

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

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# TABLE OF CONTENTS

|  |           |
|--|-----------|
| <b>1 EXECUTIVE SUMMARY .....</b>                               | <b>3</b>  |
| <b>2 Calibration and Validation .....</b>                      | <b>5</b>  |
| <b>2.1 OBJECTIVES.....</b>                                     | <b>5</b>  |
| <b>2.2 APPROACHES .....</b>                                    | <b>7</b>  |
| <b>3 L2SMA ALGORITHMS .....</b>                                | <b>9</b>  |
| <b>4 PROCESS USED FOR BETA RELEASE .....</b>                   | <b>10</b> |
| <b>4.1 L1C Radar Data .....</b>                                | <b>10</b> |
| <b>4.2 Details of major inputs.....</b>                        | <b>11</b> |
| <b>4.3 Output details .....</b>                                | <b>11</b> |
| <b>4.4 Refinements – bias correction .....</b>                 | <b>12</b> |
| <b>4.5 Refinements – VWC correction .....</b>                  | <b>12</b> |
| <b>4.6 Refinements – landcover classification update .....</b> | <b>12</b> |
| <b>5 ASSESSMENTS.....</b>                                      | <b>13</b> |
| <b>5.1 Global Maps and Baseline Selection.....</b>             | <b>13</b> |
| <b>5.2 Core Validation Sites (CVS) Validation.....</b>         | <b>15</b> |
| <b>5.3 Consistency with L2SMP Product .....</b>                | <b>20</b> |
| <b>5.4 Summary .....</b>                                       | <b>22</b> |
| <b>6 GOAL AND PLAN FOR VALIDATED RELEASE .....</b>             | <b>23</b> |
| <b>7 ACKNOWLEDGEMENTS .....</b>                                | <b>24</b> |
| <b>8 REFERENCES.....</b>                                       | <b>25</b> |

# 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 beta 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 (14<sup>th</sup> April, 2015 to 7<sup>th</sup> 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 beta 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 ( $\sigma^0$ ) 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 beta 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-beta version T11940) is  $0.088 \text{ m}^3/\text{m}^3$ , which is larger than the self-imposed target of  $0.06 \text{ m}^3/\text{m}^3$  [2]. The bias error averaged over all the CVS sites is  $0.011 \text{ m}^3/\text{m}^3$ . Despite these errors, the global map of soil moisture is in general agreement with SMAP's Level 2 Soil Moisture: Passive product.

Further improvements in retrievals are documented in this report: these are currently limited to the CVS (but not global) and will be implemented in the global retrievals in the coming year prior to release of the validated data. These improvements include optimization of the vegetation amount, realistic choice

of crop classification, forward model update, and correction of effects by topography and azimuth effects. The ubRMSE following these improvements is  $0.060 \text{ m}^3/\text{m}^3$ , meeting the internal target of  $0.06 \text{ m}^3/\text{m}^3$  [2]. The bias error averaged over all the CVS sites is  $0.003 \text{ m}^3/\text{m}^3$ .

Considering the quality of the current retrievals and the prospect of further improvements, the beta-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.

## 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 beta 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].

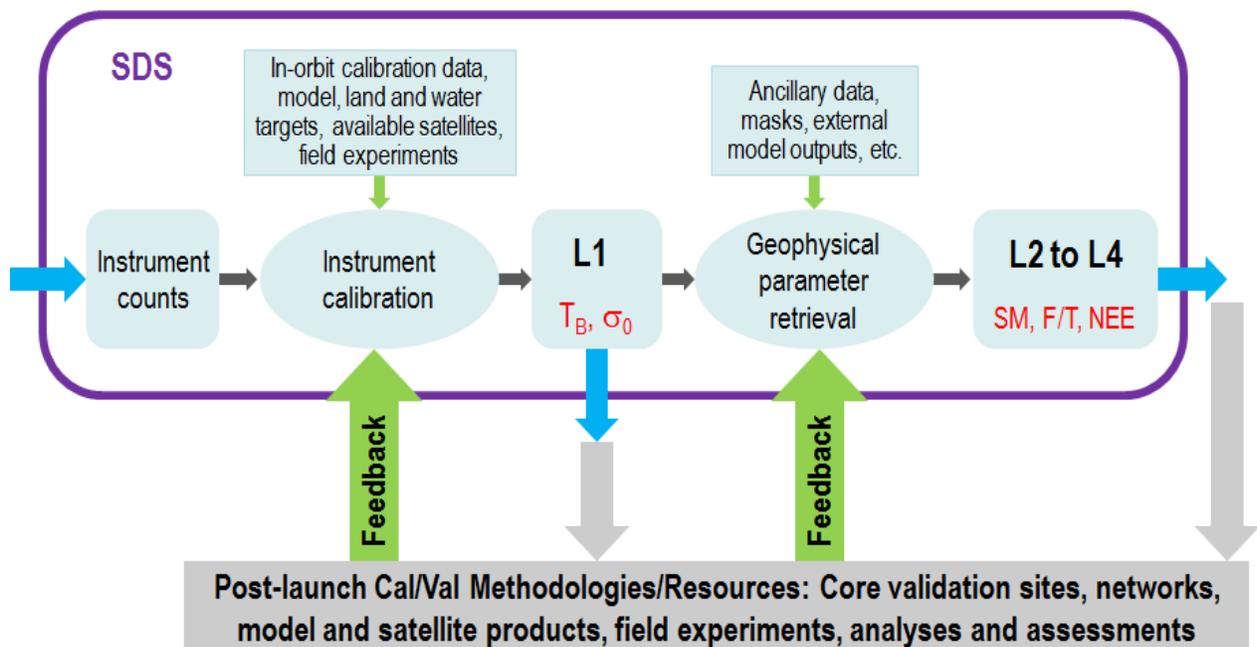


Figure 1. Overview of the SMAP Cal/Val Process.

