Assessment of the SMAP Passive Soil Moisture Product

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Abstract—The National Aeronautics and Space Administration (NASA) Soil Moisture Active Passive (SMAP) satellite mission was launched on January 31, 2015. The observatory was developed to provide global mapping of high-resolution soil moisture and freeze-thaw state every two to three days using an L-band (active) radar and an L-band (passive) radiometer. After an irrecoverable hardware failure of the radar on July 7, 2015, the radiometer-only soil moisture product became the only operational Level 2 soil moisture product for SMAP. The product provides soil moisture estimates posted on a 36 km Earth-fixed grid produced using brightness temperature observations from descending passes. Within months after the commissioning of the SMAP radiometer, the product was assessed to have attained preliminary (beta) science quality, and data were released to the public for evaluation in September 2015. The product is available from the NASA Distributed Active Archive Center at the National Snow and Ice Data Center. This paper provides a summary of the Level 2 Passive Soil Moisture Product (L2_SM_P) and its validation against in situ ground measurements collected from different data sources. Initial in situ comparisons conducted between March 31, 2015 and October 26, 2015, at a limited number of core validation sites (CVSs) and several hundred sparse network points, indicate that the V-pol Single Channel Algorithm (SCA-V) currently delivers the best performance among algorithms considered for L2_SM_P, based on several metrics. The accuracy of the soil moisture retrievals averaged over the CVSs was 0.038 m$^3$/m$^3$ unbiased root-mean-square difference (ubRMSTD), which approaches the SMAP mission requirement of 0.040 m$^3$/m$^3$.

Index Terms—Brightness temperature, land emission, L-band, Level 2 Passive Soil Moisture Product (L2_SM_P), Level 3 Daily Composite Version (L3_SM_P), passive microwave remote sensing, Soil Moisture Active Passive (SMAP), soil moisture, tau–omega ($\tau - \omega$) model, validation.

I. INTRODUCTION

THE National Aeronautics and Space Administration (NASA) Soil Moisture Active Passive (SMAP) satellite mission was launched on January 31, 2015. The observatory was developed to provide global mapping of high-resolution soil moisture and freeze-thaw state every two to three days using an L-band radar (active) and an L-band radiometer (passive) onboard an observatory. The resulting measurements are expected to advance our understanding of the processes that link the terrestrial water, energy, and carbon cycles, improve our capability in flood prediction and drought monitoring, and enhance our skills in weather and climate forecasts [1].

Table I summarizes the key instrument specifications of the SMAP radiometer as well as the orbital parameters upon which the observations are acquired. One feature that distinguishes the SMAP radiometer from previous L-band radiometers is...
its sophisticated hardware that allows high-rate acquisition of spectrogram data [2]. The resulting data are then applied to kurtois-based algorithms to mitigate the radio frequency interference (RFI) due to anthropogenic emission sources on the ground [3]. Preliminary analyses of SMAP radiometer observations to date have demonstrated the effectiveness of this approach against RFI signals [4].

SMAP began simultaneous acquisition of radar and radiometer data in April 2015, with a goal of providing three soil moisture products: a radiometer-only product at a 40 km spatial resolution, a combined radar/radiometer product at a 10 km resolution, and a radar-only product at a 3 km resolution. However, the SMAP radar encountered an irrecoverable hardware failure on July 7, 2015 and was officially declared lost shortly thereafter. Despite this setback, the remaining SMAP L-band radiometer has been nominally operating, collecting high-quality brightness temperature data in April 2015, with a goal of providing three soil moisture products: a radiometer-only product at a 40 km spatial resolution, a combined radar/radiometer product at a 10 km resolution, and a radar-only product at a 3 km resolution.

However, the SMAP radar encountered an irrecoverable hardware failure on July 7, 2015 and was officially declared lost shortly thereafter. Despite this setback, the remaining SMAP L-band radiometer has been nominally operating, collecting high-quality brightness temperature (T_B) data that enable the production of the standard Level 2 Passive Soil Moisture Product (L2_SM_P) and its Level 3 daily composite version (L3_SM_P). Since September 2015, both products have attained a preliminary (beta) science performance level and have been released to the public for evaluation from the NASA Distributed Active Archive Center (DAAC) at the National Snow and Ice Data Center (NSIDC). This release was expected to accelerate future product development in data accuracy and usability through feedback from the research and application communities.

This paper begins with an overview of the L2_SM_P product. The overview is followed by a description of the baseline and optional soil moisture retrieval algorithms that have been used in the operational product. The validation methodologies adopted by the project are then presented, followed by an early performance assessment of the product against in situ data from core validation sites (CVSs) and sparse networks through October 2015. Finally, an outlook for future improvements to the product is provided.

