

# **Soil Moisture Active Passive (SMAP) Project Assessment Report for the L2SMSP Version 3 Release Data Products**

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# 1 EXECUTIVE SUMMARY

NASA's Soil Moisture Active Passive (SMAP) mission was launched on January 31<sup>st</sup>, 2015. SMAP has an L-band radiometer and an L-band radar. The SMAP radiometer and radar shared a rotating 6-meter mesh reflector antenna. On 7<sup>th</sup> July 2015, the SMAP radar malfunctioned, and is currently inoperable. Since then the SMAP project explored ways to recover the high-resolution soil moisture capability of the SMAP mission. Specifically use of other active microwave measurements based on other satellites was investigated. Global coverage, availability of data and microwave channel wavelength were among the trade-offs considered in selecting other sources of active radar measurements. The Copernicus Project Sentinel-1A/1B synthetic aperture radar (SAR) data are found to be suitable for this purpose since Sentinel has a similar orbit configuration that provides overlap with the SMAP swath and minimizes the time difference, which is key to the SMAP active-passive algorithm. The global coverage based on both Sentinel-1A and Sentinel-1B are the best among available SAR systems. The Sentinel acquisition mode provides the co-pol and cross-pol observations required for the SMAP active-passive algorithm. Some differences do exist between the SMAP SAR data and Sentinel SAR data that include: 1) Sentinel has C-band SAR and SMAP had an L-band SAR; 2) Sentinel has multi incidence angles within its swath, whereas SMAP had a single incidence angle; and 3) Sentinel swath width is ~250 km as compared to SMAP 1000 km swath width. With regard to the last point, the SMAP and Sentinel overlap covers only ~250 km within the 1000 km swath width of the SMAP observations. Therefore, the temporal resolution (revisit interval) for the SMAP active-passive data is degraded from 3 days to 12 days when Sentinel 1A/1B data are used. One advantage of using Sentinel-1A/1B data in the SMAP active-passive algorithm is the potential of obtaining the disaggregated brightness temperature and soil moisture at much finer spatial resolutions ( $\leq 3$  km) with reasonable accuracy.

This document describes the assessment of the SMAP-Sentinel Level 2 Soil Moisture Active-Passive (L2SMSP) product for the Version-3 Release. The SMAP L2SMSP product is available from 1<sup>st</sup> May 2015 to present. The L2SMSP product replaces the SMAP L2SMAP product that was discontinued due to lack of SMAP radar data

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 science requirements of the SMAP mission.

To achieve the abovementioned objectives, assessment of the L2SMSP product is essential. Assessment methodologies utilized include comparisons of SMAP L2SMSP high-resolution disaggregated brightness temperatures with airborne L-band microwave remote sensing data and high-resolution soil moisture retrievals with *in situ* soil moisture observations from core validation sites (CVS) and sparse network. These analyses meet some of the standards established by the Committee on Earth Observing Satellites (CEOS) Stage 2 validation [1], which supports this Version-3 Release of the data based on a limited set of CVS.

The SMAP-Sentinel active-passive algorithm disaggregates the coarse resolution SMAP radiometer-based brightness temperature ( $T_B$ ) and soil moisture by using the finer spatial resolution of the Sentinel radar (SAR) data and parameters derived from a relationship between the brightness temperature and SAR data. The implementation of the L2SMSP algorithm is elaborated further in a subsequent section.

The disaggregated high-resolution brightness temperatures from the SMAP-Sentinel active passive algorithm are subjected to a radiative transfer model to retrieve soil moisture. Analyses showed that some refinements of parameters were required for the radiative transfer model (tau-omega) single channel algorithm (SCA). During the initial validation the tau-omega parameters used to generate the L2SMSP product are similar to the parameters applied in the SCA of the SMAP Level 2 Soil Moisture Passive

(L2SMP/L2SMP\_E) product. This implementation is important to maintain consistency with the SMAP L2SMP/P\_E product.

The L2SMSP product uses the Sentinel-1A/1B SAR data to disaggregate SMAP L-band radiometer measurements from the ~33 km (enhanced resolution) radiometer measurement to a 3 [km] and 1 [km] gridded products. The C-band SAR data adds spatial information to the radiometer product. It also adds the noise associated with radar measurements (instrument noise, complex surface scattering, etc.). It is expected that the spatial features in the L2SMSP product to be at higher resolution than the SMAP Level 2 Soil Moisture Passive (L2SMP/L2SMP\_E) product. But the temporal behavior of the L2SMSP product is defined by the revisit interval of Sentinel-1A/B overpasses. The temporal and spatial characteristics affects the assessments based on different ground-based data sources.

The assessment of the L2SMSP product for initial validation was primarily done using comparison statistics and time series plots with high-resolution airborne-based L-band data (as reported in previous version of assessment report), and the SMAP CVS data. Each of these assessment approaches has advantages as well as shortcomings.

The CVS are time-series of in situ stations within SMAP grids that have been spatially averaged. They thus have no information on the spatial patterns of surface soil moisture but should be robust indicators of the temporal changes in soil moisture. In this respect the CVS are not indicative of the spatial resolution advantages of L2SMSP. The temporal statistics should be equal but not appreciably worse when comparing L2SMP\_E versus CVS match-up time series and comparing L2SMSP versus CVS match-up time-series.

The spatial resolution performance of the L2SMSP can only be assessed with more complete ground sampling which is possible only with airborne field campaigns. These experiments provide a unique opportunity to demonstrate the spatial resolution advantages of L2SMSP when compared to L2SMP\_E. We use available airborne data sets in previous assessment report. However airborne field campaigns are performed over short periods and sporadically. So comparisons of temporal statistics are not possible with these data sources for assessment.

**For this Version of L2SMSP data, no sparse network comparison is not conducted before the release because of lack of availability of the L2SMSP data over the sparse network sites. The sparse network analysis description and statistics will be updated contingent upon availability of the latest version of the L2SMSP data in the repository after completion of R17 reprocessing in the JPL Ops.**

These analyses indicated that the SMAP-Sentinel active-passive algorithm implemented at 3 km to obtain disaggregated brightness temperatures at V-pol and subsequent soil moisture retrievals had reasonable unbiased root-mean-square errors (ubRMSE), bias, and correlation. The overall ubRMSE of the L2SMSP product is ~0.048 m<sup>3</sup>/m<sup>3</sup>. Based on these assessments, the Version-3 of the L2SMSP 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.

The science and application communities should take certain caveats into consideration before using the L2SMSP product. There is a tradeoff between adding spatial resolution with C-band SAR data and noise-levels. The L2SMSP high resolution (3 km) comes at a cost of degradation in temporal statistics of disaggregated brightness temperature and retrieved soil moisture. Whereas the more spatially-averaged L2SMP\_E product may have less temporal noise and temporal uncertainty when compared to L2SMSP, the L2SMSP will have more spatial resolution in term of resolving sharp and large-contrast features below the radiometer resolution. The degradation in accuracies is mainly imparted due to: 1) difficulties in comprehensively characterizing the active radar signal interactions with land surface components, 2) the uncertainties in the active-passive algorithm parameters used in the disaggregation of brightness temperature, and 3) the random errors and biases in the static and dynamic ancillary data used for soil moisture retrievals. The high resolution L2SMSP product captures the spatial details and patterns of soil moisture that are not present in the SMAP radiometer-only enhanced product (L2SMP\_E). Therefore, those

users of SMAP data who require more frequent revisit and temporal accuracy can use the L2SMP\_E product (which is posted at 9 km), and those users who need high resolution soil moisture patterns and details with slightly degraded accuracy and less frequent revisit can use L2SMSP data (posted at 3 km) for their science studies and geophysical applications.

The Version-3 of the L2SMSP product is made available to the public in September 2020.

## 2 OBJECTIVES OF CAL/VAL

During the post-launch cal/val 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 for Version-3 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].

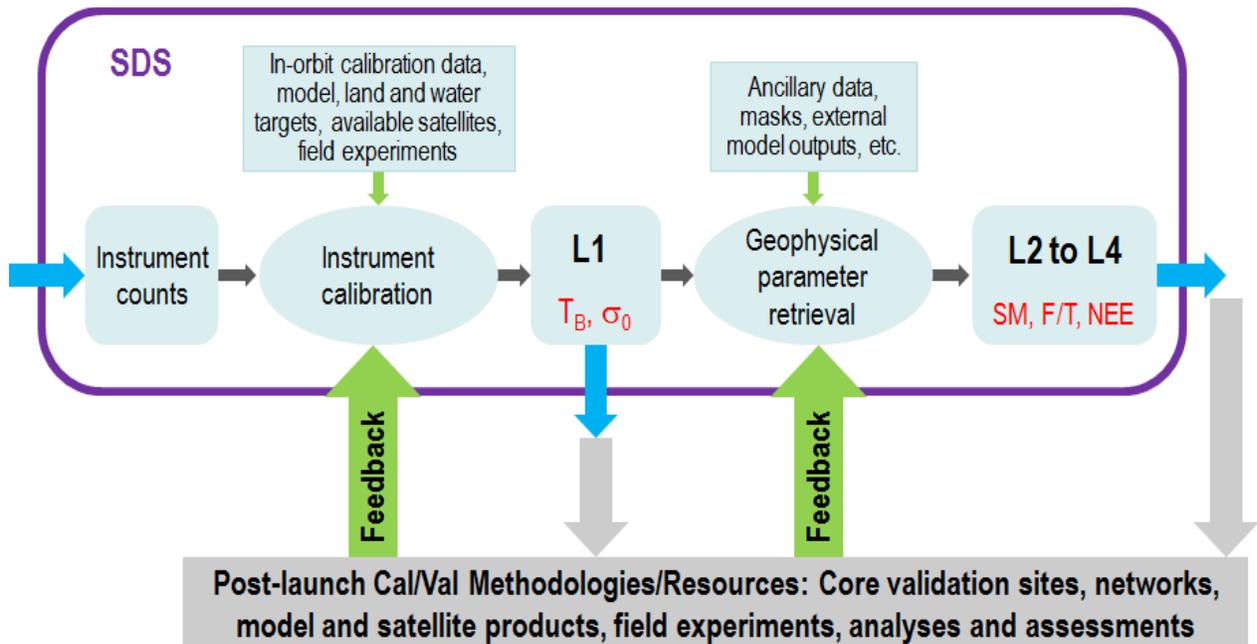


Figure 2.1. Overview of the SMAP Cal/Val Process.

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 maturity of the L2SMSP products in the Version-3 Release is defined as follows:

- All users conducting research and studies can use this Release.
- The product is validated using airborne data L-band data and core validation sites.

- The general research community is encouraged to participate in the quality assessment and validation of this product, but should be aware that product quality improvement is an ongoing process.
- Data may be used in publications. Users are urged to contact Science Team representatives if they have any question regarding the data for publications.
- The estimated uncertainties are documented in the product.

In assessing the maturity of the L2SMSP product, the L2SMSP 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 Version-3 Release the L2SMSP team has completed CVS and airborne data comparison assessment. The Cal/Val and the Algorithm/Science Team will keep working to improve the L2SMSP product.

### 3 BRIEF INTRODUCTION OF THE SMAP-SENTINEL ACTIVE-PASSIVE ALGORITHM

The legacy SMAP Active-Passive algorithm [4] is shown in Eq. 3.1:

$$T_{B_p}(M_j) = T_{B_p}(C) + \beta(C) \cdot \{[\sigma_{pp}(M_j) - \sigma_{pp}(C)] + \Gamma \cdot [\sigma_{pq}(C) - \sigma_{pq}(M_j)]\} \quad (3.1)$$

where,  $T_{B_p}(C)$  [K] is the radiometer-based brightness temperature at coarse resolution ( $\sim 36$  km). The radar backscatter aggregated to coarse-resolution is  $\sigma_{pp}(C)$  [dB] and  $\sigma_{pq}(C)$  [dB], co-pol and x-pol, respectively. The radar backscatters  $\sigma_{pp}(M)$  [dB] and  $\sigma_{pq}(M)$  [dB] are at the desired high-resolution (3 km or 9 km).  $\beta(C)$  [K/dB] and  $\Gamma$  [-] are parameters of the algorithm. The parameter  $\beta(C)$  represents the co-variation between  $T_{B_p}(C)$  and  $\sigma_{pp}(C)$  of the SMAP radiometer and radar observations, respectively, and the parameter  $\Gamma$  represents the heterogeneity within the coarse resolution that is detected by the high-resolution  $\sigma_{pp}(M)$  and  $\sigma_{pq}(M)$  observations. The parameter  $\beta(C)$  can be statistically estimated based on a time-series regression using pairs of SMAP radiometer  $T_{B_p}(C)$  and spatially-averaged radar data  $\sigma_{pp}(C)$  from successive overpasses over the same Earth grid are used in the statistical linear time-series regression  $T_{B_p}(C) = \text{intercept} + \text{slope} \cdot \sigma_{pp}(C)$ . Clearly these parameters are effective across scale  $C$ .  $\Gamma$  is estimated as  $\equiv \left[ \frac{\partial \sigma_{pp}(M_j)}{\partial \sigma_{pq}(M_j)} \right]_C$ .  $\Gamma$  is specific to the particular grid cell  $C$ . It is estimated based on the collection of co-polarization and cross-polarization radar backscatter cross-section within each grid cell  $C$ . Complete description of the algorithm is available in [3] and [4].

The SMAP-Sentinel Active-Passive algorithm draws heavily from the abovementioned algorithm. Eq. 3.1 is now modified to work in emissivity space instead of brightness temperature space and the Sentinel backscatter are in linear scale [-]. Certain aspects of implementation are changed to make it more effective and applicable to accommodate the 12 days revisit interval of the Sentinel satellite. This modification is essential as with the 12 days Sentinel revisit the  $T_{B_p}(C)$  and  $\sigma_{pp}(C)$  time series is too sparse, and this makes the parameter estimation through time series approach ineffective. Therefore, a snapshot retrieval approach [5] is adopted to estimate the co-variation parameter from the SMAP radiometer and the Sentinel radar observations. The SMAP-Sentinel Active-Passive algorithm used in the L2SMSP product is shown in Eq. 3.2:

$$T_{B_p}(M_j) = \left[ \frac{T_{B_p}(C)}{Ts} + \beta'(C) \cdot \{[\sigma_{pp}(M_j) - \sigma_{pp}(C)] + \Gamma \cdot [\sigma_{pq}(C) - \sigma_{pq}(M_j)]\} \right] \cdot Ts \quad (3.2)$$

where,  $Ts$  [K] is the effective surface temperature of the top  $\sim 5$  cm of the soil profile. The parameter  $\Gamma$  [-] is estimated the same way as mentioned above, however, in a linear scale. The parameter  $\beta'(C)$  [-] is estimated in a snapshot approach because the Sentinel revisit interval of 12 days makes the time series of the Sentinel  $\sigma_{pp}(M)$  [-] and  $\sigma_{pq}(M)$  [-] data very sparse. The snapshot  $\beta'(C)$  is shown in Eq. 3.2:

$$\beta'(C) = \frac{\frac{T_{Bp}(C)}{T_s} - (\gamma + (1 - \omega)(1 - \gamma))}{|S_{pp}(M_j)|^2 - \mu_{pp-pq} \cdot |S_{pq}(M_j)|^2} \quad (3.3)$$

where,  $\omega$  [-] is the effective single scattering albedo,  $\gamma = e^{-\tau/\cos\theta}$  [-] is the vegetation loss term, and  $\theta_i$  [rad] is the incidence angle. The nadir vegetation opacity  $\tau$  [-] is related to the physical characteristics of the vegetation layer, such as the vegetation water content (VWC).  $|S_{pp}(M_j)|^2$  is co-polarized backscatter, where  $|S_{pp}(M_j)|^2 \equiv \sigma_{pp}(M_j)$ , and  $|S_{pq}(M_j)|^2$  is cross-polarized backscatter, where  $|S_{pq}(M_j)|^2 \equiv \sigma_{pq}(M_j)$ .  $\mu_{pp-pq}$  is the same as  $\Gamma$  of Eq. 3.2, except using a linear regression of backscattering coefficients ( $\sigma_{pp}(M_j)$  [-],  $\sigma_{pq}(M_j)$  [-]) at fine scale (3 km) within each coarse-resolution TB grid cell ( $T_{Bp}(C)$ ). Detailed derivation of Eq. 3.3 is elaborated in [5]. In a nutshell,  $\beta'(C)$  is formed by eliminating surface reflectivity between emission and backscatter equations. This physically-based Eq. 3.3 to retrieve  $\beta'(C)$  also accounts for the effects of vegetation/roughness on emission as well as on backscatter. This approach to derive physically-based  $\beta'(C)$  does not require any time series of  $T_{Bp}(C)$  and  $\sigma_{pp}(C)$ . For evaluation of  $\beta'(C)$  retrieved in snapshot approach, a comparison was made with  $\beta(C)$  derived from the time series purely obtained from data of the SMAP mission. Both approaches converge with the  $\beta'(C)$  values almost similar to  $\beta(C)$  as shown in Fig. 3.1, except over locations where the time series do not have significant correlations, i.e., the dynamic range of  $T_{Bp}(C)$  and  $\sigma_{pp}(C)$  is not observed, especially over very arid regions.

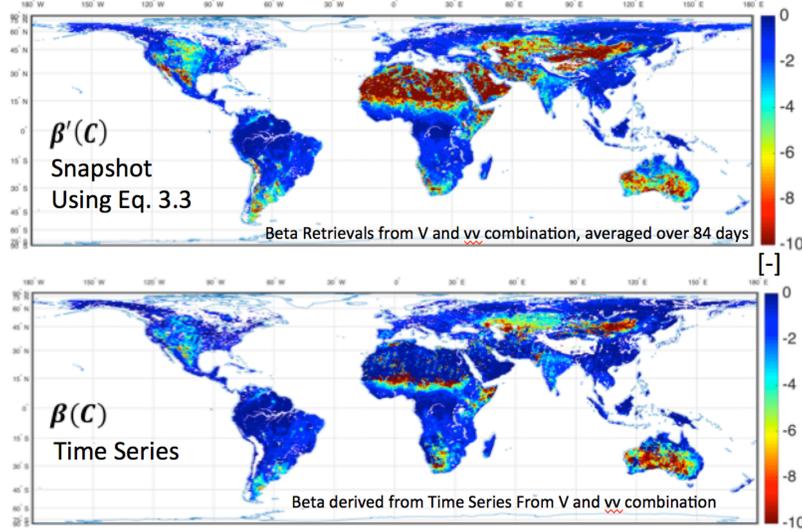


Figure 3.1: Comparison plot  $\beta'(C)$  and  $\beta(C)$  at global extent for  $\sim 2.5$  months period.

