cryosat+
cryotop
support to science element

Support to Science Element (STSE) CryoSat + Cryosphere

Theme 3: Glacier and Ice Sheet Margins Topography (CryoTop)

Requirements Baseline (RB)

Ref: UE-ESA-STSE_CryoTop_RB

v4.0

UNIVERSITY OF LEEDS

THE UNIVERSITY OF EDINBURGH

isardSAT

UCL

Prepared by	:	University of Leeds	date:	2013-09-26
Issued by	:	Andrew Shepherd	date:	2013-09-26
Checked by	:	Noel Gourmelen	date:	2014-01-08
Approved by	:	Mark Drinkwater	date:	2014-06-06

Prof. Andrew Shepherd

Dr. Noel Gourmelen

Dr. Mark Drinkwater

Change Log

Issue	Author	Affected Section	Reason	Status
1	Amber Leeson and Andrew Shepherd	All	Document creation	Released to AS and NG on 26/09/2013
2	Andrew Shepherd and Noel Gourmelen	All	Science lead and project manager approval	Released to MD on 17/10/2013
3	Mark Drinkwater	All	ESA Approval and Acceptance	Revised by ESA on 05/12/2013
4	Kate Briggs, Andrew Shepherd and Noel Gourmelen	All	Response to ESA comments	Accepted by ESA on 06/06/2014

Distribution List

UL	Andrew Shepherd
UL	Kate Briggs
UE	Noel Gourmelen
UCL	Steve Baker
UCL	Alan Muir
isardSAT	Mònica Roca
isardSAT	Maria Jose Escorihuela
ESA	Mark Drinkwater

Table of Contents

1 Acronyms and Abbreviations 5

2 Introduction 6

2.1 Purpose and Scope 6

2.2 Applicable and Reference Documents 6

2.3 Requirements Baseline Document Structure 7

3 Scientific Justification and Existing Methods 7

3.1 The need for even finer GISM topography 8

3.2 Altimetry 8

3.3 SARIn Altimetry 9

4 Related Initiatives 10

4.1 GlobGlacier 10

4.2 ESA CCI Glaciers and ESA CCI Ice Caps 11

4.3 GLITter (CS+C Theme 1) 11

4.4 APMB 12

5 Study Areas 12

6 Data Requirements 13

6.1 Product Development - CryoSat-2 data and data product formats for fine topography generation. 13

6.2 Product Validation Data 14

7 Algorithm development requirements 14

8 Risk Analysis 15

9 Consolidated Requirements for the CryoTop Project 16

References 16

1 Acronyms and Abbreviations

AIS	Antarctic Ice Sheet
AP	Antarctic Peninsula
APMB	Antarctic Peninsula Mass Balance
ASIRAS	Airborne SAR/Interferometric Radar Altimeter System
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
ATM	Airborne Topographical Mapper
CCI	Climate Change Initiative
CS+C	CryoSat plus Cryosphere
CVRT	Calibration, Validation and Retrieval Team
DEM	Digital Elevation Model
ECV	Essential Climate Variable
ERS	European Remote Sensing Satellite
ESA	European Space Agency
FBR	Full bit rate
GCOS	Gglobal Observing System for Climate
GDEM	Global Digital Elevation Model
GISM	Glacier and Ice Sheet Margin
GLAS	Geoscience Laser Altimeter System
GLIMS	Global Land Ice Measurements from Space
GPS	Global Positioning System
GrIS	Greenland Ice Sheet
GTN-G	Global Terrestrial Network for Glaciers
HRTI	High Resolution Terrain Information
IGN	Institut Géographique National
IGOS	Integrated Global Observing Strategy
IMBIE	Ice sheet Mass Balance Intercomparison Exercise
SARIn	Interferometric SAR
IPCC	Intergovernmental Panel on Climate Change
IPF	Inteferometric Instrument Processing Facility
LA	Laser Altimetry
NASA	National Aeronautics and Space Administration
NSIDC	National Snow and Ice Data Centre
PMP	Project Management Plan
RA	Radar Altimetry
SAR	Synthetic Aperture Radar
SARIn	SAR interferometry
SIRAL	Synthetic Aperture Interferometric Radar Altimeter
SLR	Sea Level Rise
SRTM	Shuttle Radar Topography Mission
STSE	Support to Science Element
UCL	University College London
UE	University of Edinburgh
UL	University of Leeds

