Soil Moisture Active Passive (SMAP) Project Calibration and Validation for the L3_FT_A Validated-Release Data Product (Version 3)

Citation:

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1 EXECUTIVE SUMMARY

During the post-launch Cal/Val Phase of SMAP there are two objectives 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. This report provides analysis and assessment of the final validated SMAP Level 3 Landscape Freeze/Thaw (L3_FT_A) product. The SMAP Level 3 Landscape Freeze/Thaw (L3_FT_A) product is a daily composite of half-orbit freeze/thaw retrievals.

Assessment methodologies utilized include comparisons of SMAP freeze/thaw retrievals with *in situ* observations from core validation sites (CVS) and sparse networks, and inter-comparison with products from the NASA Aquarius and JAXA Advanced Microwave Scanning Radiometer-2 (AMSR-2) missions. These analyses meet the criteria established by the Committee on Earth Observing Satellites (CEOS) Stage 1 validation.

Post-launch refinements to the L3_FT_A product, described further in this document, include the development and application of updated freeze and thaw references (required for the seasonal threshold classification algorithm) derived from SMAP radar measurements for thaw, and bias corrected Aquarius references for freeze. The FT retrieval algorithm is robust in the presence of relatively high lake fractions, so the water body threshold remains at 50% as evaluated with the beta release. Due to artifacts in the L1C_s0 data, radar measurements covering approximately 50 km on each site of the nadir track were excluded from the FT retrieval. This represents a narrower swath than was excluded from the beta release, which improves the timeliness of the FT retrievals included in each daily product to ensure complete coverage of the domain.

The SMAP baseline science mission objective for freeze/thaw is to provide binary estimates of landscape freeze/thaw state for the region north of 45° N latitude, which includes the boreal forest zone, with a spatial classification accuracy of 80% at 3 km spatial resolution and 2-day average intervals in AM and PM separately. Evaluation during the period of SMAP radar operation indicates this target was met during the spring 2015 high latitude freeze to thaw transition.

2 OBJECTIVES OF CAL/VAL

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

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

The process is illustrated in Figure 2.1. In this Assessment Report the progress of the L3 Freeze/Thaw Team in addressing these objectives for the final validated release is described. The approaches and procedures utilized follow those described in the SMAP Cal/Val Plan [1] and Algorithm Theoretical Basis Document for the Level 3 Freeze/Thaw Product [2].

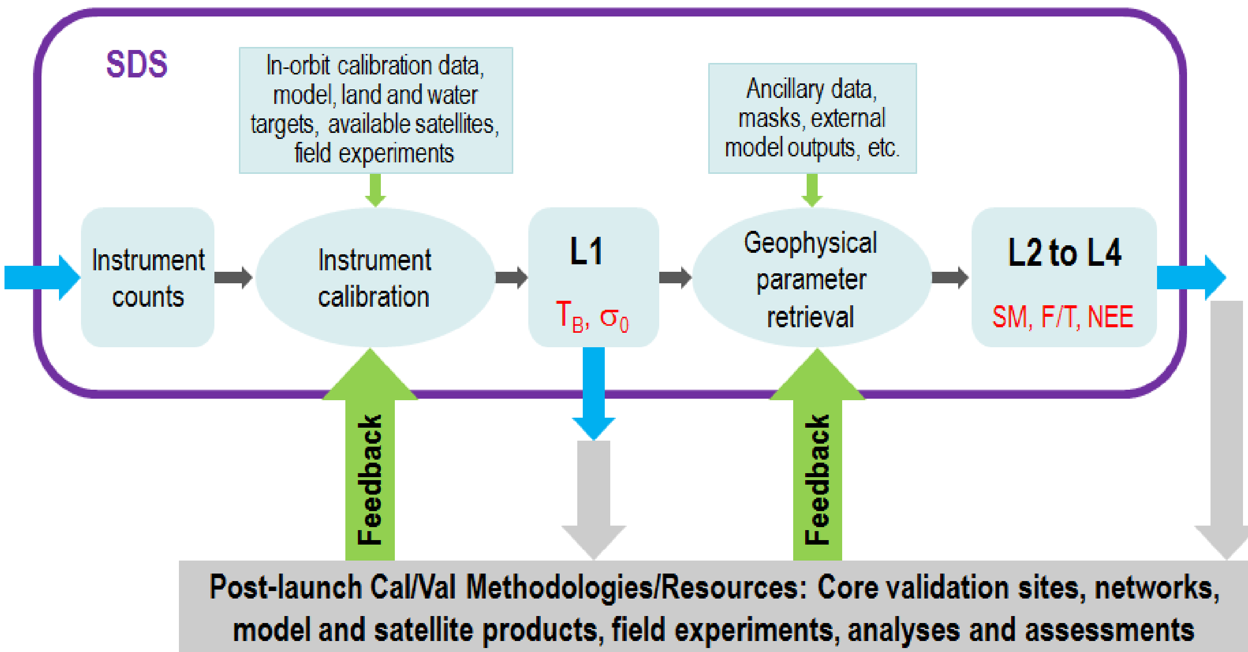

Figure 2.1. Overview of the SMAP Cal/Val Process.

SMAP established a unified definition base in order to effectively address the mission requirements. These are documented in the SMAP Handbook/ Science Terms and Definitions [3], 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 L3_FT_A Team adopted the same retrieval accuracy requirement for the fully validated L3_FT_A data (80% classification agreement) that is listed in the Mission L1 Requirements Document [4]: the baseline science mission shall provide estimates of surface binary freeze/thaw state for the region north of

45° N latitude, which includes the boreal forest zone, with a spatial classification accuracy of 80% at 3 km spatial resolution and 2-day average intervals.

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

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

In assessing the maturity of the L3_FT_A product, the L3_FT_A team also considered the guidance provided by the Committee on Earth Observation Satellites (CEOS) Working Group on Calibration and Validation (WGCV) [5]:

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

For this final validated release, the L3_FT_A team has completed Stage 1.

3 PERFORMANCE OF L1 RADAR DATA AND IMPACT ON L3_FT_A

As described in Section 6, the L1C backscatter inputs to the L3_FT_A retrieval were evaluated from pre-beta, through beta, and finally validated release, in order to understand algorithm behavior and sensitivity to the radar input. The performance of the L1 radar measurements are summarized in Table 3.1. The classification accuracy of freeze/thaw state was simulated pre-launch using the expected SMAP system noise vs. the difference in backscatter between thawed and frozen states (Figure 3.1). Based on this theoretical exercise, a step size of at least 1.5 dB will meet the classification accuracy of 80%, calculated on an annual basis. Evaluation at the limited number of high latitude core and sparse sites for which the freeze to thaw transition occurred during the operation of the SMAP radar indicates sufficient signal to noise to allow clear distinction between frozen and thawed states (more details provided in Section 7.2).

Table 3.1. Beta-level Performance of SMAP L1 Radar Data

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

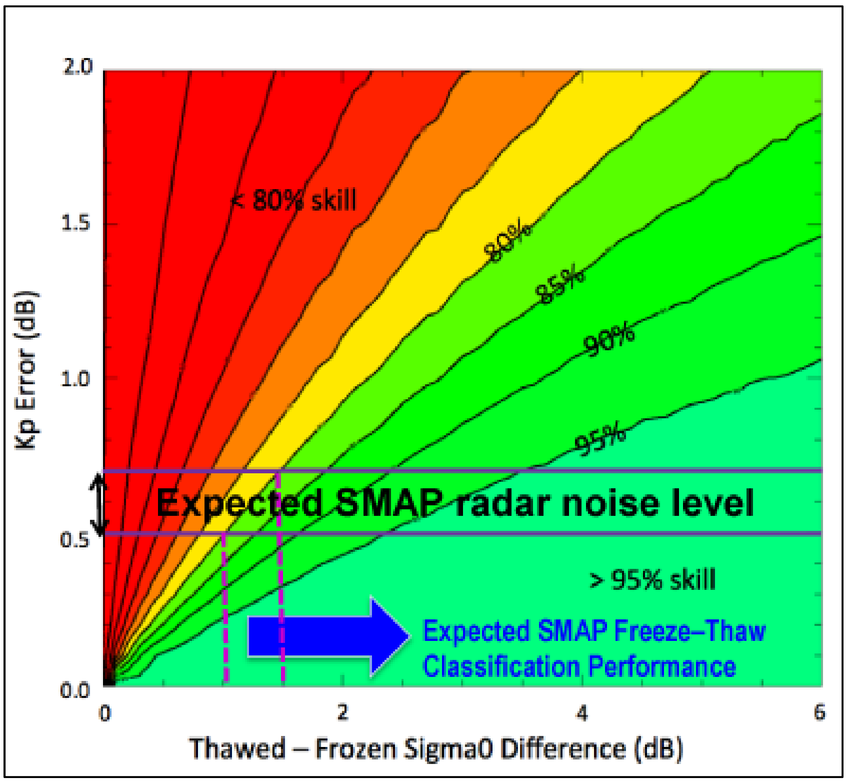

Figure 3.1 Simulation of classification accuracy versus radar noise and freeze/thaw state step size in backscatter.