Equation 3.2 is a disaggregation of brightness temperature. A similar formulation can also be used to disaggregate soil moisture  $\Theta(C)$  [ $\text{m}^3/\text{m}^3$ ] retrieved from coarse resolution brightness temperature  $T_{B_p}(C)$ . Equation 3.4 is the soil moisture disaggregation:

$$\Theta(M_j) = \Theta(C) + \beta''(C) \cdot \{[\sigma_{pp}(M_j) - \sigma_{pp}(C)] + \Gamma \cdot [\sigma_{pq}(C) - \sigma_{pq}(M_j)]\} \quad (3.4)$$

where,  $\Theta(M_j)$  [ $\text{m}^3/\text{m}^3$ ] is the disaggregated soil moisture at desired high-resolution, and the backscatter terms and parameter  $\Gamma$  are exactly same as Eq. 3.2. However, the parameter  $\beta''(C) = -1.3 \cdot \beta'(C)$ .

The algorithms (Eq. 3.2 and Eq. 3.4) operate on a coinciding coarse resolution EASE grid (33 km) over a fine resolution EASE grids of 3 km. The EASE grid resolution of 33 km is used to make the L2SMSP algorithms compatible with the spatial resolution (support scale) of  $T_{B_p}(C)$  and  $\Theta(C)$  available through the L2SMP\_E product. The grid topologies are described in detail in Section 5. A more complete description of the SMAP-Sentinel active-passive algorithms will be available in the ATBD.

## 4 IMPACT OF L1C RADIOMETER DATA AND SENTINEL RADAR DATA ON L2SMSP

The L2SMSP soil moisture retrievals are based on the Validated Release versions of the radiometer Level 1C brightness temperature (L1CTB\_E Version 3) data gridded at 9 km, L2SMP\_E (Version 1) retrieved soil moisture data gridded at 9 km, and Sentinel High-Resolution Radar backscatter data gridded at 1 km. The primary inputs to L2SMSP processing are L1CTB\_E vertical polarization (V pol) brightness temperature data that are corrected for the presence of water bodies available through L2SMP\_E, co- (vv) and cross- (vh) polarized Sentinel radar backscatter data gridded to EASE2 resolution at 1 km (averaged to 3 km during the algorithm processing), and relevant quality flags from L2SMP\_E. A detailed assessment of the data qualities of L1CTB\_E and L2SMP\_E are available at NSIDC, from which the material in this section is drawn.

Table 4.1 lists the contribution of error sources to the disaggregated brightness temperature at 3 km resulting from inputs available through L2SMP\_E and Sentinel data for the algorithm [3, 4, and 5]. The first numbered row in Table 4.1 is the estimated error in the L1CTB\_E (~33 km) which is due to the instrument, geophysical contributions to Earth surface brightness temperatures, and the gridding process. 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 0.7 K. The errors due to misspecification 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 the 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 in 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 4.1. Error budget for L2SMSP brightness temperature at 3 km.

Error Sources (1 std)		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	<b>Adjusted Corrected <math>T_B</math> RSS</b>	<b>1.47 K</b>
4	Radar calibration and contamination error	0.0 K
5	Algorithm parameter error	3.2 K
6	<b>Disaggregated <math>T_B</math> (3 km) estimation RSS</b>	<b>3.5 K</b>

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

The waterbody adjusted brightness temperature root-sum-of-squares (RSS) is reported in row three of Table 4.1. The L2SMSP algorithm uses the Sentinel radar backscatter cross-section and SMAP brightness temperature to produce disaggregated 3 km brightness temperature. The contribution of the Sentinel radar backscatter cross-section calibration and contamination noise is 0.0 K, assuming a  $Kp$  value of ~0.0. This is because the aggregation of the Sentinel backscatter from very high-resolution (~20 m) to 1 km EASE

grid resolution includes nearly ~10000 backscatter cross-sections, making the random noise almost negligible and leading to  $Kp$  value of 0.0. Another important source of error in the SMAP-Sentinel Active-Passive algorithm is the uncertainties in algorithm parameters. Nominal values of 20% uncertainties are used for the algorithm parameters to evaluate the error contribution in the disaggregated 3 km brightness temperature, and the error is 3.2 K (shown in row 5 of Table 4.1) estimated through an analytical solution. The total 3 km disaggregated brightness temperature error of 3.5 K is shown as an RSS in the sixth row of Table 4.1.

Table 4.2 represents the same error budget but with more detail and in units of percent volumetric soil moisture  $\text{cm}^3/\text{cm}^3$ . Tables 4.1 and 4.2 are different from seventh row onwards of Table 4.2. The disaggregated brightness temperatures are subjected to the single channel algorithm (SCA) for soil moisture retrievals. The subsequent rows in Table 4.2 show uncertainty contribution of ancillary data and retrieval model in percent volumetric soil moisture  $\text{cm}^3/\text{cm}^3$ . The table highlights the uncertainties expected in various parameters and variables that are needed to establish the uncertainties in the L2SMSP product. The table illustrates the upper limit of the Vegetation Water Content (VWC) of  $3 \text{ kg/m}^2$  because the Sentinel C-band SAR is expected to saturate in the presence of moderately high vegetation cover. The tentative limit of  $3 \text{ kg/m}^2$  will be investigated before the Validated Release of the L2SMSP product. Table 4.2 illustrates errors (rows seven through ten) in retrieved soil moisture (at 3 km resolution) due to 3 K error in land surface temperature, 10% uncertainty in  $3 \text{ kg/m}^2$  VWC, 5% error in dielectric model percent sand and clay specification, and 5% error on major model parameters. The total retrieval uncertainty is shown in the last row of Table 4.2.

Table 4.2: Error budget in volumetric soil moisture  $\text{m}^3/\text{m}^3$

Error Sources		Estimated Error
1	Radiometer precision and calibration stability, faraday rotation, atmospheric gases, non-precipitating clouds, and gridding	1.3 K
2	Waterbody fraction	5%
		0.70 K
3	Adjusted Corrected $T_b$ RSS	1.47 K
4	Radar $S0(pp)$ and $S0(pq)$ errors*	0.0 K
5	Algorithm Parameter error	3.2 K
6	Disaggregated $T_b$ (3 km) RSS	3.5 K
7	VWC** with 10% error	3 kg/m <sup>2</sup>
		0.025 m <sup>3</sup> /m <sup>3</sup>
8	Soil temperature (3 K)	0.025 m <sup>3</sup> /m <sup>3</sup>
9	Soil texture (5% error in sand & clay fraction )	0.01 m <sup>3</sup> /m <sup>3</sup>
10	Parameters ( $h$ , $\omega$ , and $b$ ) 10% error each	0.01 m <sup>3</sup> /m <sup>3</sup>
11	Soil moisture retrieval at 3 km	0.04 m <sup>3</sup> /m <sup>3</sup>

As shown in Table 4.2, if the terms in the error budget are correct, the soil moisture retrievals in the L2SMSP product should be able to achieve a  $0.04 \text{ m}^3/\text{m}^3$  accuracy at  $3 \text{ kg}/\text{m}^2$  VWC level. The above error budget (Table 4.2) is developed based on Monte Carlo analysis of a 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-Sentinel L2SMSP granule. An analytical uncertainty analysis formulation was developed that is based on existing conditions in an EASE2 grid cell during the SMAP overpass and is implemented in the L2SMSP processing. Under nominal conditions, the analytical solutions for uncertainty estimates are almost similar to the Monte Carlo results. This analytical uncertainty estimate accompanies every L2SMSP soil moisture retrieval in the science product data files.

## 5 L2SMSP ALGORITHM FLOW

The baseline approach (Eq. 3.2) of the L2SMSP algorithm (Fig. 5.1a) is the disaggregation of the coarse resolution SMAP radiometer brightness temperature by using the overlapping fine resolution Sentinel radar backscatter. The disaggregated brightness temperature from the baseline approach is then subjected to SCA to retrieve soil moisture at 3 km.

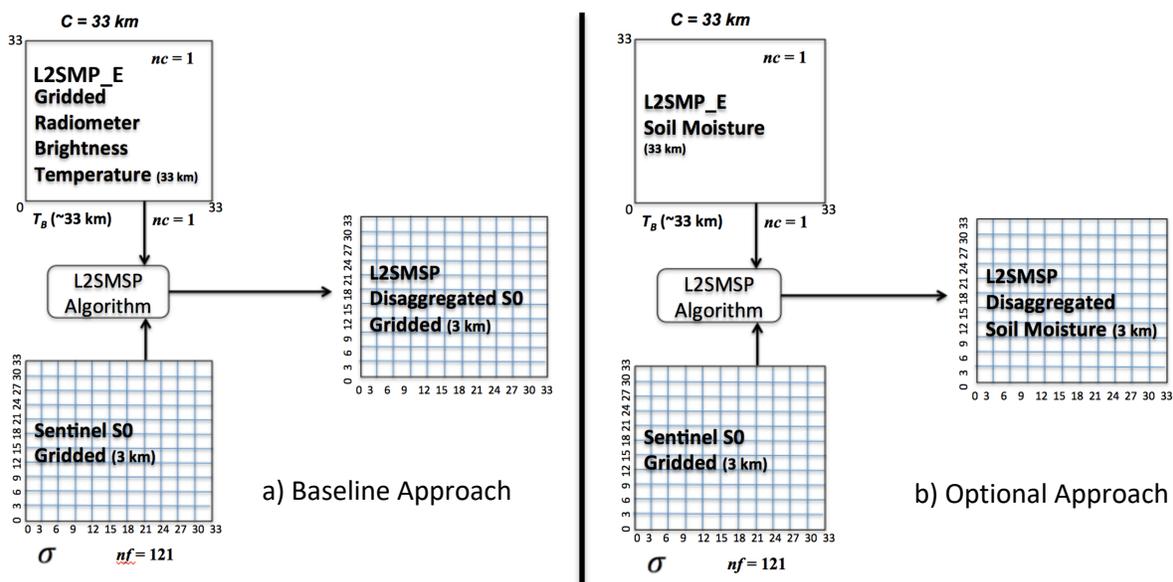
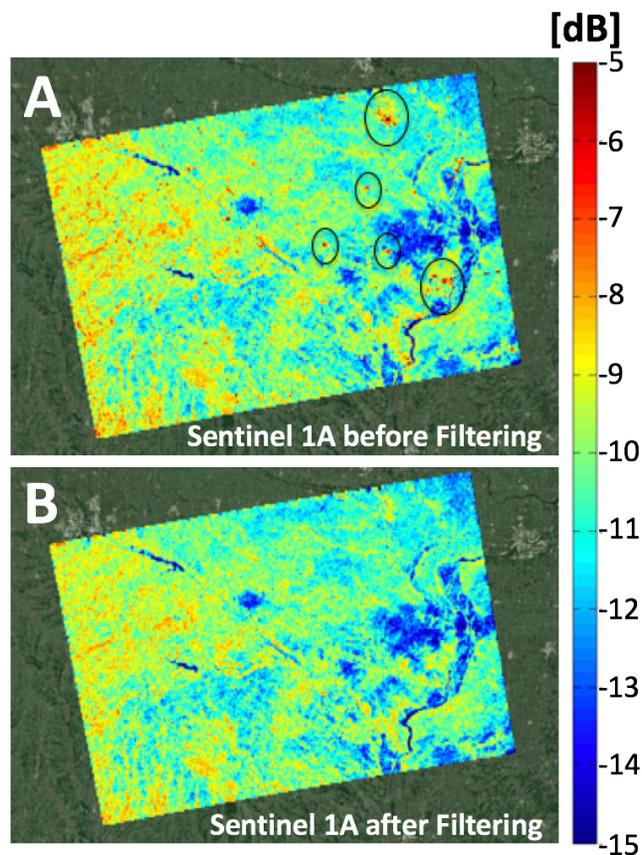


Figure 5.1. (a): Baseline Approach - Grid definition of the radiometer  $T_{B_p}(C)$ , radar  $\sigma_{pp}(C)$ , and merge product, where  $nf$  and  $nm$  are the number of area pixels of radar and merged product, respectively, within one radiometer area pixel  $nc$ . (b) Optional Approach - Grid definition of the radiometer-based  $\Theta(C)$ , radar  $\sigma_{pp}(C)$ , and merge product where  $nf$  and  $nm$  are the number of area pixels of radar and merged product, respectively, within one radiometer area pixel  $nc$ .

Another variant of the L2SMSP algorithms (Eq. 3.4) is shown in Fig. 5.1b. This is the Optional algorithm that directly disaggregates the soil moisture available in L2SMSP\_E at a resolution of 33 km but gridded at 9 km using the Sentinel backscatter cross-sections. Fig. 5.1b illustrates this variant that results in the final product of active-passive soil moisture at 3 km EASE2 grid resolution. This Optional algorithm approach does not require any new soil moisture retrieval within L2SMSP processing in contrast to the Baseline algorithm.

The Version-3 Release L2SMSP contains soil moisture fields produced by both the Baseline and the Optional Algorithms as shown in Fig. 5.1. Given the results from the recent L2SMSP Cal/Val analyses, the Baseline algorithm delivers comparable performance to the Optional algorithm at 3 km. Further analysis after the Version-3 Release will decide which variant will become the Baseline algorithm.

The Sentinel 1A/B data as shown in Fig. 5.1 is preprocessed before using as inputs to the active-passive algorithm. The native resolution of Sentinel 1A/B IW swath mode backscatter  $\sigma_{pp}$  (co-pol  $vv$ ) and  $\sigma_{pq}$  (cross-pol  $vh$ ) is  $\sim 25$  meters. The meter-resolution backscatter data is processed for calibration, noise subtraction, terrain correction (using SRTM DEM), filtering, and aggregation to 1 km. The aggregation of  $\sigma_{pp}$  and  $\sigma_{pq}$  from  $\sim 25$  meters to 1 km involves spatial filtering (a combination of standard deviation filter and median filter) to remove the effect of urban and manmade structures from the backscatter observations. Figure 5.2 illustrates the Sentinel 1A  $\sigma_{vv}$  data aggregated to 1 km over Southern Iowa. The high values of



$\sigma_{vv}$ , as highlighted in Fig. 6A, are due to non-natural scatterers (urban areas or manmade structures), these undesired high backscatter observations were filtered for the entire Sentinel granule, and then aggregated to 1 km. The filtered Sentinel 1A  $\sigma_{vv}$  granule is illustrated in Fig. 5.2

Figure 5.2: Sentinel 1A  $\sigma_{vv}$  granule from Southern Iowa on May 05, 2018. A)  $\sigma_{vv}$  unprocessed data; and B)  $\sigma_{vv}$  data after calibration, noise subtraction, terrain correction (using SRTM DEM), filtering, and aggregation to 1 km.

Figure 5.3 shows a simplistic flow diagram of the SMAP-Sentinel L2SMSP algorithm processing data flow in the JPL Science Data System. The processed Sentinel 1A/B data (Fig. 5.2B) is overlapped with/mapped onto the SMAP observations (descending  $\sim 6:00$  AM overpasses) that is closest to the Sentinel overpass within  $\pm 24$  hrs time difference. The average time difference between the Sentinel 1A/B (ascending and descending) and SMAP descending is  $\sim 12$  hrs. It is expected that the spatial distribution and pattern of the soil moisture does not change significantly because of inherent memory of the soil moisture over a short period of the time difference. The final data product is packaged in the HDF5 file format that includes all the relevant data elements and metadata information.

