NOAA NESDIS
CENTER FOR SATELLITE APPLICATIONS AND RESEARCH

SOIL MOISTURE OPERATIONAL PRODUCT SYSTEM (SMOPS)

ALGORITHM THEORETICAL BASIS DOCUMENT

Version 3.0

SMOPS ALGORITHM THEORETICAL BASIS DOCUMENT VERSION 2.2

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SMOPS ALGORITHM THEORETICAL BASIS DOCUMENT
VERSION HISTORY SUMMARY

Version	Description	Revised Sections	Date
1.0	New Document for SMOPS PDR	New Document	05/06/2010
2.0	Revised version for SMOPS CDR	3.5 Merging Function 5.0 Risks and Risks Reduction	10/17/2010
2.1	Revised version for SMOPS CDR	3.5 Merging Function 5.0 Risks and Risks Reduction	1/04/2011
2.2	Revised version for SMOPS SRR	3.5 Merging Function 3.9 Algorithm Validation 5.0 Risks and their Mitigation	8/8/2011
2.3	Revised version for SMOPS ORR	3.9 Algorithm Validation	7/25/2012
3.0	Final version	Added WindSat sensor	9/25/2012

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LIST OF ACRONYMS

AMSR	Advanced Microwave Scanning Radiometer
ASCAT	Advanced Scatterometer
ATBD	Algorithm Theoretical Basis Document
AVHRR	Advanced Very High Resolution Radiometer
CDR	Critical Design Review
CM	Configuration Management
DDS	Data Delivery Subsystem
DPP	Development Project Plan
DSA	Data Submission Agreement
EMC	Environmental Modeling Center
EOS	Earth Observing System
EPL	Enterprise Product Lifecycle
ESA	European Space Agency
FTE	Full Time Equivalent
G3D	Gate 3 Document
G3R	Gate 3 Review
G3RR	Gate 3 Review Report
G4R	Gate 4 Review
IPD	Information Processing Division
IMP	Integrated Master Plan
IMS	Integrated Master Schedule
IT	Information Technology
MODIS	Moderate Resolution Imaging Spectroradiometer
N/A	Not Applicable
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
NWP	Numerical Weather Prediction
NRL	Naval Research Laboratory
OCD	Operations Concept Document
PAR	Process Asset Repository
PBR	Project Baseline Report
PDD	Preliminary Design Document
PDR	Preliminary Design Review
PDRR	Preliminary Design Review Report

PRR	Project Requirements Review
PSR	Project Status Report
R&D	Research & Development
RAD	Requirements Allocation Document
SMOPS	Soil Moisture Operational Product System
SMOS	Soil Moisture and Ocean Salinity
SRR	System Readiness Review
STAR	Center for Satellite Applications and Research
SWA	Software Architecture Document
TB	Brightness Temperature
TBD	To Be Determined
TBS	To Be Specified
TMI	TRMM Microwave Imager
TRMM	Tropical Rainfall Measuring Mission
TRR	Test Readiness Review
UTP	Unit Test Plan
UTR	Unit Test Report
VVP	Verification and Validation Plan

ABSTRACT

This document is the Algorithm Theoretical Basis Document (ATBD) for the Soil Moisture Operational Product System (SMOPS) developed by the NOAA/NESDIS Center for Satellite Applications and Research (STAR). The main function of the SMOPS is to retrieve surface soil moisture from currently available low-frequency microwave satellite sensor, such as the Advanced Microwave Scanning Radiometer (AMSR-E) on NASA Aqua satellite and WindSat on NRL's Coriolis satellite, for applications in numerical weather and seasonal climate prediction models at National Centers for Environmental Prediction (NCEP). The retrieval algorithm used in SMOPS is the Single Channel Retrieval (SCR) algorithm. This document describes the details of the SCR algorithm. The sensitivity and the error budget of the algorithm are analyzed using the *in situ* soil moisture measurements from a number of field observation sites in the United States.

To meet the data needs of NCEP and other potential users, the SMOPS generates two categories of soil moisture data products: the global daily product and the global 6 hour product. Details of these products are presented in Section 2.

To increase spatial and temporal coverage of the satellite soil moisture observations, SMOPS will import soil moisture retrievals from other satellite sensors and merger them with the output from the SCR algorithm using AMSR-E observations. Currently these satellite sensors include the Advanced Scatterometer (ASCAT) aboard the EUMETSAT METOP satellite, and the ESA's Soil Moisture and Ocean Salinity (SMOS). The algorithm for merging these soil moisture retrievals is described in section 3. All of these soil moisture retrievals will be contained in both of the SMOPS data products.

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 soil moisture data products and techniques for assimilating them into numerical weather prediction models are believed to have significant impacts for weather forecast accuracy.

The Advanced Microwave Scanning Radiometer (AMSR-E) on NASA's Aqua satellite was launched in May 2002. Since then, a global land surface soil moisture data product has been generated continuously. However, this soil moisture data product have not been systematically used in the current numerical weather prediction operations because of the generally small spatial and temporal variations of the soil moisture retrievals comparing with various soil moisture field measurements. A Joint Center for Satellite Data Assimilation (JCSDA)-funded project has tested a single-channel retrieval (SCR) algorithm that is different from the NASA AMSR-E soil moisture baseline algorithm, and found that the soil moisture retrievals from the SCR algorithm demonstrated better agreement with the in situ measurements than the NASA AMSR-E baseline soil moisture data product (Liu et al, 2008). Based on this finding, a new project funded by NESDIS Product System Development and Implementation (PSDI) program will build an operational Global Soil Moisture Operational Product System (SMOPS) using the SCR algorithm and near-real time AMSR-E and WindSat observations. To improve the spatial and temporal coverage of the AMSR-E observations, SMOPS also combines AMSR-E retrievals with other available satellite observations such as ASCAT on MetOp satellite of EUMETSAT and the Soil Moisture and Ocean Salinity (SMOS) mission of European Space Agency (ESA).

1.1 Existing products

Several soil moisture data sets have been retrieved from microwave satellite sensors such as the Scanning multichannel Microwave Radiometer (SMRR) on Nimbus-7, the Tropical Rainfall Monitoring Mission (TRMM) Microwave Imager (TMI), the AMSR-E and the WindSat on Navy Coriollis satellite (Owe et al, 2008; Bindlish et al, 2001; Njoku et al, 2003; Li et al, 2008). However, only has the NASA AMSR-E global soil moisture data product been generated continuously and made constantly available for public users since June 2002. Others are either available for a short time period or unavailable for near real time applications.

The algorithm used to generate the NASA AMSR-E soil moisture data product is the multi-channel inversion (MCI) described in Njoku & Li (1999). It uses six microwave channels (three frequencies, each at two polarizations) of AMSR-E observations to solve for three land surface parameters: soil moisture, vegetation water content and surface skin temperature. This MCI algorithm has strong theoretical basis. However, the calibration accuracy of the AMSR-E brightness temperatures may have not met the requirement of the

MCI algorithm or the parameters of the tau-omega equation that MCI algorithm is depending on may have not been correct. Consequently, the solution procedure of the algorithm may not converge or the resulting retrievals of soil moisture become unrealistic (personal communication of the developer of the NASA AMSR-E soil moisture product). Njoku & Chan (2006) developed an alternative approach for generating the AMSR-E soil moisture product. The alternative approach uses a set of regression equations based on polarization ratios. However, the regression equations usually smooth out the impact of unknown factors and resulting soil moisture retrievals demonstrate both spatial and temporal variations significantly smaller than in situ soil moisture measurements (Choi et al, 2006; Zhan et al, 2006).

1.2 Purpose

As an effort of the Joint Center for Satellite Data Assimilation (JCSDA) of NOAA, NASA and DoD Air Force Weather Agency (AFWA), 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 better performance than the NASA baseline AMSR-E product. To meet the data needs at NOAA National Centers for Environmental Predictions (NCEP), NESDIS-StAR is tasked to develop a Soil Moisture Operational Product System (SMOPS) to create a global soil mositure data product from AMSR-E, WindSat and other available microwave satellite observations. This document describes the algorithm for SMOPS and its products.

1.3 Revisions

This is a revised version (Version 3.0) dated September 25, 2012. Dates of the original (Version 1) and previously revised version of this document are listed in a table in Page 2 of this document.

1.4 Document Overview

This DG contains the following sections:

Section 1.0 - Introduction
Section 2.0 - SMOPS Overview
Section 3.0 - Description of Algorithms
Section 4.0 - Assumptions and Limitations
Section 5.0 - Risks and Risk Reduction Efforts
Section 6.0 - List of References

2. SMOPS OVERVIEW

2.1 Objectives of Soil Moisture Retrievals

The Soil Moisture Operational Product System (SMOPS) is to meet the user request from NOAA-NCEP-EMC, numbered as #0707-17 in NESDIS Satellite Products and Services Review Board (SPSRB) Request Tracking System (https://requesttracker.osd.noaa.gov/admin_login.asp).

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 retrieving soil moisture from observations of NASA's Advanced Microwave Imaging Radiometer (AMSR-E) on the EOS-Aqua satellite, the Advanced Scatterometer (ASCAT) on EUMETSAT's MetOp satellite, and the European Space Agency (ESA) Soil Moisture and Ocean Salinity (SMOS) satellite and blending them. It's desirable also to retrieve soil moisture from the Tropical Rainfall Monitoring Mission's (TRMM) Microwave Imager (TMI) and the Naval Research Laboratory (NRL) WindSat observations and blend all of them together. But the current phase of SMOPS targets AMSR-E, ASCAT and SMOS only for a quicker turnaround of the product.

NCEP's requested product specifications are captured in the product requirements (c.f. SMOPS Development Project Plan (DPP) Section 6.1). The project's intent is to meet these requirements by making the SCR algorithm (Jackson, 1993; Zhan et al., 2008) operational to provide more accurate and complete soil moisture data/information as input to prediction models and other decision making processes.

2.2 Instrument Characteristics

2.2.1 AMSR-E

The primary satellite sensor feeding input data to SMOPS is the Advanced Microwave Scanning Radiometer (AMSR-E) onboard NASA's Earth Observation Satellite (EOS) Aqua launched in May of 2002. The AMSR-E is a conically scanning total power passive microwave radiometer sensing microwave radiation (brightness temperatures) at 12 channels and 6 frequencies ranging from 6.9 to 89.0 GHz. Horizontally and vertically polarized radiation are measured separately at each frequency (Kawanishi et a, 2003 and http://wwwghcc.msfc.nasa.gov/AMSR/instrument_descrip.html).

The AMSR-E rotates continuously about an axis parallel to the local spacecraft vertical at 40 revolutions per minute (rpm). At an altitude of 705 km, it measures the upwelling scene brightness temperatures over an angular sector of ±61 degrees about the sub-satellite track, resulting in a swath width of 1445 km. During a period of 1.5 seconds the spacecraft sub-satellite point travels 10 km. Even though the instantaneous field-of-view for each channel is different, active scene measurements are recorded at equal intervals of 10 km (5 km for the 89 GHz channels) along the scan. The half cone angle at which the reflector is fixed is 47.4° that results in an Earth incidence angle of 55.0°. Table 2.1 lists the pertinent performance characteristics.

Table 2.1 – AMSR-E performance characteristics

CENTER FREQUENCIES (GHz)	6.925	10.65 [a]	18.7	23.8	36.5	89.0
BANDWIDTH (MHz)	350	100	200	400	1000	3000
SENSITIVITY (K)	0.3	0.6	0.6	0.6	0.6	1.1
MEAN SPATIAL RESOLUTION (km)	56	38	21	24	12	5.4
IFOV (km x km)	74 x 43	51 x 30	27 x 16	31 x 18	14 x 8	6 x 4
SAMPLING RATE (km x km)	10 x 10	10 x 10	10 x 10	10 x 10	10 x 10	5 x 5
INTEGRATION TIME (MSEC)	2.6	2.6	2.6	2.6	2.6	1.3
MAIN BEAM EFFICIENCY (%)	95.3	95.0	96.3	96.4	95.3	96.0
BEAMWIDTH (degrees)	2.2	1.4	0.8	0.9	0.4	0.18

[a] The 10.65 GHz frequency data will be used in the SCR algorithm.

2.2.2 WindSat

The secondary satellite sensor feeding input data to SMOPS is the WindSat onboard NRL's Coriolis launched in January, 2003. WindSat is a satellite-based polarimetric microwave radiometer developed by the Naval Research Laboratory Remote Sensing Division and the Naval Center for Space Technology for the U.S. Navy and the National Polar-orbiting Operational Environmental Satellite System (NPOESS) Integrated Program Office (IPO). WindSat is designed to demonstrate the capability of polarimetric microwave radiometry to measure the ocean surface wind vector from space. It is the primary payload on the Coriolis mission, which is jointly sponsored by the DoD Space Test Program and the U.S. Navy (SPAWAR PMW-180). Spectrum-Astro of Gilbert, Arizona, built the spacecraft (http://www.nrl.navy.mil/WindSat/).

The WindSat radiometer operates in discrete bands at 6.8, 10.7, 18.7, 23.8, and 37.0 GHz. Table 2.2 provides key design and performance parameters of the system. The 10.7, 18.7, and 37.0 GHz channels are fully polarimetric. WindSat uses a 1.8-m offset reflector antenna fed by 11 dual-polarized feed horns. The antenna beams view the Earth at incidence angles ranging from 50 to 55°. Table 2.2 also shows the nominal beamwidth and resulting surface spatial resolution of each band. The Coriolis satellite orbits Earth at an altitude of 840 km in a Sun-synchronous orbit. The satellite completes just over 14 orbits per day. The orbit and antenna geometry result in a forward-looking swath of approximately 1000 km and an aft-looking swath of about 350 km. The fully integrated WindSat payload stands 10 ft tall and weighs approximately 675 lbs.