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  $0.06 \text{ m}^3/\text{m}^3$  as an internal target within the SMAP project.

The maturity of the products in the beta 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 beta quality is indicated by the authors. Drawing quantitative scientific conclusions is discouraged. Users are urged to contact science team representatives prior to use of the data in publications, and to recommend members of the instrument teams as reviewers.
- The estimated uncertainties will be documented.
- 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 beta 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 beta 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 beta-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:

$$\begin{aligned}
C(\bar{s}, \bar{\epsilon}_{r1}, \bar{\epsilon}_{r2}, \dots, \bar{\epsilon}_{rN}) = & \\
w_{1,HH}(\sigma_{HH,1}^0 - \sigma_{HH,fwd}^0(\bar{s}, \bar{\epsilon}_{r1}, \bar{fVWC}_1) + \bar{c})^2 & + w_{1,VV}(\sigma_{VV,1}^0 - \sigma_{VV,fwd}^0(\bar{s}, \bar{\epsilon}_{r1}, \bar{fVWC}_1) + \bar{c})^2 + \\
w_{2,HH}(\sigma_{HH,2}^0 - \sigma_{HH,fwd}^0(\bar{s}, \bar{\epsilon}_{r2}, \bar{fVWC}_2) + \bar{c})^2 & + w_{2,VV}(\sigma_{VV,2}^0 - \sigma_{VV,fwd}^0(\bar{s}, \bar{\epsilon}_{r2}, \bar{fVWC}_2) + \bar{c})^2 + \dots + \\
w_{N,HH}(\sigma_{HH,N}^0 - \sigma_{HH,fwd}^0(\bar{s}, \bar{\epsilon}_{rN}, \bar{fVWC}_N) + \bar{c})^2 & + w_{N,VV}(\sigma_{VV,N}^0 - \sigma_{VV,fwd}^0(\bar{s}, \bar{\epsilon}_{rN}, \bar{fVWC}_N) + \bar{c})^2
\end{aligned} \quad (1)$$

where the overbar denotes a parameter that is retrieved. Radar backscattering coefficients from observations and from the forward model are denoted as  $\sigma^0$  and  $\sigma_{fwd}^0$  (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 ( $\sigma^0$ ) and soil moisture.

$$M_s = (\sigma^0(t) - \sigma_{dry}^0) / (\sigma_{wet}^0 - \sigma_{dry}^0) \quad (2)$$

where  $\sigma^0(t)$  is the observation at one time.  $\sigma_{wet}^0$  and  $\sigma_{dry}^0$  are two extreme values of  $\sigma^0$  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  $\sigma^0$  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]:

$$M_v = C_0 + C_1 \frac{\sigma_{hh} + \sigma_{vv}}{2} \quad (3)$$

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

$$M_v = porosity \times M_s \quad (4)$$

Due to the failure of the SMAP radar, it is unlikely that the set of data available to derive  $\sigma_{wet}^0$ ,  $\sigma_{dry}^0$ ,  $C_1$ , and  $C_2$  from SMAP data at high resolution over a complete soil moisture cycle will be available.

## 4 PROCESS USED FOR BETA RELEASE

This section describes the input data used to produce the beta release product, the details of the production configuration, and refinements applied to the L2SMA baseline product since launch until the beta 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 beta 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 pre-beta and beta, and finally the validated release, in order to understand algorithm behavior and sensitivity to the radar input. The beta level performance of the L1 radar measurements is summarized in Table 2. The major characteristics of the L1C\_S0 beta are (see the L1C\_S0 beta 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  $0.063 \text{ m}^3/\text{m}^3$  (Table 3).

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

|                              | Beta-level | Mission Requirement |
|------------------------------|------------|---------------------|
| Relative accuracy (total Kp) | 1 dB       | 1 dB (VV and HH)    |
| Geolocation accuracy         | ~500m      | 1 km                |
| Version                      | R11850     |                     |

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 ( $\text{m}^3/\text{m}^3$ ) |            |
|---|------------------------------------|------------|
|   | Outer edge                         | Inner edge |
| A) $K_p$ 0.75-1.0 dB error ( $1\sigma$ , co-pol, fore look)       | 0.035                              | 0.043      |
| B) Vegetation water content error ( $1\sigma$ , 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 $\sim 3 \text{ kg}/\text{m}^2$ | 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 R11850, fore+aft average, averaged to 3 km. This product is the L1C\_S0 beta 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 combining multiple SMAP radar observations using R11850 L1C\_S0 and T11940 L3SMA.  $\sigma^0$  quality flags are ignored in the beta release. The following surface flags are applied to select only meaningful  $\sigma^0$  for soil moisture purposes: 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  $\sigma^0$ : To evaluate the change index approach (Option 2 and 3), monthly Aquarius  $\sigma^0$  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 T11940 (**pre-beta** version). This version incorporates the bias correction described in Section 4.4, but not the VWC correction, landcover class adjustment, and forward model update of Sections 4.5 - 4.7. Retrieval and surface flags are reported in T11940 as follows. There will be very small difference between T11940 and the L2SMA beta-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 beta-release retrievals. T11940 will be referred to as '**pre-beta**' in this assessment report. 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 <sup>2</sup>  |
| 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 – bias correction

A temporal bias may be present between LIC  $\sigma^0$  observation and the forward model due to a number of factors. The LIC 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 beta release product.

## 4.5 Refinements – 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:

$$\overline{VWC} = f \times VWC, \quad (4)$$

where  $\overline{VWC}$  is the revised VWC,  $f$  is the estimated scaling factor, and VWC is the climatological ancillary data. The iterative estimation of  $f$  has been tested at the CVS but not implemented globally in the beta release.

## 4.6 Refinements – landcover classification update

The landcover classification information based on the MODIS climatology is not current, especially when the land use involves agriculture. The cropland database is also out of date because new crop class information has a temporal lag of typically one year.  $\sigma^0$  time-series often exhibit distinct features of a landcover class. When HH is larger than VV, the most likely crop is corn. Accordingly the choices of datacubes were revised. The revision has been tested at the CVS but not implemented globally in the beta release.