### II. PRODUCT OVERVIEW

The L2_SM_P product is derived using SMAP L-band radiometer time-ordered observations (L1B_TB product) as the primary input [2]. The resulting soil moisture retrieval output fields, along with others carrying supplementary geolocation information, brightness temperatures, quality flags, and ancillary data, are posted on a 36 km Earth-fixed grid using the global cylindrical Equal-Area Scalable Earth Grid projection, Version 2 (EASEv2) [5]. [6]. The 36 km grid resolution is close to the 3-dB native spatial resolution (see Table I) of the instrument observations, although the two measures of resolution do not have to be identical. The baseline L2_SM_P operational production uses observations acquired from the 6:00 A.M. descending passes only [7]. Soil moisture estimates using observations from the 6:00 P.M. ascending passes are also produced for validation analysis, but are not made available to the public at this time.

Fig. 1 describes the processing flow of the L2_SM_P Science Production Software (SPS). The processing begins with the Level 1B time-ordered brightness temperature observations (L1B_TB) [8], being processed into the L1C_TB Gridded Radiometer Data Product on the global cylindrical 36 km EASEv2 Grid [9]. [10]. The resulting fore- and aft-look gridded brightness temperature observations are then combined in the L2_SM_P SPS. External static and dynamic ancillary data preprocessed on finer grid resolutions are then brought into the processing to evaluate the feasibility and subsequent estimated quality of the retrieval. When surface conditions favorable to soil moisture retrieval are identified at a given grid cell, retrieval is performed. Corrections for water contamination, surface roughness, effective soil temperature, and vegetation water content are applied using five preselected candidate soil moisture retrieval algorithms (described in Section III-C) to produce the final output soil moisture retrieval fields on the same 36 km EASEv2 Grid as the input L1C_TB product. Data contents of the resulting L2_SM_P output files (granules) are described in the L2_SM_P Product Specification Document [11].

The ancillary data, as well as the corresponding grid/time resolutions at which they are used in the L2_SM_P SPS, are listed in Table II. As evident in the table, most ancillary data are preprocessed on grid resolutions finer than 36 km so as to provide more comprehensive information on the extent of heterogeneity at the 36 km spatial scale (for those ancillary data that have inherent spatial resolution finer than 36 km). In operational processing, ancillary data and model parameters at finer grid resolutions are aggregated to 36 km before they are used as inputs to the soil moisture retrieval algorithms. Most
TABLE II
EXTERNAL STATIC AND DYNAMIC ANCILLARY DATA USED IN L2_SM_P OPERATIONAL PROCESSING

<table>
<thead>
<tr>
<th>Ancillary Data</th>
<th>Grid Resolution</th>
<th>Time Resolution</th>
<th>Primary Data Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Permanent water fraction</td>
<td>3 km</td>
<td>Static</td>
<td>MODIS 250-m MOD44W [12]</td>
</tr>
<tr>
<td>Urban fraction</td>
<td>3 km</td>
<td>Static</td>
<td>Global Rural Urban Mapping Proj (GRUMP) [13]</td>
</tr>
<tr>
<td>DEM slope standard deviation</td>
<td>3 km</td>
<td>Static</td>
<td>USGS 250-m GMTED 2010 [14]</td>
</tr>
<tr>
<td>Soil texture</td>
<td>3 km</td>
<td>Static</td>
<td>FAO Harmonized World Soil Database (HSWD) [15]</td>
</tr>
<tr>
<td>Land cover classification</td>
<td>3 km</td>
<td>Static</td>
<td>MODIS 500-m MCD12Q1 (V005) [16]</td>
</tr>
<tr>
<td>NDVI</td>
<td>3 km</td>
<td>2000–2011 climatology</td>
<td>MODIS 1000-m MOD13A2 (V005) [17]</td>
</tr>
<tr>
<td>Snow fraction</td>
<td>9 km</td>
<td>Daily</td>
<td>Interactive Multisensor Snow and Ice Mapping System (IMS) [18]</td>
</tr>
<tr>
<td>Freeze/thaw fraction</td>
<td>9 km</td>
<td>1 hourly</td>
<td>GMAO Goddard Earth Observing System Model, Version 5 [19]</td>
</tr>
<tr>
<td>Soil temperatures</td>
<td>9 km</td>
<td>1 hourly</td>
<td>GMAO Goddard Earth Observing System Model, Version 5 [19]</td>
</tr>
<tr>
<td>Precipitation intensity</td>
<td>9 km</td>
<td>3 hourly</td>
<td>GMAO Goddard Earth Observing System Model, Version 5 [20]</td>
</tr>
</tbody>
</table>

