Office of Satellite and Product Operations
Environmental Satellite Processing Center

Soil Moisture Operational Product System
Algorithm Theoretical Basis Document

Version 6.1
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Changes/Revisions Record

This algorithm theoretical basis document is changed as required to reflect system, operational, or organizational changes. Modifications made to this document are recorded in the Changes/Revisions Record below. This record will be maintained throughout the life of the document.

Version Number	Date	Description of Change/Revision	Section/Pages Affected	Changes Made by Name/Title/ Organization
1.0	05/06/2010	New Document for SMOPS PDR	New Document	
2.0	10/17/2010	Revised version for SMOPS CDR	Sections 3.5, 5.0	
2.1	01/04/2011	Revised version for SMOPS CDR	Sections 3.5, 5.0	
2.2	08/08/2011	Revised version for SMOPS SRR	Sections 3.5, 3.9, 5.0	
2.3	07/25/2012	Revised version for SMOPS ORR	Section 3.9	
3.0	09/25/2012	Final version for SMOPS Version 1.0	Added WindSat sensor	
3.1	08/04/2015	Final version for SMOPS Version 1.3	Added ASCAT-B	
4.0	09/20/2016	Final version for SMOPS Version 2.0	Added NRT SMOS and AMSR2 sensors	
5.0	11/01/2016	Final version for SMOPS Version 3.0	Added NRT SMAP and GMI sensors	
6.0	05/04/2022	Final version for SMOPS Version 4.0	Added ASCAT-C, Removed ASCAT-B, SMOS and NRT SMOS	
6.1	04/05/2024	Cover page, Changes/Revisions Record, and Preface added to SMOPS ATBD Version 6.0	Cover page, Changes/Revisions Record, Preface	Hannah Willett, Technical Writer, ERT Inc.
6.1	04/09/2024	Quality Assurance		Clint Sherwood, Quality Assurance Manager, ERT Inc.

Preface

This document comprises the National Oceanic and Atmospheric Administration (NOAA) National Environmental Satellite, Data, and Information Service (NESDIS), Office of Satellite and Product Operations (OSPO), publication of this Soil Moisture Operational Product System (SMOPS) Algorithm Theoretical Basis Document. This document reflects current operations for the DOC/NOAA/NESDIS Environmental Satellite Processing Center (ESPC) (NOAA5045) information technology systems. This document describes the established ESPC procedure for users of SMOPS in accordance with Federal, DOC, NOAA, NESDIS and OSPO requirements.

The published version of this document can be found at the OSPO SharePoint Products Library.

Table of Content

Page

LIST OF FIGURES

Page

LIST OF TABLES

Page

LIST OF ACRONYMS

AMSR2	Advanced Microwave Scanning Radiometer 2
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
EVI	Effective Vegetation Index
GAASP	GCOM-W1 AMSR2 Algorithm Software Processor
	Global Change Observation Mission 1st – Water
GFS	Global Forecast System
GLDAS	Global Land Data Assimilation System
GMI	GPM Microwave Imager
GPM	Global Precipitation Measurement
GVF	Green Vegetation Index
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
NRT	Near Real Time
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
SMAP	Soil Moisture Active Passive
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 sensors 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.

To increase spatial and temporal coverage of the satellite soil moisture observations, SMOPS will also import soil moisture retrievals from other satellite sensors and merger them with the output from the SCR algorithm using Global Land Data Assimilation System (GLDAS) modeled output as the reference product. Currently, these satellite sensors include the Advanced Scatterometers (ASCAT) aboard the EUMETSAT METOP-B and METOP-C satellites, Advanced Microwave Scanning Radiometer 2 (AMSR2) on JAXA's Global Change Observation Mission – Water "SHIZUKU" (GCOM-W1), the Global Precipitation Measurement (GPM) Microwave Imager (GMI) on NASA's GPM satellite, and SMAP radiometer on NASA's Soil Moisture Active Passive (SMAP) satellite. The algorithm for merging these soil moisture retrievals is described in section 3.

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. All of soil moisture retrievals from individual sensors 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.

A number of soil moisture products have been produced from different satellite sensors with different spatial and temporal coverage and quality. To make good use of all available soil moisture products, a Soil Moisture Operational Product System (SMOPS) has been developed at National Oceanic and Atmospheric Administration (NOAA) to produce a one
stop shop for all operational soil moisture products from different satellite sensors. To increase the spatial and temporal coverage of soil moisture product, SMOPS also provides a data layer that merges soil moisture retrievals from multiple satellites in addition to the individual soil moisture retrievals from each of the available satellites.

SMOPS has been operationally running at NOAA NESDIS since 2012. In the first version of SMOPS (V1.0), soil moisture products from Soil Moisture and Ocean Salinity (SMOS), the Advanced Scatterometer (ASCAT) on EUMETSAT's MetOp-A satellite and WindSat on Coriolis satellite are used to produce the blended product. SMOPS Version 2 included a near real-time SMOS soil moisture product that is produced using the Single Channel Retrieval (SCR) algorithm within SMOPS to reduce the time latency in using SMOS data. Soil moisture product from the Advanced Microwave Scanning Radiometer 2 (AMSR2) onboard the GCOM-W satellite is also ingested in SMOPS Version 2. SMOPS Version 3 improved the SMOPS product in following ways: 1) A new near real-time SMAP soil moisture product will be produced using the Single Channel Retrieval (SCR) algorithm in SMOPS to reduce the time latency in using SMAP data; 2) A new near GMI soil moisture product will be produced using the Single Channel Retrieval (SCR) algorithm in SMOPS; 3) Soil moisture product from SMAP produced by NASA will be ingested in the system; and 4) A new layer is added to indicate the standard deviation for computing the blended soil moisture when multiple soil moisture values are used for one pixel.

SMOPS has been updated to Version 4 in 2022. Changes involved in this update include 1) Dropped SMOS soil moisture layers as inputs; 2) Dropped ASCAT-A soil moisture as an input; 3) Added ASCAT-C soil moisture as a new input; 4) Changed all product format to NetCDF-4.

All soil moisture layers from individual sensors are also gridded and saved in SMOPS final product. SMOPS has a near-real time 6-hour product and a daily product. An archive product is also produced with a 2-day time latency to catch all available swath data from individual sensors.

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, these products are either available for a short time period or unavailable for near real time applications. NASA AMSR-E global soil moisture data product was the first one generated continuously and made constantly available for public users since June 2002. Since then, a number of microwave satellite soil moisture products have been 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, –B and -C 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 with this time latency requirement.

