cryosat+ cryotop
support to science element

Support to Science Element (STSE) CryoSat + Cryosphere

Theme 3: CryoSat Glacier and Ice Sheet Margins Topography

(CryoTop)

Algorithm Theoretical Basis Document (ATBD)

Ref: UE-ESA-STSE_CryoTop_ATBD

v2.0

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Prepared by	:	University of Edinburgh	date: 2014-09-03
Issued by	:	Luca Foresta	date: 2014-09-03
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Change Log

Issue	Author	Affected Section	Reason	Status
1.0	UE	All	Document creation	Released to ESA on 22.05.2014
2.0	UE	All	Document update	Released to ESA on 30.01.2015

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Acronyms and Abbreviations

ASIRAS	Airborne SAR Interferometric Radar System
ATBD	Algorithm Theoretical Basis Document
CBCP	Current Baseline Cost Plan
CPOM	Centre for Polar Observation and Modelling
CS	CryoSat
ESA	European Space Agency
GDW	Geographical Distribution of Work
GISM	Glacier and ice sheet margin
GLIMS	Global Land Ice Measurements from Space
GT	Glacier Topography
IAR	Impact Assessment Report
IGOS	Integrated Global Observing Strategy
ITT	Invitation To Tender
KO	Kick Off
MAF	Management and Financial proposal
MPP	Milestone Payment Plan
MSSL	Mullard Space Science Laboratory
OBCP	Original Baseline Cost Plan
PMP	Project Management Plan
PMR	Project Management Risk
PVR	Product Validation Report
RB	Requirements Baseline
RA	Radar Altimetry
RID	Review Item Discrepancies
RRDP	Round robin data package
SAR	Synthetic Aperture Radar
SIRAL	Synthetic Aperture Interferometric Radar Altimeter
SOW	Statement of Work
SR	Scientific Roadmap
STSE	Support To Science Element
TP	Technical Proposal
UCL	University College London
UE	University of Edinburgh
UL	University of Leeds
UNFCCC	United Nations Framework Convention on Climate Change
URD	User Requirements document
WP	Work Package

Reference documents

RD	
1	Gray L, Burgess D, Copland L, Cullen R, Galin N, Hawley R and Helm V. **Interferometric swath processing of CryoSat data for glacial ice topography.** *The Cryosphere*, 7(6):1857-1867, 2013.
2	*ESA.* **CryoSat Product handbook**, https://earth.esa.int/documents/10174/125272/CryoSat_Product_Handbook, 2013.
3	Scagliola M and Fornari M. **Known biases in CryoSat L1b Products (version 1.2).**
4	**FES2004 model.** [http://www.aviso.altimetry.fr/en/data/products/auxiliary-products/global-tide-fes/description-fes2004.html]
5	**Global Ionospheric Map.** [http://iono.jpl.nasa.gov/gim.html]
6	**Bent model. [http://modelweb.gsfc.nasa.gov/ionos/bent.html]**
7	**GIMP DEM**: http://bprc.osu.edu/GDG/gimpdem.php
8	NSIDC Antarctic DEM: http://nsidc.org/data/dems/datasets.html
9	**ESA CryoSat readers**: https://earth.esa.int/documents/10174/418704/CryoSat_Matlab_Reader_Package
10	CryoSat+ CryoTop Product Validation Report

I. Purpose and scope

This document contains the algorithm theoretical basis for the generation of swath elevation products (L2swath) produced as part of the CryoSat + Cryosphere (CS+C) Theme 3 (CryoTop project).

II. Swath altimetry from CryoSat SARIn mode

The primary payload of the CryoSat is the new generation radar altimeter Synthetic Aperture Interferometric Radar Altimeter (SIRAL), which samples the ice surface with three different modes of operation according to a configurable geographic mask. Low Resolution Mode (LRM) works as a conventional pulse-limited radar altimeter and is used over oceans and ice sheet interiors where the surface slope is negligible. Synthetic Aperture Mode (SAR) exploits the Doppler history of the radar data to increase the along-track resolution and is used over sea ice. SAR Interferometric mode (SARIn) additionally makes use of a second antenna to form an interferometer in the across-track dimension, so to locate the angle of arrival of the reflected signal across the track. This mode is activated in presence of sloping ice or rough topography, namely the margins of the Greenland and Antarctic ice sheets as well as over ice caps and mountain glaciers.

The aim of the CryoTop project is to improve upon the processing of CryoSat data acquired while operating in SARIn mode. This document describes the steps of a new approach for more comprehensive exploitation of such data, producing an ice elevation product with enhanced spatial resolution compared to the standard CS L2 height product. In this so called L2Swath processing approach, an elevation is calculated for each coherent SARIn echoes that satisfies certain signal and surface conditions, in contrast with the POCA approach for which only one elevation is produced after a retracking procedure.

