Remote Sensing of Environment xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Development and assessment of the SMAP enhanced passive soil moisture product

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ARTICLE INFO

Keywords:
SMAP
Enhanced
Soil moisture
Passive
Retrieval
Validation
Assessment

ABSTRACT

Launched in January 2015, the National Aeronautics and Space Administration (NASA) Soil Moisture Active Passive (SMAP) observatory was designed to provide frequent global mapping of high-resolution soil moisture and freeze-thaw state every two to three days using a radar and a radiometer operating at L-band frequencies. Despite a hardware mishap that rendered the radar inoperable shortly after launch, the radiometer continues to operate nominally, returning more than two years of science data that have helped to improve existing hydrological applications and foster new ones.

Beginning in late 2016 the SMAP project launched a suite of new data products with the objective of recovering some high-resolution observation capability loss resulting from the radar malfunction. Among these new data products are the SMAP Enhanced Passive Soil Moisture Product that was released in December 2016, followed by the SMAP/Sentinel-1 Active-Passive Soil Moisture Product in April 2017.

This article covers the development and assessment of the SMAP Level 2 Enhanced Passive Soil Moisture Product (L2_SM_P_E). The product distinguishes itself from the current SMAP Level 2 Passive Soil Moisture Product (L2_SM_P) in that the soil moisture retrieval is posted on a 9 km grid instead of a 36 km grid. This is made possible by first applying the Backus-Gilbert optimal interpolation technique to the antenna temperature (T_A) data in the original SMAP Level 1B Brightness Temperature Product to take advantage of the overlapped

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http://dx.doi.org/10.1016/j.rse.2017.08.025
Received 29 March 2017; Received in revised form 17 July 2017; Accepted 15 August 2017

radiometer footprints on orbit. The resulting interpolated T_A data then go through various correction/calibration procedures to become the SMAP Level 1C Enhanced Brightness Temperature Product (L1C_TB_E). The L1C_TB_E product, posted on a 9 km grid, is then used as the primary input to the current operational SMAP baseline soil moisture retrieval algorithm to produce L2_SM_P_E as the final output. Images of the new product reveal enhanced visual features that are not apparent in the standard product. Based on *in situ* data from core validation sites and sparse networks representing different seasons and biomes all over the world, comparisons between L2_SM_P_E and *in situ* data were performed for the duration of April 1, 2015–October 30, 2016. It was found that the performance of the enhanced 9 km L2_SM_P_E is equivalent to that of the standard 36 km L2_SM_P, attaining a retrieval uncertainty below 0.040 m^3/m^3 unbiased root-mean-square error (ubRMSE) and a correlation coefficient above 0.800. This assessment also affirmed that the Single Channel Algorithm using the V-polarized T_B channel (SCA-V) delivered the best retrieval performance among the various algorithms implemented for L2_SM_P_E, a result similar to a previous assessment for L2_SM_P.

1. Introduction

The synergy of active (radar) and passive (radiometer) technologies at L-band microwave frequencies in the National Aeronautics and Space Administration (NASA) Soil Moisture Active Passive (SMAP) mission provides a unique remote sensing opportunity to measure soil moisture with unprecedented accuracy, resolution, and coverage (Entekhabi et al., 2014). Driven by the needs in hydroclimatological and hydrometeorological applications, the SMAP observatory was designed to meet a soil moisture retrieval accuracy requirement of 0.040 m^3/m^3 unbiased root-mean-square error (ubRMSE) or better at a spatial resolution of 10 km over non-frozen land surfaces that are free of excessive snow, ice, and dense vegetation coverage (Entekhabi et al., 2014).

In July 2015, SMAP's radar stopped working due to an irrecoverable hardware failure, leaving the radiometer as the only operational instrument onboard the observatory. Since the beginning of science data acquisition in April 2015, the radiometer has been collecting L-band (1.41 GHz) brightness temperature (T_B) data at a spatial resolution of 36 km, providing global coverage every two to three days. The relatively high fidelity of the data provided by the radiometer's radio-frequency-interference (RFI) mitigation hardware (Piepmeier et al., 2015b; Mohammed, et al., 2016), along with the observatory's full 360-degree view that offers both fore- and aft-looking observations, presents unique advantages for SMAP data to advance established hydrological applications (Koster et al., 2016) and foster new ones (Yueh et al., 2016).