## 4.7 Refinements – forward model update

The updates of the forward models are available. Evaluation will be performed on the difference between old and updated models.

## 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 (June 19-26, 2015, when nearly all the northern hemisphere should be thawed). 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  $\sigma^0$  (more than the topography does on the radiometer data) and penetration depth may reach 1 m. Subsurface feature such as rocky terrain may cause retrieval errors. Over shrublands, the two products match well in Namibia, the southwest of the United States, southern Argentina, and Australia. The rainforest appears wetter in L2SMA than in L2SMP, but this is an area where the performances of both products are expected to be poor.

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 Korea are caused by the absence of the  $\sigma^0$  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  $0.6 \text{ m}^3/\text{m}^3$ ) and too dry (Sahara, Alaska, central US, southern Argentina). These extremes are associated with the deficiencies in the  $\sigma^0$  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  $\sigma^0$  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  $\sigma^0$  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.

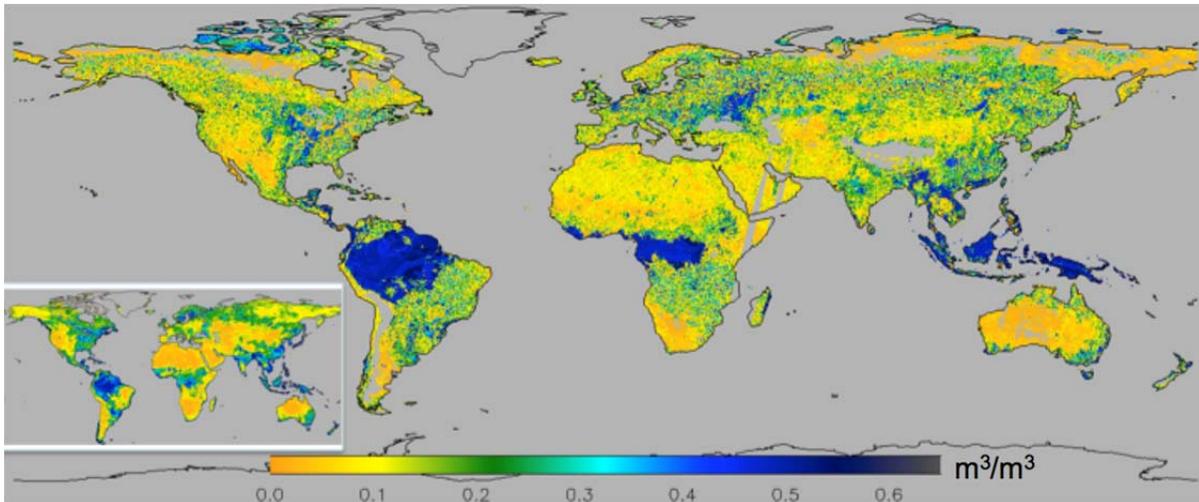


Figure 2. SMAP L2SMA baseline soil moisture for one 8-day cycle of June 19-26, 2015. The inset shows the L2SMP baseline retrievals (T11930) over the same period. Except for a few orbit gaps, they are mostly due to the frozen condition (permanent and dynamic) and failed retrievals (Australia).

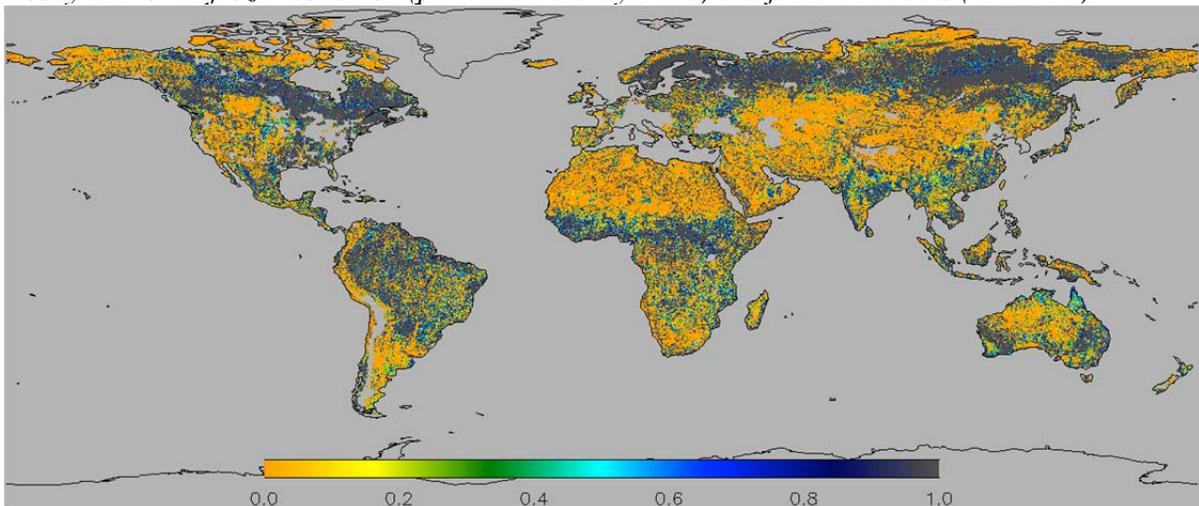


Figure 3. Same as Figure 2 except for SMAP L2SMA option 2 (change index, dimensionless).

