Tandem Phase IS2/CS2 along-track low-level comparison

Algorithm Technical Baseline Document (ATBD)

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Change Log

Issue	Author	Affected Section	Reason
1	Antoine Laforge	Entire document	
2	Sara Fleury	Entire document	Minor revisions

Distribution List

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1 Introduction

1.1 Purpose and Scope

The purpose of this project is to take advantage of the CryoSat-2/IceSat-2 tandem phase opportunity, so called Cryo2Ice project, to evaluate the performance of CryoSat-2 over sea-ice surfaces and extract novel parameters. First by comparing existing CS2 sea-ice products and secondly by producing a most adequate product for the comparison, enabling us to extract essential parameters such as Ku-band penetration or impact of footprint.

The scope of this document is to describe the adopted strategy to organize, sort and compare the IS2 and CS2 data together. CS2 data from various CS2 sea-ice products developed and distributed by the international sea-ice community will be collected and used. For IS2, only data distributed by NASA as the ATL07 and ATL10 products will be used.

1.2 Acronyms

AWI	Afred Wagner Institute
CS2	CryoSat-2
ESA	European Space Agency
IS2	IceSat-2
LRM	Low Resolution Mode
NASA	National Aeronautics and Space Administration
LEGOS	Laboratoire d'Etude en Geophysique et Océanographie Spatiale
SAR	Synthetic Aperture Radar

1.3 Contacts

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2 Data

2.1 CryoSat-2

CryoSat-2 is an Earth Explorer Opportunity Mission in ESA's Living Planet Program missions launched on the 8th of April 2010. It flies with an inclination of 92 degrees. Until September 2019, its cycle period was of 369 days with a sub-cycle period of 29 days. In the context of the Cryo2Ice project its orbit has been changed and it has no more repeat cycles but a sub-cycle of 25 days. It carries as main payload a Ku-band altimeter, SIRAL (SAR Interferometric Radar ALtimeter) consisting of two symmetric antennas, able to operate in SARin, SAR and LRM mode. It operates in SAR mode over the Arctic polar ocean. The SAR mode produces a square footprint of about 300m in the along-track direction and 1.5km across-track (Fig 1), most of the back-scattered energy is localized at nadir.

Since the beginning of its operational phase in October 2010, CryoSat-2 has enabled to provide long time series of sea-ice thickness observations over the Arctic Ocean as well as in the south Austral Ocean. The various existing products differ on several step of the processing and don’t provide the same results. Table 1 shows the products considered in the context of this project.

CS2 SEA-ICE PRODUCT	RETRACKER	REFERENCE	L2P PUBLIC AVAILABILITY
AWI	Emp - TFMRA50	(Hendricks, et al., 2016) (Ricker, et al., 2014)	Yes (only high level)
LEGOS	Emp – TFMRA50	(Laforge, et al., 2020)	Yes
LEGOS	Phy – SAM+	(Laforge, et al., 2020)	Yes
NASA	Phy - CSWfF	(Kurtz, et al., 2014)	No
CPOM	Emp - OCOG	(Tilling, et al., 2017)	No
UOB	Phy - LogNorm	(Landy, et al., 2019)	No

Table 1. Data collection of CryoSat-2 sea-ice products

2.2 IceSat-2

ICESat-2 (**Ice, Cloud, and land Elevation Satellite 2**), part of NASA's Earth Observing System, was launched on the 15 September of 2018 into a near-circular, near-polar orbit with an altitude of approximately 496 km. It is designed for measuring ice sheet elevation and sea ice thickness, as well as land topography, vegetation characteristics, and clouds. It is expected to operate for three years but carries enough propellant for seven years.

