Soil Moisture Active Passive (SMAP) Project
Calibration and Validation for the L2/3_SM_A
Validated-Stage 1 Release Data Products (Version 4)

Prepared by:

_______________________________________ _______________________

Seungbum Kim — Date

SMAP L2SMA Algorithm Team

_______________________________________ _______________________

Jakob van Zyl — Date

SMAP L2SMA Science Team Lead

_______________________________________ _______________________

Andreas Colliander — Date

SMAP Algorithm Team Cal/Val Lead

_______________________________________ _______________________

Thomas Jackson — Date

SMAP Cal/Val Lead

Approved by:

_______________________________________ _______________________

Simon Yueh — Date

SMAP Project Scientist

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National Aeronautics and Space Administration

Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, California 91109-8099
California Institute of Technology

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1 EXECUTIVE SUMMARY

SMAP Level 2 Soil Moisture Active (L2SMA) retrievals provide L-band SAR-based global routine observations of soil moisture at a 3-km spatial resolution. The retrieval algorithms were evaluated over a wide range of landcover types and vegetation amounts. This document describes the Stage 1 Calibration/Validation (Cal/Val) of the SMAP L2SMA product specifically for the validated release. The SMAP Level 3 Soil Moisture Active (L3SMA) product is a daily composite of the L2SMA half-orbit files. Hence, analysis and assessment of the L2SMA product presented in this document can be considered to cover the L3SMA product also. The SMAP L2SMA and L3SMA products are available only for ~85 days (14th April, 2015 to 7th July, 2015) because the product generation stopped after detection of an anomaly in the SMAP radar hardware that led to the discontinuation of the radar data acquisition.

For the post-launch period of the SMAP mission, there are two objectives pertaining to the 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 (note that L2SMA product is not subject to the second objective but set its own target performance).

To achieve the abovementioned objectives, assessment of the L2SMA product is essential. The potential assessment methodologies include comparisons of SMAP L2SMA soil moisture retrievals with *in situ* soil moisture observations from core validation sites (CVS), sparse networks, other spaceborne instruments, and numerical models. The analyses with the CVS meet the criteria established by the Committee on Earth Observing Satellites (CEOS) Stage 1 validation [1], which supports validated release of the data based on a limited set of core validation sites. Inclusion of soil moisture data from sparse network and modeled soil moisture data will be taken up during the Stages 2-3 of the validation phase.

The baseline L2SMA algorithm inverts a lookup table pre-calculated with sophisticated forward models using a time series of observations. Soil surface roughness is specified as being constant over the time series to resolve retrieval ambiguity. The time-series multichannel retrieval algorithm searches the lookup table for a soil moisture solution such that the difference between computed and observed backscatter is minimized in the least squares sense. A second optional algorithm uses a change index approach based on the assumption of a linear relationship between backscattering coefficients (σ^0) and soil moisture. A third optional algorithm extends the change index to estimate the absolute value of soil moisture.

Examination of global retrieval maps indicates that the baseline algorithm characterizes soil moisture patterns more accurately than the optional algorithms: retrievals from the optional algorithms were generally too wet or too dry in different locations of the globe. A full cycle of soil moisture variation is required at each location of the Earth to reliably establish the linear relationship of the optional algorithms. The lack of these cycles due to the short period of the radar operation degrades the optional algorithm performance. Based upon these results, it is recommended that the baseline algorithm be adopted for the evaluation of the validated release.

The primary assessment of the L2SMA product for Stage 1 validation was based on CVS comparisons using metrics, time series plots, and global maps. The overall ubRMSE of the baseline retrievals (pre-validated version T12400) is 0.091 m^3/m^3, which is larger than the self-imposed target of 0.06 m^3/m^3 [2]. A large part of this error is due to the saturation of retrieval associated with erroneously ingesting the data from the radar receive-only mode. This error will be fixed in the future release. The bias error averaged over all the CVS sites is 0.020 m^3/m^3. Despite these errors, the global map of soil moisture is in general agreement with SMAP's Level 2 Soil Moisture Passive product.

Further improvement in retrievals is documented in this report: instead of dynamically constraining sigma0 bias, VWC correction, and roughness for every instance, a single estimate for each of the three parameters throughout 2.5 months results in more reliable retrieval. The time-invariant roughness is consistent with the reality for non-crop landcovers, but not necessarily so for croplands. Whether this scheme is appropriate for croplands will be examined in the future. The bias in σ^0 represents any missing physics (such as topography effect) of the forward model, since the calibration bias has been corrected. The ubRMSE with the improvement is 0.060 m^3/m^3, meeting the internal target of 0.06 m^3/m^3. The bias error averaged over all the CVS sites is -0.002 m^3/m^3.

Considering the quality of the current retrievals and the prospect of further improvements, the release L2SMA product is of sufficient level of maturity and quality that it can be approved for distribution to and use by the larger communities. Lacking the Stage-2 validation at present, however, this release is still noted as State-1 validation with Version 3.

2 CALIBRATION AND VALIDATION

2.1 OBJECTIVES

During the post-launch Cal/Val (Calibration/Validation) Phase of SMAP there are two objectives for each science product [3]:

- Calibrate, verify, and improve the performance of the science algorithms, and
- Validate accuracies of the science data products as specified in the L1 science requirements according to the Cal/Val timeline (note that L2SMA product is a research product and is not subject to the second objective).

The process is illustrated in Figure 1. In this Assessment Report the progress of the L2 Soil Moisture Active Team in addressing these objectives prior to validated release is described. The approaches and procedures utilized follow those described in the SMAP Cal/Val Plan [3] and Algorithm Theoretical Basis Document for the Level 2 & 3 Soil Moisture (Active) Data Products [2].

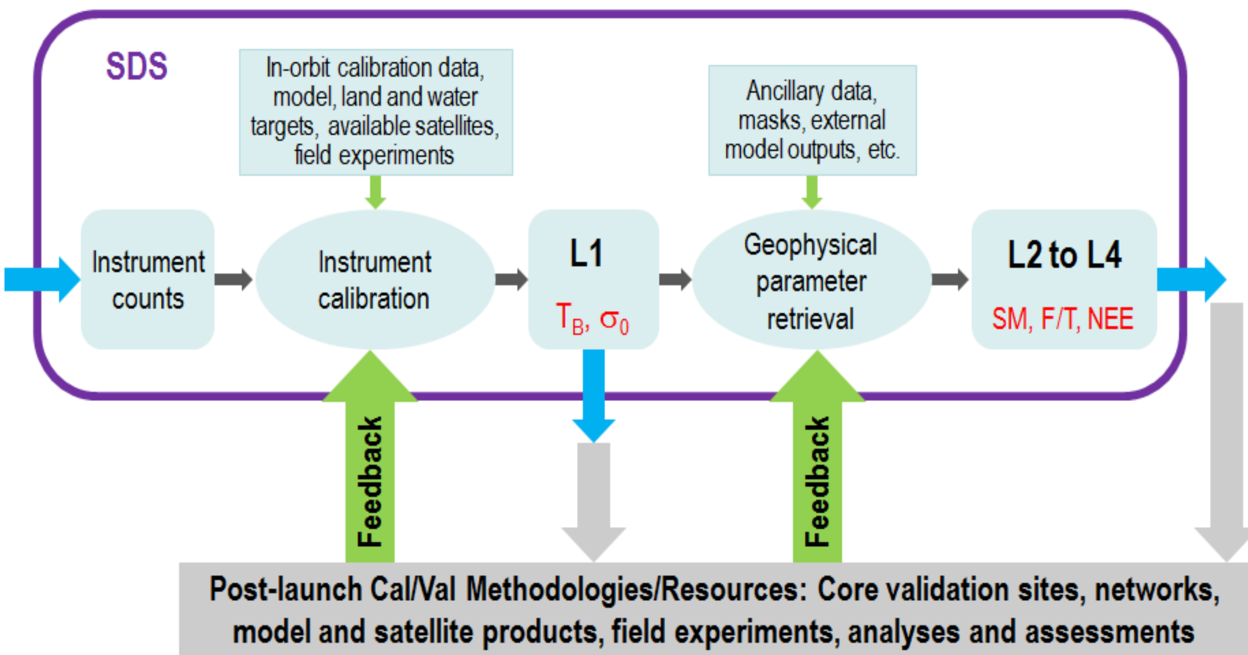


Figure 1. Overview of the SMAP Cal/Val Process.

