Satellite Products and Services Review Board

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LIST OF ACRONYMNS

AMSR2	Advanced Microwave Scanning Radiometer 2
AMSR-E	Advanced Microwave Scanning Radiometer for EOS
ASCAT	Advanced Scatterometer
ATBD	Algorithm Theoretical Basis Document
AVHRR	Advanced Very High Resolution Radiometer
DDS	Data Delivery Subsystem
EDR	Environmental Data Record
EMC	Environmental Modeling Center
EOS	Earth Observing System
ESA	European Space Agency
GAASP	GCOM-W1 AMSR2 Algorithm Software Processor
GCOM-W1	Global Change Observation Mission 1st – Water
GFS	Global Forecast System
GLDAS	Global Land Data Assimilation System
JAXA	Japanese Aerospace Exploration Agency
JPSS	Joint Polar Satellite System
LSM	Land Surface Model
MODIS	Moderate Resolution Imaging Spectroradiometer
NDE	NPOESS Data Exploitation
NCDC	National Climate Data Center
NGDC	National Geographic Data Center
NDVI	Normalized Difference Vegetation Index
NESDIS	National Environmental Satellite, Data, and Information Service
NOAA	National Oceanic and Atmospheric Administration
NPOESS	National Polar-orbiting Operational Environmental Satellite System
NPP	NPOESS Preparatory Project
NWP	Numerical Weather Prediction
NWS	National Weather Service
NRL	Naval Research Laboratory
R&D	Research & Development
OSPO	Office of Satellite and Product Operations
SMOPS	Soil Moisture Operational Product System
SMAP	Soil Moisture Active Passive
SMOS	Soil Moisture and Ocean Salinity
STAR	Center for Satellite Applications and Research
TB	Brightness Temperature

ABSTRACT

This document is the Algorithm Theoretical Basis Document (ATBD) for the Advanced Microwave Scanning Radiometer 2 (AMSR2), on board GCOMW-W1 (Global Change Observation Mission – Water), Soil Moisture Environmental Data Record (EDR) developed by the NOAA/NESDIS Center for Satellite Applications and Research (STAR). The main retrieval algorithm used in this EDR is the Single Channel Retrieval (SCR) algorithm. This document describes the details of the SCR algorithm, its parameterization and some results and preliminary validations.

1. INTRODUCTION

Land surface soil moisture status controls the sensible and latent heat exchanges between the land surface and atmosphere. These heat exchanges are among the major energy sources for atmospheric motions. Thus, reliable global soil moisture data products and techniques for assimilating them into numerical weather prediction models are believed to have significant impacts for weather forecast accuracy. Microwave satellite remote sensing provides practical way of providing near real time global soil moisture products for weather prediction model needs.

The Advanced Microwave Scanning Radiometer 2 (AMSR2) on JAXA's Global Change Observation Mission – Water "SHIZUKU" (GCOM-W1) was launched in May 17, 2012, and its observations can be used for soil moisture retrievals. It flies in a sun-synchronous orbit as part of the "A-train" satellite constellation. It successfully began collecting data on July 4, 2012. Its planned lifespan of 5 years means that the satellite is set to operate until 2017. AMSR2 is the successor to the AMSR-E carried by NASA's Aqua satellite.

1.1 Existing products

Currently, there are a number of microwave satellite soil moisture products operationally produced from different sensors, including the Soil Moisture and Ocean Salinity (SMOS) from the European Space Agency (ESA), the Advanced Scatterometer (ASCAT) on EUMETSAT's MetOp-A and –B satellites, and the Advanced Microwave Scanning Radiometer 2 (AMSR2) on the GCOM-W1 satellite. Active and passive microwave remote sensing has been shown to be a reliable tool for surface soil moisture retrievals as it is one of the key factors that control the emissive and scattering characteristics of soil surface. These products vary in both data quality and data latency. Some of these products are produced just for research purpose only while some of them are operationally produced for near-real time use. To be able to be used in NOAA Global Forecast Model (GFS) model, a soil moisture product must be produced with data latency within 6 hours. None of these currently available soil moisture products could provide a reasonable spatial coverage within this time latency requirement. To make effective use of all available microwave-based datasets, a Soil Moisture Operational Product System (SMOPS) has been developed at NOAA/NESDIS which has been operational since 2013. This system not only provides global soil moisture data products from individual sensors, such as MetOp-A and –B ASCAT of EUMETSAT, WindSat of Naval Research Laboratory (NRL) and SMOS of ESA, but also provides a blended analysis from all these products. SMOPS produces a 6-hour product with 3 hour latency and a daily product with 6-hour latency for operational use. Since the merged soil moisture product from SMOPS is from all available soil moisture data produced by individual satellite sensors within a given time latency, the more input products, the better the spatial coverage of the blended product will be. Ingesting GCOM-W1 AMSR2 soil moisture product will surely improve the spatial coverage of SMOPS soil moisture product.

1.2 Purpose of This Document

As an effort of the Joint Polar Satellite System (JPSS) of NOAA and NASA, scientists at NOAA-NESDIS Center for Satellite Applications and Research (STAR) have tested an alternative single channel algorithm (SCA) for generating global soil moisture data product from low frequency microwave satellite sensors such as AMSR-E, TMI and WindSat. Comparing with the in situ soil moisture measurements for sites around United States, the retrievals from the SCR algorithm demonstrated reasonably good quality. To meet the data needs at NOAA National Centers for Environmental Predictions (NCEP), NESDIS-STAR is tasked to develop a AMSR2 Soil Moisture EDR that will be operationally produced by GCOM-W1 AMSR2 Algorithm Software Processor (GAASP). This AMSR2 SM EDR will be ingested into SMOPS to improve its quality and spatial coverage. This document describes the algorithm for producing this product and some validation results.