4 L3_FT_A ALGORITHM

Figure 4.1 shows the data sets and processing chain associated with SMAP freeze/thaw algorithm implementation and product generation, including input and output data. There is one primary SMAP freeze/thaw product, L3_FT_A, which consists of daily composite landscape freeze/thaw state derived from the AM (descending) and PM (ascending) overpass radar data (L1C_S0_HiRes half-orbits) north of 45°N. The L1C_S0_HiRes AM data is also utilized to generate a freeze/thaw binary state flag for use in the L2/3_SM product algorithms that is not constrained by the 45°N coverage limit of the PM overpass SAR retrievals. The L3_FT_A product is gridded and provided on a 3 km Equal Area Scalable Earth grid version 2 (EASE-grid) in both global and north polar projections.

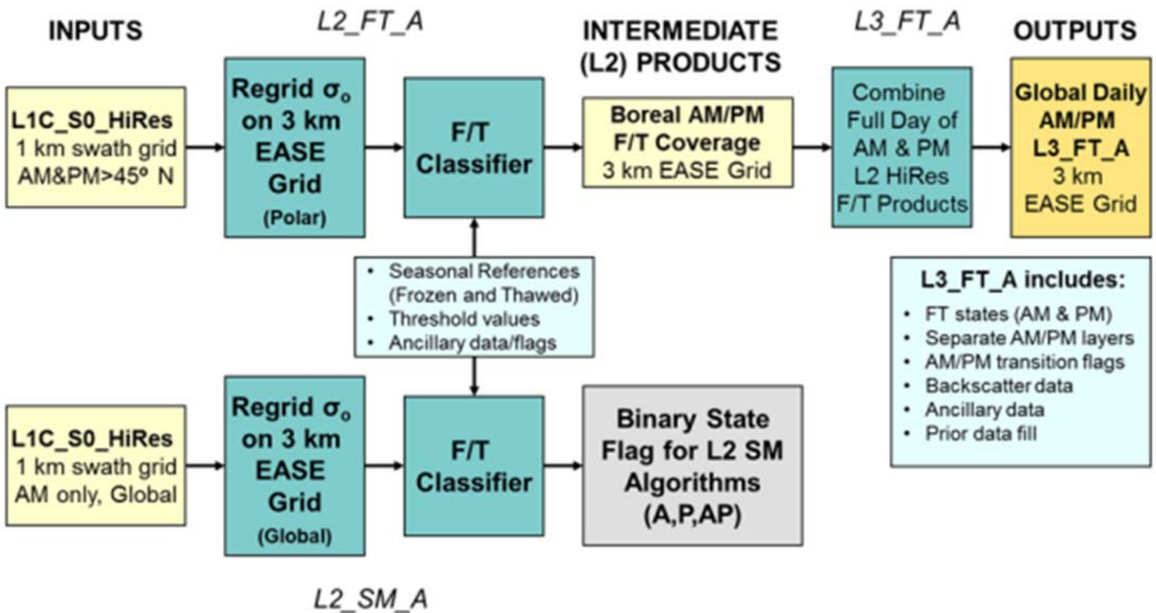

Figure 4.1 Processing sequence for generation of the L3_FT_A product and the binary freeze/thaw state flag.

The L3_FT_A algorithm is applied to the radar data granules for unmasked land regions. The resulting intermediate freeze/thaw products (Figure 4.1) serve two purposes: (1) these data are assembled into global daily composites in production of the L3_FT_A product, and (2) the freeze/thaw product derived from global AM L1C_S0_HiRes granules provide the binary freeze/thaw state flag supporting generation of the L2 and L3 soil moisture products.

The L3_FT_A algorithm is applied to the total power co-polarization radar data streams, total power being the sum of HH, VV, polarized backscatter. This provides the best signal-to-noise characteristic from the SMAP radar, thus optimizing product accuracy. No L3_FT_A data processing occurs over masked areas. The freeze/thaw retrieval takes into account the transient open water flag determined from the 3 km gridded backscatter in the L2_SM_A processing. “No-data” flags are associated with the L3_FT_A product identifying each of the masked surface types: ocean and inland open water (static), permanent ice and snow, and urban areas. The L3_FT_A algorithm does not utilize ancillary data during execution and processing, however, ancillary data will be utilized in future optimization of the state change thresholds that are employed in the baseline algorithm scheme.

The SMAP freeze/thaw algorithm is based on a seasonal threshold approach which examines the time series progression of the remote sensing signatures relative to signatures acquired during seasonal reference frozen and thawed states. A seasonal scale factor Δ(t) is defined for an observation acquired at time *t* as:

$$\Delta(t) = \frac{\sigma(t) - \sigma_{fr}}{\sigma_{th} - \sigma_{fr}} \tag{4.1}$$

where σ(*t*) is the measurement acquired at time *t*, for which a freeze/thaw classification is sought, and $\sigma_{fr}(t)$ and $\sigma_{th}(t)$ are backscatter measurements corresponding to the frozen and thawed reference states, respectively. A major component of the SMAP baseline algorithm development involved application of existing satellite L-band radar measurements from the Aquarius mission over the FT domain to develop pre-launch maps of σ_{th}, and σ_{fr}. These initial references were replaced through post-launch integration of thaw references derived directly from SMAP measurements, and bias corrected Aquarius freeze references (see Section 6.3).

A threshold level *T* is then defined such that:

$$\begin{aligned} \Delta(t) &> T \\ \Delta(t) &\leq T \end{aligned} \tag{4.2}$$

defines the thawed and frozen landscape states, respectively. This algorithm is run on a cell-by-cell basis for unmasked portions of the FT domain. The output from Equation (4.2) will be a dimensionless binary state variable designating either frozen or thawed condition for each unmasked grid cell. The parameter *T* is fixed at 0.5 across the entire FT domain. Full details on the L3_FT_A product can be found in the Algorithm Theoretical Basis Document [2].

5 L3_FT_A VALIDATION METHODOLOGY

The L3_FT_A freeze/thaw product provides estimates of land surface freeze/thaw state expressed as a categorical (frozen, thawed, or [inverse] transitional) condition. The SMAP Level 1 mission requirement is that the L3 freeze/thaw product will be provided for land areas north of 45 degrees north latitude with a mean spatial classification accuracy of 80% at 3 km spatial resolution and 2-day average temporal sampling. The accuracy of the L3 product will be determined by comparison of the SMAP freeze/thaw retrievals with in situ measurements from sites within northern latitude (≥45°N) land areas (see Section 7.2).

The in situ validation data will include all core validation sites and selected sites from the sparse networks using criteria based on site representativeness (uniform and representative terrain and land cover) consistent with the overlying 3-km resolution satellite retrieval. The validation is based on reference freeze/thaw flags derived from co-located air temperature and soil temperature corresponding to the local time of the descending and ascending satellite overpasses.

The computation of the classification accuracy proceeds as follows: Let $s_{AM/PM}(i,t) = 1$ if the L3_FT_A product at grid cell i (on the SMAP 3 km EASE grid) and time t indicates frozen conditions for AM (descending) or PM (ascending) overpass, respectively, and let $s_{AM/PM}(i,t) = 0$ if the L3_FT_A product indicates thawed conditions for AM or PM overpass, respectively. Likewise, let $v_{AM/PM}(i,t) = 1$ if the corresponding reference flag indicates frozen conditions at the AM or PM overpass, and $v(i,t) = 0$ for thawed conditions at the AM or PM overpass. Next, the error flag δ is set by comparing the SMAP product to the validating observations:

$$\delta_{AM/PM}(i,t) = \begin{cases} 0 & \text{if } s_{AM/PM}(i,t) = v_{AM/PM}(i,t) \\ 1 & \text{if } s_{AM/PM}(i,t) \neq v_{AM/PM}(i,t) \end{cases} \tag{5.1}$$

Note that a single L3_FT_A flag is produced each day, but is derived from separate descending (AM) and ascending (PM) overpasses. The L3_FT_A flags will therefore be separated back into binary freeze/thaw classes for the AM and PM orbits, producing two retrieval match-ups each day.

The mission Level 1 requirement will be satisfied if (for both AM and PM overpasses together):

$$1 - \left(\sum_{i=1}^{N_i} \sum_{t=1}^{N_t(i)} \delta(i,t) \Big/ \sum_{i=1}^{N_i} N_t(i) \right) \geq 0.8 \tag{5.2}$$

Equation 5.1 will be solved daily, to provide instantaneous determinations of freeze/thaw spatial accuracy, using the available reference sites. The mission requirement of 80% spatial accuracy will be assessed cumulatively (in a running manner with each new day of data added to the previous days). Assessment with multiple reference FT flags (air temperature, soil temperature, soil moisture) allows algorithm performance metrics to be computed for various surface conditions (i.e. wet snow versus dry snow), and assist in determining the landscape components driving the radar response. Retrieval performance is also summarized monthly to reduce sensitivity to prolonged periods of consistent frozen and thawed states in the winter and summer, respectively. In addition to overall flag agreement, counts of freeze and thaw omission and commission errors (‘false freeze’ retrievals vs. ‘false thaw’ retrievals) are also tabulated.

Comparisons between SMAP L3_FT_A, other satellite derived FT products from Aquarius [6] and AMSR-2 [7], and surface temperature fields from NASA GMAO are also performed in order to evaluate spatial agreement, and changes in continental-scale frozen area over time.