UNFCC	United Nations Framework Convention on Climate Change
WGI	World Glacier Inventory
WGMS	World Glacier Monitoring Service

2 Introduction

2.1 Purpose and Scope

This document contains the Requirements Baseline for the CryoSat + Cryosphere (CS+C) Theme 1 (CryoTop project). The requirements baseline has been written by the University of Leeds (UL), and the University of Edinburgh (UE). University College London (UCL) and isardSAT are partners with UL and UE on this project. 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: Andrew Shepherd (Science Lead)

Email: A.Shepherd@leeds.ac.uk

Telephone: +44 113 343 9014

Fax: +44 113 343 5259

ESA Bidder Code: 6000012896

2.2 Applicable and Reference Documents

Table 1: Applicable and Reference Documents

Document Name	Source
Invitation to Tender AO/1-7158/12/I-NB – CryoSat + Cryosphere	ESA
Support to Science Element (STSE) CryoSat + Cryosphere Statement of Work	ESA
Special Conditions of Tender	ESA
Draft Contract	ESA
Management Administrative and Financial Proposal	UL
Technical Proposal	UL
Project Management Plan UL-ESA-STSE-Cryosat-T3-PMP	UL

2.3 Requirements Baseline Document Structure

This document aims to consolidate the scientific requirements of the CryoTop project. In order to achieve this aim, the document is structured as follows:

- **Section 3** - A detailed review, assessment and cross-comparison of existing science products related to the CryoTop project is performed. This includes datasets, methods, models and algorithms, as well as related range of validity limitations, drawbacks and challenges.
- **Section 4** - A survey of existing initiatives and science projects related to the CryoTop project is performed to identify areas of crossover with existing activities, in addition to highlighting the unique science contribution and added value expected from CryoTop.
- **Section 5** - Identification and justification of the areas of interest (AOI's) used in the CryoTop project for product development and validation, followed by prototype product production.
- **Section 6** - A survey of relevant datasets, (space, airborne and in situ) to be used for product development, validation and prototype product generation.
- **Section 7** - the algorithm generation requirements for generating elevation swath products.
- **Section 8** - A risk analysis is performed to identify problem areas that could affect the final success of the CryoTop project, for example, technical and scientific constraints for the methods to be developed. Again, solutions to these problems are proposed.
- **Section 9** - A consolidated, coherent and complete view of the scientific requirements is presented to ensure the successful completion of the CryoTop project.

3 Scientific Justification and Existing Methods

Knowledge of GISM topography (and its change over time) is a basic parameter of glaciological research, and is identified in the Integrated Global Observing strategy (IGOS) Cryosphere Theme Report as a major shortcoming of current observations (Key et al., 2007). Regional models of ice mass trends (e.g. Raper and Braithwaite, 2006), for example, require GISM topography as a fundamental parameter, and direct assessments of glacier mass change (e.g. Rignot et al. 2003) are typically made using repeat measurements of glacier topography at discrete epochs. GISM topography is therefore a primary source of information in assessments of glacier and ice sheet mass balance, an essential climate variable as defined by the United Nations Framework Convention on Climate Change (UNFCCC). The CryoTop project is a new application of the CryoSat-2 dataset because it utilises data from the interferometric mode of the CryoSat-2 instrument to develop

elevation measurements of wide areal coverage across the satellite ground track (Hawley et al., 2009).

3.1 The need for even finer GISM topography

Reference and repeat-observations of GISM topography are critical to quantify changes in ice thickness and volume, and provide estimates of ice mass variability and the contribution of the cryosphere to sea level change. GISM present significant challenges as they require very fine spatial resolution in order to capture the variations in elevation caused by dynamic response of the ice sheets to climate variations. Although the world's small glaciers and ice caps constitute less than 5% of total land ice volume, their wide geographical distribution exposes them to changes in climate, and fluctuations in their mass are expected to constitute the greatest cryospheric component of 21st century sea level rise (Meehl et al., 2007). The benefit of finer spatial resolution and finer spatial sampling than is afforded by classical satellite altimeter applications is apparent when considering the distribution of global glaciers and the ground sampling patterns of the respective satellite missions (Fig 1). More than 90% of all glaciers and ice caps occupy an area of less than 5 km^2, and so instruments with small ground-footprints are required to survey changes in their volume.

