Soil Moisture Active Passive (SMAP) Project
Calibration and Validation for the L2/3_SM_AP
Beta-Release Data Products

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1 EXECUTIVE SUMMARY

This document describes the Stage 1 Calibration/Validation (Cal/Val) of the SMAP Level 2 Soil Moisture Active Passive (L2SMAP) product specifically for the beta release. The SMAP Level 3 Soil Moisture Active Passive (L3SMP) product is simply a daily composite of the L2SMAP half-orbit files. Hence, analysis and assessment of the L2SMAP product presented in this document can be considered to cover the L3SMAP product also. The SMAP L2SMAP and L3SMAP products are available only for ~85 days (14^{th} April, 2015 to 7^{th} July, 2015) because the product generation stopped after detection of anomaly in the SMAP radar hardware that led to discontinuation of the radar data acquisition.

For the post-launch period of the SMAP mission, there are two objectives pertaining to Cal/Val Phase for each science product team: 1) calibrate, verify, and improve the performance of the science algorithms, and 2) validate accuracies of the science data products as specified in the L1 science requirements according to the Cal/Val timeline.

To achieve abovementioned objectives, assessment of the L2SMAP product is essential. Assessment methodologies include comparisons of SMAP L2SMAP soil moisture retrievals with *in situ* soil moisture observations from core validation sites (CVS) and sparse networks. These analyses meet the criteria established by the Committee on Earth Observing Satellites (CEOS) Stage 1 validation [1], which supports beta release of the data based on a limited set of core validation sites. Inclusion of soil moisture data from other satellites (e.g., SMOS) and modeled soil moisture data will be taken up during the Stage 2 validation phase.

The SMAP Active Passive algorithm disaggregates the coarse resolution brightness temperature (T_B) of the radiometer by using finer spatial resolutions radar (SAR) data and parameter derived from temporal relationship between the brightness temperature and SAR data. The results of the initial assessment of the SMAP L2SMAP algorithm and its derived parameters are reasonable. The implementation of the L2SMAP algorithm is in three different variants (options) that are elaborated further in subsequent section.

The disaggregated high resolution brightness temperatures from the SMAP Active Passive algorithm are subjected to a radiative transfer model to retrieve soil moisture. Preliminary analyses showed that some refinements of parameters were required for the radiative transfer model (tau-omega) single channel algorithm (SCA). During Stage 1 validation the tau-omega parameters used to generate L2SMAP product are similar to the parameters applied in SCA of the SMAP Level 2 Soil Moisture Passive (L2SMP) product. The parameters used in SCA to produce L2SMP soil moisture are more valid for coarser resolution ~40 km, therefore, it is expected that the same tau-omega parameters used in SCA to retrieve soil moisture at higher resolution may be incompatible, and need scaling and calibration.

The primary assessment of the L2SMAP product for Stage 1 validation was based on CVS comparisons using metrics and time series plots. These analyses indicated that the Active Passive Option-1 Algorithm implemented at 9 km to obtain disaggregated brightness temperature at V-pol and subsequently soil moisture retrievals had better unbiased root mean square errors (ubRMSE), bias, and correlation than the Option-2 and Option-3 Active Passive soil moisture retrievals obtained using the disaggregated V- and H-pol brightness temperatures. The differences in performance metrics among the three algorithms were relatively small (generally to the third decimal place). Based upon these results, it is recommended that the Active Passive Option-1 algorithm implement at 9 km be adopted as the baseline algorithm for the beta release. The overall ubRMSE of the SMAP Active Passive Option-1 algorithm is 0.044 m^3/m^3, which is approximately the mission requirement [2]. The SMAP Active Passive algorithm was also implemented at 3 km resolutions. The initial evaluation of retrieved soil moisture at 3 km shows promise. The assessment of the L2SMAP product at 3 km against the CVS-based soil moisture observations had unbiased root mean square errors (ubRMSE) of 0.051 m^3/m^3. Comparisons with sparse network *in situ* data are subject to upscaling issues and were not used as a primary methodology for performance assessment. However, the results from over 300 sparse network sites mirrored the CVS results. [Note that the documented mission accuracy requirement is in units of cm^3/cm^3, which is mathematically identical to m^3/m^3.]

This report notes several limitations in the beta-release calibration, which will be addressed in the coming year prior to release of the validated data. These issues include optimization of algorithm parameters, tau-omega parameters, performance over very dense vegetation, and upscaling effects. In addition, the methodologies will expand prior to validated data release to include nearly double the number of CVS, model-based inter-comparisons, and the results of several intensive field experiments. Despite these remaining areas, the beta-release L2SMAP product is of sufficient level of maturity and quality that it can be approved for distribution to and used by the larger science and application communities. This beta release also presents an opportunity to enable users to gain familiarity with the parameters and data formats of the product prior to full validation.

2 OBJECTIVES OF CAL/VAL

During the post-launch Cal/Val (Calibration/Validation) Phase of SMAP there are two objectives for each science product team:

- Calibrate, verify, and improve the performance of the science algorithms, and
- Validate accuracies of the science data products as specified in L1 science requirements according to the Cal/Val timeline.

The process is illustrated in Figure 2.1. In this Assessment Report the progress of the L2 Soil Moisture Active Passive Team in addressing these objectives prior to beta release is described. The approaches and procedures utilized follow those described in the SMAP Cal/Val Plan [2] and Algorithm Theoretical Basis Document for the Level 2 & 3 Soil Moisture (Active Passive) Data Products [3].

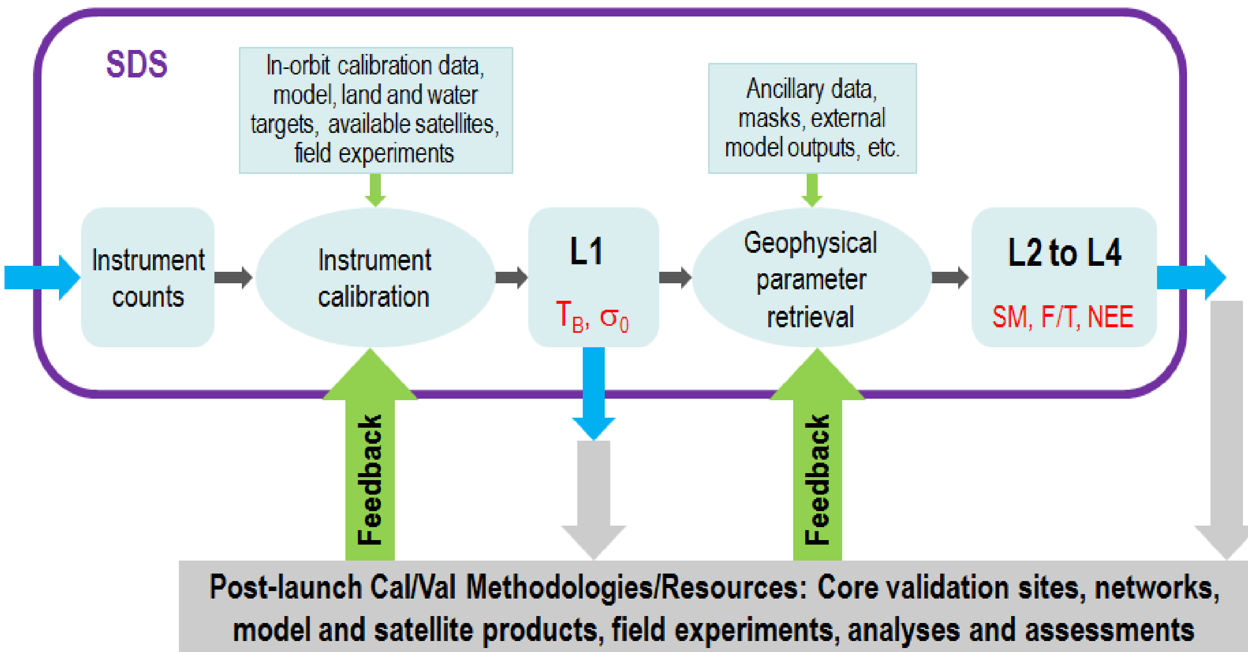


Figure 2.1. Overview of the SMAP Cal/Val Process.

SMAP established a unified definition base in order to effectively address the mission requirements. These are documented in the SMAP Handbook/ Science Terms and Definitions, where Calibration and Validation are defined as follows:

- *Calibration*: The set of operations that establish, under specified conditions, the relationship between sets of values or quantities indicated by a measuring instrument or measuring system and the corresponding values realized by standards.
- *Validation:* The process of assessing by independent means the quality of the data products derived from the system outputs.

The L2SMAP Team plans to meet the soil moisture retrieval accuracy of 0.04 m^3/m^3 that is listed in the Mission L1 Requirements Document **Error! Reference source not found.** for the active/ passive soil moisture product.

In order to insure the public's timely access to SMAP data, before releasing validated products the mission is required to release beta-quality products. The maturity of the products in the beta release is defined as follows:

- The release is used for all users to gain familiarity with data formats.
- Intended as a testbed to discover and correct errors.
- Minimally validated and still may contain significant errors.
- General research community is encouraged to participate in the quality assessment and validation, but need to be aware that product validation and quality assessment are ongoing.
- Data may be used in publications as long as the fact that it is beta quality is indicated by the authors. Drawing quantitative scientific conclusions is discouraged. Users are urged to contact science team representatives prior to use of the data in publications, and to recommend members of the instrument teams as reviewers.
- The estimated uncertainties will be documented.
- May be replaced in the archive when an upgraded (provisional or validated) product becomes available.

In assessing the maturity of the L2SMAP product, the L2SMAP team also considered the guidance provided by the Committee on Earth Observation Satellites (CEOS) Working Group on Calibration and Validation (WGCV) [1]:

- Stage 1: Product accuracy is assessed from a small (typically < 30) set of locations and time periods by comparison with *in situ* or other suitable reference data.
- Stage 2: Product accuracy is estimated over a significant set of locations and time periods by comparison with reference *in situ* or other suitable reference data. Spatial and temporal consistency of the product and with similar products has been evaluated over globally representative locations and time periods. Results are published in the peer-reviewed literature.
- Stage 3: Uncertainties in the product and its associated structure are well quantified from comparison with reference *in situ* or other suitable reference data. Uncertainties are characterized in a statistically robust way over multiple locations and time periods representing global conditions. Spatial and temporal consistency of the product and with similar products has been evaluated over globally representative locations and periods. Results are published in the peer-reviewed literature.
- Stage 4: Validation results for stage 3 are systematically updated when new product versions are released and as the time-series expands.

For the beta release the L2SMAP team has completed Stage 1 and begun Stage 2 (global assessment). The Cal/Val program will continue through these stages over Year 2016.

3 IMPACT OF L1C RADIOMETER DATA AND L1C RADAR DATA ON L2SMAP

The L2SMAP soil moisture retrievals are based on the beta-release versions of the radiometer Level 1C brightness temperature (L1CTB) data, L2SMP data, Level 1C High Resolution Radar Backscatters (L1CS0HiRes) data, and Level 2 Radar-only Soil Moisture (L2SMA) data. The primary inputs to L2SMAP processing are Brightness Temperature (at vertical (V-pol) and horizontal (H-pol) polarization) data from L1CTB that is corrected for the presence of water bodies available through L2SMP, radar backscatter (co- (vv and hh) and x- (hv or vh) polarized) and data gridded to EASE2 resolution at 3 km available through L2SMA data, and relevant quality flags from L2SMP and L2SMA data. A detailed assessment of data qualities of L1CTB, L1CS0HiRes, L2SMP and L2SMA and calibrations are available at NSIDC, from which the material in this section is drawn.

Table 1 lists the contribution of error sources to the disaggregated brightness temperature at 9 km resulting from inputs available through L1CTB, L1CS0HiRes, L2SMP and L2SMA for Option-1 algorithm [3, 4, and 5]. The first numbered row in Table 1 is the estimated error in the L1CTB (36 km EASE grid) which is due to the instrument, geophysical contributions to Earth surface brightness temperature and gridding. Effects of water bodies are removed from the brightness temperature. Assuming a nominal 5% error in the estimation of inland water bodies, the estimated contribution of error is about 0.45 K. The errors due to mis-specification of inland water bodies are dependent on the absolute percent of water fraction. A 5% error is assumed with 5% water body fraction for the error budget computation. It should be noted that source of error in the water body could be very large. For example, if a pixel contains 10% inland water and there is 10% error on its specification, the impact on brightness temperature correction can be as large as ~2.0 K uncertainty. As a nominal case 5% error on 5% water coverage is considered. The permanent water bodies within a radiometer pixel are estimated from existing data such as the MOD44W from MODIS data.

Table 3.1. Error budget for L2SMAP brightness temperature at 9 km.

	Error Sources at 36 km Ease Grid	Estimated Error
1	Radiometer precision and calibration stability, faraday rotation, atmospheric gases, non-precipitating clouds, and gridding	1.3* K
2	Waterbody fraction surface heterogeneity 5% error	0.70 K
3	**Adjusted Corrected T_B RSS**	**1.47 K**
4	Radar calibration and contamination error	1.65 K
5	Algorithm Parameter error	1.60 K
6	**Disaggregated T_B (9 km) estimation RSS**	**2.73 K**

*T_B error requirement of 1.3 K is based on a 30 km swath grid.

The water-body adjusted brightness temperature root-sum-of-squares (RSS) is reported in row three of Table 1. The Option-1 uses the radar backscatter cross-section and brightness temperature time-series to estimate a disaggregated 9 km brightness temperature. The contribution of radar backscatter cross-section calibration and contamination noise is 1.65 K estimated through Monte Carlo simulation. Beside radar backscatter cross-calibration and contamination noise, other important sources of errors the SMAP Active

Passive algorithm are the uncertainties in algorithm parameters. Nominal values of 20% uncertainties are used for the algorithm parameters to evaluate the error contribution in the disaggregated 9 km brightness temperature, and the estimated value is 1.60 K (shown in row 5 of Table 1). The total 9 km disaggregated brightness temperature error of 2.73 K is shown as an RSS in the sixth row of Table 3.1.

Table 3.2 represents the same error budget but with more detail and in units of percent volumetric soil moisture cm^3/cm^3. Tables 3.1 and 3.2 are different from seventh row onwards of Table 3.2. The disaggregated brightness temperatures are subjected to the single channel algorithm (SCA) for soil moisture retrievals. The subsequent rows in Table 3.2 show uncertainty contribution of ancillary data and retrieval model in percent volumetric soil moisture cm^3/cm^3. The table highlights the uncertainties expected in various parameters and variables that are needed to establish that the L2SMAP product is meeting the SMAP L1 requirements. The table illustrates the upper limit of the Vegetation Water Content (VWC) of 5 kg/m^2 because the L2SMAP product is expected to meet the L1 requirement below VWC 5 kg/m^2. The errors due to 2.0 K land surface temperature, 10% uncertainty in 9 km VWC, 5% error in dielectric model percent sand and clay specification, and 5% error on major model parameters are shown in rows seven through ten of Table 3.2. The total retrieval uncertainty is shown in the last row of Table 3.2.