6 FINAL RELEASE PROCESS

This section describes refinement of the L3_FT_A product from launch through the beta release (November 2015) to the final validated product. The primary activities were setting the lake fraction, mitigation of L1C_s0 nadir swath artifacts, and derivation of hybrid SMAP-Aquarius freeze and thaw references.

6.1 Lake Fraction

The pre-launch maximum lake fraction threshold of 5% was experimentally increased to 50% in order to reduce the amount of missing retrievals in lake-rich areas such as the Canadian subarctic tundra (Figure 6.1a). Sensitivity analysis on the maximum lake fraction as a function of SMAP radar performance (Kp) and land-water difference in backscatter (ranging between 8 and 12 dB in Figure 6.2) identified a threshold of approximately 20% assuming a radar Kp near 0.5. Despite this result, the F/T algorithm exhibits a tolerance to a higher water body fraction, with no apparent lake fraction related artifacts in the retrievals (Figure 6.1b), so the 50% lake fraction threshold was retained.

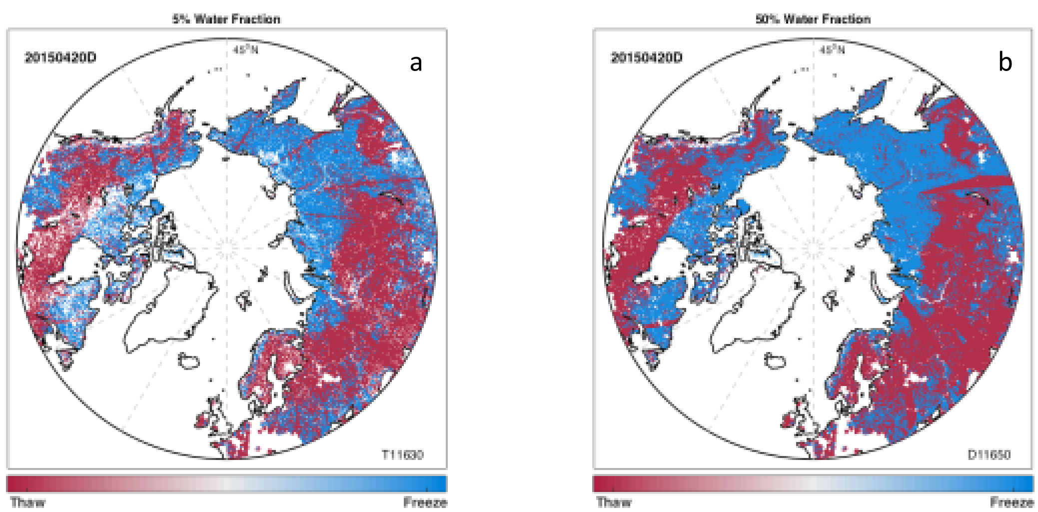

Figure 6.1 Freeze/thaw retrievals for 20 April 2015 using a lake fraction threshold of 5% (a) and 50% (b).

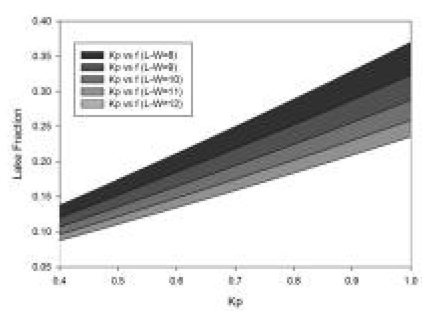

Figure 6.2 Maximum allowable lake fraction as a function of SMAP radar Kp and assumed land versus water backscatter difference (varied between 8 and 12 dB in this plot).

6.2 L1C_s0 Artifacts

L1C_s0 swath edge and nadir artifacts in the L3_FT_A beta release were addressed for the final validated product. In the L3_FT_A beta release, an expansion of the swath grid to allow for "spare" cells on the edges, resulted in missing data due to fill-valued cells with otherwise "good" quality flags. This was corrected by implementing an additional check on the values of the backscatter measurements before re-gridding of the data. Nadir track radar measurements (~150 km on either side of the nadir track) were excluded due to uncertainties in the footprint area calculations. Improvements in the L1C_s0 processing between the beta and final release allowed a larger proportion of the near-nadir swath to be included in the L3_FT_A validated release (only 50 km on either side of the nadir track were excluded), which improves the latency of measurements utilized to maintain coverage of the FT domain.

6.3 Hybrid SMAP-Aquarius References

A major component of the SMAP baseline algorithm development involved application of existing satellite L-band radar measurements from the Aquarius mission over the FT domain to develop pre-launch reference maps of σ_{th}, and σ_{fr}. These initial references were replaced through post-launch derivation of references that include SMAP measurements. The thaw reference (σ_{th}) was computed as an average over the last ten days of SMAP radar data (27 June through 6 July 2015):

$$T_{ref} = \frac{1}{n}\sum_{i=1}^{n}(\sigma_{vv} + \sigma_{hh}), \qquad n = 10 \tag{6.1}$$

The hybrid freeze reference (σ_{fr}) was derived based on the assumption that the σ_{th} reference difference between SMAP and the pre-launch Aquarius values is the same for the freeze case. The thaw reference difference between SMAP and Aquarius was thus applied as a form of post-launch bias correction to the pre-launch Aquarius reference:

$$F_{ref} = T_{ref} - (T_{AQref} - F_{AQref}) \tag{6.2}$$

The pre-launch Aquarius references derived from 2014 summer data for thaw and 2015 winter data for freeze, are shown in Figure 6.3. The resolution is approximately 100 km. Three beams with different incidence angle are combined to get hemispheric coverage. Although an incidence angle correction was performed, there are still some apparent swath artifacts. Detailed features can be seen in the final thaw reference (Figure 6.4a) because of the finer 3km SMAP resolution. In Figure 6.5a, the thaw versus freeze reference difference from pre-launch AQ data is shown; the magnitude of the reference difference on a per grid cell basis is assumed to be the same for SMAP. Therefore, the hybrid freeze reference still contains information from the 100km AQ data but the actual resolution is decreased to 3 km. Across the FT domain, the SMAP thaw references are lower than Aquarius, especially in lower latitude/low vegetation areas (Figure 6.5b). Incidence angle artifacts in the Aquarius thaw reference are also significantly reduced.

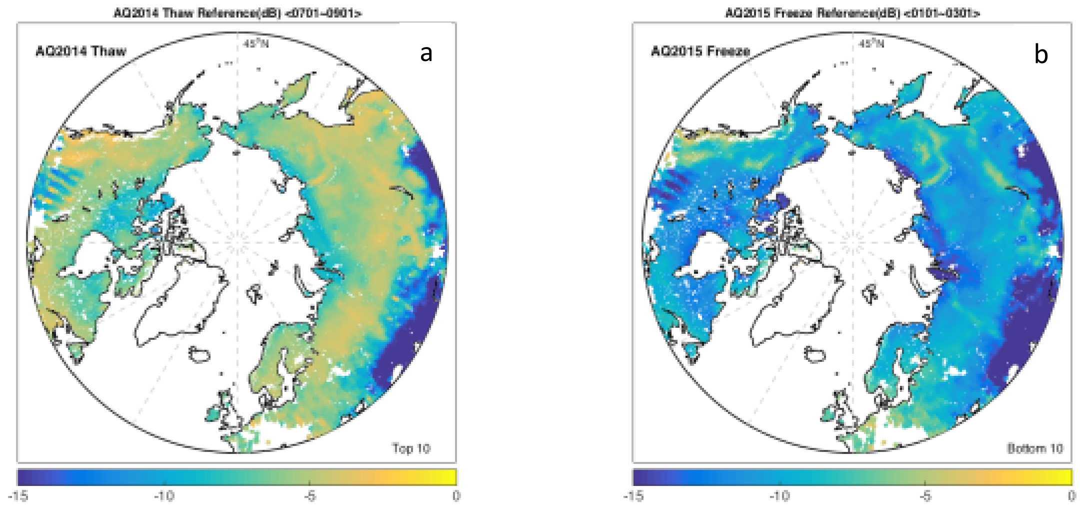

Figure 6.3. (a) Pre-launch Aquarius thaw reference and (b) freeze reference.

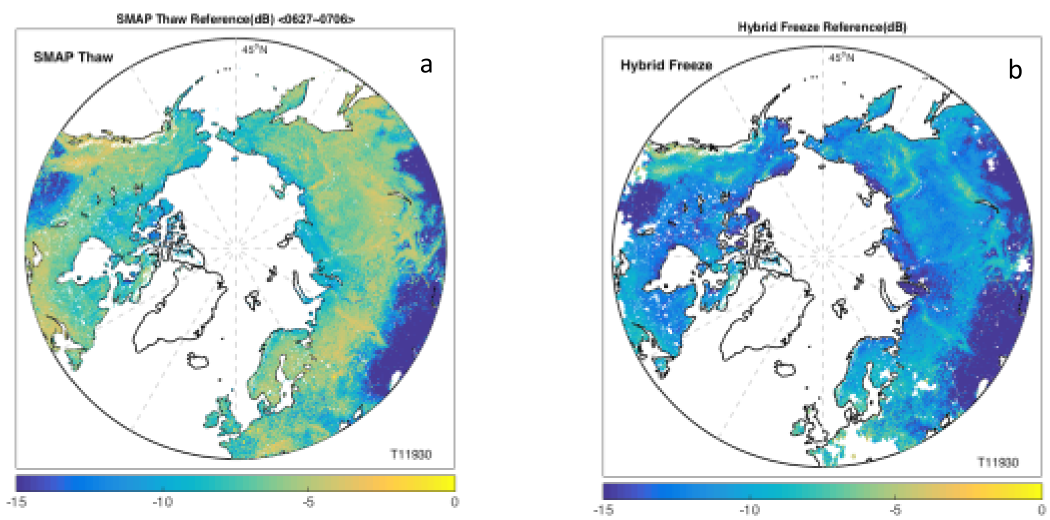

Figure 6.4. (a) SMAP thaw reference; (b) SMAP/AQ Hybrid freeze reference.