1.2 Purpose

To make effective use of all available microwave-based datasets, Soil Moisture Operational Product System (SMOPS) has been developed at NOAA/NESDIS that has been operational since 2012. This system not only provides global soil moisture data products from individual sensors, such as MetOp-A and –B ASCAT of EUMETSAT, WindSat (SMOPS V2.0 and before) of Naval Research Laboratory (NRL), SMOS of ESA, and AMSR2 from GCOM-W, but also provides a blended analysis from all these individual 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.

In the newest Version 4 of SMOPS, individual soil moisture layer inputs from SMOS and ASCAT-A have been dropped due to their lifetime spans. A new soil moisture layer from ASCAT-C is added.

This document describes the SMOPS Version 4.0, its retrieval algorithm and its products.

1.3 Revisions

This is a revised version (Version 6.0) dated May 4, 2022. 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 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 blended global soil moisture product by merging soil moisture observations from the Advanced Scatterometer (ASCAT) on EUMETSAT's MetOp satellites, Advanced Microwave Scanning Radiometer 2 (AMSR2) on JAXA's Global Change Observation Mission – Water "SHIZUKU" (GCOM-W1), and SMOPS own retrievals from Near Real Time (NRT) SMAP NRT L1B product and GMI L1CR product.

2.2 Instrument Characteristics

2.2.1 ASCAT

ASCAT sensors are on board of the MetOp satellites. They are 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 satellites 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.

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.

2.2.2 AMSR2

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.					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	

2.2.3 GMI

The Global Precipitation Measurement (GPM) Microwave Imager (GMI) instrument onboard GPM satellite of NASA is a multi-channel, conical- scanning, microwave radiometer serving an essential role in the near-global-coverage and frequent-revisit-time requirements of GPM. The GMI is characterized by thirteen microwave channels ranging in frequency from 10 GHz to 183 GHz. In addition to carrying channels similar to those on the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI), the GMI carries four high frequency, millimeter-wave, channels about 166 GHz and 183 GHz. With a 1.2 m diameter antenna, the GMI will provide significantly improved spatial resolution over TMI.

The off-nadir-angle defining the cone swept out by the GMI is set at 48.5 degrees which represents an earth-incidence-angle of 52.8 degrees. To maintain similar geometry with the predecessor TMI instrument, the-earth-incidence angle of GMI was chosen identical to that of the TMI. Rotating at 32 rotations per minute, the GMI gathers microwave radiometric brightness measurements over a 140-degree sector centered about the spacecraft ground track vector. The 140 degree GMI swath represents a swath of 904 km (562 miles) on the Earth's surface.

2.2.4 SMAP

The Soil Moisture Active Passive (SMAP) mission is the first of the Earth observation satellites being developed by NASA in response to the National Research Council's Earth Science Decadal Survey, *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond*. SMAP satellite was launched on January 31, 2015 and SMAP data became available since April 2015.

The SMAP instrument incorporates an L-band radar and an L-band radiometer that share a single feedhorn and parabolic mesh reflector. The reflector is offset from nadir and rotates about the nadir axis at 14.6 rpm (nominal), providing a conically scanning antenna beam with a surface incidence angle of approximately 40°. The provision of constant incidence angle across the swath simplifies the data processing and enables accurate repeat-pass estimation of soil moisture and freeze/thaw change. The reflector has a diameter of 6 m, providing a radiometer 3 dB antenna footprint of 40 km (root-ellipsoidal-area).

The SMAP radiometer measures the four Stokes parameters, V, H, T3, and T4 at 1.41 GHz. The T3-channel measurement can be used to correct for possible Faraday rotation caused by the ionosphere, although such Faraday rotation is minimized by the selection of the 6 am/6 pm sun-synchronous SMAP orbit.

2.2.5 VIIRS

SMOPS requires the vegetation index data for estimating the vegetation water content (VWC) that is a critical input to the SCR algorithm used to retrieval soil moisture from brightness temperature observations. The vegetation index data will be acquired from the Visible Infrared Imaging Radiometer Suite (VIIRS) on board the Suimi National Polar orbiting Partnership (Suimi NPP) weather satellite that was launched on October 28, 2011.

VIIRS was designed to expand upon the data collected by the aging MODIS and AVHRR sensors by collecting radiometric measurements of Earth in the visible and infrared spectra. This data is used to provide insight into the properties and dynamics of different geophysical phenomena, including aerosol and cloud properties, sea, land and ice surface temperatures, ice motion, fires, and the albedo of Earth surface.

VIIRS has a swath width of 3060km at the satellite's average altitude of 829km. This swath width is able to provide complete coverage of Earth across the day. The VIIRS instrument can collect data in 22 different spectral bands of the electromagnetic spectrum, in the wavelengths between 0.412µm and 12.01µm. The spatial resolution of the sensor depends on the band of the electromagnetic spectrum. Out of the 22 different spectral bands the sensor has, 16 are moderate resolution bands (M-bands) which have a spatial resolution of 750m at the Nadir. The other six bands are made up of five imaging resolution bands (I bands), which have a spatial resolution of 375m at the nadir, and one day/night panchromatic band with a spatial resolution of 750m.

2.3 Retrieval Strategy

The basic retrieval strategy of SMOPS is to retrieve soil moisture from a baseline satellite sensor, and then to potentially extend spatial and temporal coverage using soil moisture retrievals from other satellite sensors. More algorithm details will be described in the next sections.

3.0 ALGORITHM DESCRIPTION

3.1 Processing Outline

SMOPS Version 4 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 all available satellite sensors (ASCAT-B, ASCAT-C, AMSR2, GMI and SMAP), 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 swath data, and gridded soil moisture retrievals from other available satellite sensors 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 re-gridding

· 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 VIIRS EVI map

· Read EVI 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.