TABLE III
LUT BETWEEN MODEL COEFFICIENTS AND LAND COVER CLASSES FOR L2_SM_P MODEL PARAMETER INITIALIZATION

<table>
<thead>
<tr>
<th>Land Cover Class</th>
<th>h</th>
<th>b</th>
<th>c</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evergreen needleleaf forest (ENF)</td>
<td>0.160</td>
<td>0.100</td>
<td>0.050</td>
</tr>
<tr>
<td>Evergreen broadleaf forest (EBF)</td>
<td>0.160</td>
<td>0.100</td>
<td>0.050</td>
</tr>
<tr>
<td>Deciduous needleleaf forest (DNF)</td>
<td>0.160</td>
<td>0.120</td>
<td>0.050</td>
</tr>
<tr>
<td>Deciduous broadleaf forest (DBF)</td>
<td>0.160</td>
<td>0.120</td>
<td>0.050</td>
</tr>
<tr>
<td>Mixed forest (MXF)</td>
<td>0.160</td>
<td>0.110</td>
<td>0.050</td>
</tr>
<tr>
<td>Closed shrublands (CSH)</td>
<td>0.110</td>
<td>0.110</td>
<td>0.050</td>
</tr>
<tr>
<td>Open shrublands (OSH)</td>
<td>0.110</td>
<td>0.110</td>
<td>0.050</td>
</tr>
<tr>
<td>Woody savannas (WSV)</td>
<td>0.125</td>
<td>0.110</td>
<td>0.050</td>
</tr>
<tr>
<td>Savannas (SAY)</td>
<td>0.150</td>
<td>0.110</td>
<td>0.080</td>
</tr>
<tr>
<td>Grasslands (GRS)</td>
<td>0.150</td>
<td>0.130</td>
<td>0.050</td>
</tr>
<tr>
<td>Croplands (CRP)</td>
<td>0.108</td>
<td>0.110</td>
<td>0.050</td>
</tr>
<tr>
<td>Urban and built-up (URB)</td>
<td>0.000</td>
<td>0.100</td>
<td>0.030</td>
</tr>
<tr>
<td>Cropland/vegetation Mosaic (MOS)</td>
<td>0.130</td>
<td>0.110</td>
<td>0.065</td>
</tr>
<tr>
<td>Barren or sparsely vegetated (BAR)</td>
<td>0.150</td>
<td>0.000</td>
<td>0.000</td>
</tr>
</tbody>
</table>

The coefficients listed in the table currently do not have polarization dependence, which means that for a given land cover class, the same coefficients (h, b, and c) are used in forward-model computations of both horizontally and vertically polarized brightness temperature (\( T_{Bv} \) and \( T_{Bh} \)). These preliminary coefficients have yielded estimates of soil moisture that are in good agreement with \( in situ \) data (as will be shown in this paper). However, additional improvement is expected by further optimization of these coefficients during the cal/val phase of the product. The optimized coefficients will incorporate polarization dependence and variability within a given land cover class and may have seasonal dependence.

B. Effective Soil Temperature

Dynamic surface and soil temperature data from the Global Modeling and Assimilation Office (GMAO) Goddard Earth Observing System Model, Version 5 (GEOS-5) model are used to estimate \( T_{\text{eff}} \) in the forward radiative transfer model to provide the necessary surface temperature correction. The prelaunch approach was to compute \( T_{\text{eff}} \) as the average of the surface temperature (TSURF) and the layer-1 soil temperature (TSOIL1) GEOS-5 model fields. During the postlaunch cal/val phase, it was found that this approach did not adequately account for the temperature contributions to microwave emission from deeper soil layers. Therefore, the following modified form of the Choudhury model [26] was used instead. This model resulted in improved soil moisture retrievals particularly over arid areas, i.e.,

\[
T_{\text{eff}} = T_{\text{soil, deep}} + C(T_{\text{soil, top}} - T_{\text{soil, deep}}) \quad (1)
\]

where \( T_{\text{soil, top}} \) refers to GEOS-5’s layer-1 soil temperature at 0–10 cm, and \( T_{\text{soil, deep}} \) refers to the layer-2 soil temperature at 10–20 cm. This formulation of \( T_{\text{eff}} \) allows for more accurate modeling of emission emanating from deeper soil layers. \( C \) is a coefficient that depends on the observing frequency and was set to 0.246 for L-band frequencies, as reported in [26].

C. Retrieval Algorithms

There are five soil moisture retrieval algorithms implemented in the operational processing software. Soil moisture retrieval fields from all algorithms are available in the beta-release data products. For completeness, a brief description of these
algorithms is given below; a more thorough discussion of them can be found in [7].