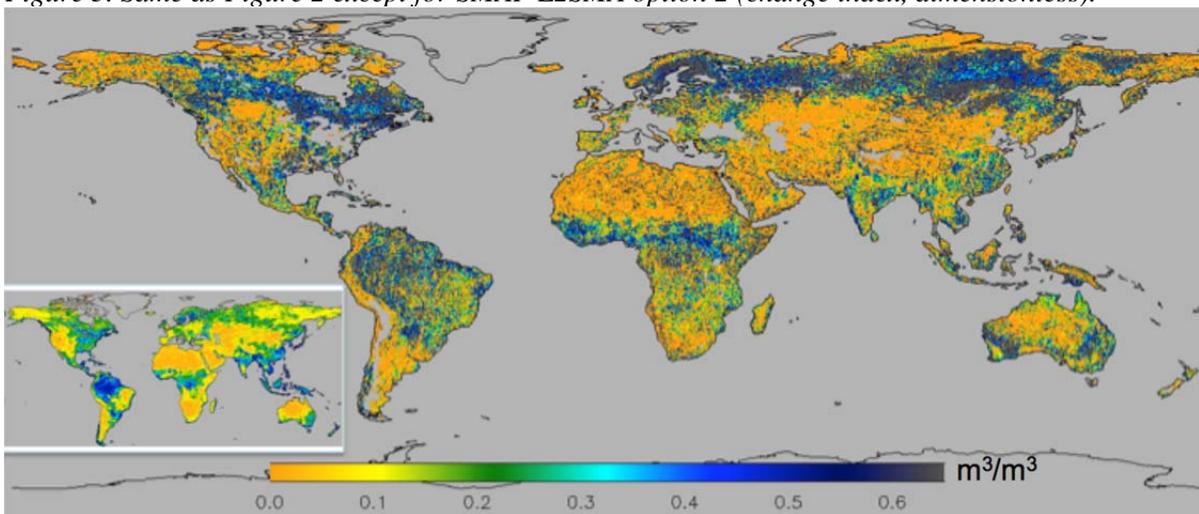


Figure 4. Same as Figure 2 except for SMAP L2SMA option 3 (change index absolute).

## 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. 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 5. 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  $\sigma^0$  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-beta release product (T11940) as well as beta product implements only the bias correction described in Section 4.4. The VWC correction, landcover reclassification, and forward model updates described in Sections 4.5, 4.6, and 4.7 were tested at the CVS but not yet as a global product. The future CRID T11950 is assigned to the test these updated outputs.
- Validation statistics of L2SMAP at 3 km are included since they are unambiguously comparable with the L2SMA comparison statistics.

Table 5 SMAP L2SMA pre-beta Release (T11940) CVS Assessment at 9 km. T11950 includes the future improvements (VWC and landcover adjustments). L3SMAP beta release (T11930) statistics are from the baseline L2SMAP at 3-km resolution (Das et al. SMAP Science Team #6, Sept. 2015). See Table 1 for complete site information.

| Cropland               | ubRMSE (m <sup>3</sup> /m <sup>3</sup> ) |              |              | Bias (m <sup>3</sup> /m <sup>3</sup> ) |               |               | RMSE (m <sup>3</sup> /m <sup>3</sup> ) |              |              | R            |             |             |
|------------------------|--|--------------|--------------|--|---------------|---------------|--|--------------|--------------|--------------|-------------|-------------|
|                        | SMA pre-beta                             | T11950       | AP pre-beta  | SMA pre-beta                           | T11950        | AP pre-beta   | SMA pre-beta                           | T11950       | AP pre-beta  | SMA pre-beta | T11950      | AP pre-beta |
| St Josephs             | 0.113                                    | 0.086        | 0.057        | 0.015                                  | 0.058         | -0.038        | 0.114                                  | 0.104        | 0.069        | 0.52         | 0.49        | 0.54        |
| Kenaston (301)         | 0.102                                    | 0.102        | 0.044        | -0.038                                 | -0.019        | -0.081        | 0.109                                  | 0.104        | 0.092        | 0.37         | 0.41        | 0.42        |
| Kenaston (302)         | 0.088                                    | 0.073        | 0.087        | 0.053                                  | -0.013        | -0.051        | 0.102                                  | 0.074        | 0.101        | 0.33         | 0.62        | 0.23        |
| Monte Buey             | 0.120                                    | 0.091        | 0.045        | 0.059                                  | -0.039        | -0.089        | 0.133                                  | 0.099        | 0.100        | 0.25         | 0.73        | 0.79        |
| Valencia               | 0.036                                    | 0.026        | 0.033        | -0.047                                 | 0.022         | -0.081        | 0.059                                  | 0.034        | 0.088        | 0.49         | 0.58        | 0.47        |
| Yanco (301)            | 0.085                                    | 0.043        | 0.093        | 0.001                                  | 0.004         | 0.029         | 0.085                                  | 0.043        | 0.097        | 0.69         | 0.89        | 0.80        |
| <b>Average</b>         | <b>0.090</b>                             | <b>0.070</b> | <b>0.060</b> | <b>0.007</b>                           | <b>0.002</b>  | <b>-0.052</b> | <b>0.100</b>                           | <b>0.070</b> | <b>0.091</b> | <b>0.44</b>  | <b>0.62</b> | <b>0.54</b> |
| <b>Grassland</b>       |  |              |              |  |               |               |  |              |              |              |             |             |
| Walnut Gulch(301)      | 0.039                                    | 0.022        | 0.030        | 0.065                                  | 0.016         | -0.015        | 0.075                                  | 0.027        | 0.033        | 0.20         | 0.23*       | 0.39        |
| TxSON (301)            | 0.075                                    | 0.049        | 0.034        | -0.075                                 | -0.035        | -0.078        | 0.106                                  | 0.060        | 0.085        | 0.17         | 0.77        | 0.91        |
| TxSON (302)            | 0.203                                    | 0.083        | 0.038        | -0.007                                 | -0.007        | -0.096        | 0.203                                  | 0.083        | 0.103        | -0.44        | 0.64        | 0.82        |
| Yanco (302)            | 0.060                                    | 0.048        | 0.060        | 0.008                                  | -0.008        | -0.011        | 0.061                                  | 0.049        | 0.061        | 0.80         | 0.80        | 0.77        |
| Yanco (303)            | 0.085                                    | 0.026        | 0.063        | 0.023                                  | -0.022        | -0.048        | 0.088                                  | 0.034        | 0.079        | 0.82         | 0.316       | 0.36        |
| Yanco (304)            | 0.104                                    | 0.098        | 0.059        | 0.110                                  | 0.082         | 0.034         | 0.151                                  | 0.128        | 0.068        | 0.71         | 0.12        | 0.49        |
| <b>Average</b>         | <b>0.094</b>                             | <b>0.055</b> | <b>0.047</b> | <b>0.021</b>                           | <b>0.004</b>  | <b>-0.036</b> | <b>0.114</b>                           | <b>0.055</b> | <b>0.072</b> | <b>0.38</b>  | <b>0.50</b> | <b>0.62</b> |
| <b>Shrubland</b>       |  |              |              |  |               |               |  |              |              |              |             |             |
| Walnut Gulch(302)      | 0.028                                    | 0.028        | 0.034        | -0.003                                 | -0.003        | 0.010         | 0.028                                  | 0.028        | 0.036        | 0.48         | 0.48        | 0.54        |
|                        |  |              |              |  |               |               |  |              |              |              |             |             |
| <b>All CVS Average</b> | <b>0.088</b>                             | <b>0.060</b> | <b>0.052</b> | <b>0.011</b>                           | <b>0.0025</b> | <b>-0.040</b> | <b>0.102</b>                           | <b>0.060</b> | <b>0.078</b> | <b>0.45</b>  | <b>0.56</b> | <b>0.58</b> |