· Check the land cover type associated with the footprint and other conditions to proceed on doing SCR soil moisture retrieval

· Read one NRT SMAP L1B file name from the file name list

· Open the NRT SMAP L1B file and process it into brightness temperature

· Check the land cover type associated with the footprint and other conditions to proceed on doing SCR soil moisture retrieval

· Read one GMI L1C file name from the file name list

· Open the GMI L1C file and process it into brightness temperature

· 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 EVI
- 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 retrieved 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 ASCAT-B soil moisture data

· Read the Cumulative Distribution Functions (CDFs) for ASCAT-B and GLDAS soil moisture

· Scale ASCAT-B soil moisture retrievals by matching the CDFs

· Read ASCAT-C soil moisture data

· Read the Cumulative Distribution Functions (CDFs) for ASCAT-C and GLDAS soil moisture

· Scale ASCAT-C soil moisture retrievals by matching the CDFs

· Read AMSR2 soil moisture data

· Read the Cumulative Distribution Functions (CDFs) for AMSR2 and GLDAS soil moisture

· Scale AMSR2 soil moisture retrievals by matching the CDFs

· Read the Cumulative Distribution Functions (CDFs) for GMI and GLDAS soil moisture

· Scale GMI soil moisture retrievals by matching the CDFs

· Read the Cumulative Distribution Functions (CDFs) for NRT SMAP and GLDAS soil moisture

· Scale NRT SMAP soil moisture retrievals by matching the CDFs

· Composite all soil moisture retrievals from ASCAT-B, ASCAT-C, AMSR2, GMI, and NRT SMAP 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

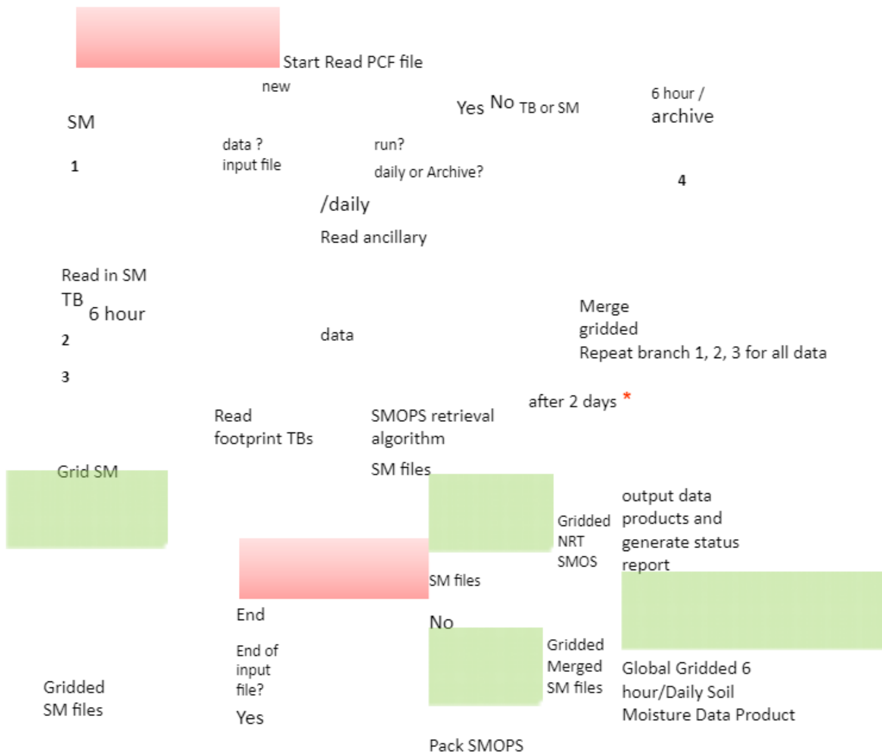
· Output daily soil moisture product with QA and meta data

· 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 ASCAT-B L2

SM, ASCAT-C L2 SM, AMSR2 L2 SM, GMI TB, or NRT SMAP TB 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 GMI L1C Data

The standard Level 1B GMI data are geolocated and calibrated microwave antenna temperatures (Ta) and brightness temperatures (Tb) in two separate data files. The base Ta data file will include all calibration parameters and measurements that are used to generate Ta and all navigation parameters that are used to "geolocate" each pixel. The Tb data file will include all parameters for corrections of Ta. Standard L1B data will be in the format of a full orbit (about 90 minutes). Real-time L1B data are processed in a 5-minute time period. SMOPS ingests GMI real-time L1B data and produces soil moisture product for each of the input GMI granule. More detailed information about this data set can be found at https://pmm.nasa.gov/sites/default/files/document_files/GMIL1B_ATBD.pdf.

3.2.2 SMAP NRT L1B Data

The SMAP L-Band Radiometer measures antenna temperatures referenced to the instrument feedhorn before and after RFI mitigation. SMAP antenna temperatures are then used to calculate the four Stokes parameters: TV, TH, T3, and T4 at 1.41 GHz. These parameters represent the vertically and horizontally polarized brightness temperatures, and the third and fourth cross-polarized brightness temperatures, respectively. The cross polarized T3-channel measurement can be used to correct for possible Faraday rotation caused by charged particles in the upper atmosphere. The near real-time version of SMAP L1B data has been produced with much shorter time latency for operational use. SMOPS is ingesting SMAP NRT L1B TB data and produces soil moisture product for each of the input SMAP NRT L1B TB orbit. More detailed information about this data set can be found at http://nsidc.org/data/docs/daac/smap/sp_l1b_tb/.

3.2.3 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.

3.2.3.1 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.