1) H-pol Single Channel Algorithm: In the H-pol Single Channel Algorithm (SCA-H) [24], the observed $T_{bh}$ data are used. After accounting for the presence of water within the inversion domain, corrections for $T_{eff}$ [26] and vegetation water content [17] are applied to the emissivity, followed by correction for surface roughness. The last step in SCA-H invokes a soil dielectric model to relate the corrected horizontally polarized emissivity to soil moisture retrieval through the Fresnel equations. The soil dielectric model used is the Mironov model [27]. Other soil dielectric models are also under evaluation for possible future use [28], [29]. The SCA-H algorithm was considered the baseline algorithm at launch.

2) V-pol Single Channel Algorithm: The V-pol Single Channel Algorithm (SCA-V) is similar to the SCA-H except that $T_{bv}$ is used instead of $T_{bh}$. As discussed in subsequent sections, it was found that SCA-V yielded the best overall soil moisture performance metrics among the five algorithms coded. For this reason, it was selected as the new (postlaunch) baseline retrieval algorithm for the beta release.

3) Dual Channel Algorithm: The Dual Channel Algorithm (DCA) makes use of complementary information in the $T_{bh}$ and $T_{bv}$ data to retrieve soil moisture and vegetation opacity [30], under the assumption that the vegetation opacity is the same for horizontal and vertical polarizations. In DCA, a cost function consisting of the sum of squares of the differences between the observed and estimated $T_B$ is iteratively minimized until the corresponding retrieved quantities are determined. Polarization-dependent model coefficients (e.g., $\omega_h$ being different from $\omega_v$) can also be specified in the DCA minimization process. Despite the apparent complexity of DCA, efficient and well-established algorithms exist that allow for DCA retrieval of soil moisture [31].

4) Microwave Polarization Ratio Algorithm: The Microwave Polarization Ratio Algorithm (MPRA) is based on the Land Parameter Retrieval Model [32] and was first applied to multifrequency satellites such as AMSR-E. Similar to DCA, MPRA attempts to solve for soil moisture and vegetation opacity using $T_{bh}$ and $T_{bv}$. However, it does so under the assumptions that 1) the soil and canopy temperatures are considered equal and that 2) vegetation transmissivity ($\gamma$) and the vegetation single-scattering albedo ($\omega$) are the same for both horizontal and vertical polarizations. When these assumptions are satisfied, it can be shown that the soil moisture and vegetation opacity can be analytically solved in closed form [33].

5) Extended Dual Channel Algorithm: In DCA, the $T_{bh}$ and $T_{bv}$ data are used together to construct a cost function that consists of the sum of squares of the differences between the observed and estimated $T_B$ (V-pol and H-pol). Uncertainty in $T_{eff}$ originating from its modeling or ancillary data source propagates to both V-pol and H-pol $T_B$ terms in the cost function, potentially causing DCA nonconvergence. The Extended Dual Channel Algorithm (E-DCA) mitigates this problem by using the polarization ratio (PR), which is defined as $(T_{bv} - T_{bh})/(T_{bv} + T_{bh})$, as one of the cost function terms, since the PR is relatively insensitive to $T_{eff}$. Thus, in E-DCA, the first cost function term is the difference between the observed and estimated PR (in natural logarithm); the second term is the difference between the observed and estimated $T_{bh}$ (also in natural logarithm). Analytically, the cost function $\varphi^2$ can be written as

$$\varphi^2 = \left[ \log \left( \frac{T_{obs}^{Bv} - T_{obs}^{Bh}}{T_{obs}^{Bv} + T_{obs}^{Bh}} \right) - \log \left( \frac{T_{est}^{Bv} - T_{est}^{Bh}}{T_{est}^{Bv} + T_{est}^{Bh}} \right) \right]^2$$

$$+ \left[ \log (T_{obs}^{Bh}) - \log (T_{est}^{Bh}) \right]^2$$

(2)

where the superscripts $obs$ and $est$ represent, respectively, the observed and estimated quantities. Under nominal conditions, E-DCA and DCA converge to the same solutions, since solutions that globally minimize the DCA cost function also globally minimize the E-DCA cost function.

IV. PRODUCT ASSESSMENT

This section describes results of the soil moisture retrieval performance assessment leading up to the beta release. Of the five soil moisture retrieval algorithms implemented, only SCA-H, SCA-V, and DCA are discussed in this assessment. Analyses of the MPRA and E-DCA are similar to DCA in their current implementation. The performance of MPRA and E-DCA will be more fully investigated along with the SCA-H, SCA-V, and DCA as cal/val moves toward the validated release of the product in May 2016.

A. General Methodology

All soil moisture retrieval algorithms considered in this assessment are compared with the same in situ data sets with the same performance metrics applied. The in situ data sets consist of appropriately scaled aggregations of ground-based in situ soil moisture observations from 1) CVSs and 2) individual stations of sparse networks. Agreement between the L2_SM_P soil moisture and the in situ data sets over space and time are reported in 1) time-series correlation; 2) bias; 3) root-mean-square difference (RMSD); and 4) unbiased root-mean-square difference (ubRMSD). Together, these metrics provide a more comprehensive description of product performance than any one alone [34]. The ubRMSD (in units of m³/m³) is the metric adopted by SMAP for reporting product accuracy across all Level 2 through Level 4 soil moisture products. The SMAP Level 1 mission requirement for the active/passive soil moisture product accuracy is ubRMSD = 0.040 m³/m³. The same accuracy target was adopted for the L2_SM_P soil moisture product.