The next sections describe the necessary input datasets (CryoSat and auxiliary), the processing steps to generate the elevation product, and the elevation product format; the scheme is summarized in **Figure 1**.

III. Input Data

The input to the CryoTop algorithm is L1b format data from SARIn mode directly downloaded from ftp://science-pds.cryosat.esa.int. In its simplest form, the algorithm does not require additional ancillary data products. However, we found that the use of a reference Digital Elevation Model (DEM) greatly improves the quality of the phase unwrapping and in terms of the location and elevation, and is therefore included in the current processing strategy. The DEM used for Greenland is the GIMP 90m DEM [RD7], the DEM used for Antarctica is the NSIDC ICESAT/GLAS 500m DEM

Table 1 List of L1b fields used to generate L2 Swath elevation products. Fields numbers correspond to Table 4.2-1 of the CS Handbook [RD2]. When the field is not indicated, it is constant and hard coded.

Field	Description	Units
Constants		
	Uncompressed pulse length	s
	Sampling frequency	Hz
	Instrument bandwidth	Hz
	Number of samples [512]	
Time and Orbit Group		
2	USO Correction	10^{-15}
7	Latitude of measurement	10^{-1} µm
8	Longitude of measurement	10^{-1} µm
11	Satellite velocity vector[3] in ITRF	mm/s
12	Real Beam direction vector [3] in CRF	µm
13	Interferometer baseline vector [3] in CRF	µm
Measurements Group		
15	Window Delay (2-way) uncorrected for instrument delays	10^{-12} s
Corrections Group		
35	Dry Tropospheric Correction	mm
36	Wet Tropospheric Correction	mm
39	GIM Ionospheric Correction	mm
43	Ocean Loading Tide	mm
44	Solid Earth Tide	mm
45	Geocentric Polar Tide	mm
Waveform Group (SARIn)		
54	Averaged Power Echo Waveform [512 samples]	scaled
88	Coherence [512 samples]	10^{-3}
89	Phase difference [512 values] between –π and +π	10^{-6} rad

[RD8].

A complete list of the SARIn L1b fields used in the processing [RD2] is given in **Table 1**. The L2Swath product depends on models and assumptions used to generate these fields and discussed in the CS handbook [RD2]. Such models/assumptions are mentioned and referenced in this document where relevant.

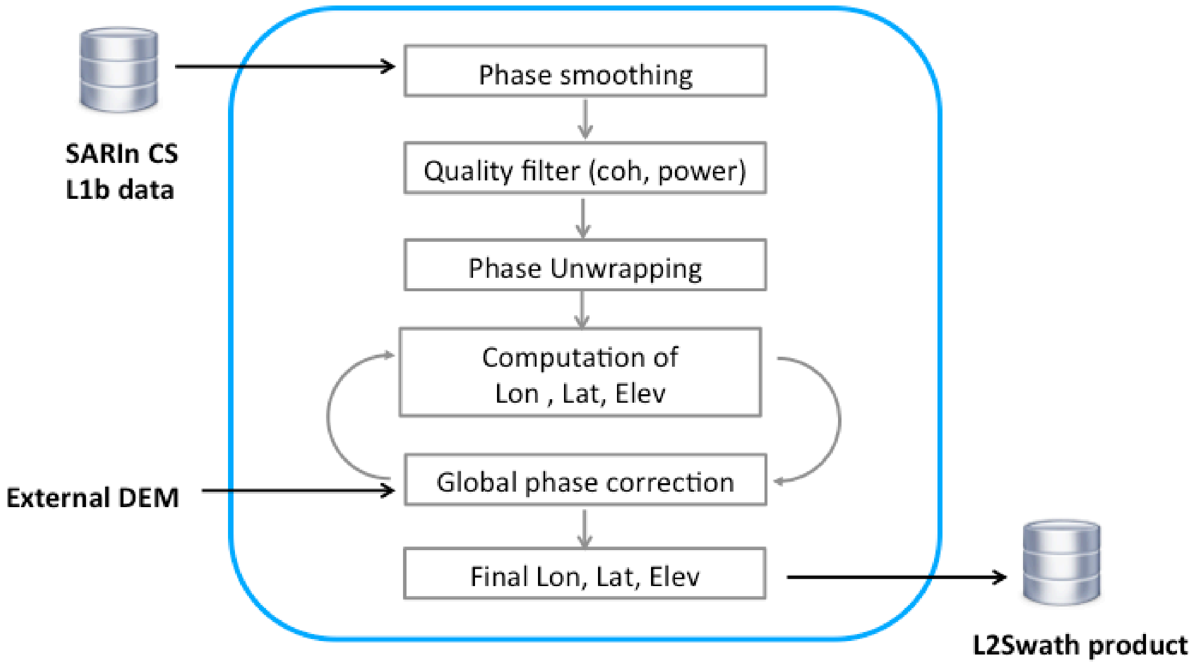

Figure 1 Schematic diagram indicating the components of the CryoTop algorithm, which processes CryoSat SARIn L1b data to the final L2Swath output product. An external DEM is needed as additional input when evaluating the global phase correction. This block, as suggested by the arrows, is iterative.