**SMAP and Sentinel  
L2SMSP  
Active – Passive  
Implementation**

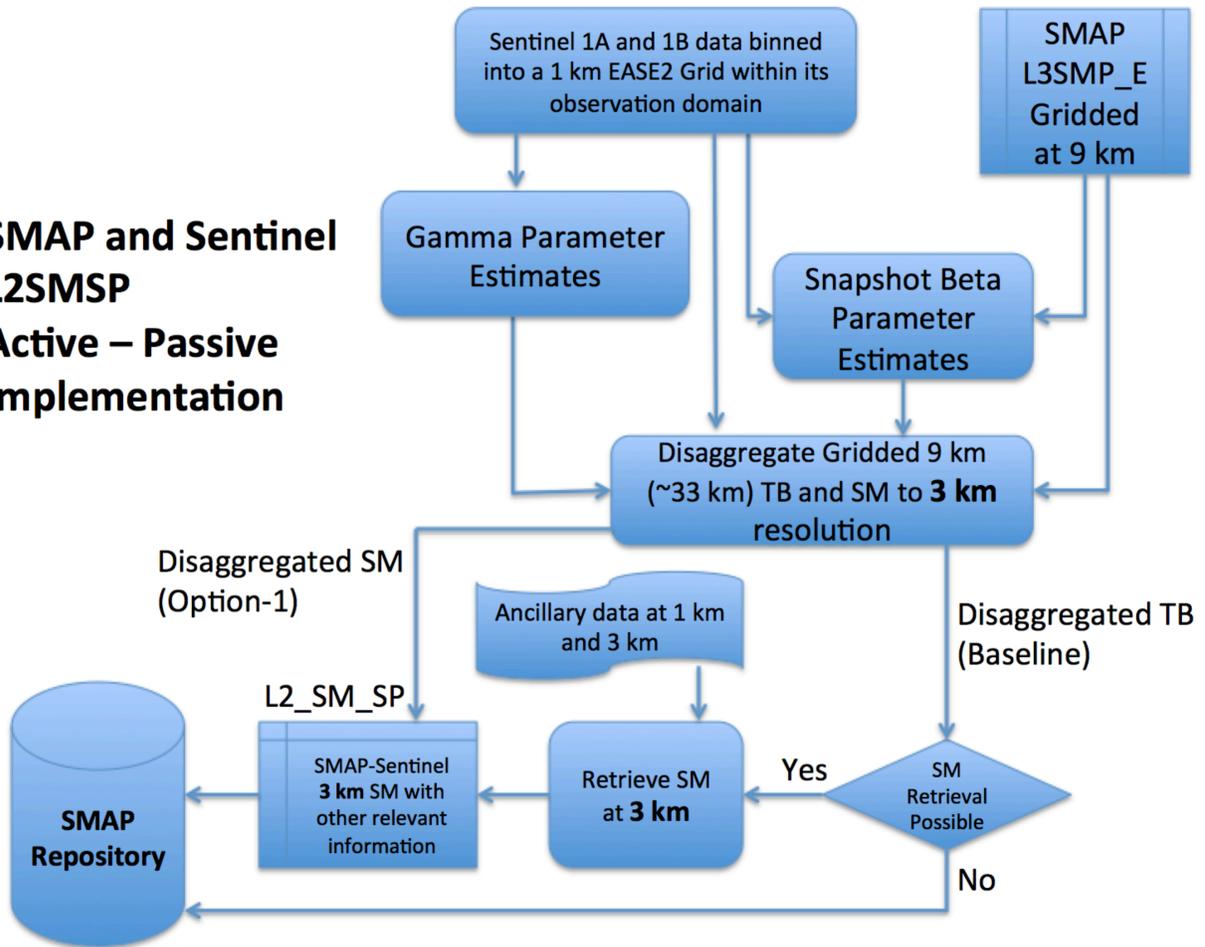


Figure 5.3: Process flow of the SMAP-Sentinel L2SMSP algorithm in the JPL Science Data System.

## 6 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 a 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 (CVS): 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 L2SMSP data product, all of these methodologies can contribute to product assessment and improvement. With regard to the CEOS Cal/Val stages, CVS address Stage 1 and Satellite and Model Products are used for Stage 2 and beyond. For this release the validation is done using the CVS (Stage 1) and Field Campaign data.

## 7 PROCESS USED FOR VERSION-3 RELEASE ASSESSMENT

The L2SMSP Version-3 assessment is warranted due to many changes that are introduced in the latest (R17) release of the SMAP products. Listed subsequently are the important changes brought into the L2SMSP SAS processing:

- a) The input brightness temperature from L2\_SM\_P\_E carried forward from newly calibrated from LIC\_TB product.
- b) The coefficients to compute the effective land-surface-temperature (LST) from the soil profile temperature data obtained from GMAO are also revised. The new coefficients are  $C=0.246$   $K=1.007$  for the AM passes, and  $C=1.0$ ,  $K=1.007$  for the PM passes. These coefficients are consistent with the values used in the L2\_SM\_P/\_E SAS.
- c) The albedo parameter of the tau-omega model for LULC 1 – 5 are changed from 0.05 to 0.07.
- d) Soil bulk density data are now used to set the upper thresholds of the soil moisture retrievals. Earlier, the L2SMSP product upper threshold was set to  $0.65 \text{ m}^3/\text{m}^3$ .
- e) The L2SMSP SAS now uses a new high-resolution soil database known as SoilGrid250m (Hengl et al., 2017) available through [www.openlandmap.org](http://www.openlandmap.org) web portal. The details of the new soil database is also available in the SMAP Ancillary Report (Soil Attribute Ancillary Report, JPL D-53058, Version-B).

Other minor fixes are made to the L2SMSP Version-3 product based on user feedbacks and to provide additional information about the product to the users. The fixes are as follows:

- EASE2 grid row and col at 3 km and 1 km for APM data fields fixed (subtracted 1 to make it 0-based).
- Bit flag included in the TB retrieval flag to identified the whether the TB data used comes from AM overpass of the PM overpass.
- A bit flag is introduced that indicates the data comes from the overlap between SMAP and Sentinel that has time difference less than or greater than 36 hrs. In the previous versions of the L2SMSP data, the TB fields is populated when the time difference is more than 36 hours, however, now the data are populated with bit flag that shows that the overlap time is beyond 36 hrs.
- Range beginning and ending time fixed.

The SMAP L2SMSP team chose to define the assessment period as May 01, 2015 to Dec 31, 2019. This is the period of data availability over the core Cal/Val sites prior to the SMAP R17 data product release. The team conducted assessments reported here and will continue to do this throughout the period of data availability after every L2SMSP product version update due to parameter calibration or other fixes for the next scheduled release.

Many reviews of performance based upon CVS were conducted for the selected period of record (May 01, 2015 to Dec 31, 2019) that captured a range of conditions over various parts of the world. These analyses included the intercomparison of two SMAP-Sentinel L2SMSP retrieval algorithms that established consistent levels and patterns of performance. Four algorithm-related actions were taken based on these performance reviews. First, a median filter was applied to the Sentinel data to remove outliers mostly due to urban areas, manmade structures, and small water bodies. These small urban areas, manmade structures, and small water bodies are not available in the masks used to quality control the SMAP and the Sentinel data. Second, surface flags were introduced to identify regions on the edge of the Sentinel granule to warn users about the poor quality of the algorithm parameter estimates there that may lead to inferior disaggregation of the SMAP-based brightness temperature and soil moisture. Third, another surface flag was introduced to indicate to users about the Sentinel backscatter values that are designated as outliers. Fourth, a flag in the retrieval quality now shows whether the retrievals are more than the expected soil

porosity (computed from the soil texture ancillary data) of the given EASE grid cell. Other bit flags are also added in the disaggregated TB quality flag as mentioned above to provide more information to the users.

## 8 ASSESSMENTS

### 8.1 Stability of Algorithm Parameters

The baseline SMAP L2SMSP algorithm has two parameters ( $\beta'(C)$  and  $\Gamma$ ), as shown in Eq. 3.2. The performance of the brightness temperature disaggregation that results in the 3 km soil moisture retrievals is heavily dependent on robust estimates of the parameters  $\beta'(C)$  and  $\Gamma$ . The parameters are specific to a given location and reflect the local roughness and vegetation cover conditions. Figure 8.1.a and Fig. 8.1.b illustrate the mean and coefficient of variation (CV) of  $\beta'(C)$  at global extent using all data from May 1, 2015 to April 30, 2017. The global evolution of mean  $\beta'(C)$  (Fig. 8.1.1a) shows the typical feature of reducing magnitude (approaching zero) with increasing VWC. However, the CV in Fig. 8.1.1b represents high variability except over very arid regions. This is a clear indication of seasonality/variability in  $\beta'(C)$  and the gradually changing values with the surface conditions, especially VWC.

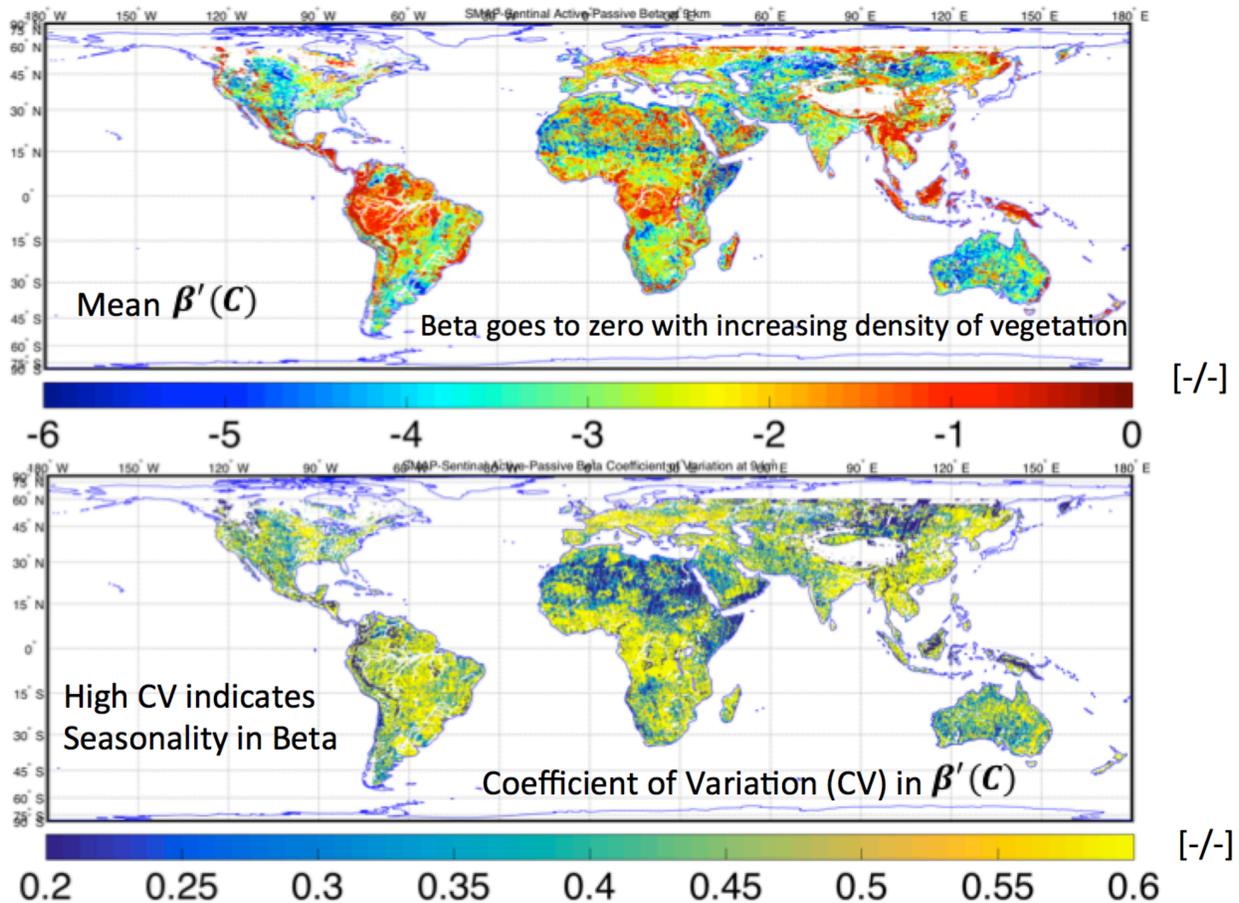


Figure 8.1.1:  $\beta'(C)$  mean and CV computed using all the available SMAP radiometer data and Sentinel 1A/1B  $\sigma_{pp}$  data from May 01, 2015 to April 30, 2017.

The parameter  $\Gamma$  is determined statistically for any particular overpass using the radar backscatter  $\sigma_{pp}$  and  $\sigma_{pq}$  at the finest available resolution (in this case at 1 km) that are encompassed within the 33 km  $T_{B_p}(C)$  grid cell. Figure 8.1.2 illustrates the mean and CV of  $\Gamma$  values over the global extent using all data

from May 1, 2015 to April 30, 2017. This algorithm parameter is spatial and temporally more stable than  $\beta'(C)$ . At a global scale, the mean values range from 2.5 to 4.5 with a median of 3.5. The CV in  $\Gamma$  is also very low for any given location, indicating temporal stability of this parameter.

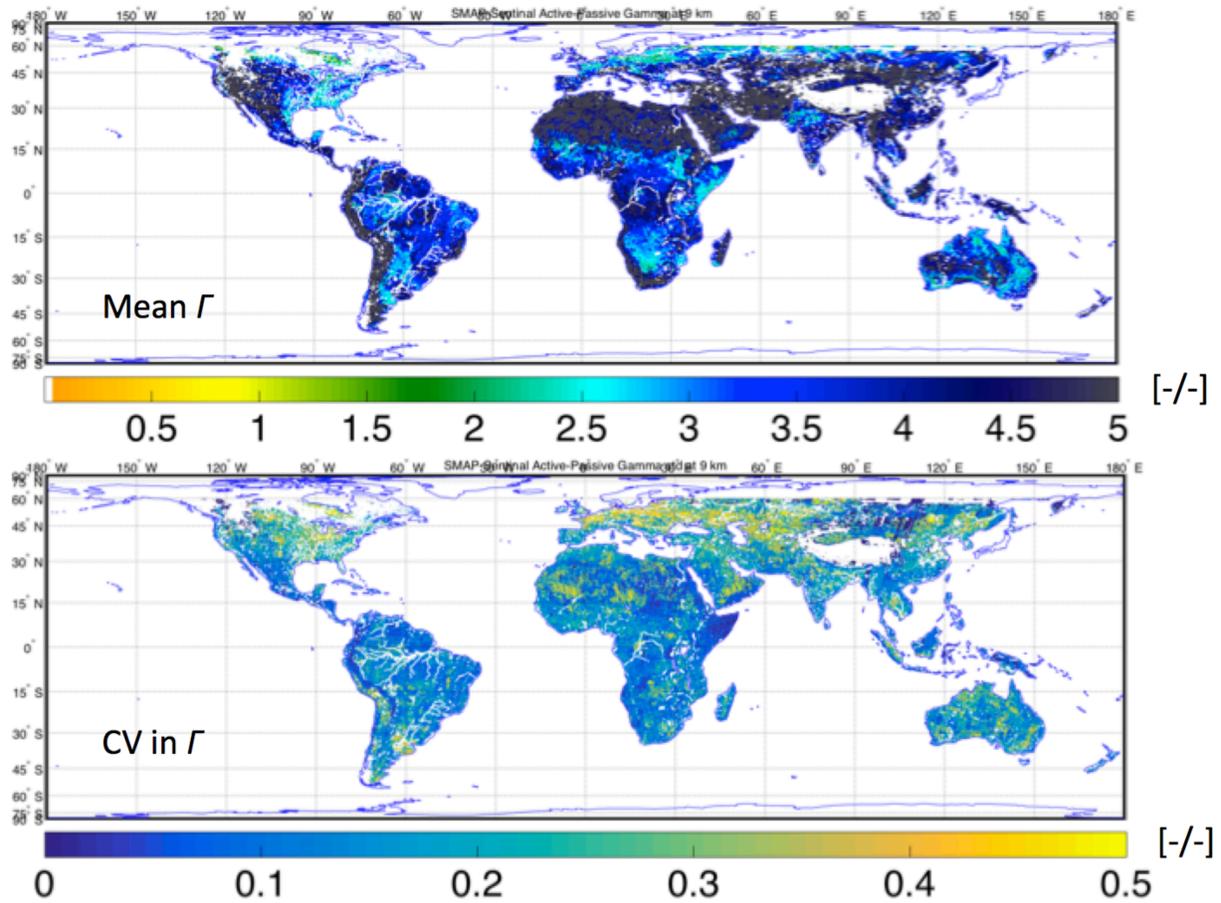


Figure 8.1.2:  $\Gamma$  mean and CV computed using all the available SMAP radiometer data and Sentinel 1A/1B  $\sigma_{pp}$  data from May 01, 2015 to April 30, 2017.

The evolution of  $\beta'(C)$  and  $\Gamma$  over the global domain is consistent and has expected behavior that is comparable to results from field campaigns (e.g., SMAPEX 2015, SMAPVEX15).

## 8.2 Soil Moisture Patterns and Features in L2SMSP product

In this section, prior to the quantitative assessments that follow, the general features of global images are reviewed for the baseline L2SMSP product. In tandem, the Sentinel-1A and Sentinel-1B spacecraft have a revisit interval of 12 days. Therefore the composite of L2SMSP for 12 days should nearly cover most parts of the Earth. The images in Fig. 8.2.1 and Fig. 8.2.2 show a 12-day composite of L2SMSP granules from 1<sup>st</sup> Sep 2019 to 12<sup>th</sup> Sep 2019 and a monthly composite of L2SMSP granules from 15<sup>th</sup> Sep 2019 to 26<sup>th</sup> Sep 2019, respectively, illustrating the global coverage between +60° and -60° latitudes.

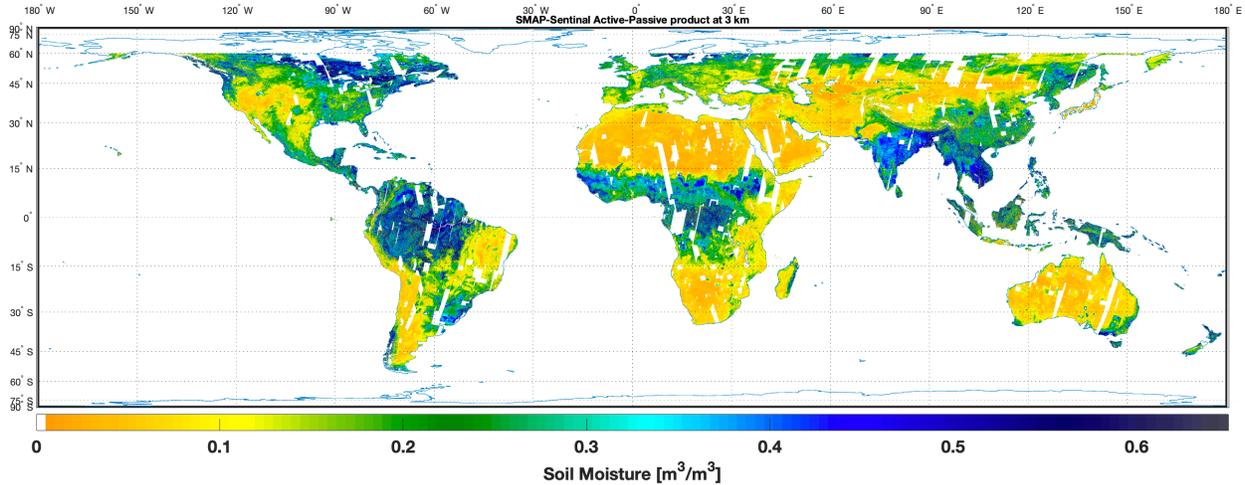


Figure 8.2.1: Twelve Days Coverage of SMAP-Sentinel L2SMSP high-resolution (3 km) soil moisture data from 15<sup>th</sup> Sep, 2019 to 26<sup>th</sup> Sep, 2019.

