Sentinel-3 Performance improvement for ICE sheets

Product Validation Plan

Scientific Exploitation of Operational Missions (SEOM)

Sentinel-3 SAR Altimetry

Study 4: Ice Sheets

Prepared by	:	Malcolm McMillan	date: 1/11/2016
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Acronyms and Abbreviations

AD	Applicable Documents
AIS	Antarctic Ice Sheet
ATM	Airborne Topographic Mapper
CLS	Collecte Localisation Satellites
CryoSat-2	CryoSat-2 satellite
DEM	Digital Elevation Model
ESA	European Space Agency
FBR	Full Bit Rate
GIS	Greenland Ice Sheet
GLAS	Geoscience Laser Altimeter System
ITT	Invitation To Tender
KO	Kick off meeting
LEGOS	Laboratoire d'Etudes en Géophysique et Océanographie Spatiales
LiDAR	Light Detection And Ranging
LRM	Low Resolution Mode
NASA	National Aeronautics and Space Administration
NSIDC	National Snow and Ice Data Center
pLRM	Pseudo-LRM
pSAR	Pseudo-SAR
PVP	Product Validation Plan
PVR	Product Validation Report
RB	Requirements Baseline document
SAR	Synthetic Aperture Radar
SARin	Synthetic Aperture Radar interferometric
SEOM	Scientific Exploitation of Operational Missions

SoW	Statement Of Work
SPICE	Sentinel-3 Performance improvement for Ice sheets
SPOT	Satellite Pour l'Observation de la Terre
UL	University of Leeds
WP	Work Package

Applicable Documents

AD1	Scientific Exploitation of Operational Missions (SEOM). Sentinel-3 SAR Altimetry Statement of Work (SEOM S3-4SCI SAR Altimetry). Issue 1, 27/09/2014.
AD2	Special Conditions of Tender. Appendix 4 to AO/1-8080/14/I-BG.
AD3	SPICE Technical Proposal.
AD4	SPICE Implementation Proposal.
AD5	SPICE Requirements Baseline document.

1. Introduction

1.1 Purpose

This document comprises the Project Validation Plan (PVP) for the Sentinel-3 Performance improvement for ICE sheets (SPICE) proposal (AD3), which is a response to the European Space Agencies (ESA's) Sentinel 3 For Science – SAR Altimetry Studies (S3 4 SCI – SAR Altimetry Studies) Invitation To Tender (ITT), Ref. AO/1-8080/I-BG (AD1 and AD2). SPICE addresses the Study 4 theme related to Ice Sheets. The Project Validation Plan has been written by the University of Leeds (UL), with contributions from isardSAT, CLS and LEGOS. UL as the prime contractor is the contact point for all communications regarding this document.

Address:

School of Earth and Environment,

Maths/Earth and Environment Building,

The University of Leeds,

Leeds,

LS2 9JT,

UK

Att: Malcolm McMillan (Science Lead)

Email: m.mcmillan@leeds.ac.uk

Telephone: + 44(0) 113 34 39085

Fax: +44 113 343 5259

ESA Bidder Code: 6000012896

1.2 Project Validation Plan structure

The aim of the Project Validation Plan is to define the approach, validation data sets, sites and methods that will be used to verify the developed algorithms and evaluate the derived data products. This document serves as the basis for the validation activities that constitute WP4. The results from these activities will be returned within the Product Validation Report (PVR) deliverable, which is due at KO+21 months. The remainder of the PVP document is structured into the following sections:

- **Section 2 –** Overview of validation approach.
- **Section 3** – Definition and justification of validation sites.
- **Section 4** – Validation datasets.
- **Section 5** – Validation methods.
- **Section 6** – WP2 and WP3 software validation.
- **Section 7** – References.

2. Overview of validation approach

The SPICE project aims to develop novel Delay-Doppler Processing and SAR retracking algorithms, and evaluate their performance over ice sheets. These activities will therefore deliver new Level 2 datasets, which aim to optimise SAR altimetry ice sheet surface elevation retrievals. To evaluate these novel data, and to compare them to datasets compiled using existing processing methodologies, several high level validation activities will be undertaken. These validation activities form part of Work Package 4 and are aimed at assessing both the internal consistency of the data and their absolute accuracy with respect to the compiled high quality reference datasets. In summary, to evaluate the data we shall perform three experiments:

1) Validation with airborne and satellite datasets.
2) Validation with internal cross-overs.
3) Validation of shot-to-shot repeatability.

Regarding the first experiment, we shall conduct an independent validation of the derived satellite altimetry L2 products, by comparing our datasets to co-located surface elevation measurements acquired during Operation IceBridge airborne and ICESat campaigns. An example of a similar analysis conducted at Austfonna in the Svalbard Archipelago is shown in Figure 1. Further description of the method is given in Section 5.1.