The sole instrument on board ICESat-2 is the Advanced Topographic Laser Altimeter System (ATLAS), a space-based lidar. ATLAS measures the travel time of laser photons from the satellite to Earth and back. ATLAS emits visible laser pulses at 532 nm wavelength. ATLAS generates six beams arranged in three pairs in order to better determine the surface's slope and provide more ground coverage (Fig. 1). Each beam pair is 3.3 km apart across the beam track, and each beam in a pair is separated by 2.5 km along the beam track. The laser array is rotated 2 degrees from the satellite's ground track so that a beam pair track is separated by about 90 m. The laser pulse rate combined with satellite speed results in ATLAS taking an elevation measurement every 70 cm along the satellite's ground path. The laser fires at a rate of 10 kHz. Each pulse sends out about 200 trillion photons, almost all of which are dispersed or deflected as the pulse travels to

Earth's surface and bounces back to the satellite. About a dozen photons from each pulse return to the instrument and are collected with a 79 cm.

In this project three ATL data products will be studied (Table 2).

Product	Content	Segment aggregates (photons)
ATL07	Sea-ice height / surface type	150
ATL10	Snow freeboard	150
ATL12	Ocean surface height	8000

Table 2. IS2 products used in this study

2.3 Cryo2Ice

Between 16 and 31 July 2020, ESA raised the orbit of Earth Explorer CryoSat-2 to periodically align with NASA's ICESat-2. Its aim was to achieve a partial parallel ground-track every 19th revolution of CryoSat-2 and every 20th revolution of ICESat-2 that would allow data in the polar areas to be collected by the two satellites within a few hours of each other. The change provides radar and lidar measurements of the same ice, at nearly the same time, allowing scientists to compare and later on improve the accuracy of sea ice thickness measurements and ice-sheet elevation time series.

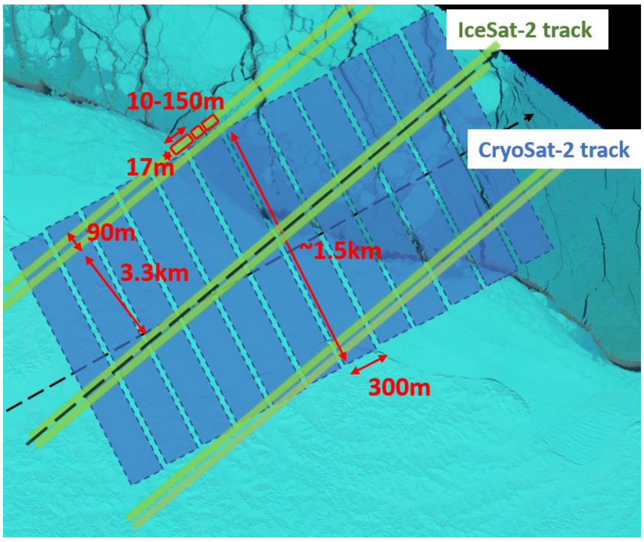


Fig1. Schematic view of overlapping ground footprints of CryoSat-2 (in blue) and IceSat-2 (in green) over a Sentinel-2 image of sea-ice.