IV. Swath processing

A. Read L1b data

The list of files to be processed is generated according to i) filename (either as a single file or as a folder, with/without subfolders, containing the relevant files); ii) start and stop date and time; iii) geographical region of interest. The ESA CryoSat L1b reader [RD9] is used to read the binary files. The auxiliary DEM is also loaded.

B. Phase smoothing

To reduce instrument noise, the phase and amplitude are filtered by recreating the interferogram, filtering its real and imaginary components with a low pass filter and retrieving the phase from the smoothed interferogram, a procedure similar to that described in RD1. We filter each waveform independently with a filter size equal to 3 bins, an example is given in **Figure** 2.

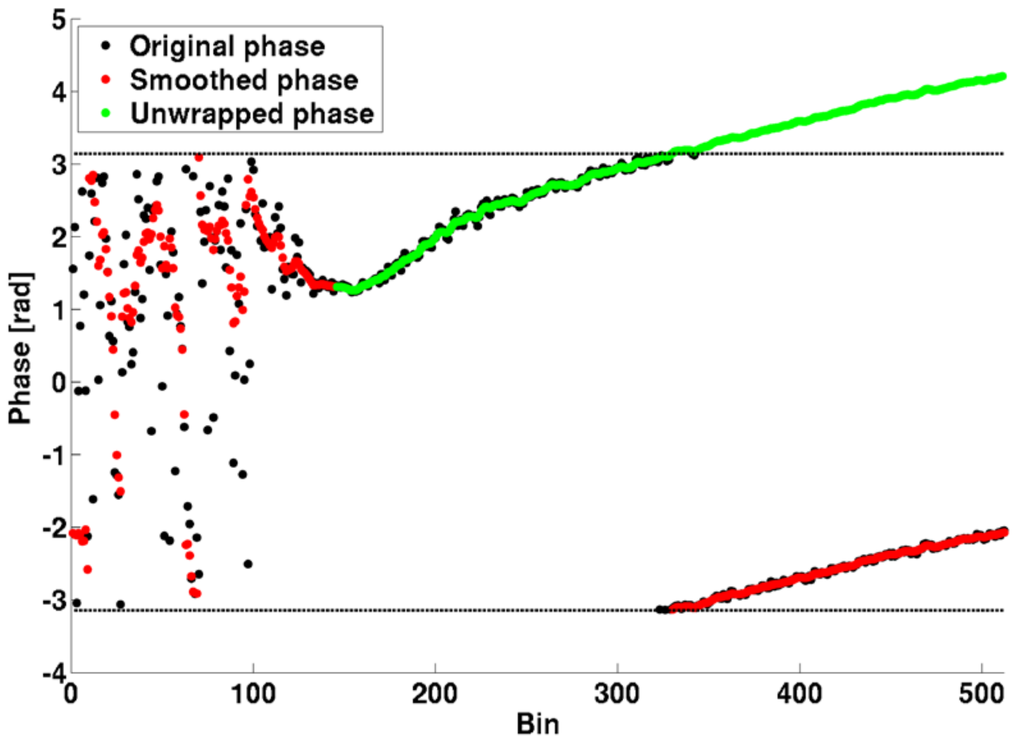

Figure 2 Original (black), smoothed (red) and unwrapped (green) phase. The black dashed lines highlight the [-π, π] interval. Note that unwrapping is performed after smoothing and that phase values are filtered for low power/coherence (see also **Figure 4**).

C. Local phase unwrapping

Phase difference can only be known within a [-π π] interval, a phase ambiguity will be present when surface slope exceeds about half a degree, which requires a phase unwrapping procedure (**Figure 2** and **Figure 3**). An example of a phase ambiguity is observed in Figure 2 beyond bin 300, where the original smoothed phase value (in red) has a -2π ambiguity which requires correction in order to successfully unwrap the phase (shown as resulting continuous green line). The unwrapping procedure is applied to each waveform separately by adding or subtracting 2π when the absolute phase change between 2 consecutive bins exceeds π.

In order to minimize phase unwrapping errors, the phase signal is masked according to coherence and power. This is to ensure that only quality data is further processed and will be refined during the validation exercise. The default thresholds parameters are coh > 0.8 and power >1.10^4. Measurements with power or coherence below one of these thresholds are discarded before the unwrapping procedure and are not used for further processing.