Table 3.2: Error budget in volumetric soil moisture cm^3/cm^3

	Error Sources at 36 km Ease Grid	**Estimated Error**
1	Radiometer precision and calibration stability, faraday rotation, atmospheric gases, non-precipitating clouds, and gridding	1.3* K
2	Waterbody fraction surface heterogeneity 5% error	0.70 K
3	**Adjusted Corrected T_B RSS**	**1.47 K**
4	Radar calibration and contamination error	1.65 K
5	Algorithm Parameter error	1.60 K
6	**Disaggregated T_B (9 km) estimation RSS**	**2.73 K**
7	VWC at 5 kg/m2, with 10% error	0.025 cm^3/cm^3
8	Soil temperature (2 K)	0.025 cm^3/cm^3
9	Soil texture (5% error in sand & clay fraction)	0.01 cm^3/cm^3
10	Parameters (h, ω, and b) 5% error each	0.010 cm^3/cm^3
11	**Soil moisture retrieval at 9 km**	**0.0375** cm^3/cm^3

As shown in Table 3.2 the soil moisture retrievals in L2SMAP product can meet the SMAP L1 requirement of 0.04 cm^3/cm^3. The above error budget (Table 3.2) is developed based on Monte Carlo analysis of nominal set of conditions, e.g., mean VWC level, waterbody fraction, soil texture, soil moisture, etc. The error and uncertainty depend on these conditions and hence do not apply to each and every grid cell of the SMAP L2SMAP granule. An analytical uncertainty analysis formulation [6] was developed that is based on existing conditions of a EASE2 grid cell during the SMAP overpass, and is implemented in the L2SMAP processing. This uncertainty estimate accompanies every L2SMAP soil moisture retrieval in the science product data files.

4 L2SMAP ALGORITHMS

The basic approach of the L2SMAP algorithm (Fig. 4.1) is disaggregation of the coarse resolution SMAP radiometer brightness temperature by using the fine resolution co-registered SMAP radar backscatters [3, 5].

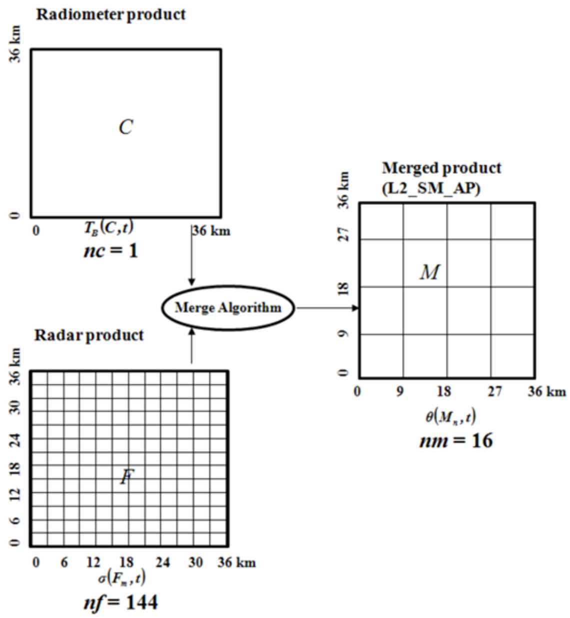


Figure 4.1. Grid definition of radiometer, radar, and merge product where *nf* and *nm* are the number of area pixels of radar and merged product, respectively, within one radiometer area pixel *nc*.

The L2SMAP algorithms are variants of this general disaggregation approach (Fig. 4.1), and Fig. 4.2 illustrates these variants that results in the final product of active-passive soil moisture at 9 km EASE2 grid resolution.

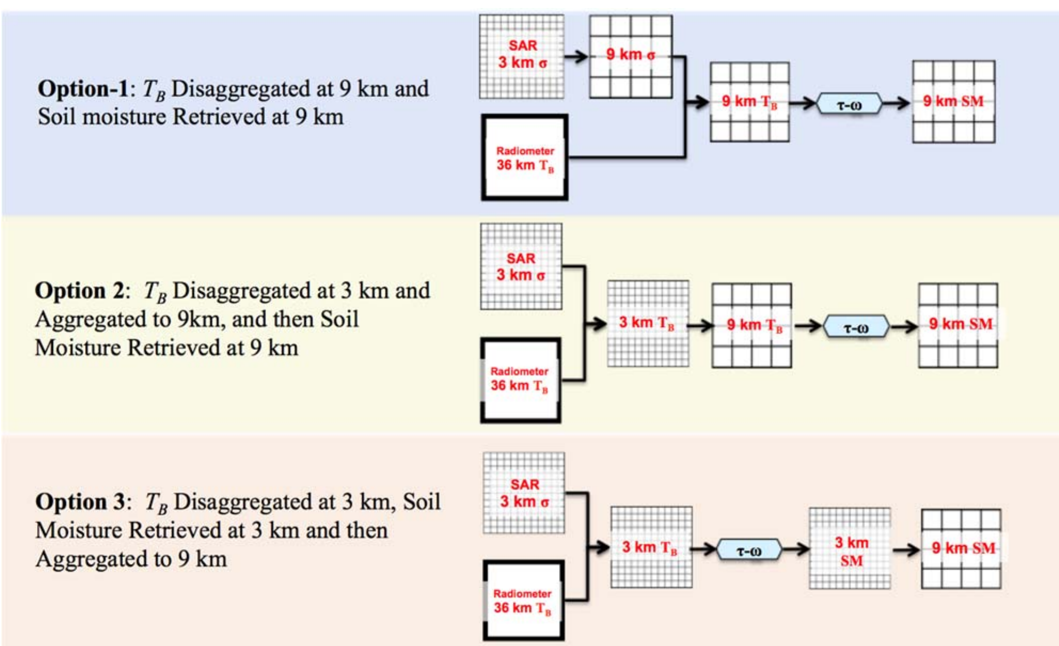


Figure 4.2. Variant of the L2SMAP Algorithms.

The beta-release L2SMAP contains soil moisture retrieval fields produced by all the options as shown in Fig. 4.2. The three variants of L2SMAP algorithm shown in Fig. 4.2 can be applied to two (V-pol and H-pol) brightness temperatures of the SMAP radiometer. Therefore, a total of six options are available for the SMAP L2SMAP algorithm. The current L2SMAP baseline algorithm is the V-pol Option-1algorithm. Beside these six options of L2SMAP algorithm at 9 km, two additional soil moisture fields of 3 km EASE2 grid resolution are also included in the L2SMAP product. These 3 km soil moisture fields are the byproduct of the Option-3 algorithm (Fig. 4.2) applied with the V-pol and H-pol brightness temperatures of the SMAP radiometer.

Inside an L2SMAP granule the *soil_moisture* field is the one that links to the retrieval result produced by the currently-designated baseline algorithm. At present, the operational L2SMAP Science Production Software (SPS) produces and stores soil moisture retrieval results from the following five algorithms:

1. Option-1 V-pol (9 km), Baseline
2. Option-2 V-pol (9 km)
3. Option-3 V-pol (9 km)
4. Option-1 H-pol (9 km)
5. Option-2 H-pol (9 km)
6. Option-3 H-pol (9 km)
7. Soil Moisture 3 km V-pol
8. Soil Moisture 3 km H-pol

Given the preliminary results from the current L2SMAP Cal/Val analyses, the Option-1 V-pol algorithm seems to deliver slightly better performance than other options at 9 km, which was designated as the pre-launch baseline retrieval algorithm. For this reason, the Option-1 V-pol is designated as the current baseline algorithm for the beta release of L2SMAP. Throughout the rest of the entire post-launch Cal/Val period, all six algorithms at 9 km and two algorithms at 3 km will be continuously assessed. The choice of the final baseline algorithm for the validated release of the product will be evaluated based on the analyses conducted on new versions of L2SMAP product available due to fixes and calibration of the parameters.

5 APPROACH FOR L2 CAL/VAL: METHODOLOGIES

Validation is critical for accurate and credible product usage, and must be based on quantitative estimates of uncertainty. For satellite-based retrievals, validation should include direct comparison with independent correlative measurements. The assessment of uncertainty must also be conducted and presented to the community in normally used metrics in order to facilitate acceptance and implementation.

During the mission definition and development, the SMAP Science Team and Cal/Val Working Group identified the metrics and methodologies that would be used for L2-L4 product assessment. These metrics and methodologies were vetted in community Cal/Val Workshops and tested in SMAP pre-launch Cal/Val rehearsal campaigns. The methodologies identified and their general roles are;

- Core Validation Sites: Accurate estimates of products at matching scales for a limited set of conditions
- Sparse Networks: One point in the grid cell for a wide range of conditions
- Satellite Products: Estimates over a very wide range of conditions at matching scales
- Model Products: Estimates over a very wide range of conditions at matching scales
- Field Campaigns: Detailed estimates for a very limited set of conditions

In the case of the L2SMAP data product, all of these methodologies can contribute to product assessment and improvement. With regard to the CEOS Cal/Val stages, Core Validation Sites address Stage 1 and Satellite and Model Products are used for Stage 2 and beyond. Sparse Networks fall between these two stages.

6 PROCESS USED FOR BETA RELEASE

The SMAP L2SMAP team chose to define the assessment period as April 14-July 07, 2015. This is the period of data availability from the SMAP mission when the radar and the radiometer were acquiring observations in tandem before the anomaly was detected in the radar hardware. The start date was based on when the radar data were judged to be stable following instrument start-up operations. The team conducted assessments on a weekly basis and will continue to do this throughout the period of data availability after every L2SMAP product version update due to parameter calibration or other fixes.

Weekly reviews of performance based upon CVS, and Sparse Networks were conducted for the available period of record (~2.5 months) that captured a range of conditions over various parts of the world. These analyses included the intercomparison of three SMAP L2SMAP retrieval algorithms, and established consistent levels and patterns of performance. Two algorithm-related actions were taken based upon these performance reviews. First, flags based upon ancillary data (specifically rainfall) were implemented and these data were removed from calculations of performance metrics. Second, retrieval issues were found in arid regions (i.e., non-retrievals in very dry areas). Further investigation indicated that the effective soil temperature being used was not appropriate to the conditions in these areas. As a result, a study was conducted to examine alternative approaches to determination of the effective soil temperature to use in the soil moisture retrievals. This analysis is described in a following section. The resulting effective temperature approach was applied globally (not just in arid regions).

It should be noted that a small underestimation bias should be expected when comparing satellite retrievals to *in situ* soil moisture sensors during drying conditions. Satellite L-band microwave signals respond to a surface layer of a depth that varies with soil moisture (this depth is taken to be ~0-5 cm for average soils under average conditions). The *in situ* measurement is centered at 5 cm and measures a layer from ~ 3 to 7 cm. For some surface conditions and climates, it is expected that the surface will be slightly drier than the layer measured by the *in situ* sensors. For example, Adams et al. [7] reported that a mean difference of 0.018 m^3/m^3 existed between the measurements obtained by inserting a probe from the surface versus horizontally at 5 cm for agricultural fields in Manitoba, Canada. Drier conditions were obtained using the surface measurement and this difference was more pronounced for mid to dry conditions and minimized during wet conditions.

6.1 Effective Temperature

Dynamic surface temperature forecast information is routinely ingested by SMAP from the GMAO GEOS-5 model and processed as an ancillary data input as part of the operational processing of the SMAP passive soil moisture product. The original baseline computation of the effective surface temperature (T_{eff}) consisted of using the average of the GMAO surface temperature (TSURF) and the GMAO layer 1 soil temperature at 10 cm (TSOIL1). Preliminary analyses showed that a more sophisticated model for computing T_{eff} was required due to non-uniform soil temperature profiles, especially in arid areas, which led to soil moisture retrieval issues. In order to address this problem, several options for T_{eff} were considered and evaluated using SMAP T_B observations along with GMAO soil temperatures for the soil profile [8].

The SMAP beta release L2SMAP product uses the Choudhury [8] model to compute the effective soil temperature:

$$T_{eff} = T_{soil\_deep} + C\,(T_{soil\_top} - T_{soil\_deep}) \qquad (1)$$

where T_{soil_top} refers to the GMAO layer 1 soil temperature (TSOIL1) and T_{soil_deep} refers to the GMAO layer 2 soil temperature (TSOIL2). This formulation allows for correct modeling of the deeper sensing depth of emission emanating from deeper in the soil than the surface. C is a coefficient that depends on the observing frequency – for the SMAP L-band beta release data, C= 0.264.

This approach to the calculation of T_{eff} was then applied to all regions in SMAP L2SMAP soil moisture retrievals, and did minimize the number of non-retrievals due to soil temperature issues. More details of the effective temperature computation is provided in the L2SMP Beta Release Assessment Report.

7 ASSESSMENTS

7.1 Stability of Algorithm Parameters

The SMAP L2SMAP algorithm has two parameters ($\boldsymbol{\beta}$ and $\boldsymbol{\Gamma}$), as shown in (2).

$$T_{B_p}(M_j) = T_{B_p}(C) + \boldsymbol{\beta}(C) \cdot \{[\sigma_{pp}(M_j) - \sigma_{pp}(C)] + \boldsymbol{\Gamma} \cdot [\sigma_{pq}(C) - \sigma_{pq}(M_j)]\} \quad (2)$$

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 x-pol radar backscatters at corresponding resolution (9 km or 3 km) of the disaggregated brightness temperature, and $\sigma_{pp}(C_j)$ and $\sigma_{pq}(C_j)$ are the co-pol and x-pol radar backscatters aggregated to 36 km.

The performance of the brightness temperature disaggregation that results in the 9 km or 3 km soil moisture retrievals is heavily dependent on robust estimates of the parameters β and Γ in (2). Regression of the time-series (formed based on multiple overpasses) for $T_{B_p}(C)$ and $\sigma_{pp}(C)$ are used to statistically estimate $\boldsymbol{\beta}$. The statistically-estimated slope parameters are specific for a given location and reflect the local roughness and vegetation cover conditions with the assumption that they are fairly stable during the time period of $\boldsymbol{\beta}$ estimation. The parameter $\boldsymbol{\Gamma}$ is also determined statistically for any particular overpass using the radar backscatters σ_{pp} and σ_{pq} at the finest available resolution (in this case at 3 km) that are encompassed within the 36 km $T_{B_p}(C)$ grid cell.

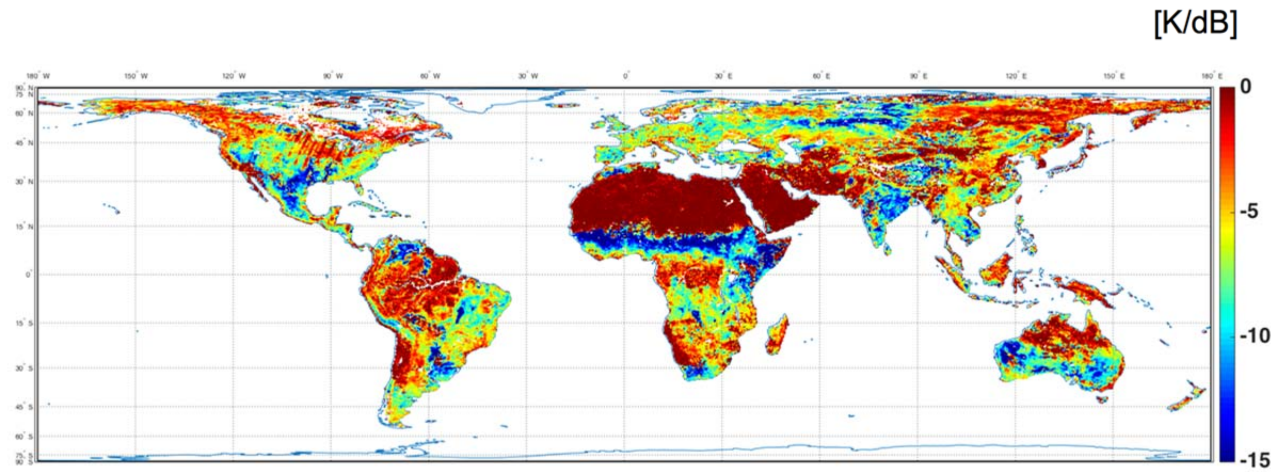


Figure 7.1.1. $\boldsymbol{\beta}$ parameter computed using all the available SMAP radar (vv-pol) and radiometer (V-pol) data from April 15, 2015 to July 7th, 2015. The $\boldsymbol{\beta}$ parameter is actually determined in emissivity and SAR dB terms. To represent $\boldsymbol{\beta}$ in K/dB units, effective surface temperature is multiplied to create the above image.