The L2_SM_P product is processed on a relatively coarse grid (36 km EASEv2 Grid). To mitigate the comparison error caused by misalignment between the L2_SM_P grid cell domain and the distribution of in situ soil moisture sensors, validation grid (VG) processing uniquely tailored to each CVS and sparse network location is used for the L2_SM_P cal/val. The VG processing adopts a shift-and-retrieve approach allowing the L2_SM_P retrieval grid cell domain to more accurately align with the distribution of in situ soil moisture sensors at the CVSs and sparse networks. In VG processing, a 36 km grid cell (“inversion domain”) is defined for each CVS and sparse network location. The exact position of the domain depends on the actual distribution of the sensors relative to the closest 36 km EASEv2 grid lines. If most of the sensors fall within a standard 36 km EASEv2 grid cell, the resulting 36 km inversion domain will coincide with that grid cell. If, however, the sensors cover more than one standard 36 km
EASEv2 grid cell, the resulting 36 km inversion domain will be defined such that its final position will 1) capture most of the sensors and 2) align with the standard 3 km EASEv2 grid lines. Such a 3 km grid permits finer alignment between the VG inversion domain and the distribution of the sensors, although other grid resolutions are also possible and are being evaluated. Once the exact position of the VG inversion domain is defined for a given CVS, the same L2_SM_P processing depicted in Fig. 1 is applied to the L1B_TB observations to produce passive soil moisture estimates at the 36 km shifted VG locations.

B. Global Patterns

Global maps of soil moisture serve as the first step in the assessment. Fig. 2 shows global composites of 6:00 A.M. descending soil moisture of SMAP and the Soil Moisture and Ocean Salinity (SMOS) mission [35] over a one-week period from June 1, 2015 to June 7, 2015.
TABLE IV
CVSS Used in L2_SM_P Beta-Release Assessment

<table>
<thead>
<tr>
<th>Site Name</th>
<th>Site PI(s)</th>
<th>State, Country</th>
<th>Climate Regime</th>
<th>Land Cover</th>
<th>Number of Sensors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Walnut Gulch</td>
<td>Cosh, Goodrich</td>
<td>AZ, USA</td>
<td>Arid</td>
<td>Shrub open</td>
<td>29</td>
</tr>
<tr>
<td>Reynolds Creek</td>
<td>Cosh, Seyfried</td>
<td>ID, USA</td>
<td>Arid</td>
<td>Grasslands</td>
<td>20</td>
</tr>
<tr>
<td>Fort Cobb</td>
<td>Cosh, Starks</td>
<td>OK, USA</td>
<td>Temperate</td>
<td>Grasslands</td>
<td>15</td>
</tr>
<tr>
<td>Little Washita</td>
<td>Cosh, Starks</td>
<td>OK, USA</td>
<td>Temperate</td>
<td>Grasslands</td>
<td>20</td>
</tr>
<tr>
<td>South Fork</td>
<td>Cosh</td>
<td>IA, USA</td>
<td>Cold</td>
<td>Croplands</td>
<td>20</td>
</tr>
<tr>
<td>Little River</td>
<td>Cosh, Bosch</td>
<td>GA, USA</td>
<td>Temperate</td>
<td>Cropland/mosaic</td>
<td>28</td>
</tr>
<tr>
<td>TxSON</td>
<td>Caldwell</td>
<td>TX, USA</td>
<td>Temperate</td>
<td>Grasslands</td>
<td>36</td>
</tr>
<tr>
<td>Kenaston</td>
<td>Berg, Rowlandson</td>
<td>Canada</td>
<td>Cold</td>
<td>Croplands</td>
<td>28</td>
</tr>
<tr>
<td>Carman</td>
<td>McNairn, Pacheco</td>
<td>Canada</td>
<td>Cold</td>
<td>Croplands</td>
<td>9</td>
</tr>
<tr>
<td>Monte Buay</td>
<td>Thibeault</td>
<td>Argentina</td>
<td>Arid</td>
<td>Croplands</td>
<td>14</td>
</tr>
<tr>
<td>REMEDHUS</td>
<td>Martinez</td>
<td>Spain</td>
<td>Semi-arid</td>
<td>Croplands</td>
<td>19</td>
</tr>
<tr>
<td>Yanco</td>
<td>Walker</td>
<td>Australia</td>
<td>Arid</td>
<td>Croplands/grasslands</td>
<td>28</td>
</tr>
<tr>
<td>Kyeamba</td>
<td>Walker</td>
<td>Australia</td>
<td>Temperate</td>
<td>Grasslands</td>
<td>9</td>
</tr>
</tbody>
</table>