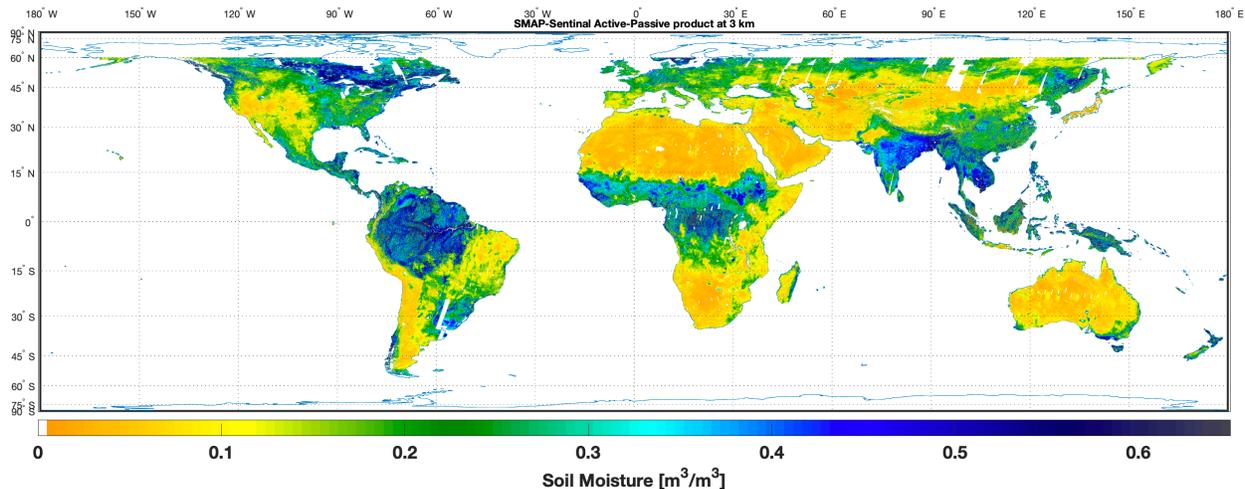


Figure 8.2.2: Monthly average of SMAP-Sentinel L2SMSP high-resolution (3 km) soil moisture data from 1<sup>st</sup> Sep, 2019 to 30<sup>th</sup> Sep, 2019.

In the above Fig 8.2.1 and Fig. 8.2.2, 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 of soil moisture variability. They also illustrate the high soil moisture values over the Southeast Asia due to the monsoon rains. There are a number of quality flags that are applied to L2SMSP 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 L2SMSP processing can be found in the Product Specification Document [L2SMSP Product Specification Document, JPL D-56548]. The reliability of soil moisture retrieval algorithms is known to decrease when the VWC exceeds a certain threshold. For the L2SMSP product, a  $3 \text{ kg/m}^2$  VWC value is used as a flag threshold to indicate areas of high 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 areas near large lakes).

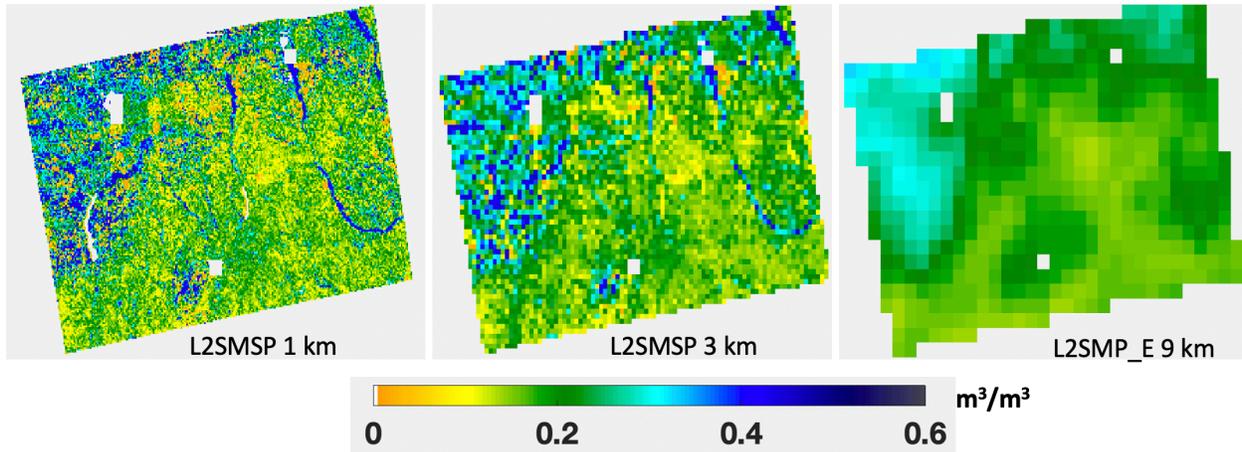


Figure 8.2.3: Example of an L2SMSP granule over agricultural landscape in Georgia, United States for date 5<sup>th</sup> May, 2019, showing enhancement of spatial details of soil moisture retrievals through the L2SMSP algorithm as compared with the L2SMSP\_E soil moisture data.

The L2SMSP algorithm captures high-resolution spatial features of soil moisture through Sentinel observations and disaggregates them. Figure 8.2.3 shows one such example. Appendix A contains further examples of L2SMSP fields. These fields surround the SMAP CVS. The plots in Fig. 8.2.3 show that the L2SMSP product has the same general spatial features as the L2SMSP\_E. But the L2SMSP fields have more spatial definition and spatial resolution. The small-scale features also have higher dynamic range associated with less spatial smoothing.

The difference in soil moisture retrievals between the old version and the new (R17) version of L2SMSP data products is illustrated in Fig 8.2.4. Over most parts of the world, the differences are within  $\pm 0.02 \text{ m}^3/\text{m}^3$ . However, in some regions, the differences are as high as  $\pm 0.08 \text{ m}^3/\text{m}^3$ . We attribute such high differences in soil moisture retrievals due to the use of a new updated/upgraded clay fraction data (Reference: SMAP Soil Attribute Ancillary Data Report). Figure 8.2.5 shows a difference map of old and new clay fraction data. The correspondence between Fig. 8.2.4 and Fig. 8.2.5 is high over the regions where the clay fraction differences are high, for example over Southeast Asia and India. The higher clay fraction in the old database led to higher soil moisture retrievals during the wet season (September, monsoon season). The new clay fraction data is  $\sim 40\%$  less than the old clay fraction data resulting in lower soil moisture retrievals and show up as red regions (lower retrievals) in Fig. 8.2.4, and vice-versa. However, there are also arid regions where the clay fraction differences are high ( $\sim 40\text{-}50\%$ ), and due to low soil moisture estimates the differences in retrievals are not accentuated.

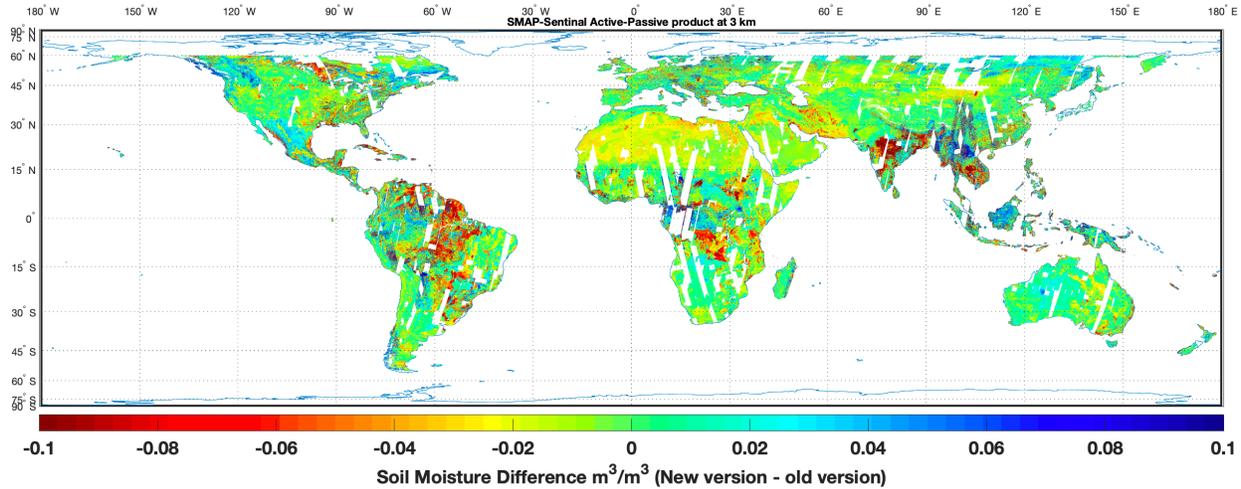


Figure 8.2.4: Difference in soil moisture volumetric content between the new version (R17) and old version.

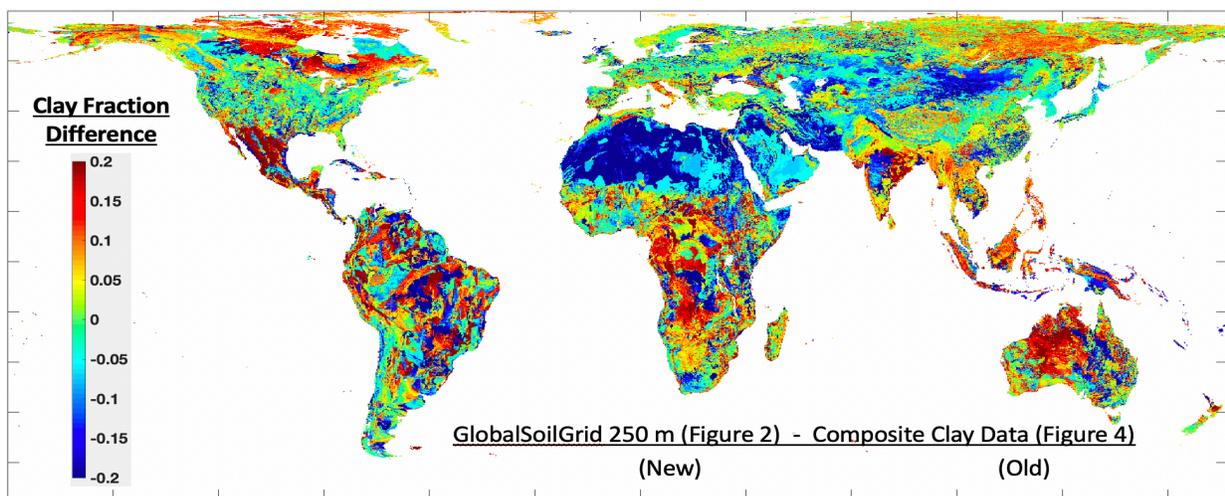
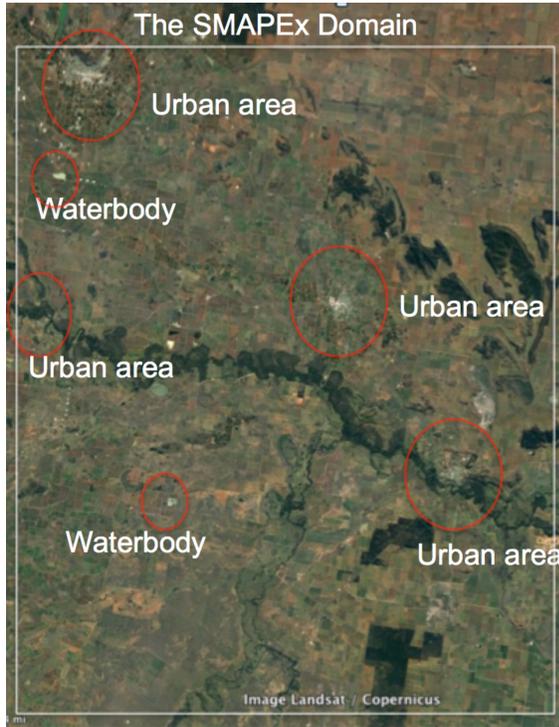


Figure 8.2.5: Clay fraction difference between GlobalSoilGrid250m (New) and the Composite Clay fraction (Old) created using the FAO, HWSD, STATSGO, NSDC, and ASRIS.

### 8.3 Evaluation of L2SMSP Against SMAPEX Airborne Data

A part of the Stage 1 assessment for the L2SMSP algorithm is the comparison of disaggregated high-resolution brightness temperatures with L-band airborne remote sensing data. For this release, validation is done using airborne data from the SMAPEX 2015 campaign held in Southeastern Australia [8]. The brightness temperature data from SMAPEX 2015 has a resolution of ~1 km with varying incidence angles. For better comparison with SMAP satellite data, the SMAPEX airborne data are subjected to normalization to bring all the observations to a uniform 40 deg incidence angle. This process introduced an error of ~4-5 K in the SMAPEX airborne data [8]. The normalized data are actually used for assessment of the L2SMSP disaggregated high-resolution brightness temperature. On two days (May 5<sup>th</sup>, 2015 and May 13<sup>th</sup>, 2015) SMAP, Sentinel, and Polarimetric L-band Microwave Radiometer (PLMR) airborne data from the

SMAPEX field campaign are available. These concurrent acquisitions of data from different platforms provide the ideal combination to validate the L2SMSP high-resolution disaggregated brightness temperature. These specific dates of SMAPEX airborne data are also considered due to very different surface conditions in the observation domain: a) May 5<sup>th</sup>, 2015, low vegetation cover (~1 kg/m<sup>2</sup>); and b) September 13<sup>th</sup>, 2015, moderately high vegetation cover (~2.7 kg/m<sup>2</sup>). A Google map of the SMAPEX 2015 domain is shown in Fig. 8.3.1.



As illustrated in Fig. 8.3.1, the SMAPEX study domain contains many urban areas, small manmade structures, and waterbodies. SMAPEX or L2SMSP data over urban areas and waterbodies are undesirable for assessment purposes. Therefore, such data need to be flagged or masked during L2SMSP Science Application Software (SAS) processing. Some of the bigger urban area locations are noted in the SMAP project’s urban area Mask. When implemented in the SAS processing, this mask flags the L2SMSP data from the urban areas. It was noticed during analysis of the SMAPEX domain that some small urban areas and waterbodies are not identified/flagged properly during the L2SMSP processing because the urban area and waterbody masks are erroneous at very high resolution.

Figure 8.3.1: Study domain of SMAPEX Airborne campaign.

Figure 8.3.2a shows the PLMR airborne  $T_{B_v}$  data, Fig. 8.3.2b shows the Sentinel  $\sigma_{vv}$  data, and Fig. 8.3.2c shows the Sentinel  $\sigma_{vh}$  data from May 5<sup>th</sup>, 2015 over the SMAPEX study area. It is apparent that PLMR  $T_{B_v}$  from SMAPEX are not impacted adversely by small urban areas or manmade structures, unlike the Sentinel  $\sigma_{vv}$  and  $\sigma_{vh}$  data. The small urban areas and manmade structures are visible as unexpectedly high backscatter. Figure 8.3.2b/c also show that in the Sentinel data, the large urban areas are masked and removed but the small urban areas and manmade structures are not identified and masked. These types of undesirable outliers in the Sentinel backscatter data create anomalies in the L2SMSP disaggregated  $T_{B_v}$  data. A [3X3] Median Filter (MFi) at 1 km resolution is applied to overcome the outliers in the Sentinel observations. The MFi removed most of the outliers from the Sentinel  $\sigma_{vv}$  and  $\sigma_{vh}$  data (Figure 8.3.3), although a mild smoothing effect is also clearly visible. Since the SMAP-Sentinel product baseline spatial resolution is 3 km, the smoothing effect does not impact results at 3 km EASE grid.

May 5<sup>th</sup>, 2015

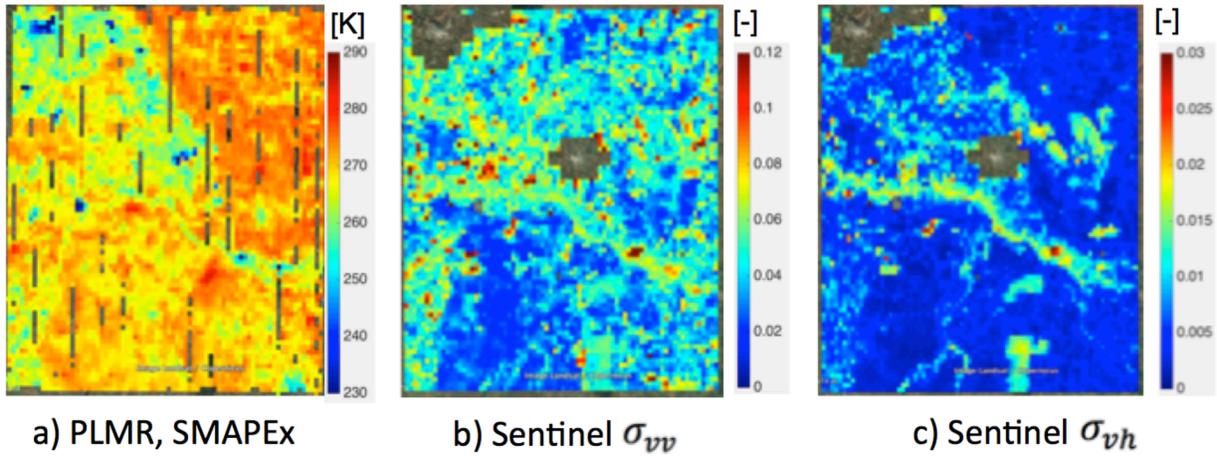
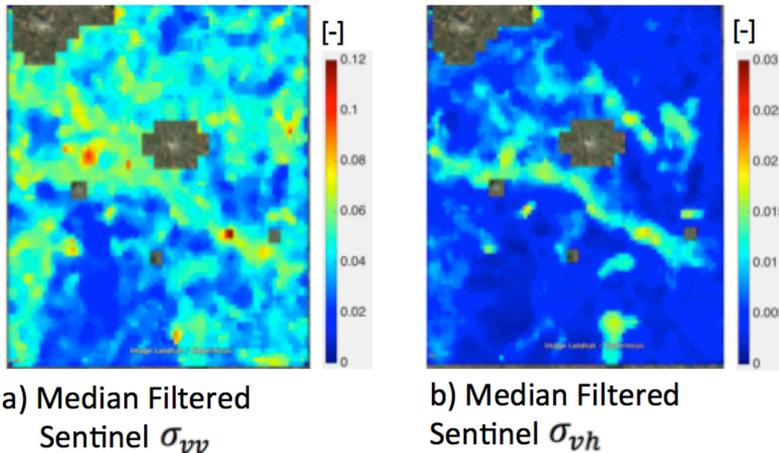


Figure 8.3.2: PLMR and the Sentinel observations at EASE grid 1 km resolution over the SMAPEX study domain on May 5<sup>th</sup>, 2015.