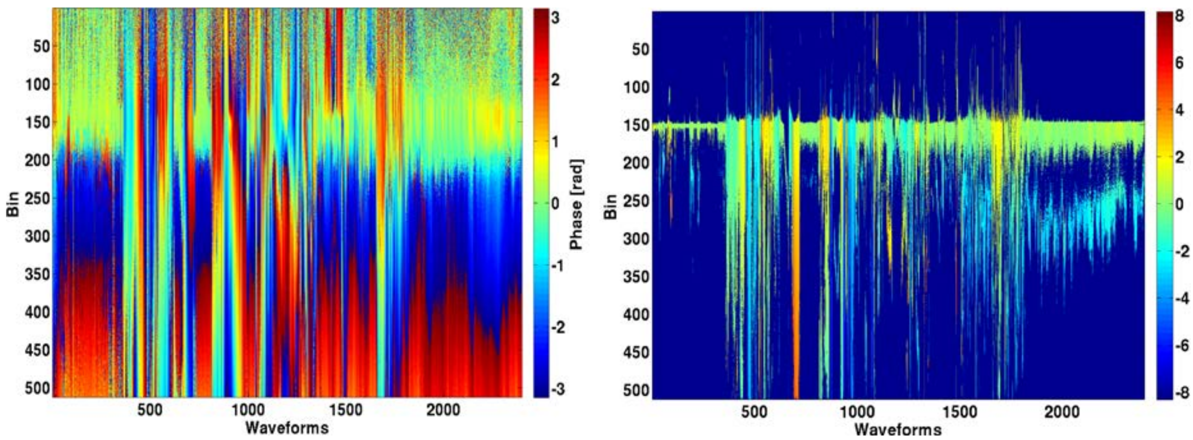

Figure 3 Wrapped (left) and unwrapped (right) phase difference for all waveforms in a sample file CS L1b file. Note that the phase difference is always within [-π, +π] on the left (i.e. it is wrapped) as opposed to the right panel. No global phase correction is applied at this stage (see 'Global phase correction' section for details).

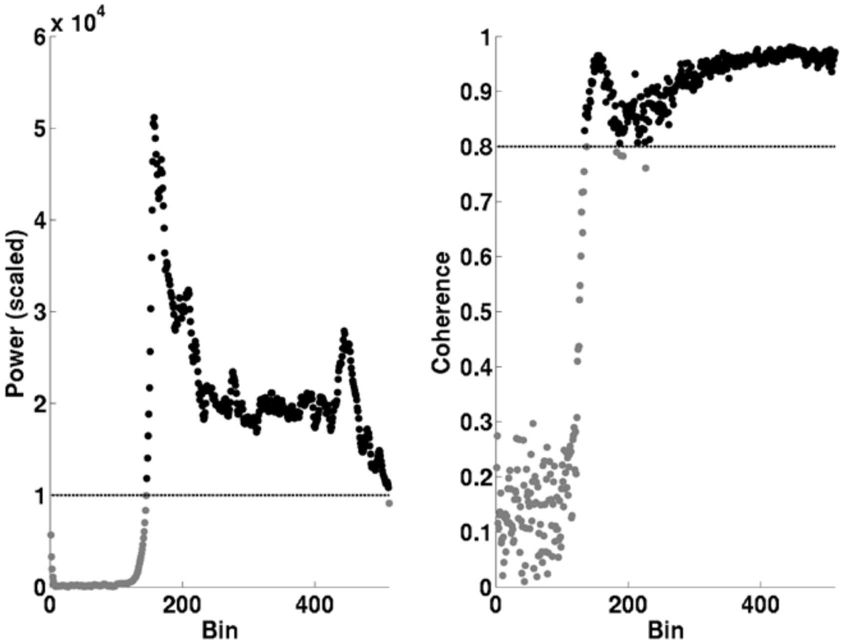

Figure 4 Power (left) and coherence (right) for waveform 700 in CS L1b file used in **Figure 3**. The black dashed lines represent the power and coherence thresholds. Values below their respective threshold are shown in gray and the corresponding phase difference is not used for the unwrapping, nor for further processing.