The above Fig. 7.1.1, illustrates the distribution of $\boldsymbol{\beta}$ parameter at global extent. The $\boldsymbol{\beta}$ parameter values obtained were found to be consistent with priors data based on analysis of all Soil Moisture Field Experiments (SGP99, SMEX02, CLASIC, and SMAPVEX08), and 3 years of Aquarius data. One noteworthy aspect that is obvious in Fig. 7.1.1 is the radar data artifact over the Midwest region of the Continental United States. Values of the $\boldsymbol{\beta}$ parameter over arid regions like the Sahara Desert are lower than expected. The reason for such anomalies is the absence of a dynamic range of conditions over arid regions within the duration (~2.5 months) of available data. Figure 7.1.2 shows the correlation map of $T_{B_V}(C)$ and $\sigma_{vv}(C)$ for the ~2.5 month period. The map (Fig. 7.1.2) also represent the statistical robustness in the estimated $\boldsymbol{\beta}$ parameter. High correlations are observed over most part of the world except for the arid and heavily forested regions. This validates the inferior quality of $\boldsymbol{\beta}$ parameter estimates over arid regions, however, over the heavily forested regions the lack of dynamic ranges in $T_{B_p}(C)$ and $\sigma_{pp}(C)$ is due to high volume scattering and lack of sensitivity to the underlying soil layer. Figure 7.1.3 shows the trend in the $\boldsymbol{\beta}$ parameter against the x-pol SMAP radar backscatter that is a proxy for vegetative regions. An almost linear trend (shown as red line in Fig. 7.1.3) is observed in the $\boldsymbol{\beta}$ parameter with respect to SMAP radar x-pol for the regions where the correlation is high. The nonlinearity in the $\boldsymbol{\beta}$ parameter trend for x-pol radar data less then -20 [dB] is due to inadequate data that leads to inferior estimation. Given the dynamic ranges of $T_{B_p}(C)$ and $\sigma_{pp}(C)$ over arid regions the trend should follow the red line. Therefore, in the L2SMAP algorithm implementation, the model that follows the red line as shown in Fig. 7.1.3 is used where the error of $\boldsymbol{\beta}$ parameter estimation is higher (or correlation < 0.4).

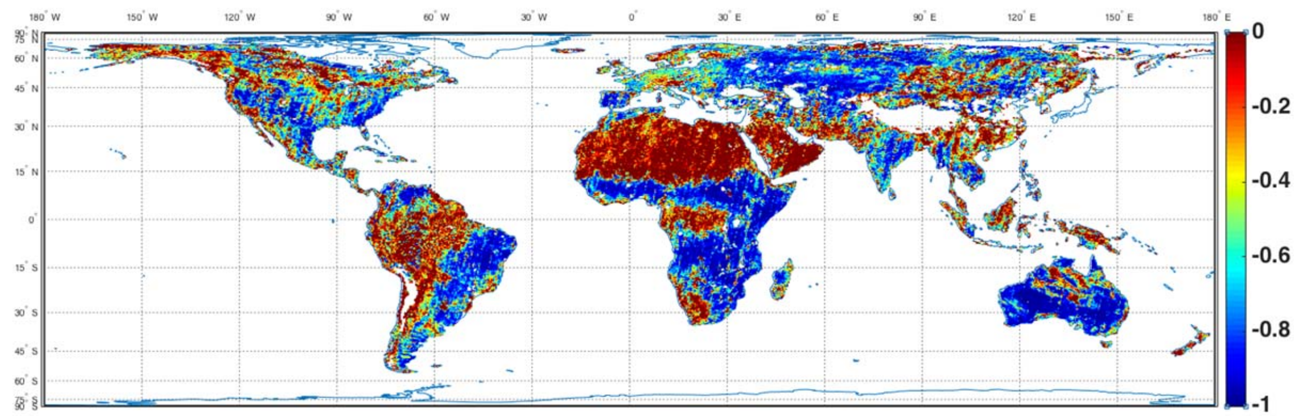


Figure 7.1.2. Correlation map of $T_{B_V}(C)$ and $\sigma_{vv}(C)$ computed using all the available SMAP radar (vv-pol) and radiometer (V-pol) data from April 15, 2015 to July 7th, 2015.

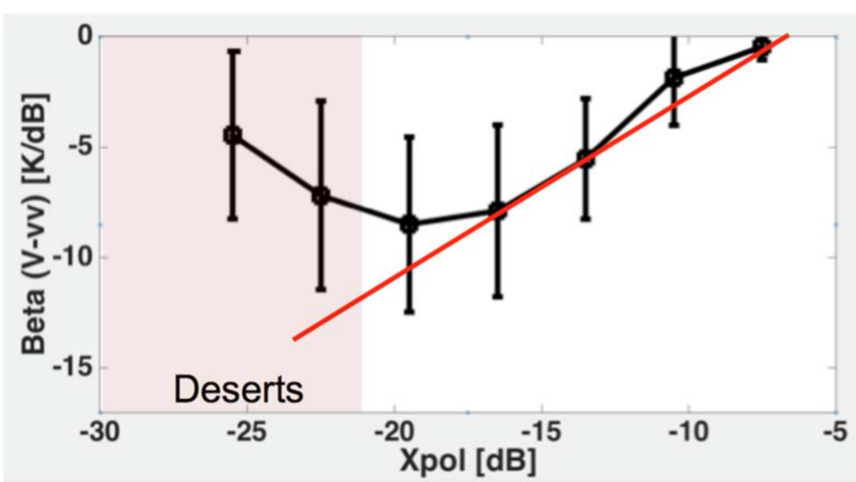


Figure 7.1.3. Trend in $\boldsymbol{\beta}$ parameter with respect to the SMAP radar x-pol measurements.

The algorithm parameter $\boldsymbol{\Gamma}$ exhibits more stability as compared to the $\boldsymbol{\beta}$ parameter. Figure 7.1.4 shows the global distribution of the $\boldsymbol{\Gamma}$ parameter. The range of values of $\boldsymbol{\Gamma}$ parameters correspond with the parameters derived from the Soil Moisture Field Campaigns (SGP99, SMEX02, CLASIC, and SMAPVEX08) data. To evaluate the stability of the $\boldsymbol{\Gamma}$ parameters the coefficient of variation was computed for one month as shown in Fig. 7.1.5. The coefficient of variation is very low for most part of the world suggesting stability in derived $\boldsymbol{\Gamma}$ parameters.

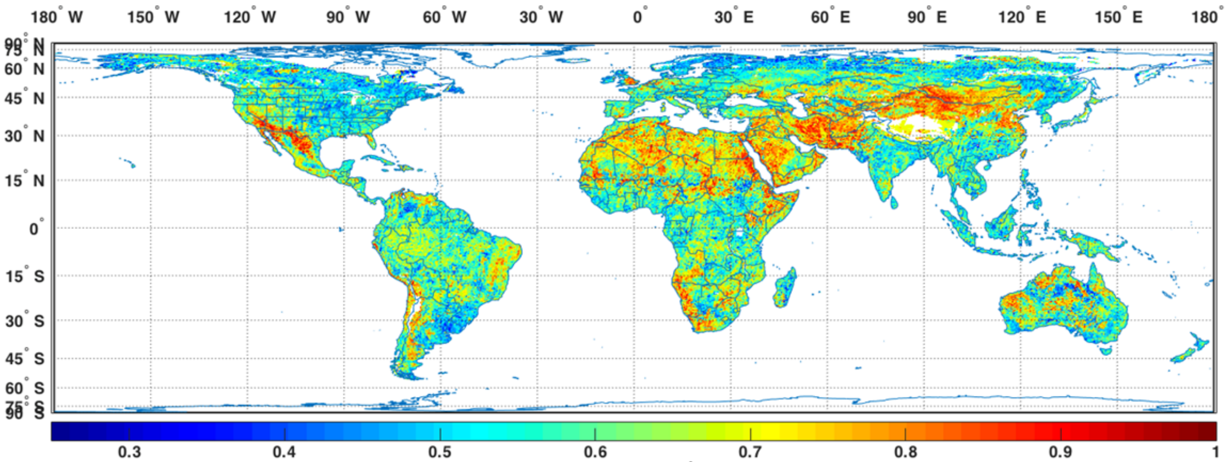


Figure 7.1.4. Global map of $\boldsymbol{\Gamma}$ parameters at global extent averaged for 04-28-2015 to 05-28-2015.

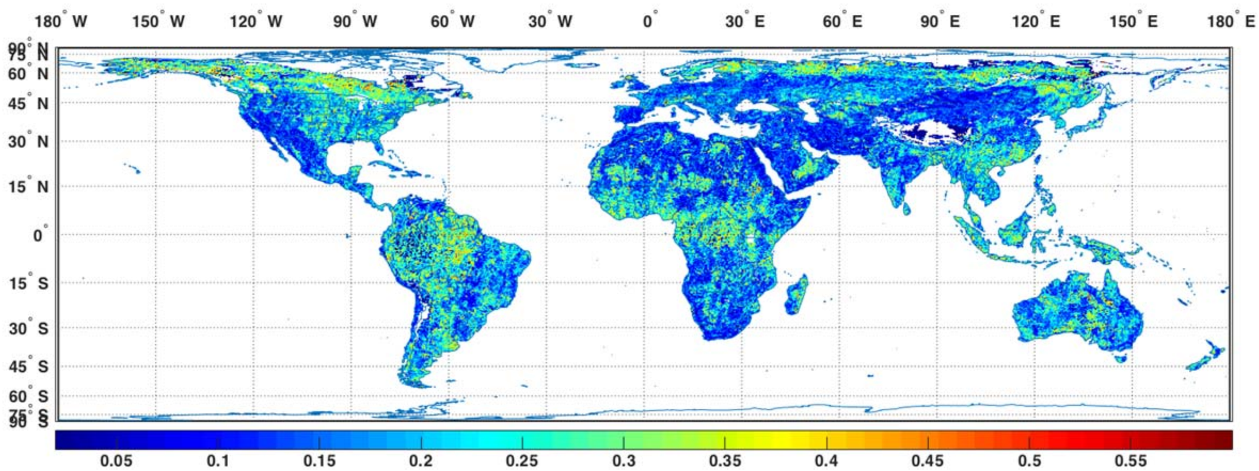


Figure 7.1.5. Coefficient of variation of $\boldsymbol{\Gamma}$ parameters computed for 04-28-2015 to 05-28-2015.

7.2 Global Patterns and Features in L2SMAP product

In this section, prior to the quantitative assessments that follow, the general features of global images are reviewed for various combinations of algorithms and products. All images shown in following figures are global composites of SMAP L2SMAP over a one-week period in June (June 8-15, 2015). These images are composites of all 6 AM Equator crossing (descending) L2SMAP half-orbits within the stated period. This is equivalent to the SMAP L3SMAP product composited over the same time period. Note that complete global coverage can be achieved by compositing three days of SMAP L2SMAP descending orbits provided all the descending half orbits are available. Some example of global images shown below include:

- SMAP L2SMAP algorithms (Option-1 for V-pol at 9 km) with and without flags applied.
- SMAP L2SMAP algorithms (Option-1 for H-pol at 9 km) with and without flags applied.
- SMAP L2SMAP algorithms (V-pol at 3 km) with and without flags applied.

Figures 7.2.1 – 7.2.2 show global images at 9 km developed from the SMAP L2SMAP Option-1 algorithms being evaluated in this beta-release assessment report. The regions that are expected to be very dry (i.e., the Sahara desert) and wet (i.e., the Amazon Basin) reflect the expected levels of retrieved soil moisture, and the global patterns with expected soil moisture variability. Similar figures for L2SMAP Option-2 and Option-3 for V-pol and H-pol at 9 km were created for assessing the global soil moisture patterns, and were almost similar to the patterns shown in Figures 7.2.1 – 7.2.2. The SMAP L2SMAP algorithm at 3 km for V-pol is illustrated in Fig. 7.2.3. The global pattern and dynamic range of soil moisture are similar to the pattern shown in Figs. 7.2.1 – 7.2.2 for 9 km, however, greater spatial details of soil moisture fields are clearly visible.

There are a number of quality flags that are applied to SMAP products. Some of these flags indicate that the data should be used with caution while others imply that the data should not be used at all. A complete description of the flags and flag thresholds used in L2SMAP processing can be found in the Product Specification Document [L2SMAP Product Specification Document, JPL D-72548]. Figures 7.2.1 – 7.2.3 also illustrate the impact of applying the quality flags. Quite a bit of the global land surface area is removed (white areas show where flags indicate a possible issue with retrieval quality). A large amount of the white area is related to the vegetation water content (VWC). The reliability of soil moisture retrieval algorithms is known to decrease when the VWC exceeds 5 kg/m^2 – this VWC value is used by SMAP as a flag threshold to indicate areas of dense vegetation where soil moisture retrievals are possibly less accurate. It is anticipated that some of the flag thresholds may be relaxed in time as the algorithms are improved for the presence of certain currently problematic surface conditions. Other areas that are flagged include regions with topography features (mountain ranges), and presence of large water bodies (coastal regions and area near large lakes).

The Level-1 requirement drove the development of L2SMAP 9 km product. However, the L2SMAP algorithm can also provide 3 km soil moisture retrievals. Figure 7.2.4 highlights the spatial details in soil moisture for 9 km and 3 km data fields captured by the SMAP L2SMAP algorithm when compared to soil moisture retrievals at 36 km from L2SMP product. The spatial features at higher 3 km resolution look consistent and conform to the pattern of soil moisture at 36 km and 9 km resolutions. The soil moisture data at 3 km is similar to 9 km data in terms of data characteristics such as retrieval flag and surface flag. Figure 7.2.5 shows a typical swath of soil moisture retrievals at 9 km over Africa, and the associated retrieval recommended flag. The dark portion in swath (Fig. 7.2.5) has the soil moisture values that are recommended for use for any application or study, and the soil moisture values at white area in the swath are not recommended due to variety of reasons, mostly due to surface conditions. The surface conditions for the corresponding swath of Fig. 7.2.5 is illustrated in Fig. 7.2.6 that shows where the non-recommended flags are triggered due to dense vegetation, nadir region, waterbodies, mountainous terrain, urban area, and coastal region. The data characteristics between the 9 km and 3 km soil moisture retrievals are similar, however, one major difference is in the surface nadir flag. Figure 7.2.7 illustrates the difference in widths of nadir regions at 3 km and 9 km data comprised in L2SMAP product. The difference is due to the native resolution of the SMAP radar; it is 3 km and 9 km spatial resolution at 150 km and 24 km from the nadir, respectively.