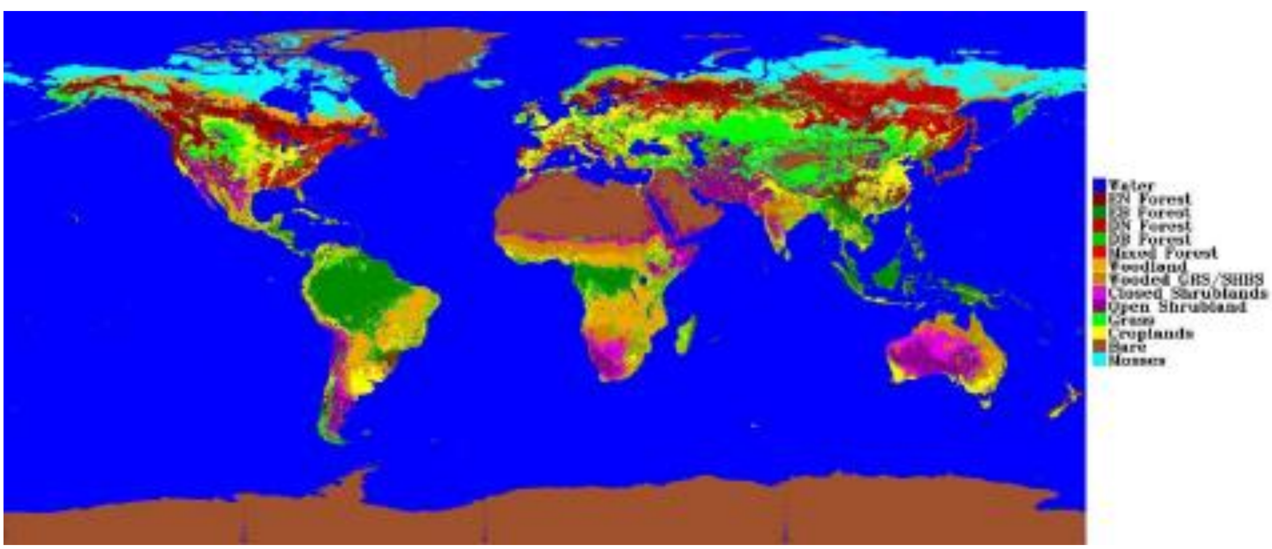


Figure 3.2.1 – Land Cover Map Used by the SCR Algorithm.

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 microwave observation footprint size level (usually 20km-50km), 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

3.2.3.2 Clay Map

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

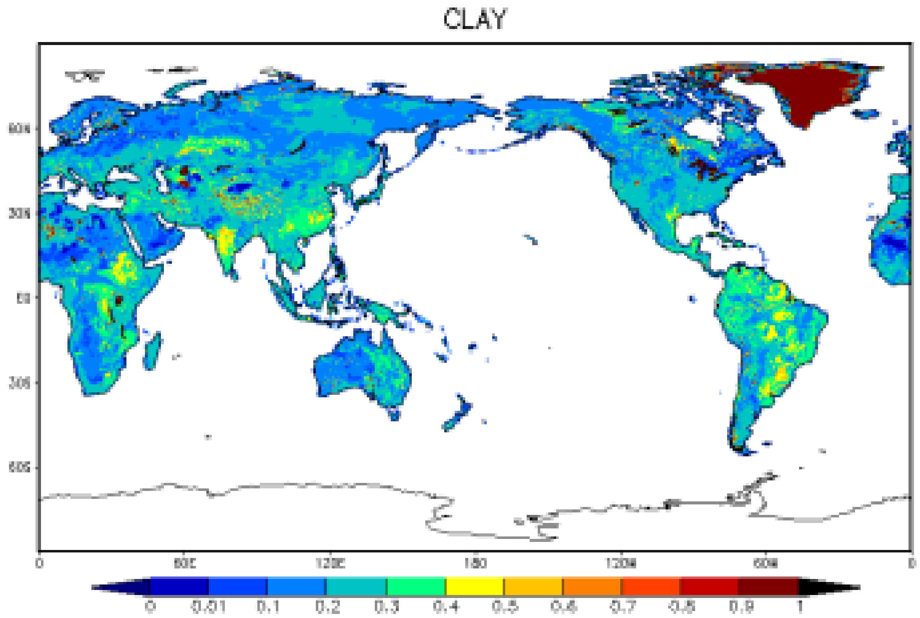


Figure 3.2.4 – Clay Fraction Map Used by the SCR Algorithm

3.2.3.3 Sand Map

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

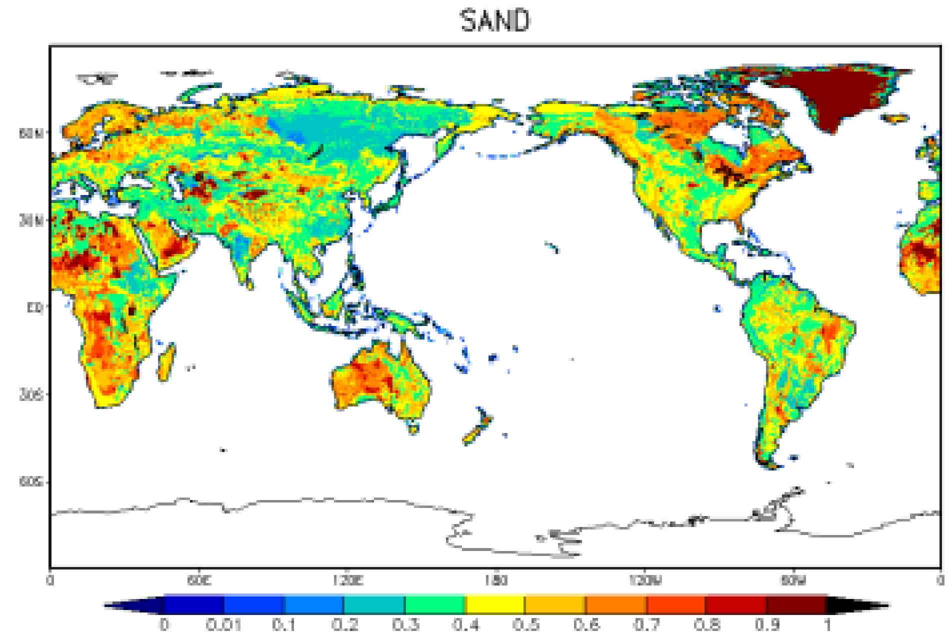


Figure 3.2.5 – Sand Fraction Map Used by the SCR Algorithm

3.2.3.4 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.