D. CryoSat Reference Frame (CRF) to International Terrestrial Reference Frame (ITRF)

The CS real antenna boresight (i.e. real beam vector) is taken from the L1b structure and its components are given in CRF. Such vector points downward from the satellite to the surface and includes a correction accounting for the instantaneous pitch angle of the satellite. In order to pass from CRF to ITRF, yaw and heading angles must be known. The satellite's roll angle, instead, is needed when calculating the look angle θ. Roll, yaw and pitch can be taken directly from the L1b product (according to RD [2], page 15):

roll =	+ interferometer_baseline(x)	/ 1e6 [rad]	(relative to axis Y in CRF)
yaw =	- interferometer_baseline(y)	/ 1e6 [rad]	(relative to axis X in CRF)
pitch =	- real_beam(y)	/ 1e6 [rad]	(relative to axis Z in CRF)

The heading angle is calculated using the satellite's velocity vector and the normal to the xz-plane (both in CRF), using the following equations:

$$heading = \frac{\pi}{2} + (\bar{v} \cdot \hat{n}_{xz}) \qquad \text{Descending pass}$$

$$heading = \frac{\pi}{2} - (\bar{v} \cdot \hat{n}_{xz}) \qquad \text{Ascending pass}$$

The real beam vector is then rotated by [heading + yaw] degrees around the Z axis, in order to pass from local (CRF) to global (ITRF) coordinates.

E. Computation of echo latitude, longitude and elevation

For each waveform, the following processing steps are performed.

1. Slant range R

   The distance R of each measurement to the satellite, given in meters, is generated according to RD2 on page 33:

   $$R(n) = \frac{\mathrm{T} \cdot \mathrm{c}}{2} - \frac{\mathrm{N} \cdot \mathrm{c}}{8 \cdot B} + \frac{\mathrm{n} \cdot \mathrm{c}}{4 \cdot B} \quad [m]$$

   where n = [0:511] is the sample number (range bin), T is the window delay in seconds, N is the amount of samples per waveform (512), B is the instrument bandwidth (320 MHz) and c is the speed of light. The window delay is corrected using the USO correction factor (RD2).
2. Apply range bias

   The constant range bias identified for baseline B processed files (RD3) is taken into account and suitably added to the range value.
3. Geo-physical corrections to R

   A number of geo-physical corrections must be applied to the slant range R. The corrections relevant to land ice applications (RD [2]) are listed in **Table 1** and are provided in the L1b product. The models used to generate such corrections are referenced here for completeness as the CryoTop processing depends on their accuracy. Including the relevant corrections (given in meters) the range becomes:

$$\begin{aligned} R = \quad R \quad & + LOAD\ TIDE(-0.02\text{m} - 0.02\text{m}) + EARTH\ TIDE(-0.3 - 0.3\text{m}) \\ & + POLAR\ TIDE(-0.02\text{m} - 0.02\text{m}) \ + \ DRY\ TROP.\ (1.7 - 2.5\text{m}\ ) \\ & + \ WET\ TROP.(0 - 0.5\text{m}) + \ GIM\ ION.(0.06 - 0.12\text{m}) \end{aligned}$$

Typical range corrections are given in parenthesis, according to RD2.

The ocean loading tide correction is needed to remove the deformation of the Earth's crust due to the weight of the overlying ocean tides and is derived using the Finite Element Solution Tide model, FES2004 (RD4). Deformation of the Earth due to tidal forces from the Sun and Moon is taken into account via the solid Earth tide correction, whose values are estimated using the Cartwright model. The geocentric polar tide correction accounts for crust distortions due to centrifugal force variations induced by movement of the planetary rotational axis and is derived by historical pole locations' data.

The dry and wet tropospheric corrections (respectively the effect of non-polar gases, e.g. oxygen and nitrogen, and polar gases, e.g. water vapor) depend on atmospheric temperature and pressure (provided by Meteo France CNES SSALTO system). Finally, the bias introduced from the total electron content in the ionosphere is estimated by using the Global Ionospheric Map (RD5) or, in case of unavailability, by using the Bent model (RD6).

As specified, above, the geo-physical corrections (in meters) are added to range R. Due to geometrical reasons, a change in R is mirrored almost one-to-one by a change in the computed measurements' elevation h. Therefore, errors in the geo-physical corrections directly affect the final elevation of the measurements.

4. Calculation of look angles θ

   Equation 2 is used to calculate the look angles θ, i.e. the angles between the range measurements and the nadir direction.

5. Conversion from satellite coordinate system to latitude, longitude and elevation

   The measurement location position and range R are then used to compute the Cartesian coordinates of the satellite center of mass and of the echo location at nadir. In this Cartesian reference frame, the nadir projected echo location is rotated by the heading, yaw, theta and pitch angles to obtain the Cartesian coordinates of the actual echo location. Latitude, longitude and elevation of the echo is then simply obtained by converting the Cartesian coordinates into latitude, longitude and elevation above the ellipsoid (WGS84).