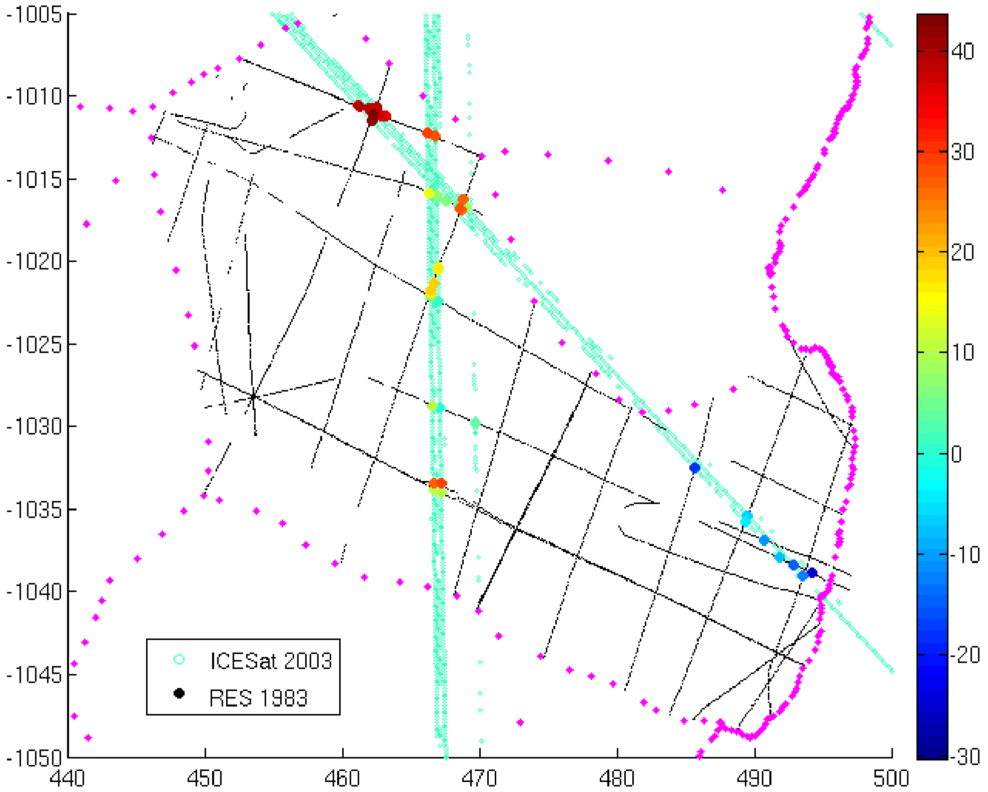

Figure 1. Example of a comparison between satellite and airborne surface elevation data acquired over Austfonna, from *McMillan et al.* [2014]. Ice surface elevation difference (m) between co-located airborne (black lines) and ICESat data (turquoise tracks). The pink dots mark glaciological basin boundaries. Note that here the auxiliary and airborne data acquisitions were separated by two decades, to facilitate an analysis of elevation change, whereas for SPICE we will aim to utilise contemporaneous measurements.

The second experiment is designed to assess the internal consistency of the altimeter measurements, by comparing elevations recorded at the crossing points of satellite tracks [*Wingham et al.*, 1998]. This approach allows an assessment of the repeatability of altimeter measurements by computing elevation differences where ascending and descending tracks intersect. In essence, the methodology is similar to that described in the first experiment, except that the data are compared internally, rather than relative to an external source. Further details of the methodology are given in Section 5.2 of this document.

The third experiment will evaluate shot-to-shot precision of consecutive altimeter elevation measurements acquired along the satellite track. This assessment necessarily requires minimal topographic signals, and will therefore be focused on the ice surface above the subglacial Lake Vostok in East Antarctica, where the ice sheet floats locally in hydrostatic equilibrium. An example of a similar analysis, based upon standard

CryoSat-2 L2 products, is shown in Figure 2. Further details of this experiment is given within Section 5.3 of this document.