SMAP established a unified definition in order to effectively address the mission requirements. These are documented in the SMAP Handbook/ Science Terms and Definitions [4], 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 L2SMA Team plans to meet the soil moisture retrieval accuracy of 0.06 m^3/m^3 as an internal target within the SMAP project.

The maturity of the products in the validated release is defined as follows:

- Early release is used to gain familiarity with data formats.
- Intended as a testbed to discover and correct errors.
- Minimally validated and may still 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 validated 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.
- The products may be replaced in the archive when an upgraded (provisional or validated) product becomes available.

In assessing the maturity of the L2SMA product, the L2SMA 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 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 validated release the L2SMA team has completed Stage 1 and begun Stage 2 (global assessment). The Cal/Val program will continue through these stages over year 2016.

2.2 APPROACHES

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 L2SMA 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.

Table 1 List of core and candidate validation sites for L2SMA cal/val (the validated assessment is limited to the core sites only)

Core Site				Candidate Site			
Name	Country	ID	Landcover	Name	Country	ID	Landcover
St Josephs	USA	16060301	Crop	HOAL	Austria	06010301	Crop
Kenaston	Canada	27010301	Crop	Little River	USA	16040301	Crop/Mix
Kenaston	Canada	27010302	Crop	South Fork	USA	16070301	Crop
Monte Buey	Argentina	19020301	Crop	South Fork	USA	16070302	Crop
Valencia	Spain	41100301	Crop	EURAC	Italy	44010301	Crop/Mix
Walnut Gulch	USA	16010301	Grass	Mpala	Kenya	24010301	Grass
Walnut Gulch	USA	16010302	Shrub	Zapotes	Mexico	32010301	Crop
TxSON	USA	48010301	Grass	Zapotes	Mexico	32010302	Crop
TxSON	USA	48010302	Grass	Walnut Gulch	USA	16010303	Shrub
Yanco	Australia	07010301	Crop	Tonzi	USA	25010301	Savanna
Yanco	Australia	07010302	Grass	Tonzi	USA	35010302	W. Savanna
Yanco	Australia	07010303	Grass	Sodankyla	Finland	17010301	W. Savanna
Yanco	Australia	07010304	Grass	Sodankyla	Finland	17010302	W. Savanna
				Sodankyla	Finland	17010303	W. Savanna

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. A site has to reach a level of maturity that would support them being used as a CVS. In some cases this is simply a latency problem that will be resolved in time. Prior to initiating validated-release assessments, the L2SMA 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 (see Section 4.4.1 of [3]):

- Assess the site for conditions that would introduce uncertainty
- Determine if the number of points is large enough to provide reliable estimates (at least 2)
- 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. 27 *in situ* locations around the world were selected as candidate validation sites. 13 out of these sites were chosen as *core* sites that meet the above criteria. The remaining 14 sites are currently *candidate* sites until remaining issues are resolved to satisfy the above criteria. The core and candidate sites are listed in Table 1.

3 L2SMA ALGORITHMS

The baseline SMAP Active algorithm inverts a lookup table representation of sophisticated forward models [5] (Eq. 1). Soil surface roughness is specified as being constant in time, to help resolve retrieval ambiguity. These concepts were implemented using time-series observations as a multichannel retrieval algorithm that searches the lookup table for a soil moisture solution such that the difference between computed and observed backscatter is minimized in the least squares sense:

$$
\begin{aligned}
&C(\overline{s},\overline{\varepsilon}_{r1},\overline{\varepsilon}_{r2},...,\overline{\varepsilon}_{rN}) = \\
&w_{1,HH}(\sigma^0_{HH,1} - \sigma^0_{HH,fwd}(\overline{s},\overline{\varepsilon}_{r1},\overline{f}VWC_1)+\overline{c})^2 + w_{1,VV}(\sigma^0_{VV,1} - \sigma^0_{VV,fwd}(\overline{s},\overline{\varepsilon}_{r1},\overline{f}VWC_1)+\overline{c})^2 + \\
&w_{2,HH}(\sigma^0_{HH,2} - \sigma^0_{HH,fwd}(\overline{s},\overline{\varepsilon}_{r2},\overline{f}VWC_2)+\overline{c})^2 + w_{2,VV}(\sigma^0_{VV,2} - \sigma^0_{VV,fwd}(\overline{s},\overline{\varepsilon}_{r2},\overline{f}VWC_2)+\overline{c})^2 + ... + \\
&w_{N,HH}(\sigma^0_{HH,N} - \sigma^0_{HH,fwd}(\overline{s},\overline{\varepsilon}_{rN},\overline{f}VWC_N)+\overline{c})^2 + w_{N,VV}(\sigma^0_{VV,N} - \sigma^0_{VV,fwd}(\overline{s},\overline{\varepsilon}_{rN},\overline{f}VWC_N)+\overline{c})^2
\end{aligned} \tag{1}
$$

where the overbar denotes a parameter that is retrieved. Radar backscattering coefficients from observations and from the forward model are denoted as σ^0 and σ^0_{fwd} (both in dB), respectively. Numeric subscripts, 1, 2, .., N, denote time indexes. f is a VWC adjustment factor to retrieve, ranging from 0 and 2, and c is an estimated bias correction.

The second optional algorithm is the change index (M_s, [6]) approach implementing the linear relationship between backscattering coefficients (σ^0) and soil moisture.

$$M_S = \left(\sigma^0(t) - \sigma^0_{dry}\right) / \left(\sigma^0_{wet} - \sigma^0_{dry}\right) \tag{2}$$

where $\sigma^0(t)$ is the observation at one time. σ^0_{wet} and σ^0_{dry} are two extreme values of σ^0 of a pixel (reference states). The reference states were obtained from the Aquarius data at 100-km resolution (36-km posting), in the absence of the 3-km global σ^0 over a complete soil moisture cycle.

The third optional algorithm extends the linear relationship of the change index approach to estimate the absolute value of soil moisture, based on concepts developed in [7]:

$$M_v = C_0 + C_1 \frac{\sigma_{hh} + \sigma_{vv}}{2} \tag{3}$$

These two coefficients for each pixel will be determined using the expected minimum and maximum values for soil moisture and SMAP's 3-km σ^0 over a complete soil moisture cycle. In its absence, the validated release output converts the change index of Eq. 2 into soil moisture using porosity:

$$M_v = porosity \times M_s \tag{4}$$

Due to the failure of the SMAP radar, it is unlikely that the set of data available to derive σ^0_{wet}, σ^0_{dry}, C1, and C2 from SMAP data at high resolution over a complete soil moisture cycle will be available.