Table 2.2 – WindSat Configuration

Band (GHz)	Polarization	Bandwidth (MHz)	Earth Incidence Angle (deg.)	Horizontal Spatial Resolution (Km)
6.8	V, H	125	53.5	39 X 71
10.7	V,H, ±45,L,R	300	49.9	25 X 38
18.7	V,H, ±45,L,R	750	55.3	16 X 27
23.8	V,H	500	53.0	20 X 30
37.0	V,H, ±45,L,R	2000	53.0	8 X 13

2.2.3 AVHRR

SMOPS requires the Normalized Difference Vegetation Index (NDVI) data for estimating the vegetation water content that is a critical input to the SCR algorithm used to retrieval soil moisture from AMSR-E observations. The NDVI data will be acquired from the Advanced Very High Resolution Radiometer (AVHRR) onboard all NOAA Polar-orbiting Satellites. NOAA-19 satellite is currently the operational primary satellite for NOAA weather monitoring.

The AVHRR is a six channel scanning radiometer providing three solar channels in the visible-near infrared region and three thermal infrared channels (Table 2.3). More information on AVHRR is provided at

http://www.ncdc.noaa.gov/oa/pod-guide/ncdc/docs/klm/html/c7/sec7-1.htm

Table 2.3 – Summary of AVHRR/3 Spectral Channel Characteristics

Parameter	Ch. 1	Ch. 2	Ch. 3A	Ch. 3B	Ch. 4	Ch. 5
Spectral Range (μm)	0.58-0.68	.725-1.0	1.58-1.64	3.55-3.93	10.3-11.3	11.5-12.5
Resolution (km)	1.09	1.09	1.09	1.09	1.09	1.09

NDVI is basically a calculation of the differences between AVHRR channels 1 (RED) and 2 (NIR) using the equation:

$$NDVI = \frac{\rho_{NIR} - \rho_{RED}}{\rho_{NIR} + \rho_{RED}} \tag{2.1}$$

The NDVI data has been generated operationally at NESDIS-OSDPD from current operational NOAA-19 and made available on OSDPD DDS.

2.2.4 ASCAT

For more spatial and temporal coverage of satellite soil moisture data, SMOPS combines soil moisture retrievals from two satellite sensors, the Advanced Scatterometer (ASCAT) and the Soil Moisture Ocean Salinity (SMOS).

ASCAT is on board of the MetOp-A satellite launch in October 2006. It is an advanced version of the Scatterometer (called ESCAT) on board of the European Remote Sensing Satellites (ERS). These scatterometers are originally designed for indirectly determining wind stress over oceans by measuring the radar backscattering coefficient (σ_0) from the wind induced water ripples and waves. ASCAT has three radar antenna beams that illuminate a continuous ground swath at three different azimuth angles (45, 90, and 135 degrees sideward from the direction of the satellite motion) on both sides of the track. The result is a triplet of spatially averaged σ_0 values for each location along the swath. The ASCAT measurements have a 50-km spatial resolution along and across the swath, with an additional 25-km resolution product with experimental status. ASCAT also features a symmetrical second swath, which practically increases its temporal sampling capabilities to double that of the ESCAT—this is, on average 0.8 to more than 5 passes per day, depending on latitude (Bartalis et al. 2005; Gelsthorpe et al. 2000). Because of the significant width of the swath, the σ_0 measurements come not only at six different azimuth angles but also at various incidence angles ranging from 25 to 64 degrees. The C-band radar frequency is 5.255 GHz.

The European Organization of Satellite Meteorology (EUMETSAT) MetOp satellite that carries ASCAT is a sun-synchronous polar-orbiting operational satellite with an altitude of about 800 km above the earth's surface and an orbital period of about 100 min. The descending and ascending equator crossings occur at about 0930 and 2130.

A more detailed description of the ASCAT instrument is given in Figa-Saldana et al. (2002) and Gelsthorpe et al. (2000). An overview of ASCAT data product can be found in http://oiswww.eumetsat.org/WEBOPS/eps-pg/ASCAT/ASCAT-PG-4ProdOverview.htm#TOC42.

Note that the main purpose of adding ASCAT soil moisture is to increase the spatial and temporal coverage of the SMOPS soil moisture product. Loss of ASCAT soil moisture data may reduce the temporal and spatial coverage of the SMOPS products.

2.2.5 SMOS

Soil Moisture Ocean Salinity (SMOS) mission of European Space Agency (ESA) is the first ever satellite mission designated for soil moisture observation. SMOS was launched on November 2, 2009 and carries the Microwave Imaging Radiometer using Aperture Synthesis (MIRAS). The MIRAS senses L-band microwave emission (1.400-1.427 GHz) that could penetrate soil depth to about 5cm and vegetation cover with vegetation water content up to 5 kg/m^2 (Kerr et al, 2000). The SMOS radiometer exploits the interferometry principle, which by way of 69 small receivers will measure the phase difference of incident radiation. The technique is based on cross-correlation of observations from all possible combinations of receiver pairs. A two-dimensional 'measurement image' is taken every 1.2 seconds. As the satellite moves along its orbital path each observed area is seen under various viewing angles.

From an altitude of around 758 km, the antenna will view an area of almost 3000 km in diameter. However, due to the interferometry principle and the Y-shaped antenna, the field of view is limited to a hexagon-like shape about 1000 km across called the 'alias-free zone'. This area corresponds to observations where there is no ambiguity in the phase-difference. SMOS achieves global coverage every three days. More details of the SMOS mission can be found at http://www.esa.int/esaLP/ESAL3B2VMOC_LPsmos_0.html.

As with ASCAT, the loss of SMOS soil moisture data may reduce the temporal and spatial coverage of the SMOPS soil moisture products.

2.3 Retrieval Strategy

The basic retrieval strategy of SMOPS is to retrieve soil moisture from a baseline satellite sensor (either AMSR-E or WindSat), and then to potentially extend spatial and temporal coverage using soil moisture retrievals from other satellite sensors. The baseline satellite sensor may be replaced with a future, more reliable satellite sensor such as NASA's decadal survey mission, Soil Moisture Active/Passive (SMAP) or the Microwave Imager/Sounder (MIS) on future Defense Weather Satellite System (DWSS). More algorithm details will be described in the next sections.

3.0 ALGORITHM DESCRIPTION

3.1 Processing Outline

SMOPS generates two sets of global soil moisture data products: Daily Gridded Product and 6 Hour Gridded Product. Each product contains surface soil moisture retrievals from the baseline satellite sensor (AMSR-E or WindSat) and other available satellite sensors (ASCAT and SMOS), and a combined soil moisture data layer that merges all soil moisture retrievals for each global grid. The daily product contains all soil moisture retrievals and their merged values acquired during the past 24 hours while the 6 Hour product include all soil moisture retrievals and their merged values acquired during the past 6 hours. The processing procedure includes the following stages:

Stage 1: Preprocess the ancillary data required by the SCR algorithm, the baseline satellite sensor (AMSR-E or WindSat) swath data, and gridded soil moisture retrievals from other available satellite sensors (i.e. ASCAT & SMOS) acquired within the past 6 hours.

Stage 2: Use the SCR algorithm to retrieve soil moisture from the baseline satellite sensor swath data and ancillary data and grid retrieved soil moisture to global 0.25 degree grids.

Stage 3: Combine the baseline satellite sensor soil moisture retrievals and the soil moisture retrievals from other available satellite sensors at the global 0.25 degree grids using a Retrievals Merging algorithm.

Stage 4: Pack the 6 Hour Gridded Global Soil Moisture Product with the soil moisture retrievals from the baseline satellite sensor, the other available satellite sensors, their combination, their quality flags and their metadata acquired or generated within the past 6 hours.

Stage 5: Pack the Daily Gridded Global Soil Moisture Product with the soil moisture retrievals from the baseline satellite sensor, the other available satellite sensors, their combination, their quality flags and their metadata acquired or generated within the past 24 hours if the current processing time is the last of the day.

Stage 6: Deliver the 6 Hour Gridded Global Soil Moisture Product and the Daily Gridded Global Soil Moisture Product (if the current processing time is the last time of the day) to DDS and users.

The SMOPS algorithm consists of the following major functions:

1) A pre-processing function that ingests the required input data and prepares it for processing through formatting and regridding

- Read the process control file
- Read Lat/Long information from the process control file if the validation mode is turned on
- Read soil texture (sand and clay fractions and porosity) maps
- Read land cover map
- Read AVHRR NDVI map
- Read NDVI climatology map
- Read land cover parameter file
- Check validity and QA for the above maps. If any one of them is invalid, stop the process.
- Read one AMSR-E or WindSat L2A swath Tb file name from the file name list
- Open the AMSR-E or WindSat L2A file and read the file footprint by footprint
- Check the land cover type associated with the footprint and other conditions to proceed on doing SCR soil moisture retrieval

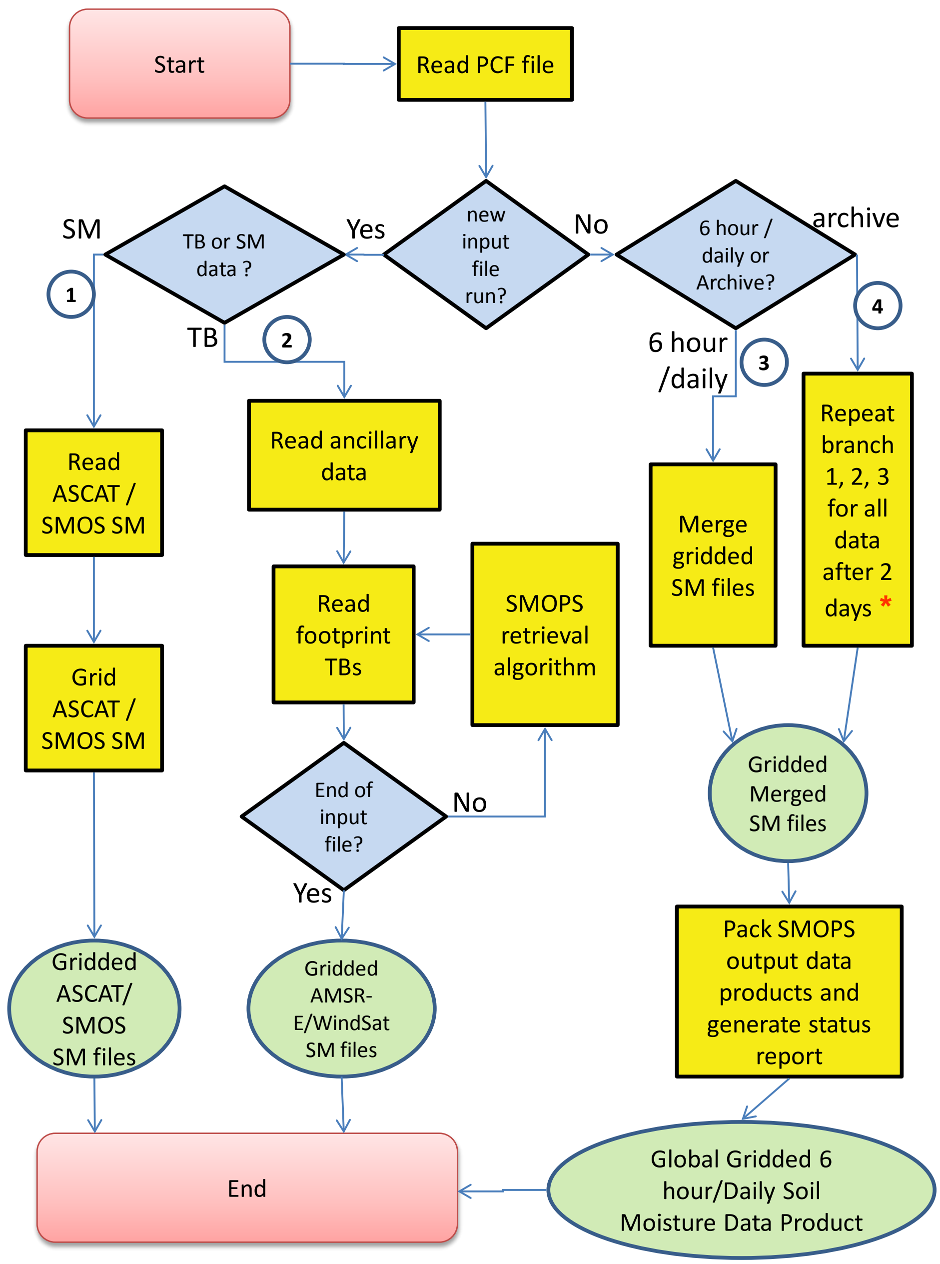
2) The retrieval function that derives soil moisture from microwave brightness temperatures and ancillary data

- Compute the surface emissivity:
  - Correct surface reflectivity for surface roughness effect
  - Estimate vegetation water content from NDVI
  - Compute vegetation optical depth
- Compute soil dielectric constant
- Call the mixing model to calculate soil moisture from the computed soil dielectric constant.
- Grid the all AMSR-E or WindSat footprint soil moisture retrievals within the past 6 hours to a global 0.25 degree Lat/Long grid.

3) A merging function that merges soil moisture retrievals into the desired output composite products

- Read SMOS soil moisture data
- Read the Cumulative Distribution Functions (CDFs) for SMOS and AMSR-E soil moisture retrievals
- Scale SMOS soil moisture retrievals by matching the CDFs
- Read ASCAT soil moisture data
- Read the Cumulative Distribution Functions (CDFs) for ASCAT and AMSR-E soil moisture retrievals
- Scale ASCAT soil moisture retrievals by matching the CDFs
- Composite all soil moisture retrievals from AMSR-E, SMOS, ASCAT acquired within the previous 6 hour window
- Generate QA layer
- Generate meta data
- Output 6 Hour soil moisture product with QA and meta data
- Generate the status report file for 6 Hour product
- Composite the daily soil moisture product with QA and meta data from previous four 6 Hour products
- Output daily soil moisture product with QA and meta data
- Generate the status report file for daily product
- Output the soil moisture values for the validation sites if the validation mode is turned on

The algorithm processing flow is shown in Figure 3.1. Branches 1 – 3 are corresponding to the about 3 functions. There is a possibility that the delivery of the AMSR-E/Windsat, ASCAT or SMOS data acquired in the past 24 hours is delayed. If these data become available within the next day (i.e. the past 48 hours), another SMOPS archive run will be activated to generate the daily global soil moisture product for archiving. This step is shown as Branch 4 in Figure 3.1.