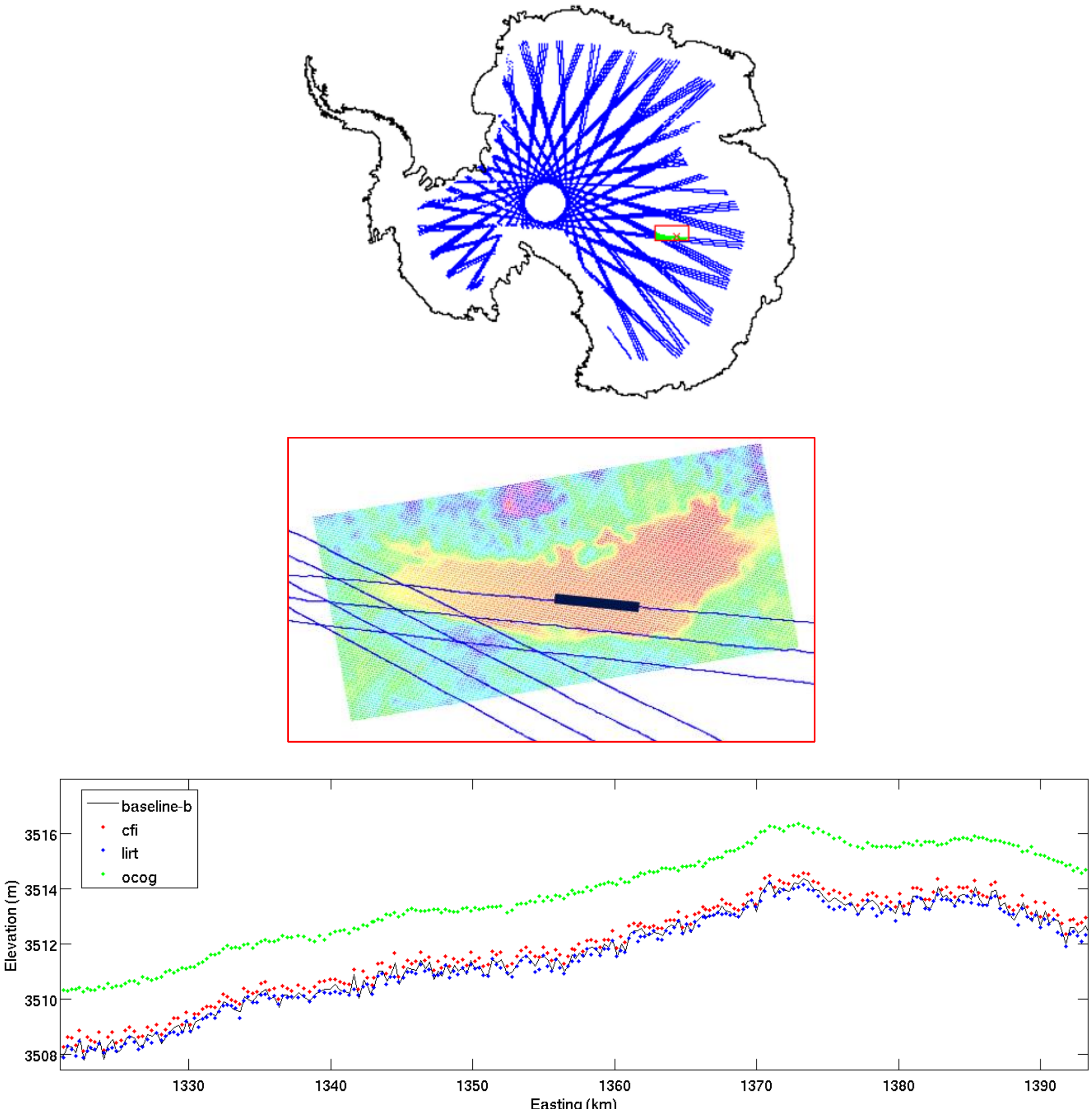

Figure 2. Example of comparison of along-track shot-to-shot elevation variability over Lake Vostok, East Antarctica, according to different CryoSat-2 baselines and the customer furnished Item (cfi), land ice retracker (lirt) and offset centre of gravity (ocog) retrackers. During SPICE, a similar analysis will be used to measure shot-to-shot precision, and evaluate different processing strategies.

3. Definition and justification of validation sites

This section outlines the principle validation sites used for the SPICE project, and the scientific and technical justification for these choices. The principle study sites selected for this project are the Lake Vostok, Dome C and Spirit and sites in East Antarctica (Figure 3), and the Russell Glacier site on Greenland's western margin (Figure 4). The choice of these sites was governed by the following criteria:

(1) The availability of CryoSat-2 SAR acquisitions over land ice.
(2) The availability of high quality reference data for product validation.
(3) The requirement to include sites in both Greenland and Antarctica.

The three Antarctic study sites were chosen because they were the focus of dedicated CryoSat-2 SAR campaigns in 2014 and are, additionally, covered by validation datasets. They therefore represent the only land ice SAR acquisitions made prior to the launch of Sentinel-3 with suitable validation data, and are as such a completely unique and valuable SAR altimeter dataset. In Greenland, no SAR data has been acquired by CryoSat-2 to date. Nonetheless, there remains a need to evaluate SAR performance over regions with different ice sheet characteristics, such as those found in the ablation zone of Greenland. We have therefore selected a site within the SARIn mode mask, where there is the opportunity to reprocess SARIn FBR via a single receive chain, to derive a pseudo-SAR (pSAR) product. For this analysis the Russell Glacier site in western Greenland was selected due to its proximity to Kangerlussuaq Airport, which has led to extensive surveying of this region by airborne campaigns and therefore offers a large amount of validation data. The periods of SAR data acquisition, where appropriate, are given in Table 1.

The four sites each offer specific characteristics that are beneficial to the aims of the SPICE study. The Vostok and Dome C sites both lie within the standard CryoSat-2 LRM mode mask. As such, they present not only the opportunity to inter-compare the dedicated SAR acquisitions processed with different methodologies, but also to analyse both pLRM generated from the same FBR data, and standard LRM acquired along the same ground track during a different orbital cycle. At these sites we will therefore be able to compare LRM, pLRM and SAR data. Both Vostok and Dome C are located within the East Antarctic interior (Figure 3) and are characterised by relatively simple topography, low accumulation rates [*Arthern et al.*, 2006] and an absence of surface melting. They will therefore allow an evaluation of SPICE products in regions representative of a large part of the Antarctic interior region.

The remaining Antarctic site, Spirit, lies within the standard CryoSat-2 SARIn operational mode mask, in a region of steeper ice sheet topography. However, uniquely, in 2014 several cycles of SAR mode data were acquired across this region to facilitate the evaluation of SAR mode over ice sheets. This site therefore provides the opportunity to use these dedicated SAR acquisitions to assess the merits of different SAR processing methodologies in a region more representative of the ice sheet margins, and also to compare SAR with pLRM generated from the same FBR data. The Spirit site has been included as a SPICE validation region because unlike the Vostok and Dome C sites, it is located at the ice sheet margin. These regions tend to exhibit the greatest changes in ice mass, yet offer challenging terrain for conventional radar altimeters. It is therefore important that, within SPICE, we identify the performance improvement that can be achieved in these steeper ice margin areas with new SAR processing methodologies.