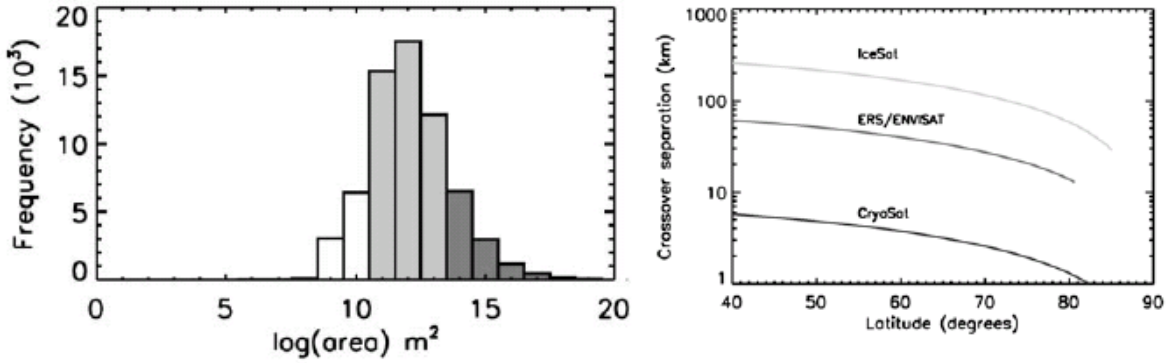

Figure 1: (left) Frequency distribution of world glacier area (World Glacier Monitoring Service and National Snow and Ice Data Center/World Data Center for Glaciology, 1999) showing the fraction that may potentially be surveyed by the ERS/Envisat (dark grey), and ICESat/CryoSat (light grey) altimeters. (right) Orbital ground track spacing of the same satellites by latitude.

3.2 Altimetry

An estimated ~50 & ~75% of Antarctic and Greenland ice sheet mass losses are within 100 km of the coast, but <10% of these regions are surveyed by conventional pulse limited altimetry. This is because of sparse ground tracks and sensor tracking failures over high slopes due to relatively coarse footprints. Given coincident ground tracks, the conventional, pulse-limited altimeters of ERS and

Envisat are able to survey approximately 15 % of the area of global glaciers and ice caps, whereas the fine-resolution ICESat and CryoSat altimeters together with their higher inclination orbit are capable of surveying up to 85 % of their area. However, modifications to the ICESat ground track implemented to accommodate the reduced capacity of the instrument after launch means that, at sub-polar latitudes the separation of ground tracks falls in the range of 50-200 km. In consequence, the proportion of all global glaciers and ice caps that are surveyed by the ICESat altimeter is small in relation to the entire population (though large in relation to the fraction currently sampled by ground-based observations). In contrast, the ground track of CryoSat-2 provides a capacity to survey glaciers with a ground track spacing in the range 2-10 km (depending on latitude), or 25 times more than those surveyed by the ICESat altimeter.

3.3 SARIn Altimetry

Synthetic aperture radar interferometry (SARIn) is able to resolve substantially more than just the elevation at the point of closest approach (the standard SARIn mission product). In regions where the ground terrain slope is moderate (greater than 1 degree), the CryoSat altimeter operates in a manner such that the interferometric phase of the altimeter echoes may be unwrapped to produce a wide swath of elevation measurements across the satellite ground track (Wingham et al., 2006). In tests of the method applied to data acquired by the Airborne SAR/Interferometric Radar system (ASIRAS) airborne prototype of the CryoSat instrument, and to data acquired by the Synthetic aperture Interferometric Radar ALtimeter (SIRAL) instrument on board CryoSat-2 (Fig. 2), the resulting swath of elevation measurements was between 25- and 75-times wider than the single measurement at the point of closest approach. Because the vast majority of GISM exhibit surface slopes of greater magnitude than the threshold at which the effect emerges, the technique provides a method for surveying the topography of GISM with a density of ground sampling sufficient to form continuous digital elevation models (DEMs). A simple scaling of the result of the ASIRAS experiment to the CryoSat platform and system, for example, provides an estimated swath width of between 3 and 9 km sampled at 250 m intervals – values that are comparable to the ground-track spacing (Fig. 1). The objective of WP2000 is to exploit L1b full-Bit-Rate CryoSat-2 SARIn mode data to provide dense and fine spatial resolution GISM topography.