4 PROCESS USED FOR VALIDATED RELEASE

This section describes the input data used to produce the validated release product, the details of the production configuration, and refinements applied to the L2SMA baseline product since launch until the validated release. The primary refinement was the addition of a "bias" error into the retrieval. The optimization of VWC, landcover classification, and forward model update were tested at each CVS: however, these are not implemented in the global validated release data and will be part of the validated release next year.

4.1 L1C Radar Data

The L1C backscatter inputs to the L2SMA retrieval were evaluated for the validated release, in order to understand algorithm behavior and sensitivity to the radar input. The validated level performance of the L1 radar measurements is summarized in Table 2. The major characteristics of the validated L1C_S0 are (see the L1C_S0 validated release report)

- Major artifacts were removed
- Radiometric accuracy is within 1 dB with respect to Aquarius and PALSAR
- Azimuthal variation is reduced to 0.3 dB with respect to L1B_S0
- Geolocation accuracy is within 500m
- Faraday rotation has not yet been corrected.

The 1dB error is compatible with the pre-launch error budget, which should allow soil moisture retrieval with an accuracy of 0.063 m^3/m^3 (Table 3).

Table 2. Validated-level Performance of SMAP L1 Radar Data.

	Validated-level	**Mission Requirement**
Relative accuracy (total Kp)	1 dB	1 dB (VV and HH)
Geolocation accuracy	~500m	1 km
Version	T13030	

Table 3. Pre-launch error budget for the baseline algorithm [2]. The values of the Kp error range are given for the outer and inner swath edge. Soil moisture retrieval uses both fore and aft looks to reduce the effective Kp error.

Error sources	Budget (m^3/m^3)	
	Outer edge	Inner edge
A) K_p 0.75-1.0 dB error (1σ, co-pol, fore look)	0.035	0.043
B) Vegetation water content error (1σ, 10%)	0.01	
C) Forward model error	0.04	
D) Dielectric model uncertainty	0.02	
E) Soil texture: 5% error	0.004	
m_v retrieval error up to VWC of ~ 3 kg/m^2	*0.058*	*0.063*

4.2 Details of major inputs

The SMAP L2SMA team chose to define the assessment period as April 24-July 07, 2015. This is the period of data availability from the SMAP mission when the radar was acquiring observations 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. Full details of the inputs are available in the L2/3SMA User Guide.

L1C_S0: version T13030, fore+aft average, averaged to 3 km. This product is the L1C_S0 validated release. The differences between beta and validated release are expected to be smaller than a few tenth of dB.

GBTS (Global Backscatter Time Series): GBTS is an internal product that is created by compositing multiple SMAP radar observations. σ^0 quality flags are ignored in the validated release during the composite. The following surface flags are applied to select only meaningful σ^0 for soil moisture purposes: excluding static urban flag, static frozen/ice flag, snow flag, precipitation flag, and nadir gap flag. Dynamic freeze/thaw, DEM, and dense vegetation flags are not applied since these will be examined during the L2SMA retrieval.

Reference states of σ^0: To evaluate the change index approach (Option 2 and 3), monthly Aquarius σ^0 data were compiled to derive the maximum and minimum values of each grid cell.

4.3 Output details

The retrievals that are assessed in this report have the version T12400 (*pre-validated release* version). In addition to the baseline algorithms described in the ATBD, this version incorporates refinements: bias correction and VWC correction in Sections 4.4 to 4.4.2. The estimate of constant roughness in Section **Error! Reference source not found.** is not implemented in T12400. Retrieval and surface flags are eported in T12400 as follows. There will be very small difference between T11940 and the pre-validation release product due to the slight difference in the input L1C_S0 data. The L1C_S0 difference is expected to be very small. Therefore the assessments in the current report will be applicable to those for the pre-validated release retrievals. Full details of the inputs are available in the L2/3SMA User Guide.

Table 4. Important details of output flags

Retrieval flag	
Attempt	Retrieval is not attempted if a grid cell is flagged by static water/urban/wetland, permanent snow, or frozen condition according to surface temperature
Success	Attempted retrieval is successful if the optimization is completed
Recommend	Successful retrieval is recommended if the pixel lies outside the nadir gap and is not densely vegetated
Surface flag	
Dense vegetation	Is set if VWC > 5 kg/m^2
Urban	Is set if the static urban fraction > 5%
Permanent water	Is set if the static water fraction > 10%
Mountain	Is set if stdev (DEM) > 250m

4.4 Refinements

In addition to the baseline algorithms described in the ATBD, the pre-validation release version incorporates refinements of correcting for bias and VWC, as detailed below. In the offline implementation of retrieval, these refinements were applied to the entire 2.5-month time-series. For example, one bias value is removed from the entire time-series in the offline implementation; while in the pre-validation release, the bias changes in the retrieval at each time. The differences between pre-validation release and the offline retrieval are summarized in Table 5.

Table 5 Differences between pre-validation release and the offline retrieval.

	Pre-validation release	Offline
Bias estimate	Each retrieval*	One value**
Estimate of VWC correction factor	Each retrieval*	One value**
Roughness estimate	Each retrieval*	One value**

* One value is estimated using the most recent 6 observations of HH and VV at each time of observation per pixel

** One value is estimated using the entire 2.5-months of HH and VV per pixel.

4.4.1 Bias correction

A temporal bias may be present between L1C σ^0 observation and the forward model due to a number of factors. The L1C calibration process removed this temporal bias. Some of the factors that impact the bias include the fact that the forward model may not have simulated the density of vegetation scatterers, which is expected to appear as a quasi-bias in the time-domain. Also, topography was not modeled in the forward model, which also may introduce a quasi-bias in the time-domain. A single temporal bias was removed during the optimization of each pixel. The bias is expected to be relatively independent of polarization; also a single value helps reduce the number of unknowns during the optimization. The optimization of Eq. 1 searches for the bias between -5 to 5 dB. This refinement significantly improves the retrieval, resolves retrieval failure, and has been implemented in the pre-validated release product.

4.4.2 VWC correction

VWC is an ancillary parameter used during the retrieval. However, the VWC is currently derived from a climatology database. To revise the VWC to incorporate contemporary conditions while keeping the number of unknowns smaller than those of independent observation, a single scaling factor is estimated. The estimate is an optimization of the cost function in Eq. 1 during the retrieval over the entire time-series:

$$\overline{VWC} = \mathrm{f}\times\mathrm{VWC}, \tag{4}$$

where $\overline{VWC}$ is the revised VWC, f is the estimated scaling factor, and VWC is the climatological ancillary data.

5 ASSESSMENTS

5.1 Global Maps and Baseline Selection

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 the following figures are global composites of SMAP L2SMA over a single 8-day cycle (May 18-25, 2015). Due to the nadir gap in coverage, 8-days of data are needed to cover the globe without gaps.

Figure 2 shows a global image developed from the SMAP L2SMA algorithms. 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. The global patterns show the expected soil moisture variability. Compared with the L2SMP retrievals in the inset of Figure 2, the global spatial patterns are in agreement but there are some regional bias differences between the two. L2SMA is less dry over the Sahara desert than L2SMP. The bare surface forward model assumes no topography and no penetration, while the topography in the area is expected to increase σ^0 (more than the topography does on the radiometer data) and penetration depth may reach 1 m. Subsurface features such as rocky terrain may cause retrieval errors. Over shrublands (Namibia, the southwest of the United States, southern Argentina, and Australia), the beta-release version and SMP agreed fairly well (see the beta assessment report). However, the pre-validated release retrievals of L2SMA are very wet, which are under investigation. The rainforest appears wetter in L2SMA than in L2SMP, but this is an area where the performances of both products are expected to perform poorly.