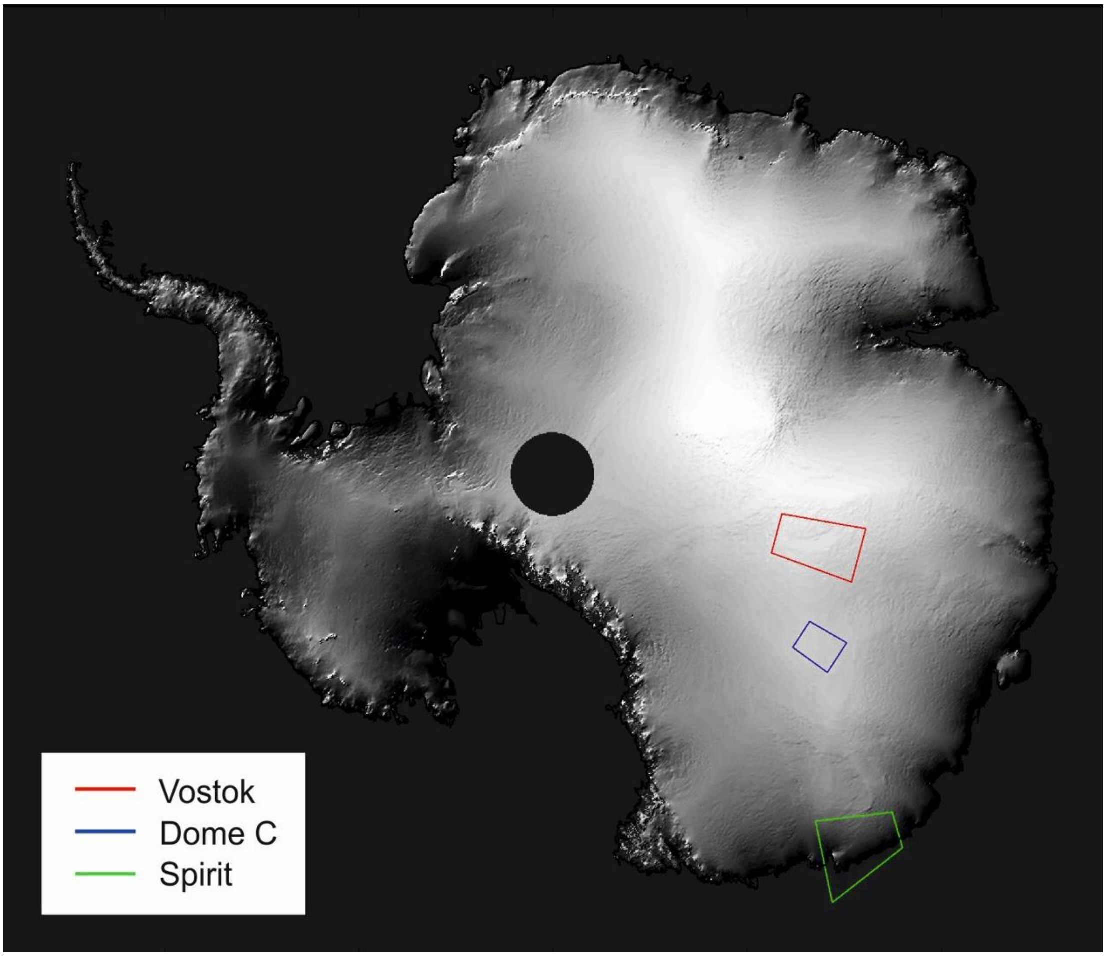

Figure 3. Antarctic validation sites.

The final site, Russell Glacier in Western Greenland, lies predominantly within the ablation zone of the ice sheet. It therefore experiences a range of atmospheric and snowpack conditions, including periods of surface melt and bare ice. As such it provides the opportunity to evaluate SAR performance in a region which is challenging for radar altimeters because of the significant changes in the scattering properties of the ice surface. Lying within the SARIn mode mask, and without dedicated SAR acquisitions, it is however necessary to undertake the exploratory reprocessing of SARIn FBR to pLRM and pSAR L2 products.