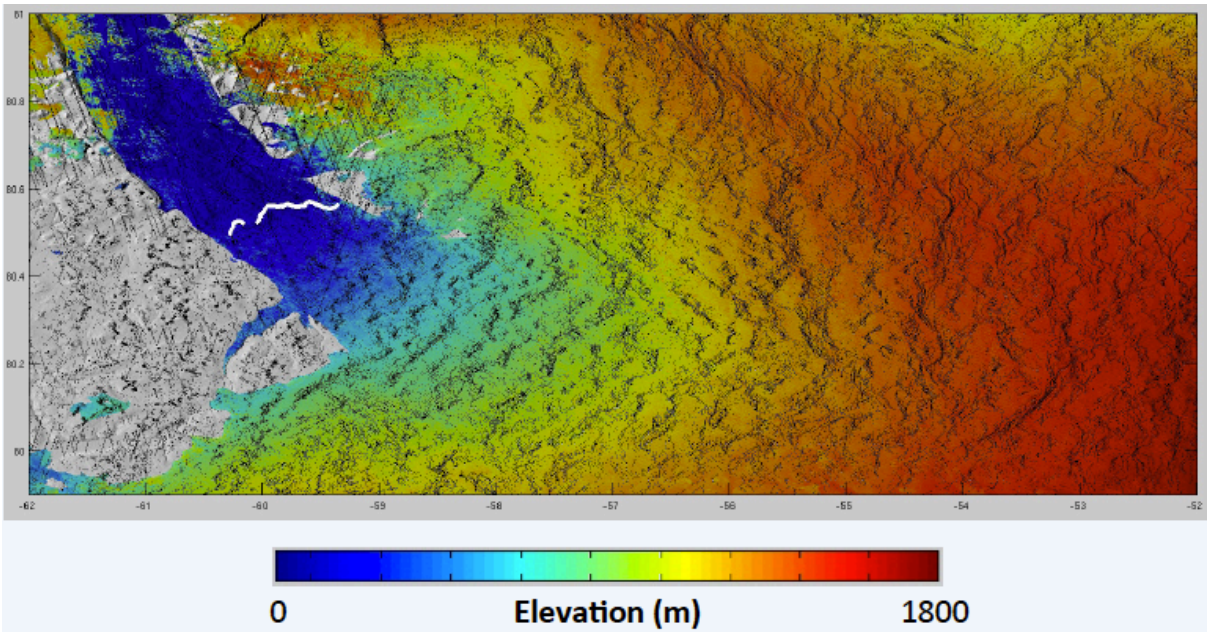

Figure 2 Example of results from prototype CryoSat-2 swath processing over Petermann Gletscher, Greenland

The objective above would be fulfilled by providing Level 2 elevation products across a swath, as retrieved from L1b data. Thus the principal requirement is to derive geolocated elevation values (i.e. lat/lon/height above ellipsoid) from the Cryosat SARIn mode L1b format data, accompanied by ancillary parameters characterising the relative height across swath in relation to the POCA value, coherence across swath, and other necessary quality metrics related to the quality and complexity of the L1b waveform.

4 Related Initiatives

CryoTop benefits from past related initiatives (e.g. Ice2Sea, GlobGlacier), and will inform and contribute to current and future projects (e.g. ESA CCI Glaciers and ESA CCI Ice Caps). Here, GlobGlacier ESA CCI Glaciers, ESA CCI Ice Caps, TanDEm-X, Ice2Sea, GLITter and APMB projects are briefly described.