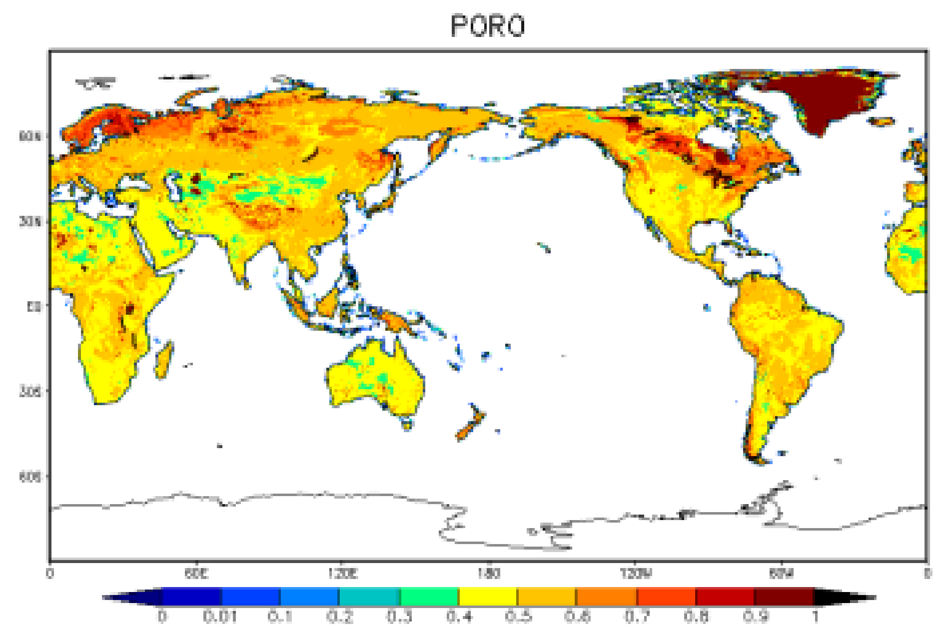


Figure 3.2.6 – Porosity Map Used by the SCR Algorithm

3.2.4 ASCAT-B, ASCAT-C, AMSR2 and NASA SMAP Soil Moisture

To increase the spatial and temporal coverage of the soil moisture data product, soil moisture retrievals from, ASCAT-B, ASCAT-C, NOAA AMSR2 and NASA SMAP are imported to the merging function of the algorithm (see Section 3.5).

3.2.4.1 ASCAT (B and C) 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).

3.2.4.2 AMSR2 Soil Moisture

The NOAA Operational GCOM-W1 AMSR-2 Products System (NOGAPS) is developed to process GCOM data and generate NOAA unique operational products for users. Soil moisture product is one of its major level 2 products. Detailed description can be found on their Website (http://www.ospo.noaa.gov/Products/atmosphere/gpds/).

3.2.4.3 NASA SMAP Soil Moisture

The NASA SMAP soil moisture product provides estimates of global land surface conditions retrieved by the Soil Moisture Active Passive (SMAP) passive microwave radiometer during 6:00 a.m. descending half-orbit passes. SMAP L-band brightness temperatures are used to derive soil moisture data, which are then resampled to an Earth-fixed, global, cylindrical 36 km Equal-Area Scalable Earth Grid, Version 2.0 (EASE-Grid 2.0). Detailed description can be found at following link: https://nsidc.org/data/docs/daac/smap/sp_l2_smp/.

3.3 Pre-processing Function

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

GMI L1C data and NRT SMAP L1B data will be extracted from original files and reformatted to SMOPS plain binary files. ASCAT, AMSR2 and SMAP soil moisture data will be extracted from their original formats, formatted to SMOPS plain binary format, and re gridded to SMOPS 0.25-degree lat/long grids. Ancillary data (VIIRS EVI, 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 microwave 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.

3.4.1 Brightness Temperature / Emissivity Relation

The major input for this algorithm is the 10.7 GHz H-pol brightness temperature, Tb, from a satellite 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

$$T_b = e_s T_s \quad (3.1)$$

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

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

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

$$T_B = T_S [1 - R_r \exp(-2\tau / \cos\theta)] \quad (3.3)$$

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:

$$\tau = bW \quad (3.4)$$

where *b* is an empirical parameter associated with different land cover types defined with the land cover parameters file. Vegetation water content, *W*, is estimated using AVHRR NDVI and the method described in this document: https://smap archive.jpl.nasa.gov/files/smap2/L2&3_SM_P_RevA_web.pdf.

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):