May 5<sup>th</sup>, 2015



Even after applying the MFil on the Sentinel observations, some residual impact of urban areas is still visible because there are locations where the urban areas are greater than the [3X3] window at 1 km EASE grid resolution. The MFil data are now used in the Science Algorithm Software (SAS) to produce the L2SMSP product.

Figure 8.3.3: Median Filtered Sentinel observations at EASE grid 1 km resolution over the SMAPEX study domain on May 5<sup>th</sup>, 2015.

Examples of disaggregated high-resolution 3 km  $T_{B_v}$  from L2SMSP data are shown in Fig. 8.3.4a and Fig. 8.3.4b, and compared against the SMAPEX PLMR data and the SMAP L2SMSP\_E ( $T_{B_v}$  data corrected for presence of water) data gridded at 9 km for May 5<sup>th</sup>, 2015 and Sep. 13<sup>th</sup>, 2015, respectively. The plots in Fig. 8.3.4 show the finer details captured by the L2SMSP algorithm through the MFil Sentinel observations, and the finer spatial features are very similar to the PLMR  $T_{B_v}$  data. To evaluate the SMAP-Sentinel Active-Passive algorithm performance, the L2SMSP high-resolution disaggregated  $T_{B_v}$  are compared against Minimum Performance criteria to determine the value of combining Sentinel radar data with SMAP L2SMSP\_E brightness temperature data. The Minimum Performance is the SMAP L2SMSP\_E  $T_{B_v}(C)$  that is applied to all the 3 km EASE grid cells within the overlapping 9 km EASE grid cell; in other words, it can be obtained by setting  $\beta'(C) = 0$  in Eq. 3.2.

Ideally the slope and correlation between the L2SMSP brightness temperature and airborne high-resolution brightness temperature should be one (unity). In Fig. 8.3.5 we show the slope and correlation between Minimum Performance and airborne data, between L2SMSP and airborne data and ideal performance. In the two available airborne images (May 5<sup>th</sup>, 2015 and Sep 13<sup>th</sup>, 2015) the slope and correlation between L2SMSP and airborne data are higher than the Minimum Performance (and approaching Ideal). A similar analysis conducted at EASE grid 9 km also shows (Fig. 8.3.6) that the L2SMSP  $T_{B_p}(M_j)$  aggregated to 9 km has better slopes and correlations when compared against L2SMSP\_E  $T_{B_p}(C)$ . These results (Fig. 8.3.5 and Fig. 8.3.6) clearly indicate that Sentinel  $\sigma_{vv}$  and  $\sigma_{vh}$  bring valuable information to disaggregate the coarse-resolution L2SMSP\_E  $T_{B_p}(C)$  to obtain L2SMSP  $T_{B_p}(M_j)$  that matches better with the high-resolution spatial features as observed by the SMAPEX PLMR platform.

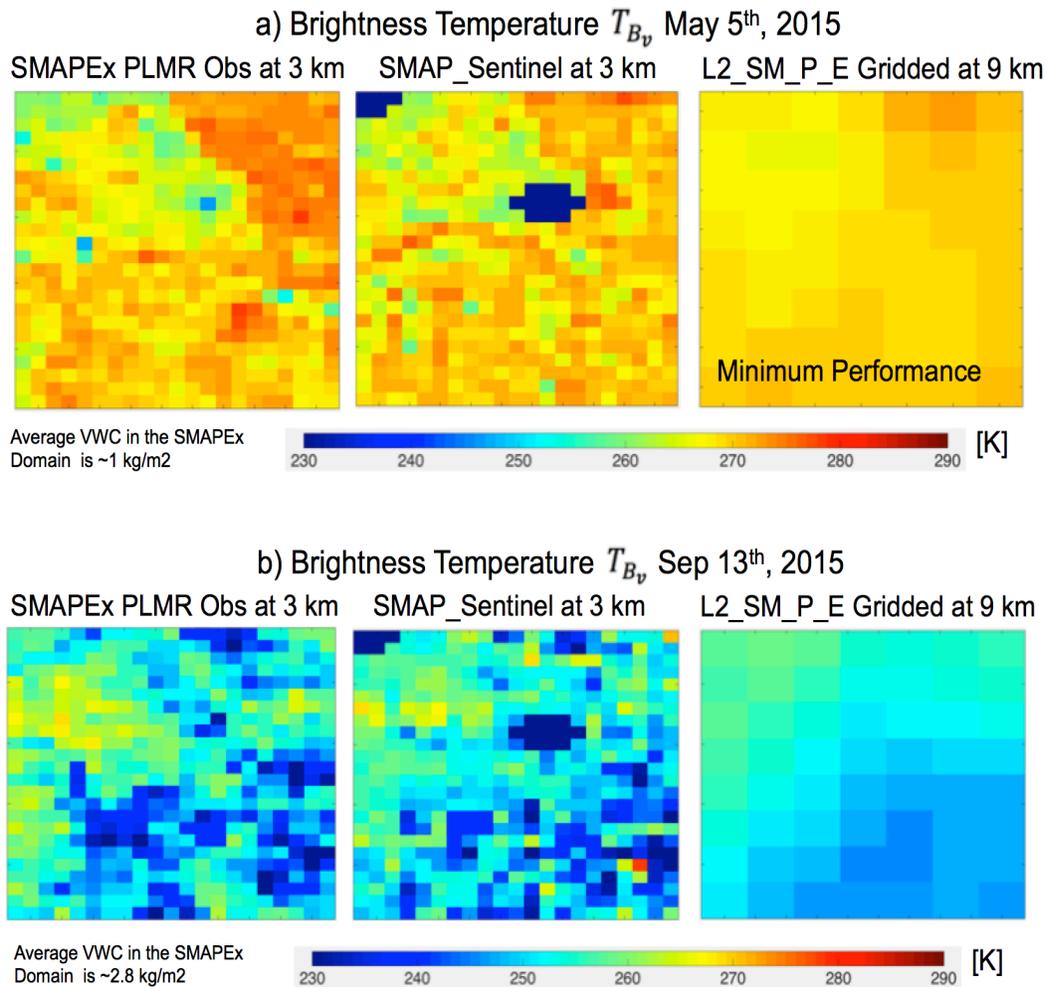


Figure 8.3.4: Output of L2SMSP compared against PLMR  $T_{B_v}$  data from SMAPEX and the Minimum Performance ( $T_{B_v}$  from L2SMP\_E at 9 km).

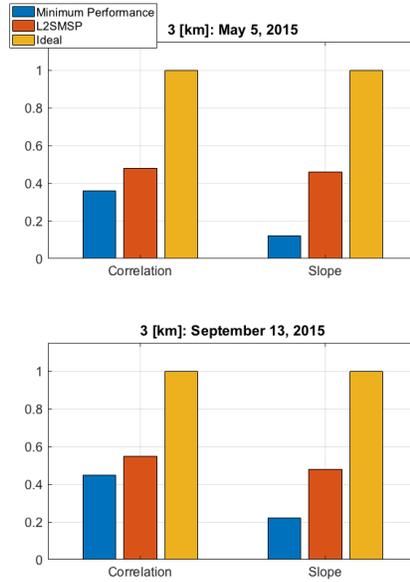


Figure 8.3.5: Plots of SMAPE<sub>x</sub> PLMR observations against L2SMSP  $T_{B_p}$  (black scatter) at 3 km and Minimum Performance ( $T_{B_v}$  from L2SMP\_E, red scatter) at 3 km.

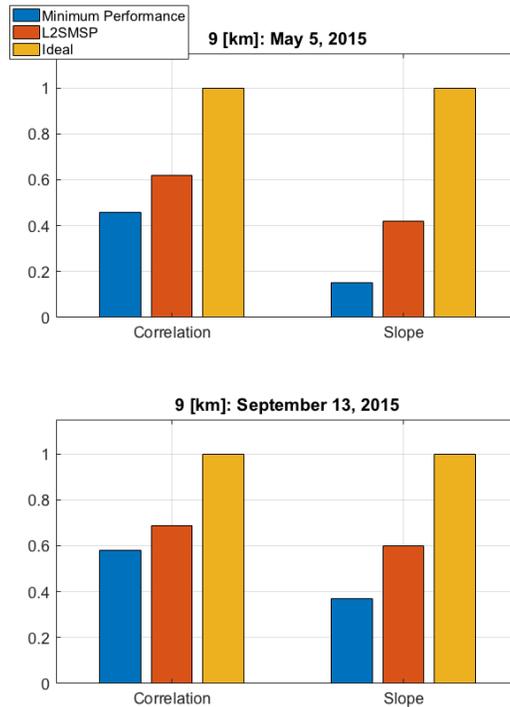


Figure 8.3.6: Plots of SMAPE<sub>x</sub> PLMR observations against L2SMSP  $T_{B_p}$  (black scatter) at 9 km and Minimum Performance ( $T_{B_v}$  from L2SMP\_E, red scatter) at 9 km.

## 8.4 Core Validation Sites (CVS)

*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 the SMAP Cal/Val. The current set of candidate sites that could provide validation data at the L2SMSP resolution are listed in Table 8.4.1.

The Stage 1 assessment for the L2SMSP soil moisture is a comparison of retrievals at 3 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]. For SMAP and this analysis, a CVS at 3 km is valid if it has 3 *in situ* sensor sites within a 3 km EASE grid cell. Based on this criterion only a handful of the candidate sites are eligible as CVS.

Not all of the candidate sites in Table 8.4.1 have reached a level of maturity that would support them being used as CVS. Prior to initiating this release assessments, the L2SMSP and Cal/Val Teams reviewed the status of all sites to determine which sites were ready to be designated as CVS for this product. The basic process for CVS selection that is adopted across all the SMAP Level-2 products is mentioned below:

- 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 widely used and known to be well-calibrated or 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 (to increase the number of sites) will be used in the quantitative assessment of algorithm performance for the this release and the subsequent validated release. A total of 9 CVS/candidate sites (highlighted in Table 8.4.1) that meets the basic requirements to be categorized as a CVS site at 3 km were used in this assessment.

The key tool used in L2SMSP analyses is the chart illustrated in Figures 8.4.1 – 8.4.21. The charts show the comparison of the upscaled *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-Sentinel L2SMSP 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 L2SMSP 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 8.4.1. SMAP Cal/Val Partner sites providing *in situ* data for L2SMSP assessment.

Site Name	Site PI	Area	Climate regime	IGBP Land Cover
<b>Walnut Gulch*<sup>#</sup></b>	M. Cosh	USA (Arizona)	Arid	Shrub open
Reynolds Creek	M. Cosh	USA (Idaho)	Arid	Grasslands
<b>Fort Cobb<sup>#</sup></b>	M. Cosh	USA (Oklahoma)	Temperate	Grasslands

<b>Little Washita<sup>#</sup></b>	M. Cosh	USA (Oklahoma)	Temperate	Grasslands
<b>South Fork<sup>#</sup></b>	M. Cosh	USA (Iowa)	Cold	Croplands
<b>Little River</b>	M. Cosh	USA (Georgia)	Temperate	Cropland/natural mosaic
<b>TxSON<sup>*#</sup></b>	T. Caldwell	USA (Texas)	Temperate	Grasslands
Millbrook	M. Temimi	USA (New York)	Cold	Deciduous broadleaf
Tonzi Ranch	M. Moghaddam	USA (California)	Temperate	Savannas
<b>Kenaston<sup>#</sup></b>	A. Berg	Canada	Cold	Croplands
<b>Carman</b>	H. McNairn	Canada	Cold	Croplands
<b>Monte Buey</b>	M. Thibeault	Argentina	Arid	Croplands
Bell Ville	M. Thibeault	Argentina	Arid	Croplands
<b>REMEDHUS<sup>#</sup></b>	J. Martinez	Spain	Temperate	Croplands
<b>Valencia<sup>*</sup></b>	J. Martinez	Spain	Arid	Shrub (open)
Twente	Z. Su	Holland	Temperate	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
<b>Yanco<sup>*#</sup></b>	J. Walker	Australia	Arid	Croplands
Kyeamba	J. Walker	Australia	Temperate	Croplands

\*=CVS used in L2SMSP 3 km assessment, # = CVS used in L2SMSP 9 km assessment

It should be noted that a small underestimation bias should be expected when comparing satellite retrievals to *in situ* soil moisture sensors (Chan et al., 2017). 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<sup>3</sup>/m<sup>3</sup> 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. Initial results from studies have also shown that at 9 km the upscaling errors of *in situ* soil moisture sensors from CVS are (on average)  $\geq 0.015 \text{ m}^3/\text{m}^3$  (personal communication with Dr. Wade Crow/USDA ARS; SMAP Science Team Member).

Table 8.4.2, and Table 8.4.3 give the overall results for the latest Release dataset. The tables are for CVS comparison at EASE grids of 3 km and 9 km. Only 8 sites qualify to become as CVS for the 3 km EASE grid. This is a severe limitation when only a handful of CVS sites are used for validating the L2SMSP product at 3 km resolution. More sites need to be prepared or explored to improve the robustness of CVS assessment at 3 km. However, 8 sites are now used for the this Release assessment and it does provide insight and a path forward for further improvement of the L2SMSP product on the 3 km EASE grid.

Another strategy was developed to overcome the limitation of L2SMSP at 3 km assessment due to a low number of CVS sites. This strategy involve validating the L2SMSP product at 9 km by aggregating

all nine L2SMSP 3 km EASE grid cells within the 9 km EASE grid and use most of the CVS sites developed for the SMAP-only Active-Passive L2SMAP 9 km product. This approach optimizes the CVS site usage and has potential to evaluate the spatially upscaled L2SMSP product at 9 km.

The figures in Appendix B illustrate the CVS assessment at 3 km EASE grid resolutions. They correspond to the map of the sites in Appendix A. Appendix C contains the CVS assessment at 9 km EASE grid resolutions.

Table 8.4.2. SMAP-Sentinel L2SMSP Release (R16700) CVS Assessment at 3 km

Site Name	ubRMSE	Bias	RMSE	R
Walnut Gulch	0.031	0.042	0.052	0.948
Walnut Gulch	0.030	0.085	0.090	0.886
TxSON	0.030	-0.064	0.070	0.895
TxSON	0.024	-0.048	0.054	0.863
Kenaston	0.069	-0.021	0.072	0.459
Kenaston	0.052	-0.052	0.073	0.620
Monte Buey	0.034	-0.071	0.078	0.800
Valencia	0.029	-0.028	0.041	0.570
Yanco	0.080	0.023	0.083	0.470
Yanco	0.070	0.032	0.077	0.649
Yanco	0.056	0.047	0.073	0.785
Yanco	0.069	0.076	0.103	0.752
<b>SMAP Average</b>	<b>0.048</b>	<b>0.002</b>	<b>0.072</b>	<b>0.725</b>

*The term RMSE in the analysis is interchangeably used for root-mean-square-difference (RMSD). However, RMSD is more appropriate because the upscaled CVS values are not the truth.*

Table 8.4.3. SMAP-Sentinel L2SMSP Release (R16700) CVS Assessment at 9 km

Site Name	ubRMSE	Bias	RMSE	R
Walnut Gulch	0.024	0.031	0.039	0.901
Walnut Gulch	0.030	0.063	0.070	0.803
TxSON	0.016	-0.034	0.038	0.910
TxSON	0.018	-0.023	0.029	0.927
Fort Cobb	0.027	-0.020	0.033	0.877
Little Washita	0.035	-0.030	0.046	0.842
South Fork	0.043	-0.056	0.071	0.813
St Josephs	0.022	-0.042	0.048	0.913
Little River	0.037	0.095	0.102	0.763
Kenaston	0.034	-0.068	0.076	0.781
Kenaston	0.038	-0.076	0.084	0.741
Carman	0.072	-0.043	0.084	0.439
Monte Buey	0.014	-0.049	0.051	0.800
REMEDHUS	0.059	0.112	0.126	0.831
Valencia	0.023	-0.026	0.035	0.412
Yanco	0.058	0.009	0.058	0.882
Yanco	0.052	0.046	0.070	0.777
<b>SMAP Average</b>	<b>0.035</b>	<b>-0.007</b>	<b>0.062</b>	<b>0.789</b>

The key results of this assessment are summarized in the results in Table 8.4.2, and Table 8.4.3 for the SMAP L2SMSP algorithms applied at 3 km and 9 km, respectively. Table 8.4.2 highlights the results for Baseline L2SMSP at 3 km. The Baseline and Option-1 (not shown in the Table 8.4.2) algorithms have comparable performance for all the metrics (ubRMSE, Bias, RMSE, and R-value), Option-1 (direct soil moisture disaggregation) has slightly better ubRMSE. The Baseline algorithm (brightness temperature disaggregation and then soil moisture retrievals) can likely be further improved in the future by the inclusion of better high-resolution ancillary information/data (e.g., soil texture map, actual NDVI, and surface temperature data) and optimization of tau-omega parameters at 3 km resolution. This might help in reducing the high bias now observed for most of the CVS sites at 3 km. For the subsequent releases, we expect to have more CVS at 3 km for a robust assessment.