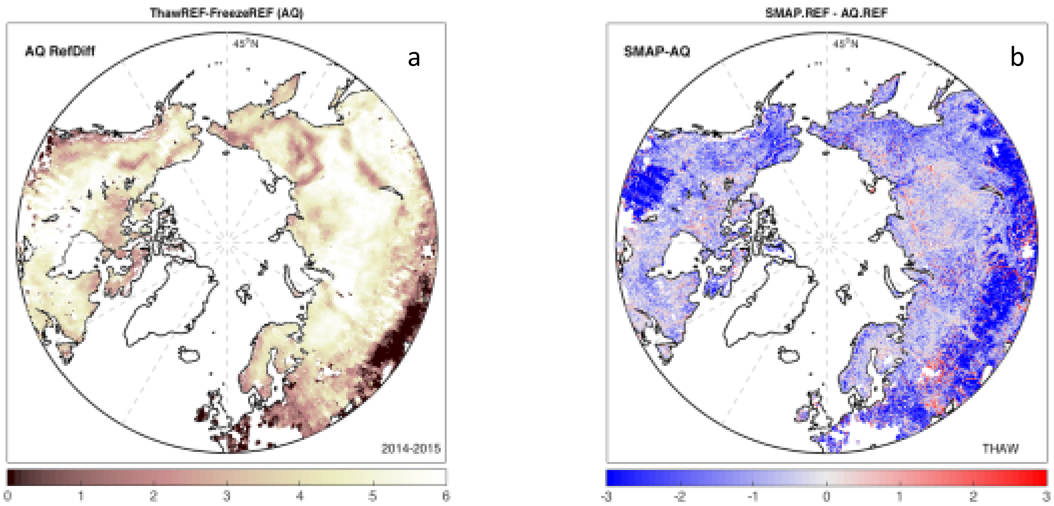

Figure 6.5 (a) Reference difference from Aquarius data (2014 summer – 2015 winter; (b) reference difference between SMAP derived thaw reference and AQ 2014 thaw reference

6.4 Validated Release Testing

Testing of the L2/L3_FT_A final release algorithm code, including all of the algorithm enhancements described above, was conducted using the final release L1C_S0_HiRes version R12400 data set. The test run covered the full extent of the available SMAP radar data from April 13 to July 7. The CRID for this test dataset was T12400. All of the analyses described in Section 7 are based on this dataset, and forms the basis of our final release assessment.

7 ASSESSMENTS

7.1 Large Scale Patterns and Features

Example freeze-thaw maps generated using the pre-launch Aquarius references and hybrid SMAP-Aquarius references are shown in Figure 7.1. While differences in the frozen area across high latitudes are small, the final references result in a notable reduction in false freeze retrievals across high elevation areas and the southern portion of the FT domain. This improvement is particularly clear by July, when essentially the entire FT domain was thawed. Qualitative assessment of the FT time series produced using the hybrid references indicated clean and coherent algorithm performance (lake fraction set to 50%; nadir track radar measurements not included) so this dataset was evaluated prior to final release as described in Sections 7.2 to 7. 4.

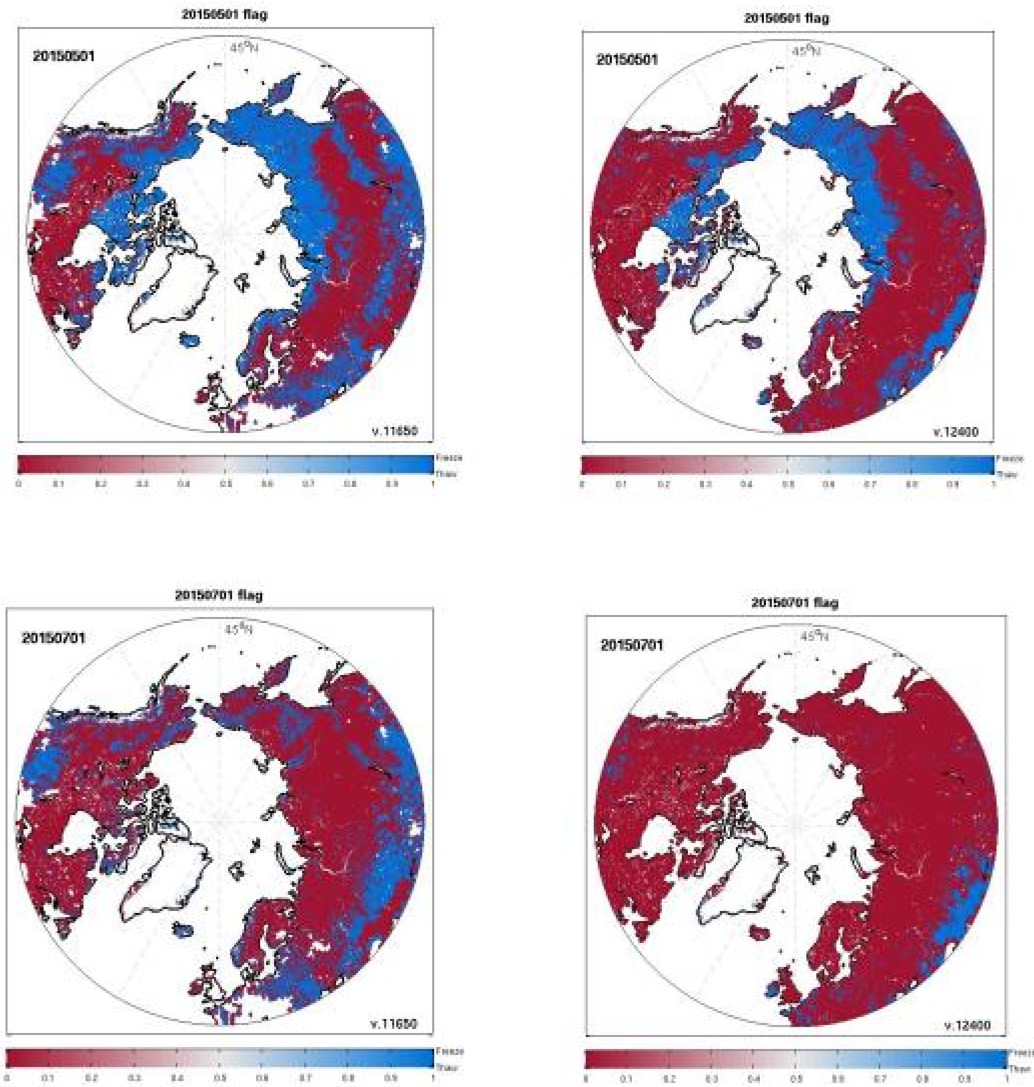

Figure 7.1 Example FT images derived using pre-launch Aquarius references (left) and SMAP thaw/hybrid SMAP-Aquarius freeze references (right) for 1 May 2015 (top) and 1 July 2015 (bottom).

7.2 Core Validation Sites (CVS)

A summary of core validation sites for L3_FT_A is provided in Figure 7.2 and Table 7.1. Only three sites transitioned from freeze to thaw following the availability of SMAP radar measurements on 13 April 2015: Cambridge Bay, Canada, Imnavait, Alaska, and Saariselka, Finland. Additional in situ measurements were acquired for Trail Valley Creek, Canada in September 2015.

Table 7.1 Summary of L3_FT_A core validation sites.

Site Name	Site PI	Area	IGBP Land Cover	Freeze to Thaw Transition during SMAP Radar operation
Reynolds Creek	M. Cosh	Idaho, USA	Grasslands	No
Kenaston	A. Berg	Saskatchewan, Canada	Croplands	No
Carman	H. McNairn	Manitoba, Canada	Croplands	No
Boreal Ecosystem Research and Monitoring Sites	H. Wheater	Saskatchewan, Canada	Coniferous Forest	No
Caribou Creek	C. Smith	Saskatchewan, Canada	Coniferous Forest	No
Casselman	H. McNairn	Ontario, Canada	Deciduous Broadleaf	No
Sodankyla	J. Pulliainen	Finland	Coniferous Forest	No
Saariselka	J. Pullianen	Finland	Grasslands	Yes
Imnavait	E. Eukirchen	Alaska, USA	Barren/Sparse	Yes
Kuujjuaripik	A. Langlois	Quebec, Canada	Coniferous Forest	No
Baie-James	A. Langlois	Quebec, Canada	Coniferous Forest	No
Cambridge Bay	A. Langlois	Northwest Territories, Canada	Barren/Sparse	Yes
Trail Valley Creek*	P. Marsh	Northwest Territories, Canada	Barren/Sparse	Yes

*Measurements from Trail Valley Creek are not ingested in near real time for L3_FT_A validation but are provided annually.