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

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:

```
mv = (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.

To increase the spatial coverage of 6 hour and 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.

3.5.2 Merging Approach

To generate a merged global soil moisture data product, the soil moisture retrievals from ASCAT-B, ASCAT-C, AMSR2, GMI and NRT SMAP will need to be combined into one value for each grid. 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 all footprint retrievals to SMOPS grid, scale them to GLDAS climatology, and finally merge them to a single value.

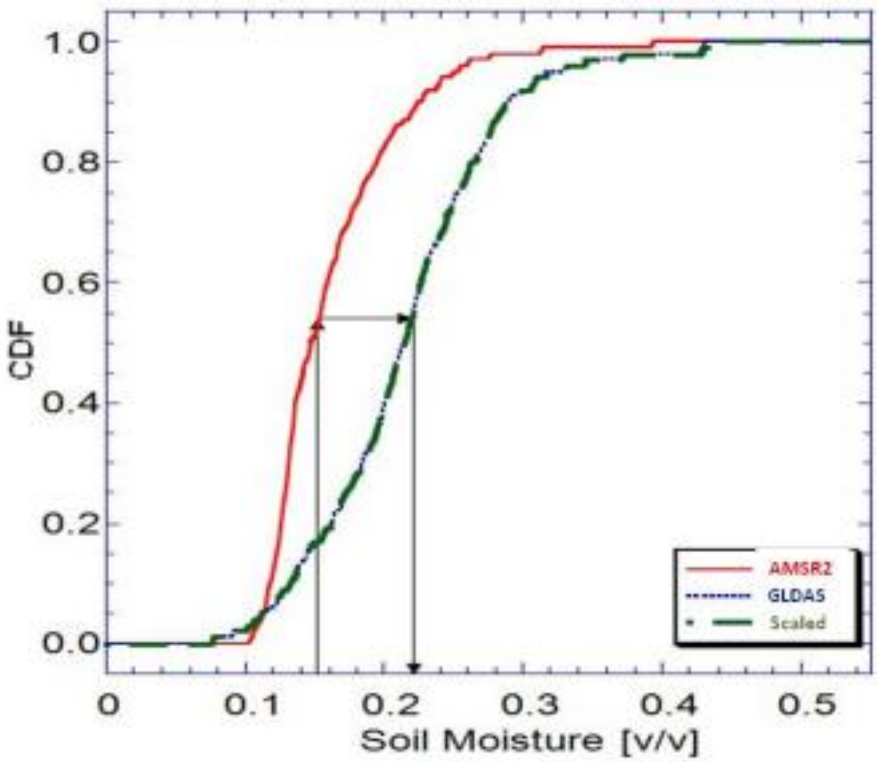
3.5.2.1 Grid NRT GMI and NRT SMAP Footprint Retrievals

Each 0.25-degree lat/lon grid may be represented by multiple NRT 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.

Same above process is applied to both NRT GMI footprint retrievals and NRT SMAP retrievals.

3.5.2.2 Scale ASCAT-B, ASCAT-C, AMSR-2, TMI and NRT SMAP Retrievals

For each 0.25-degree lat/lon grid, there may be soil moisture retrievals from, ASCAT-B, ASCAT-C, AMSR2, GMI and NRT SMAP. Each of them may have different climatology. Before merging them together, retrievals from all these products are scaled to GLDAS model output 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 GLDAS soil moisture values are a_1, a_2, …, a_n and their daily corresponding AMSR-2 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 GLDAS soil moisture values are A_1, A_2, …, A_n. Similarly, AMSR-2 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 AMSR2 data.



$c, B_j A_j$

Figure 3.5.1 – Scaling AMSR2 Soil Moisture Retrievals to GLDAS 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 GLDAS, the latest retrieval will be selected to represent the soil moisture observation for the day.

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 NRT GMI L1C data and NRT SMAP L1B data using the SCR algorithm, the imported ASCAT-B and ASCAT-C soil moisture, the imported AMSR2 soil moisture, the imported NASA SMAP 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 = good retrievals; 1 = questionable
	1	0 = no ASCAT-B; 1 = ASCAT-B included
	2	0 = no ASCAT-C; 1 = ASCAT-C included
	3	0 = no AMSR2; 1 = AMSR2 included
	4	0 = no GMI; 1 = GMI included
	5	0 = no NRT SMAP; 1 = NRT SMAP included
	6	0 = no NASA SMAP; 1 = NASA SMAP included
	7	Spare
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) 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)

(c) AMSR2 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	Spare
	7	Spare

(d) GMI 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	Spare
	7	Spare

(e) NRT SMAP 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	Spare
	7	Spare

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 metadata file fields

(a) Common metadata

Elements	**Data Type**	**Content**
Conventions	char	CF-1.5
cdm_data_type	char	Grid
creator_email	char	Xiwu.zhan@noaa.gov, jichengliu@noaa.gov
creator_name	char	DOC/NOAA/NESDIS/STAR > Land Team, Center for Satellite Applications and Research, NESDIS, NOAA, Department of Commerce
creator_url	char	https://www.star.nesdis.noaa.gov/smcd/emb/soilmoisture