Table 8.4.3 summarizes the alternative approach for assessing the L2SMSP at 9 km EASE grid by maximizing the use of available CVS at 9 km originally prepared for the L2SMAP product. The results from Table 8.4.3 are encouraging. Both the Baseline and Option-1 (Not shown in the Table 8.4.3) have similar performance and high R values. The Baseline algorithm has better bias and meets the L1 accuracy requirement of the SMAP mission previously applied to the SMAP L2SMAP product. It is expected that the performance of the Baseline algorithm at 3 km will improve further, consequently improving the statistics of the Baseline algorithm at 9 km.

Based upon the metrics and considerations discussed, it is recommended that the L2SMSP Baseline algorithm be carried forward for this Release because it has reasonable ubRMSE, bias and correlation (R). It also has high probability of further improvement of these statistics for the future releases in the following years.

## 8.5 Sparse Network Analysis

**This section is not updated.**

**The sparse network analysis description and statistics will be updated contingent upon availability of the latest version of the L2SMSP data in the repository after completion of R17 reprocessing in the JPL Ops.**

## 8.6 Summary

The L2SMSP product uses the Sentinel-1A/1B SAR data to disaggregate SMAP L-band radiometer measurements from the ~40 km (half-power or -3 [dB] definition) radiometer measurement to a 3 and 9 [km] gridded product. The C-band SAR data adds spatial information to the radiometer product. It also adds the noise associated with radar measurements (instrument noise, complex surface scattering, etc.). It is expected that the spatial features in the L2SMSP product to be at higher resolution than the SMAP Level 2 Soil Moisture Passive (L2SMP/L2SMP\_E) product. But the temporal behavior is expected to be comparable between the two products. These differences in the expected temporal and spatial characteristics affects the assessments based on different ground-based data sources.

The assessment of the L2SMSP product was primarily done using comparison statistics and time series plots with high-resolution airborne-based L-band data, and the SMAP CVS. Each of these assessment approaches has advantages as well as shortcomings.

The CVS are time-series of in situ stations within SMAP grids that have been spatially averaged. They thus have no information on the spatial patterns of surface soil moisture but should be robust indicators of the temporal changes in soil moisture. In this respect the CVS are not indicative of the spatial resolution advantages of L2SMSP. The temporal statistics should be equal but not appreciably worse when comparing L2SMP\_E versus CVS match-up time series and comparing L2SMSP versus CVS match-up time-series.

The spatial resolution performance of the L2SMSP can only be assessed with more complete ground sampling which is possible only with airborne field campaigns. These experiments provide a unique opportunity to demonstrate the spatial resolution advantages of L2SMSP when compared to L2SMP-E. We use available airborne data sets in this assessment report. However airborne field campaigns are performed over short periods and sporadically. So comparisons of temporal statistics are not possible with these data sources for assessment.

For this Release, the goal was to conduct a Stage 1 validation assessment based primarily on airborne data and CVS comparisons using metrics and time series plots. The comparison of L2SMSP disaggregated brightness temperature with the SMAPEX 2015 airborne data showed that the Sentinel data do provide valuable surface information that is critical for obtaining high-resolution brightness temperature. The CVS and the sparse network analyses indicated that the baseline algorithm has comparable unbiased root-mean-square-errors (ubRMSE), bias, and correlation R to the Option-1 algorithm and also has a chance of further improvement in performance statistics. Based on these results, it is recommended that the Baseline approach be used as the primary algorithm for this Release. In the CVS analysis the overall ubRMSE of the SMAP-Sentinel active-passive baseline algorithm at 3 km and 1 km resolutions is ~0.05 m<sup>3</sup>/m<sup>3</sup>. However, at 9 km the ubRMSE is 0.035 m<sup>3</sup>/m<sup>3</sup>, which is below the SMAP mission L1 accuracy requirement for the original SMAP active-passive 9-km product.

The science and application communities should take certain caveats into consideration before using the L2SMSP product. There is a tradeoff between adding spatial resolution with C-band SAR data and noise-levels. The L2SMSP high resolution (3 km) comes at a cost of degradation in temporal statistics of disaggregated brightness temperature and retrieved soil moisture. Whereas the more spatially-averaged L2SMP\_E product may have less temporal noise and temporal uncertainty when compared to L2SMSP, the L2SMSP will have more spatial resolution in term of resolving sharp and large-contrast features below the radiometer resolution. The degradation in accuracies is mainly imparted due to: 1) difficulties in comprehensively characterizing the active radar signal interactions with land surface components, 2) the uncertainties in the active-passive algorithm parameters used in the disaggregation of brightness temperature, and 3) the random errors and biases in the static and dynamic ancillary data used for soil moisture retrievals. The high resolution L2SMSP product captures the spatial details and patterns of soil

moisture that are not present in the SMAP radiometer-only enhanced product (L2SMP\_E). Therefore, those users of SMAP data who require more frequent revisit and temporal accuracy can use the L2SMP\_E product (which is posted at 9 km), and those users who need high resolution soil moisture patterns and details with slightly degraded accuracy and less frequent revisit can use L2SMSP data (posted at 3 km) for their science studies and geophysical applications.

## 9 OUTLOOK AND PLAN BEYOND THIS 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. The soil moisture retrievals from such radiometer have spatial resolution ranging from ~40-50 km.

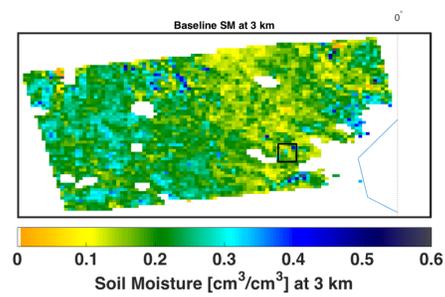
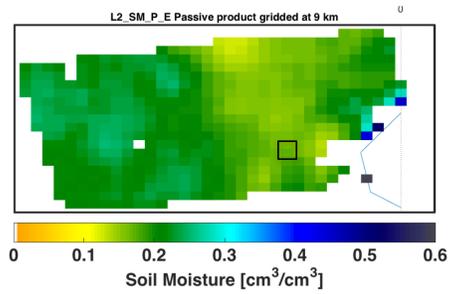
The SMAP observatory was the first of its kind delivering coincident and collocated measurements using an L-band radar and an L-band radiometer. The SMAP radar stopped working on 7<sup>th</sup> July 2015, but the SMAP radiometer continues to provide high-quality brightness temperature data. The SMAP active-passive algorithm produced data for nearly ~85 days at 9 km resolution before the SMAP radar stopped functioning. However, the SMAP Active-Passive algorithm has potential to use other satellite radar observations. This provides a unique opportunity to obtain the status of geophysical information such as soil moisture at much higher spatial resolutions by incorporating the Sentinel SAR data in the SMAP active-passive algorithm. The higher resolution SMAP-Sentinel Active-Passive (L2SMSP) soil moisture retrievals require assessment in order to assess their 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 assessment. As a result, one should not expect that the assessment 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 beyond the this Version-3 Release include the following:

- *The Stage 2+ validated product.* In a future release, we expect to improve the Baseline algorithm parameters and the tau-omega model parameters, ultimately improving the absolute RMSE, bias and unbiased RMSE. With this, the L2SMSP assessment should exceed Stage 2+.
- *Increasing the number of CVS.* There are only a limited number of sites that qualify as CVS at 3 km. Efforts have to be made to increase the number of CVS. This is key for a more robust assessment at 3 km.
- *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 dataset used in its development. For example, use of organic content in the dielectric mixing model to determine better estimate of dielectric constant for organic rich soils of forest and high latitudes.
- *Use of retrieved Tau.* The parameter set defined in the L2SMP ATBD was implemented for computing *tau* using the climatology of vegetation-water-content (VWC). Using a retrieved tau or alternatively, the real VWC (based on real-year NDVI) instead of climatology may help reduce the high unbiased RMSE observed for some cropland regions. We plan to also explore retrieval of *tau* using the cross-pol backscatter signature from the SAR data used in the SMAP Active-passive algorithm. Studies have shown that the SAR cross-pol backscatters carry valuable information about the vegetation attributes such as VWC and the structure.

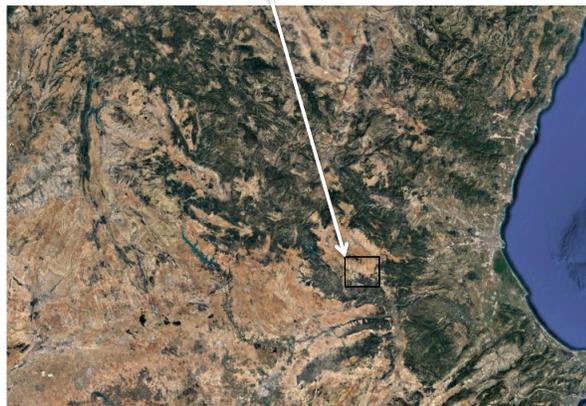
# 10 APPENDIX

## 10.1 Appendix A: L2SMSP Maps Surrounding SMAP CVS

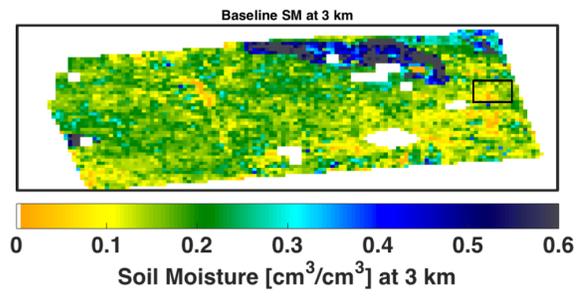
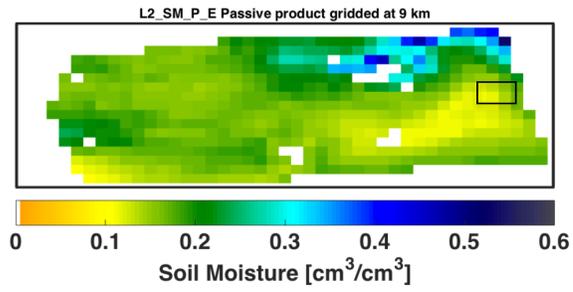
Date: 2016-03-23



### Core Site: Valencia



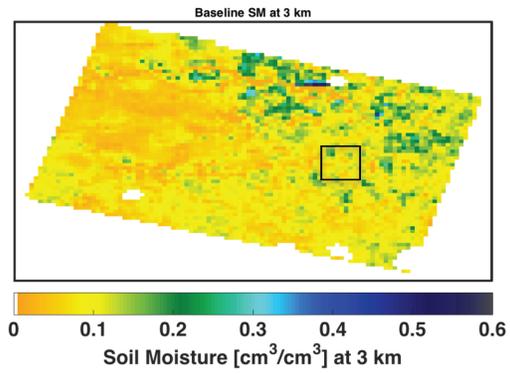
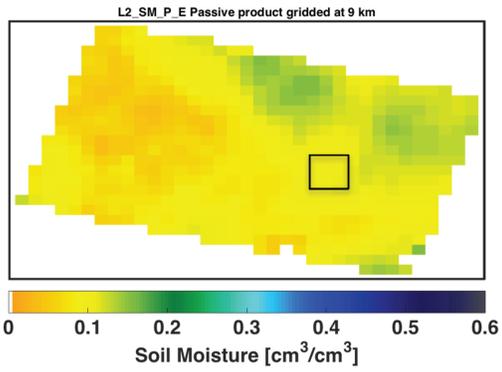
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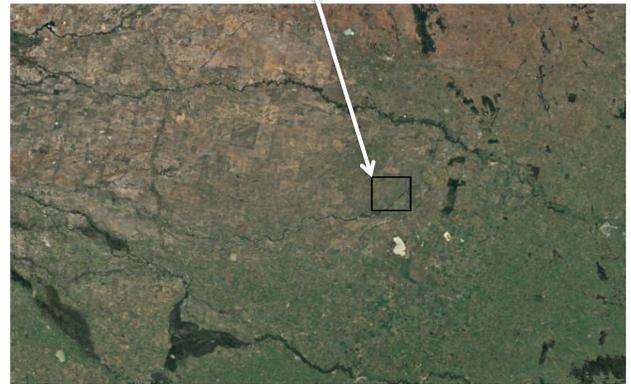
## Core Site: Carman