1.3 Document Overview

This document contains the following sections:

Section 1.0 - Introduction
Section 2.0 - AMSR2 SM EDR Overview
Section 3.0 - Description of Algorithms
Section 4.0 - Assumptions and Limitations
Section 5.0 - List of References

2. AMSR2 SM EDR OVERVIEW

2.1 Objectives of Soil Moisture Retrievals

The National Centers for Environmental Prediction (NCEP) Global Forecast System (GFS) and North American Mesoscale Model (NAM), and their associated assimilation systems, include a land surface model (LSM) component that requires soil moisture information for accurate weather and seasonal climate predictions. Currently, surface soil moisture is estimated via the background simulation of the LSM of the assimilation system. This simulated soil moisture contains considerable biases and uncertainties. A satellite-based global soil moisture observational data product will provide a substantial constraint that is expected to greatly reduce these uncertainties and thereby improve the global and mesoscale model forecast accuracy.

To meet NCEP's soil moisture data needs, NESDIS is supporting the SMOPS project to develop a global soil moisture product by blending available operational soil moisture products from different sensors, including the Advanced Scatterometer (ASCAT) on EUMETSAT's MetOp-A and MetOp-B satellites, European Space Agency (ESA) Soil Moisture and Ocean Salinity (SMOS) satellite, and WindSat on Naval Research Laboratory (NRL)'s Coriolis satellite. AMSR2 soil moisture EDR will be another product that will be ingested into SMOPS to increase its spatial and temporal coverage.

2.2 AMSR2 Instrument

The Advanced Microwave Scanning Radiometer 2 (AMSR2) onboard the GCOM-W satellite is a remote sensing instrument for measuring weak microwave emission from the surface and the atmosphere of the Earth. From about 700 km above the Earth, AMSR2 will provide us highly accurate measurements of the intensity of microwave emission and scattering.The antenna of AMSR2 rotates once per 1.5 seconds and obtains data over a 1450 km swath. This conical scan mechanism enables AMSR2 to acquire a set of daytime and nighttime data with more than 99% coverage of the Earth every 2 days. GCOM-W1 is part of the "A-train" constellation along with Aqua. AMSR2 and AMSR-E have the same center frequencies and corresponding bandwidths and is considered as the successor to AMSR-E. AMSR2 has several enhancements: larger main reflector, additional 7.3 GHz channels, an improved calibration system (Imaoka et al., 2010), and improved spatial resolution (Table 2.1).

Table 2.1 – AMSR2 performance characteristics

Center Freq.	Band width	Pol.	Beam width	Ground res.	Sampling interval
GHz	MHz		degree	km	km
6.925/7.3	350	V/H	1.8	35 x 62	10
10.65	100		1.2	24 x 42	
18.7	200		0.65	14 x 22	
23.8	400		0.75	15 x 26	
36.5	1000		0.35	7 x 12	
89.0	3000		0.15	3 x 5	5

3. ALGORITHM DESCRIPTION

3.1 Algorithm Input

3.1.1 AMSR2 Brightness Temperature

AMSR2 brightness temperature data are Level 1b calibrated microwave brightness temperatures produced by GAASP.

3.1.2 Ancillary Data

The ancillary data for the SCR algorithm include land cover map, clay map and sand map, and porosity map, and land cover parameters.

3.1.2.1 Land Cover Map

The global land cover map is needed in this algorithm mainly for a land/water mask and to correctly set the Quality Assessment (QA) for areas where the soil moisture retrieval capability of SCR algorithm is weak, such as densely forested area.