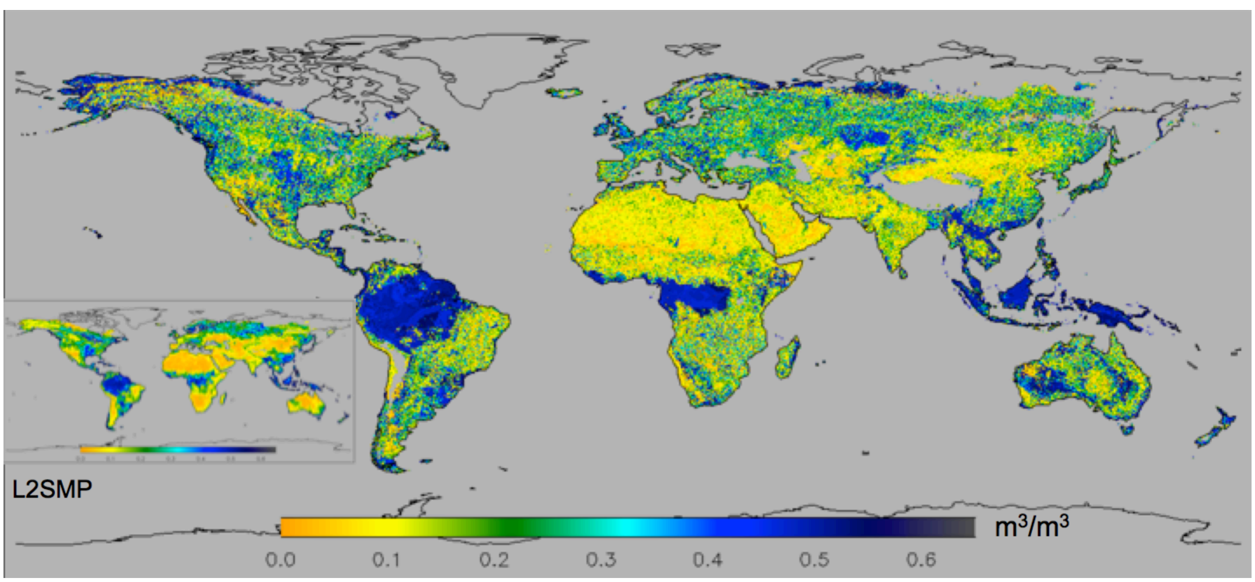


Figure 2. SMAP L2SMA baseline soil moisture for one 8-day cycle of May 19-26, 2015. The inset shows the L2SMP baseline retrievals (T12400, with the same color scale) over the same period. Retrieval gaps are due to the frozen condition (permanent and dynamic).

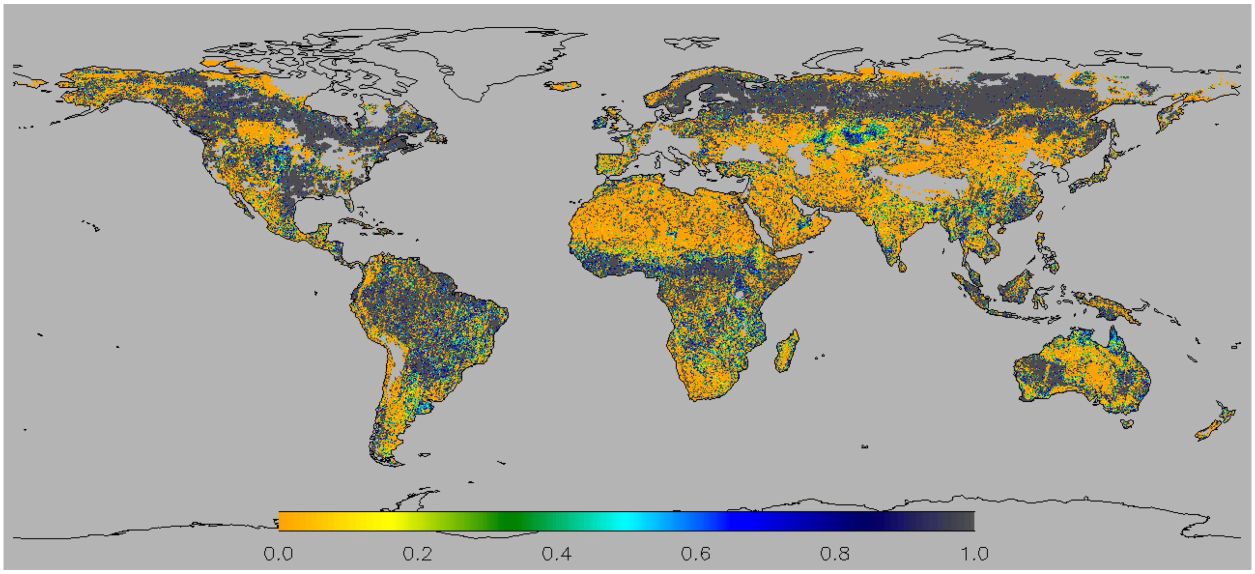


Figure 3. Same as Figure 2 except for SMAP L2SMA option 2 (change index, dimensionless).

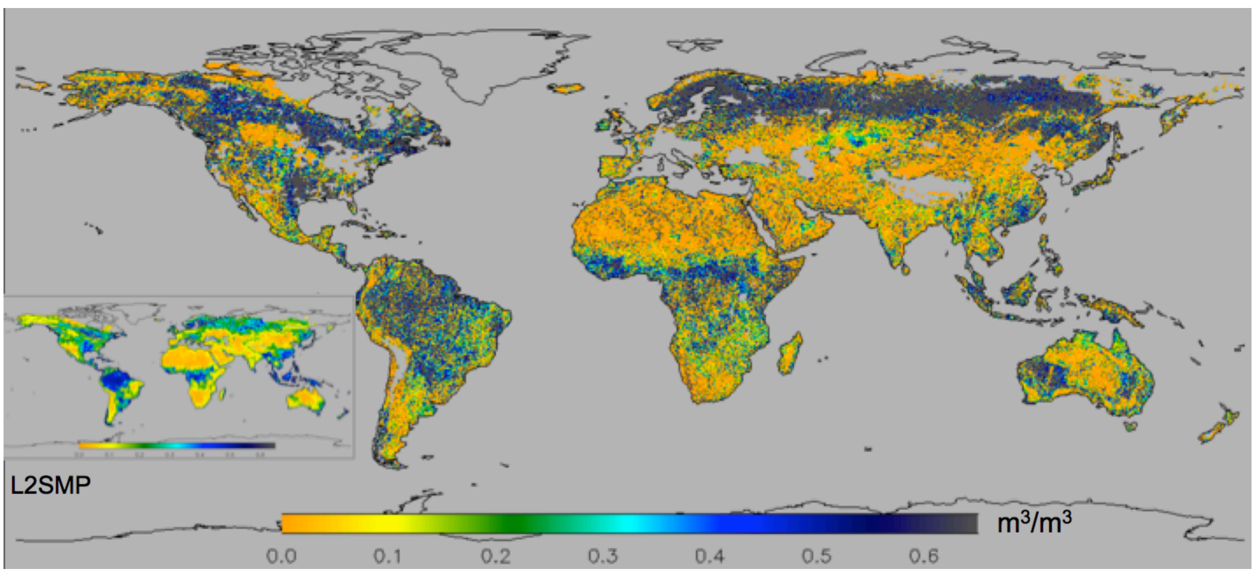


Figure 4. Same as Figure 2 except for SMAP L2SMA option 3 (change index absolute).