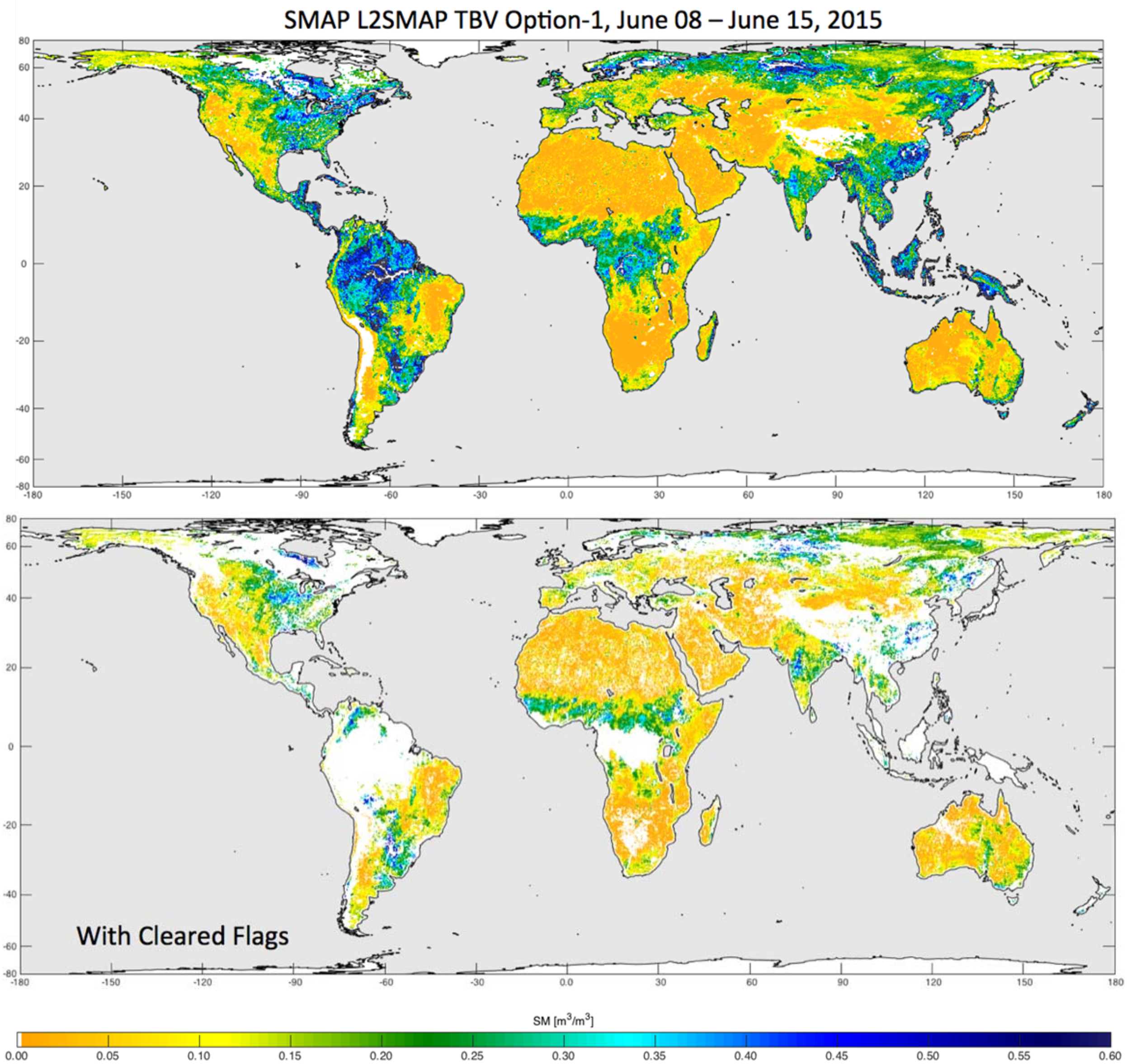


Figure 7.2.1. SMAP L2SMAP (TBV) Option-1 global images with flags and with cleared flags for soil moisture products.

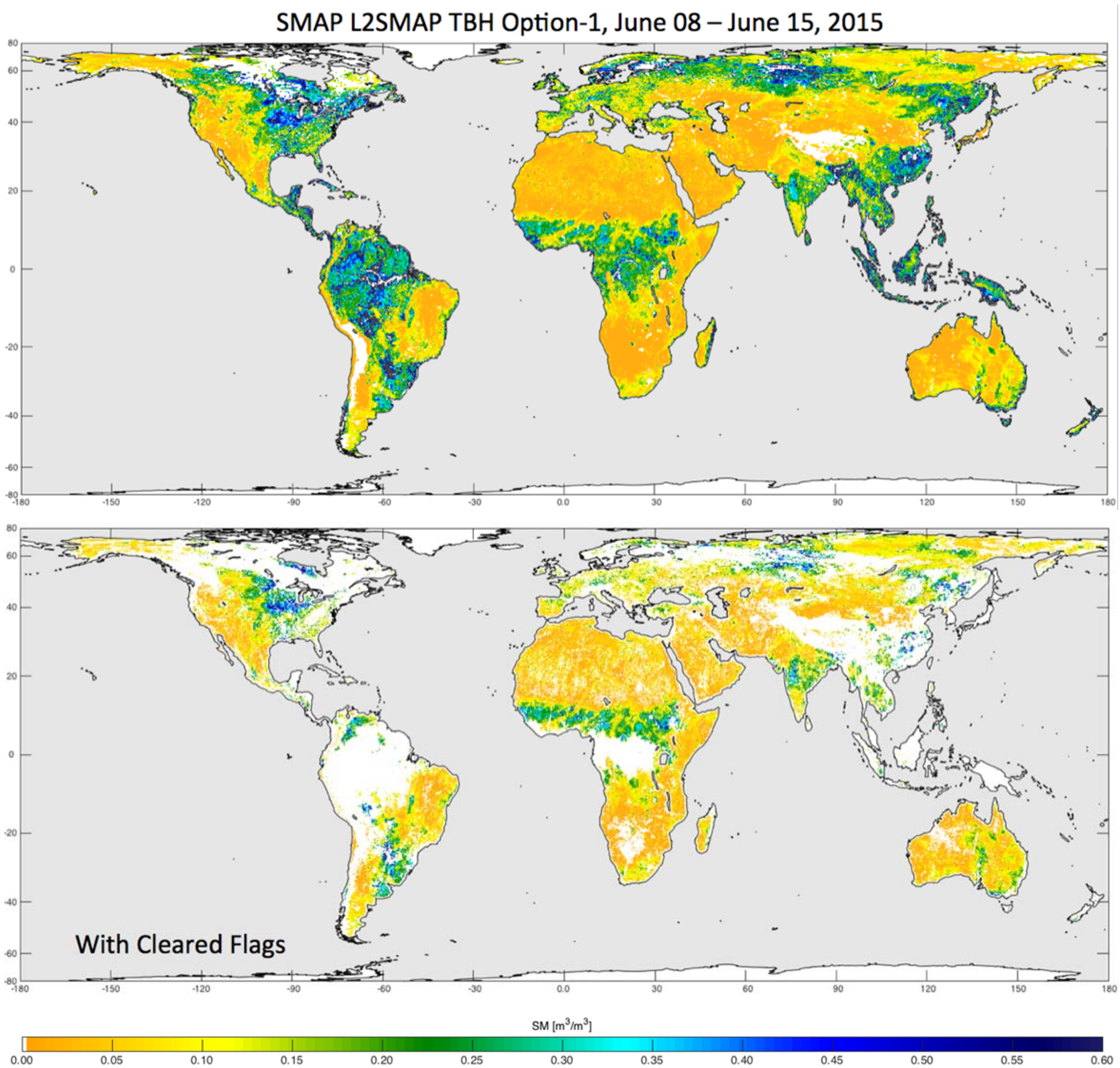


Figure 7.2.2. SMAP L2SMAP (TBH) Option-1 global images with flags and with cleared flags for soil moisture products.

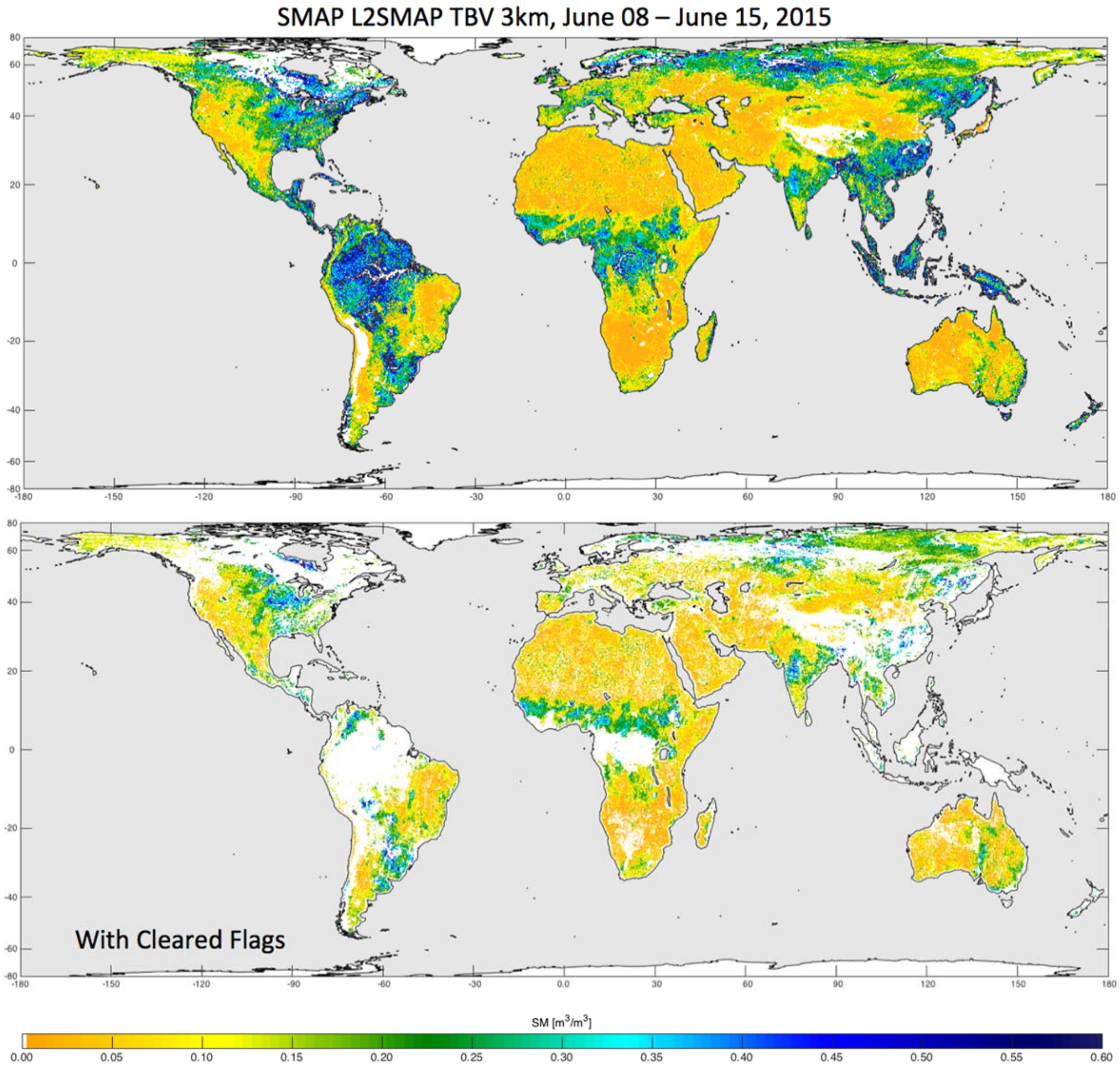


Figure 7.2.3. SMAP L2SMAP (TBV) 3km global images with flags and with cleared flags for soil moisture products.

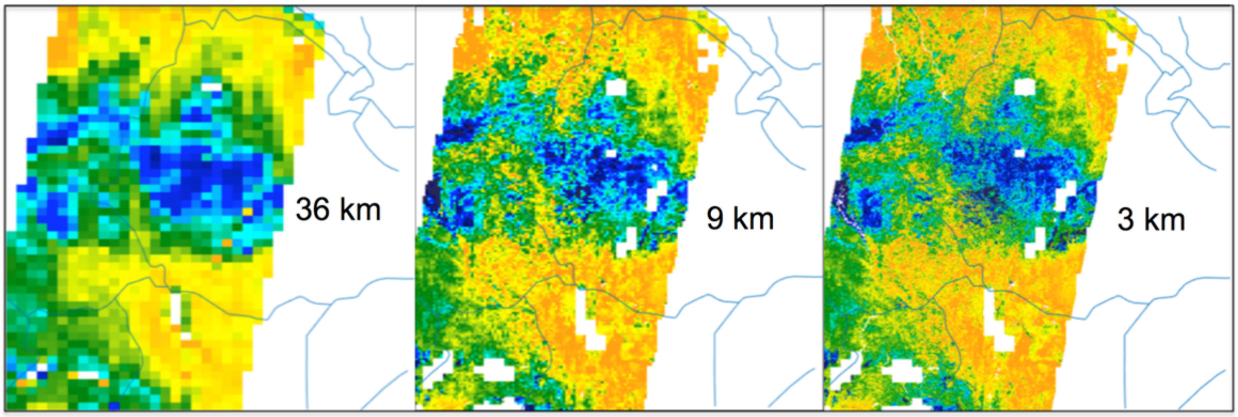


Figure 7.2.4. Enhancement of spatial details of soil moisture retrievals through L2SMAP algorithm, example from Africa (Central and Western Ethiopia, and Western part of Kenya).

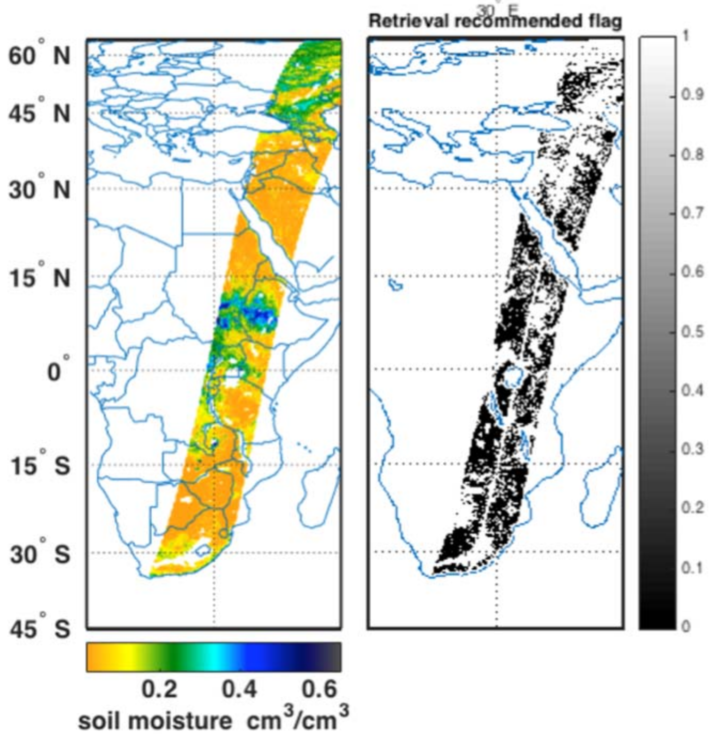


Figure 7.2.5. A typical L2SMAP swath with associated retrieval quality flag.

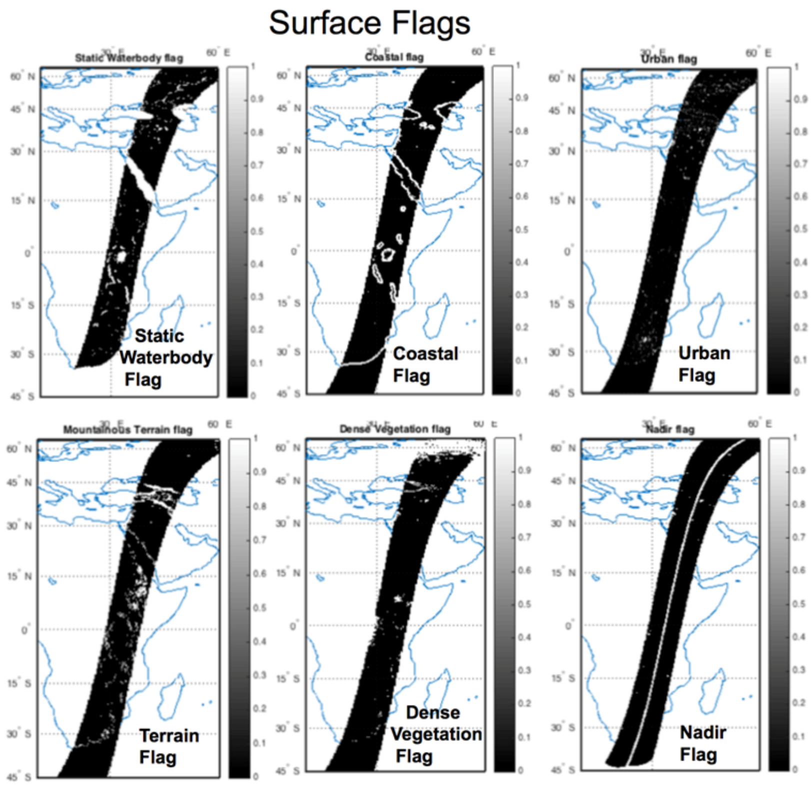


Figure 7.2.6. Surface flags in the L2SMAP product.