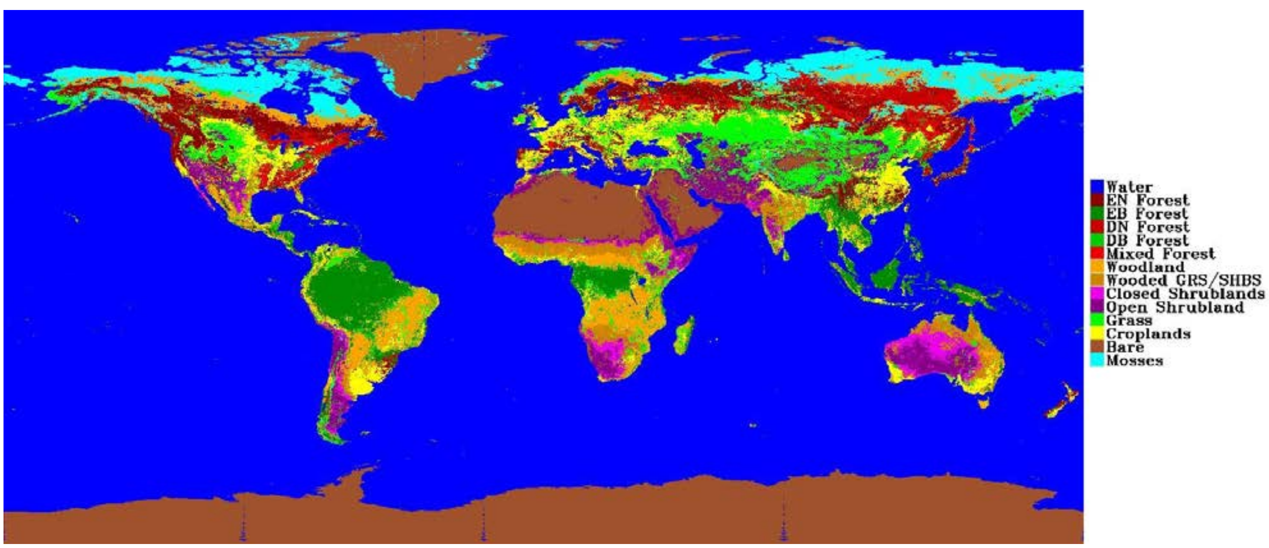


Figure 3.1.1 – Land Cover Map Used by the SCR Algorithm.

The land cover map used in this algorithm is the 8-km land cover map produced by University of Maryland Geography Department (Figure 3.2.1). Land cover type rarely changes at AMSR2 footprint size level, therefore, the static land cover map is sufficient.

Table 3.1 lists the land cover code in the land cover map and QA configuration.

Table 3.1 – Land Cover Types

Code	Land Cover Type
0	Water
1	Evergreen Needleleaf Forests
2	Evergreen Broadleaf Forests
3	Deciduous Needleleaf Forests
4	Deciduous Broadleaf Forests
5	Mixed Forests
6	Woodlands
7	Wooded Grasslands/Shrubs
8	Closed Bushlands or Shrublands
9	Open Shrublands
10	Grasses
11	Croplands
12	Bare
13	Mosses and Lichens

3.1.2.2 Clay Map

A clay fraction map is used in the SCR algorithm as input of the Dobson mixing model. The clay map (Figure 3.1.2) is from Food and Agriculture Organization (FAO, Reynolds et al. 2000). It has a 5-arcmin spatial resolution, which is equivalent to a 9 km x 9 km cell size at equator.

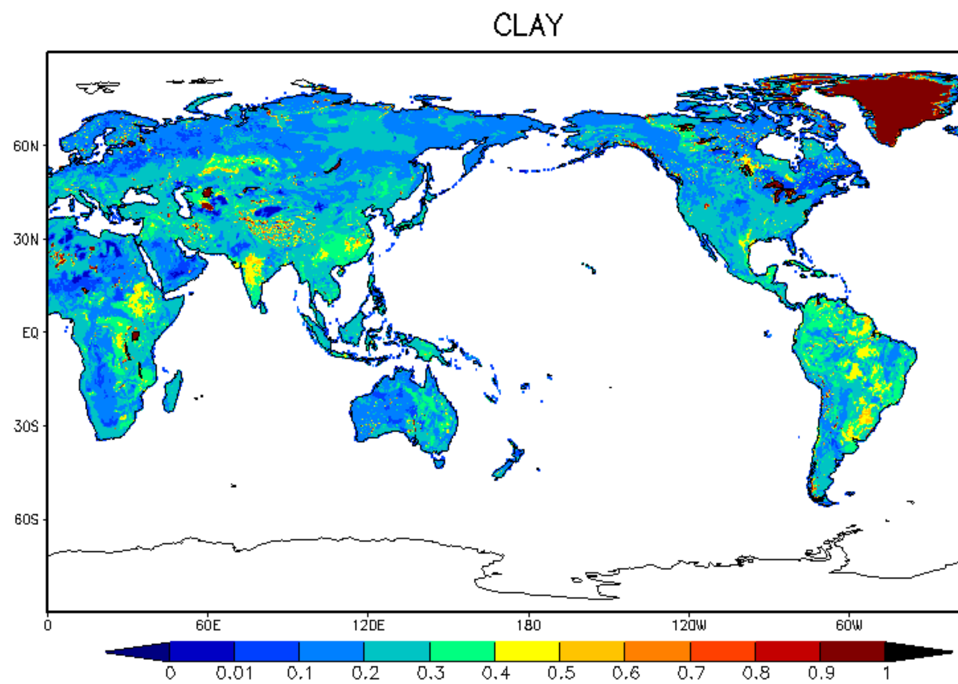


Figure 3.1.2 – Clay Fraction Map Used by the SCR Algorithm

3.1.2.3 Sand Map

A sand fraction map is used in the SCR algorithm as input of the Dobson mixing model. The sand map (Figure 3.1.3) is from FAO (Reynolds et al., 2000) with the same spatial resolution as the clay map.