* *All data acquired within the 6 hour or whole day time period arrived in the past 48 hours*

Figure 3.1 – SMOPS Algorithm Process Flow.

3.2 Algorithm Input

3.2.1 AMSR-E and WindSat Brightness Temperature

AMSR-E and WindSat brightness temperature data are Level 1b calibrated microwave brightness temperatures. The SCR algorithm uses brightness temperatures for a single observation channel, the 10.7 GHz horizontally polarized (H-pol) channel. Both AMSR-E and WindSat files are supplied through the DDS in orbital files (TBR).

3.2.2 Ancillary Data

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

3.2.2.1 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 forested area. To convert the vegetation water content to the vegetation optical depth, an empirical constant, *b*, is needed for different land cover types. In the current implementation of the algorithm, *b* value is simply assumed a universal constant across different land cover types.

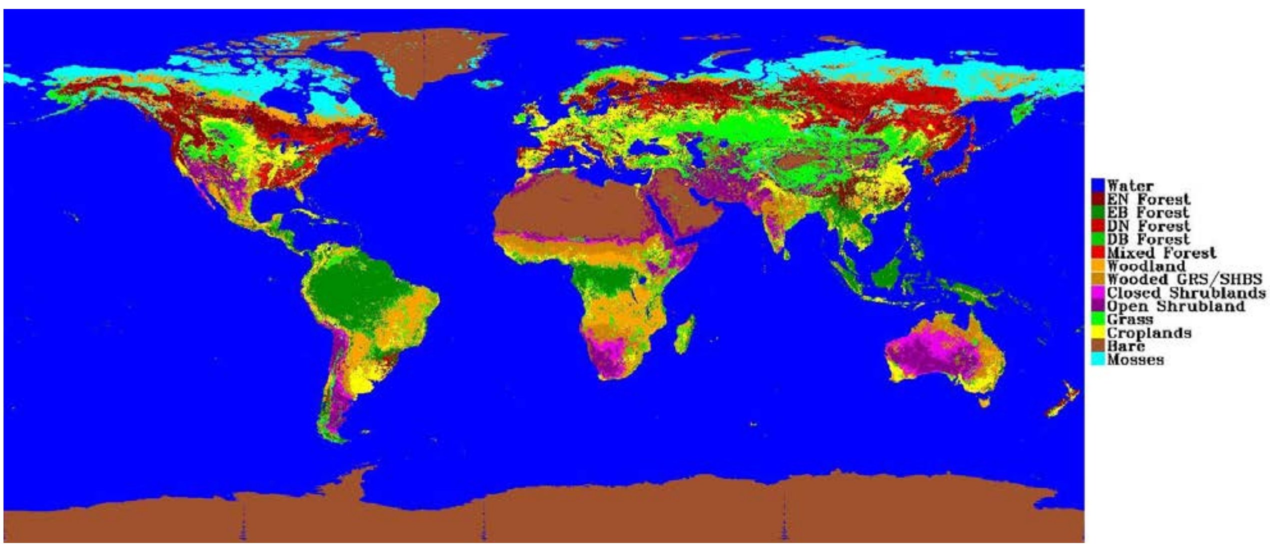


Figure 3.2.1 – Land Cover Map Used by the SCR Algorithm.

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 AMSR-E footprint size level (around 40-km), 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

3.2.2.2 AVHRR NDVI

AVHRR NDVI maps are used to derive the vegetation water content maps, which is further converted to vegetation optical thickness maps using a land cover type-based constant *b* (see Eq. (4)). In case where the AVHRR NDVI data are not available, a multiyear AVHRR NDVI climatology data set is used. Considering the nonlinearity of scale impact of vegetation water content (VWC) on soil moisture retrieval, a non-linear aggregation method [Zhan et al, 2008] for scaling 4km NDVI data to AMSR-E footprint scale VWC will be applied.

The AVHRR NDVI data to be used have a temporal resolution of 7 days and spatial resolution of 4 km. To aggregate this finer resolution NDVI to SMOPS quarter-degree grids, a simple arithmetic average of NDVI values of all the 4-km grids that fall into a quarter-degree grid is used for this quarter-degree grid. The quarter-degree NDVI value is then used for all the AMSR-E footprints with their center located within this grid. To investigate the effect of this aggregation method on those footprints located on the edge of the grids, another quarter-degree aggregation map is made with the centers of the grids located at the edge of the native quarter-degree map. Figure 3.2.2 shows that the difference of these two NDVI maps is minor. Therefore, using the aggregated quarter-degree NDVI map at the native grid has minor effect on the retrievals of the footprints located on the grid edges.

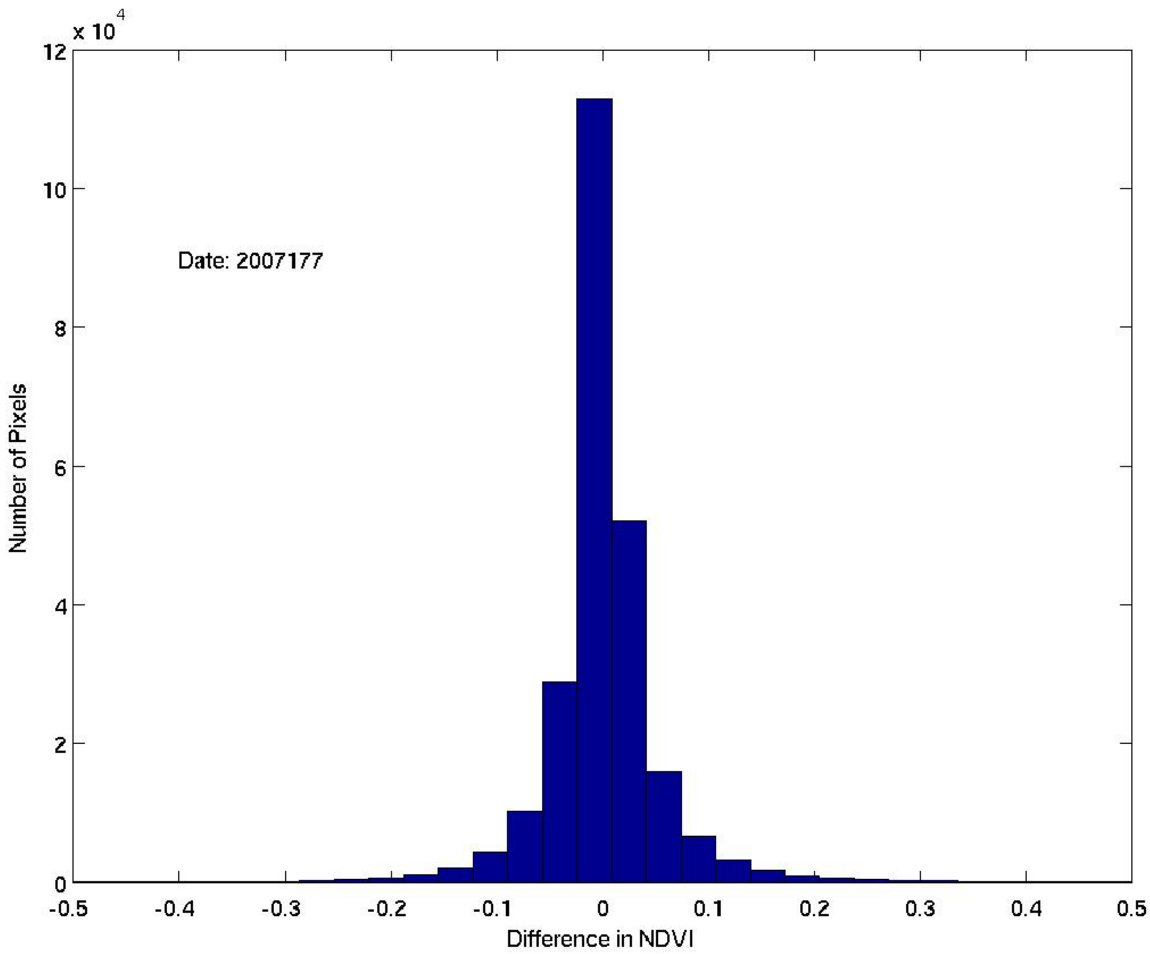


Figure 3.2.2 – NDVI difference histogram from NDVI maps using two different aggregation methods.

An NDVI climatology map is used when the real time NDVI map is not available. The climatology map is generated using all the NDVI data from 1982 to 2010. To investigate the soil moisture retrieval error caused by the use of climatology map, a soil moisture difference map is generated from the soil moisture maps using the real time NDVI map and the multiyear climatology map. Figure 3.2.3 shows that over 95% of the difference is lower than 2% vol/vol. Therefore, the soil moisture map generated using NDVI climatology is comparable with the map generated using the real time NDVI data.

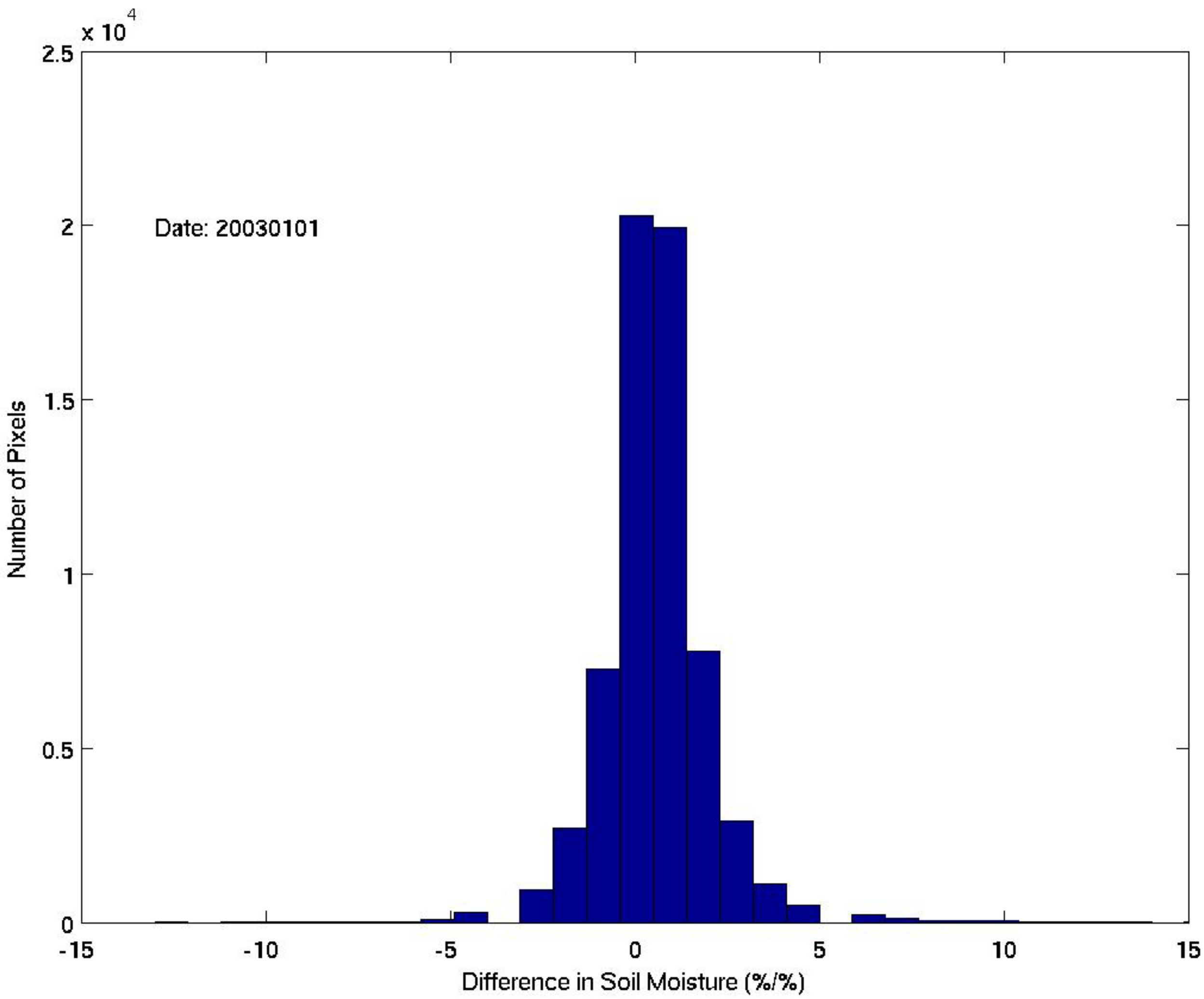


Figure 3.2.3 – Histogram of the difference soil moisture map from two soil moisture maps using NDVI climatology and real time NDVI map.

3.2.2.3 Clay Map

A clay fraction map is used in the SCR algorithm as input of the Dobson mixing model. The clay map (Figure 3.2.4) 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.