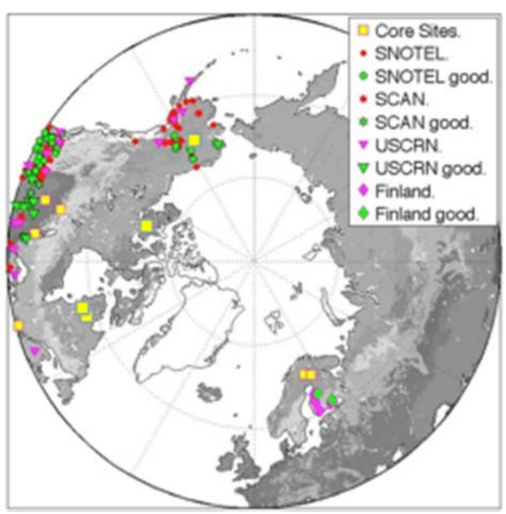

Figure 7.2. Core and sparse sites for L3_FT_A validation.

L3_FT_A validation results for the four core sites are summarized in Figures 7.3 through 7.6. Panels show time series of L1C_s0 and in situ measurements (air temperature, soil temperature) separated by overpass. Corresponding time series of F/T flags are also provided, with in situ flags determined from soil and air temperature (<= 0°C = frozen). Tables 7.2 through 7.5 provide a summary of the frequency of flag agreement (1 represents perfect flag agreement through each available time series) as well as an error matrix for each site showing the total absolute occurrence of flag agreement (green cells) false freeze (SMAP = freeze, reference flags = thaw; blue cells), and false thaw (SMAP = thaw, reference flags = freeze, yellow cells). Overall, there is excellent agreement between the SMAP radar derived FT state and the reference flags derived from air and temperature. The 80% flag agreement requirement is met for all sites, orbits, and in situ flags with the exception of descending orbits with air temperature flags at Saariselka.

At Cambridge Bay (Figure 7.3), there is evidence that the radar FT flags are responding to the onset of wet snow, because the first thaw retrievals occurred when air temperatures exceeded zero (hence inducing snow melt) but soil temperatures remained below zero. Transient diurnal thaw events (frozen at night/thawed during the day) before the primary thaw transition are captured by the ascending overpass retrievals. Similar results are evident at Imnavait (Figure 7.4), where descending overpass thaw retrievals are coincident to air temperatures increasing above zero, but lead soil thaw by approximately one week. At Saariselka, (Figure 7.5) the L3_FT_A retrievals indicated a thawed state from the beginning of the SMAP radar record likely due to wet snow cover since the air temperature flags were above zero by early April 2015, before SMAP radar data were available. A decrease in descending orbit radar backscatter was coincident to a period of cooler air temperatures later in April, but the response was not sufficiently strong to drop the backscatter value below the threshold. This is an example of the potential benefit of threshold optimization at this site. There was close agreement between the retrieved and observed primary thaw transition at Trail Valley Creek (Figure 7.6), although there was insufficient sensitivity to a transient refreeze event in May to trigger freeze retrievals.

The relatively similar overall performance of the L3_FT_A retrievals compared to soil versus air temperature is likely a function of melt processes at these open tundra sites. Melt onset was rapid at Cambridge Bay, Imnavait, and Trail Valley; with a relatively thin tundra snow pack there was a short offset between air temperatures and soil temperatures rising above zero. Still, the tendency for SMAP to classify melt onset slightly before the soil temperature reference flags (note the yellow cells in Tables 7.2 – 7.5) indicates radar and hence retrieval response to the onset of wet snow cover. The similar flag agreement statistics for air temperature and soil temperature based metrics is also due to competing effects of different errors. Higher errors with soil temperature (false thaw retrieval) during the primary thaw transition occur because the radar responds to wet snow while the soil is still frozen, hence better agreement with air temperature derived flags. Once the soil is thawed, transient freeze events observed in the air temperature record (but not sufficient to induce soil re-freeze) are not captured by the radar, hence better agreement with soil temperature.

In summary, evaluation of the final release L3_FT_A product with updated post-launch freeze and thaw references (see Section 6.3) using observations from the core validation sites showed excellent agreement with in situ reference flags with no threshold optimization. There was modest improvement in retrieval performance compared to the beta release (likely due to improved calibration and temporal radar coverage achieved by retaining more the nadir swath, see section 6.2), and a significant improvement over pre-beta retrievals produced using the pre-launch Aquarius references.

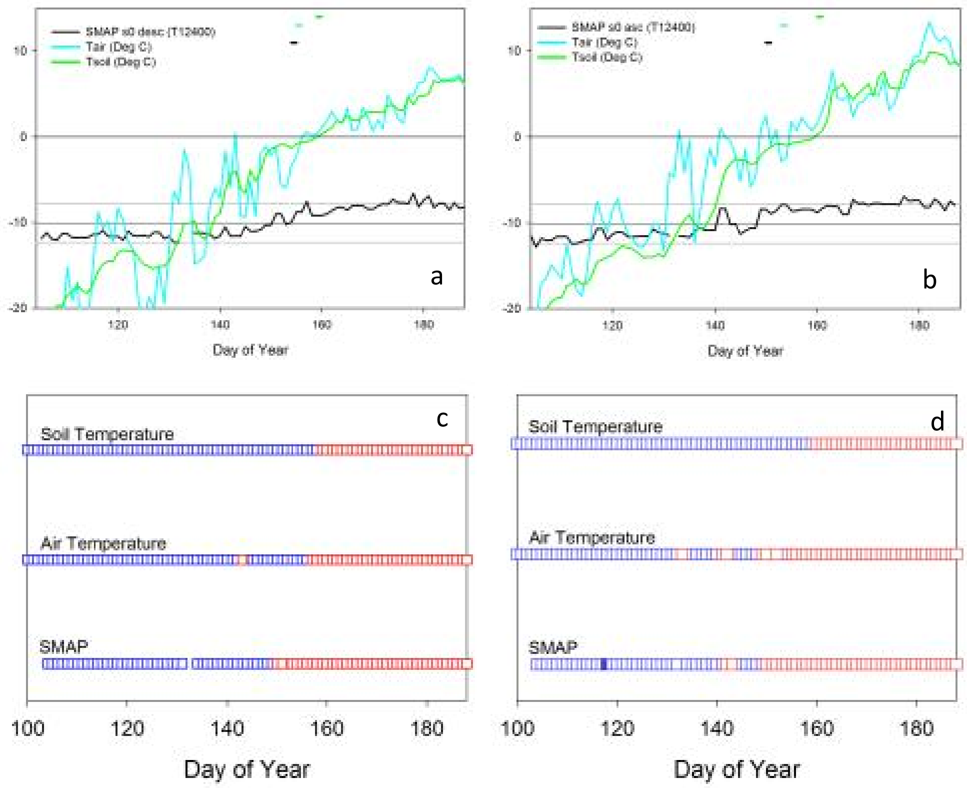

Figure 7.3 (a) Descending and (b) ascending overpass time series of backscatter, air temperature, and soil temperature for Cambridge Bay. Horizontal lines note date of primary freeze – thaw transition. Flag agreement (blue = freeze, red = thaw) for (c) descending and (d) ascending overpasses.

Table 7.2 Summary of freeze/thaw flag agreement and error matrix for Cambridge Bay.

	Cases	Agreement SMAP Tair	Agreement SMAP Tsoil
Des	82	0.93	0.91
Asc	84	0.93	0.86

Cambridge Bay	Tair-PM-F	Tair-PM-T	Tair-AM-F	Tair-AM-T
SMAP-Asc-F	41	2		
SMAP-Asc-T	4	37		
SMAP-Des-F			44	1
SMAP-Des-T			5	32

CambridgeBay	Tsoil-PM-F	Tsoil-PM-T	Tsoil-AM-F	Tsoil-AM-T
SMAP-Asc-F	43	0		
SMAP-Asc-T	12	29		
SMAP-Des-F			45	0
SMAP-Des-T			7	30