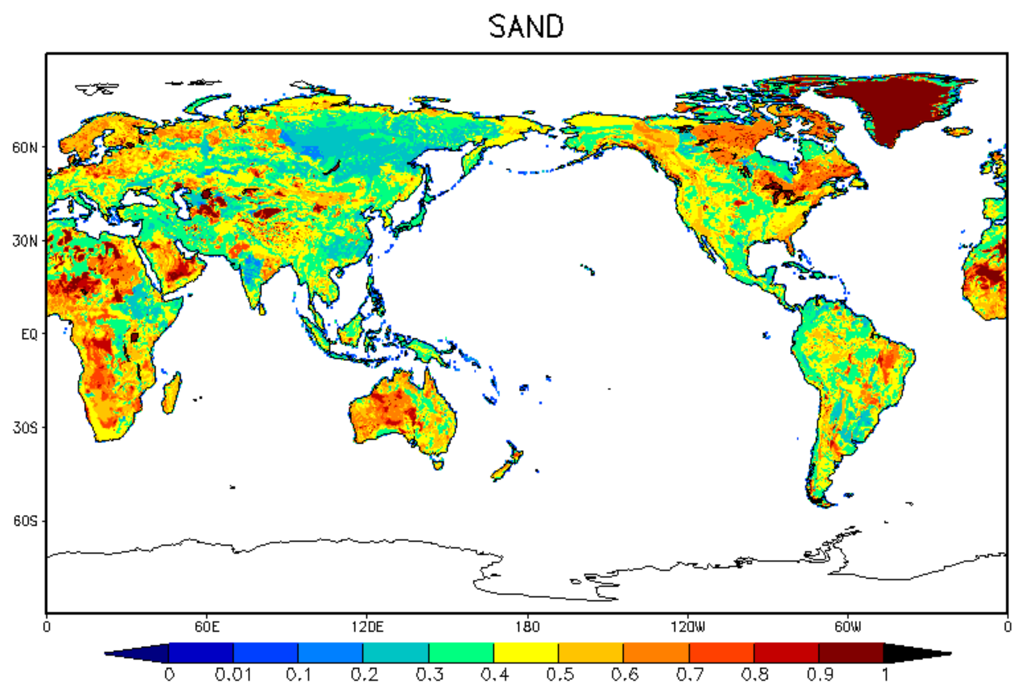


Figure 3.1.3 – Sand Fraction Map Used by the SCR Algorithm

3.1.2.4 Porosity Map

Soil porosity is used in the SCR algorithm as input of the Dobson mixing model. The porosity map (Figure 3.1.4) is from FAO (Reynolds et al., 2000) with the same spatial resolution as the clay map and sand map.

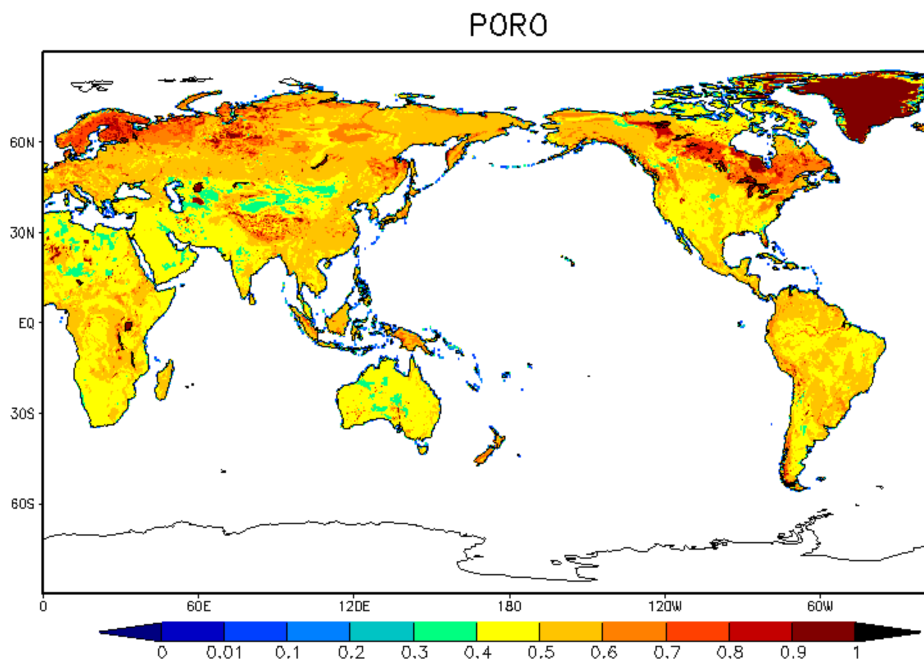


Figure 3.1.4 – Porosity Map Used by the SCR Algorithm

3.2 Theoretical description of soil moisture retrieval (SCR) algorithm

The SCR method used in GAASP SM EDR is mainly based on an algorithm developed by Jackson (1993). In this approach, brightness temperature from a single channel is converted to emissivity that is further corrected for vegetation and surface roughness effect. The Fresnel equation is then used to determine the dielectric constant and a dielectric mixing model is used to obtain the soil moisture.

3.2.1 Brightness Temperature / Emissivity Relation

The major input for this algorithm is the 10.7 GHz H-pol brightness temperature, Tb, from AMSR-E sensor, which includes contributions from the land surface, the atmosphere, and reflected sky radiation. Considering the latter two are negligible at the frequency we are using, the relationship between land surface emissivity, e_s, and Tb for pure soil can be expressed as

$$T_b = eT_s \tag{3.1}$$

where T_s is the soil effective temperature. If T_s is estimated independently, emissivity can then be determined.