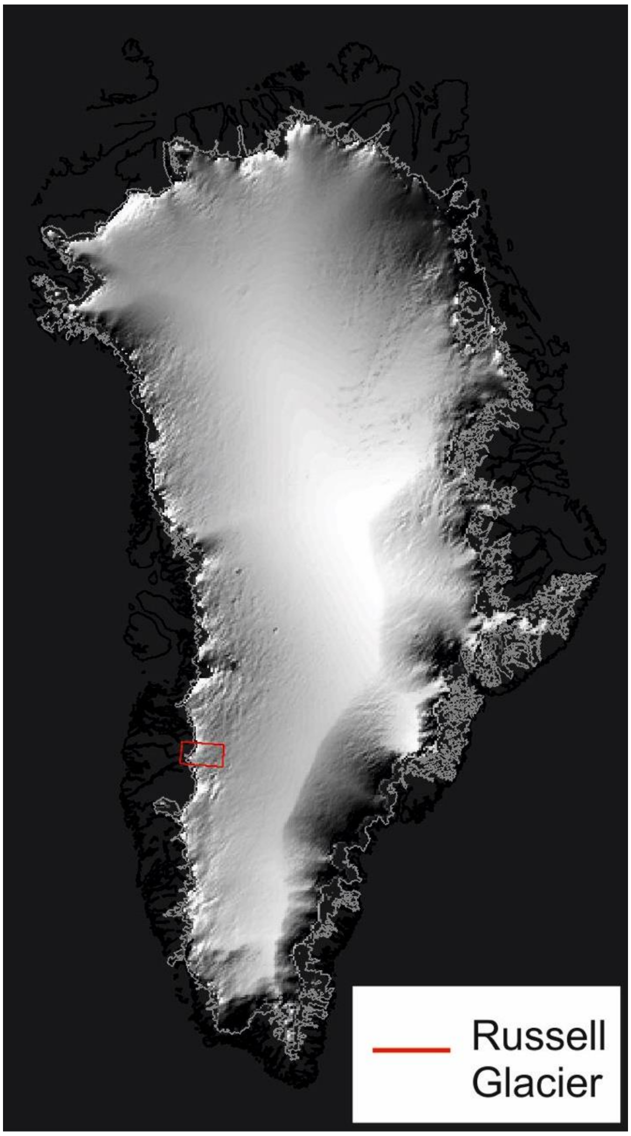

Figure 4. Greenland validation site.

Study Site	SAR acquisition period	Latitude bounds	Longitude bounds
Vostok	24/11/2014 – 30/11/2014	79-75°S	100-110°E
Dome C	1/12/2014 – 7/12/2014	76-74°S	120-126°E
Spirit	17/11/2014 – 30/11/2014	66-69.5°S	135-147°E
Russell Glacier	none	67-67.5°N	50.5-48°W

Table 1. Spatial extent of each study site and acquisition period of CryoSat-2 SAR data. Note that no SAR data has been acquired at Russell Glacier and instead we will process SARIn FBR to form a pseudo-SAR product.

4. Validation datasets

This section describes the auxiliary validation datasets that will be used to evaluate the products generated during the SPICE project. Specifically, these data are independent ice sheet elevation measurements compiled from several airborne and satellite platforms. During the first 12 months of the project, consolidated validation datasets have been compiled at each of the SPICE study sites. These data are described in more detail below and summarised in Table 2.

The principle validation datasets are comprised of airborne surface elevation measurements acquired by the Airborne Topographic Mapper (ATM) and Riegl Laser Altimeter instruments flown on-board NASA's Operation IceBridge campaigns (http://nsidc.org/icebridge/portal/). These datasets provide the most comprehensive airborne coverage of the polar ice sheets since 2009, with the high accuracy, spatial resolution and precision achievable with an airborne laser altimeter. The coverage of these data across each of the SPICE study sites is shown in Figure 5 and in Figure 6. IceBridge campaign data such as these have been used previously by members of the consortium to evaluate satellite radar altimeter measurements, and are well-suited to this task [*McMillan et al.*, 2014a, 2016]. To supplement these airborne data, ICESat satellite laser altimetry will be used as an additional source of reference, in regions where IceBridge acquisitions are sparse. A brief description of each dataset is given below.

The Airborne Topographic Mapper (ATM) is an airborne scanning LIDAR developed by NASA to map ice surface elevation in the polar regions. Since 2009, it has been one of the principal instruments carried by NASA's Operation IceBridge. Elevation measurements are resampled to approximately 50 m along-track (varying with aircraft speed) and have a fixed 80 m across-track platelet at aircraft nadir. At a nominal operating altitude (500 to 750 m above the ice surface) the ATM elevation measurements have been estimated to achieve a horizontal accuracy of 74 cm, a horizontal precision of 14 cm, a vertical accuracy of 7 cm and a vertical precision of 3 cm [*Martin et al.*, 2012].

The Riegl Laser Altimeter is a Laser Altimeter System, also flown on selected Operation IceBridge campaigns in Antarctica. This instrument acquires elevation measurements with a range resolution of 2 mm and a ground footprint of 25 m along track by 1 meter across track. The reported error associated with these elevation measurements is 12cm (http://nsidc.org/icebridge/portal/).

The Geoscience Laser Altimeter System (GLAS) flown on-board the ICESat mission operated on a ~35-day campaign basis between 2003 and 2009, with approximately three campaigns acquired each year. The ground footprints are spaced at 172 m along-track and have a varying elliptical shape with average dimensions of approximately 50 x 95 m. GLAS has been shown to achieve a single shot elevation accuracy better than 0.05 m under optimal conditions, although performance degrades over sloping terrain and under the presence of atmospheric forward scattering and detector saturation [*Fricker et al.*, 2005]. Data coverage is also adversely affected by the presence of clouds. The coverage achieved by ICESat at each of the SPICE study sites is shown in Figure 5 and in Figure 6. Finally, at the Spirit site, CLS has access to a SPIRIT stereoscopic DEM, which they will also use for validation purposes in WP5.