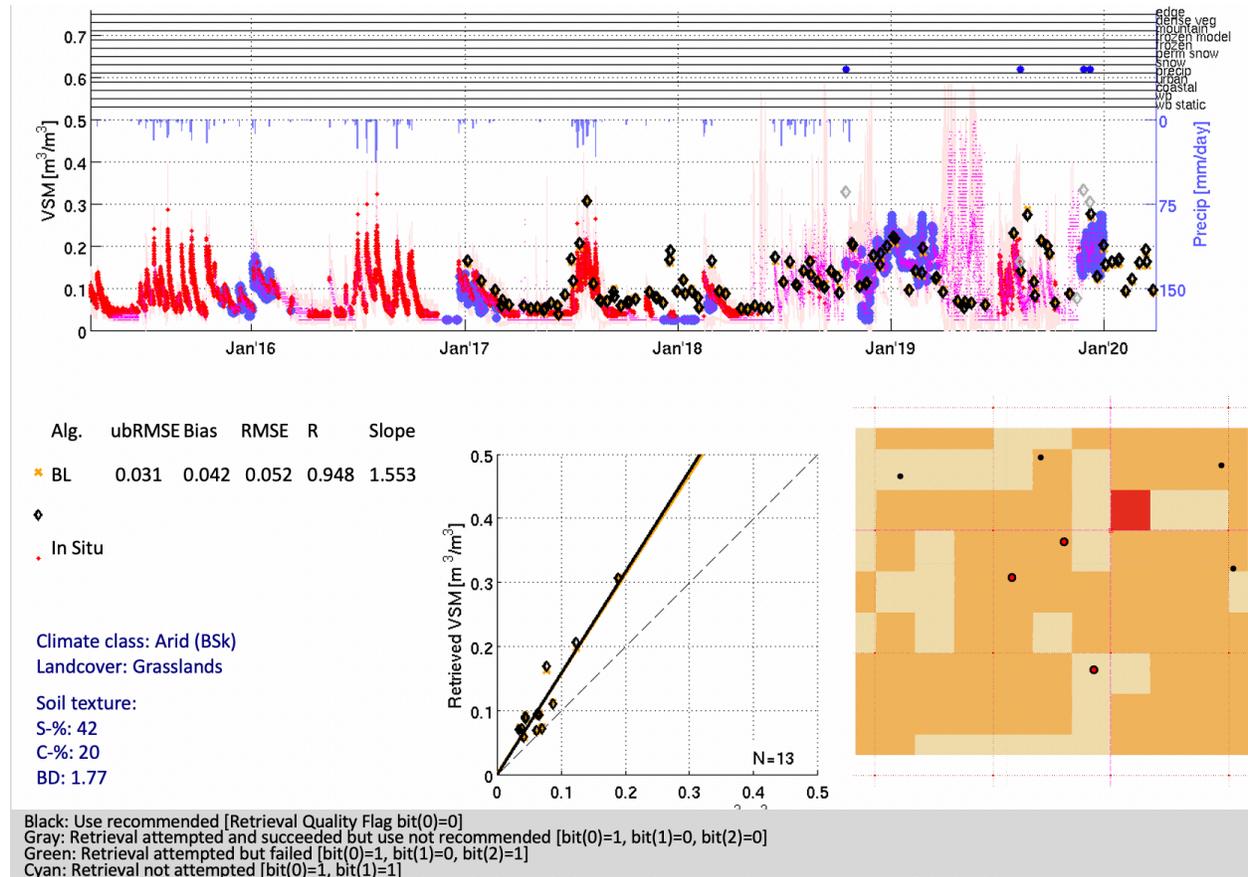
Date: 2016-03-12



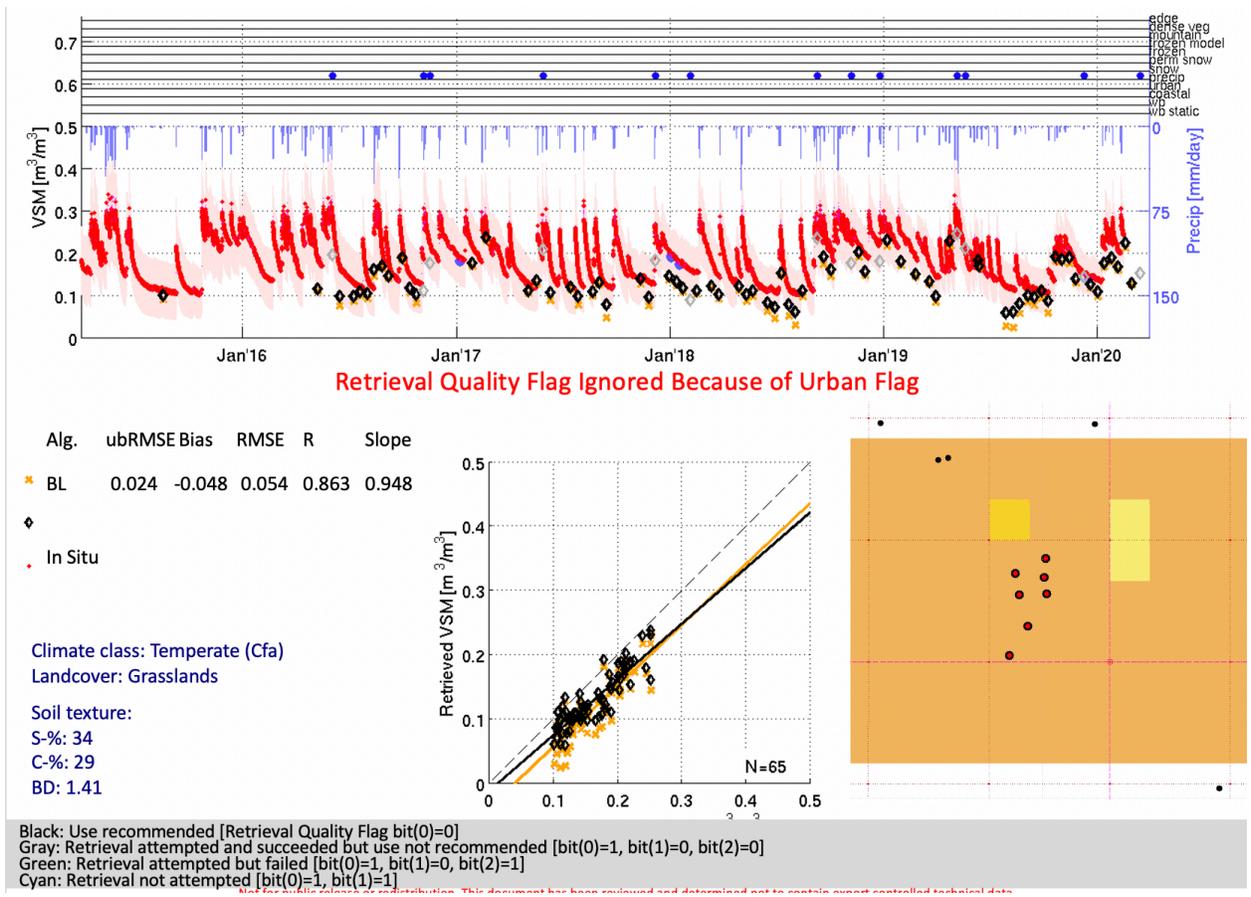
## Core Site: Yanco



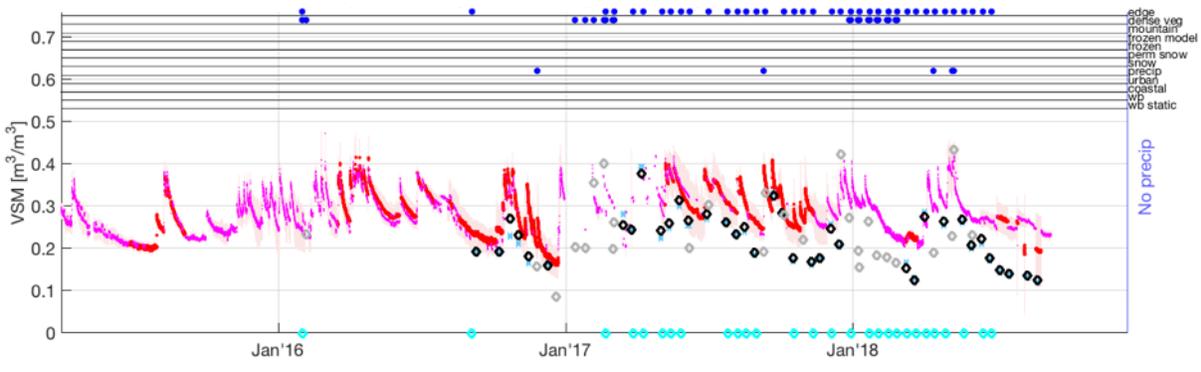
## 10.2 Appendix B: SMAP CVS Matchup Time Series at 3 [km] EASE Grid



L2SMSP Assessment Tool Report for Walnut Gulch, Arizona, USA, at 3 km EASE grid.

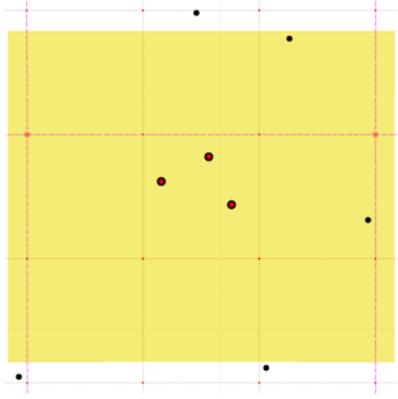
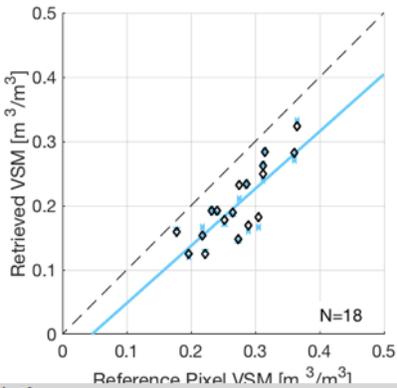


L2SMSP Assessment Tool Report for TxSON (Site-1), Texas, USA, at 3 km EASE grid.



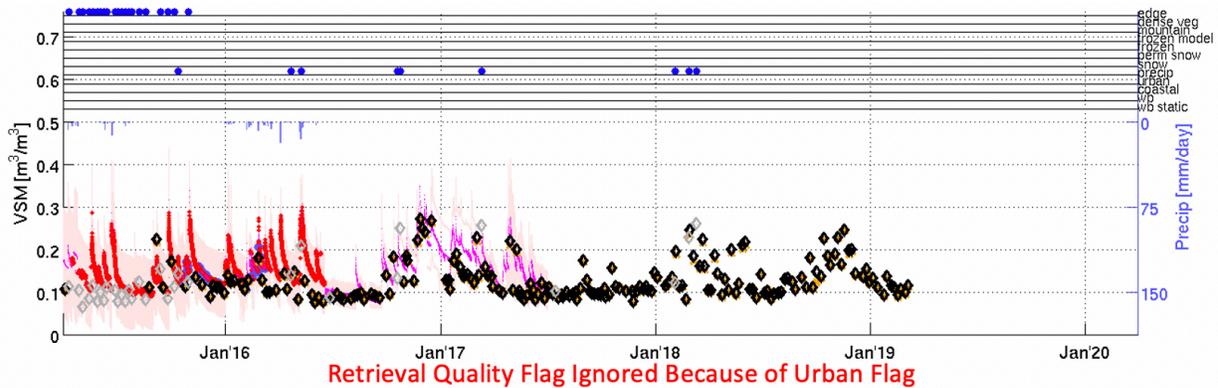
Alg.	ubRMSE	Bias	RMSE	R	Slope
BL	0.034	-0.071	0.078	0.800	0.891
In Situ					

Climate class: Temperate (Cwa)  
 Landcover: Croplands  
 Soil texture:  
 S-%: 26  
 C-%: 19  
 BD: 1.30



Black: Use recommended [Retrieval Quality Flag bit(0)=0]  
 Gray: Retrieval attempted and succeeded but use not recommended [bit(0)=1, bit(1)=0, bit(2)=0]  
 Green: Retrieval attempted but failed [bit(0)=1, bit(1)=0, bit(2)=1]  
 Cyan: Retrieval not attempted [bit(0)=1, bit(1)=1]

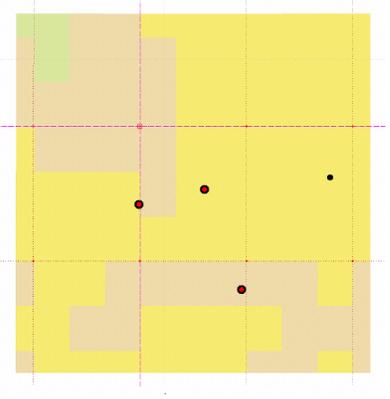
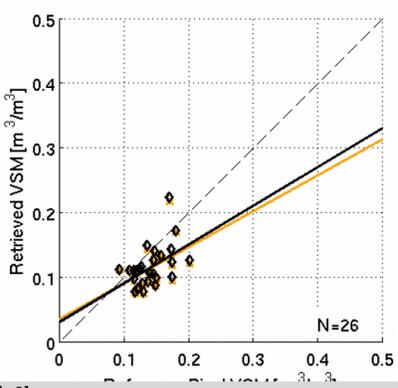
L2SMSP Assessment Tool Report for Monte Buey, Argentina, at 3 km EASE grid.



Alg.	ubRMSE	Bias	RMSE	R	Slope
✱ BL	0.029	-0.029	0.041	0.470	0.556

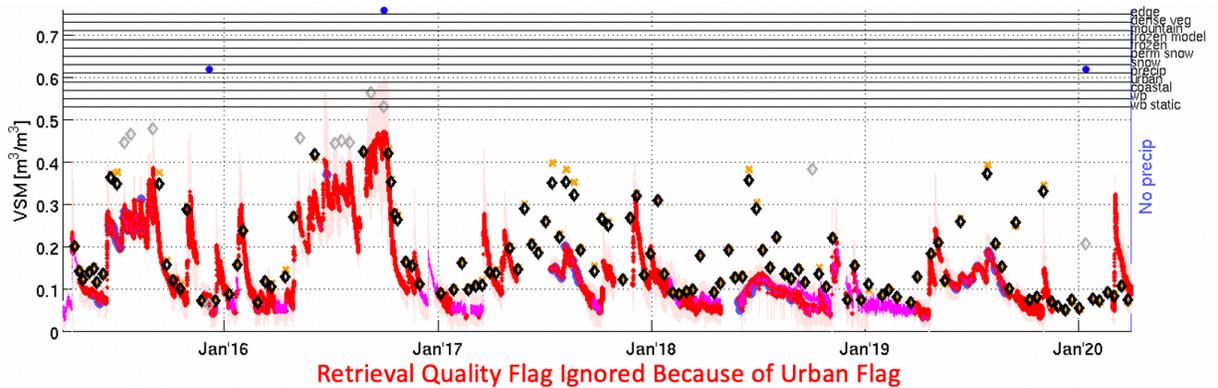
◆ In Situ

Climate class: Arid (BSk)  
 Landcover: Croplands  
 Soil texture:  
 S-%: 19  
 C-%: 49  
 BD: 1.40



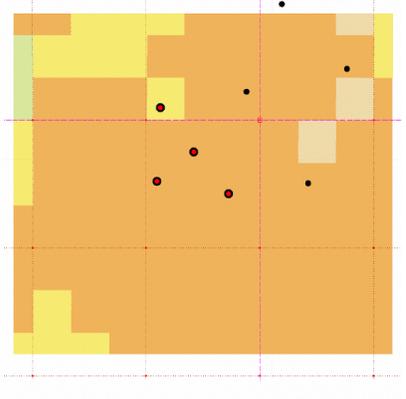
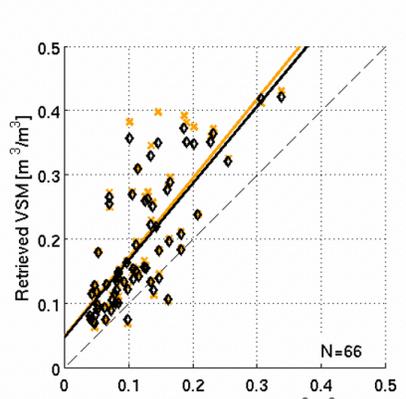
Black: Use recommended [Retrieval Quality Flag bit(0)=0]  
 Gray: Retrieval attempted and succeeded but use not recommended [bit(0)=1, bit(1)=0, bit(2)=0]  
 Green: Retrieval attempted but failed [bit(0)=1, bit(1)=0, bit(2)=1]  
 Cyan: Retrieval not attempted [bit(0)=1, bit(1)=1]

L2SMSP Assessment Tool Report for Valencia, Spain, at 3 km EASE grid.



Alg.	ubRMSE	Bias	RMSE	R	Slope
★ BL	0.069	0.076	0.103	0.752	1.234
◆ In situ					

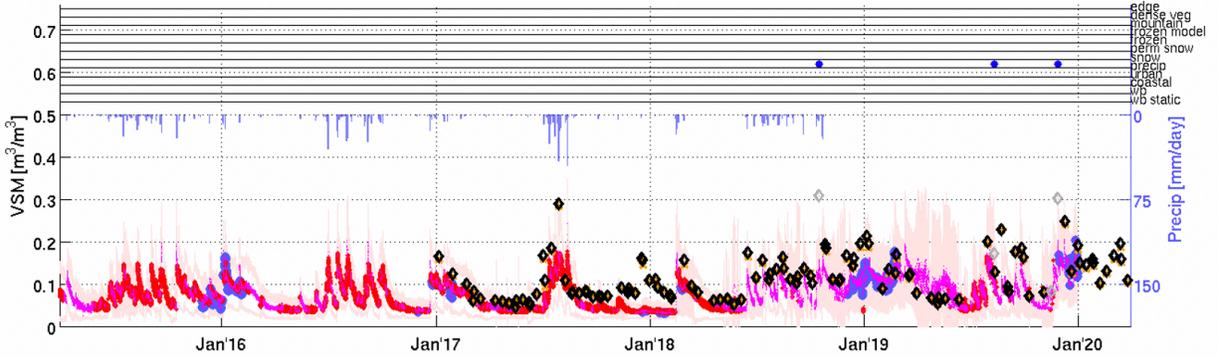
Climate class: Arid (BSk)  
 Landcover: Grasslands  
 Soil texture:  
 S-%: 46  
 C-%: 31  
 BD: 1.44



Black: Use recommended [Retrieval Quality Flag bit(0)=0]  
 Gray: Retrieval attempted and succeeded but use not recommended [bit(0)=1, bit(1)=0, bit(2)=0]  
 Green: Retrieval attempted but failed [bit(0)=1, bit(1)=0, bit(2)=1]  
 Cyan: Retrieval not attempted [bit(0)=1, bit(1)=1]

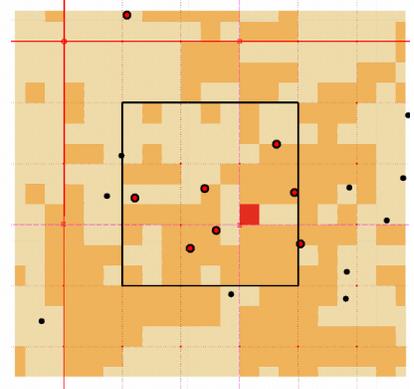
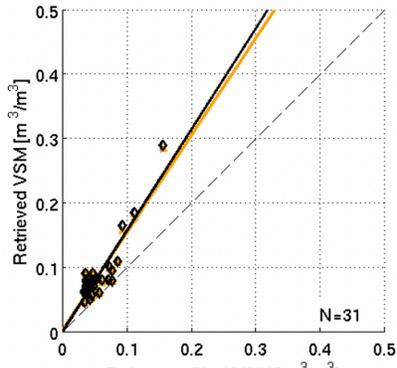
L2SMSP Assessment Tool Report for Yanco, Australia, at 3 km EASE grid.

# 10.3 Appendix C: SMAP CVS L2SMSMP Matchup Time Series at 9 [km] EASE Grid



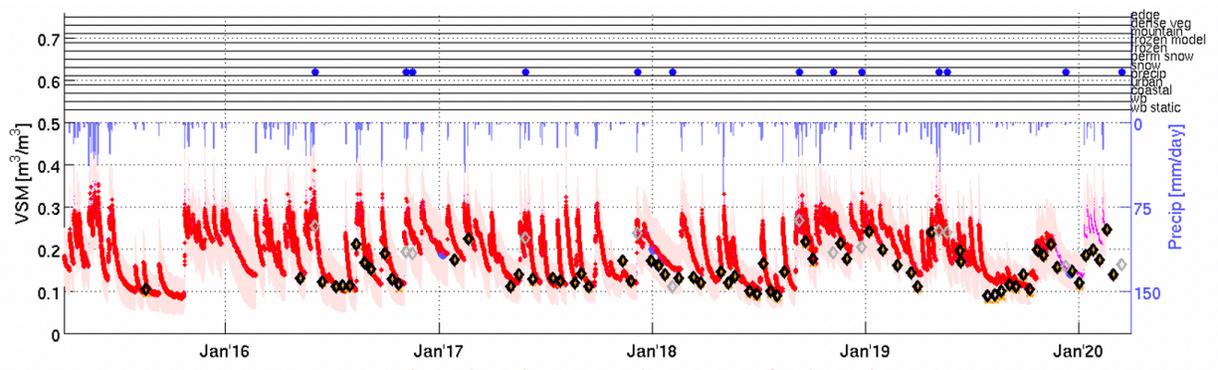
Alg.	ubRMSE	Bias	RMSE	R	Slope
★ BL	0.024	0.031	0.039	0.901	1.510
◆					
● In Situ					

Climate class: Arid (BSk)  
 Landcover: Grasslands  
 Soil texture:  
 S-%: 47  
 C-%: 18  
 BD: 1.42



Black: Use recommended [Retrieval Quality Flag bit(0)=0]  
 Gray: Retrieval attempted and succeeded but use not recommended [bit(0)=1, bit(1)=0, bit(2)=0]  
 Green: Retrieval attempted but failed [bit(0)=1, bit(1)=0, bit(2)=1]  
 Cyan: Retrieval not attempted [bit(0)=1, bit(1)=1]

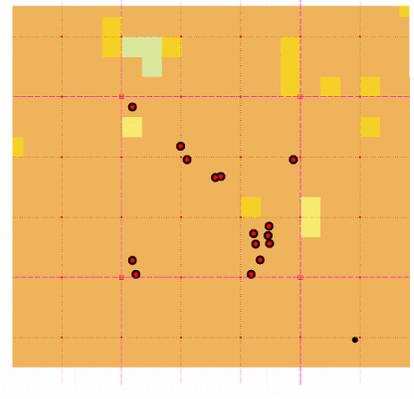
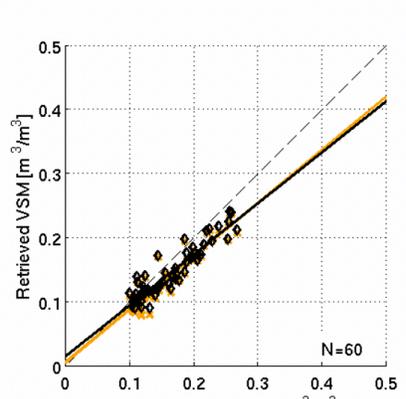
L2SMSMP Assessment Tool Report for Walnut Gulch, Arizona, USA, at 9 km EASE grid.