F. Global phase correction

In the presence of large slopes, the conventional unwrapping procedure described above will not be able to resolve the phase ambiguity as the entire measurement might be affected by a phase shift; in this situation we will need to apply a 'global' phase correction, i.e. adding or subtracting a suitable multiple of 2π to the entire waveform. Without accounting for this correction, elevation estimates can be off by tens of meters and their location off by a few kilometers (**Figure 5**).

We implemented a procedure involving a reference DEM. For each waveform, latitude, longitude and elevation are computed for a number of 2π multiples (positive and negative). The 2π multiple which minimizes the elevation difference against the reference DEM is selected as the suitable correction to the phase and elevation corresponding to phase corrected with that value is stored (**Figure 6)**. **Figure 7** and **Figure 8** show the impact of the phase ambiguity and its correction on the location (lat/lon) and elevation of the measurements.

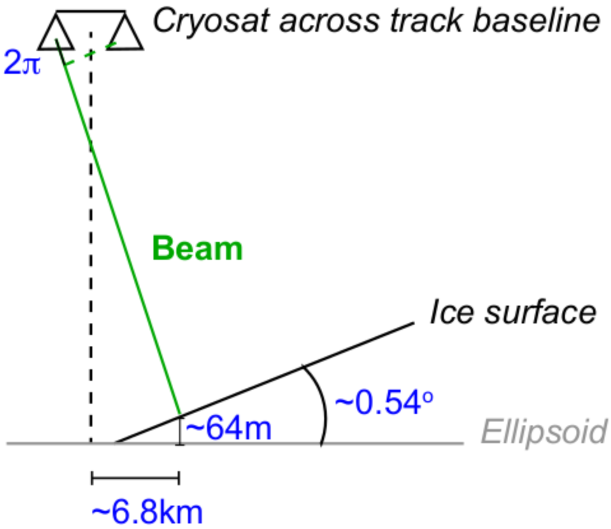

Figure 5 Phase ambiguity results in elevation errors of tens of meters and mis-location in the order of kilometres in presence of ~0.5 degrees surface slope using a flat Earth approximation.

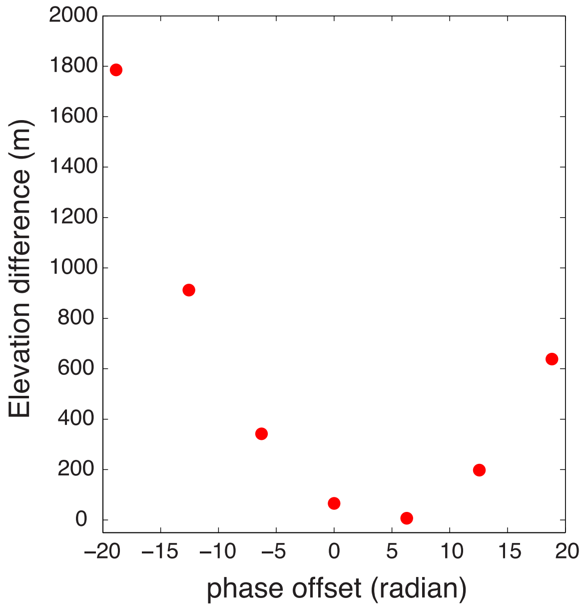

Figure 6: Elevation difference between the L2swath solution and the reference DEM for phase ambiguity equal to [-6 -4 -2 0 2 4 6]*π.