Data Type	Location	Parameter	Acquisition Date (month/year)	Sensor	Data Provider	Availability Status
Airborne	Vostok	Ice surface elevation	11/2013	ATM	NASA, available online from nsidc.org	Archived at UL
Airborne	Vostok	Ice surface elevation	1/2009	Riegl	NASA, available online from nsidc.org	Archived at UL
Airborne	Dome C	Ice surface elevation	11/2013	ATM	NASA, available online from nsidc.org	Archived at UL
Airborne	Dome C	Ice surface elevation	1/2009 2/2009 12/2009 12/2011 12/2012	Riegl	NASA, available online from nsidc.org	Archived at UL
Airborne	Spirit	Ice surface elevation	1/2009 12/2009 1/2010 12/2010 11/2011 12/2011	Riegl	NASA, available online from nsidc.org	Archived at UL
Satellite	Spirit	Ice surface elevation	2007-2009	SPOT-5	LEGOS	Archived at LEGOS
Airborne	Russell	Ice surface elevation	4/2009 5/2009 5/2010 3/2011 4/2011 4/2012 5/2012 4/2013 4/2014 4/2015	ATM	NASA, available online from nsidc.org	Archived at UL
Satellite	All	Ice surface elevation	2003-2009	ICESat	NASA	Archived at UL

Table 2. SPICE auxiliary data.

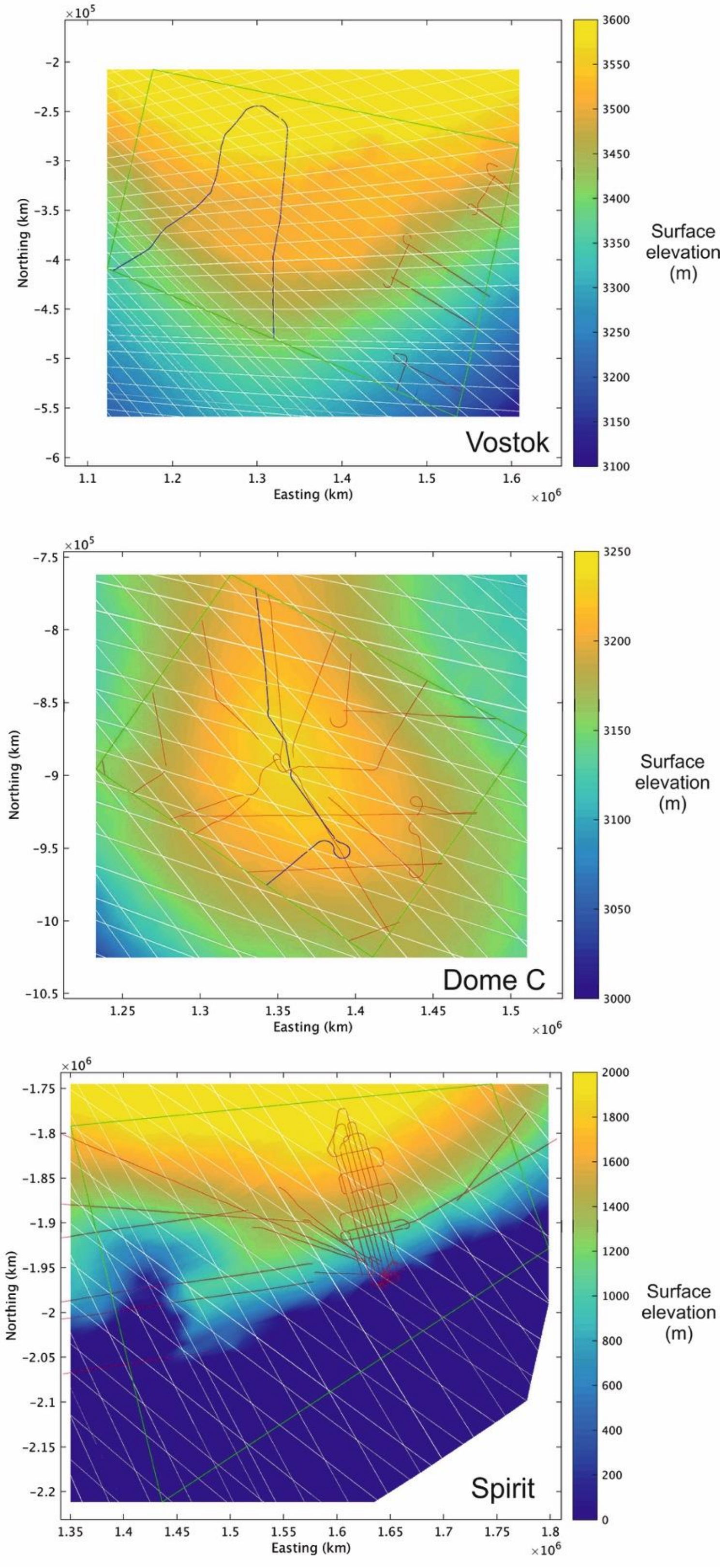

Figure 5. Operation IceBridge ATM (blue) and Riegl (red) airborne laser altimetry flightlines, and ICESat (white) ground tracks over the SPICE Antarctic study sites. The green polygon marks the boundary of each site.