Retrieval Quality Flag Ignored Because of Urban Flag

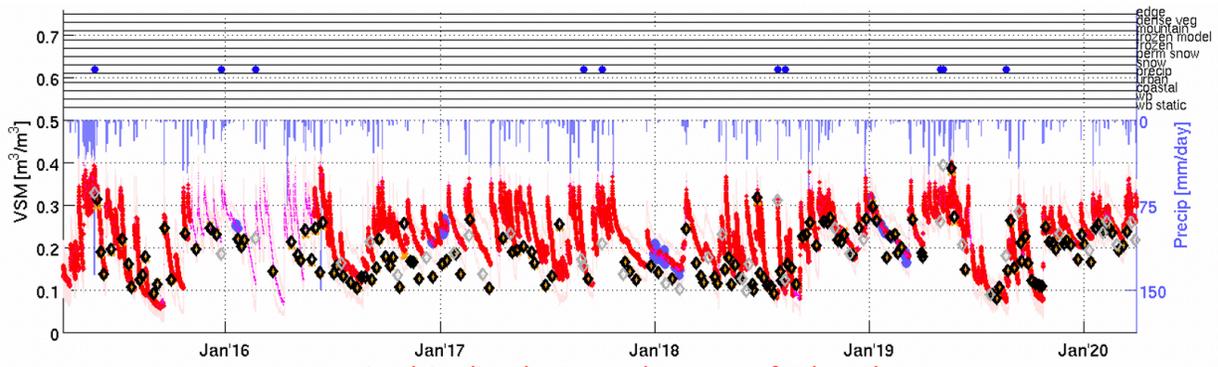
Alg.	ubRMSE	Bias	RMSE	R	Slope
* BL	0.018	-0.023	0.029	0.927	0.829

◆ In Situ  
 Climate class: Temperate (Cfa)  
 Landcover: Grasslands  
 Soil texture:  
 S-%: 26  
 C-%: 36  
 BD: 1.40



Black: Use recommended [Retrieval Quality Flag bit(0)=0]  
 Gray: Retrieval attempted and succeeded but use not recommended [bit(0)=1, bit(1)=0, bit(2)=0]  
 Green: Retrieval attempted but failed [bit(0)=1, bit(1)=0, bit(2)=1]  
 Cyan: Retrieval not attempted [bit(0)=1, bit(1)=1]

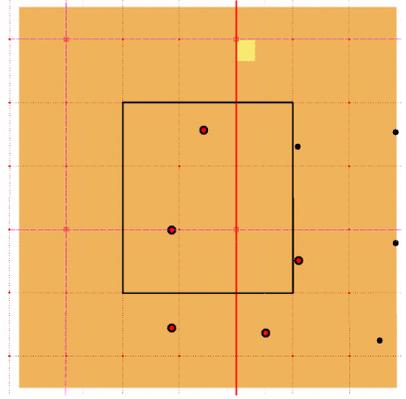
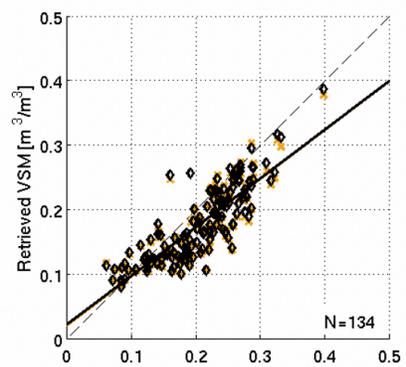
L2SMSP Assessment Tool Report for TxSON (Site-2), Texas, USA, at 9 km EASE grid.



Alg.	ubRMSE	Bias	RMSE	R	Slope
★ BL	0.035	-0.030	0.046	0.842	0.758

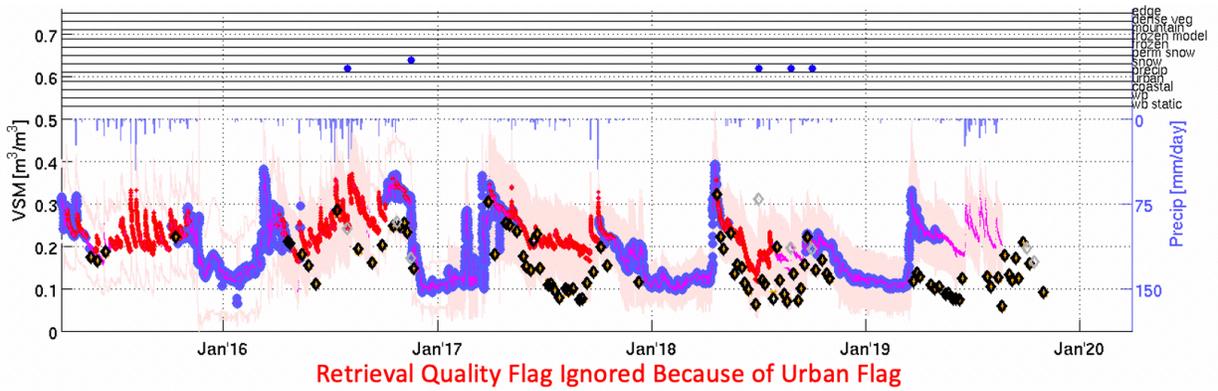
◆ In Situ

Climate class: Temperate (Cfa)  
 Landcover: Grasslands  
 Soil texture:  
 S-%: 16  
 C-%: 20  
 BD: 1.41



Black: Use recommended [Retrieval Quality Flag bit(0)=0]  
 Gray: Retrieval attempted and succeeded but use not recommended [bit(0)=1, bit(1)=0, bit(2)=0]  
 Green: Retrieval attempted but failed [bit(0)=1, bit(1)=0, bit(2)=1]  
 Cyan: Retrieval not attempted [bit(0)=1, bit(1)=1]

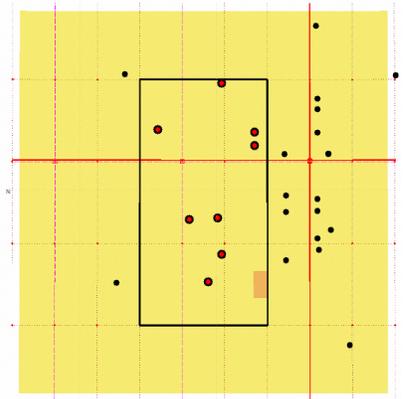
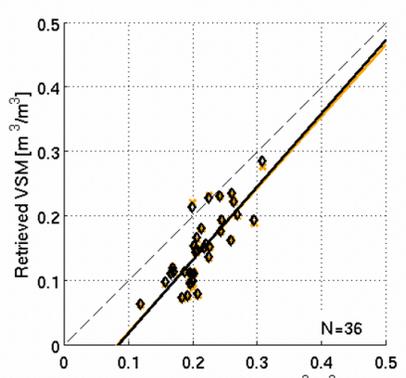
L2SMSP Assessment Tool Report for Little Washita (Site-1), Oklahoma, USA, at 9 km EASE grid.



Alg.	ubRMSE	Bias	RMSE	R	Slope
✱ BL	0.034	-0.068	0.076	0.781	1.114

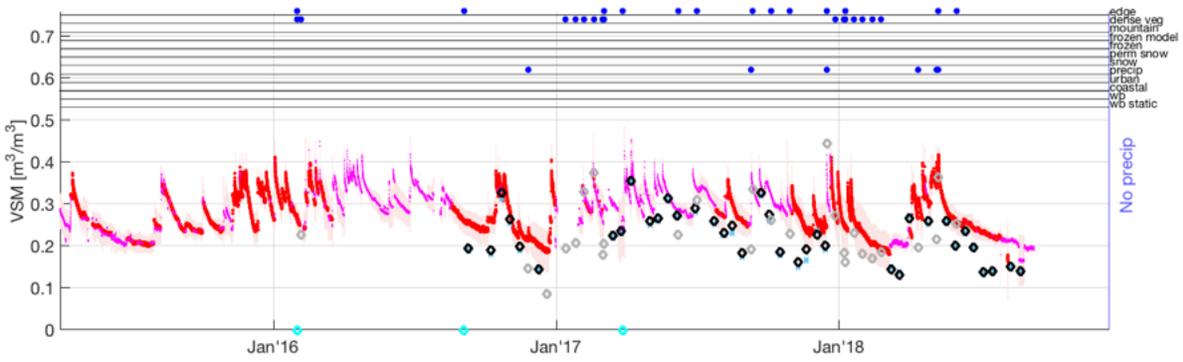
◆ In Situ  
 • In Situ

Climate class: Cold (Dfb)  
 Landcover: Croplands  
 Soil texture:  
 S-%: 32  
 C-%: 24  
 BD: 1.22



Black: Use recommended [Retrieval Quality Flag bit(0)=0]  
 Gray: Retrieval attempted and succeeded but use not recommended [bit(0)=1, bit(1)=0, bit(2)=0]  
 Green: Retrieval attempted but failed [bit(0)=1, bit(1)=0, bit(2)=1]  
 Cyan: Retrieval not attempted [bit(0)=1, bit(1)=1]

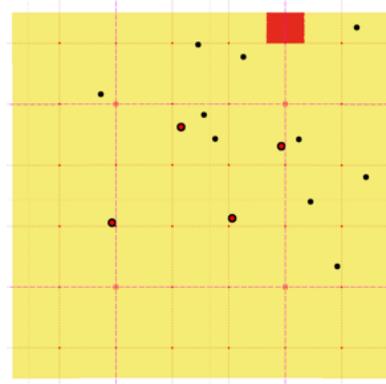
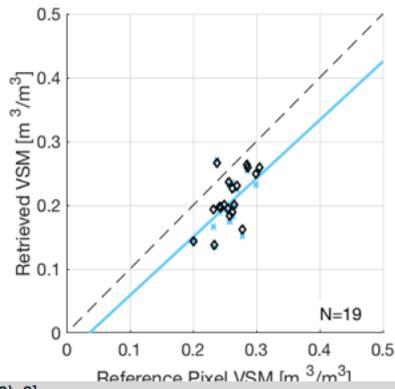
L2SMSP Assessment Tool Report for Kenaston (Site-1), Canada, at 9 km EASE grid.



Alg.	ubRMSE	Bias	RMSE	R	Slope
BL	0.032	-0.055	0.063	0.575	0.917

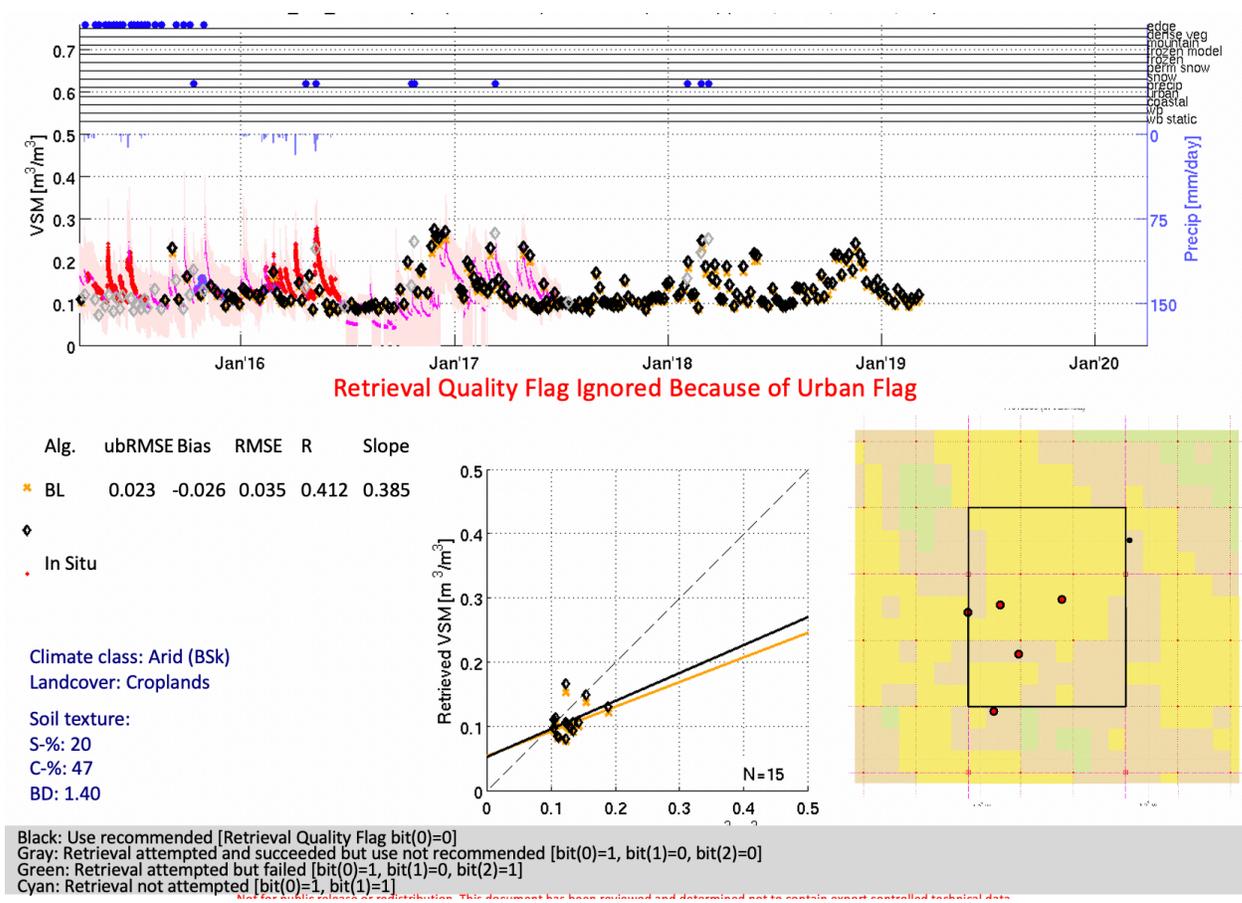
■ In Situ  
■

Climate class: Temperate (Cwa)  
 Landcover: Croplands  
 Soil texture:  
 S-%: 26  
 C-%: 19  
 BD: 1.30

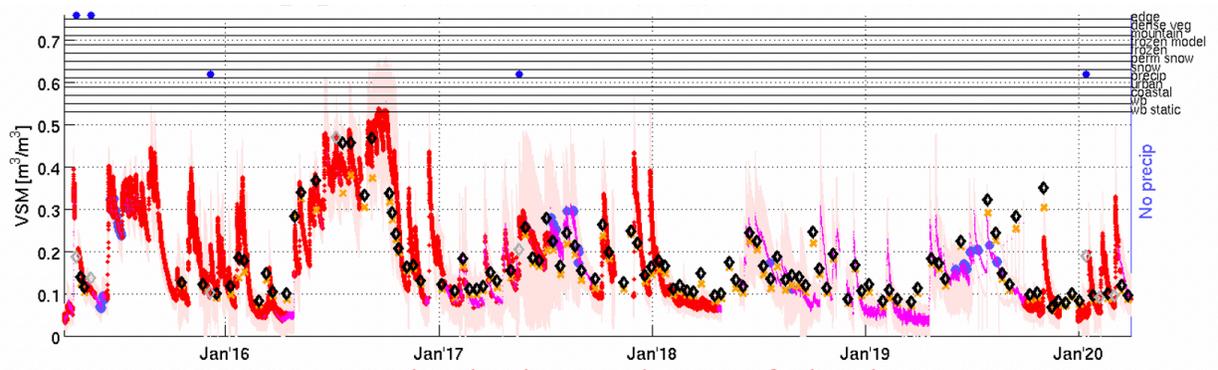


Black: Use recommended [Retrieval Quality Flag bit(0)=0]  
 Gray: Retrieval attempted and succeeded but use not recommended [bit(0)=1, bit(1)=0, bit(2)=0]  
 Green: Retrieval attempted but failed [bit(0)=1, bit(1)=0, bit(2)=1]  
 Cyan: Retrieval not attempted [bit(0)=1, bit(1)=1]

L2SMSP Assessment Tool Report for Monte Buey, Argentina, at 9 km EASE grid.

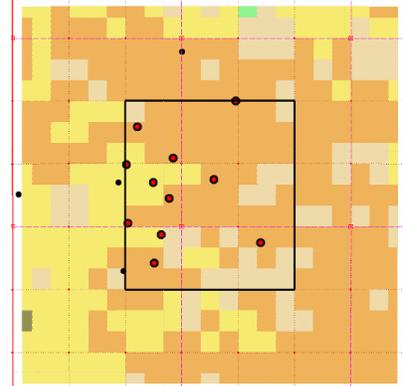
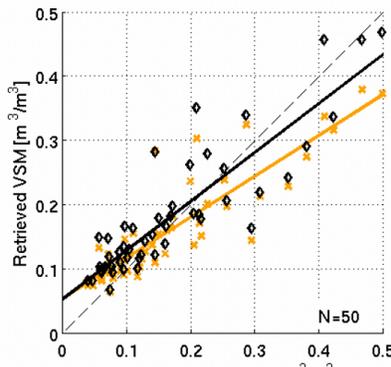


L2SMSP Assessment Tool Report for Valencia, Spain, at 9 km EASE grid.



Alg.	ubRMSE	Bias	RMSE	R	Slope
★ BL	0.058	-0.009	0.058	0.882	0.636
◆ In Situ					

Climate class: Arid (BSk)  
 Landcover: Grasslands  
 Soil texture:  
 S-%: 37  
 C-%: 43  
 BD: 1.34



Black: Use recommended [Retrieval Quality Flag bit(0)=0]  
 Gray: Retrieval attempted and succeeded but use not recommended [bit(0)=1, bit(1)=0, bit(2)=0]  
 Green: Retrieval attempted but failed [bit(0)=1, bit(1)=0, bit(2)=1]  
 Cyan: Retrieval not attempted [bit(0)=1, bit(1)=1]

Not for public release or redistribution. This document has been reviewed and determined not to contain export controlled technical data.

L2SMSP Assessment Tool Report for Yanco, Australia, at 9 km EASE grid.

## 11 ACKNOWLEDGEMENTS

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