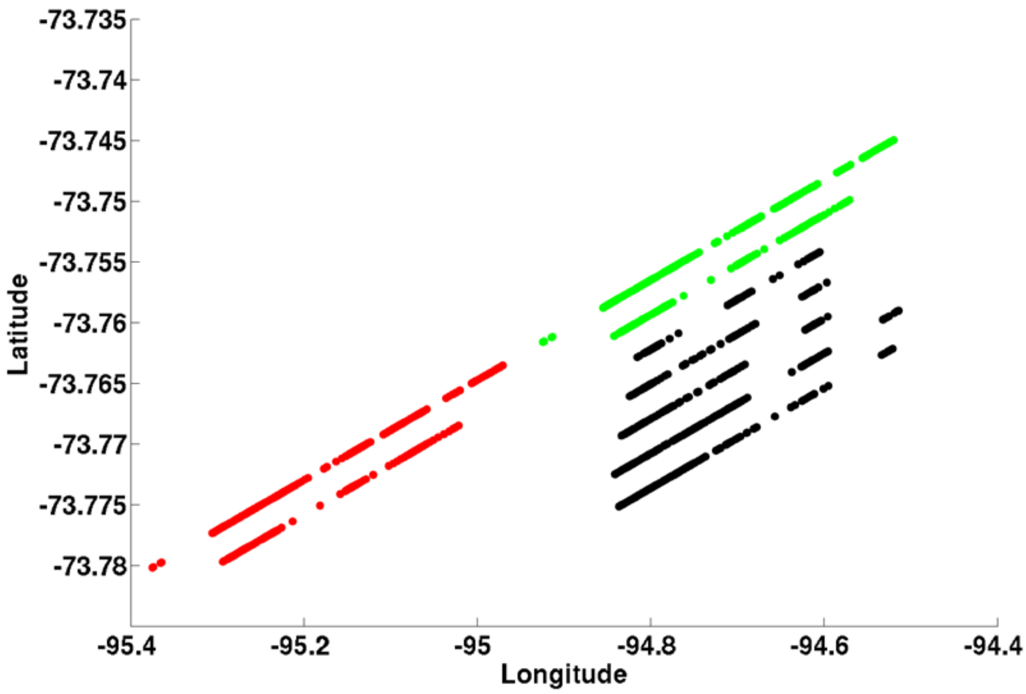

Figure 7 Effect of the global phase correction. Each line corresponds to data from a specific waveform in the CS L1b file used in Figure 3. Black data do not need global phase correction. The next two waveforms are mis-located (red) in the absence of the global phase correction (green data). The mis-location is about 14 km.

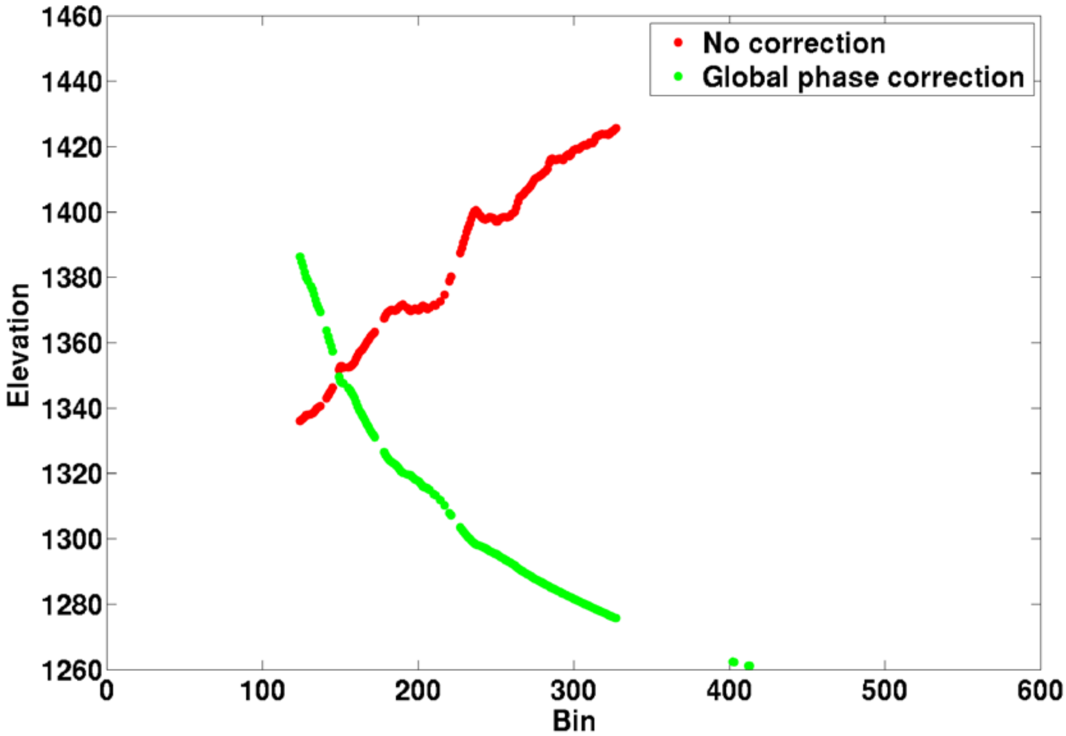

Figure 8 Effect of the global phase correction on the final elevation product for one of the two corrected waveforms shown in **Figure 7**. In this example the trend is opposite for the two cases because the phase difference changes sign when the correction is applied (not shown). Errors can be up to several tens of meters.

G. Filtering waveform with spurious elevation

We do not have a retracking step within CryoTop, therefore the quality (e.g. presence of leading edge) of the waveform is not assessed beyond the simple amplitude and coherence filtering during the local phase unwrapping step. We have noticed that in some cases waveforms with no significant leading edge and that were not sampling the surface of the Earth (i.e. the range window is several 100 meter from the expected elevation) made it to the final elevation product (**Figure 9**). We therefore filter out elevation that are unrealistic (i.e. when elevation difference between our product and the reference DEM are larger than a threshold which we take as the size of the range window, i.e. 120 m). This threshold has to be taken with caution when the ice surface elevation is suspected to vary greatly in time and/or when the reference DEM is from a significantly different time period than the CryoSat measurement.