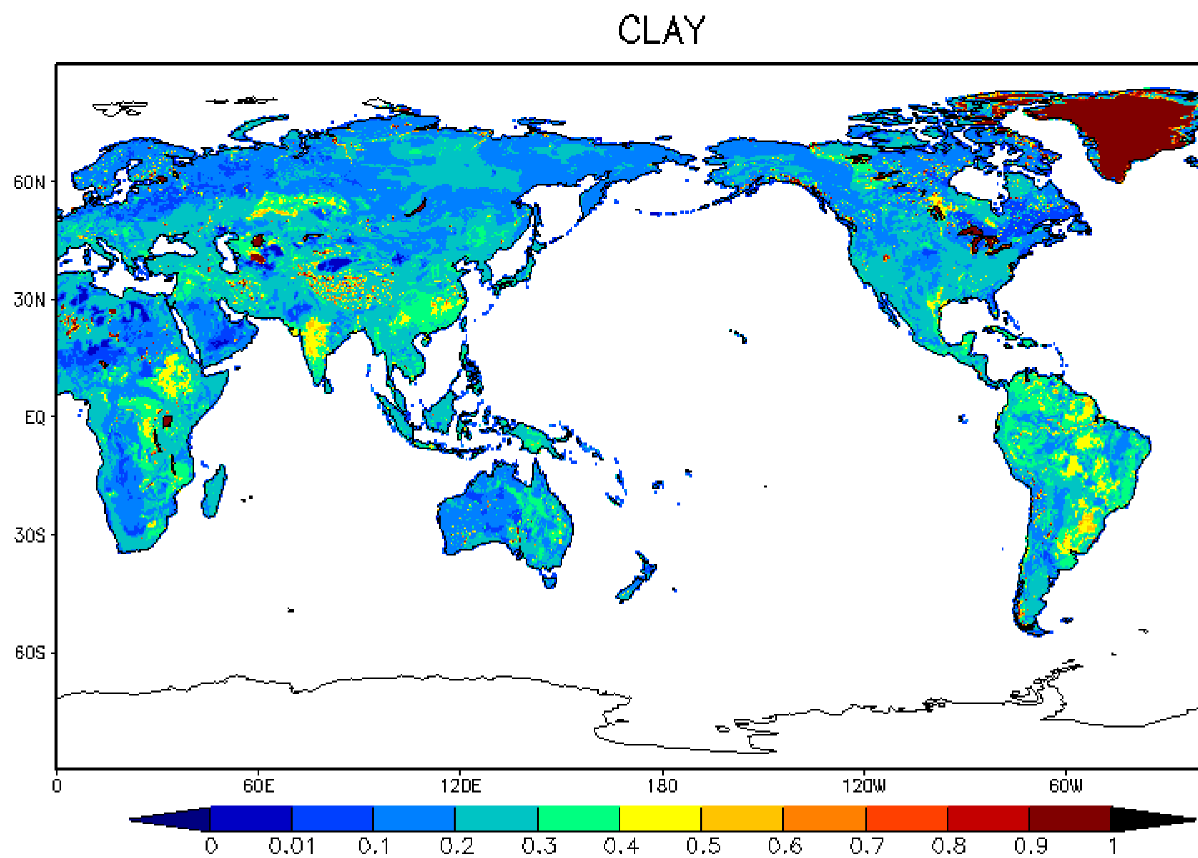


Figure 3.2.4 – Clay Fraction Map Used by the SCR Algorithm

3.2.2.4 Sand Map

A sand fraction map is used in the SCR algorithm as input of the Dobson mixing model. The sand map (Figure 3.2.5) is from FAO (Reynolds et al., 2000) with the same spatial resolution as the clay map.

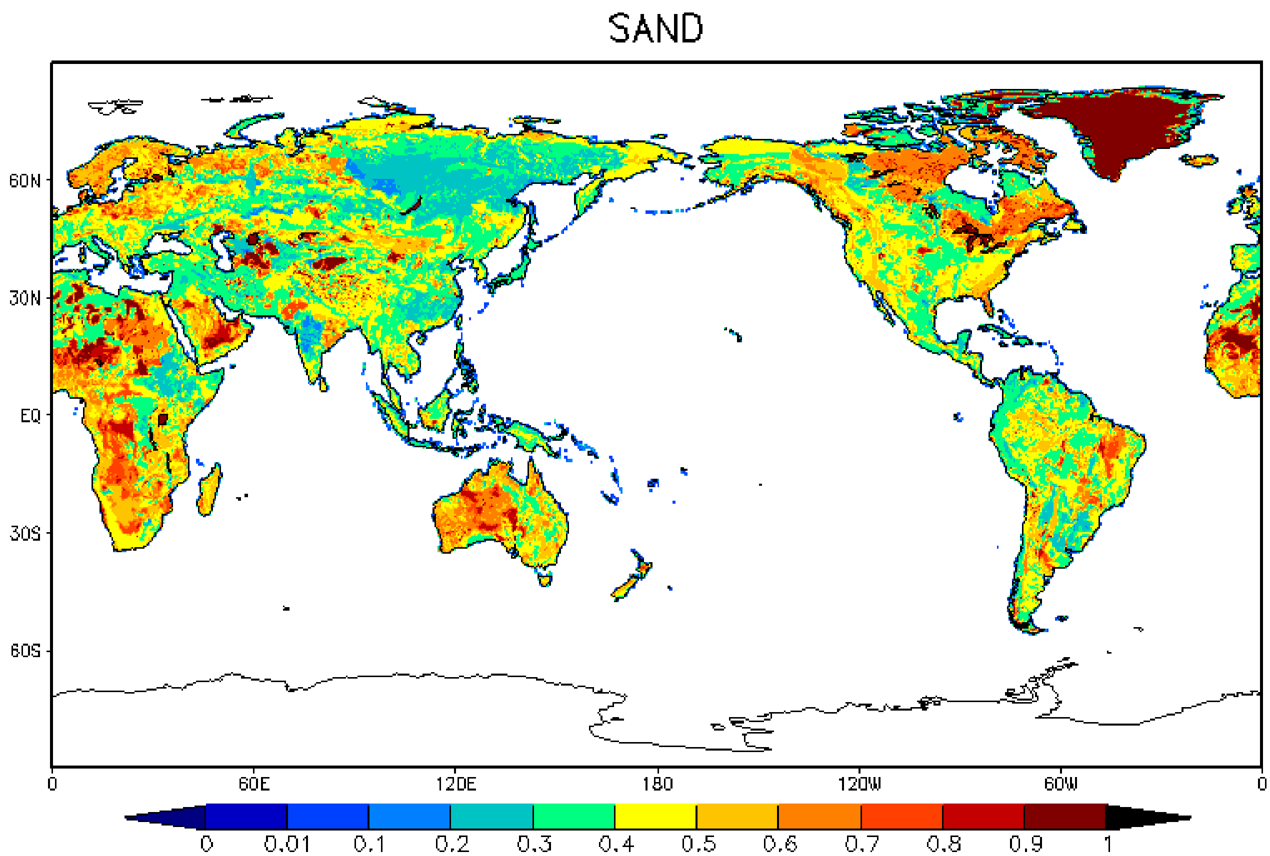


Figure 3.2.5 – Sand Fraction Map Used by the SCR Algorithm

3.2.2.5 Porosity Map

Soil porosity is used in the SCR algorithm as input of the Dobson mixing model. The porosity map (Figure 3.2.6) is from FAO (Reynolds et al., 2000) with the same spatial resolution as the clay map and sand map.

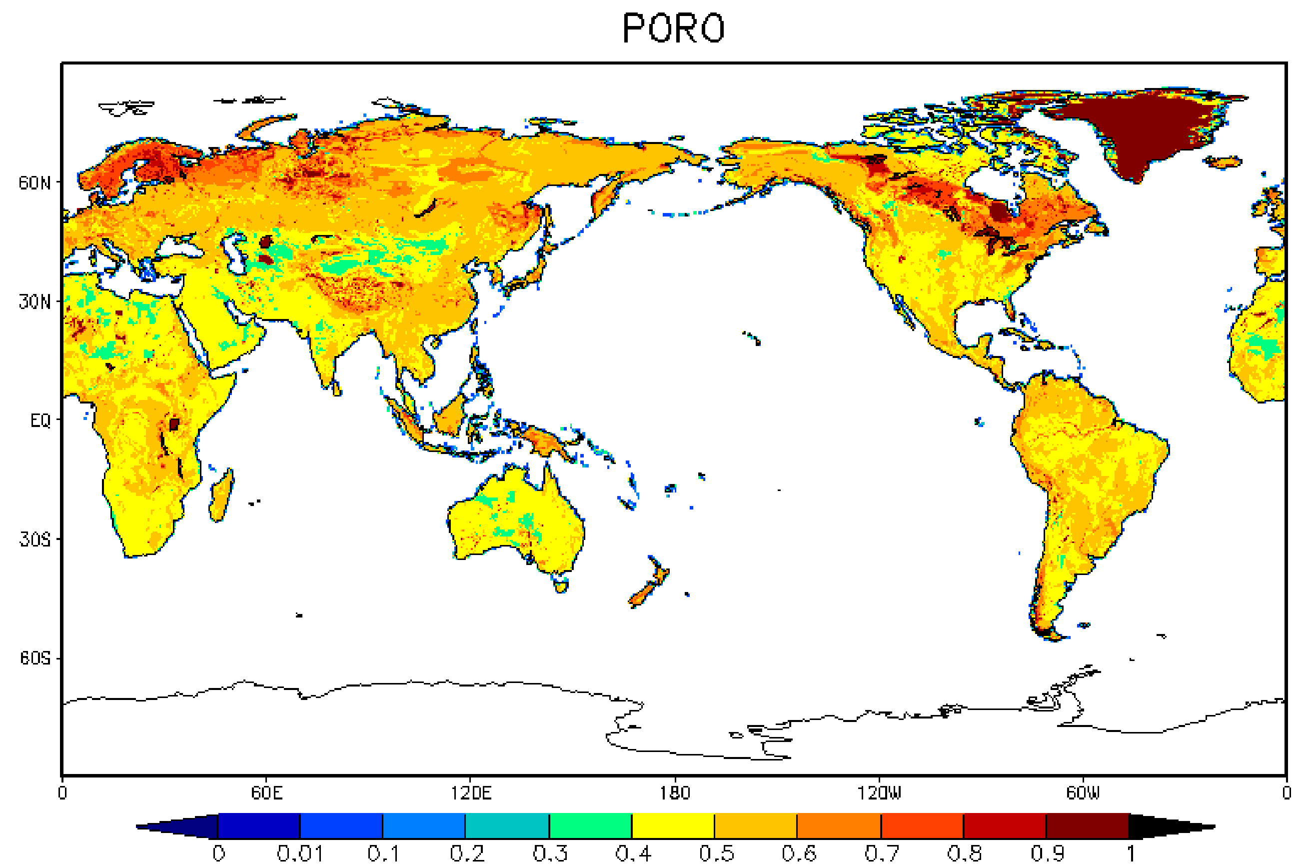


Figure 3.2.6 – Porosity Map Used by the SCR Algorithm

3.2.3 ASCAT and SMOS Soil Moisture

To increase the spatial and temporal coverage of the soil moisture data product, soil moisture retrievals from ASCAT and SMOS are imported to the merging function of the algorithm (see Section 3.5).

3.2.3.1 ASCAT Soil Moisture

The ASCAT Level 2 Soil Moisture product is generated and distributed in near real-time. The main geophysical parameter is relative land surface soil moisture, based on the swath-based grid. The expected average RMS error of the ASCAT soil moisture index is about 25%, which corresponds to about 0.03-0.07 [vol/vol], depending on soil type. ASCAT soil moisture data is available at 25km global grids. With two 500km subswath widths, ASCAT revisit time for a specific location is about 6 days.

More details about the ASCAT soil moisture product can be found in the Soil Moisture Product Guide (Bartalis et al, 2005).

3.2.3.2 SMOS Soil Moisture

SMOS soil moisture retrievals are available at 40km global grids with a 4% accuracy expectation. SMOS revisit time is 2-3 days for each grid. Details of the SMOS soil moisture data will be determined by an agreement with ESA and described in a future version of this ATBD (http://www.cesbio.ups-tlse.fr/us/smos/ smos_atbd.html).

3.3 Pre-processing Function

The pre-processing function is to ingest the required input data and prepares it for processing through formatting and regridding.

AMSR-E data will be extracted from HDF files and reformatted to SMOPS plain binary files. ASCAT and SMOS soil moisture data will be extracted from BUFR or GRIB files, formatted to SMOPS plain binary format, and regridded to SMOPS 0.25-degree lat/long grids. Ancillary data (AVHRR NDVI, FAO soil texture maps, land cover types) are read from plain binary files.

3.4 Theoretical description of soil moisture retrieval (SCR) algorithm

The SCR method used in SMOPS is mainly based on an algorithm developed by Jackson (1993). In this approach, brightness temperature from a single AMSR-E channel (10.7 GHz Horizontal Polarization) 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.

3.4.1 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 $R_s = R_r \exp(h \cos 2\theta)$ 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*). A simple linear relationship is employed to calculate τ from *W*:

$$\tau = bW \tag{3.4}$$

where *b* is an empirical parameter associated with different land cover types defined with the land cover parameters file. Table 3.2 is a list of the b parameter values obtained in Jackson & Schmugge (1991). Vegetation water content, *W*, is estimated using AVHRR NDVI and the method described in Jackson & Schmugge (1991).

Table 3.2 – Value of parameter *b* associated with land cover types

Land Cover	Grass	Crops	Forests
b	0.2	0.25	0.33

3.4.2 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.

3.4.3 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. The following equations are used for the Dobson mixing model:

```
m_v  = (eps_r**alpha-fv*(eps_solid_r**alpha-1.0)-1.0)/(eps_water_r**alpha-
            1.0)**(1.0/betar)
       por = 0.505-0.142*sf-0.037*cf
       fv  = 1.0-por
       ew0 = 88.045 - 0.4147*tt + 6.295e-04*tt**2 + 1.075e-05*tt**3
       rt  = (1.1109e-10 - 3.824e-12*tt + 6.938e-14*tt**2 -5.096e-16*tt**3)*fi
       eps_water_r = 4.9 + (ew0-4.9)/(1+rt**2)
       betar = 1.2748-0.519*sf-0.152*cf                                  (3.6)
```

where m_v is the soil moisture retrieval, eps_r, eps_water_r and eps_solid_r are dielectric constants for the soil, pure water and solid rock (4.7). Symbol alpha is a shape parameter and equals 0.65. Symbol fi is the microwave frequency in Hz. cf & sf are clay & sand fraction and tt is surface temperature in degree Celsius, Other variables (fv, betar, ew0, tt, and rt) are intermediate symbols and used for programming convenience.

3.5 Merging Function

3.5.1 Objectives of Merging Soil Moisture Retrievals from Different Satellites

All microwave soil moisture remote sensing satellites, currently in space or to be launched in near future, do not have a full global coverage for every day. Each of these satellite sensors may not have observations or soil moisture retrievals for the day. Figure 3.5.1 shows example maps of soil moisture retrieved from AMSR-E by SMOPS for Jan 12 (winter) and July 1 (summer), 2010. Significant gaps exist, especially during winter time.