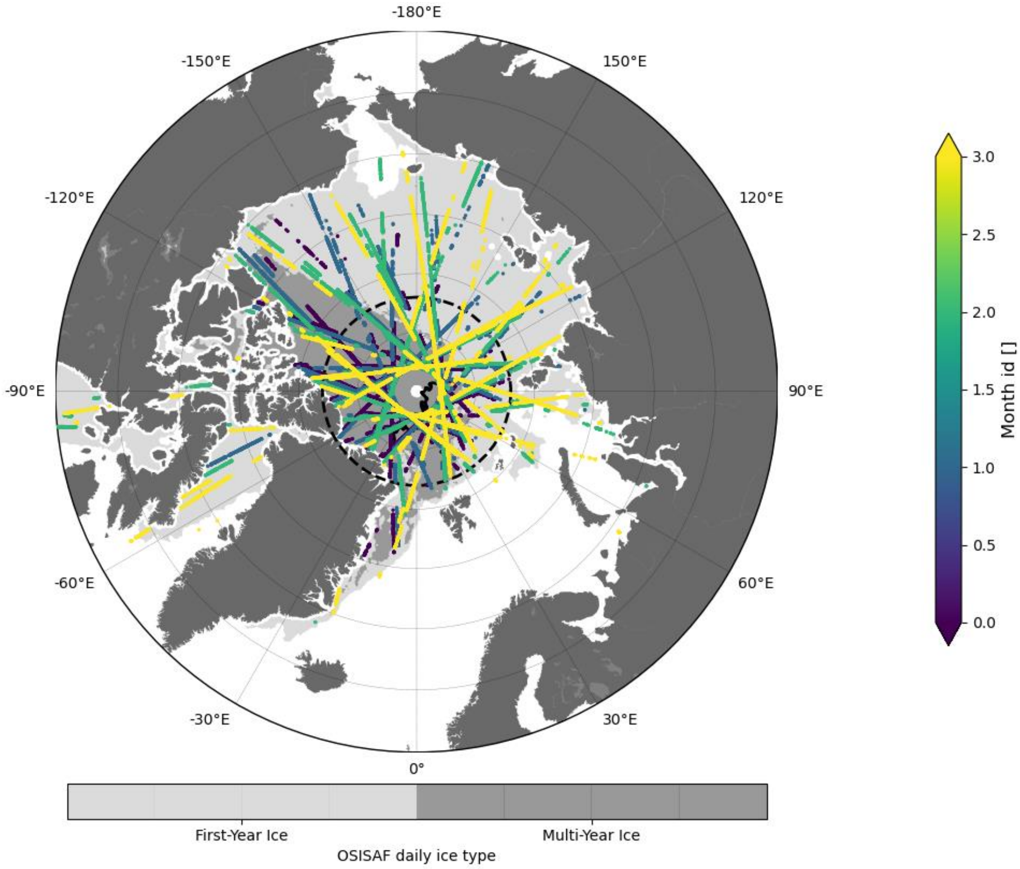


Fig2. Collocated tracks between CS2 and IS2 over the Arctic Ocean for period 01/10/20 to 31/01/21

3 Methodology

This section details the approach used to sort, align and record the Cryo2Ice data in order to enable direct comparison between IceSat-2 and CryoSat-2 measurements.

3.1 Algorithm

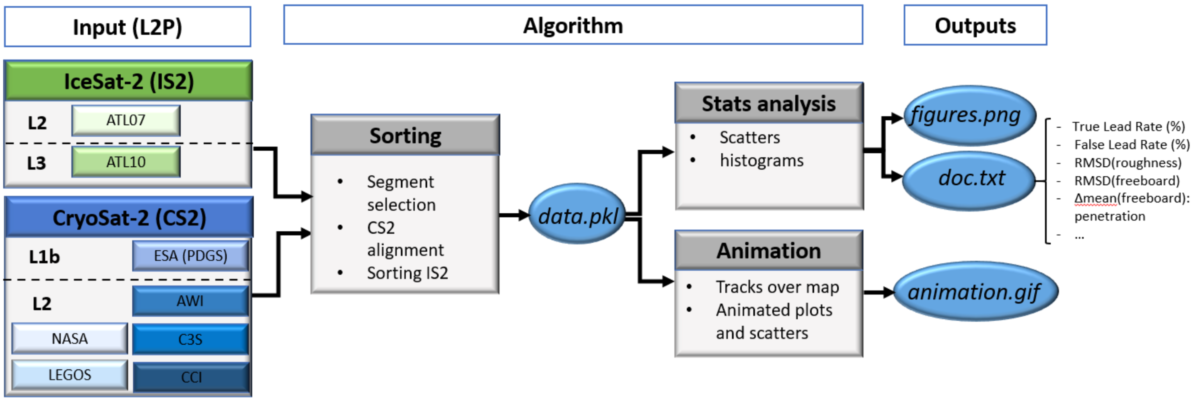


Fig 3. Diagram showing algorithmic logic to compare IceSat-2 and CryoSat-2 measurements.