The retrievals of the two optional algorithms are shown in Figure 3 and Figure 4. The data gaps in the US Midwest, Europe, Northeast China, and Koreas are caused by the absence of the σ^0 reference states resulting from radio frequency interference (RFI) in the Aquarius observations. Compared with L2SMP, the optional algorithms are characterized as too wet (southern US, northeast US, southwest Australia, Amazon, boreal forests; often reaching 0.6 m^3/m^3) and too dry (Sahara, Alaska, central US, southern Argentina). These extremes are associated with the deficiencies in the σ^0 reference states that are derived from the Aquarius observations. Particularly in the areas of significant RFI contamination (US, Europe, East Asia), there are not enough RFI-clean samples to represent the driest and wettest conditions on the ground. For example, if the σ^0 reference states capture only a limited range of soil moisture variation, the change index of the option 2 algorithm will be larger than it should be, which will lead to too dry or too wet soil moisture retrievals in the option 3 result. Another issue is the spatial resolution of the Aquarius-based reference states (100 km), which will incorrectly modulate the outputs of the option 2 and 3 algorithms in the spatial domain. To resolve these two issues in the rigorous derivation of the σ^0 reference states at the appropriate spatial resolution, SMAP L1C_S0 data over at least one hydrological cycle are required. This is not feasible because of the SMAP radar failure. Consequently, the datacube approach is chosen as the baseline for the beta release.

5.2 Core Validation Sites (CVS) Validation

The Stage 1 validation for the L2SMA 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. Complete details of the validation results are available at [8]. The list of the CVS is provided in Table 1. Each CVS comparison is carefully reviewed and discussed by the L2SMA Team and Cal/Val Partners. All sites are then compiled to summarize the metrics and compute the overall performance shown in Table 6. The assessment results incorporate the following perspectives:

- As discussed in Section 5.1, the two optional algorithms are subject to inherent deficiencies (the inadequate length of record and spatial resolution of the σ^0 reference states). The validation of these two products is not included in the beta report, because the deficiencies limit the rigorous analysis of the validation results, and the future improvements of the optional algorithms.
- The pre-validation release product (T12400) implements temporally-varying correction of bias, VWC, and roughness. The offline version estimates static values of bias, VWC, and roughness over the 2.5 months, and reports higher precision. The details of these differences are summarized in Section 4.4.
- Validation statistics of L2SMAP at 3 km are included since they are unambiguously comparable with the L2SMA comparison statistics.

Table 6 SMAP L2SMA pre-validated Release (T12400) CVS Assessment. 'Offline' includes best performance achievable but not yet implemented in the validated products (see Section 4.4). L3SMAP validated release (T12400) statistics are from the baseline L2SMAP at 3-km resolution (Das et al. L3SMAP validated release report). See Table 1 for complete site information.

	ubRMSE (cm^3/cm^3)			**Bias (cm^3/cm^3)**			**RMSE (cm^3/cm^3)**			**R**		
Cropland	**pre-validated**	**offline**	**3km AP validated**	**pre-validated**	**offline**	**3km AP validated**	**pre-validated**	**offline**	**3km AP validated**	**pre-validated**	**offline**	**3km AP validated**
St Josephs	0.109	0.086	0.109	0.062	0.054	0.053	0.125	0.102	0.122	0.69	0.48	0.51
Kenaston (301)	0.123	0.104	0.057	-0.3	-0.025	-0.064	0.324	0.107	0.086	0.41	0.43	0.28
Kenaston (302)	0.092	0.077	0.101	0.21	-0.008	-0.040	0.229	0.077	0.109	0.48	0.63	0.09
Monte Buey	0.128	0.08	0.065	0.075	-0.016	-0.053	0.148	0.082	0.084	0.17	0.59	0.82
Valencia	0.039	0.032	0.042	-0.013	0.026	-0.064	0.041	0.041	0.077	0.34	0.42	0.27
Yanco (301)	0.124	0.049	0.110	0.069	-0.02	0.038	0.142	0.053	0.117	0.47	0.83	0.80
Average	**0.103**	**0.071**	**0.081**	**0.017**	**0.002**	**-0.022**	**0.104**	**0.071**	**0.099**	**0.43**	**0.56**	**0.46**
Grassland												
Walnut Gulch(301)	0.036	0.014	0.036	0.081	0.024	-0.010	0.089	0.028	0.037	0.16	-0.47	0.32
TxSON (301)	0.064	0.047	0.031	-0.089	-0.038	-0.063	0.110	0.060	0.070	0.44	0.8	0.92
TxSON (302)	0.19	0.08	0.041	-0.033	-0.028	-0.081	0.193	0.085	0.090	-0.42	0.61	0.79
Yanco (302)	0.057	0.058	0.071	0.024	-0.013	0.005	0.062	0.059	0.071	0.8	0.75	0.73
Yanco (303)	0.094	0.045	0.071	0.071	-0.052	-0.022	0.118	0.069	0.074	0.66	0.78	0.76
Yanco (304)	0.097	0.078	0.068	0.105	0.073	0.072	0.143	0.107	0.099	0.69	0.61	0.74
Average	**0.090**	**0.054**	**0.053**	**0.027**	**-0.006**	**-0.016**	**0.094**	**0.054**	**0.074**	**0.39**	**0.51**	**0.71**
Shrubland												
Walnut Gulch(302)	0.028	0.028	0.042	-0.003	-0.003	0.011	0.028	0.028	0.044	0.48	0.48	0.38
All CVS Average	**0.091**	**0.060**	**0.065**	**0.020**	**-0.002**	**-0.017**	**0.135**	**0.069**	**0.083**	**0.41**	**0.53**	**0.57**

Figure 5. CVS comparison of L2SMA validated product (black), offline retrievals (blue), and in situ (red). The Qflag is the σ^0 quality flag (the flag indicates good quality if shown scaled at -20 dB). NoRec, fail, and noAtt refer to 'successful retrieval but not recommended', 'retrieval attempted but failed', and 'retrieval not attempted' respectively. VWC_clim and VWC_retrieved refer to climatology and simultaneous retrieval respectively. Rough12400 and Rough_offl refer to the bare soil roughness estimate of the validated (T12400) and offline products, respectively.