4.1 GlobGlacier

The GlobGlacier project took place from 2007 to 2011. The GlobGlacier project established a service for glacier monitoring from space based on user requirements and builds upon, complements and strengthens the existing network for global glacier monitoring (Global Terrestrial Network for Glaciers -GTN-G). The project helped to establish a global picture of glaciers and ice caps, and their

role as Essential Climate Variables (ECVs) as defined in the Global Observing System for Climate (GCOS) implementation plan for the UNFCCC (GIP, 2004). The most-requested goal is to complete the world glacier inventory (WGI) from the 1970s, by producing glacier outlines in regions where few or no data exist, and to complement the point-information already stored in the WGI by 2D information to allow change assessment. Moreover, GlobGlacier integrated satellite data from various sensors to create value added products for a wide range of user communities. A close cooperation with major user groups (e.g. WGMS) and related projects (e.g. GLIMS) ensured a maximum benefit of the generated products from a global perspective.

CryoTop adds value to this initiative by developing a new method by which fine topographic data for small glaciers and ice caps can be extracted from CryoSat SarIn mode data.

4.2 ESA CCI Glaciers and ESA CCI Ice Caps

The main objective of the ESA Glaciers Climate Change Initiative (Glaciers_cci) project (see ESA CCI glaciers website for further details) is to contribute to the efforts of creating a globally complete and detailed glacier inventory as requested in action T2.1 by GCOS (2006). This activity has two major parts: One is data creation (glacier outlines) in selected and currently still missing key regions, and the other one is in establishing a more consistent framework for glacier entity identification to enhance the integrity and error characterization of the available data sets. Although the current phase of the CCI project is coming to an end, CryoTop will be of use to the project by developing a new method of exploiting SARIn data to retrieve fine GISM topography that could potentially be implemented in a future phase of the CCI Programme.

4.3 GLITter (CS+C Theme 1)

The Grounding Line Ice Thickness (GLITter) project will provide new and improved estimates of ice sheet Grounding Line Location, Grounding Line Ice Thickness, and Ice Mass Flux, by exploiting data from the CryoSat-2 (CS2) mission (see GLITter Website for further details). GLITter is an international collaboration between five institutions and is supported by the European Space Agency's (ESA) Support To Science Element (STSE). The project began in July 2013 and will run for 18 months. GLITter will deliver important new scientific results, using CryoSat-2, while establishing a solid scientific basis for the development of novel retrieval methods and prototype products.

4.4 APMB

The APMB (Antarctic Peninsula Mass Balance) project, following on from the ESA/NASA sponsored Ice Sheet Mass Balance Inter-comparison Exercise (IMBIE), will provide an improved estimate of Antarctic Peninsula Ice Sheet mass balance from satellite techniques by increasing the spatial extent and time period that measurements currently cover (see APMB and IMBIE websites for further details). The project began in 2013 and will run for two years. It is an international collaboration between seven institutions, and is supported by the European Space Agency's (ESA) Support to Science Element (STSE). Novel measurements of fine GISM will be of interest to this project since these data are of principal importance to estimates of ice sheet mass balance, particularly those exploiting volume and mass changes via the Input-Output method.

5 Study Areas

The experimental dataset will consist of tests sites with steep ice terrain found in large mountain glaciers and in ice sheet margins (Figure 3). We propose to first concentrate on the ice margin around the main outlet glaciers in Greenland (e.g. Jakobshavn, Petermann), Arctic Ice Caps such as on Devon Island (Gray et al, 2013) and the Antarctic Peninsula and Amundsen Sea Sector. These regions are key for studying changes currently affecting the cryosphere and an extensive topographic dataset is being acquired as part of international efforts from field, airborne and spaceborne missions, which is of critical importance and benefit to the validation of the CryoTop prototype products. Some of these will also provide synergy with the CS+ GLITter project.

We will also provide experimental datasets over the major mountain glaciers in the Himalaya range, and in European glaciers where the investigators of this proposal have active project or partnership (Dragon project in the Himalaya and French Alpine glaciers for NG) and where validation datasets are available (e.g. Gardelle et al., 2012; various topography products over the French alpine glaciers including very high resolution IGN topography derived from airborne optical campaigns). However, because relief in these areas is typically comparable to, or greater than the range window, it is uncertain how effective the CryoTop method will prove to be in these regions. We anticipate that the CryoTop product will be most successful over ice sheet margins and ice caps.