Averaged over 13 CVS, the ubRMSE of the beta product is  $0.088 \text{ m}^3/\text{m}^3$ , larger than the internal target of  $0.06 \text{ m}^3/\text{m}^3$ . Only the bias correction of Section 4.4 was implemented in the beta product. The input VWC (a climatology) may still be incorrect; and the choice of the crop class during the retrieval is based on the climatological crop classification.

With the additional refinements (T11950), the ubRMSE is reduced to  $0.06 \text{ m}^3/\text{m}^3$ . The difference over croplands is larger than those of non-croplands, which is anticipated because the climatology VWC is less realistic in croplands than in non-croplands. The VWC correction of Section 4.5 merely re-scales the ancillary VWC, and does not change its temporal trend. The VWC correction is not expected to correct for the interannual variations in the crop growth cycle. The cropland database used to choose the forward model is also outdated. Examining the time-series of  $\sigma^0$ , the choice of the crop class is adjusted appropriately. Another potential source of error is the fact that, in all the CVS retrievals, the ratio of correlation length to rms height is fixed to 10 in the forward model computations, based on the insensitivity of retrieval to the ratio for the bare surface [8]. The CVS retrievals were not too sensitive to the ratio according to limited tests, but allowing this ratio to vary in future retrieval algorithms may allow for additional improvements in the future.

Figure 5. CVS comparison of L2SMA beta product (black), further refinements (blue, T11950), and in situ (red). The Qflag is the  $\sigma^0$  quality flag (the flag indicates good quality if shown scaled at -20 dB). NoRec, fail, and noAtt refer to ‘not recommended’, ‘attempted but failed’, and ‘not attempted’ respectively. noAtt at the early period for the beta product is due to the  $\sigma^0$  time-series being too short.