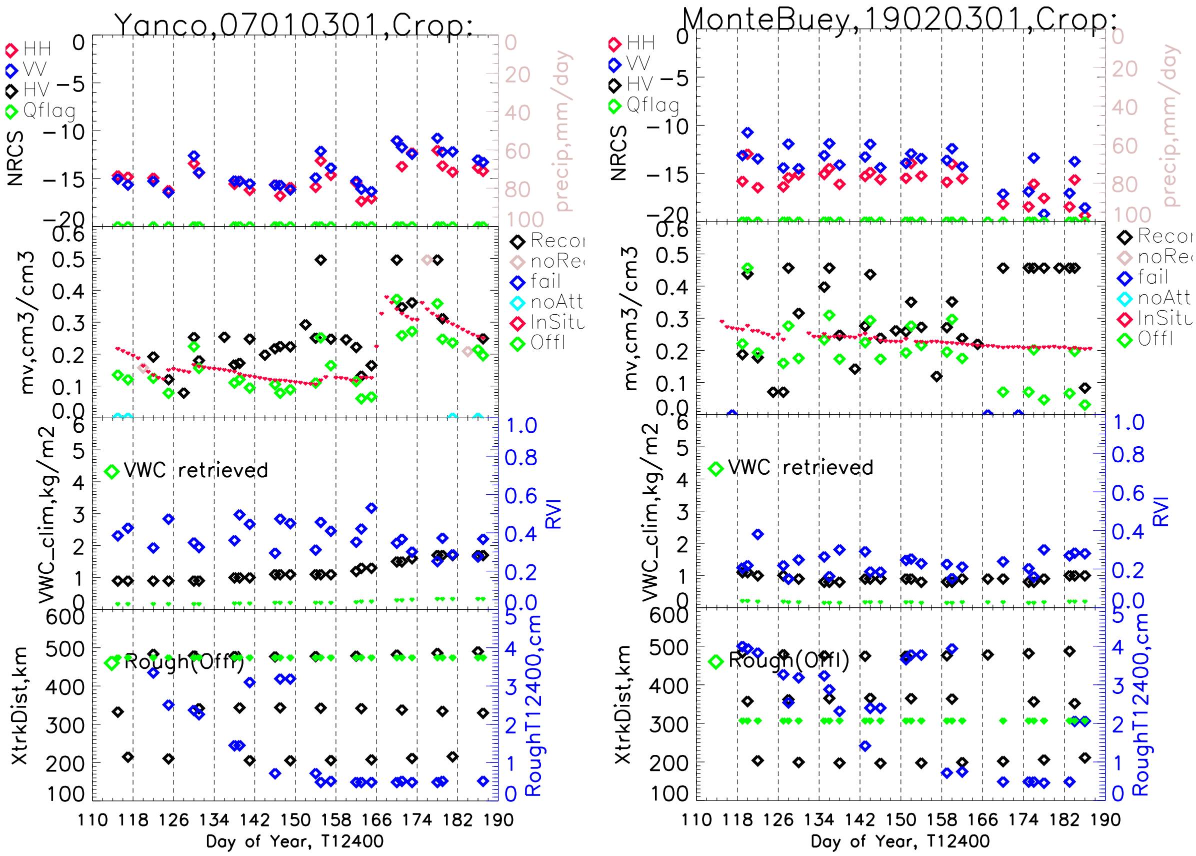
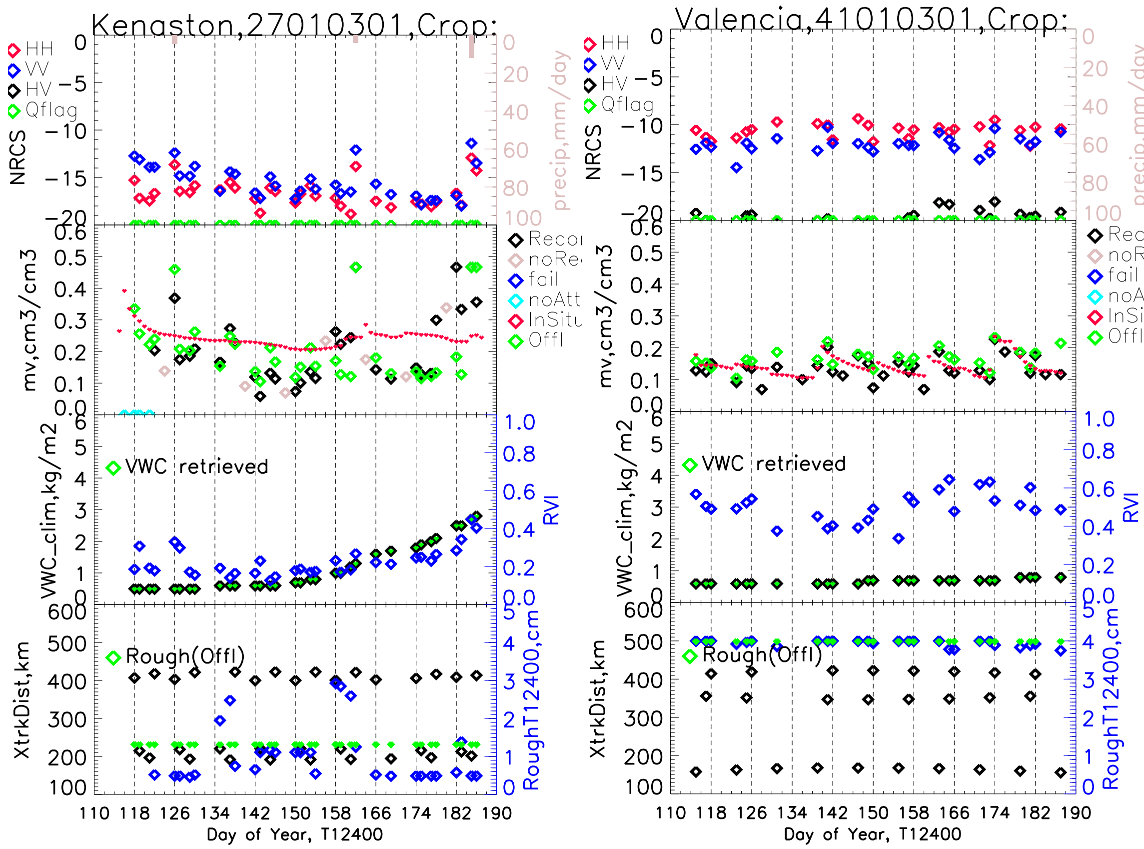


Figure 5 *(cont.)*



Analyses for individual CVS sites are discussed in detail in Figure 5 when the ubRMSE is significantly larger than the target of 0.060 cm^3/cm^3 with the offline retrieval. It is found that a part of the differences in the CVS comparison has non-algorithmic causes. Instead the differences may be attributed to sensing depth of radar vs. in situ, inaccurate VWC input, and possible residual error in σ^0 calibration.

At Yanco, the anomalous retrievals of the offline implementation, around day 130 (May 10) and 155 (Jun 5) contribute significantly to the large ubRMSE of the refined retrievals. These anomalies are also found in the passive and active passive retrievals when there was light rainfall. When the light rain impacts only the surface layer, there will be difference between *in situ* (5cm depth average) and the L-band remote sensing (typically penetrating a few centimeters deep but less when the soil is wet). When these anomalies can be systematically accounted for, the ubRMSE will reduce significantly. The too wet retrievals after day 170 are commonly found in the 3-km L2SMAP retrieval as well. The ancillary VWC of up to 1 kg/m^2 is too large for grassland, so that the retrieval algorithm retrieved f=10% of the climatology amount.

At Monte Buey, the consistent and large fluctuations in σ^0 and retrievals are most likely caused by periodic row structures of the cropland. The forward model does not yet incorporate the effects of this structure. The discrepancy most likely causes the large ubRMSE, and its correction would reduce the ubRMSE. The actual field is covered by stubble and seeding that occurred around day 170. This suggests that the optimized VWC level is closer to the reality more than the climatology is. The too dry retrieval after day 170 is not well understood, but occurs consistently with the L2SMAP 3-km results.

At Kenaston, the large retrieval anomalies on days 126, 160, and 185 are responsible for the large ubRMSE of the refined retrieval (Offline). The retrieval anomalies are responses to the anomalous σ^0. Closer examination of L1B σ^0 shows that the anomalous σ^0 are found consistently between L1B S0 and L1C S0. The cause is unclear at present among σ^0 calibration, tillage, or difference between L-band penetration and *in situ* sensing depths.