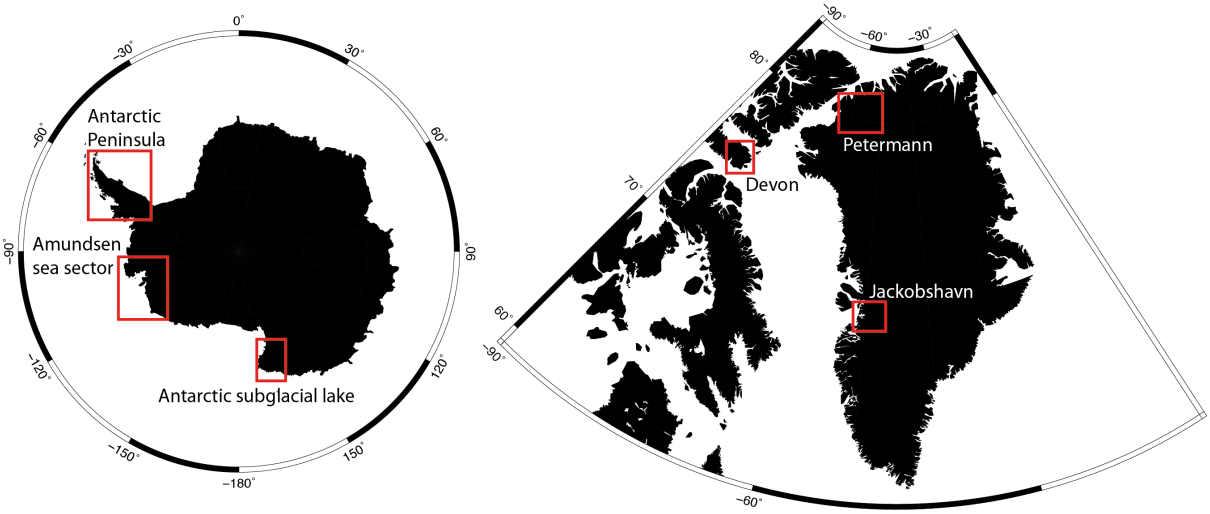

Figure 3: Map of CryoTop study sites.

Table 1: AOI and primary data products

ID	AOI	Primary data product needs
1	Petermann Gletscher, GrIS	L1b SARIn mode
2	Jakobshavn Glacier, GrIS	L1b SARIn mode
3	Amundsen Sea Sector, AIS	L1b SARIn mode

6 Data Requirements

6.1 Product Development - CryoSat-2 data and data product formats for fine topography generation.

All of the data required for this product are derived from ESA missions (ASIRAS, ERS, Envisat, CryoSat-2), are freely available (SRTM), or will be developed within the baseline proposal (glacier area). CryoSat-2 and ASIRAS data are available through membership of the CVRT. Data required for product development are as follows: CryoSat-2 Level-1b data are required for processing of the across-track interferometric altimetry. UCL will provide this data by processing our archive (since start of mission) of CS2 Level-0 data, using our CS2 L0-L2 Processing software. This data is equivalent to that currently supplied by ESA's IPF from February 2012 (known as Baseline-B). UCL are able to provide L2I or limited FBR data (to Baseline-B spec.) from the start of mission, so we are not requiring FBR data from ESA. Note that L2I is an intermediate product used as an input to the second stage of the CS2 SAR processing chain and provides access to many low level parameters originating from the L1b or L2 IPF processor which are not available in the L2 product. L2I format, required for this proposal, is directly available from UCL.

- *CryoSat L1b SARIn elevation data is required (compliant with full Baseline B specifications) for all AOI and periods of overlapping validation data, to be accomplish prototype processing of uniform quality products and validation*

6.2 Product Validation Data

For product validation, a large number of high quality DEMs are available (partly for free) from national services and mapping agencies (Table 1 – here we concentrate solely on validated products). ICESat and Laser scanning data, though not a DEM with full spatial coverage, represent an excellent global elevation reference system for GISM monitoring purposes. Ground based observations for validation of the satellite datasets are available within the WGMS database and precise national DEMs.