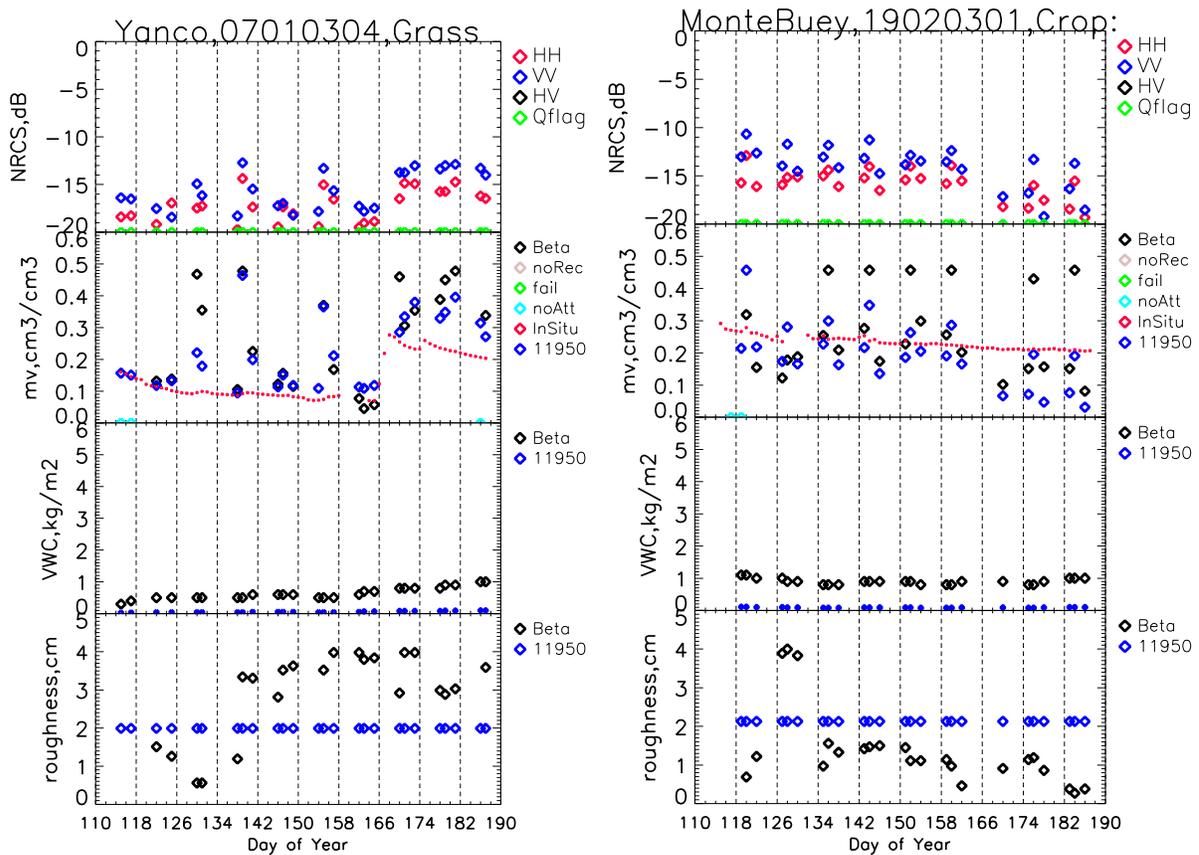
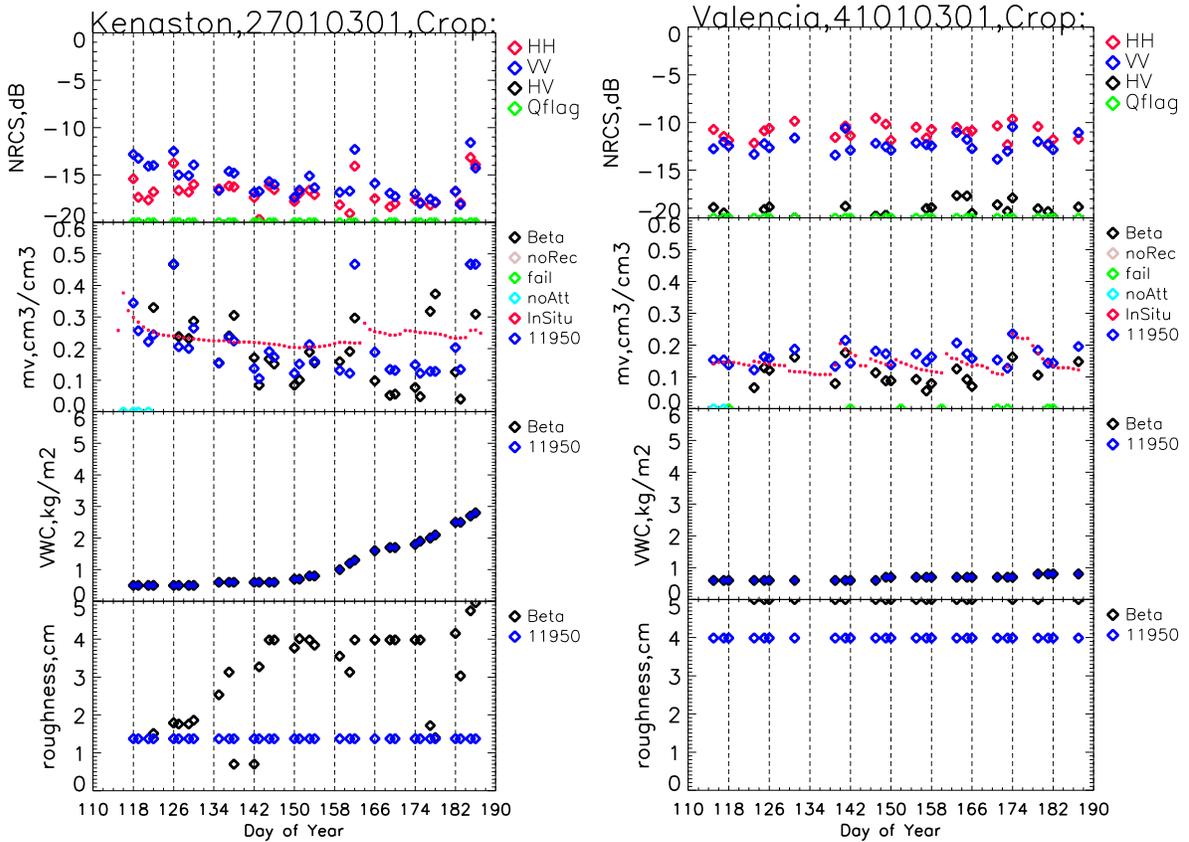


Figure 5 (cont.)



Analyses for individual CVS sites are discussed in detail in Figure 5 when the ubRMSE is significantly larger than the target of  $0.060 \text{ cm}^3/\text{cm}^3$  with the T11950 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  $\sigma^0$  calibration.

At Yanco, the anomalous retrievals around day 140 (May 20) and 155 (Jun 5) contribute significantly to the large ubRMSE of the refined retrievals (T11950). 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  $1 \text{ kg/m}^2$  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  $\sigma^0$  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 (T11950). The retrieval anomalies are responses to the anomalous  $\sigma^0$ . Closer examination of L1B  $\sigma^0$  shows that the anomalous  $\sigma^0$  are found consistently between L1B S0 and L1C S0. The cause is unclear at present among  $\sigma^0$  calibration, tillage, or difference between L-band penetration and *in situ* sensing depths.

According to the retrievals at the Valencia site, the  $\sigma^0$  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 (T11950) improves the ubRMSE metric.

Figure 6 shows the scatter diagram of the L2A retrievals at the CVS. The beta products contain saturated retrievals over croplands, many of which are corrected in the refined T11950. The retrieval errors in the grassland are also reduced in the refined T11950.