In the case where there is vegetation above the soil, the above forward microwave emission model can be expressed as

$$T_{Bp} = T_s e_{r,p} \exp(-\tau_p / \cos\theta) + T_c (1-\omega_p)$$
$$[1-\exp(-\tau_p / \cos\theta)][1+R_{r,p} \exp(-\tau_p / \cos\theta)] \tag{3.2}$$

where, the subscript p refers to polarization (H or V) and subscript r stands for rough surface, T_s is the soil skin temperature, T_c is the vegetation temperature, τ_p is the nadir vegetation opacity, ω_p is the vegetation single scattering albedo, and $R_{r,p}$ is the soil reflectivity. The rough surface soil reflectivity is related to the soil emissivity by $e_{r,p} = (1 - R_{r,p})$, and ω_p, $R_{r,p}$ and $e_{r,p}$ are values at an assumed radiometer incident angle of $\theta=55°$. $R_{r,p}$ is related to smooth surface soil reflectivity R_s through the soil roughness parameter h so that $R_s = R_r \exp(h \cos2\theta)$ without notification for polarization. While Eq. (3.2) and these parameterizations of τ and R_s represent simplifications of the actual microwave emission process, they are widely utilized for low-frequency (L-band) microwave emission and retrieval modeling of the land surface – especially within lightly to moderately vegetated regions.

In SCR algorithm, with the assumptions of $T_c = T_s$ and $\omega_p = 0$ (Jackson, 1993), Eq. (3.2) can be simplified as

$$T_B = T_S [1 - R_r \exp(\frac{-2\tau}{\cos\theta})] \tag{3.3}$$

Note that SCR algorithm only uses the H-pol T_b observations, polarization indications in Eq. (3.3) has been dropped.

The vegetation optical depth, τ, is dependent upon vegetation water content (W). It is traditionally calculated using empirical relationships with vegetation indices, such as NDVI. In our approach, we used the vegetation optical depth retrieved from Land Parameter Retrieval Model (LPRM). To further adjust the vegetation optical depth climatology, we used a CDF matching method to match the retrieved vegetation optical depth value to that valued inversed from SCR using GLDAS model soil moisture.

3.2.2 Emissivity / Dielectric Constant Relation

The Fresnel reflection equations are used to predict the surface microwave emissivity as a function of dielectric constant (ε_r) and the viewing angle (θ) based on the polarization of the sensor (Ulaby, 1986). Since the imaginary part of the complex dielectric constant is relatively small and thus is often ignored, the Fresnel equation can be simplified by including only the real part of the complex dielectric constant (only H-pol is presented):

$$e_H = 1 - \left| \frac{\cos\theta - \sqrt{\varepsilon_r - \sin^2\theta}}{\cos\theta + \sqrt{\varepsilon_r - \sin^2\theta}} \right|^2 \tag{3.5}$$

The real part (ε_r) of the dielectric constant of the soil can be solved given the calculated emissivity and known sensor viewing angle.

3.2.3 Dielectric Constant / Volumetric Soil Moisture Relation

Both components of wet soil, soil and water, contribute to its dielectric constant. The fundamental principle of this algorithm is the large contrast in dielectric properties of water and soil. Water has a complex dielectric constant of about 80 for the real part as compared to about 3.5 for dry soil. Thus, the real part of dielectric constant for wet soil can be 3.5 - 80. This large dielectric constant difference between wet and dry soil correspondingly impacts the soil emissivity that can be related to the brightness temperature measured by the satellite sensor as showing in above section. Since the dielectric constant is a volume property, the volumetric fraction of each component must be considered.

In the SCR algorithm, the Dobson mixing model is used to calculate the volumetric soil moisture from the computed dielectric (Dobson et al., 1985). This model is based upon the index of refraction, and yields an excellent fit to the measured data at frequencies above 1.4 GHz and should be adequate for most applications requiring estimated soil dielectric properties for use in emission and scattering calculations. This model requires soil textural composition as input, such as proportions of clay and sand.