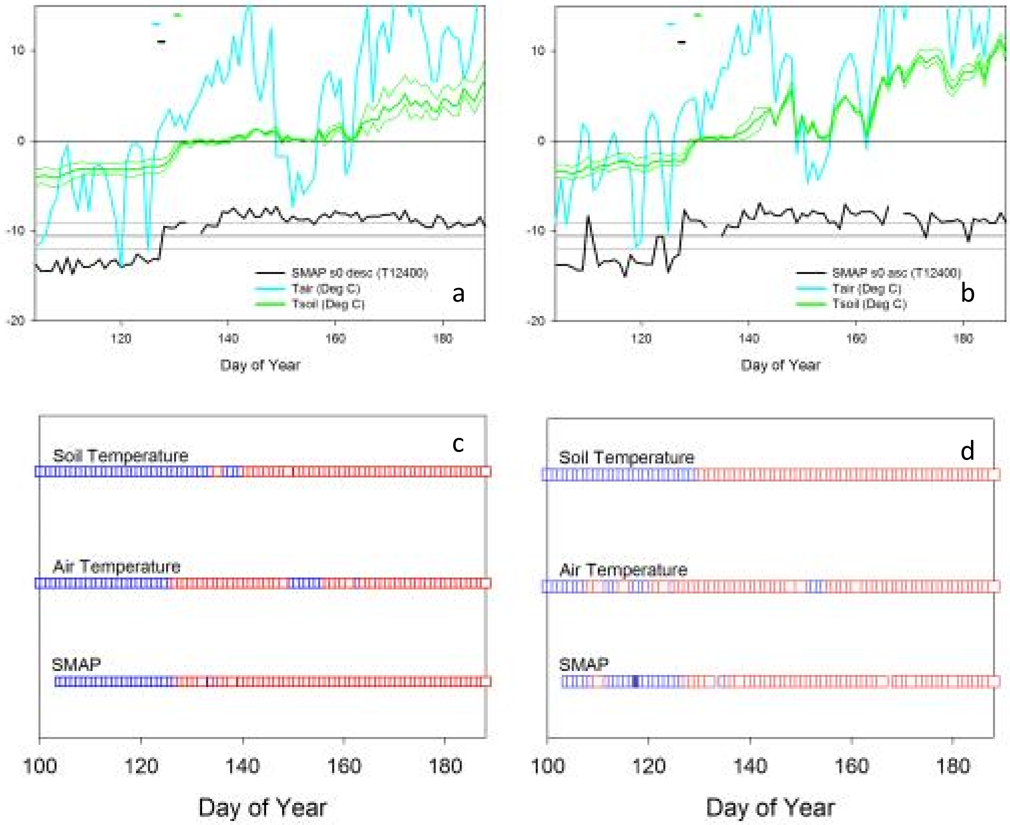

Figure 7.4 (a) Descending and (b) ascending overpass time series of backscatter, air temperature, and soil temperature for Imnavait. Horizontal lines note date of primary freeze – thaw transition. Flag agreement (blue = freeze, red = thaw) for (c) descending and (d) ascending overpasses.

Table 7.3 Summary of freeze/thaw flag agreement and error matrix for Imnavait.

	Cases	Agreement SMAP Tair	Agreement SMAP Tsoil
Des	83	0.86	0.88
Asc	81	0.80	0.90

Imnavait	Tair-PM-F	Tair-PM-T	Tair-AM-F	Tair-AM-T
SMAP-Asc-F	16	11		
SMAP-Asc-T	7	47		
SMAP-Des-F			23	2
SMAP-Des-T			0	17

Imnavait	Tsoil-PM-F	Tsoil-PM-T	Tsoil-AM-F	Tsoil-AM-T
SMAP-Asc-F	23	4		
SMAP-Asc-T	4	50		
SMAP-Des-F			25	0
SMAP-Des-T			10	48

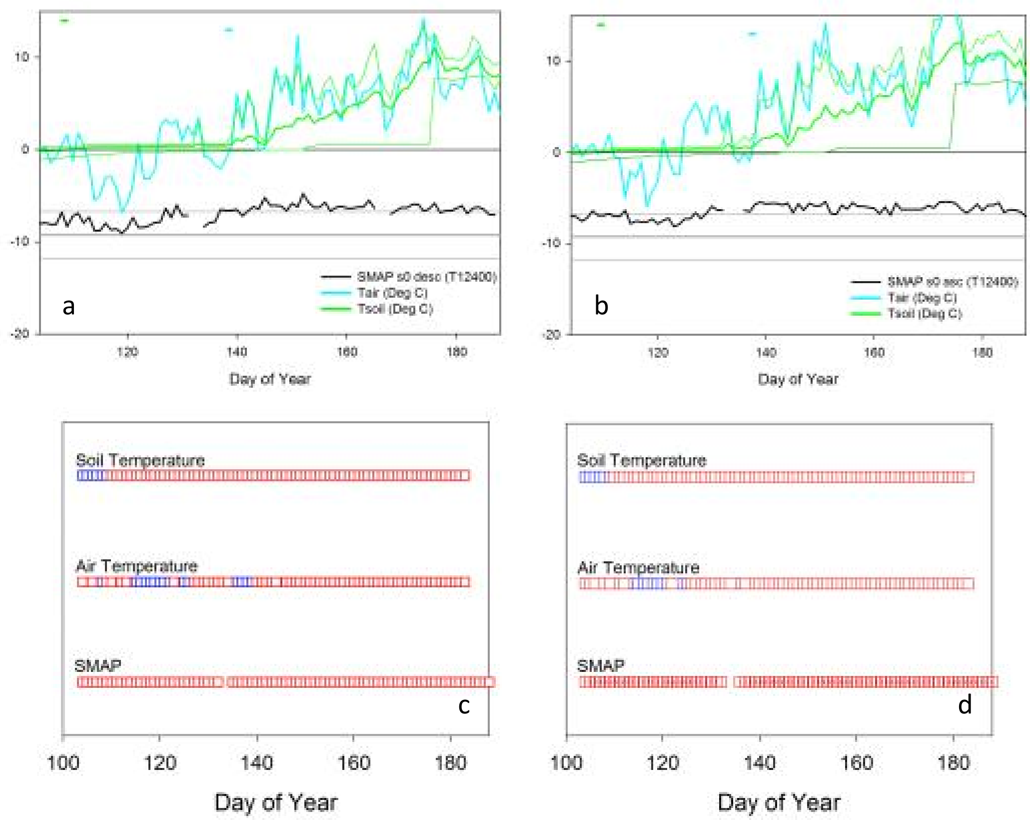

Figure 7.5 (a) Descending and (b) ascending overpass time series of backscatter, air temperature, and soil temperature for Saariselka. Horizontal lines note date of primary freeze – thaw transition. Flag agreement (blue = freeze, red = thaw) for (c) descending and (d) ascending overpasses.

Table 7.4 Summary of freeze/thaw flag agreement and error matrix for Saariselka.

	Cases	Agreement SMAP Tair	Agreement SMAP Tsoil
Des	81	0.74	0.94
Asc	82	0.82	0.94

Saariselka	Tair-PM-F	Tair-PM-T	Tair-AM-F	Tair-AM-T
SMAP-Asc-F	0	0		
SMAP-Asc-T	15	67		
SMAP-Des-F			0	0
SMAP-Des-T			21	60

Saariselka	Tsoil-PM-F	Tsoil-PM-T	Tsoil-AM-F	Tsoil-AM-T
SMAP-Asc-F	0	0		
SMAP-Asc-T	5	77		
SMAP-Des-F			0	0
SMAP-Des-T			5	76

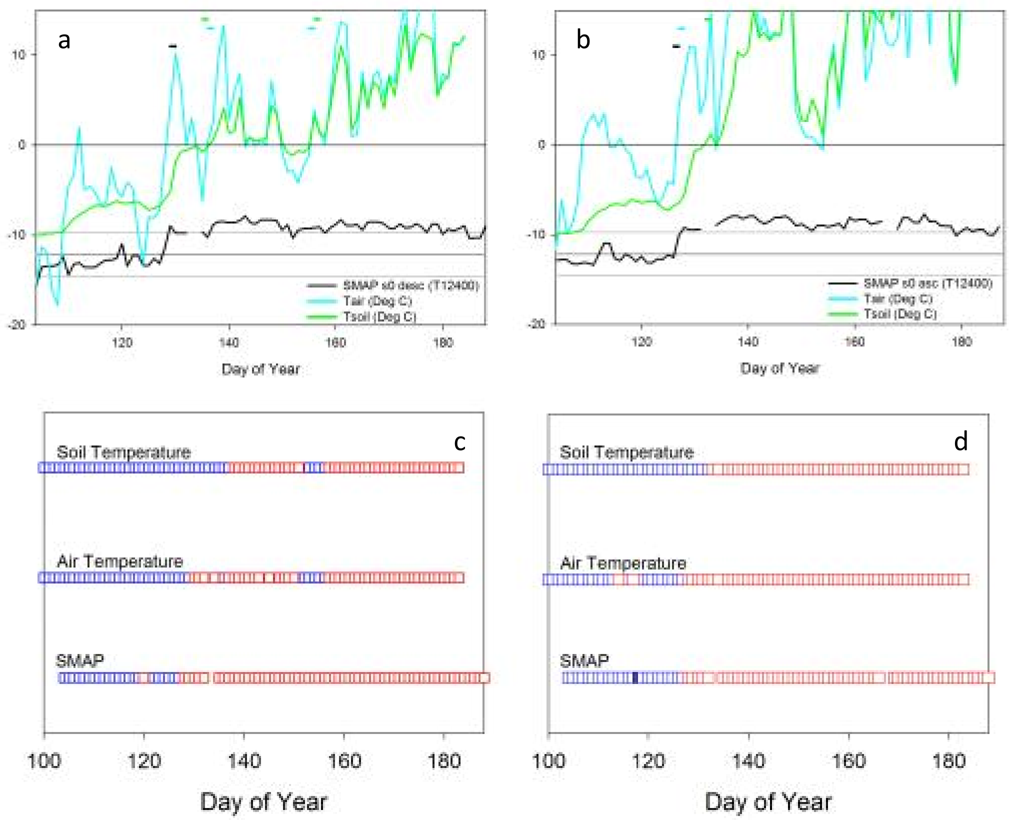

Figure 7.6 (a) Descending and (b) ascending overpass time series of backscatter, air temperature, and soil temperature for Trail Valley Creek. Horizontal lines note date of primary freeze – thaw transition. Flag agreement (blue = freeze, red = thaw) for (c) descending and (d) ascending overpasses.