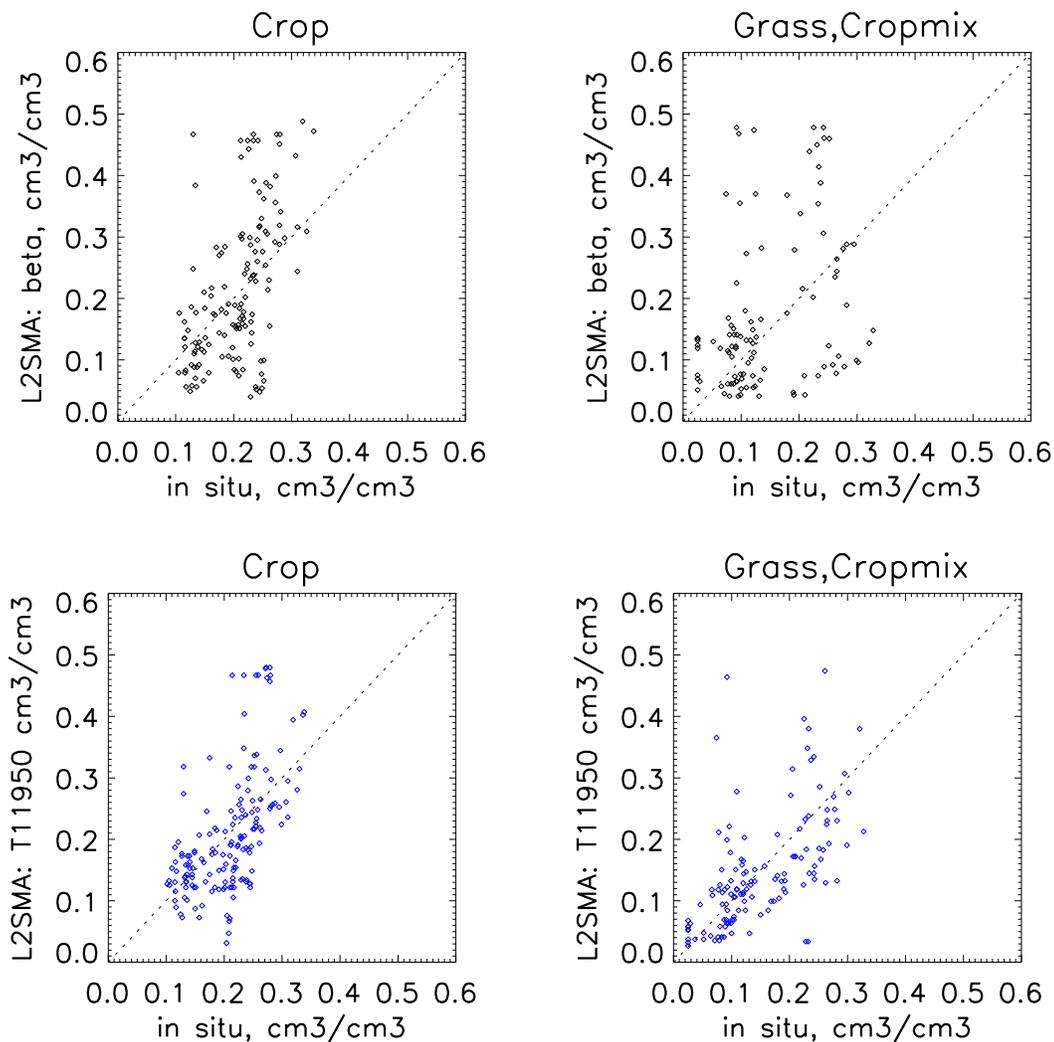


Figure 6. Scatter diagram of in situ vs. retrieval at CVS: pre-beta (T11940) and further improvements (T11950)

Compared with the 3-km L2SMAP product (Table 5), the beta release (T11940) statistics show larger errors; however further refinements in T11950 deliver nearly comparable performance as the 3-km L2SMAP retrievals. The ubRMSE of T11950 is slightly larger than that of L2SMAP 3-km, but the mean error and the RMSE is smaller for T11950 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 (SMOS and ASCAT results may also be referred to). Surface temperature used for the Passive retrieval may be too high. The VWC correction and datacube updates may further improve the L2SMA retrievals.

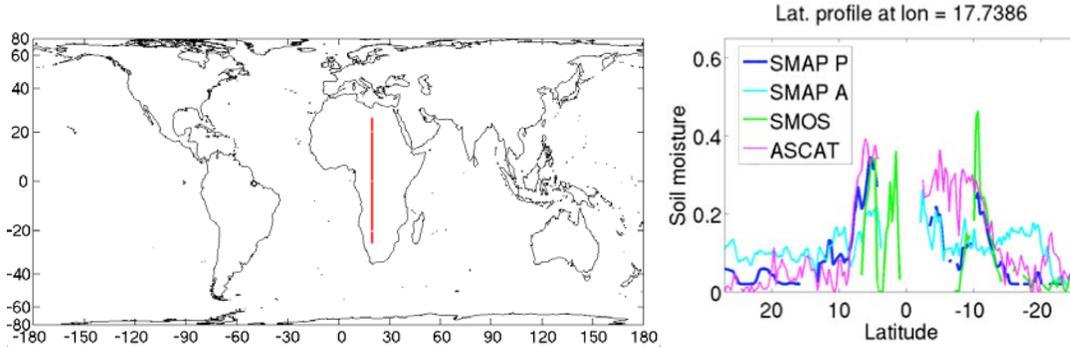


Figure 7. Comparison between L2SMA (pre-beta, T11940, baseline) and L2SMP (pre-beta, T11930) for May 19-25, 2015 [courtesy of M. Burgin]

In order to make a global comparison, the L2SMA soil moisture at 3 km was averaged to the 36-km EASE2 grid using a drop-in-a-bucket technique. 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 recommendation status are included to allow comparison over dense vegetation). According to the CVS validation, the L3SMA beta version has a bias with respect to the CVS data (Table 5). 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:

$$\Delta = \text{Active minus Passive retrievals}$$

$$\Delta_1(\text{June 19 to 26}) = \delta_1(t_1) + \text{unknown bias}$$

$$\Delta_2(\text{June 27 to July 3}) = \delta_2(t_1) + \text{unknown bias}$$

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

The anomaly difference in Figure 8 shows that the difference is smaller than  $0.05 \text{ m}^3/\text{m}^3$  in much of the world. Larger differences are found in the forest regions (Amazon, Congo, Indochina, boreal forests, and eastern US), where both algorithms have weak performance. The large discrepancies in Indian and Argentinean croplands, African savanna, and Australian shrublands 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)  $\text{m}^3/\text{m}^3$ .