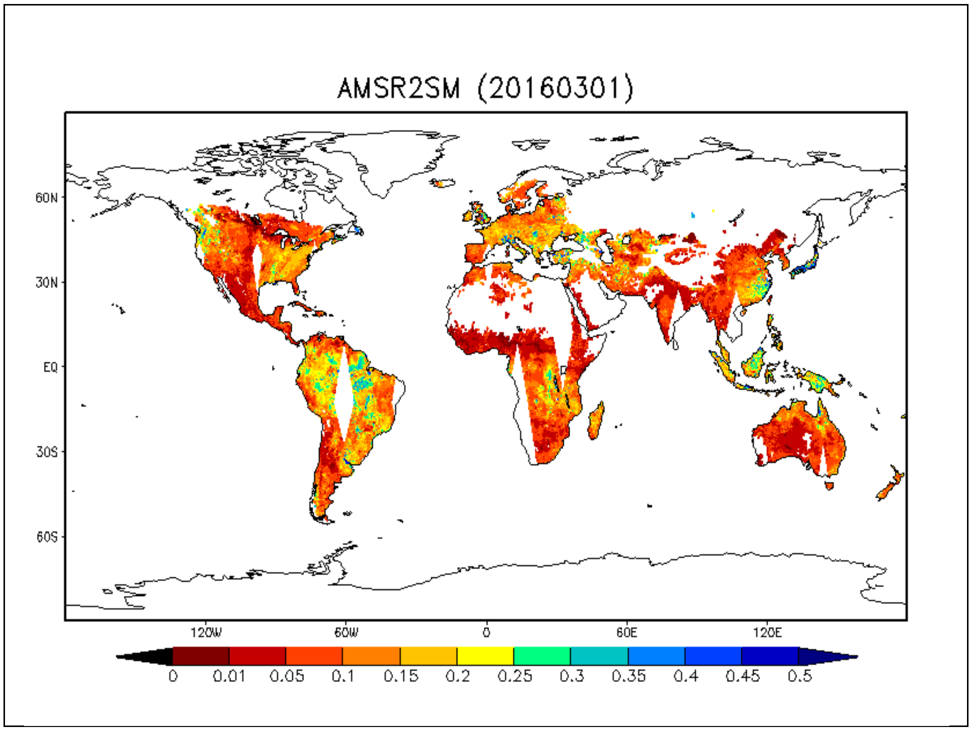
3.3 Algorithm Output

The output from this algorithm will be orbital soil moisture files at footprint level. For each footprint, the output includes soil moisture values (%vol/vol) of the surface (top 1-5 cm) soil layer with associated quality information and metadata.

3.4 Algorithm Validation

3.4.1 Sample Results

Figure 3.4.1 shows examples of AMSR2 soil moisture maps produced by this algorithm. The retrieved soil moisture values generally exhibit a good dynamic range from 0-50%[v/v], indicating that this algorithm is capable of retrieving the required range of soil moisture values given different vegetation type and brightness temperature inputs from satellite sensors. The spatial patterns shown in the maps are also consistent with global dry/wet patterns of climate regimes.



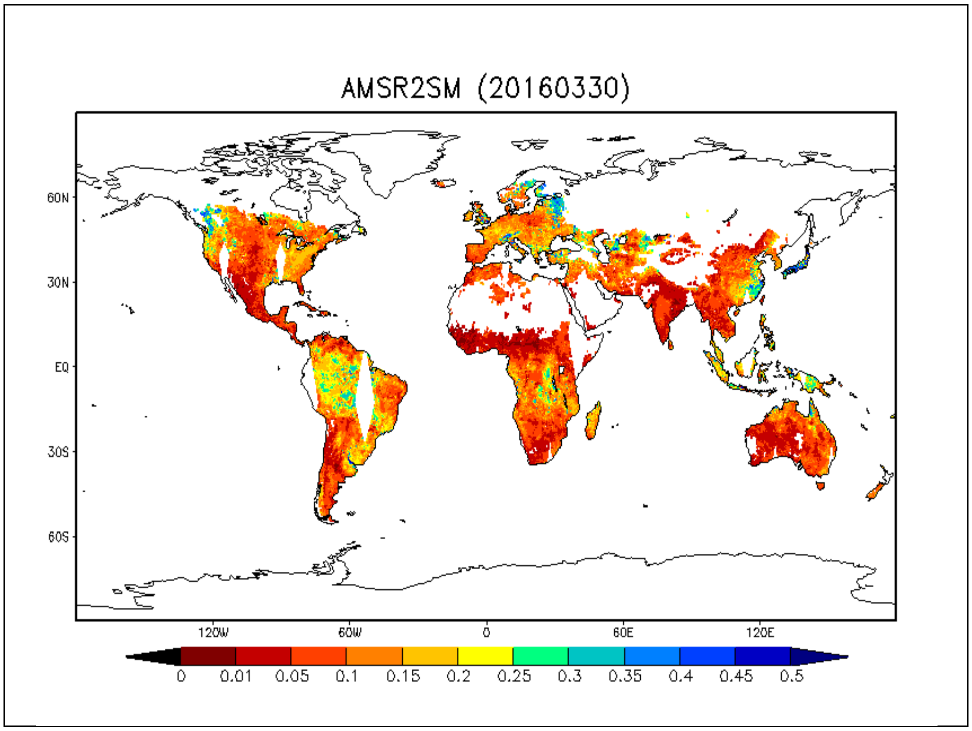


Figure 3.4.1 – Soil moisture maps produced by the SCR algorithm.

3.4.2 Validation Efforts

3.4.2.1 Validation using in-situ data

In the efforts to quantitatively assess the soil moisture retrieval quality, ground soil moisture observations from The Soil Climate Analysis Network (SCAN) were used to compare with the soil moisture retrievals from the AMSR2. SCAN was established by US Department of Agriculture (USDA). The network has been measuring soil moisture at more than 120 stations around US since late 1990s. Figure 3.4.2 shows the spatial distribution of SCAN sites. These soil moisture measurements are mostly available from the SCAN website (http://www.wcc.nrcs.usda.gov/scan/).