According to the retrievals at the Valencia site, the σ^0 time-series offers a guide on the choice of the correct landcover classification. The case of HH>VV for cropland is most commonly found in corn fields. The selection of the corn forward model in the refined retrieval (Offline) improves the ubRMSE metric.

Figure 6 shows the scatter diagram of the L2A retrievals at the CVS. The pre-validated products contain saturated retrievals over croplands, many of which are corrected in the refined Offline retrieval. The saturated retrievals occur after June 18: erroneously the receive-only radar data collected during June 15 to June 17 were included in the time-series archive (GBTS) and impact all the retrievals after June 18. The validated-release of L2SMA will correct this error. The retrieval errors in the grassland are also reduced in the refined Offline retrieval.

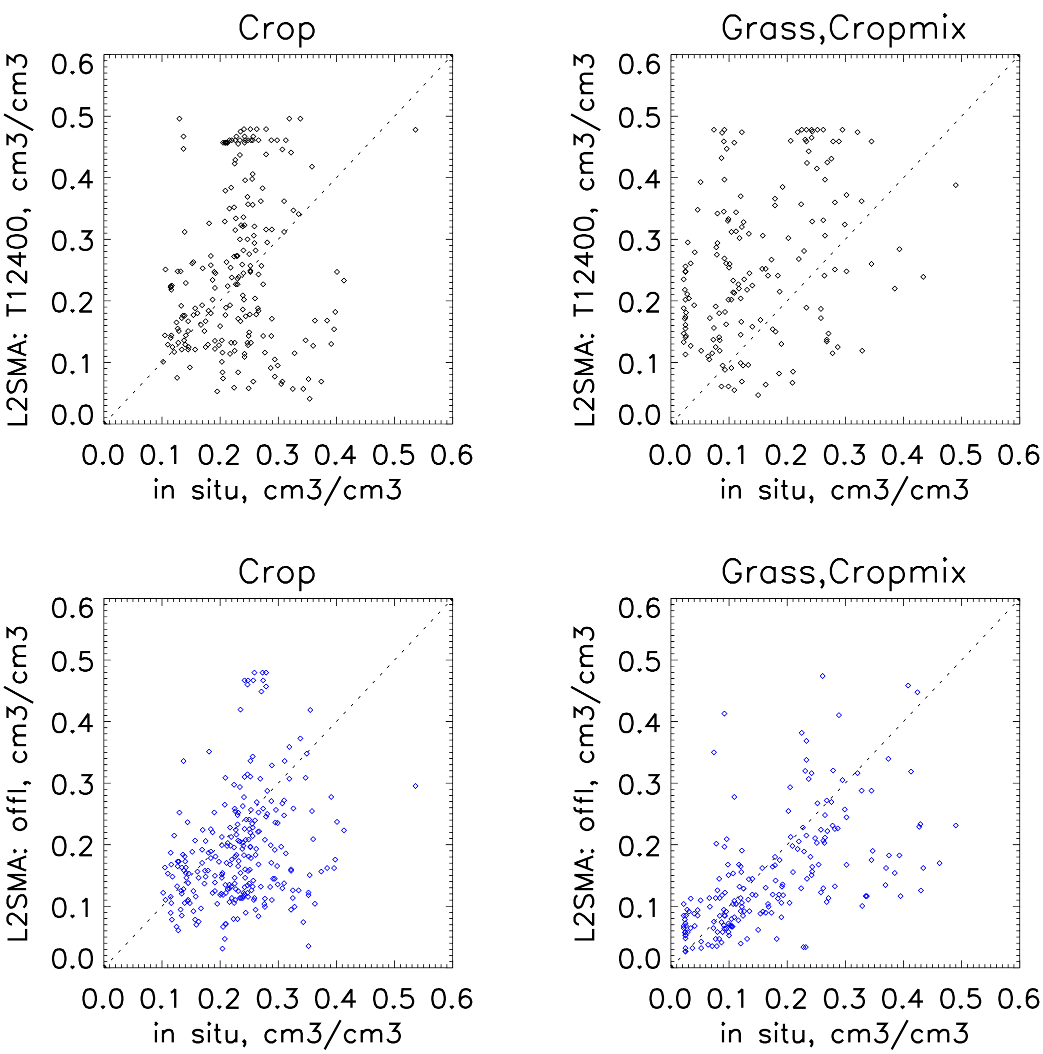


Figure 6. Scatter diagram of in situ vs. retrieval at CVS: validated (T12400) and Offline.

Compared with the 3-km L2SMAP product (Table 6), the pre-validated release (T12400) statistics show larger errors; however further refinements in the Offline deliver nearly comparable performance as the 3-km L2SMAP retrievals. The ubRMSE of the Offline retrieval is slightly larger than that of L2SMAP 3-km, but the mean error and the RMSE is smaller for the Offline retrieval than for the L2SMAP 3-km results.

5.3 Consistency with L2SMP Product

The L2SMA and L2SMP algorithms differ substantially in terms of the forward model used and the retrieval approaches, but they share the same set of ancillary data. The independence allows comparisons that might identify strengths and weaknesses of each approach. The long heritage of the passive approach and its stability will be taken into account in interpreting the comparison results.

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 L3SMA descending pass product. A transect across Africa is compared in Figure 7. Over the Sahara desert north of 15N, L2SMA is too wet most likely because of the uncorrected effects from topography and subsurface features (see Section 5.1 for more discussions). The region between 15S and 18S is the woody savanna in Angola (arid Namibia starts southward from 18S): the passive retrieval is nearly at the residual soil moisture level, which appears too dry for a woody savanna (ASCAT results may also be referred to). In this region, L2SMA retrievals are too high although the spatial profile resembles that of the ASCAT retrievals. Further investigation is ongoing to identify the cause of the L2SMA overestimation in this region.

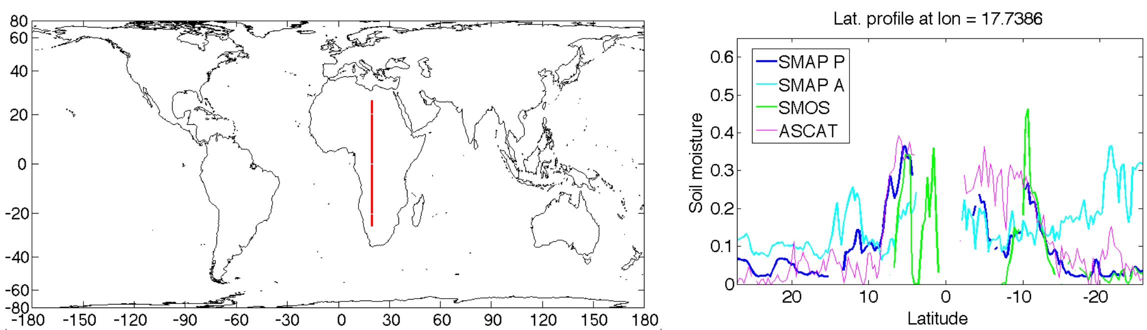


Figure 7. Comparison between L2SMA (pre-beta, T11940, baseline) and L2SMP (pre-beta, T11930) for May 19-25, 2015 [courtesy of M. Burgin]