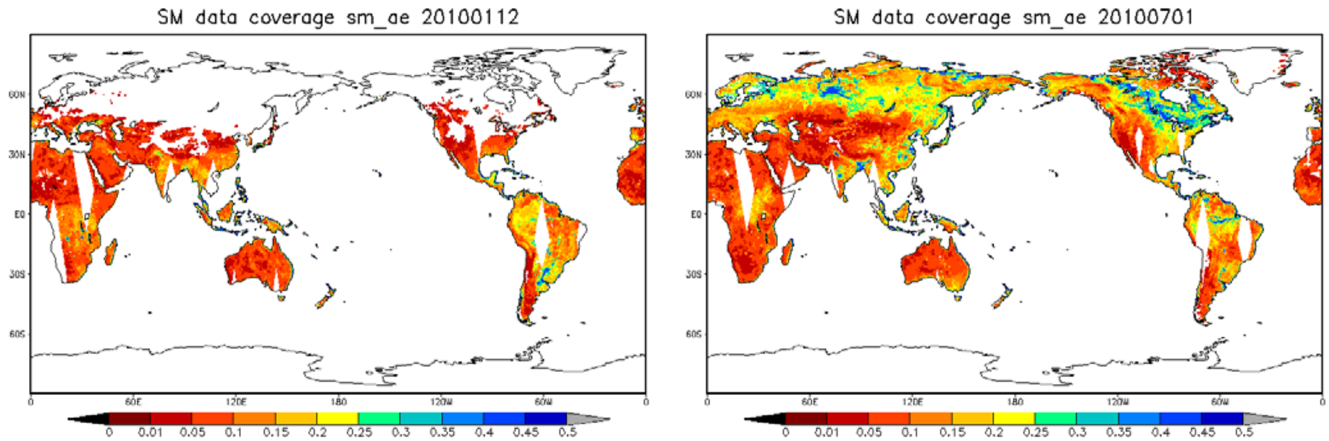


Figure 3.5.1. Maps of soil moisture retrievals from AMSR-E by SMOPS for a winter (Jan. 12, 2010) and a summer (July 1, 2010) day. The daily coverage of AMSR-E data has significant gaps.

To increase the spatial coverage of daily soil moisture retrievals, SMOPS provides a soil moisture data layer that merges all available satellite soil moisture retrievals in addition to the individual soil moisture retrievals from each of the available satellites. Figure 3.5.2 is the spatial coverage of soil moisture retrievals from all three satellite sensors in the winter and summer days. Figure 3.5.3 indicates the spatial coverage expanded by ASCAT from the AMSR-E coverage in the winter and summer days. The ASCAT spatial coverage increment was about 84% in the winter day and 17% in the summer day. Figure 3.5.4 demonstrates the spatial coverage extended by SMOS from the AMSR-E coverage in the winter and summer days. The extension was about 5% and 7% in the winter day and the summer day, respectively.

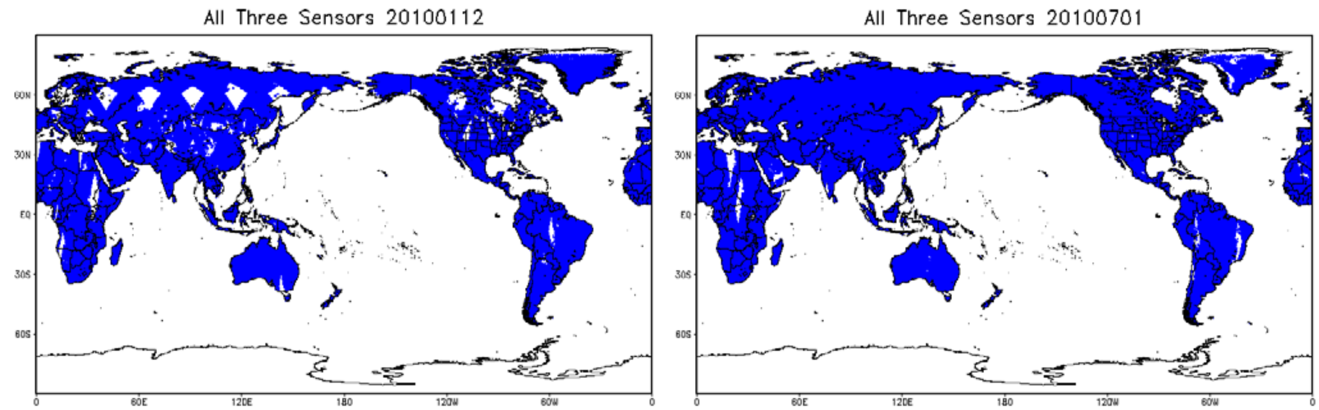


Figure 3.5.2 – Spatial coverage (blue areas) of ASCAT, SMOS and AMSR-E data in a winter (Jan 12, 2010) and a summer (July 1, 2010) day.

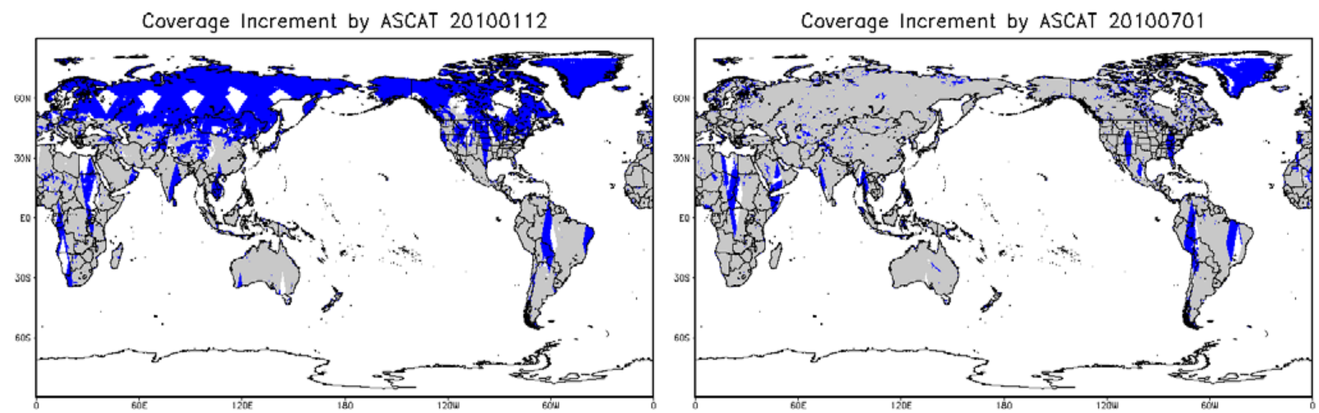


Figure 3.5.3 – Spatial coverage increments (blue areas) by ASCAT over AMSR-E data in a winter (Jan 12, 2010) and a summer (July 1, 2010) day.

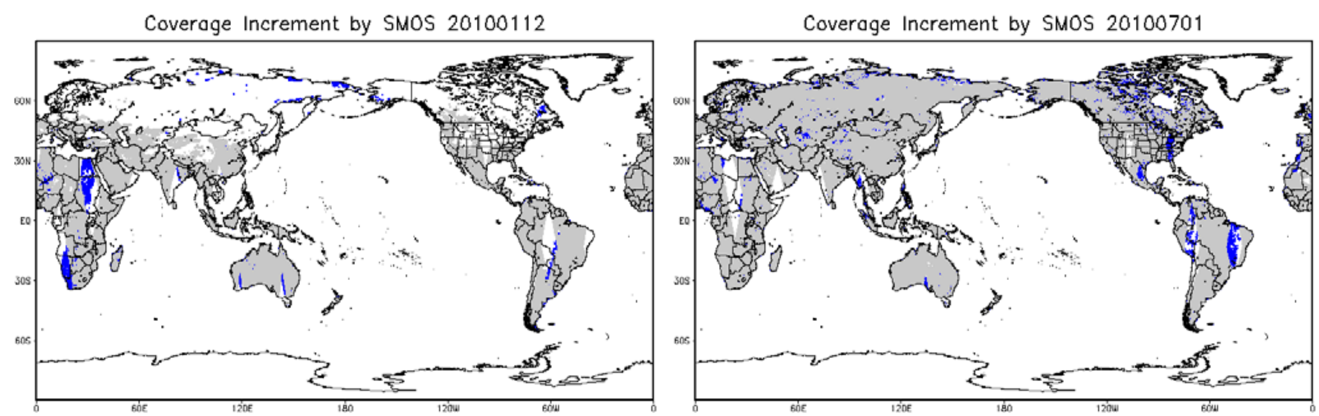


Figure 3.5.4 – Spatial coverage increments (blue areas) by SMOS over AMSR-E data in a winter (Jan 12, 2010) and a summer (July 1, 2010) day.

The spatial coverage benefit from SMOS seemed not significant. However, SMOS is an L-band radiometer and have better penetration through vegetation and soil layers. The soil moisture sensible depth could be up to 5cm. Therefore, SMOS soil moisture observations theoretically could have better accuracy then the C-band or X-band observations by ASCAT or AMSR-E.

3.5.2 Merging Approach

To generate a merged global soil moisture data product, the soil moisture retrievals from AMSR-E/WindSat footprints, SMOS, ASCAT and future satellite sensors will need to be combined into one value for each grid. Retrievals from AMSR-E or WindSat are at footprint while the retrievals from SMOS, ASCAT and other satellite sensors are already gridded. Retrievals from different satellite sensors have their own climatology. The soil moisture retrievals from different satellite sensors should have been gridded to the same grid and have the same climatology. For this purpose, three steps are taken to merge them into one value for each grid: Grid AMSR-E or WindSat footprint retrievals, scale SMOS, ASCAT and other sensor retrievals to AMSR-E climatology, and finally merge them to a single value.

3.5.2.1 Grid AMSR-E or WindSat Footprint Retrievals

Each 0.25 degree lat/lon grid may be represented by multiple AMSR-E or WindSat footprints. Observation times of these footprints may be very different from each other when they belong to different overpass swaths. To represent the most current situation of the grid, the retrieval based on the latest observation covering the grid is selected as soil moisture value of the grid. The latest observation time together with the soil moisture value are recorded for the grid.

3.5.2.2 Scale SMOS, ASCAT and other Soil Moisture Retrievals

For each 0.25 degree lat/lon grid, there may be soil moisture retrievals from AMSR-E/WindSat, SMOS, ASCAT and other sensor observations. Each of them may have different climatology. Before merging them together, retrievals from SMOS, ASCAT and other sensors are scaled to AMSR-E retrieval climatology using the CDF-matching method (Reichle & Koster, 2005). The CDF-matching method is to match the cumulative distribution function of two variables. For a single grid x, assume that AMSR-E retrievals are a_1, a_2, …, a_n and their daily corresponding SMOS retrievals are b_1, b_2, …, b_n. Rearrange a_1, a_2, …, a_n from their minimum A_1 gradually to their maximum A_n and the new AMSR-E retrievals are A_1, A_2, …, A_n. Similarly, SMOS retrievals can be rearranged from their minimum B_1 to maximum B_n. If a new SMOS retrieval for the grid is c and $B_{j-1} <= c <= B_{j+1}$, then its CDF-matched value will be A_j. Fig 3.5.5 demonstrates the CDF-match process. A Look-Up Table A = F(c) will be used to represent this CDF-matching process. F(x) represents the value of A corresponding to the value of B based on at least one year of SMOS and AMSR-E data.

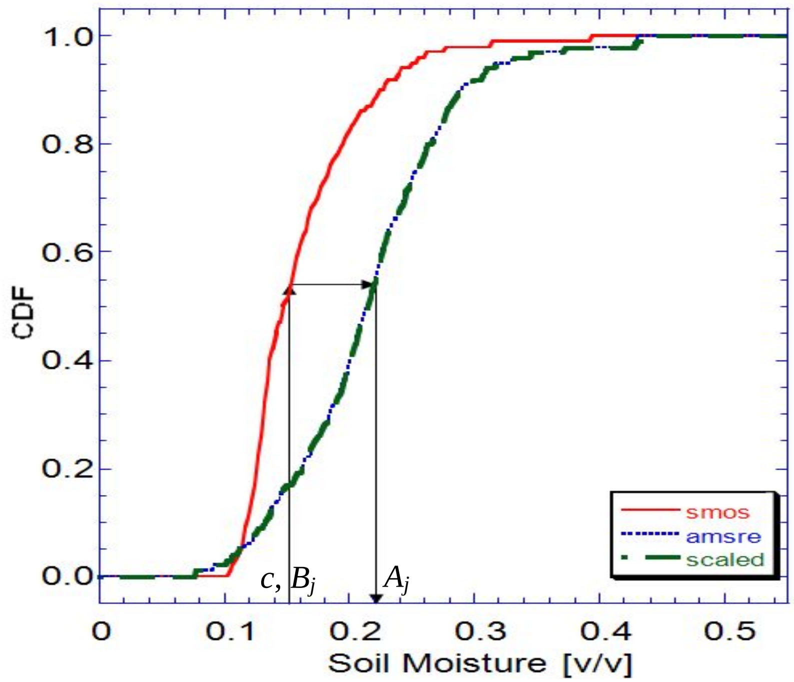


Figure 3.5.5 – Scaling SMOS Soil Moisture Retrievals to AMSR-E Retrieval Climatology Using the CDF-matching Method

3.5.2.3 Merge Gridded Soil Moisture Retrievals

Once the soil moisture retrievals of the day are obtained from the available satellite sensors and are scaled to the climatology of AMSR-E retrievals, the latest retrieval will be selected to represent the soil moisture observation for the day. Figure 3.5.6 is maps of soil moisture retrievals merged without scaling either ASCAT or SMOS retrievals to AMSR-E retrievals for a winter (Jan 12, 2010) and summer day (July 1, 2010). The strips caused by different climatology of different retrievals are apparent. Merging the scaled retrievals of ASCAT and SMOS to AMSR-E can significantly removed the artificial strips (see Figure 3.5.7).

In future version of SMOPS, the average of the available soil moisture retrievals may be used to represent the soil moisture level of the pixel for the day if further evaluation of the averaged soil moisture will be proven to be superior over the latest observations. If SMOS retrievals will be proven to be more accurate than other retrievals, its weight in the average may set to be larger than the average weight (0.33 if 3 retrievals are involved in the merging). The weights are decided after retrievals from each of the satellite sensors are compared with in situ soil moisture measurements from global ground networks (see section 3.9.2). Furthermore, the variance of the multi-soil moisture retrievals for each pixel will be used as an error estimate of the combined soil moisture value.