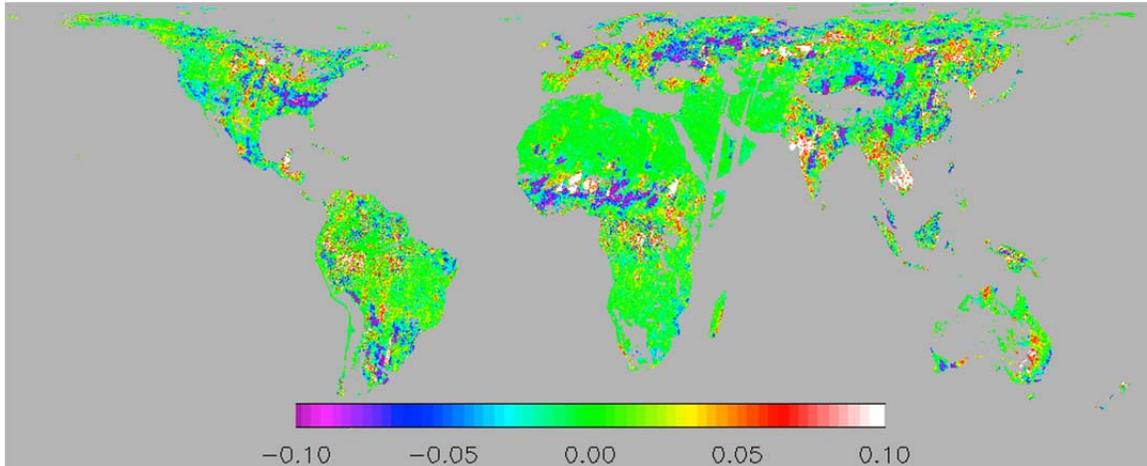


Figure 8. Comparison of unbiased retrieval between L2SMA (beta, T11940) and L2SMP (beta, T11930), in terms of the double difference in  $\text{m}^3/\text{m}^3$  over the two 8-day cycles starting on June 19 and June 27, respectively. The gaps are due to the retrieval failures in L2SMA and orbit gaps.

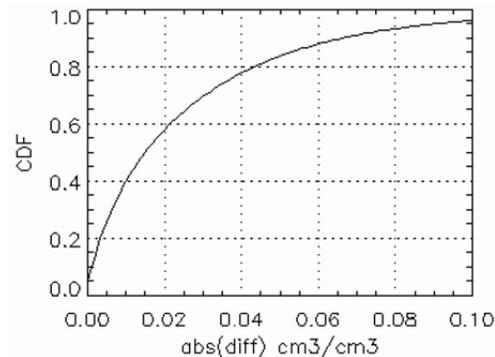


Figure 9. CDF of the absolute value of the unbiased difference between L2SMA (beta, T11940) and L2SMP (beta, T11930) shown in Figure 8, including the dense vegetation areas.

## 5.4 Summary

Three L2SMA retrieval algorithms were assessed in preparation for the beta 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 optional 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 the beta release was to conduct the Stage 1 assessment based primarily on CVS comparisons using metrics and time series plots. The overall ubRMSE of the SMAP Active baseline retrievals version T11940 is  $0.088 \text{ m}^3/\text{m}^3$ , which is larger than the internal target of  $0.06 \text{ m}^3/\text{m}^3$  [2]. The bias error averaged over all the CVS sites is  $0.011 \text{ m}^3/\text{m}^3$ .

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 release of the validated data. After the refinements, the ubRMSE improved to  $0.060 \text{ m}^3/\text{m}^3$ , meeting the internal target of  $0.06 \text{ m}^3/\text{m}^3$  [2]. The bias error averaged over all the CVS sites is  $0.003 \text{ m}^3/\text{m}^3$ .

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  $0.05 \text{ m}^3/\text{m}^3$  over 85% of the comparison pixels globally.

## 6 GOAL AND PLAN FOR 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 (T11950 results). Among these, the VWC adjustment and landcover optimization are not implemented globally at present and will be included for the validated release.
- *Update ancillary data.* The cropland classification is out of date, as its update typically has a one-year lag. By the validated release, the crop classification for 2015 will be available for US and Canada. The datacubes were updated with respect to the beta release product, by improving surface conditions and vegetation models. T11950 incorporates the latest datacubes. The validated release product will incorporate these updates.
- *Effects of topography, periodic structure, and heterogeneity.* Analyses at a few CVS described the effects of these geophysical effects. The current retrieval and forward models do not explicitly address these effects, and the correction of these effects will be investigated.
- *Increase the number of CVS.* There are a number of additional sites that may qualify as CVS. The primary targets are the 14 candidate sites. As the processing and transfer of the *in situ* data become reliable and the upscaling is better characterized, these candidate sites will become core sites.
- *Include Sparse Networks and Triple Co-Location.* Comparisons with sparse network data will be evaluated. These activities will contribute towards the Cal/Val at CEOS Stage 2 and 3 levels.
- *Compare with Model-based Products.* Sufficiently high-resolution models are available over the CONUS region. Some effort is required to further evaluate this tool and how to utilize it in the validated assessment.
- *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 (T11950) has higher ubRMSE and lower bias than L2SMAP 3-km retrievals. The comparison will extend to the global domain and entire period.
- *Field Campaign results.* SMAPE<sub>x4</sub> in Australia was conducted during the period of the radar operation. Retrievals from this campaigns will be compared with the SMAP L2SMA outputs.

## **7 ACKNOWLEDGEMENTS**

This document resulted from many hours of diligent analyses and constructive discussion among the Cal/Val Partners and other members of the SMAP Project Team.

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