3.2 Data loading

Collocated tracks between the CryoSat-2 and IceSat-2 missions from September 2020 are identified thanks to the Cryo2Ice website (https://cryo2ice.org/).

IceSat-2 ATL07 and ATL10 data are downloaded from the NSIDC website (https://nsidc.org/data/) for each Reference Ground tracks.

CryoSat-2 L1b baseline-D data are downloaded from ftp://science-pds.cryosat.esa.int/.

CryoSat-2 L2P sea-ice products were requested from each institute: AWI, CPOM, UOB as they are not available online. The LEGOS data are directly processed with access to the SIT processing algorithm.

3.3 Data sorting

In this section, we describe the approach used to sort and arrange the IceSat-2 beam data relatively the CryoSat-2 data.

1/ Data collection

The first step consists in gathering the CS2/IS2 collocated track. Two tools are available: the Cryo2Ice website or KML orbits files of both missions. The track files corresponding to collocated tracks are stored in a separated folder. Since there are collocated tracks about every 1.5 days, files can be identified by their dates. These tracks can also be identified by their absolute orbit number or RGT for reference ground track as the tracks are coincident every 19 orbits for CS2 and every 20 orbits for IS2.

For IceSat-2, ATL07 and ATL10 data are used. For CryoSat-2, ESA Baseline-D product is used as reference track, the used sea-ice products are summarized in table 1.

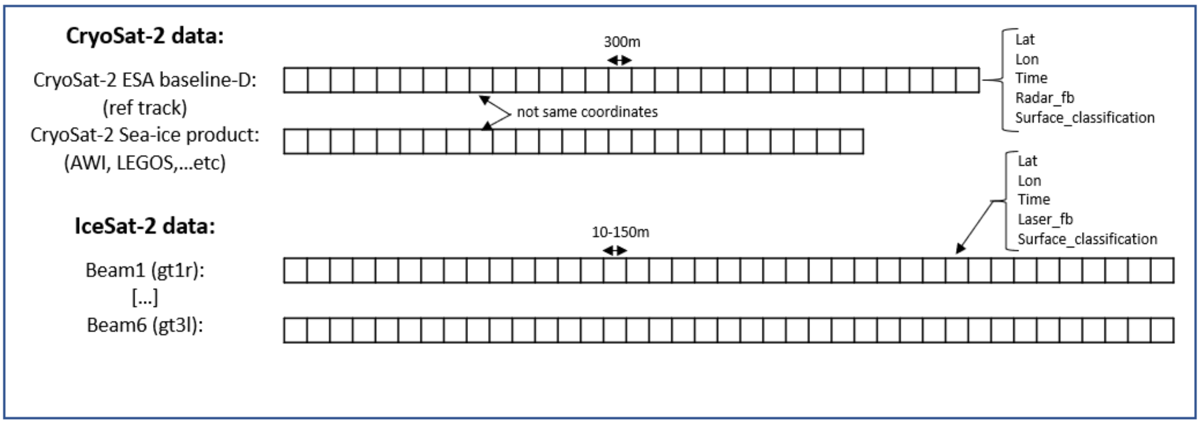


Fig 4.

Algorithm step1

2/ Data selection

This step consists in selecting common collocated track sections between IS2 and CS2.

All IS2 beam measurements are associated to their closest CS2 data point using a KDTree algorithms (Maneewongvatana and Mount 1999). Collocated sections are selected if distance from each IS2 beam data centre to closest CS2 beam centre is under a given distance MIN_DIST (usually 200m). The common collocated section is acquired by finding maximum common section between all IS2 beams. Thus, we determine the extreme coordinates of each common section: (latmin, lonmin)/(latmax,lonmax).