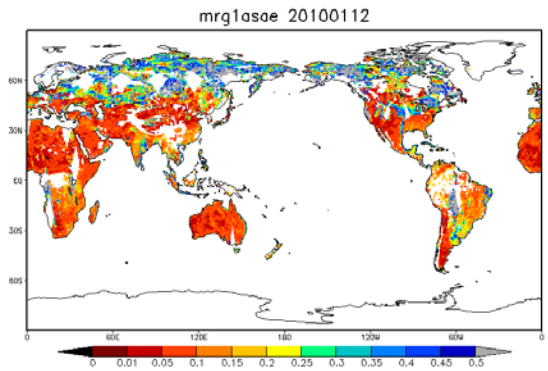


Figure 3.5.6 – Merged soil moisture retrievals from AMSR-E, ASCAT and SMOS without climatology scaling for a winter (Jan 12, 2010) and a summer (July 1, 2010) day. Artificial strips are seen in the merged map.

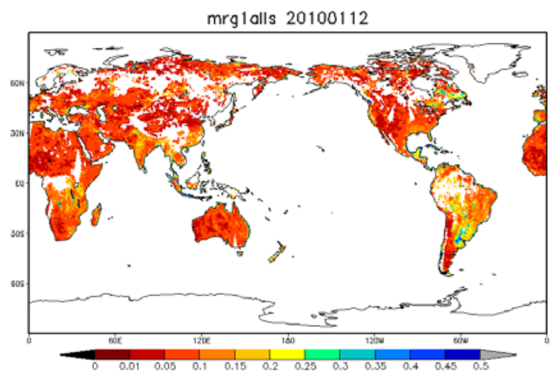


Figure 3.5.7 – Merged soil moisture retrievals from AMSR-E, ASCAT and SMOS after ASCAT or SMOS data are scaled to AMSR-E retrieval climatology for a winter (Jan 12, 2010) and a summer (July 1, 2010) day. Artificial strips are reduced in the merged maps.

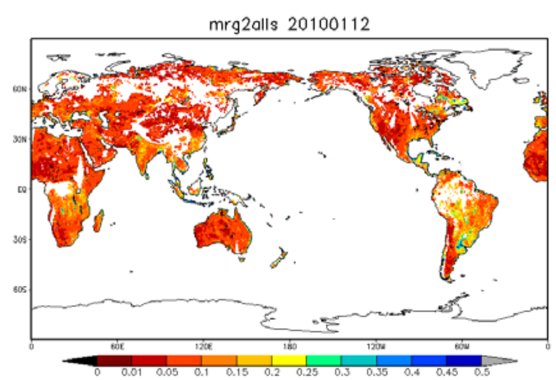


Figure 3.5.8 – Averaged soil moisture retrievals from AMSR-E, ASCAT and SMOS after ASCAT and SMOS data are scaled to AMSR-E retrieval climatology for a winter (Jan 12, 2010) and a summer (July 1, 2010). Artificial strips are seen in the merged map. Certain differences from the maps in Figure 3.5.7 exist.

3.6 Algorithm Output

The pre-processing, retrieval, and merging functions of the algorithm result in an output soil moisture map on a global Lat/Lon 0.25 degree grid. For each grid point of the map, the output includes soil moisture values (%vol/vol) of the surface (top 1-5 cm) soil layer with associated quality information and metadata. These soil moisture values are the retrieval from AMSR-E using the SCR algorithm, the imported ASCAT soil moisture, the imported SMOS soil moisture, and their merged value. The merged soil moisture value is expected to have better accuracy and coverage, but users can choose any of these data layers.

The SMOPS product files also contain a quality assessment (QA) data layer for each of the soil moisture data layers. Details of the QA data layer are provided in the following tables.

Table 3.6.1 – SMOPS soil moisture product Quality Assessment (QA) bits.

(a) Blended Soil Moisture Layer QA

Byte	Bit	Description
1	0	0 = questionable; 1 = good retrievals
	1	0 = no AMSR-E/Windsat; 1 = AMSR-E included/Windsat
	2	0 = no SMOS; 1 = SMOS included
	3	0 = no ASCAT; 1 = ASCAT included
	4	0 = not open water; 1 = open water
	5	0= not cold desert; 1 = cold desert
	6	0= not snow or rain; 1 = snow or rain
	7	0= not frozen ground; 1 = frozen ground
2	0	0 ≤ GVF < 0.1
	1	0.1 ≤ GVF < 0.2
	2	0.2 ≤ GVF < 0.3
	3	0.3≤ GVF < 0.4
	4	0.4≤ GVF < 0.5
	5	0.5 ≤ GVF
	6	Spare
	7	Spare

(b) AMSR-E Soil Moisture Layer QA

Byte	Bit	Description
1	0	0 = overall quality is not good; 1 = overall quality is good
	1	1 = retrieval attempted but quality is not good; 0 = otherwise
	2	1 = retrieval attempted but unsuccessful due to input brightness temperature data quality; 0 = otherwise
	3	1 = retrieval attempted but unsuccessful due to the quality of other input data; 0 = otherwise

	4	1 = retrieval not attempted; 0 = retrieval attempted
	5	0= not cold desert; 1 = cold desert
	6	0= not snow or rain; 1 = snow or rain
	7	0= not frozen ground; 1 = frozen ground
2	0	1: 0 ≤ GVF < 0.1; 0: otherwise
	1	1: 0.1 ≤ GVF < 0.2; 0: otherwise
	2	1: 0.2 ≤ GVF < 0.3; 0: otherwise
	3	1: 0.3≤ GVF < 0.4; 0: otherwise
	4	1: 0.4≤ GVF < 0.5; 0: otherwise
	5	1: 0.5 ≤ GVF; 0: otherwise
	6	1: overall input TB quality is good; 0 overall input TB quality is not good
	7	1 = real time NDVI; 0 = NDVI climate

(c) SMOS Soil Moisture Product QA

Byte	Bit	Description
1	0	Spare bit
	1	1 = RFI for H pol above threshold, 0 = otherwise
	2	1 = RFI for V pol above threshold, 0 = otherwise
	3	Spare bit
	4	1 = No products are generated, 0 = otherwise
	5	1 = Retrieval values outside range, 0 = otherwise
	6	1 = High retrieval DQX, 0 = otherwise
	7	1 = Poor fit quality, 0 = otherwise
2	0	1 = Presence of other than nominal soil; 0 = otherwise
	1	1 = Rocks; 0 = not rocks
	2	1 = Moderate or strong topography; 0 = otherwise
	3	1 = Open water; 0 = not open water
	4	1 = Snow; 0 = not snow
	5	1 = Forest; 0 = not forest
	6	1 = Flood risk; 0 = no flood risk
	7	1 = Urban area; 0 = not urban area

(d) ASCAT Soil Moisture Product QA

Byte	Description
0	Estimated Error in Soil Moisture. (Integer. Scale factor: 0.01)
1	Soil Moisture Quality (Integer, Scale factor: 0.01)

(e) WindSat Soil Moisture Layer QA

Byte	Bit	Description
1	0	0 = overall quality is not good; 1 = overall quality is good
	1	1 = retrieval attempted but quality is not good; 0 = otherwise
	2	1 = retrieval attempted but unsuccessful due to input brightness temperature data

		quality; 0 = otherwise
	3	1 = retrieval attempted but unsuccessful due to the quality of other input data; 0 = otherwise
	4	1 = retrieval not attempted; 0 = retrieval attempted
	5	0= not cold desert; 1 = cold desert
	6	0= not snow or rain; 1 = snow or rain
	7	0= not frozen ground; 1 = frozen ground
2	0	1: 0 ≤ GVF < 0.1; 0: otherwise
	1	1: 0.1 ≤ GVF < 0.2; 0: otherwise
	2	1: 0.2 ≤ GVF < 0.3; 0: otherwise
	3	1: 0.3≤ GVF < 0.4; 0: otherwise
	4	1: 0.4≤ GVF < 0.5; 0: otherwise
	5	1: 0.5 ≤ GVF; 0: otherwise
	6	1: overall input TB quality is good; 0 overall input TB quality is not good
	7	1 = real time NDVI; 0 = NDVI climate

Each SMOPS 6 hour soil moisture product data file also comes with a Metadata file that carries some overall information on the generation of this product. Table 3.6.2 shows the fields carried in the metadata file.

Table 3.6.2 – SMOPS SMOPS metadata file fields

(a) Common metadata

Elements	Data Type	Content
Satellite	char	Multi-Satellites
Instrument	char	AMSR-E, ASCAT, SMOS, WindSat
Projection	char	Cylindrical
Latitude at lower left corner	16-bit integer	
Longitude at lower left corner	16-bit integer	
Latitude at upper right corner	16-bit integer	
Longitude at upper right corner	16-bit integer	
Date & Time	16-bit integer	
Product Resolution (at nadir)	16-bit integer	0.5x0.5 degree
RowNumbers	16-bit integer	
ColumnNumbers	16-bit integer	

ByteOrderInfo (leftmost/rightmost)	16-bit integer	
Product Units	char	vol/vol
Product Version Number	16-bit integer	1.0
Data Compression Type	char	0=none
Scaling Factor	16-bit integer	10000.0
Offset	16-bit integer	0
Missing value	16-bit integer	
Production Location	char	NOAA/NESDIS/OSPO at Camp Springs, MD
Contact Information	char	Science Lead : Xiwu Zhan, NOAA/NESDIS/STAR, xinwu.zhan@noaa.gov Operation Lead: Limin Zhao, NOAA/NESDIS/OSPO, limin.zhao@noaa.gov

(b) Specific metadata

Category	Elements	Type
Input Data Quality	Percentage of valid AMSR-E retrievals over land	16-bit integer
	Percentage of valid ASCAT retrievals over land	16-bit integer
	Percentage of valid SMOS retrievals over land	16-bit integer
	Percentage of valid WindSat retrievals over land	16-bit integer
	Percentage of valid retrievals in the blended product over land	16-bit integer
	Percentage of valid AMSR-E retrievals in the blended product	16-bit integer
	Percentage of valid ASCAT retrievals in the blended product	16-bit integer
	Percentage of valid SMOS retrievals in the blended product	16-bit integer
	Percentage of valid WindSat retrievals in the blended product	16-bit integer
Retrieval Statistics	Minimum Value	16-bit integer
	Maximum Value	16-bit integer
	Mean	16-bit integer
	Standard Deviation	16-bit integer
Retrieval Quality	Total number of pixels with valid observations over land	16-bit integer
	Total number of pixels with valid retrievals	16-bit integer
	Total number of pixels with good retrievals	16-bit integer

3.7 Performance Estimates

To evaluate the algorithm performance under certain circumstances, sensitivity analysis is performed. Overall, this algorithm can retrieve reasonable soil moisture values in most cases where the input data are meaningful while the sensitivity to the input variable does vary for different soil types. Figure 3.7.1, for example, shows the retrieved soil moisture from SCR as a function of 10.7 GHz channel brightness temperature (H10 TB) for three different soil types with all other inputs fixed. The SCR algorithm is most sensitive in the brightness temperature range from around 150 K to 200 K, which is the typical range for real soil brightness temperature. In this brightness temperature range, the retrieved soil moisture could differ up to ten percent for different soil type, meaning that reliable soil texture maps are necessary as the inputs for the SCR.

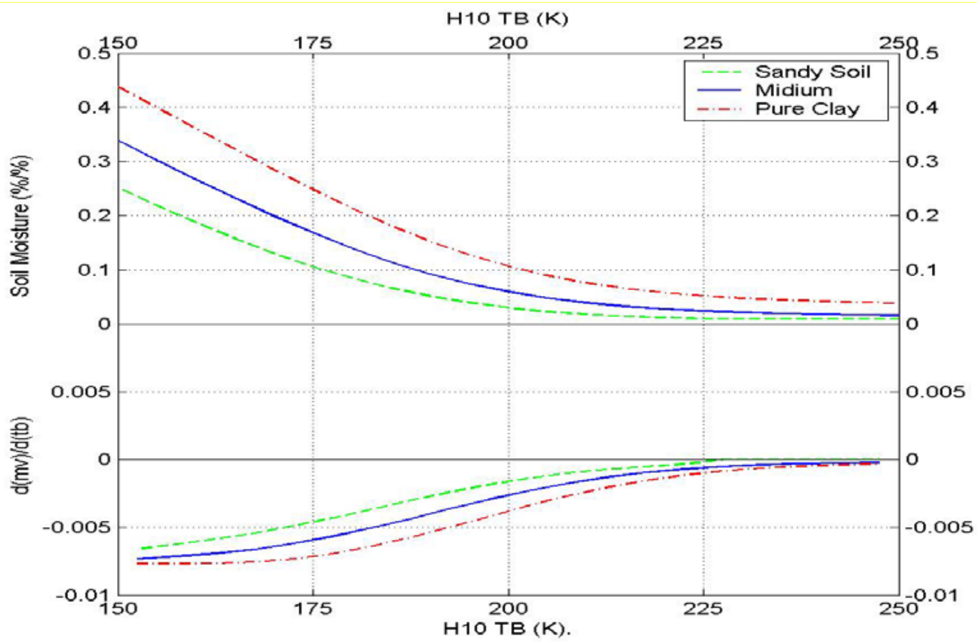


Figure 3.7.1 – Retrieved soil moisture from SCR Algorithm

To produce the soil moisture maps from different satellite sensors using the same algorithm, one needs to know if the calibration of the brightness temperature between these sensors is necessary. Figure 3.6 shows the SCR retrieval as a function of 10.7 GHz H-pol brightness temperatures (H10 TB) for three different types of soils. The lower part of this figure shows the changing rate of retrieved soil moisture as a function of brightness temperature. In the "sensitive" range (150 – 200 K), the changing rate can go as high as 0.007 (i.e., 0.7%/K). With soil moisture accuracy requirement of 0.10 (10%), this translates to a maximum brightness temperature difference of approximately 14 K. This places an upper limit on the acceptable AMSR-E brightness temperature accuracy. Because there are other sources of accuracy error (e.g. soil condition and vegetation condition), the acceptable accuracy will be less than 14 K. AMSR-E brightness temperature estimated accuracy is about 4K.