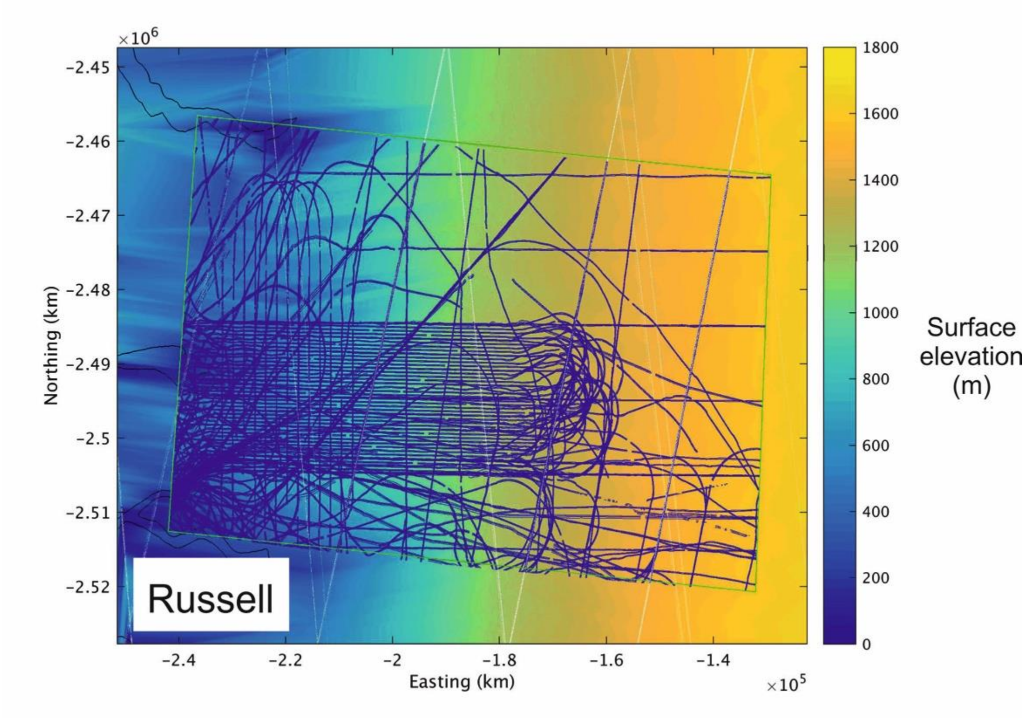

Figure 6. Operation IceBridge ATM (blue) airborne laser altimetry flightlines, and ICESat (white) ground tracks over the SPICE Greenland study site. The green polygon marks the boundary of the Russell Glacier site.

5. Validation methods

This section describes the validation methods used to assess the products generated by the SPICE study. Principally, SPICE validation activities fall within Work Package 4 and consist of three separate experiments:

1) Validation with airborne and satellite datasets.
2) Validation with internal cross-overs.
3) Validation of shot-to-shot repeatability.

In the following subsections we address each method of validation in turn.

5.1 Validation with airborne and satellite datasets

To assess the absolute accuracy of the SAR, pSAR, LRM and pLRM elevation retrievals, the auxiliary airborne and satellite datasets outlined in Section 4 will be used. Each of the generated elevation datasets will be evaluated in comparison to these auxiliary measurements. To ensure minimal impact of temporal or topographic variations in elevation, the auxiliary datasets will be chosen so as to be located as closely in space and time as is feasible. In practice, this means that we shall place two constraints upon the selected validation records:

1) Only auxiliary data acquired over a restricted time period will be used.
2) Only auxiliary data within a specific proximity of the altimeter record to be evaluated will be used.

The particular constraints relating to point (1) will vary between sites, in recognition of inter-site differences in the sampling frequency of auxiliary data. In Antarctica, where airborne surveys are sparse and infrequent, we shall use all IceBridge acquisitions between 2009 and 2015 to ensure that we make the best use of any available data. In contrast, at the Russell Glacier site where campaigns have been flown over multiple years, we shall select the time period to match as closely as possible the data that is being evaluated. Finally, for the ICESat datasets, we shall use campaigns from 2009 only, as they represent the most recent acquisitions and therefore the best match to the CryoSat-2 data that is being validated.

To address point (2), we shall require that validation elevations are acquired within close proximity of the CryoSat-2 measurement that is being validated. The exact choice of threshold will be guided by the need to balance data quantity and proximity. Additionally, because proximal records will nonetheless not be exactly co-located, we will apply an elevation adjustment to each auxiliary record to account for its slightly different location [*McMillan et al.*, 2013]. This correction will be based upon a local digital elevation model formed from elevation data acquired during the most recent ICESat campaigns.

For each study site, all SPICE-auxiliary record pairs that satisfy the above constraints will be identified. Broadly speaking, these criteria are met, and therefore a data pair is retrieved, at each point where the ground tracks intersect. These data will then be used to generate a set of elevation differences that describe the relative agreement between the SPICE and auxiliary data. From this, standard performance metrics of the mean, median, standard deviation and root mean square of the differences will be calculated, and used to describe the magnitude of the bias and dispersion of the differences. These metrics will form the basis for conclusions about the relative performance of the different operating modes and processing methodologies that are implemented during the SPICE study.

5.2 Validation with internal cross-overs

To assess the internal consistency, or repeatability, of the derived SPICE products, we shall compare elevation measurements at locations where ascending and descending satellite tracks intersect. In essence, the methodology will be the same as described for the external validation using auxiliary datasets, except that SPICE data will be compared to itself rather than independent measurements. Again, sets of internal cross-over elevation differences will be generated at each study site, and used to derive associated performance metrics, such as mean and standard deviation of the elevation differences. These metrics will form the basis for conclusions about the relative performance of the different operating modes and processing methodologies, for example the precision of the elevation measurements and the degree to which the retrievals are affected by snowpack backscattering anisotropy.

