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The SMAP mission combined active-passive soil moisture product at 9 km and 3 km spatial resolutions

Narendra N. Das[a,*], Dara Entekhabi[b], R. Scott Dunbar[a], Andreas Colliander[a], Fan Chen[c], Wade Crow[d], Thomas J. Jackson[d], Aaron Berg[e], David D. Bosch[f], Todd Caldwell[g], Michael H. Cosh[h], Chandra H. Collins[i], Ernesto Lopez-Baeza[j], Mahta Moghaddam[k], Tracy Rowlandson[e], Patrick J. Starks[l], Marc Thibeault[m], Jeffrey P. Walker[n], Xiaoling Wu[n], Peggy E. O'Neill[o], Simon Yueh[a], Eni G. Njoku[a]

[a] *Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA*
[b] *Massachusetts Institute of Technology, Cambridge, MA 02139, USA*
[c] *Science System and Application, Inc, United State Department of Agriculture, Beltsville, Maryland, USA*
[d] *United State Department of Agriculture, Beltsville, Maryland, USA*
[e] *University of Guelph, Canada*
[f] *USDA ARS Southeast Watershed Research, Tucson, AZ, USA*
[g] *University of Texas at Austin, Texas, USA*
[h] *USDA ARS Hydrology and Remote Sensing Laboratory, Beltsville, MD, USA*
[i] *USDA ARS Southwest Watershed Research, Tucson, AZ, USA*
[j] *University of Valencia, Spain*
[k] *University of Southern California, California, USA*
[l] *USDA ARS Grazinglands Research Laboratory, El Reno, OK, USA*
[m] *Comisión Nacional de Actividades Espaciales (CONAE), Argentina*
[n] *Monash University, Australia*
[o] *Goddard Space Flight Center (GSFC), NASA, 8800 Greenbelt, MD 20771, USA*

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ABSTRACT

The NASA Soil Moisture Active Passive (SMAP) mission was launched on January 31st, 2015. The spacecraft was to provide high-resolution (3 km and 9 km) global soil moisture estimates at regular intervals by combining for the first time L-band radiometer and radar observations. On July 7th, 2015, a component of the SMAP radar failed and the radar ceased operation. However, before this occurred the mission was able to collect and process ~2.5 months of the SMAP high-resolution active-passive soil moisture data (L2SMAP) that coincided with the Northern Hemisphere's vegetation green-up and crop growth season. In this study, we evaluate the SMAP high-resolution soil moisture product derived from several alternative algorithms against *in situ* data from core calibration and validation sites (CVS), and sparse networks. The baseline algorithm had the best comparison statistics against the CVS and sparse networks. The overall unbiased root-mean-square-difference is close to the 0.04 m^3/m^3 the SMAP mission requirement. A 3 km spatial resolution soil moisture product was also examined. This product had an unbiased root-mean-square-difference of ~0.053 m^3/m^3. The SMAP L2SMAP product for ~2.5 months is now validated for use in geophysical applications and research and available to the public through the NASA Distributed Active Archive Center (DAAC) at the National Snow and Ice Data Center (NSIDC). The L2SMAP product is packaged with the geo-coordinates, acquisition times, and all requisite ancillary information. Although limited in duration, SMAP has clearly demonstrated the potential of using a combined L-band radar-radiometer for proving high spatial resolution and accurate global soil moisture.

* Corresponding author.
E-mail addresses: Nndas@jpl.nasa.gov (N.N. Das), Darae@mit.edu (D. Entekhabi), Roy.S.Dunbar@jpl.nasa.gov (R.S. Dunbar), Andreas.Colliander@jpl.nasa.gov (A. Colliander), Fan.Chen@ars.usda.gov (F. Chen), Wade.Crow@ars.usda.gov (W. Crow), Tom.jackson@ars.usda.gov (T.J. Jackson), aberg@uoguelph.ca (A. Berg), David.Bosch@ars.usda.gov (D.D. Bosch), todd.caldwell@beg.utexas.edu (T. Caldwell), Michael.Cosh@ars.usda.gov (M.H. Cosh), chandra.holifield@ars.usda.gov (C.H. Collins), Ernesto.Lopez@uv.es (E. Lopez-Baeza), mahta@usc.edu (M. Moghaddam), trowland@uoguelph.ca (T. Rowlandson), Patrick.Starks@ars.usda.gov (P.J. Starks), mthibeault@conae.gov.ar (M. Thibeault), jeff.walker@monash.edu.au (J.P. Walker), xiaoling.wu@monash.edu.au (X. Wu), Peggy.E.O'Neill@nasa.gov (P.E. O'Neill), Simon.Yueh@jpl.nasa.gov (S. Yueh).