ASCAT soil moisture validation (http://oiswww.eumetsat.org/WEBOPS/eps-pg/ASCAT/ASCAT-PG-4ProdOverview.htm) shows that ASCAT soil moisture retrievals have 3-7%[v/v] RMSE.

SMOS soil moisture retrievals are expected to have smaller than 4% [v/v] RMSE according to their ATBD (http://www.cesbio.ups-tlse.fr/data_all/SMOS-doc/SM_ATBD_v05a_CDR.pdf).

Soil roughness is an input variable to the SCR algorithm, thus error in the specified roughness parameter may cause error in the soil moisture retrieval. A roughness parameter sensitivity analysis shows that doubling or halving the roughness parameter does not change soil moisture retrieval more than 5%[v/v] (Zhan et al, 2009). However, the soil moisture retrievals from the SCR algorithm are strongly impacted by the vegetation cover.

Based on the in situ soil moisture measurements and the green vegetation fraction (GVF, represented by NDVI) computed from NASA MODIS NDVI data, RMSEs of the AMSR-E soil moisture retrievals from SCR algorithm are plotted against the GVF values in Figure 3.7.2. The relationships were not consistent across different sites. But the general trend is: the thicker the vegetation cover, the higher the retrieval errors.

This is evident in Figure 3.7.3 which is based on the RMSEs between AMSR-E retrievals and model reanalysis results of surface layer soil moisture. The latter is treated as “truth” for the satellite retrievals. Therefore, in the quality flag associated with soil moisture retrieval, a value of retrieval reliability ranging 1-5 is included based on the vegetation water content estimates or the NDVI level of the grid. More details on this quality flag will be given by the code-unit test review (CTR) or system readiness review (SRR).

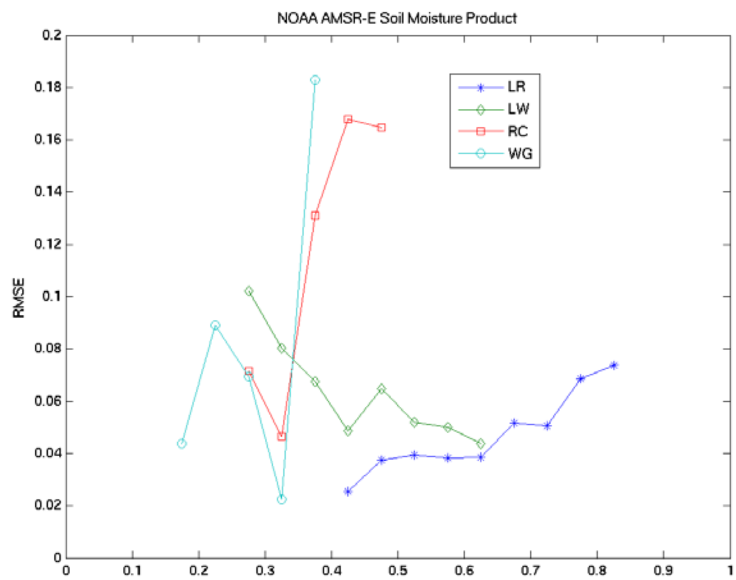


Figure 3.7.2 – RMSE values of SCR algorithm as a function of Normalized Difference Vegetation Index (NDVI) based on in situ soil moisture measurements from the USDA-ARS Ground Network stations: LR - Little River, Georgia; LW - Little Washita, Oklahoma; RC - Reynolds Creak, ID; and WG - Walnut Gulch, Arizona.

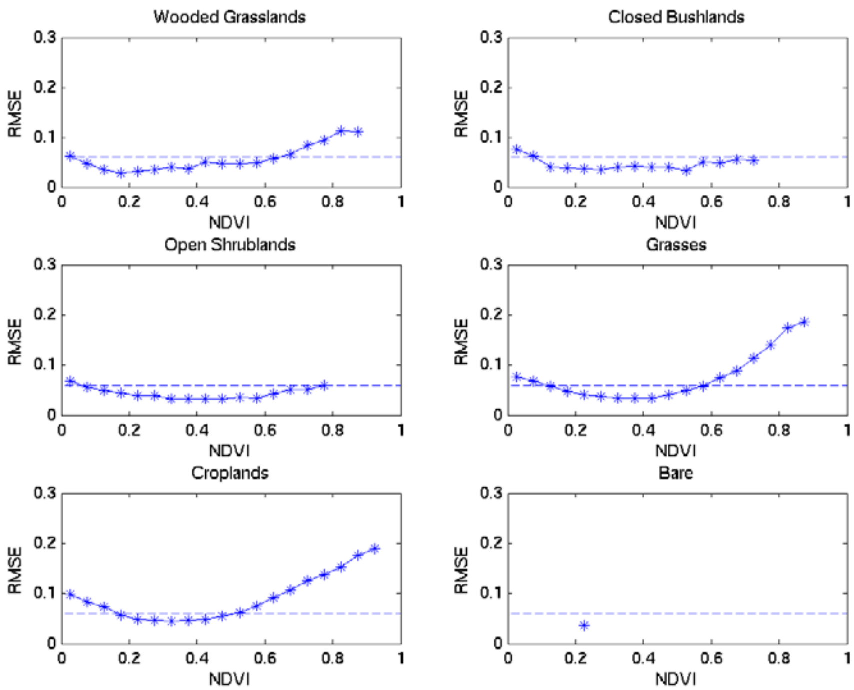


Figure 3.7.3 (a) – RMSE values of NOAA AMSR-E soil moisture retrieval as a function of Normalized Difference Vegetation Index (NDVI) based on Noah land surface model reanalysis soil moisture over the whole North America Land Data Assimilation System (NLDAS) domain for the year of 2003. Samples were too small to make a plot for Bare and Deciduous Needleleaf areas. The dashed line in the plots shows the 6% RMSE accuracy NCEP data requirement. Only a portion of soil moisture retrievals will meet this accuracy requirement.

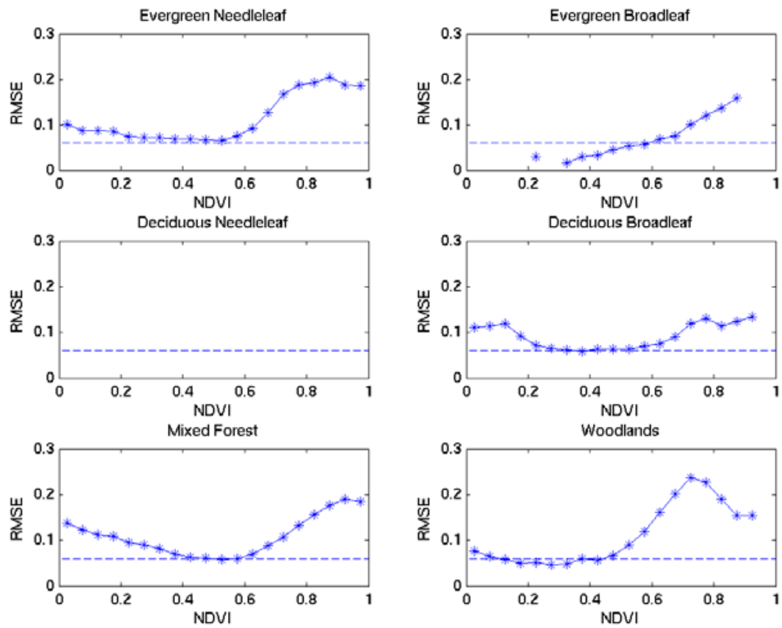


Figure 3.7.3 (b) – Same as Figure 3.7.3 (a) but for 6 other land cover types. Samples were too small to make a plot for Deciduous Needleleaf areas.

3.8 Practical Considerations

3.8.1 Numerical Computation Considerations

The whole algorithm is composed of many straightforward calculations, thus, it is light computationally.

3.8.2 Programming and Procedural Considerations

SMOPS code is run every 6 hours with all the available AMSR-E or WindSat L2A input data for the previous 6 hours to produce the 6 Hour product. In the case that the input AMSR-E L2A data come in late, the operational procedure will run without the later swath(s). The daily product is produced once every day using 4 6 Hour products on that day.

3.8.3 Quality Assessment and Diagnostics.

Unit testing and system testing will include quality assessment with historical in situ observations.

3.8.4 Exception Handling

The expected exceptions, and a description of how they are identified, trapped, and handled, will be provided in a future version.

3.9 Algorithm Validation

3.9.1 Sample Results

Figure 3.9.1 shows examples of composite maps presenting typical summer and winter soil moisture maps produced by this algorithm. The upper map is for the period of 1-5 June 2004, and the lower map is for 1-5 December 2004. Soil moisture is expressed in volumetric soil moisture content (m^3 water/m^3 soil).

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. In the summer time, the map clearly shows the humid vegetated East in the United States and the arid low vegetation in the West. In the winter time, however, the East becomes relatively dry as well.

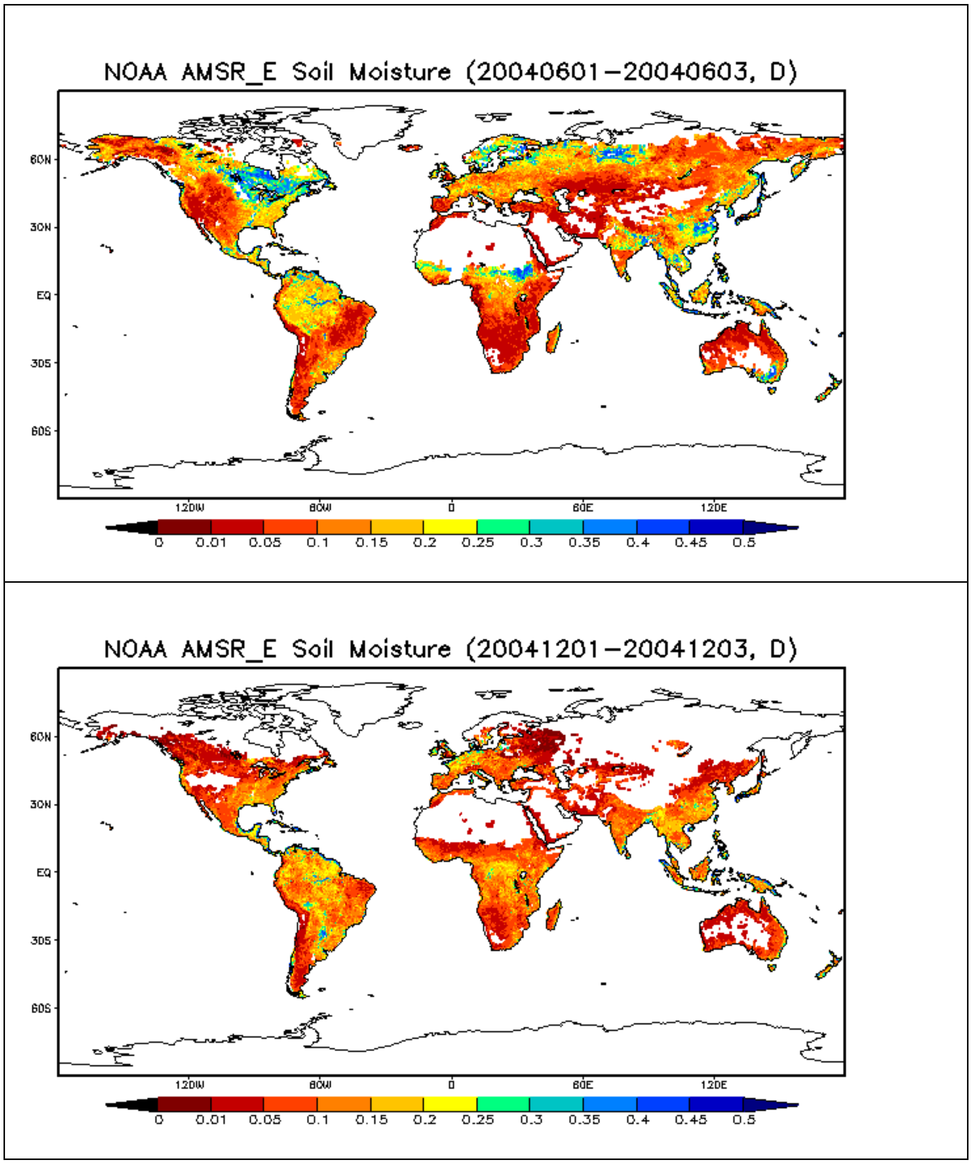


Figure 3.9.1 – Soil moisture maps produced by the SCR algorithm.

3.9.2 Validation Efforts

3.9.2.1 Validation of SCR algorithm with science data

In the efforts to quantitatively assess the soil moisture retrieval quality from the SCR algorithm, in-situ soil moisture measurements from soil moisture measurement networks established by USDA Agricultural Research Service in Little Washita, Oklahoma and Walnut Gulch watersheds were used to compare with the soil moisture retrievals from the AMSR-E 10GHz H-pol brightness temperature observations in year 2003. Another in situ soil moisture measurement data set from a similar network created in Mongolia by University of Tokyo, Japan is also used for validating the SCR soil moisture retrievals. Figures 3.9.2 and 3.9.3 demonstrate the time series comparison and scatter plots of the retrievals versus the in situ measurements. Table 3.3 lists the comparison statistics.

Table 3.9 – Statistics of the soil moisture comparison

Site	Alg	RMSE	Bias	R	Slope
WG01	NASA	3.1%	3.2%	0.626	0.201
	SCR	3.0%	-0.7%	0.564	0.379
LW01	NASA	4.6%	2.4%	0.508	0.255
	SCR	3.6%	-0.7%	0.756	0.601
MG01	NASA	7.7%	-3.8%	0.089	0.025
	SCR	6.4%	-4.1%	0.583	0.460

The above validation of the SCR algorithm using science data basically demonstrated that soil moisture retrievals from the SCR algorithm had agreement with the in situ observations better than the NASA-Land3 soil moisture product (labeled as “Njoku” in time series plots). The scatter plots in Figure 3.9.2 shows better slope as indicated in Table 3.3. The temporal dynamic ranges displayed in the time series plots in Figure 3.9.3 are larger than the NASA product and closer to in situ measurements.