5.3 Validation of shot-to-shot repeatability

The final method for product inter-comparison will be employed where ice surface topography is minimal, namely the Lake Vostok site in East Antarctica. Here, we will evaluate the variability of consecutive records acquired along the satellite track, in order to assess the shot-to-shot precision of the different elevation retrievals [*Richter et al.*, 2014; *Cipollini and Calafat*, 2016]. More specifically, we will remove kilometre scale topography using a piecewise linear regression to model elevation as a function of along-track distance. The remaining elevation residuals (observed - modelled) will be used as a measure of the (uncorrelated) shot-to-shot noise. Again, summary statistics will be generated from these sets of residuals and used to draw conclusions regarding the relative performance of each of the various SPICE products.

6. WP2 and WP3 software validation

In order to validate WP2 and WP3 processing chains and ensure the quality of the products delivered to both the final users and the users within the project, validation will be carried out in both WP2 and WP3 (see Figure 7).

Regarding WP2, the processing chains and L1B data will be validated by comparing the generated L1B products to the corresponding L1B products from CryoSat Baseline C.

For WP3, we plan to validate the processing chains and L2 products in two different ways, depending on the mode:

SAR (from both SAR and SARin FBR products)

- Comparing L2A outputs[1] with L2 outputs from CryoSat Baseline C.
- Retracking CryoSat L1B products and comparing the L2A outputs that will be generated by the retracker used in SPICE.

pLRM[2] (from both SAR and SARin FBR products)

- Comparing L2A outputs with CryoSat L2 outputs.
- Comparing L2A outputs with SAR L2A outputs.

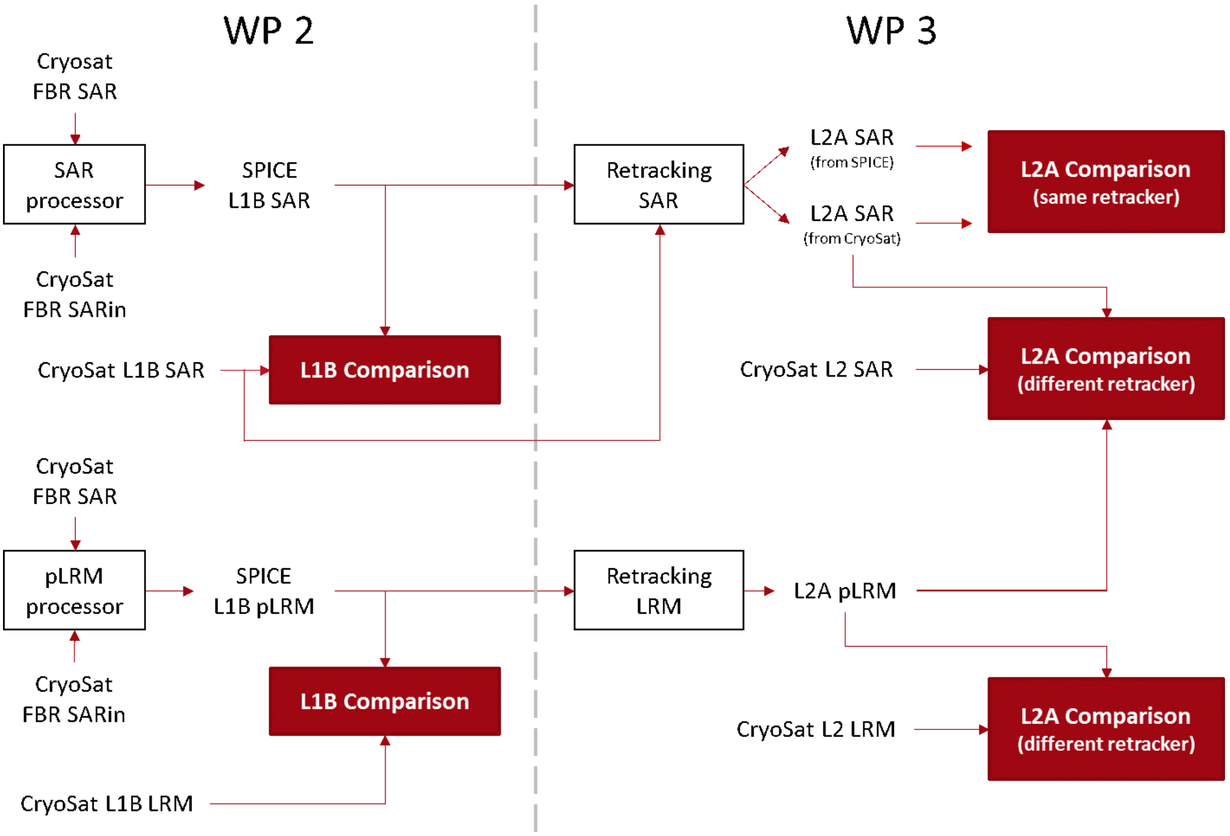

Figure 7. WP2 and WP3 software validation procedures.

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[1] L2A is associated to a L2 product without the slope correction. Basically, what will be compared is the height, without the slope correction applied.

[2] Note that pLRM and LRM do not follow the same orbit. Thus, we decided to compare height with SAR products, which have the same input file.

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