In Fig. 2(a), both the nominal and flagged soil moisture retrievals from SMAP are shown. The flagged retrievals include results that should be used/interpreted with caution due to surface/instrument conditions that may lead to inaccurate passive soil moisture retrieval (e.g., frozen ground, mountainous terrain, excessive vegetation, high noise equivalent delta temperature (NEDT) due to residual uncorrectable RFI, etc.). A complete description of the flags and their thresholds used in L2_SM_P operational production can be found in [11].

Soil moisture retrievals from SMAP and SMOS in Fig. 2 showed the expected spatial patterns of soil moisture, from the drier arid regions to the wetter forest regions. There are differences however, particularly over densely vegetated areas and areas depicted in white (e.g., some parts of the Middle-East and Asia) where SMOS is more susceptible to low-to-moderate RFI contamination than SMAP.

C. Core Validation Sites

The first stage of cal/val involves comparisons of SMAP soil moisture with ground-based in situ observations that have been aggregated to provide a reliable spatial average of soil moisture at the 36 km grid scale [34]. The availability of high-quality in situ observations is important as these data provide a basis for algorithm refinement and performance evaluation of the L2_SM_P product. Early in the mission, SMAP established a Cal/Val Partners Program to foster collaboration with domestic and international partners who operate field sites populated with dense clusters of well-calibrated soil moisture sensors. Under this program, the partners agreed to make their data available to support SMAP cal/val in exchange for early access to SMAP data products for their research. Sites that are used in the quantitative assessment of SMAP soil moisture product performance are referred to as CVSs. A total of 13 CVSs are identified in [36] and are listed in Table IV. Analyses of error estimates using ground-based in situ observations at a depth of 5 cm from these CVSs are the primary means for the first stage of cal/val for L2_SM_P.

Fig. 3 shows time-series comparisons between L2_SM_P soil moisture and in situ data from a few selected CVSs between March 31, 2015 and October 26, 2015.

The Little Washita watershed in Oklahoma has been utilized for many microwave soil moisture validation and scaling studies; hence, there is high confidence in the in situ estimates for this site. Fig. 3(a) shows the wide range of soil moisture observed at the Little Washita site during the three-month assessment period. Dry conditions in April were followed by historic amounts of precipitation in May. This was followed by an extended dry-down (end of May) that clearly illustrates the correlation of the in situ and satellite observations. A subsequent dry-down in June shows a difference in the rate of decrease in soil moisture, with the satellite soil moisture drying out faster than the in situ measured soil moisture. This difference may be associated with the satellite versus in situ contributing depths or with vegetation changes not adequately accounted for. Multiple wetting and drying periods followed in July and later, exhibiting similar patterns. Overall, the site exhibits very high correlation between the satellite and in situ soil moisture. SMAP and SMOS have approximately the same level of performance.

The recently instrumented TxSON site in Texas was specifically designed for validation of all three SMAP surface soil moisture products (L2_SM_A, L2_SM_AP, and L2_SM_P, at 3, 9, and 36 km spatial scales, respectively). As shown in Fig. 3(b), the precipitation pattern over the six months was similar to Oklahoma, with dry conditions followed by a very wet May followed by an extended dry-down period. This site also shows high correlation between satellite-derived and in situ soil moisture, with similar performance between SMOS and SMAP SCA-V. The larger errors and positive bias of the DCA appear to be associated with rain events. This type of error could involve smaller rain events that wet the near surface but not the depth of the in situ sensor, thus causing SMAP DCA to overestimate the soil moisture present.

The Little River watershed in Georgia has served as a satellite in situ soil moisture validation site since the beginning of the AMSR-E mission [37] and was the only site representing humid agricultural environments. It includes a substantial amount of tree cover, has very sandy soils, and utilizes irrigation. Fig. 3(c) indicates overestimation by SMOS while SCA-H performs best followed by SCA-V. Regardless of the ubRMSD and bias, all algorithms have high correlations. The results for Little River illustrate that there may be inherent performance limitations in some algorithms under specific conditions. These differences between in situ observations and different algorithm outputs can challenge the assumptions and premises that have
Fig. 3. Soil moisture time series at (a) Little Washita, OK; (b) TxSON, TX; and (c) Little River, GA between March 31, 2015 and October 26, 2015. In situ soil moisture data are in magenta, and precipitation data are in blue. In all cases, L2_SM_P soil moisture showed good correlation ($R > 0.750$) with the in situ data. Retrieval results by SCA-V, SCA-H, DCA, and SMOS are indicated by black diamonds, green crosses, red triangles, and orange squares, respectively. Whenever inversion succeeded but the corresponding retrieval was deemed to have insufficient quality due to instrument/surface conditions (e.g., high NEDT, frozen ground, mountainous terrain, dense vegetation with vegetation water content in excess of 5 kg/m$^2$, etc.), the data point was masked in gray.