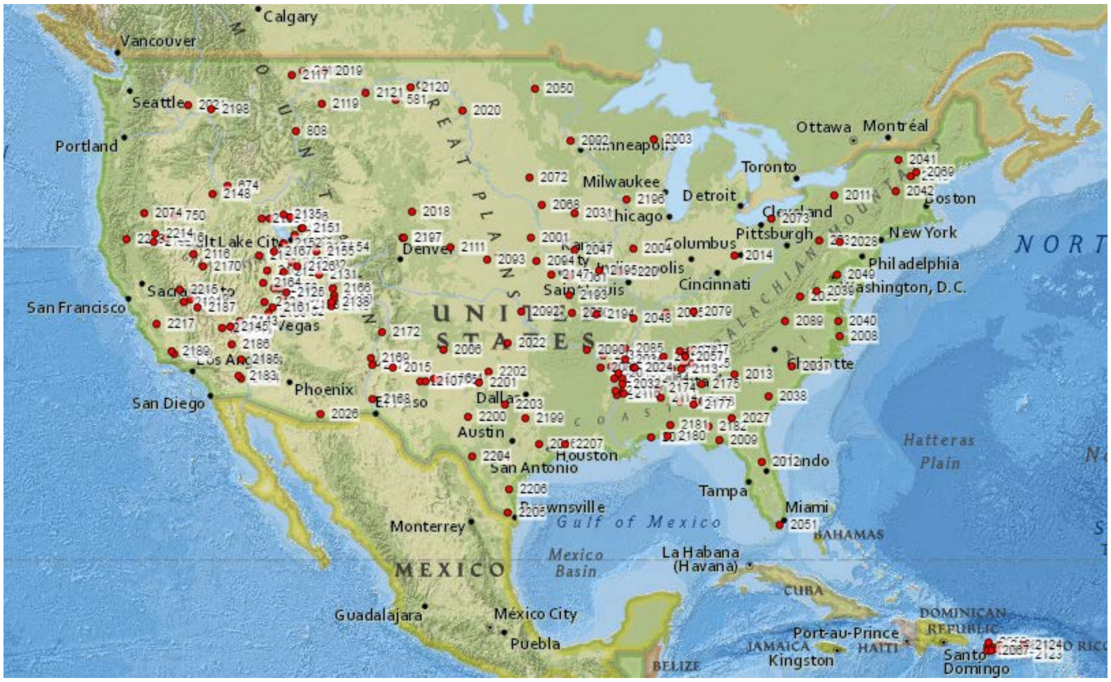


Figure 3.4.2 – The Soil Climate Analysis Network (SCAN) stations.

All the data from year 2014 to 2015 are used to do the comparison. The total number of SCAN sites used in this validation work is 150. For each individual site, soil moisture value from AMSR2 EDR is extracted and the ground observation at AMSR2 observation hour is used to pair up with the AMSR2 soil moisture. For all the sites that have 30 or more valid soil moisture pairs, correlation coefficient, bias and root mean square error (RMSE) are calculated for this station. Overall, the mean value of the correlations coefficient for all ground stations is 0.545, 0.021 for mean bias and 0.038 for RMSE. The AMSR2 soil moisture retrievals show reasonably good correlation with the ground observations. It slightly overestimated the soil moisture but the RMSE is well within the data quality requirement range (<0.05). This is just a very preliminary examination of the data quality. Ground stations are not carefully selected based the homogeneity of the surroundings. We do see quality differences for different stations. Figure 3.4.3 shows two examples: one with reasonably good quality while the other shows the opposite.