Table 7.5 Summary of freeze/thaw flag agreement and error matrix for Trail Valley Creek.

	Cases	Agreement SMAP Tair	Agreement SMAP Tsoil
Des	79	0.84	0.84
Asc	77	0.90	0.95

Trail Valley	Tair-PM-F	Tair-PM-T	Tair-AM-F	Tair-AM-T
SMAP-Asc-F	17	7		
SMAP-Asc-T	1	52		
SMAP-Des-F			22	1
SMAP-Des-T			12	44

Trail Valley	Tsoil-PM-F	Tsoil-PM-T	Tsoil-AM-F	Tsoil-AM-T
SMAP-Asc-F	24	0		
SMAP-Asc-T	4	49		
SMAP-Des-F			23	0
SMAP-Des-T			13	43

7.3 Sparse Networks

Measurements from sparse networks are also available for F/T validation (Table 7.6). The majority of these sites are outside of the L3 F/T domain but can be used for evaluation of the L2 freeze/thaw retrievals (not covered in this assessment document). A pre-launch assessment of the CRN, SCAN, and SnoTel networks was performed in order to separate the sites into primary and secondary categories based on land cover. Sites located in homogeneous land cover within the 3 km grid were classified as primary, and assumed to be reasonably representative of the entire grid cell. Sites located in grid cells with heterogeneous land cover were classified as secondary and presumed to contain greater uncertainty with respect to scaling of the single sparse network measurements. For the evaluation of L3_FT_A, 8 sites from the SnoTel network located in Alaska were available for the freeze to thaw transition during the operating period of the SMAP radar (Figure 7.7). These sites were all identified as primary, and located in locations classified as either woody savannah or open shrub.

Table 7.6. Sparse Networks Providing L3_FT_A Validation Data. Brackets indicate number of sites with freeze to thaw transition during the period of SMAP radar operation.

Network Name	PI /Contact	Area	Primary Sites[1]	Secondary Sites[2]
NOAA Climate Reference Network (CRN)	M. Palecki	USA	8 (0)	13 (0)
USDA Soil Climate Analysis Network (SCAN)	M. Cosh	USA	7 (0)	11 (0)
NRCS SnoTel		Northwestern USA; Alaska	32 (8)	46 (0)

[1]Sites with homogeneous land cover at the 3 km SMAP radar resolution
[2]Site with hetergeneous land cover at the 3 km SMAP radar resolution

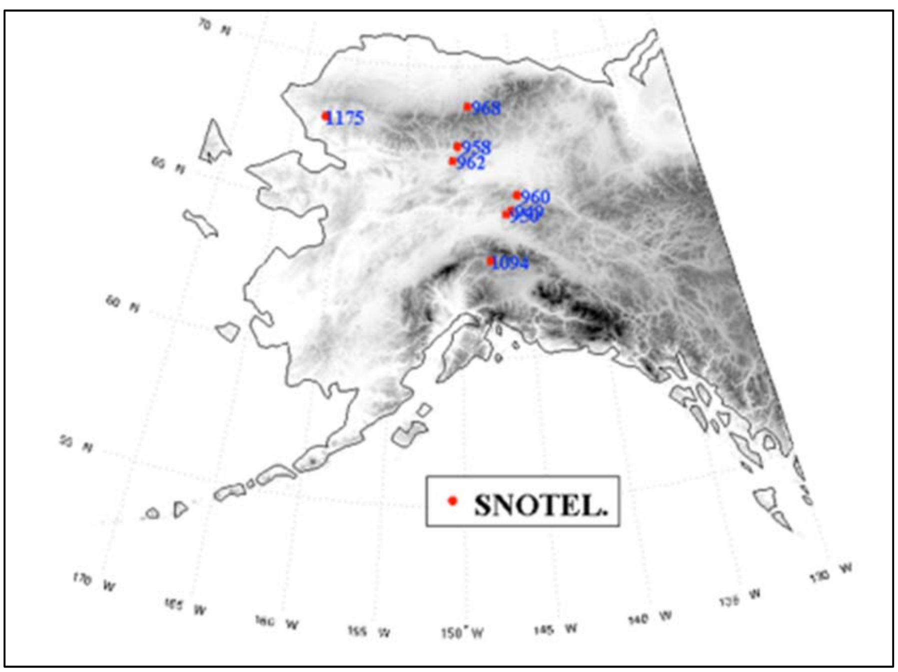

Figure 7.7. SnoTel sites used for L3_FT_A evaluation.

A comparison of L3_FT_A retrievals was performed using air and soil temperature derived reference flags. Flag agreement was computed separately by orbit and by month. Because only a single measurement point is available, the value in the sparse network evaluation is the overall performance across the network, instead of the statistic produced on a location-to-location basis. Collective results for the 8 SnoTel sites indicate the 80% agreement target is met over the 12 weeks of radar measurements with the exception of soil temperature flags during descending orbits (Table 7.7). Consistent agreement after the main thaw season (May/June) drives the overall strong performance.

The primary disagreement is caused by SMAP retrievals of thaw when reference flags are indicating frozen conditions (Table 7.8). The lower frequency of false thaw retrievals for ascending orbits is consistent with warmer afternoon surface temperatures (triggering the thaw reference flag in agreement with SMAP retrievals) compared to the morning. The sparse network sites show a larger difference in flag agreement between air and soil temperature than was found for the core sites (see Section 7.2). The underlying reason for this is not immediately clear, but could be related to reduced representativeness of the point soil temperature measurements.

Table 7.7. Summary of flag agreement between SMAP retrievals and in situ measurements.

Summary	Cases	Agreement SMAP Tair	Agreement SMAP Tsoil
Des	579	0.86	0.79
Asc	561	0.93	0.83

Apr 2015	Cases	Agreement SMAP Tair	Agreement SMAP Tsoil
Des	118	0.58	0.54
Asc	115	0.75	0.55

May 2015	Cases	Agreement SMAP Tair	Agreement SMAP Tsoil
Des	202	0.91	0.72
Asc	202	0.96	0.80

June 2015	Cases	Agreement SMAP Tair	Agreement SMAP Tsoil
Des	210	0.94	0.95
Asc	195	0.98	0.98

Table 7.8 Error matrix for sparse sites shown in Figure 7.7

Fraction	Tair-PM-F	Tair-PM-T	Tair-AM-F	Tair-AM-T
SMAP-Asc-F	0.04	0.05		
SMAP-Asc-T	0.02	0.89		
SMAP-Des-F			0.09	0.04
SMAP-Des-T			0.10	0.77

Fraction	Tsoil-PM-F	Tsoil-PM-T	Tsoil-AM-F	Tsoil-AM-T
SMAP-Asc-F	0.07	0.02		
SMAP-Asc-T	0.16	0.76		
SMAP-Des-F			0.10	0.02
SMAP-Des-T			0.19	0.69

7.4 Satellite Inter-comparison

Other satellite-derived datasets provide an opportunity to compare FT spatial patterns and time series information. This includes other L-band radar and radiometer measurements from Aquarius, and higher frequency AMSR2 retrievals. An example of four coincident FT estimates for 20 April 2015 is shown in Figure 7.8 (note the Aquarius data cover a week centered on 20 April). While there are resolution differences (3 km for SMAP; 100 km for Aquarius; 25 km for AMSR2), all four datasets capture the same general FT pattern, with some regional differences in areas of complex elevation, and along freeze-thaw transition areas. In general, the passive products (Aquarius and AMSR2) retrieve less frozen area than the active products.