Table V summarizes the assessment of L2_SM_P retrieval accuracy based on in situ comparisons at all the CVSs [36]. The ubRMSD varies considerably among sites. For example, ubRMSD is far below 0.040 m$^3$/m$^3$ at Walnut Gulch, Fort Cobb, Little Washita, Little River, and Kenaston for the baseline algorithm (SCA-V). It is noticeably above 0.040 m$^3$/m$^3$ at South Fork and Carman. Sources of these differences will be investigated in future studies.

All SMAP algorithms have about the same ubRMSD, differing only by 0.006 m$^3$/m$^3$, which are close to the SMAP Level-1 mission accuracy target of 0.040 m$^3$/m$^3$. The correlations are also very similar among algorithms. For both of these metrics, the SCA-V yields slightly better values. More obvious differences among the algorithms are found in the bias with DCA being unbiased, whereas SCA-H and SCA-V underestimate the CVS soil moisture. However, the SCA-V bias is also relatively low. The SMAP and SMOS averages are based on the respective average values reported for each CVS. It is clear from the table that the results of both missions are quite comparable for all metrics. However, this assessment is based on a limited time frame, and the relative performances of algorithms and products could vary as the record lengths and seasons captured expand.

Based on the metrics and considerations discussed, the SCA-V was selected as the baseline algorithm for the L2_SM_P beta release. Going forward, additional investigations will be completed on model coefficient optimization for all algorithms, additional CVS will be incorporated, and a longer period of observations will be considered, all of which will influence the decision on which algorithm to designate as the SMAP baseline algorithm at the validated release scheduled for May 2016.

D. Sparse Networks

The CVS validation activity previously described is complemented for SMAP by the use of in situ data from sparse networks as well as by new/emerging types of soil moisture...
networks. The defining feature of these networks is that the measurement density is low, usually resulting in (at most) one point within an SMAP footprint. These observations cannot be used for validation without addressing two issues: verifying that they provide a reliable estimate of the 0–5 cm surface soil moisture layer and that the one measurement point is representative of the footprint.

SMAP has been evaluating methodologies for upscaling data from these networks to SMAP footprint resolutions. A key element of the upscaling approach is the triple collocation technique [39], [40] that combines the in situ data and SMAP soil moisture data with another independent source of soil moisture such as a model-based product. The implementation of this technique will be part of the later L2_SM_P product assessment.

Although limited, sparse networks do offer a large number of sites in varied environments and are typically operational with very predictable latency. Table VI lists the set of networks used by SMAP in the current assessment.

Because of the larger number of sites, it is possible to examine the intercomparison metrics between satellite-derived and sparse network in situ soil moisture, aggregated by land cover types according to the International Geosphere-Biosphere Programme (IGBP) land cover classification used in the MODIS products. The results are summarized in Table VII [36]. The reliability of the analyses based upon these classes depends on the number of sites available. The SMAP average was based on the average values reported for each land cover class.

Overall, the ubRMSD and bias values are similar to those obtained from the CVS. This result provides additional confidence in the previous conclusions based on the CVS. In addition, the SCA-V has, marginally, the best overall bias, ubRMSD, and correlation. These are similar to the results observed for the CVS.

Interpreting the results based on land cover is more complex. There are no clear patterns associated with broader vegetation types. The ubRMSD values for SCA-V range from 0.025 m$^3$/m$^3$ for barren lands to 0.077 m$^3$/m$^3$ for evergreen broadleaf forests. In general, large ubRMSD values were observed in forest classes. This is not surprising since forests have high vegetation water content. However, the large ubRMSD and bias for grasslands warrant further investigation.

SMOS metrics are also included in Table VII as supporting information. Overall, the SMOS products show a higher bias and ubRMSD than the SCA-V when partitioned by land cover class. Although the errors for the forest categories are large, the values of $N$ are small.

V. OUTLOOK

The SMAP Level 2 Passive Soil Moisture Product (L2_SM_P) has been in routine production since March 2015. Cal/val analyses and assessments indicate that the product quality is suitable for beta release based on comparisons with in situ data from CVSs and sparse networks. These comparisons demonstrate a retrieval accuracy level approaching 0.040 m$^3$/m$^3$, as described in Section IV. The spatial and temporal patterns of the soil moisture have also been shown to correspond well with recent flood and rainstorm events [41], [42].