H. Final L2swath product

The global phase correction step leads to the final latitude, longitude and elevation; for each processed SARIn CS L1b file, the final CryoTop product contains the fields listed in **Table 2**, namely 1D arrays for the longitude, latitude and elevation of the measurements as well as their corresponding waveform number, coherence, power and phase difference. Additional fields saved are the elevation difference with the external DEM, the phase ambiguity in multiples of π. Finally, the original L1b structure, which includes the heading angle, is also stored.

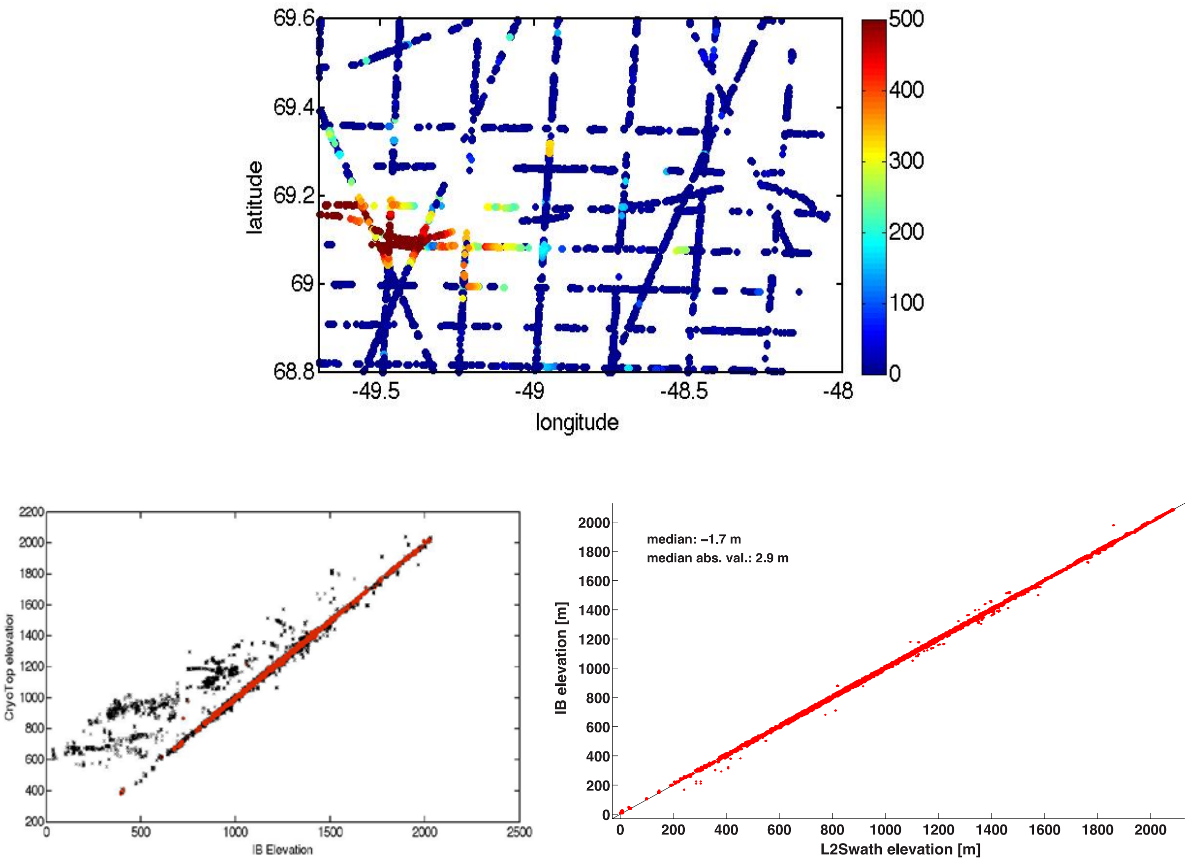

Figure 9 Top, elevation difference between L2swath (no global phase correction, no masking of elevation > range window) and IceBridge over Jakobshavn for the months of March, April and May 2011. High elevation differences are visible over the Jakobshavn glacier trunk. Bottom left, same as Top but for the entire Jakobshavn sector. Bottom right, same as left but with global unwrapping and filtering out of elevation difference above the range window size. Details about the validation can be found in RD10.

Table 2. List of fields in the CryoTop L2swath product. They are all 1D arrays beside the L1b structure. Details are given in the text.

Field	Unit
Longitude	degree
Latitude	degree
Elevation	m
Waveform number	-
Coherence	-
Power	scaled
Phase difference	rad
Elevation difference with external DEM	m
Phase ambiguity	rad (in π multiples)
L1b structure	see RD [2] for details