Table 2 –List of Digital Elevation Models available to this project for product validation purposes.

Data	Spatial resolution	Sensor	Coverage	Availability
SPOT Spirit DEM	40 m	Optical	Polar Ice	Freely available (IPY)
LIDAR DEM	2-1 m	LIDAR	Antarctica	Freely available (USGS)
ICESat	500 m -1 km	Laser Altimeter	Antarctica - Greenland	Freely available (NSIDC)
CryoVEx	Variable	Laser scanner/Radar	Arctic	Freely available (ESA)
IceBridge	Variable	LIDAR	Antarctica/Greenland	Freely available

- *Validation data are required for all AOI during periods of overlapping L2 swath elevation data.*

7 Algorithm development requirements

The algorithm to generate elevation swath will use SARin mode L1b format CryoSat dataset in order to produce individual elevation swath products. Algorithm steps will be (i) delay processing of the

sphase, amplitude and coherence record, (ii) phase filtering, (iii) phase unwrapping, (iv) computation of elevation in radar geometry and (v) mapping of elevation in geographical reference frame (latitude, longitude and height above ellipsoid). The Potential algorithms and subroutines required for the processing of CryoSat SARIn mode data will be tested and validated, including a selection of approaches for phase unwrapping, ground-geo-coding, and ortho-rectification of the data. Information about timing of acquisition and orbit direction (i.e. ascending and descending orbit) will be available for each elevation point.

8 Risk Analysis

Problem areas and technical constraints that are germane to the technique of repeat-pass satellite radar altimetry will not be discussed here. Here, we focus on issues that are directly related to the retrieval of topography using CryoSat-2 SARIn mode elevation data. Although the basic procedure for elevation retrieval has been demonstrated using both simulated (Cullen and Wingham, 2002) and real (Hawley et al., 2009) observations, there are known factors that provide restrictions upon both the reliability and scope of the retrieval. These include:

(i) limitation to regions of minimum effective slope

(ii) limitation to regions of maximum effective slope

(iii) Omission of regions of shadow

(iv) limitation to regions of interferometric phase-coherence

The first three limitations reflect geometrical limitations of the retrieval and are technical constraints. A minimum surface slope is required to ensure that point of closest approach falls at or beyond the antenna half-beam width (1.2 degrees), allowing the interferometric phase to be unambiguously attributed to one side of the satellite ground track. A maximum surface slope will exist as beyond this value aliasing of the interferometric phase will occur. Finally, regions of shadow will (theoretically) exist in areas of steep terrain. Geographical regions affected by all three geometrical factors will be identified and isolated during the data processing chain, through generation of a look-up-table based upon a global DEM (e.g. the Shuttle Radar Topography Mission (Rabus et al., 2003)).

The fourth limitation – interferometric phase incoherence - is an artefact of the surface scattering properties to which there are many contributing factors (Bamler and Hartl, 1998). It is not practical

to simulate the phase coherence of natural snow- and ice-covered surfaces. However, an analysis of ASIRAS airborne data (Hawley et al., 2009) acquired over a 2.5km section of favourably-oriented terrain (effective slope in the range 2.5 to 5.5 degrees) shows that high levels of coherence are maintained at all times within the central region of the range window. In practice, the root mean square difference between elevation measurements derived from ASIRAS SARIn mode data and those of an airborne scanning laser varied little (from 1.36 to 2.08 m) when processing interferometric data at of decreasing coherence (from 1.0 to 0.4) and increasing swath width (from 5 to 25 % of the range window). Such levels of coherence are commonly handled in large-scale SARIn data processing schemes (e.g. (Rabus et al., 2003)) and are well within the tolerance of conventional SARIn phase unwrapping software (Goldstein et al., 1988).

9 Consolidated Requirements for the CryoTop Project

- Develop a prototype to produce elevation swath from CryoSat SARin mode L1b data format
- Validate the elevation product against in situ and airborne auxiliary data in test locations in the Arctic and Antarctic.
- Produce time series of overlapping elevation in synergy with the objectives of the CryoSat+ GLITter project.
- Assess the advantages and limitations of the CryoTop products against existing elevation products and for specific snow and ice conditions.