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1. Introduction

NASA's Soil Moisture Active Passive (SMAP) mission was launched on January 31st, 2015. The objective of the mission is global mapping of high-resolution surface soil moisture and landscape freeze/thaw state (Entekhabi et al., 2010). SMAP utilizes an L-band radar and radiometer sharing a rotating 6-meter mesh reflector antenna. The SMAP spacecraft is in a 685-km Sun-synchronous near-polar orbit and views the surface at a constant 40-degree incidence angle with a 1000-km swath width. The basic premise of the mission was that merging of the high-resolution active (radar) and coarse-resolution but high-sensitivity passive (radiometer) L-band observations would enable an unprecedented combination of accuracy, resolution, coverage, and revisit-time for soil moisture and freeze/thaw state retrievals (Entekhabi et al., 2010; Das et al., 2014). However, on July 7th, 2015, the SMAP radar ceased operations due to a component failure. As a result, the observatory was only able to provide ~2.5 months (from the end of In-Orbit-Check April 13th, 2015 to July 7th, 2015) of the SMAP active-passive product (L2SMAP) (the radiometer continues to be fully operational). The product is based on downscaling of gridded 36 km SMAP brightness temperature (T_{B_p}) data to a higher spatial resolution (9 km) using SMAP radar backscatter observations and the subsequent inversion of the resulting high-resolution T_{B_p} fields into soil moisture retrievals. Another higher resolution at 3 km global surface soil moisture data set is also produced for assessment and potential implementation.

Prior to this investigation, the active-passive algorithm (presented in subsequent section) had only been implemented with simulated data and limited aircraft-based observations. The work presented here shows the operational capability of the SMAP active-passive algorithm and provides a calibration/validation of the products using various core sites. Although the duration of the L2SMAP is only ~2.5 months (due to the malfunction of the SMAP radar), within this period, it provided a demonstration that the active-passive algorithm could work under all hydroclimatic domains with moderate and heterogeneous vegetation cover. The product also provided the first satellite demonstration of the effectiveness of using the combination of L-band radar and radiometer observations as an effective approach to high spatial resolution and accurate soil moisture retrieval. Hence, this product supports the development of this approach in current and future missions.

2. Active-passive algorithm review

In the past, numerous studies (Kim and Barros, 2002; Kim and Barros, 2003; Chauhan et al., 2003; and Reichle et al., 2001) have attempted to obtain high-resolution soil moisture by downscaling coarse resolution (~50 km) soil moisture products from satellite-based microwave radiometers. These studies used high-resolution remote sensing observations and fine-scale ancillary geophysical information such as topography, vegetation, soil type, and precipitation that exert physical control over the evolution of soil moisture. For example, high-resolution thermal infrared data from MODIS and soil parameters were utilized in a deterministic approach to disaggregate the SMOS ~40 km soil moisture product to a ~1 km soil moisture estimate (Molero et al., 2016; Merlin et al., 2008). A common factor in these approaches is the use of static and dynamic geophysical data in the downscaling/disaggregation approach. The geophysical observations come from different sources with some inherent errors, as well as temporal registration mismatch that can affect the accuracy of the downscaled soil moisture estimates. For example, the MODIS thermal infrared data is measured at ~10:00 AM local time and are not co-registered (in the SMAP mission the radar and radiometer observations are acquired at the same time *i.e.*, ~6:00 AM for descending orbits) along with the satellite-based radiometer observations (SMAP and SMOS). This mismatch of observation times can change the surface soil moisture spatial pattern. The MODIS thermal infrared penetration depth is also very shallow (skin deep) as compared to the penetration depth of ~5 cm or more for the satellite-based L-band microwave radiometer observations. SMAP mitigates these sources of errors by the use of co-registered and concurrent L-band radiometer and the L-band radar observations.