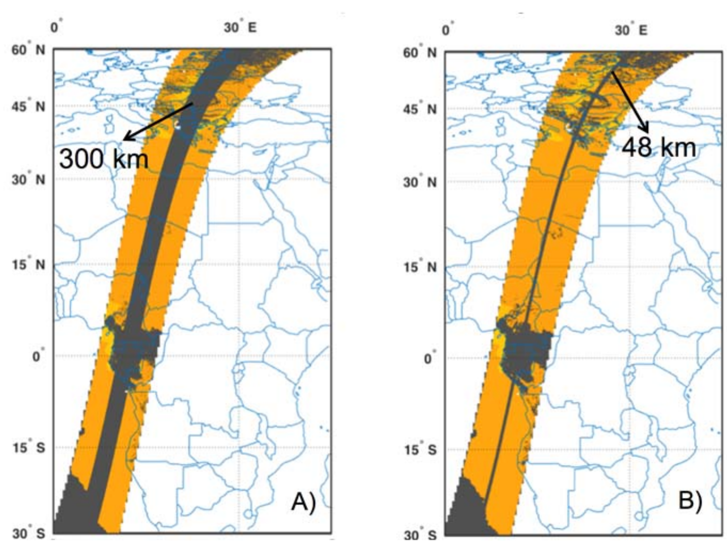


Figure 7.2.7. Difference in nadir regions in the SMAP L2SMAP at 3 km (A) and 9 km (B) surface flag.

7.3 Core Validation Sites (CVS)

The Stage 1 validation for the L2SMAP soil moisture is a comparison of retrievals at 9 km with ground-based observations that have been verified as providing a spatial average of soil moisture at the same scale, referred to as core validation sites (CVS) in the SMAP Calibration/Validation Plan [9].

In situ data are critical in the assessment of the SMAP products. These comparisons provide error estimates and a basis for modifying algorithms and/or parameters. A robust analysis will require many sites representing diverse conditions. However, there are relatively few sites that can provide the type and quality of data required. SMAP established a Cal/Val Partners Program in order to foster cooperation with these sites and to encourage the enhancement of these resources to better support SMAP Cal/Val. The current set of sites that provide data for L2SMAP are listed in Table 7.3.1.

Not all of the candidate sites in Table 7.3.1 have reached a level of maturity that would support them being used as CVS. In some cases this is simply a latency problem that will be resolved in time. Prior to initiating beta-release assessments, the L2SMAP and Cal/Val Teams reviewed the status of all sites to determine which sites were ready to be designated as CVS. The basic process is as follows:

- Assess the site for conditions that would introduce uncertainty
- Determine if the number of points is large enough to provide reliable estimates
- Assess the geographic distribution of the *in situ* points
- Determine if the instrumentation has been either (1) widely used and known to be well-calibrated or (2) calibrated for the specific site in question
- Perform quality assessment of each point in the network
- Establish a scaling function (default function is a linear average of all stations)
- Review any supplemental studies that have been performed to verify that the network represents the SMAP product over the grid domain

The status of candidate sites will be periodically reviewed to determine if they should be classified as CVS. Only the CVS and some mature Candidate sites will be used in quantitative assessment of algorithm performance for the beta release. A total of 11 CVS/Candidate were used in this assessment.

The key tool used in L2SMAP analyses is the chart illustrated by Figures 7.3.1 – 7.3.5. The charts show the comparison of the upscale in situ soil moisture observations with the coinciding soil moisture retrievals. These charts include a time series plot of upscaled *in situ* and retrieved soil moisture as well as flags that were triggered on a given day, an XY scatter plot of SMAP retrieved soil moisture compared to the average *in situ* soil moisture, and the quantitative statistical metrics. Each CVS/Candidate site is carefully reviewed and discussed by the L2SMAP Team and Cal/Val Partners. Systematic differences and anomalies are identified for further investigation. All sites are then compiled to summarize the metrics and compute the overall performance. Table 7.3.2, Table 7.3.3, and Table 7.3.4 give the overall results for the beta-release data set.

Table 7.3.1. SMAP Cal/Val Partner Sites Providing L2SMAP Validation Data

Site Name	Site PI	Area	Climate regime	IGBP Land Cover
Walnut Gulch*	M. Cosh	USA (Arizona)	Arid	Shrub open
Reynolds Creek**	M. Cosh	USA (Idaho)	Arid	Grasslands
Fort Cobb*	M. Cosh	USA (Oklahoma)	Temperate	Grasslands
Little Washita*	M. Cosh	USA (Oklahoma)	Temperate	Grasslands
South Fork*	M. Cosh	USA (Iowa)	Cold	Croplands
Little River*	M. Cosh	USA (Georgia)	Temperate	Cropland/natural mosaic
TxSON*	T. Caldwell	USA (Texas)	Temperate	Grasslands
Millbrook	M. Temimi	USA (New York)	Cold	Deciduous broadleaf
Kenaston*	A. Berg	Canada	Cold	Croplands
Carman***	H. McNairn	Canada	Cold	Croplands
Monte Buey*	M. Thibeault	Argentina	Arid	Croplands
Bell Ville	M. Thibeault	Argentina	Arid	Croplands
REMEDHUS*	J. Martinez	Spain	Temperate	Croplands
Twente	Z. Su	Holland	Cold	Cropland/natural mosaic
Kuwait	H. Jassar	Kuwait	Temperate	Barren/sparse
Niger	T. Pellarin	Niger	Arid	Grasslands
Benin	T. Pellarin	Benin	Arid	Savannas
Naqu	Z. Su	Tibet	Polar	Grasslands
Maqu	Z. Su	Tibet	Cold	Grasslands
Ngari	Z. Su	Tibet	Arid	Barren/sparse
MAHASRI	JAXA	Mongolia	Cold	Grasslands
Yanco*	J. Walker	Australia	Arid	Croplands
Kyeamba*	J. Walker	Australia	Temperate	Croplands
*=CVS used in assessment, **=Reynolds Creek, the length of record was too short due to snow cover				

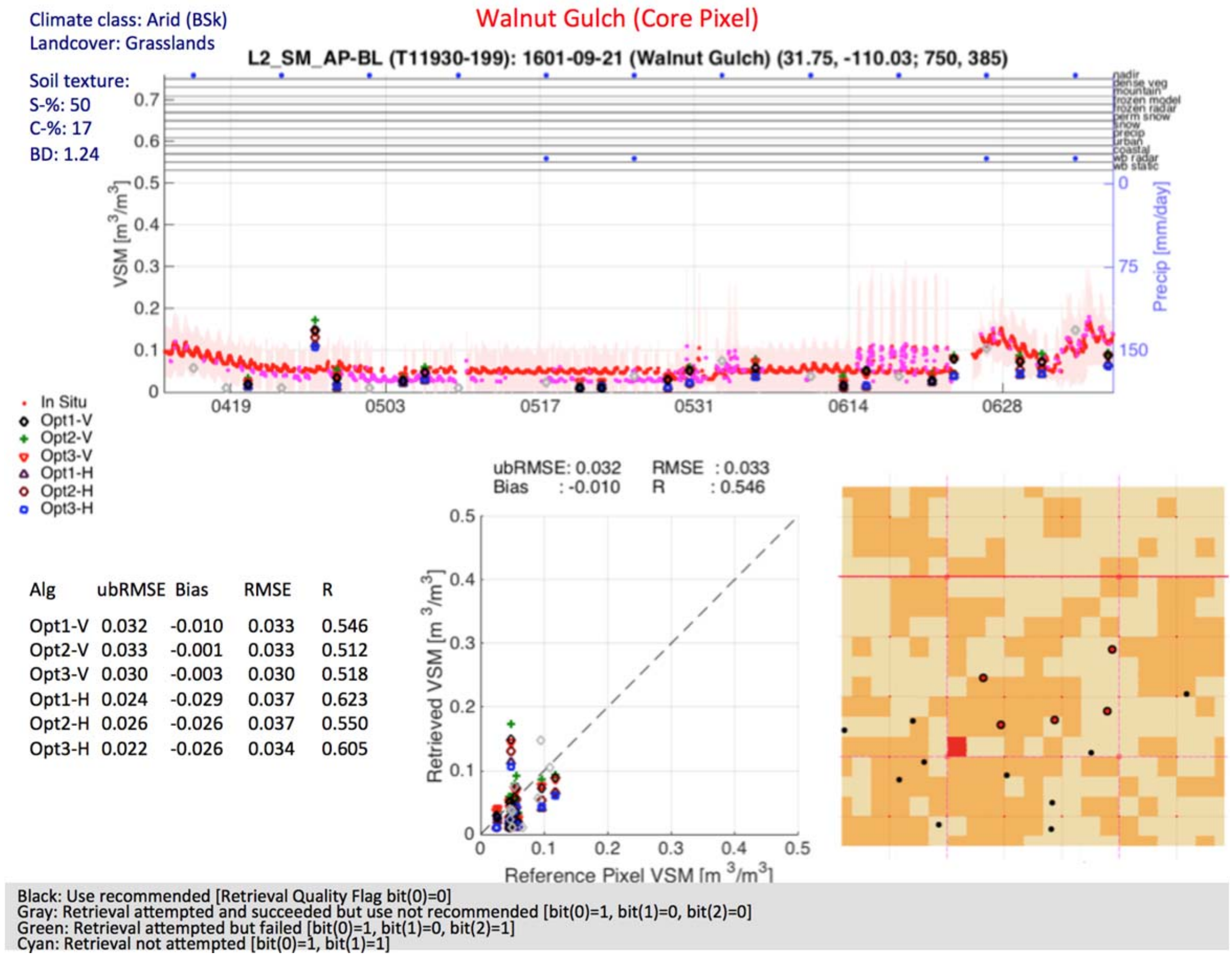


Figure 7.3.1. L2SMAP Assessment Tool Report for Walnut Gulch, Az.

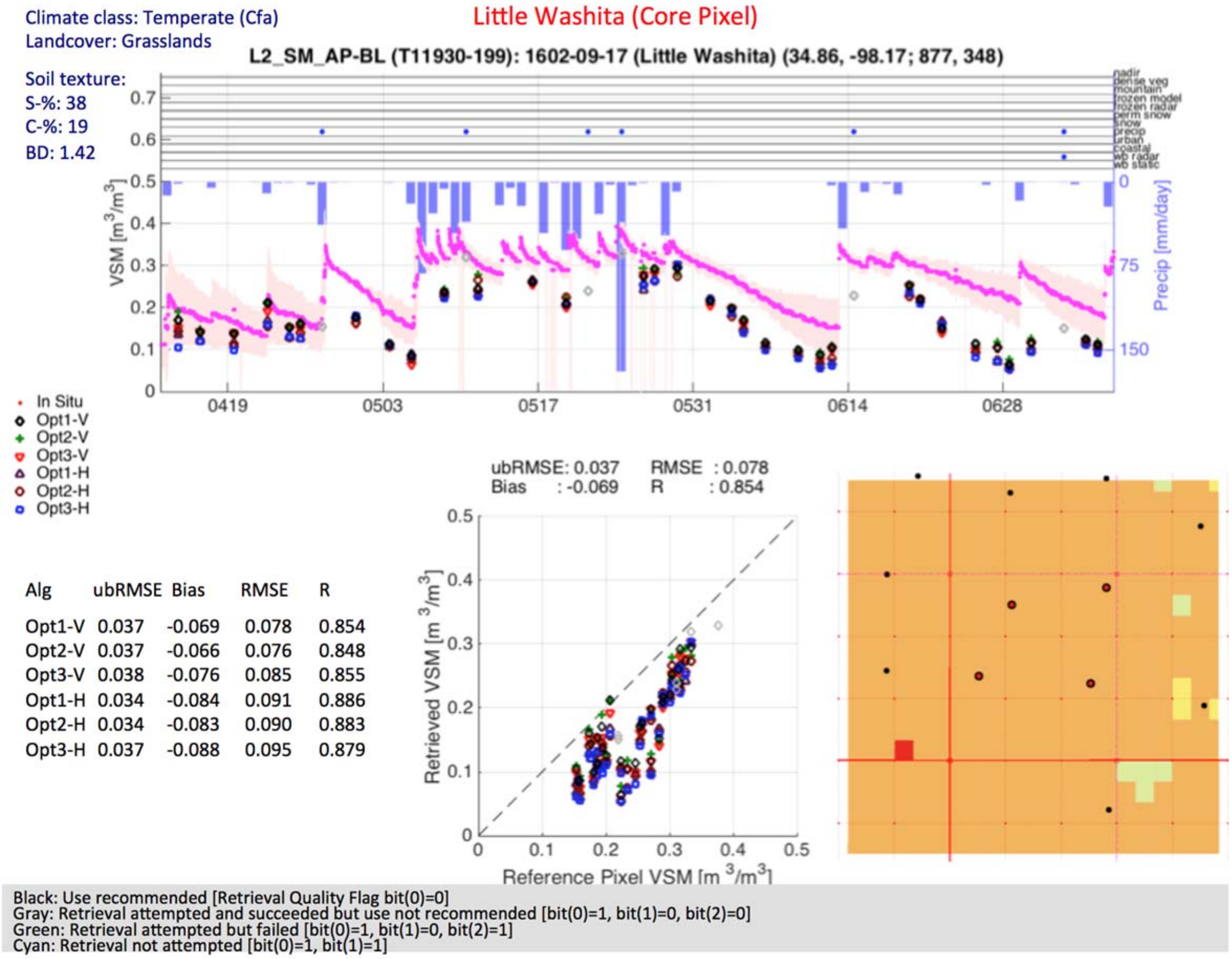


Figure 7.3.2. L2SMAP Assessment Tool Report for Little Washita, OK.