In order to make a global comparison, the L2SMA soil moisture at 3 km was averaged to the 36-km EASE2 grid using a simple binning procedure. Retrieval quality flags provided in the respective product files are applied to both L2SMA and L2SMP to insure comparison of high quality soil moisture retrievals (all successful retrievals regardless of the quality recommendation flags are included to allow comparison over dense vegetation). According to the CVS validation, the L3SMA retrievals have a bias with respect to the CVS data (Table 6). Also application users such as data assimilation community are often interested in the temporal variations from the bias. Therefore in this report, only the unbiased errors are compared. The 2.5-month period of the Active product, however, is too short to characterize a bias (annual or seasonal) at each pixel. As a solution, the double-differencing approach is applied:

Δ = Active minus Passive retrievals

Δ_1(May 10 to 17) = $\delta_1(t_1)$ + unknown bias

Δ_2(May 18 to 25) = $\delta_2(t_1)$ + unknown bias

Double différence (DD) = $(\delta_1(t_1) - \delta_2(t_2))/\sqrt{2}$

The anomaly difference in Figure 8 shows that the discrepancy is smaller than 0.05 m^3/m^3 in much of the world. Larger differences are found in the forest regions (North American boreal forests), where both algorithms have weak performance. The large discrepancies in croplands (US and southern Russia), African savanna, and shrublands in west Australia need to be understood. The cumulative distribution function of the unbiased difference is shown in Figure 9: 95% (85%) of the comparisons have a discrepancy smaller than 0.1 (0.05) m^3/m^3.

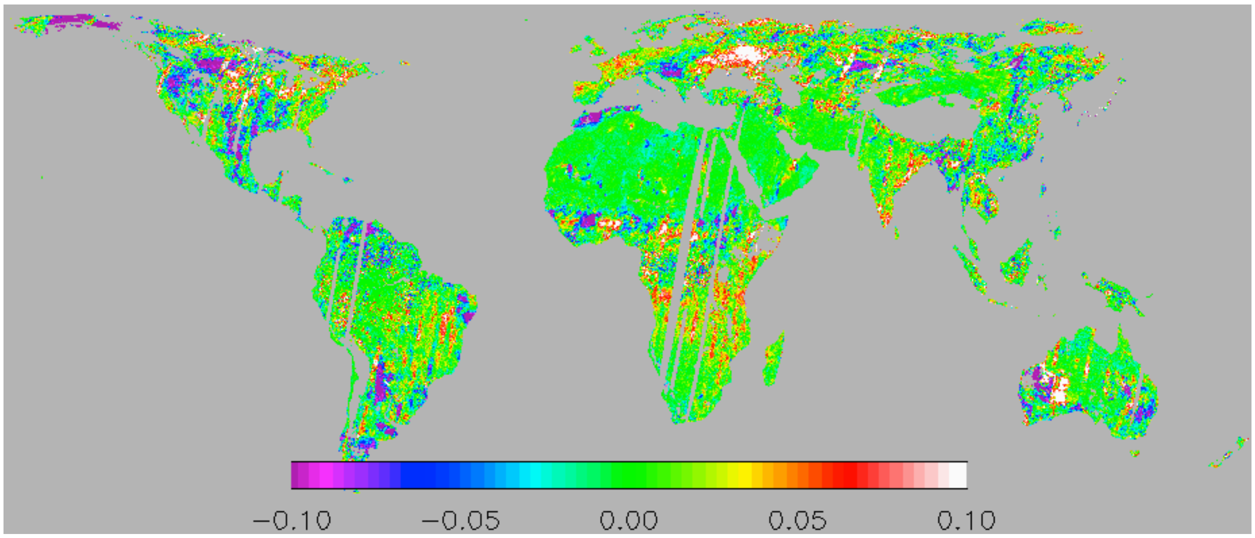


Figure 8. Comparison of unbiased retrieval between L2SMA (validated, 12400) and L2SMP (validated, T12400), in terms of the double difference in m^3/m^3 over the two 8-day cycles starting on May 10 and May 18, respectively. The gaps are due to the retrieval failures in L2SMA and orbit gaps.

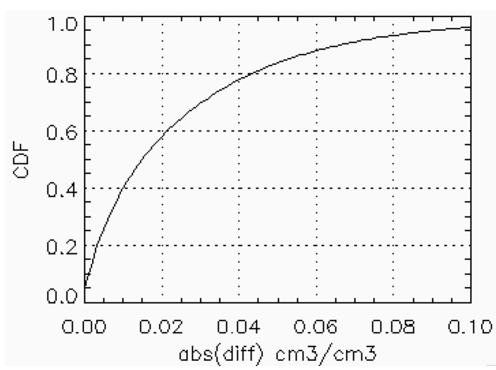


Figure 9. CDF of the absolute value of the unbiased difference between L2SMA (T12400) and L2SMP (T12400) shown in Figure 8, including the dense vegetation areas.

5.4 Summary

Three L2SMA retrieval algorithms were assessed in preparation for the validated release. The retrievals from the optional algorithms are too wet or too dry in different parts of the globe. A full cycle of soil moisture variation is lacking due to the short period of the radar operation, which degrades the option algorithm performance. Based upon these results, it is recommended that the baseline algorithm be adopted for the evaluation of the beta release.

The goal of this assessment report was to conduct the Stage 1 assessment based on the comparisons using metrics and time series plots at CVS. The overall ubRMSE of the SMAP Active baseline retrievals is 0.091 m^3/m^3, which is larger than the internal target of 0.06 m^3/m^3 [2]. A large part of this error is due to the saturation of retrieval associated with erroneously injecting the data from the radar receive-only mode (see Section 5.2) – this error will be fixed in the future release. The bias error averaged over all the CVS sites is 0.020 m^3/m^3.

Additional algorithm improvements are documented in this report. Evaluating these retrievals are currently limited to the CVS (but not global) and will be implemented in the global retrievals in the coming year prior to the final release of the validated data. After the refinements, the ubRMSE improved to 0.060 m^3/m^3, meeting the internal target of 0.06 m^3/m^3 [2]. The bias error averaged over all the CVS sites is 0.003 m^3/m^3. Lacking the Stage-2 validation at present, however, this release is still noted as State-1 validation with Version 3.

SMAP L2SMA retrievals were compared globally with the SMAP L2SMP retrievals. The global maps of the two retrievals are in general agreement. Bias differences exist between the two products. The unbiased differences are mostly smaller than 0.05 m^3/m^3 over 85% of the comparison pixels globally.

6 GOAL AND PLAN FOR FINAL VALIDATED RELEASE

SMAP L2SMA retrievals provide the first L-band SAR-based global routine observations of soil moisture at a 3-km spatial resolution. The retrieval algorithms were tested over a range of landcover types and vegetation amounts. The assessment of the beta product is limited to the 13 CVS and their landcover types. The goal for the validated release is to rigorously understand when and where the radar-only algorithms perform reliably, and refine the algorithms toward the goal. To achieve the goal the following activities are planned.

- *Implement algorithm refinements*. The refinements listed in Section 4 were found effective according to the test at CVS (Offline results). Among these, the estimates of time-invariant correction to each of the three parameters (σ^0, VWC correction, and roughness) are not implemented globally at present and will be included for the validated release.
- *Include Sparse Networks*. Comparisons with sparse network data will be evaluated. These activities will contribute towards the Cal/Val at CEOS Stage 2 and 3 levels.
- *Satellite intercomparison*. The most suitable dataset is the L2SMAP 3-km product because of collocation and synchronization. The comparisons at CVS indicated that the L2SMA (Offline) has higher ubRMSE and lower bias than L2SMAP 3-km retrievals. The comparison will extend to the global domain and entire period.

7 ACKNOWLEDGEMENTS

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