publisher_name	char	DOC/NOAA/NESDIS/OSPO > Office of Satellite and Product Operations, NESDIS, NOAA, U.S. Department of Commerce
publisher_url	char	http://www.ospo.noaa.gov/

date_created	char	<date and time when the product is created>
day_night_data_flag	char	2
history	char	Soil Moisture Operational Product System (SMOPS) v?r?
history_package	char	<SMOPS delivery package version.
keywords (leftmost/rightmost)	char	NOAA, NESDIS, STAR, SMOPS, Blended, Global, Soil Moisture, ASCAT, AMSR2, GMI, SMAP
Keyword_vocabulary	char	None
id	char	<product file id>
institution	char	DOC/NOAA/NESDIS/OSPO > Office of Satellite and Product Operations, NESDIS, NOAA, U.S. Department of Commerce.
instrument	char	ASCAT, AMSR2, GMI, SMAP
metadata_link	char	<metadata file name>
naming_authority	char	gov.noaa.nesdis.ospo
platform	char	Metop-B, Metop-C, GCOM-W, GPM, SMAP
platform_type	char	Polar
processing_level	char	NOAA Level 3 data
production_environment	char	<production environment>
production_site	char	NOAA/NESDIS/STAR
project	char	NESDIS Common Cloud Framework
source	char	AMSR2-SM, ASCAT-B-SM, ASCAT-C-SM, GMI-SM, NRT-SMAP-SM, SMAP-SM, VIIRS_EVI
standard_name_vocabulary	char	CF Standard Name Table v50
summary	char	Blended soil moisture product and soil moisture products from individual sensors.
time_coverage_end	char	<time coverage end>
time_coverage_start	char	<time coverage start>

title	char	NPR_SMOPS_CMAP
geospatial_lat_min	float	-90.00
geospatial_lat_max	float	90.00
geospatial_lon_min	float	-180.00
geospatial_lon_max	float	180.00
geospatial_lat_units	char	degrees_north.
geospatial_lon_units	char	degrees_east.
geospatial_lat_resolution	float	0.25
geospatial_lon_resolution	float	0.25
projection	char	Plate Carree (Equirectangular Projection)
byte_order	char	<byte order>

(b) Specific metadata

Category	**Elements**	**Type**
Input Data Quality	Percentage of valid ASCAT-B retrievals over land	
	Percentage of valid ASCAT-B retrievals over land	16-bit integer
	Percentage of valid AMSR2 retrievals over land	16-bit integer
	Percentage of valid GMI retrievals over land	16-bit integer
	Percentage of valid NRT SMAP retrievals over land	16-bit integer
	Percentage of valid SMAP retrievals over land	16-bit integer
	Percentage of valid retrievals in the blended product over land	16-bit integer
	Percentage of valid ASCAT-A retrievals in the blended product	

	Percentage of valid ASCAT-B retrievals in the blended product	16-bit integer
	Percentage of valid AMSR2 retrievals in the blended product	16-bit integer
	Percentage of valid GMI retrievals in the blended product	16-bit integer
	Percentage of valid NRT SMAP retrievals in the blended product	16-bit integer
	Percentage of valid NASA SMAP 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
	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
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

Both SMOPS Daily and 6-hour products are in NetCDF-4 format.

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 brightness temperature 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.

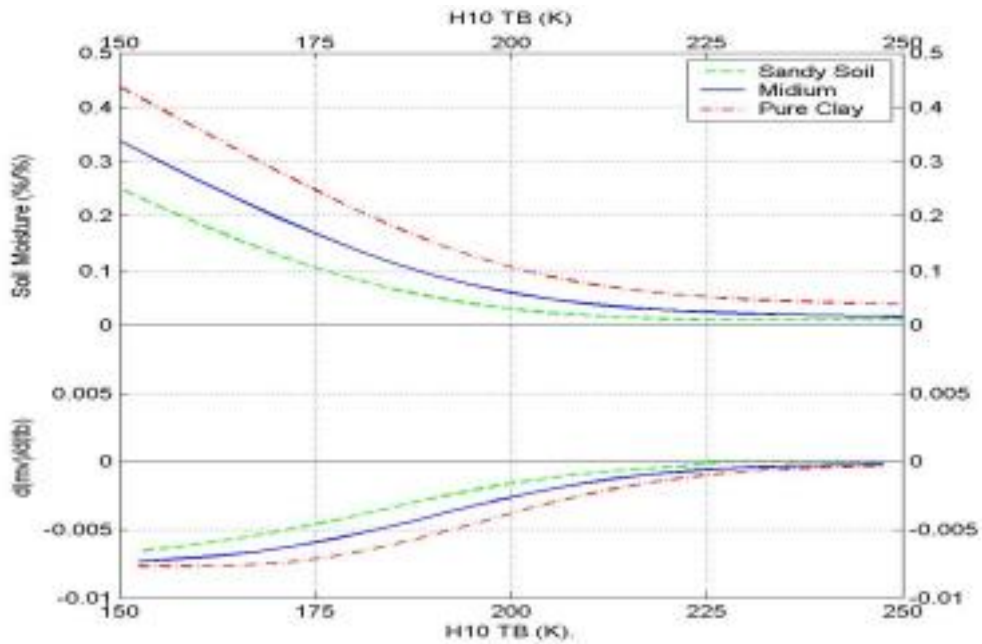


Figure 3.7.1 – Retrieved soil moisture from SCR Algorithm