Despite these initial findings, some important issues remain to be addressed prior to the validated product release (currently scheduled for May 2016). Among these issues are the following.

- **Limited SMAP observations and in situ data**: The current assessment was based on only six months of SMAP observations and in situ data at a limited number of CVSs and sparse networks. It is anticipated that by the time of the validated release, there will be a year of data covering the full annual cycle. This will help improve the statistical representativeness of the current performance assessment.
- **Optimization of model parameters**: The current L2_SM_P beta release uses a version of model parameters largely adopted before launch. Time-series approaches are being developed to determine optimal parameters over time for the same grid on which the retrieval of soil moisture is performed. A particular objective is to better represent the polarization dependence of vegetation parameters in the $\tau - \omega$ model.
TABLE VI
SPARSE NETWORKS USED IN L2_SM_P BETA-RELEASE ASSESSMENT

<table>
<thead>
<tr>
<th>Sparse Network Name</th>
<th>Contact/PI</th>
<th>Country</th>
<th>Number of Sites</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOAA Climate Reference Network</td>
<td>Palecki</td>
<td>USA</td>
<td>110</td>
</tr>
<tr>
<td>USDA NRCS Soil Climate Analysis Network</td>
<td>Cosh</td>
<td>USA</td>
<td>155</td>
</tr>
<tr>
<td>GPS</td>
<td>Small</td>
<td>Western USA</td>
<td>123</td>
</tr>
<tr>
<td>COSMOS</td>
<td>Zreda</td>
<td>Mostly USA</td>
<td>53</td>
</tr>
<tr>
<td>SMOSMANIA</td>
<td>Calvet</td>
<td>Southern France</td>
<td>21</td>
</tr>
<tr>
<td>Pampas</td>
<td>Thibault</td>
<td>Argentina</td>
<td>20</td>
</tr>
</tbody>
</table>

TABLE VII
BEST PERFORMANCE AMONG SMAP ALGORITHMS IN EACH NETWORK/METRIC IS TYPESET IN BOLDFACE

VI. CONCLUSION

Following SMOS and Aquarius, SMAP became the third mission in less than a decade utilizing an L-band radiometer to estimate soil moisture in the top 5 cm of soil. The sophisticated RFI mitigation hardware and software used in the SMAP radiometer design has allowed SMAP to acquire brightness temperature observations that are relatively well filtered against RFI. Despite the premature failure of the SMAP radar, the radiometer has been operating nominally, collecting data that enable the production of high-quality soil moisture products at level 2 (L2_SM_P, half-orbit) and level 3 (L3_SM_P, daily global composite). Since September 2015, both products have been made available to the public for evaluation, as beta release, from the NASA DAAC at the NSIDC.

This paper has provided a description of the design, operational processing, algorithm implementation, and preliminary validation of the L2_SM_P soil moisture product. Based on comparisons with in situ data from CVSs and sparse networks over a period of six months (March 31, 2015 and October 26, 2015), it was found that SCA-V delivered better ubRMSD, bias, and correlation than SCA-H, and SCA-H had better ubRMSD and correlation than DCA. DCA had the lowest bias of all the algorithms (essentially zero bias); however, the bias of SCA-V was only 0.018 m^3/m^3 over that of CVSs. These differences were relatively small. Based on these results, the SCA-V was adopted as the baseline algorithm for the beta release. The overall ubRMSD of the SCA-V is 0.038 m^3/m^3 over CVS, which approaches the SMAP mission requirement of 0.040 m^3/m^3.

The sparse networks of in situ data available to SMAP provide many more data locations than the CVSs, although of lesser ability to represent soil moisture at the SMAP footprint scale. Despite this limitation, the analyses of sparse network data presented in this paper support the conclusions reached using data from the CVSs.

This assessment was based on an evaluation period of only six months of SMAP observations, and in situ data at a limited number of CVSs and sparse networks. As such, it is anticipated that by the time of the validated release, there will be a year of data covering the full annual cycle. This will help improve the statistical representativeness of the current performance assessment. Additional tasks remain prior to the planned L2_SM_P validated product release in May 2016. Among these tasks are more robust comparisons with in situ data from additional sites and networks, optimization of model parameters, and adjustments of flag thresholds. Improvements in the L2_SM_P retrieval performance are expected upon conclusion of these tasks.

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Dr. Kerr has organized all the SMOS workshops and was a Guest Editor on three IEEE Special Issues and one RSE. He received the World Meteorological Organization First Prize (Norbert Gerbier), the U.S. Department of Agriculture Secretary’s Team Award for excellence (SALSA Program), the GRSS Certificate of Recognition for leadership in the development of the first synthetic aperture microwave radiometer in space and success of the SMOS mission, and the ESA Team Award. He was nominated as Highly Cited Scientist by Thomson Reuters in 2015.