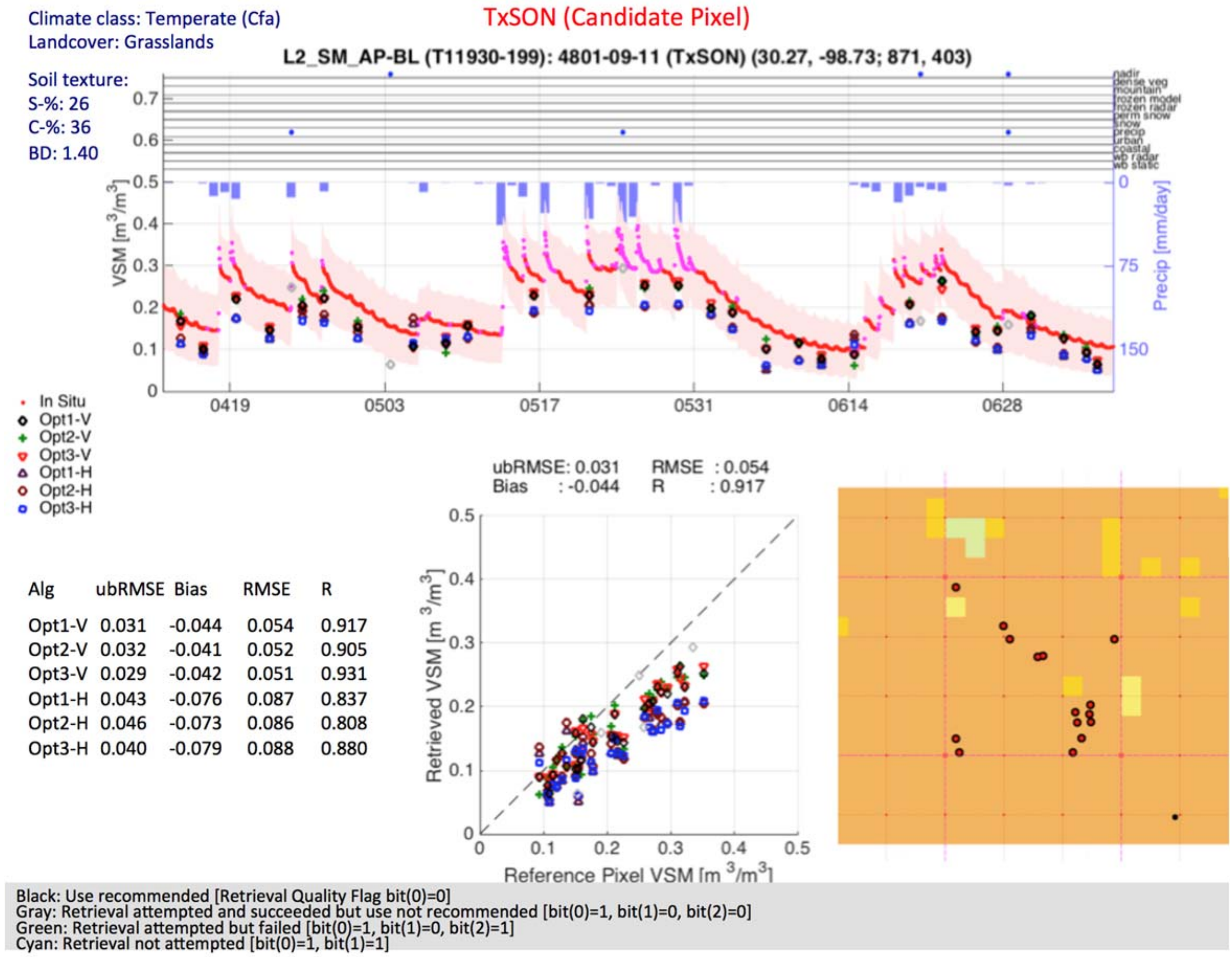


Figure 7.3.3. L2SMAP Assessment Tool Report for TxSON, TX.

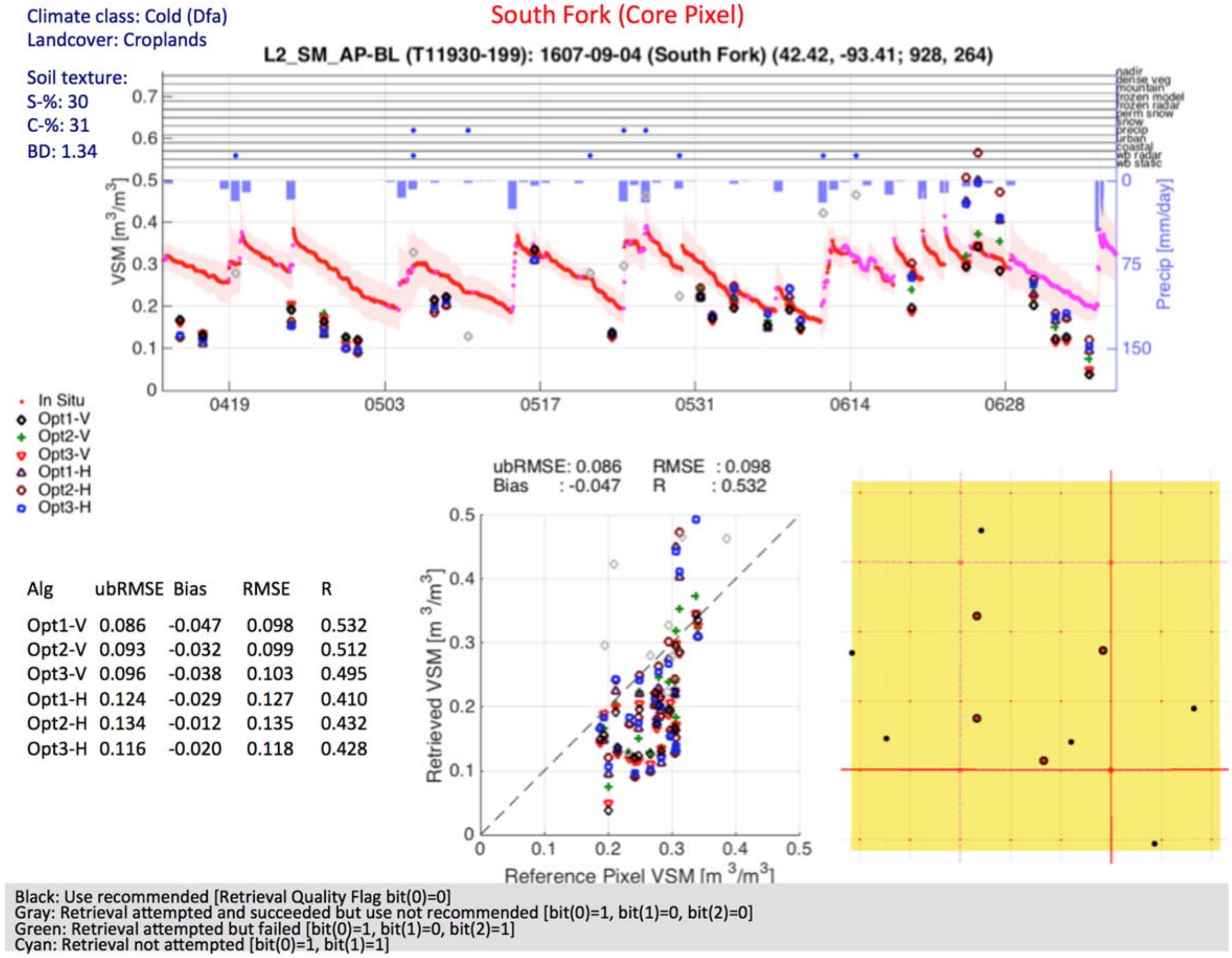


Figure 7.3.4. L2SMAP Assessment Tool Report for South Fork, IA.

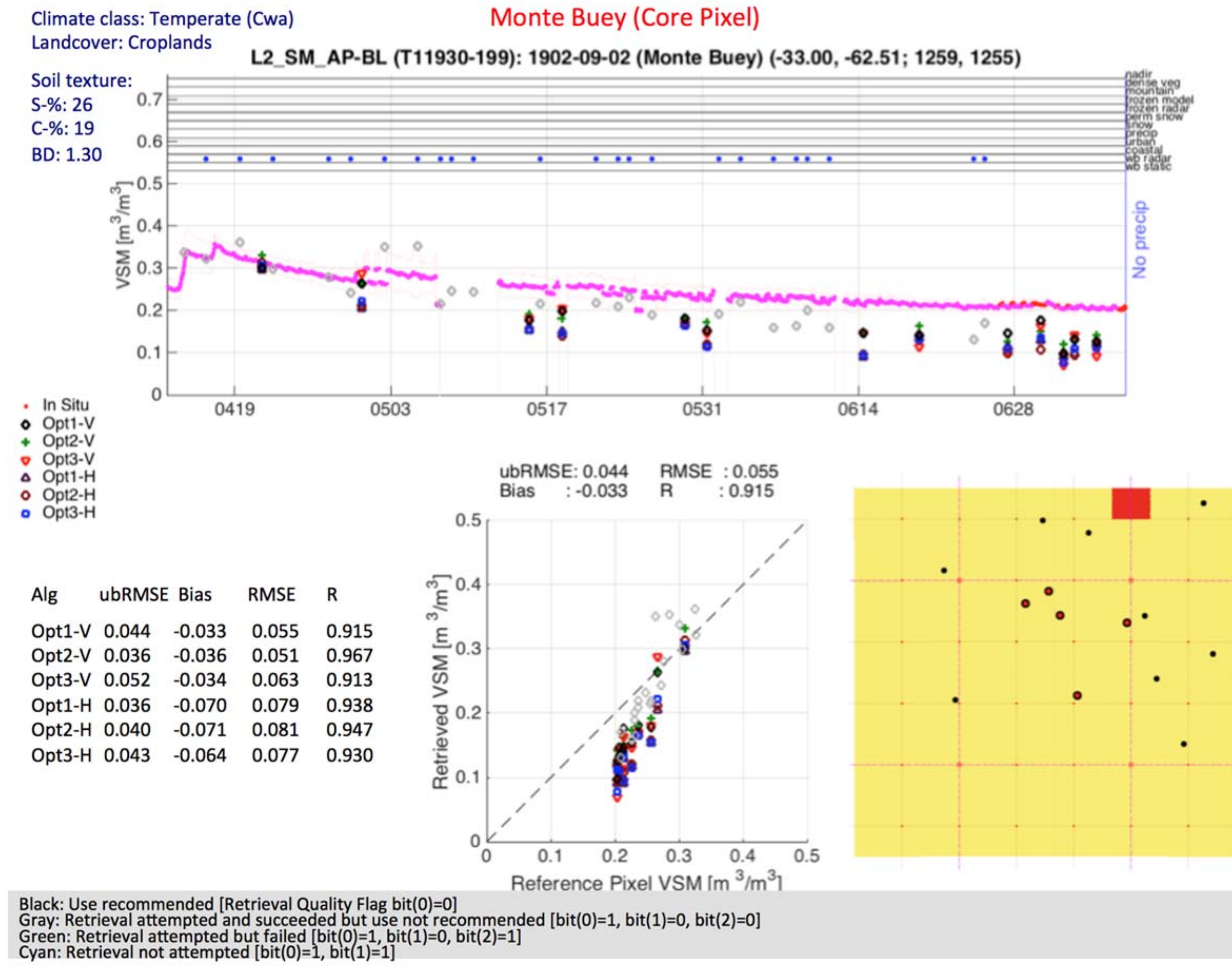


Figure 7.3.5. L2SMAP Assessment Tool Report for Monte Buey, Argentina.

Table 7.3.2. SMAP L2SMAP Beta Release CVS Assessment for Disaggregated TBVs at 9 km

	ubRMSE (m^3/m^3)			Bias (m^3/m^3)			RMSE (m^3/m^3)			R		
Site name	**Opt-1**	**Opt-2**	**Opt-3**	**Opt-1**	**Opt-2**	**Opt-3**	**Opt-1**	**Opt-2**	**Opt-3**	**Opt-1**	**Opt-2**	**Opt-3**
Walnut Gulch	0.021	0.028	0.018	-0.017	-0.010	0.011	0.027	0.030	0.021	0.858	0.819	0.882
TxSON	0.031	0.032	0.029	-0.044	-0.041	-0.042	0.054	0.052	0.051	0.917	0.905	0.931
Tonzi Ranch	0.025	0.022	0.025	-0.079	-0.037	-0.080	0.083	0.043	0.084	0.798	0.843	0.800
Little Washita	0.037	0.037	0.038	-0.069	-0.066	-0.076	0.078	0.076	0.085	0.854	0.848	0.855
South Fork	0.086	0.093	0.096	-0.047	-0.032	-0.038	0.098	0.099	0.103	0.532	0.512	0.495
Little River	0.035	0.036	0.037	0.090	0.112	0.086	0.096	0.118	0.094	0.799	0.784	0.782
Kenaston	0.049	0.052	0.044	-0.046	-0.057	-0.041	0.067	0.077	0.060	0.641	0.662	0.612
Monte Buey	0.044	0.036	0.052	-0.033	-0.036	-0.034	0.055	0.051	0.063	0.915	0.967	0.913
Valencia	0.031	0.028	0.031	-0.051	-0.024	-0.059	0.060	0.037	0.066	0.615	0.646	0.599
Yanco	0.081	0.080	0.076	0.053	0.063	0.033	0.097	0.102	0.083	0.771	0.778	0.797
SMAP Average	**0.044**	**0.045**	**0.0446**	**-0.045**	**-0.034**	**-0.040**	**0.0715**	**0.0685**	**0.071**	**0.770**	**0.776**	**0.766**
L2SMP Average	**0.041**			**-0.014**			**0.065**			**0.796**		
Averages are based on the values reported for each CVS												

Table 7.3.3. SMAP L2SMAP Beta Release CVS Assessment for Disaggregated TBHs at 9 km

	ubRMSE (m^3/m^3)			Bias (m^3/m^3)			RMSE (m^3/m^3)			R		
Site name	**Opt-1**	**Opt-2**	**Opt-3**	**Opt-1**	**Opt-2**	**Opt-3**	**Opt-1**	**Opt-2**	**Opt-3**	**Opt-1**	**Opt-2**	**Opt-3**
Walnut Gulch	0.024	0.026	0.022	-0.029	-0.026	0.026	0.037	0.037	0.034	0.546	0.512	0.518
TxSON	0.043	0.046	0.040	-0.076	-0.073	0.079	0.087	0.086	0.088	0.837	0.808	0.880
Tonzi Ranch	0.026	0.021	0.026	-0.097	-0.079	-0.094	0.101	0.081	0.098	0.808	0.891	0.792
Little Washita	0.034	0.034	0.037	-0.084	-0.083	-0.088	0.091	0.090	0.095	0.886	0.883	0.879
South Fork	0.124	0.134	0.116	-0.029	-0.012	-0.020	0.127	0.135	0.118	0.410	0.432	0.428
Little River	0.040	0.044	0.037	0.061	0.074	0.070	0.073	0.087	0.079	0.853	0.847	0.846
Kenaston	0.050	0.052	0.050	-0.087	-0.100	-0.079	0.100	0.112	0.093	0.733	0.729	0.707
Monte Buey	0.036	0.040	0.043	-0.070	-0.071	-0.064	0.079	0.081	0.077	0.938	0.947	0.930
Valencia	0.026	0.024	0.022	-0.086	-0.077	-0.086	0.090	0.081	0.089	0.674	0.688	0.643
Yanco	0.073	0.074	0.068	0.017	0.028	0.013	0.075	0.079	0.069	0.822	0.809	0.839
SMAP Average	**0.038**	**0.042**	**0.039**	**-0.073**	**-0.072**	**-0.042**	**0.086**	**0.087**	**0.084**	**0.751**	**0.755**	**0.746**
L2SMP Average	**0.044**			**-0.044**			**0.075**			**0.752**		
Averages are based on the values reported for each CVS												

Table 7.3.4. SMAP L2SMAP Beta Release CVS Assessment for Disaggregated TBV and TBH at 3km

	Ub-RMSE (m^3/m^3)		Bias (m^3/m^3)		RMSE (m^3/m^3)		R	
Sites	TBV	TBH	TBV	TBH	TBV	TBH	TBV	TBH
Walnut Gulch	0.030	0.043	-0.015	-0.020	0.033	0.024	0.389	0.147
TxSON	0.034	0.044	-0.078	-0.028	0.085	0.052	0.912	0.821
Tonzi Ranch	0.027	0.04	-0.068	-0.066	0.073	0.077	0.844	0.685
St Josephs	0.057	0.072	-0.038	-0.034	0.069	0.079	0.534	0.371
South Fork	0.119	0.099	-0.085	-0.119	0.0146	0.155	0.510	0.285
Little River	0.050	0.053	0.039	0.058	0.063	0.078	0.608	0.653
Kenaston	0.044	0.068	-0.081	-0.032	0.092	0.075	0.423	0.394
Monte Buey	0.045	0.076	-0.089	-0.062	0.100	0.098	0.791	0.746
Valencia	0.033	0.041	-0.081	-0.048	0.088	0.063	0.468	0.540
Yanco	0.060	0.063	-0.011	0.022	0.061	0.067	0.770	0.802
HOAL	0.059	0.057	-0.068	-0.029	0.091	0.064	0.182	0.202
SMAP Average	**0.051**	**0.060**	**-0.052**	**-0.032**	**0.070**	**0.075**	**0.59**	**0.51**
L2SMAP 9km	**0.044**	**0.038**	**-0.040**	**-0.073**	**0.071**	**0.086**	**0.77**	**0.75**
L2SMP	**0.041**	**0.044**	**-0.014**	**-0.044**	**0.065**	**0.075**	**0.79**	**0.75**

The key results for this assessment are summarized in the results in Table 7.3.2, Table 7.3.3, and Table 7.3.4 for the SMAP L2SMAP algorithms applied at 9 km and 3 km, respectively. Table 7.3.2 highlights the results for all options of disaggregated TBV at 9 km, Table 7.3.3 shows the results for all options of disaggregated TBH at 9 km, and Table 7.3.4 shows the results for all options of disaggregated TBH and TBV at 3 km. First, all option algorithms for L2SMAP at 9 km (Table 7.3.2 – 7.3.3) have about the same ubRMSE, and lesser than the all option algorithms for L2SMAP at 3 km (Table 7.3.4), and are very close to the SMAP mission goal of 0.04 m^3/m^3. Second, the correlations are also very similar. For both of these metrics the Option-1 algorithm for TBH at 9 km has slightly better values. All options shown in Table 7.3.2 – 7.3.4 underestimate the CVS soil moisture.

