^{-3}). An *in-situ* soil moisture data collection network was set up over the tropical region. The *in-situ* data stations include the collection of soil moisture at deeper layers (50 cm and 100 cm) and surface soil temperature. These measurements are useful for future study related to root zone soil moisture validation and estimation, which is also one of the objectives of SMOS mission to increase the understanding of the roles of surface and root zone soil moisture in the hydrological cycle. Preliminary validation results between the SMOS L2 Soil Moisture Products and *in-situ* soil moisture data at 5 cm depth was conducted over a densely vegetated area. Results showed that there is still room for improvements for the SMOS products to meet the targeted accuracy. This can be done by calibration of the retrieval algorithm with the input of local derived parameters to replace the existing ones. The use of local instead of global generalized datasets in the retrieval algorithm can help to provide site-specific information to improve the accuracy of SMOS product over the world.

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