Only a few studies have been conducted that attempted to merge high-resolution radar and coarse resolution radiometer measurements in order to obtain an intermediate resolution product. Change detection techniques have demonstrated a potential to monitor temporal evolution of soil moisture by taking advantage of the approximately linear dependence of radar backscatter and brightness temperature change on soil moisture change. The feasibility of using the change detection approach was demonstrated with the Passive and Active L-band System airborne sensor (PALS) radar and radiometer data obtained during the SGP99 campaign (Narayan et al., 2006). A similar approach was also used to downscale PALS radiometer data with AIRSAR (radr) data from the SMEX02 campaign. The limitation of this technique is that it only provides the soil moisture relative change and not the absolute value of soil moisture. As a consequence, the errors can accumulate because the cumulative errors propagate over a time period.

A different approach is presented in Zhan et al. (2006) where a Bayesian method is used to downscale radiometer observations using radar measurements. Kim and van Zyl (2009) developed a time-series algorithm based on a linear model of backscatter and soil moisture. In order to estimate soil moisture at intermediate resolution (9 km), they determine the two unknowns of the linear model for each pixel within the coarser radiometer pixel. Piles et al. (2009) presented another change detection scheme compatible with SMAP that uses the approximately linear dependence of change in radar backscatter on soil moisture change at radiometer resolution, the temporal change in backscatter at the radar resolution and the previous day's soil moisture data to estimate soil moisture at ~9 km resolution. This is similar to Narayan et al. (2006) but also suffers from the accumulation of errors over time. A spatial variability technique developed by Das et al. (2012) to blend SMAP radar measurement and radiometer-based soil moisture data also takes advantage of the approximately linear dependence of backscatter change to soil moisture change at the radiometer resolution, which constraints the relative backscatter difference within the coarse radiometer footprint, to estimate soil moisture at ~9 km resolution. Unlike Zhan et al. (2006) and Piles et al. (2009), the spatial variability technique used in Das et al. (2012) does not require the previous satellite overpass observations to estimate the current soil moisture value. The SMAP active-passive algorithm (Das et al., 2014) draws from all the above algorithms and techniques (Molero et al., 2016; Merlin et al., 2008; Zhan et al., 2006; Narayan et al., 2006; Kim and van Zyl, 2009; Piles et al., 2009; Das et al., 2012). In particular, it downscales the coarse-scale radiometer-based gridded brightness temperature using the fine resolution radar backscatter, and then near-surface soil moisture is retrieved from the downscaled brightness temperature (Fig. 1).

The SMAP active-passive algorithm (Das et al., 2014) has two parameters ($\boldsymbol{\beta}$ (K/dB) and dimensionless Γ), as shown in Eq. (1).

$$T_{B_p}(M_j) = T_{B_p}(C) + \boldsymbol{\beta}(C)\cdot\{[\sigma_{pp}(M_j) - \sigma_{pp}(C)] + \boldsymbol{\Gamma}\cdot[\sigma_{pq}(C) - \sigma_{pq}(M_j)]\} \quad (1)$$

where $T_{B_p}(M_j)$ is the disaggregated brightness temperature (V-pol or H-pol) at 9 km or 3 km, $T_{B_p}(C)$ is the gridded radiometer brightness temperature (V-pol or H-pol) at 36 km, $\sigma_{pp}(M_j)$ and $\sigma_{pq}(M_j)$ are the co-pol and cross-pol radar backscatters at the corresponding resolution (9 km or 3 km), and $\sigma_{pp}(C_j)$ and $\sigma_{pq}(C_j)$ are the co-pol and cross-pol radar backscatters aggregated to 36 km. The notation M_j represents one of the indexed (j) medium resolution grid cells within the coarse resolution '*C*'. A comprehensive description and physical basis of Eq. (1) is presented in Entekhabi et al., (2010) and Das et al. (2014). However, for the sake of brevity, clarity and completeness Eq. (1) can be summarized as follow:

$T_{B_p}(M_j)$ = *Disaggregated brightness temperature at 9 km or 3 km.*