For guidance in expected performance and comparison, the L2SMP soil moisture products for each site over the same time period were also analyzed and these summary statistics are included in Table 7.3.2 – 7.3.4. The results are quite similar to the SMAP L2SMAP results for all metrics. In addition, this assessment is based on a limited time frame (~85 days). One obvious revealation is higher ubRMSE for the core validation sites that are located in agricultural domain. The primary reason for such behavior is the quality of vegetation attribiutes that are based on climatology, and used in soil moisture retrieval process. The climatology of vegetation attribute does not match with the reality because in the cropland landcover the planting date, the crop growth and phenology generally vary from year to year, and is primarily dependent on local weather conditons and status of rootzone soil moisture.

Based upon the metrics and considerations discussed, it is recommended that the L2SMAP Option-1 for TBV at 9 km be used as the baseline algorithm for the beta release because it has reasonable ubRMSE close to mission requirement, lower bias, lower RMSE and higher correlation as compared to all other options algorithms. Prior to the validated release, it is expected that additional investigations will be completed on parameter optimzation for all algorithms on which algorithm to designate as the SMAP L2SMAP baseline algorithm going forward.

7.4 Sparse Networks

The intensive CVS validation described above can be complemented by sparse networks as well as by new/emerging types of soil moisture networks. The current set of networks being utilized by SMAP as well as those planned for the future are listed in Table 7.4.1.

The defining feature of these networks is that the measurement density is low, usually resulting in one point per SMAP 9 km grid cell. 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 9 km grid cell.

SMAP Project has been evaluating methodologies for upscaling data from these networks to SMAP defined grid resolutions. A key element of the upscaling approach will be a method called Triple Co-location that combines the *in situ* data and SMAP soil moisture product with another independent source of soil moisture, likely to be a model-based product. However, Triple Co-location cannot be implemented for L2SMAP product because the data length of the product is too short. Therefore, we will not attempt to correct the upscaling error using Triple Co-location even in the validated product assessment.

Although limited by upscaling, sparse networks do offer many sites in different environments and are typically operational with very low latency. At this stage of validation, they are very useful as a supplement to the limited number of CVS.

Table 7.4.1. Sparse Networks Providing L2SMAP Validation Data

Network Name	PI /Contact	Area	Number of Sites	Status
NOAA Climate Reference Network (CRN)	M. Palecki	USA	110	Implemented
USDA Soil Climate Analysis Network (SCAN)	M. Cosh	USA	155	Implemented
GPS	E. Small	Western USA	123	Implemented
COSMOS	-	Mostly USA	53	Implemented
SMOSMania	J. Calvet	Southern France	21	Implemented
OZNet-Murrumbidgee	J. Walker	Australia	7	
Oklahoma Mesonet	C. Fiebrich	USA (Oklahoma)	120	
Pampas	M. Tiebault	Argentina	20	Implemented
South Africa	J. Qu	South Africa	18	

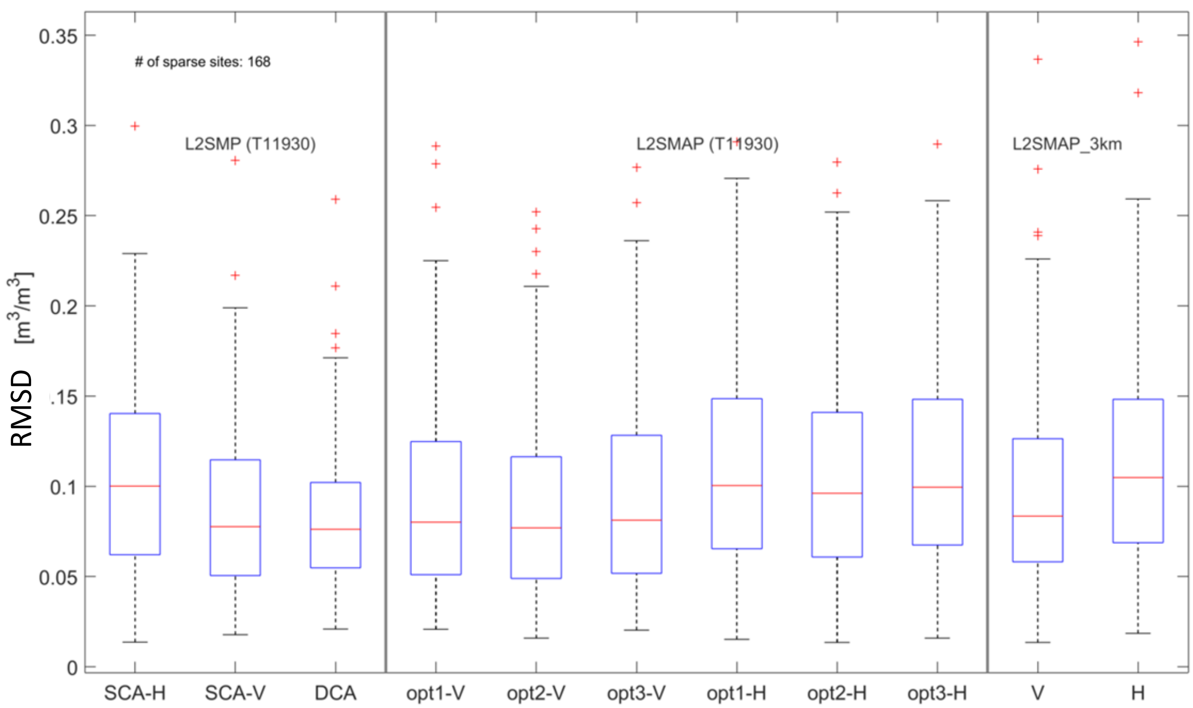
For the Beta release of L2SMAP product, retrievals available for over 200 global sparse network sites were compared with *in situ* observations. The sparse network metrics by direct one to one comparison classified by land cover types are shown in Table 7.4.2 and Table 7.4.3 for L2SMAP 9 km and 3 km products, respectively. No Triple Co-location method is used for the statistics presented in Table 7.4.2 and Table 7.4.3. Due to the short temporal coverage of L2SMAP product, correction of the validation metrics for the upscaling error contained in the point-scale in situ data will not be attempted. It should be noted that the validation metrics presented in this section based on sparse sites may be subject to negative impact by the upscaling error of the in situ data and therefore, appear to be poorer than the CVS results. Figure 7.4.1 cross-compares the metrics with L2SMP and L2SMAP (9 km and 3 km) products. Overall, the ubRMSD and bias values are similar to those obtained from the CVS. These results (Fig. 7.4.1) provide further confidence in the previous conclusions based on the CVS. In addition, the SMAP L2SMAP TBV Option-1 has one of the best overall ubRMSD and correlation as compared to all other options algorithms implemented at 9 km and 3 km.

Table 7.4.2: Statistics of L2SMAP (9 km) product comparison against 217 sparse network *in situ* sites.

	RMSD (m^3/m^3)						ubRMSD (m^3/m^3)						Bias (m^3/m^3)						R						
IGBP Class	OPT1_V	OPT2_V	OPT3_V	OPT1_H	OPT2_H	OPT3_H	OPT1_V	OPT2_V	OPT3_V	OPT1_H	OPT2_H	OPT3_H	OPT1_V	OPT2_V	OPT3_V	OPT1_H	OPT2_H	OPT3_H	OPT1_V	OPT2_V	OPT3_V	OPT1_H	OPT2_H	OPT3_H	N
Deciduous Broadleaf forest	0.057	0.075	0.111	0.057	0.075	0.157	0.015	0.026	0.024	0.034	0.044	0.038	0.054	0.069	0.108	0.039	0.048	0.151	0.811	0.643	0.769	0.037	0.056	0.128	2
Mixed forest	0.075	0.084	0.102	0.077	0.086	0.119	0.047	0.046	0.053	0.047	0.049	0.047	0.017	0.024	0.070	0.003	0.003	0.094	0.588	0.603	0.641	0.626	0.608	0.635	4
Open shrublands	0.052	0.052	0.052	0.057	0.055	0.056	0.038	0.037	0.038	0.033	0.033	0.033	-0.006	0.003	-0.005	-0.034	-0.027	-0.033	0.136	0.183	0.118	0.175	0.192	0.182	20
Woody savannas	0.110	0.106	0.115	0.122	0.121	0.126	0.049	0.047	0.049	0.046	0.046	0.048	-0.050	-0.029	-0.047	-0.079	-0.066	-0.068	0.620	0.683	0.630	0.683	0.721	0.693	13
Savannas	0.066	0.060	0.069	0.081	0.066	0.079	0.021	0.016	0.020	0.020	0.020	0.018	-0.052	-0.010	-0.059	-0.075	-0.052	-0.075	0.782	0.740	0.814	0.777	0.768	0.771	2
Grasslands	0.101	0.095	0.100	0.120	0.117	0.119	0.044	0.043	0.043	0.045	0.044	0.045	-0.080	-0.072	-0.080	-0.105	-0.101	-0.103	0.642	0.664	0.654	0.633	0.645	0.629	112
Croplands	0.114	0.113	0.115	0.135	0.136	0.135	0.057	0.057	0.057	0.069	0.070	0.067	-0.065	-0.056	-0.067	-0.065	-0.059	-0.065	0.600	0.605	0.594	0.548	0.554	0.542	37
Crop/Natural vegetation	0.094	0.089	0.093	0.109	0.104	0.105	0.052	0.052	0.051	0.055	0.055	0.054	-0.064	-0.050	-0.055	-0.084	-0.075	-0.073	0.624	0.611	0.628	0.615	0.604	0.629	24
Barren/Sparse	0.071	0.059	0.063	0.087	0.075	0.080	0.019	0.021	0.019	0.018	0.020	0.020	-0.068	-0.055	-0.060	-0.085	-0.072	-0.077	0.569	0.512	0.559	0.568	0.531	0.454	3
All	**0.097**	**0.093**	**0.098**	**0.114**	**0.111**	**0.114**	**0.046**	**0.045**	**0.046**	**0.049**	**0.048**	**0.048**	**-0.063**	**-0.053**	**-0.061**	**-0.084**	**-0.078**	**-0.078**	**0.586**	**0.602**	**0.591**	**0.572**	**0.581**	**0.571**	**217**

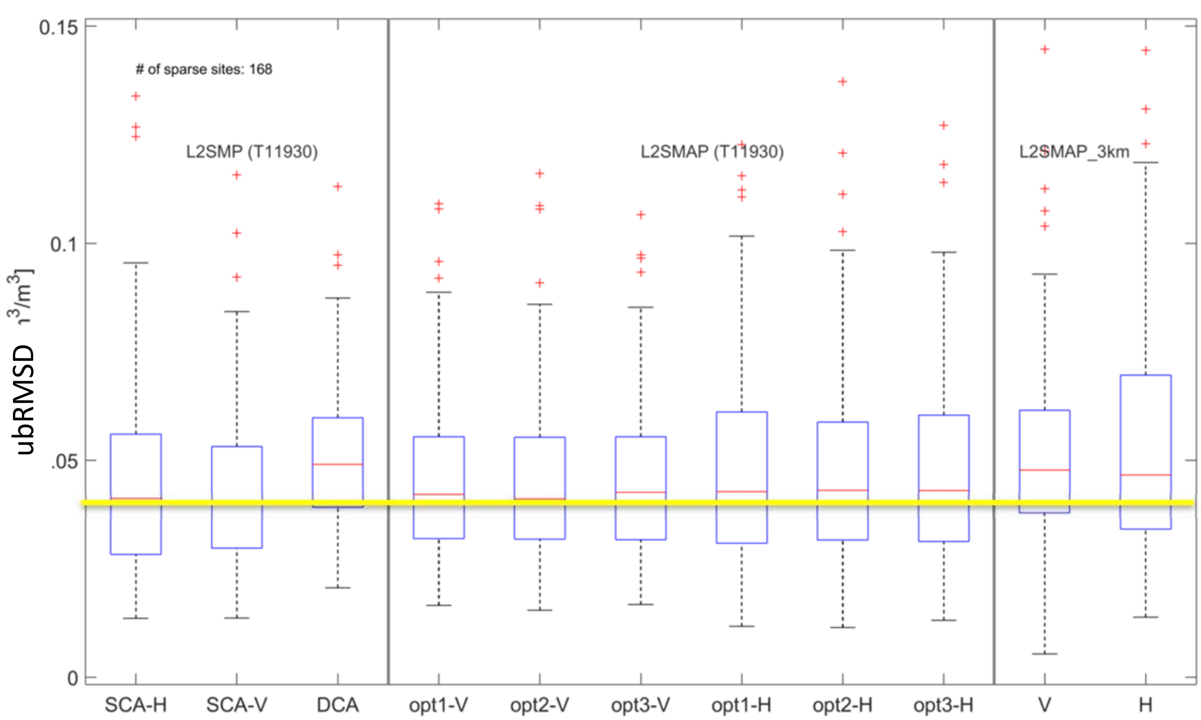
Table 7.4.3: Statistics of L2SMAP (3 km) product comparison against 226 sparse network *in situ* sites.