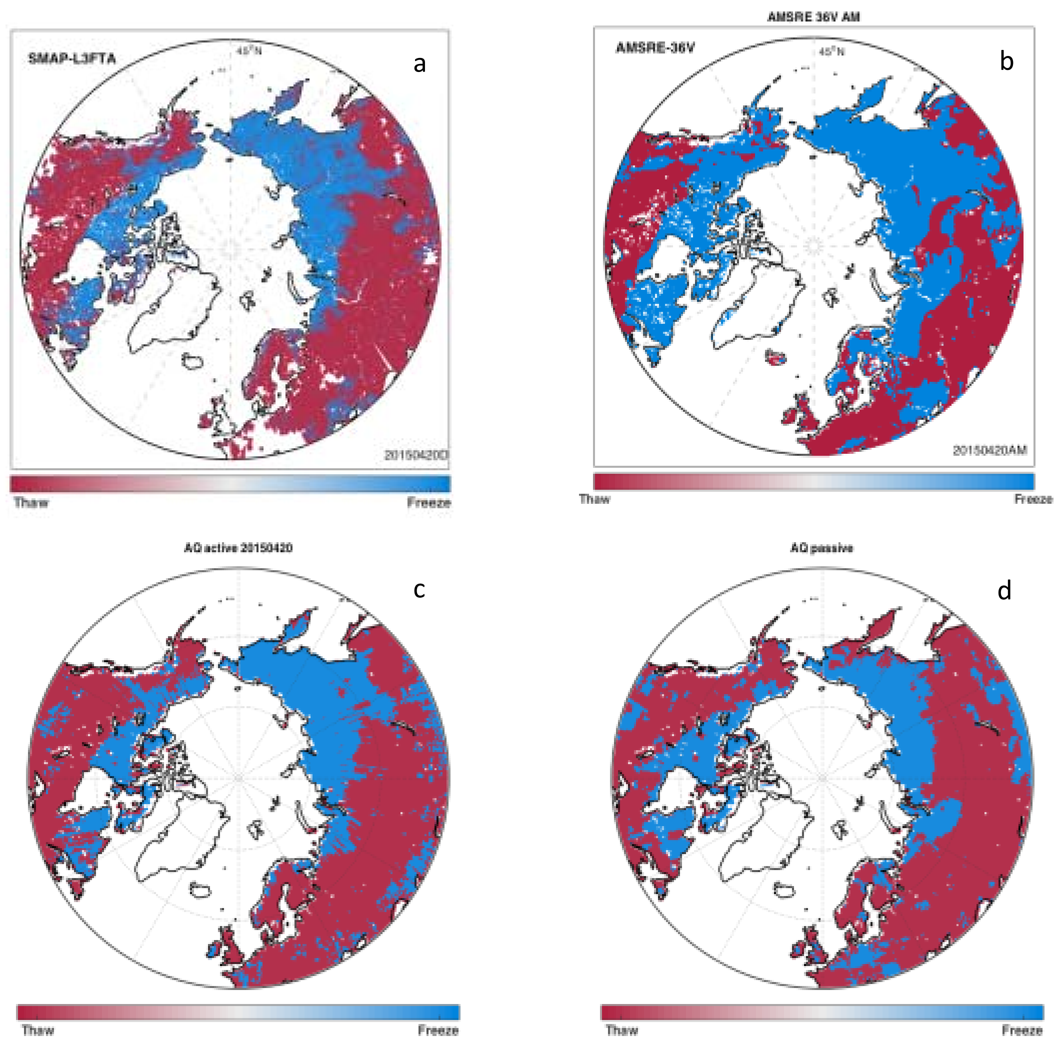

Figure 7.8 Snapshot comparison (20 April 2015) of four satellite derived FT retrievals: (a) SMAP L3_FT_A; (b) AMSR-E; (c) Aquarius active; (d) Aquarius passive.

A comparison of the time series of L3_FT_A derived frozen area across land areas north of 45° compared to Aquarius, AMSR2, and GMAO surface temperature derived estimates are shown in Figure 7.9. These time series are intended only to illustrate a similar seasonal evolution. Closer agreement between products was not expected due the differences in frequency (L-band for SMAP and Aquarius; Ka-band for AMSR2) and spatial resolution (3 km for SMAP; 25 km for AMSR2; 100 km for Aquarius). The GMAO surface temperature fields integrate the lowest level simulated air temperature and highest level soil temperature .The AMSR2 retrievals were optimized using surface air temperature [7] which minimizes false freeze events present in the L-band products. False freeze flags can be removed from L3_FT_A through the use of a surface temperature derived threshold. Post-launch experimentation indicated fixing the FT retrieval to thaw when surface temperature >10 Celsius is an effective screen for false freeze retrievals. The use of a conservative +10C temperature threshold ensures non-physical spurious false freeze retrievals are removed while not removing legitimate freeze retrievals.

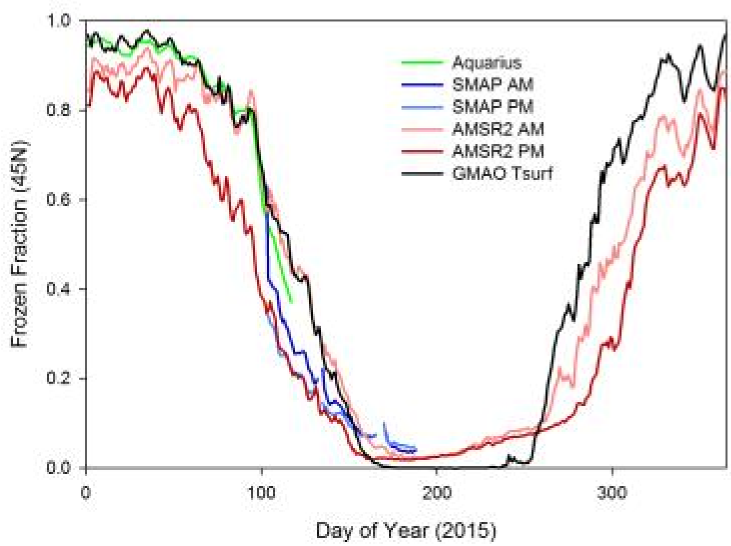

Figure 7.9 Time series of % frozen area across the FT domain for AMSR-E, Aquarius radar, and SMAP L3_FT_A datasets.

A preliminary FT product is also available from the ESA Soil Moisture and Ocean Salinity (SMOS) mission [8]. This product will be utilized for future comparisons, and is of particular interest as the SMAP FT product shifts to radiometer inputs.

7.5 Summary

L3_FT_A retrievals produced using SMAP thaw references and hybrid SMAP/Aquarius freeze references, 50% lake fraction, and excluded nadir radar measurements (inner 100 km of the nadir swath) show clean algorithm perform with spatially coherent retrievals and no processing artifacts. Some false freeze flags are apparent across the southern portion of the FT domain, which can be easily mitigated using conservative air temperature screening from reanalysis products.

Assessment at high latitude core validation sites showed excellent agreement with in situ flags, exceeding the 80% mission requirement. Similar performance was found for air temperature and soil temperature derived flags, although there was a tendency for SMAP thaw retrievals to lead the surface flags due to the influence of wet snow on the radar signal.

The use of sparse network measurements was limited to SnoTel sites in Alaska. Weaker overall flag agreement was found than at the core sites, though still exceeding the 80% mission requirement overall.

Other satellite products are available for spatial and time series evaluations. There is limited overlap with Aquarius measurements, but AMSR2 and SMOS provide opportunities for comparison with passive products derived from different frequencies.

8 OUTLOOK

This report describes the final validated release of the SMAP radar derived landscape freeze/thaw product. Given the failure of the SMAP radar in July 2015 and the short measurement period, there are no planned updates to the L3_FT_A product. Instead, the priority is the development and validation of a SMAP radiometer derived FT product (L3_FT_P). In the context of the passive product development, the SMAP freeze/thaw team will continue to pursue developments in the following areas:

- *Moving toward a Stage 2+ validated product.* To meet CEOS stage 2 requirements, additional validation sites (i.e. Svalbard, Tiksi) will be pursued. Comparisons with other satellite derived FT datasets as discussed in Section 7.4 will also be extended to include the Soil Moisture Ocean Salinity (SMOS) mission. Because of the limited duration of the SMAP radar measurements, it will prove challenging to address the CEOS stage 2 goal of "globally representative locations and time periods" but this should be achieved for L3_FT_P.
- *Optimization of algorithm parameters.* Future improvement in the processing and calibration of SMAP radar measurements (L1C_s0) will result in updated version(s) of L3_FT_A. For instance, a significant change from the beta release was the inclusion of additional measurements from the outer portion of the nadir track which were previously excluded. The original plan for L3_FT_A product updates was based on a rotating schedule of reference updates, threshold optimization, and re-processing. While this plan cannot be implemented due to the short SMAP radar time series, it is still possible to perform a threshold optimization across portions of the FT domain. Optimization experiments may be conducted at core and sparse network sites in order to determine the potential impact. Threshold optimization will occur as part of L3_FT_P product development and validation.
- *Implementing Categorical Triple Co-Location as an assessment and algorithm improvement tool.* Triple collocation (TC) is used within the SMAP project to validate soil moisture retrievals using sparse network observations. However, application of TC to categorical target variables such as FT results in biased error estimates and violation of critical TC assumptions. Categorical Triple Collocation (CTC), a variant of TC that relaxes these assumptions was recently developed for application to categorical target variables such as FT [9]. The method estimates the rankings of the three measurement systems for each category with respect to their balanced accuracies (a binary-variable performance metric). In addition to the more conventional application to time series data (which can be limited by the need to have a significant sample size), CTC can also be applied to single spatial snapshots, which will be critical given the short L3_FT_A time series.
- *Incorporating Field Campaign results.* Unlike soil moisture, there is no legacy of airborne L-band remote sensing campaigns to support process studies, scaling, and algorithm development for FT. An active/passive L-band airborne freeze-thaw campaign (collaboration between NASA, Environment Canada, and Agriculture and Agri-Food Canada) was conducted during transient FT events over agricultural land in Manitoba, Canada during the first two weeks of November 2015. Analysis of this dataset will primarily support L3_FT_P development.

With the loss of the SMAP radar, FT science activities will be recovered/mitigated by using the radiometer data for passive FT retrieval. Recent analysis of SMOS and Aquarius measurements illustrates the potential for L-band radiometer retrievals of landscape freeze/thaw using a retrieval method conceptually similar to the SMAP radar retrieval [10,11]. Expected impacts on retrieval performance compared to L3_FT_A will likely be related to change in sensitivity, stability, and signal to noise ratio from the active to passive case, and increased spatial classification error due to the coarser spatial resolution (36 vs 3 km).

9 ACKNOWLEDGEMENTS

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