Despite the loss of the radar, SMAP is committed to providing high-resolution observations to the extent that is possible. This initiative of acquiring high-resolution information proceeds in two distinct approaches. The first approach involves combining the current SMAP coarse-resolution passive observations with high-resolution radar observations from *other* satellites in space to produce an operational soil moisture product similar to the now discontinued SMAP Level 2 Active-Passive Soil Moisture Product (L2_SM_AP). To attain this objective, the high-resolution synthetic aperture radar (SAR) data from the European Space Agency (ESA) Sentinel-1 C-band radar constellation (Torres et al., 2012) represent the most optimal candidate data source that would provide partial fulfillment of the original science benefits of L2_SM_AP. Although there are technical challenges due to data latency, global coverage, revisit frequency, and retrieval performance from such a combined L/C-band SMAP/Sentinel-1 soil moisture product, these challenges are expected to be mitigated over time under the close collaboration between the two mission teams. The resulting SMAP/Sentinel-1 Level 2 Active-Passive Product (L2_SM_SP) will be available to the public in April 2017.

The second approach is based on the application of the Backus-Gilbert (BG) optimal interpolation technique (Poe, 1990; Stogryn, 1978) to the antenna temperature (T_A) measurements in the original SMAP Level 1B Brightness Temperature Product (L1B_TB) (Piepmeier et al., 2015a, 2015b). The resulting interpolated T_A data then go through the standard correction/calibration procedures to produce the SMAP Level 1C Enhanced Brightness Temperature Product (L1C_TB_E) on a set of 9 km grids (Chaubell et al., 2016). The objective of the BG interpolation as implemented by SMAP is to achieve optimal brightness temperature (T_B) estimates at arbitrary locations as if original observations were available at the same locations (Poe, 1990). This estimation is achieved by linearly combining optimally weighted radiometric measurements overlapped in both along- and across-scan directions. The BG procedure is an improvement over what the current SMAP Level 1C Brightness Temperature Product (L1C_TB) (Chan et al., 2014, 2015) offers, in that it makes explicit use of antenna pattern information and finer grid posting to more fully capture the high spatial frequency information in the original oversampled radiometer measurements in the along-scan direction (Chaubell, 2016). It is important to note that this recovery of high spatial frequency information as implemented in this approach primarily comes from interpolation instead of beam sharpening. As such, the native resolution of the interpolated data remains to be about the same as the spatial extent projected on earth surface by the 3-dB beamwidth of the radiometer. For SMAP, this spatial extent is roughly an ellipse with 36 km as its minor axis and 47 km as its major axis (Entekhabi et al., 2014). As the SMAP project adopted the square root of footprint *area* as the definition of native resolution of the radiometer, the corresponding native resolution is estimated to be $(\pi / 4 \times 36 \times 47)^{1/2} \sim 36$ km. The resulting L1C_TB_E data are posted on the EASE Grid 2.0 projection (Brodzik et al., 2012, 2014) at a grid spacing of 9 km, even though the data actually exhibit a native resolution of ~36 km. The L1C_TB_E product is then used as the primary input in subsequent passive geophysical inversion to produce the SMAP Level 2 Enhanced Passive Soil Moisture Product (L2_SM_P_E) (O'Neill et al., 2016), which is the focus of this paper.

The retrieval performance of L2_SM_P_E was assessed and reported in this paper using > 1.5 years (April 1, 2015–October 30, 2016) of *in situ* data from core validation sites (CVSs) and sparse networks representing different seasons and biomes all over the world. The assessment findings presented in this paper represent a significant extension of the work reported in (Chan et al., 2016). Additional metric statistics from this assessment can be found in a separate report that covers the standard and enhanced passive soil moisture products (Jackson et al., 2016).

2. Product development

The SMAP observatory was to present a unique opportunity to demonstrate the synergy of radar and radiometer observations at L-band frequencies in the remote sensing of soil moisture and freeze/thaw state detection from space. Unfortunately, this demonstration was shortened due to a hardware failure that eventually halted the operation of the radar after about three months of operation. While the loss necessarily ended the operational production of several key soil moisture and freeze/thaw data products that rely on the high-resolution radar data, it also spurred the development of several new data products designed to