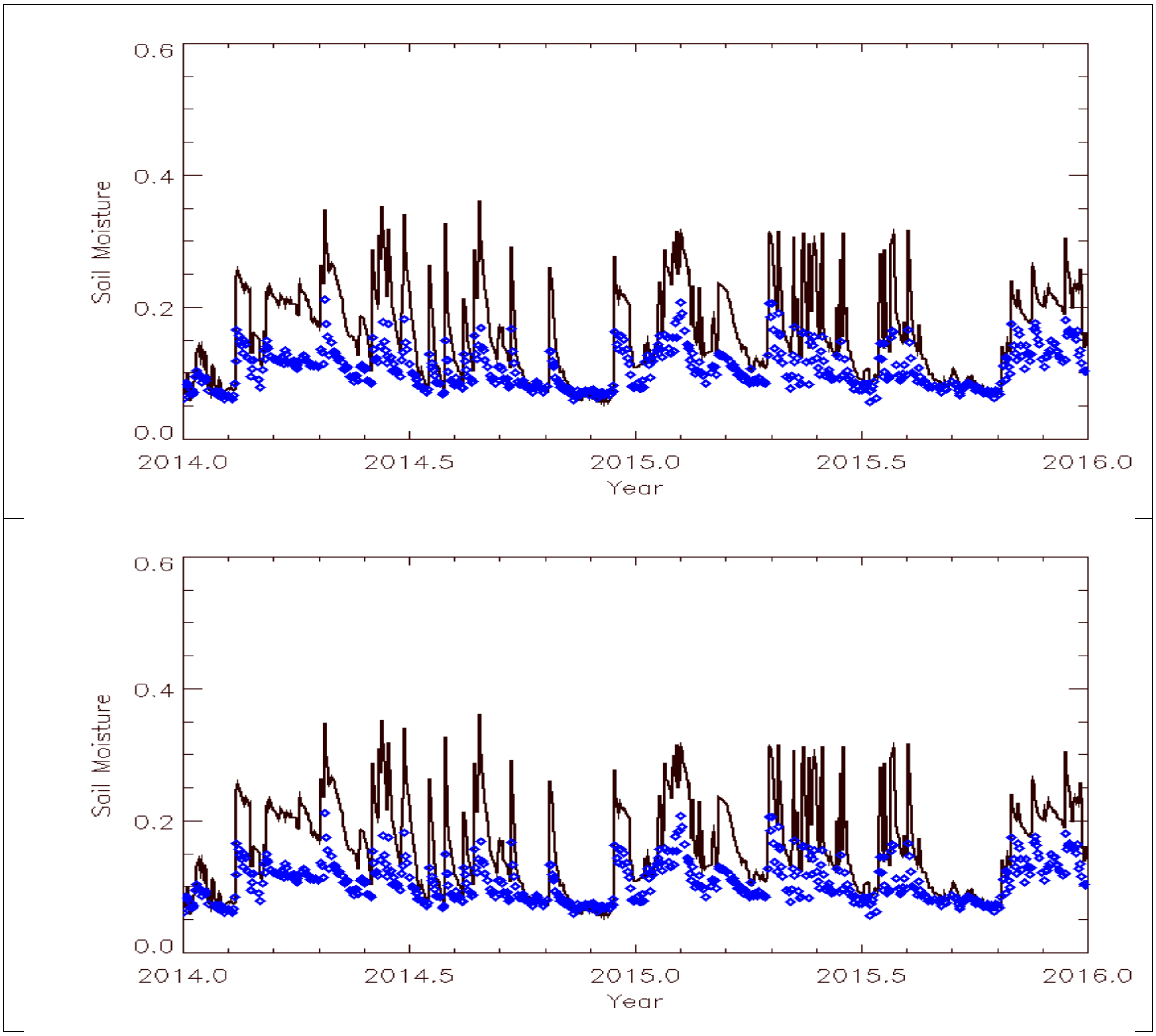


Figure 3.4.3 – Time series from two SCAN stations.

3.4.2.2 Comparison with other SM products

Soil moisture products from other satellite sensors are compared with AMSR2 SM product. Figure 3.4.4 shows four different products for the same day of December 1st, 2015, including AMSR2 SM, ASCAT-A L2 soil moisture, SMAP L3 soil moisture (passive only) and SMOS L2 soil moisture. As we can see, not only do they show different spatial coverage, but also very big difference in dynamic range. These differences are mainly caused by the fundamental differences in the observation system design as well as the algorithms used for the retrieval. One might have better quality than the other in certain areas. Further validation work using the in situ data and inter-comparison between different products will be carried out in the future.

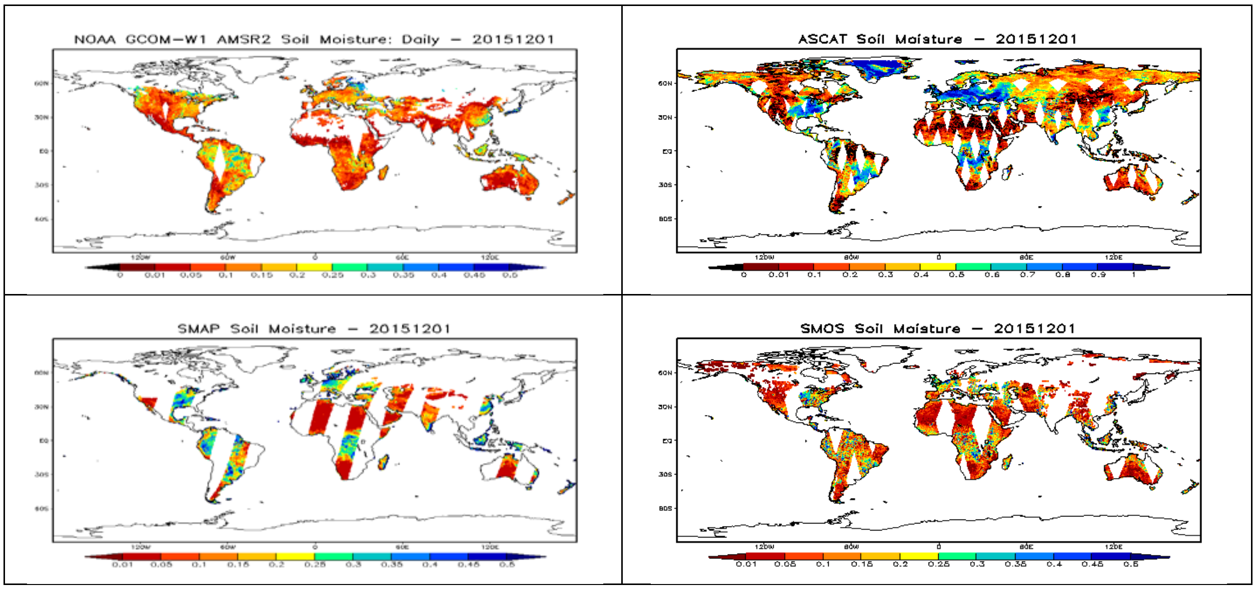


Figure 3.4.4 – Soil moisture maps from different satellite sensors.

3.4.3 Further Validation plan for AMSR2 SM EDR

To further validate AMSR2 SM EDR, we plan to collect more in situ observations from different networks around the globe, including but not limited to SCAN, the United States Climate Reference Network (USCRN), COSmic-ray Soil Moisture Observing System (COSMOS), ground observation network from China. These continuous soil moisture measurements are available from either websites or ftp servers.

4. ASSUMPTIONS AND LIMITATIONS

4.1 Assumptions

The assumptions that were made in SCR for producing AMSR2 soil moisture include:

1. Soil texture, namely sand, clay and porosity, does not change in time at 1/12 degree spatial resolution.
2. Land cover classification does not change in time at the 1/16 degree spatial resolution. This could be a risk as the land cover type may change slowly. Resolution to this problem could be updating the input land cover map every several years.

4.2 Limitations

1. The SCR will not retrieve soil moisture in densely vegetated areas.
2. The SCR will not retrieve soil moisture in the cold desert area.

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