References

Bamler, R. and Hartl, P. 1998. Synthetic aperture radar interferometry. *Inverse Problems*. **14**, p. R1-R54.

Gardelle, J., Berthier, E. & Arnaud Y, Slight mass gain of Karakoram glaciers in the early twenty-first century, Nature Geoscience, 15 avril 2012, doi: 10.1038/ngeo1450.

GCOS 2006. Systematic observation requirements for satellite based products for climate. Supplemental details to the satellite based component of the “Implementation Plan for the Global Observing System for Climate in Support of the UNFCCC. World Meteorological Society.

Goldstein, R.M., Zebker, H., and Werner, C., 1988, Satellite radar interferometry: Two dimensional phase unwrapping. *Radio Science*, **23**, p. 713-720.

Gray, L., Burgess, D., Coplan, L., Cullen, R., Galin, N., Hawley, R., and Helm, V. 2013. Interferometric swath processing of Cryosat data for glacial ice topography. *The Cryosphere.* **7,** 1857-1867.

Hawley, R.L., Shepherd, A., Cullen, R., Helm, V., and Wingham, D.J. 2009. Ice-sheet elevations from across-track processing of airborne interferometric radar altimetry. *Geophysical Research Letters*, **36**, L22501, doi:10.1029/2009GL040416

Key, J., Drinkwater, M., Ukita, J., Ryabinin, V., Kaczmarska, M., and et al, 2007, IGOS Cryosphere Theme Report, World Meteorological Organisation, p. 1-114.

Meehl, G.A., Stocker, T.F., Collins, W.D., Friedlingstein, P., Gaye, A.T., Gregory, J.M., Kitoh, A., Knutti, R., Murphy, J.M., Nada, A., Raper, S.C.B., Watterson, I.G., Weaver, A.J., and Zhao, Z.-C., 2007, Global Climate Projections. in Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., and Miller, H.L., eds., Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change: Cambridge, United Kingdom and New York, NY, USA., Cambridge University Press, p. 747-846.

Rabus, B., Eineder, M., Roth, A., and Bamler, R., 2003, The shuttle radar topography mission - a new class of digital elevation models acquired by spaceborne radar: Isprs Journal of Photogrammetry and Remote Sensing, 57, p. 241-262.

Raper, S.C.B. and Braithwaite, R.J., 2006, Low sea level rise projections from mountain glaciers and icecaps under global warming: Nature, 439, p. 311-313.

Rignot, E., Rivera, A., and Casassa, G., 2003, Contribution of the Patagonia Icefields of South America to sea level rise: Science, 302, p. 434-437.

Wingham, D.J., Francis, C.R., Baker, S., Bouzinac, C., Brockley, D., Cullen, R., de Chateau-Thierry, P., Laxon, S.W., Mallow, U., Mavrocordatos, C., Phalippou, L., Ratier, G., Rey, L., Rostan, F., Viau, P., and Wallis, D.W. 2006. CryoSat: A mission to determine the fluctuations in Earth's land and marine ice fields. *Natural Hazards and Oceanographic Processes from Satellite Data.* **37**(4), 841-871.

Websites Referenced

APMB website: http://www.stse-apmb.org/index.html

ESA CCI Glaciers Website: http://www.esa-glaciers-cci.org/

GLITter Website: http://www.stse-glitter.org/glitter_about.html

Ice2sea website: http://www.ice2sea.eu/

IMBIE website: http://imbie.org/

IPCC: http://www.ipcc.ch/

SPIRIT SPOT DEMS: http://www.astrium-geo.com/en/2934-spirit-spot-5-stereoscopic-survey-of-polar-ice-reference-images-and-topographies

LiDAR DEMs of Antarctica from USGS: http://usarc.usgs.gov/lidar_dload.shtml

ICESat data available from NSIDC: http://nsidc.org/data/icesat/order.html

CryoVEx data available from ESA: https://earth.esa.int/web/guest/data-access

IceBridge data available from NSIDC: http://nsidc.org/icebridge/portal/