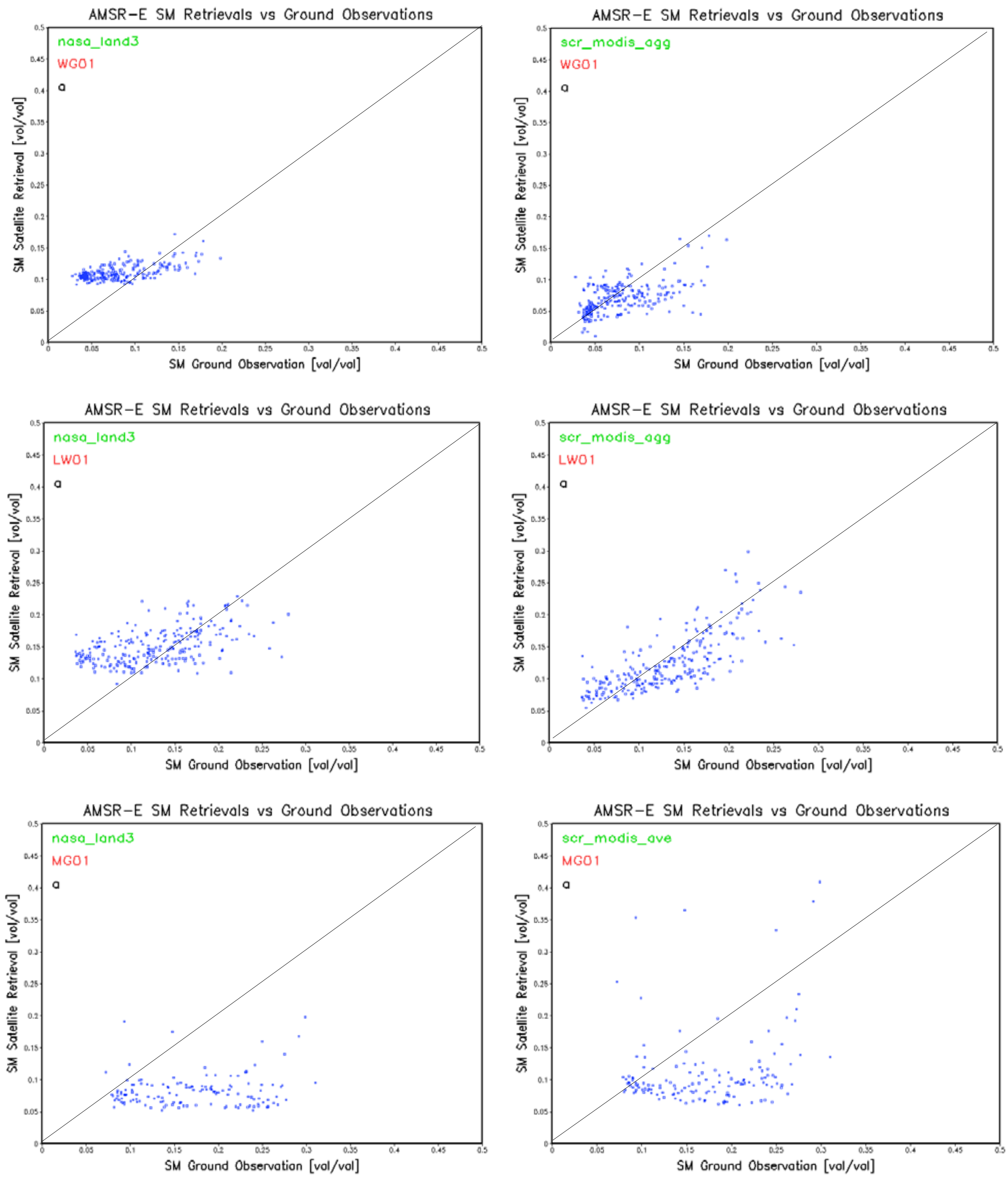


Figure 3.9.2 – Scatter plots of soil moisture retrieved from AMSR-E and in situ measurements

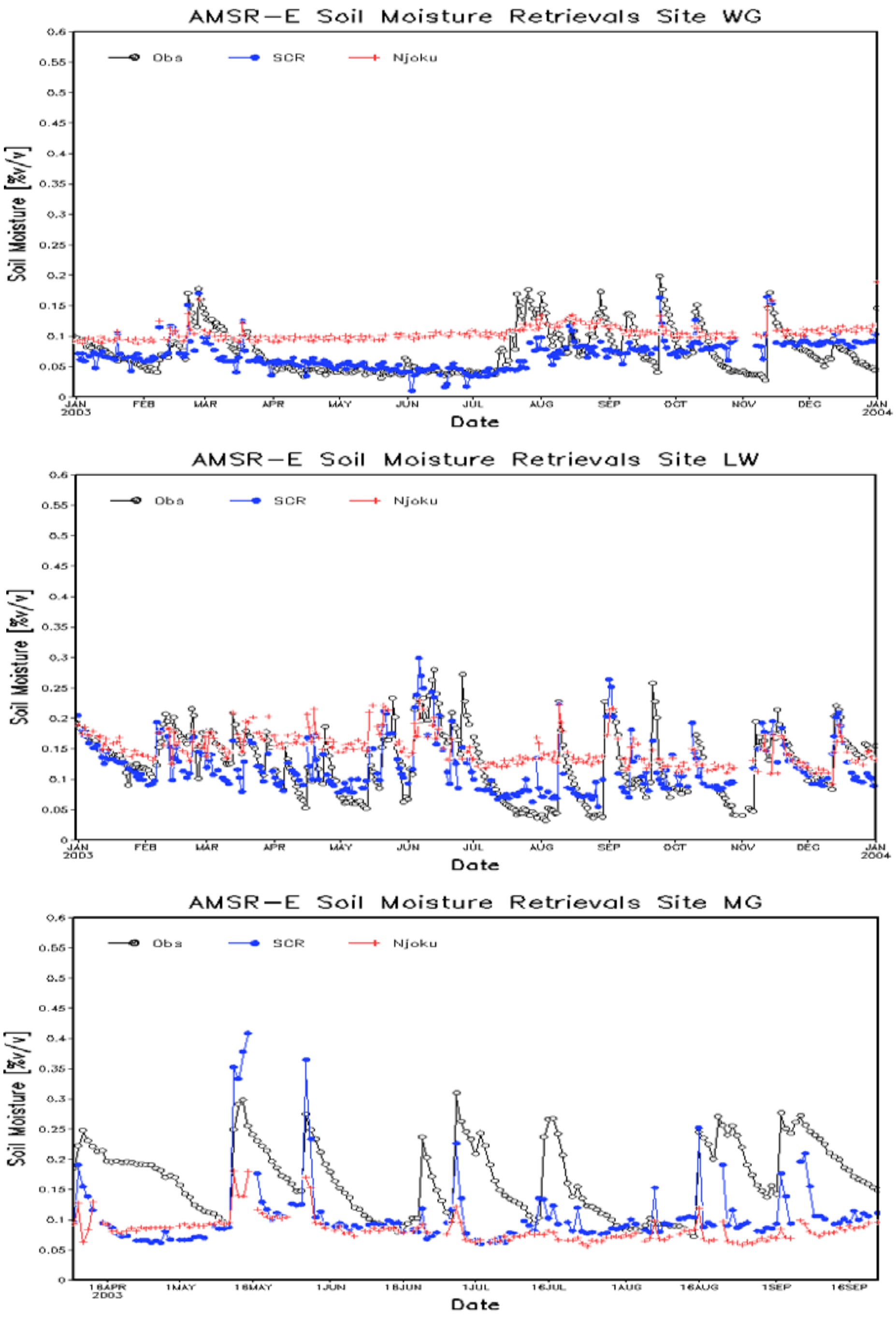


Figure 3.9.3 – Comparison time series of soil moisture AMSR-E retrievals and in situ measurements in year 2003.

3.9.2.2 Validation plan for SMOPS products

To further validate the SCR soil moisture retrievals from SMOPS, we plan to use the following in situ in dependent soil moisture measurements. These continuous soil moisture measurements are available from either websites or ftp servers. An up to date test data sets for validating SMOPS output will be presented during System Readiness Review (SRR).

USCRN: The United States Climate Reference Network (USCRN) was created by NOAA National Climate Data Center. In situ soil moisture measurement sensors have been installed gradually to most of the more than 100 stations spreading over all US 50 states. More than 40 stations have been equipped with the soil moisture and soil temperature sensors currently (October 2010). Some of these soil moisture measurements are currently available from the USCRN website (http://www.ncdc.noaa.gov/crn/products.html).

SCAN: The Soil Climate Analysis Network (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. These soil moisture measurements are mostly available from the SCAN website (http://www.wcc.nrcs.usda.gov/scan/).

COSMOS: National Science Foundation (NSF) has funded University of Arizona to establish a COSmic-ray Soil Moisture Observing System (COSMOS) to measure surface soil moisture over an about 300m sampling area surrounding a cosmic-ray sensor. About a dozen of this kind of soil moisture sensors have been installed around the US since later 2009. Soil moisture data from these sites have been available from the project website (http://cosmos.hwr.arizona.edu).

OZNet: Several small ground networks of soil moisture observation have been setup in Australia. The data are generally measured by Stevens Hydro Probes and are periodically available from OZNET website (http://www.oznet.org.au).

ChinaNet: There are several soil moisture measurement networks in China. They are managed by either China Meteorological Administration (CMA) or Chinese Academy of Science (CAS). Parts of their observational data are obtained through collaborative projects to validate SMOPS retrieval algorithms.

Evaluation of the SMOPS output against these in situ data sets will be provided for the SMOS System Readiness Review (SRR) and comparison results will be presented in this ATBD document after the SRR.

4.0 ASSUMPTIONS AND LIMITATIONS

4.1 Assumptions

The assumptions that were made in producing soil moisture product using SMOPS include:

1. The assumptions that were made in SCR for producing AMSR-E soil moisture include:
    a. Soil texture, namely sand, clay and porosity, does not change in time at 1/12 degree spatial resolution.
    b. 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.
    c. NDVI does not change within a week. This would not be a risk as the change of NDVI within one week is usually very small and, thus, only has marginal impact on soil moisture retrievals.
2. The time latency of AMSR-E Level 2A brightness temperature is within 2.5 hours.
3. The 6 Hour soil moisture product can be produced by SCR Unit within 0.5 hour. This would not be a risk based on the experimental runs of the R&D code.
4. The time latency of Level 2 SMOS soil moisture data is about hours. Therefore, the 6-hour SMOPS soil moisture data product will not contain the SMOS retrievals. The daily SMOPS soil moisture data product will have 12 hour time latency. The archive SMOPS soil moisture data product will be generated 48 hours after sensing.
5. The time latency of daily ASCAT soil moisture data is within 5.0 hours.
6. At least one of soil moisture products from SCR, SMOS and ASCAT is available at the time when the algorithm is doing composites.
7. The daily soil moisture product can be produced by SMA Unit within 1.0 hour after all data arrive.

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.

5.0 RISKS AND RISK REDUCTION EFFORTS

5.1 Failure of AMSR-E Sensor

The AMSR-E on Aqua satellite has been in space since June 2002. Its design lifetime is 3 years. It has been over design lifetime for 5 years and may fail anytime. SMOPS uses AMSR-E observations as the primary data input and its success has a risk of AMSR-E failure. However, the 10.7GHz channels of AMSR-E are similar to the 10.7GHz channels of the WindSat on Naval Research Lab's Coriolis satellite and the 10.7GHz channels of the Tropical Rainfall Monitoring Mission (TRMM) Microwave Imager (TMI). SMOPS software design has considered ingesting WindSat or TMI data. The near real time TMI and WindSat data are currently routinely available on the OSDPD DDS with similar data latency to the AMSR-E data. Therefore, SMOPS can be immediately switched to ingesting WindSat or TMI data as the primary input. WindSat swath width (1200 km) is smaller than the AMSR-E swath (1445 km), resulting in revisit time increased from 3 days to about 8 days. The accuracy of soil moisture value retrieved from WindSat or TMI 10GHz observations may not be impacted significantly. An inter-comparison of WindSat or TMI 10GHz brightness temperatures with AMSR-E shows that their differences were about 4K which may result in about 1%[v/v] difference in soil moisture retrievals from the SCR algorithm (Zhan, 2009).

Since the failure of AMSR-E in October, 2011, WindSat has been added to SMOPS.

5.2 Lack of ASCAT Data

ASCAT data are imported to SMOPS to increase the spatial and temporal coverage of satellite soil moisture data from AMSR-E or WindSat or TMI. If they are not available to SMOPS, the coverage of SMOPS output will be the same as AMSR-E or WindSat or TMI. Considering the small soil moisture temporal variation, this coverage reduction may be acceptable for numerical weather prediction if a 5 day revisit time can be eventually met (Walker & Houser, 2004).

5.3 SMOS Unavailability

SMOS soil moisture retrievals are also imported to SMOPS to increase the spatial and temporal coverage of AMSR-E observations. SMOS uses L-band observations that may increase the accuracy of SMOPS soil moisture product. However, SMOPS is based on the X-band observations from AMSR-E or WindSat or TMI that has long time data record and meets NCEP soil moisture data needs. Thus, it is desirable to have SMOS observations included in SMOPS product, but it's not critical.

5.4 Unavailability of NDVI Weekly Composite

Weekly composite of NDVI is required for estimating vegetation water content and optical depth. If the current week NDVI data is not available, the previous week data will be used. If both weeks are not available, a static NDVI climatology data for the current week will be used. The accuracy of retrieved soil moisture based on the climatology NDVI data could be compromised to a certain degree, depending on the difference of the climatological NDVI value from the current week real situation. If NDVI difference is 0.10, it may cause 5-10%[v/v] soil moisture difference. Further assessment of the NDVI impact will be provided by the unit test or system test.

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