	RMSD (m^3/m^3)		ubRMSD (m^3/m^3)		Bias (m^3/m^3)		R		
IGBP Class	V	H	V	H	V	H	V	H	N*
Evergreen Needleleaf forest	0.135	0.132	0.060	0.052	-0.120	-0.121	0.347	0.577	2
Mixed forest	0.089	0.089	0.060	0.060	0.066	0.066	0.627	0.627	1
Open shrublands	0.061	0.066	0.038	0.033	-0.010	-0.039	0.172	0.188	21
Woody savannas	0.111	0.118	0.054	0.055	0.002	-0.024	0.578	0.612	15
Savannas	0.104	0.114	0.039	0.032	-0.033	-0.039	0.281	0.240	2
Grasslands	0.102	0.118	0.047	0.048	-0.073	-0.100	0.572	0.554	116
Croplands	0.131	0.146	0.067	0.071	-0.085	-0.092	0.541	0.530	41
Crop/Natural vegetation	0.116	0.147	0.058	0.058	-0.092	-0.126	0.517	0.553	21
Barren/Sparse	0.045	0.053	0.023	0.020	-0.015	-0.035	0.418	0.582	7
All-site Average	**0.104**	**0.119**	**0.050**	**0.051**	**-0.064**	**-0.087**	**0.515**	**0.518**	**226**



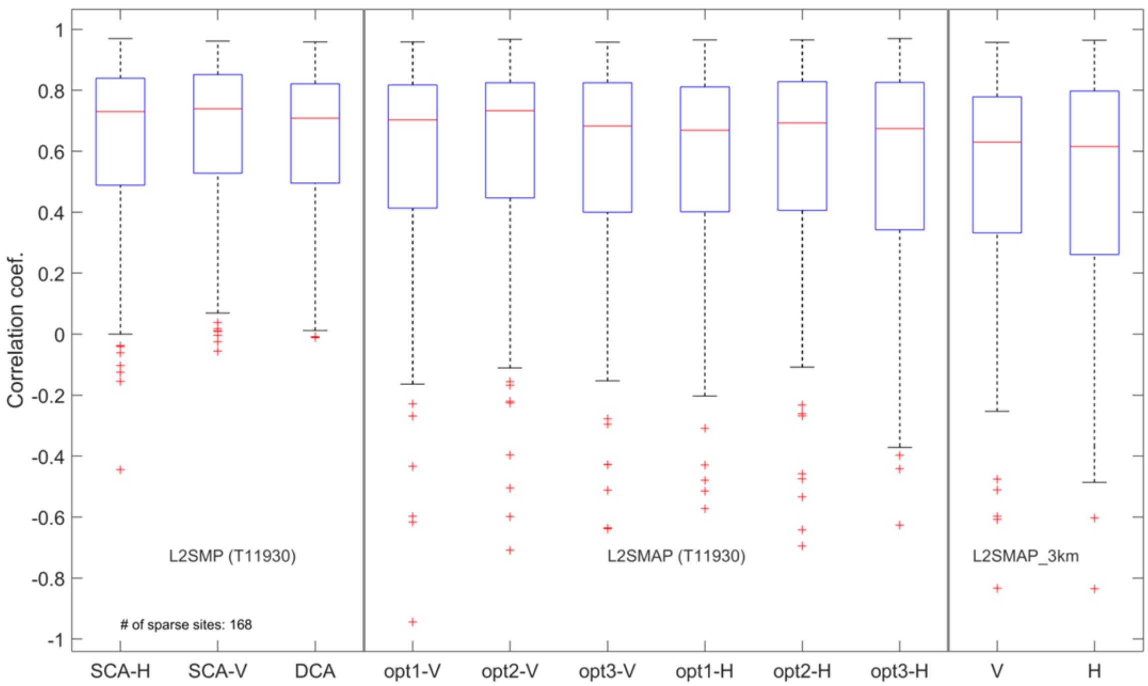
# of sparse sites: 168
L2SMP (T11930)
L2SMAP (T11930)
L2SMAP_3km
RMSD [m³/m³]
SCA-H
SCA-V
DCA
opt1-V
opt2-V
opt3-V
opt1-H
opt2-H
opt3-H
V
H

A)



# of sparse sites: 168
L2SMP (T11930)
L2SMAP (T11930)
L2SMAP_3km
ubRMSD
SCA-H
SCA-V
DCA
opt1-V
opt2-V
opt3-V
opt1-H
opt2-H
opt3-H
V
H

B)



C)

Figure 7.4.1. Results of comparison between L2SMAP with the sparse network sites (168 *in situ* sites): A) RMSE; B) unbiased RMSE; and C) Correlation for L2SMAP soil moisture retrievals for all algorithm options.

7.5 Consistency with L2SMP Product

Intercomparison of the SMAP L2SMAP soil moisture with the L2SMP soil moisture is useful in Cal/Val of L2SMAP because they uses the same radiative-transfer-model and base brightness temperature data in their respective algorithms.

For this intercomparison, the SMAP L3SMP data on a 36 km EASE2 grid are used. The soil moisture product from the descending pass (6 AM) is used to match the SMAP L3SMAP descending pass product. For comparison, the L2SMAP soil moisture at 9 km is averaged to 36 km EASE2 grid using a drop-in-a-bucket technique. Retrieval quality flags provided in the respective product files are applied to both L2SMAP and L2SMP to allow comparison of high quality soil moisture retrievals. The data available for whole L2SMAP period is used in this intercomparison. Figure 7.5.1 shows good agreement between L2SMAP and L2SMP soil moisture estimates for 8 days period. The differences in the L2SMAP and L2SMP are within the acceptable limit because soil moisture upscaling by averaging is not purely linear. Noticeable differences are visible over regions where more surface heterogeneity exist, for example over forest (Amazon, Congo basin), and sandy bare soil with rock outcrops (as visible in the Sahara Desert).

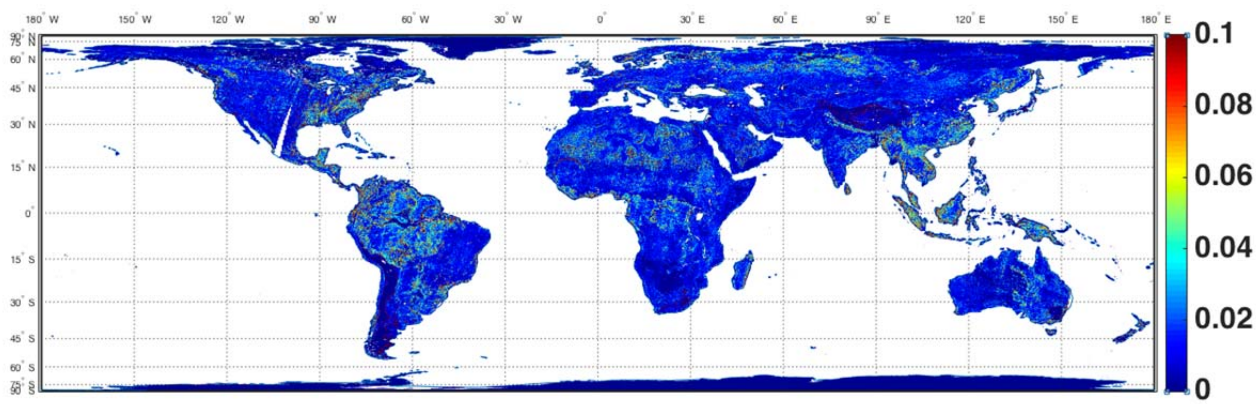


Figure 7.5.1. Comparison of L2SMAP and L2SMP soil moisture without using retrieval quality flags.

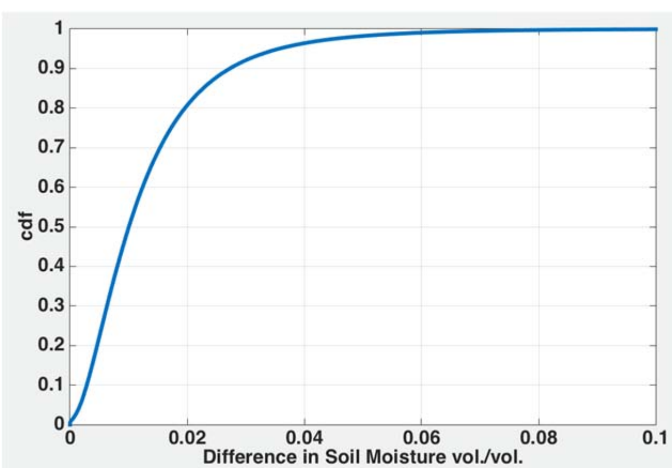


Figure 7.5.2. CDF of comparison of L2SMAP and L2SMP soil moisture without using retrieval quality flags.

7.6 Summary

Six alternative L2SMAP retrieval algorithms at 9 km and two L2SMAP algorithms at 3 km were evaluated using three methodologies in preparation for beta release. The algorithms included are Option-1 (TBV), Option-2 (TBV), Option-3 (TBV), Option-1 (TBH), Option-2 (TBH), Option-3 (TBH), L2SMAP (TBV) at 3 km, and L2SMAP (TBH) at 3 km.

For beta release the goal was to conduct a Stage 1 assessment based primarily on CVS comparisons using metrics and time series plots. These analyses indicated that the Option-1 (TBV), and Option-1 (TBH) have better and comparable unbiased root mean square errors (ubRMSE), bias, and correlation R than the rest of algorithms. However, Option-1 (TBV) has also one of the best performance in sparse network analysis. Based on the results, it is recommended that the Option-1 (TBV) be adopted as the baseline algorithm for the beta release. In the CVS analysis, the overall ubRMSE of the Option-1 (TBV) is 0.044 m^3/m^3, which is close to the mission requirement. It is expected that with availability of more Core/Candidate sites, further validation of all options of the L2SMAP algorithm will be refined and will lead to a final selection of baseline algorithm.

SMAP L2SMAP retrievals were also compared globally with the SMAP L2SMP retrievals. The agreement between the L2SMAP retrievals and the L2SMP retrievals is good. The observed differences are expected where more surface heterogeneity exists. These inter-comparisons indicated similar performance by some SMAP algorithms for the same land cover types.

8 OUTLOOK AND PLAN FOR VALIDATED RELEASE

Satellite passive microwave retrieval of soil moisture has been the subject of intensive study and assessment for approximately the past fifteen years. Over this time there have been improvements in the microwave instruments used, primarily in the availability of L-band sensors on orbit. However, sensor resolution has remained roughly the same over this period, which is actually an achievement considering the increase in sensor wavelength from X band to C band to L band over the years. With spatial resolution in the 25-50 km range using the radiometer only observations.

SMAP observatory is the first of its kind that delivered coincident and collocated measurements using a L-band radar and a L-band radiometer. This provides a unique opportunity to obtain the status of geophysical information such as soil moisture at a much higher spatial resolutions (3 km and 9 km) than done prior to SMAP. However, the higher resolution SMAP Active Passive product (L2SMAP) soil moisture retrievals require validation to assess its accuracy and uncertainty. It is expected that there will always be heterogeneity within the satellite footprint that will influence the accuracy of the retrieved soil moisture as well as its validation. Precipitation types and patterns are one of the biggest contributors to this heterogeneity. As a result, one should not expect that the validation metric ubRMSE will ever approach zero except in very homogeneous domains. Bias tends to be indicative of a systematic error, possibly related to algorithm parameterization and model structure. Quality data are needed to discover and address these systematic errors. Some issues that should be considered between the beta and validated release include the following:

- *Moving toward a Stage 2+ validated product.* The beta release is limited by the period of record (~85 days) available for L2SMAP product that is utilized in this assessment report. By the time of the validated release in Spring/Summer 2016, we expect to improve the algorithm parameters and the Tau-Omega model parameters, ultimately improving the absolute RMSE, bias and unbiased RMSE. With this, the L2SMAP validation should exceed Stage 2 and possibly achieve Stage 3.
- *Increasing the number of CVS.* There are a number of additional sites that may qualify as CVS. Several of these are only awaiting data delivery due to the once-per-year downloading of stations (Mongolia and Tibet). Others need processing by the providers (Twente, Niger, Benin, Barambadi).
- *Increasing the number of Sparse Networks.* Efforts are underway to complete the operational acquisition of all the networks listed in Table 7.4.1. There are other networks that exist but utilizing these may involve issues that cannot be addressed in the near term. However, these other networks will be considered if they offer a unique resource and require a reasonable effort to integrate.
- *Implementing Triple Co-Location as an assessment and algorithm improvement tool.* This technique has been used to assess satellite soil moisture products. It is currently implemented by SMAP; however, it requires a long record of observations (> 1 year) for objective assessment. However, in case of L2SMAP the data record is limited to ~85 days. Therefore the assessment by Triple co-location may not be optimal. Therefore this technique will not be implemented for validated data release.
- *Implementing Model-based Products as an assessment and algorithm improvement tool.* Model intercomparisons are one of the methodologies considered for SMAP L2SMAP. There are several readily available products that include the GMAO Nature Run, ECMWF, NCEP, and a Canadian Met Office product. One problem faced when using these model products is the depth of their surface layer, which is typically thicker than the 5 cm layer used by SMAP. Preliminary assessments suggest that the model responses may be dampened relative to satellite estimates.

Some effort is required to further evaluate this tool and how to utilize it in the validated assessment.

- *Incorporating Field Campaign results into algorithm assessment and improvement.* With the existing length of data record of L2SMAP, there is be no overlap of SMAP Active Passive observation with any airborne field campaign such as SMAPVEX15 in Arizona, SMAPEx in Australia, and upcoming field campaigns in 2016. However, the SMAP Active Passive algorithm was verified using past field campaign data from SMEX 2002 [6] and SMAPVEX 2012 [7].
- *Evaluate the impacts of algorithm structure and components on retrieval.* There are some aspects of soil moisture retrieval algorithms that are used because they facilitate operational soil moisture retrieval. One of these simplifying aspects is the use of the Fresnel equations that specify that conditions in the microwave contributing depth are uniform. While there is ample evidence that this is true in most cases, it should be recognized that this assumption is a potential source of error – some effort should be made to evaluate when and where it limits soil moisture retrieval accuracy. Another assumption is that a single dielectric mixing model applies under all conditions globally. Any of the commonly-used dielectric models is highly dependent on the robustness of the data set used in its development. The impact of this assumption on retrieval error needs further evaluation.
- *Optimization of algorithm parameters.* For the beta release the parameter set defined in the L2SMP ATBD was implemented. These parameters are mostly valid for 36 km resolution. For L2SMAP retrievals at 9 km and 3 km, the parameter may not be suitable because of scaling effects. It is hypothesized that by using time series observations, the algorithm parameters for each grid cell at 9 km or 3km can be optimized. The improvement in soil moisture retrieval accuracy gained by using these new optimized parameters can be evaluated using data from the *in situ* networks and CVS. In addition, systematic tuning of parameters will be evaluated prior to validated release.

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10 REFERENCES

[1] Committee on Earth Observation Satellites (CEOS) Working Group on Calibration and Validation (WGCV): http://calvalportal.ceos.org/CalValPortal/welcome.do and WWW: Land Products Sub-Group of Committee on Earth Observation Satellites (CEOS) Working Group on Calibration and Validation (WGCV): http://lpvs.gsfc.nasa.gov

[2] SMAP Level 1 Mission Requirements and Success Criteria. (Appendix O to the Earth Systematic Missions Program Plan: Program-Level Requirements on the Soil Moisture Active Passive Project.). NASA Headquarters/Earth Science Division, Washington, DC, version 5, 2013.

[3] Dara et al., "Algorithm Theoretical Basis Document (ATBD): L2/3_SM_AP," Initial Release, v.3, October 1, 2015. Available at http://smap.jpl.nasa.gov/science/dataproducts/ATBD/

[4] Entekhabi, D., S. Yueh, P. O'Neill, K. Kellogg et al., SMAP Handbook, JPL Publication JPL 400-1567, Jet Propulsion Laboratory, Pasadena, California, 182 pages, July, 2014.

[5] Das, N. N., D. Entekhabi, E. Njoku, J. Shi, J. Johnson, and A. Colliander, "Tests of the SMAP combined radar and radiometer algorithm using airborne field campaign observations and simulated data," IEEE Transactions on Geoscience and Remote Sensing, vol. 52, pp. 2018–2028, 2014.

[6] Das, N. N., D. Entekhabi, S. Dunbar, E. G. Njoku, and S. Yueh, "Uncertainty Estimates in the SMAP Combined Active-Passive Downscaled Brightness Temperature," IEEE Transactions on Geoscience and Remote Sensing, IEEE Transactions on Geoscience and Remote Sensing, In Press.

[7] Adams, J. R., McNairn, H., Berg, A. A., and Champagne, C. Evaluation of near-surface soil moisture data from an AAFC monitoring network in Manitoba, Canada: Implications for L-band satellite validation. Journal of Hydrology 521: 82-592, 2015.

[8] Choudhury, B. J., Schmugge, T. J., and Mo, T. A parameterization of effective soil temperature for microwave emission. J. Geophys. Res., 87: 1301-1304, 1982.

[9] Science Data Calibration and Validation Plan Release A, March 14, 2014 JPL D-52544.