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 3.7.1 shows the SCR retrieval as a function of 10 brightness temperatures 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 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.

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.

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 input data for the previous 6 hours to produce the 6 Hour product. In the case that the input 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.

Quality assessment with historical in situ observations will be presented in later

sections.

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 SMOPS daily product. The retrieved NRT soil moisture products generally exhibit a good dynamic range, 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 3.9.1 also shows much better spatial coverage of SMOPS blended product (bottom row) than any of the products from individual satellite sensors. Because of the CDF matching approach used to merge all the individual soil moisture products into this blended product, the overall magnitude of this merged product is different from all other sensors.

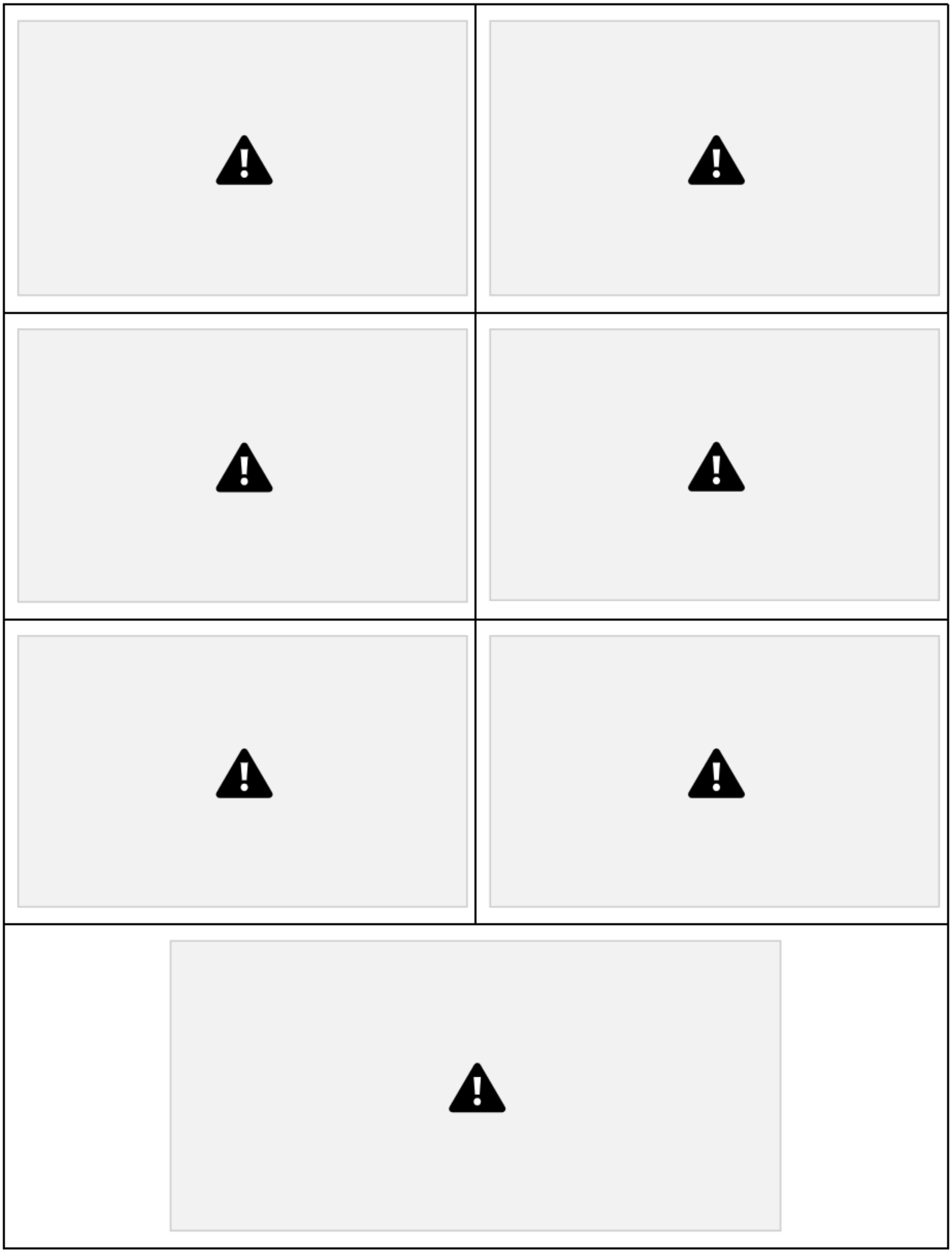
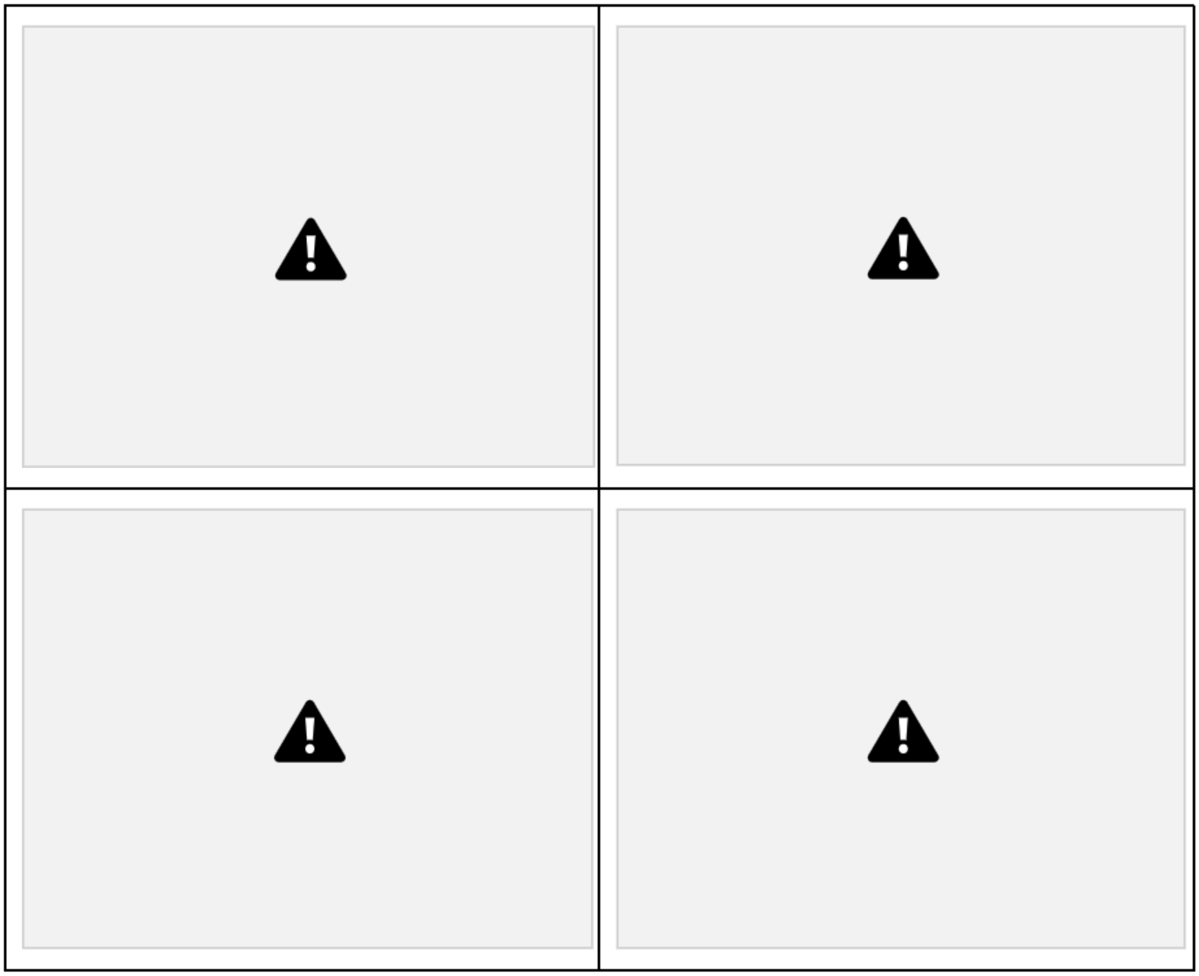


Figure 3.9.1 – Soil moisture maps produced by the SMOPS Version 4.0.

3.9.2 Validation Efforts

3.9.2.1 Validation of SCR algorithm with science data

In the efforts to quantitatively assess SMOPS soil moisture product quality, in-situ soil moisture measurements from a number of in-situ measurement sites are used to evaluate the overall performance of each product from SMOPS. Although this is still an on-going effort, the preliminary validation results show fairly good agreement between the satellite retrievals and in-situ data. Figure 3.9.2 shows a sample validation result using in-situ ground observation data from a Soil Climate Analysis Network (SCAN) station. Almost all SMOPS soil moisture layers show very good dynamics following the precipitation events with correlation coefficient above 0.5. Because SMOPS daily blended product has almost full land coverage, it has data available for this site for almost every single day.



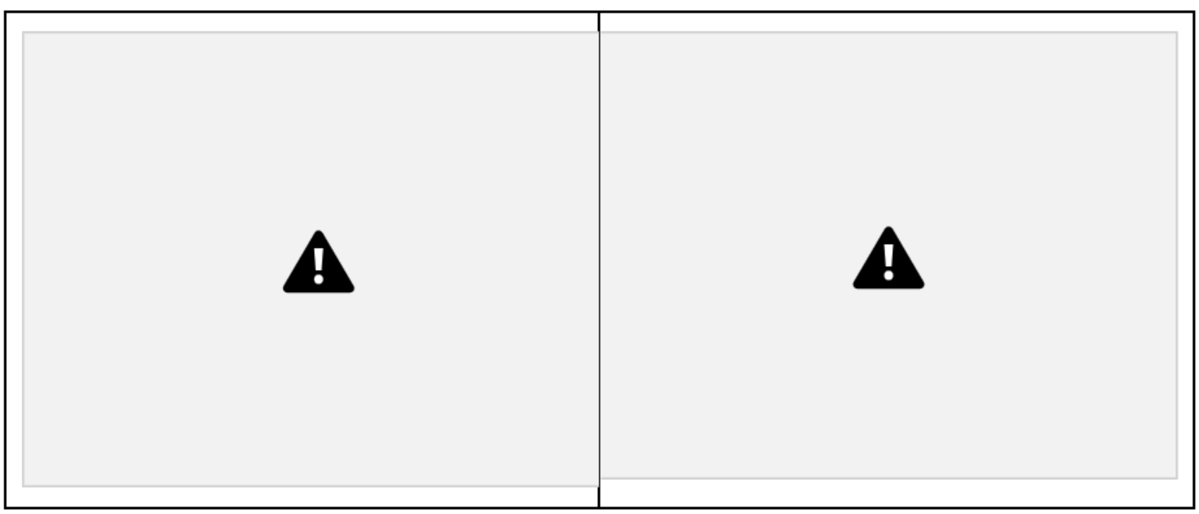


Figure 3.9.2 – Time series of newly added SMOPS soil moisture products vs. a SCAN sites in Phillipsburg, GA and Torrington, WY.

More validation work will be carried out as more SMOPS Version 3 data becomes available. The future validation plan is described in next section.

3.9.2.2 Validation plan for SMOPS products

To further validate the 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.

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.

4.0 ASSUMPTIONS AND LIMITATIONS

4.1 Assumptions

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

1. The time latency of GMI L1C brightness temperature is within 2.5 hours.
2. The time latency of NRT SMAP L1B 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 AMSR2 soil moisture data is about 2.5 hours.

5. The time latency of daily ASCAT soil moisture data is within 5.0 hours.

6. At least one of soil moisture products from ASCAT-A, ASCAT-B, AMSR2, GMI, NRT SMAP and NASA SMAP 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.

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