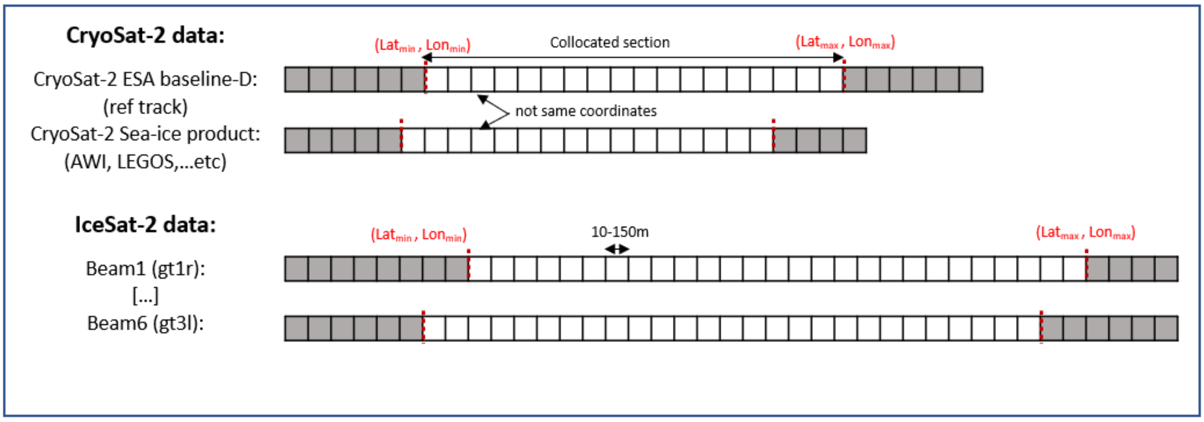


Fig 5.

Algorithm step2

3/ Alignment of CS2 products on reference track

The various CS2 sea-ice products (table 1) do not contain the same list of data points. These data must be realigned on a reference track in order to have corresponding coordinates. The KDtree algorithm allows establishing the correspondence between the indexes of each data points and the indexes in the reference track. Missing data are identified and masked.

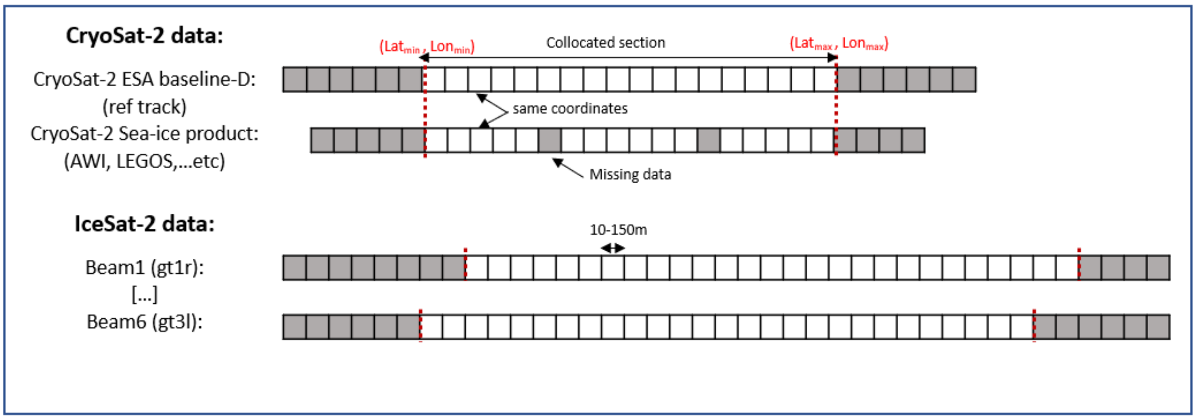


Fig 6.

Algorithm step3

4/ Alignment of IS2 products on reference track

The KDTree algorithm is once again used to associate each IS2 beam data point within the section limits: (latmin, lonmin)/(latmax,lonmax) to CS2 reference track beams. The distance (Δd) and the time delay (Δt) between associated data points are recorded.

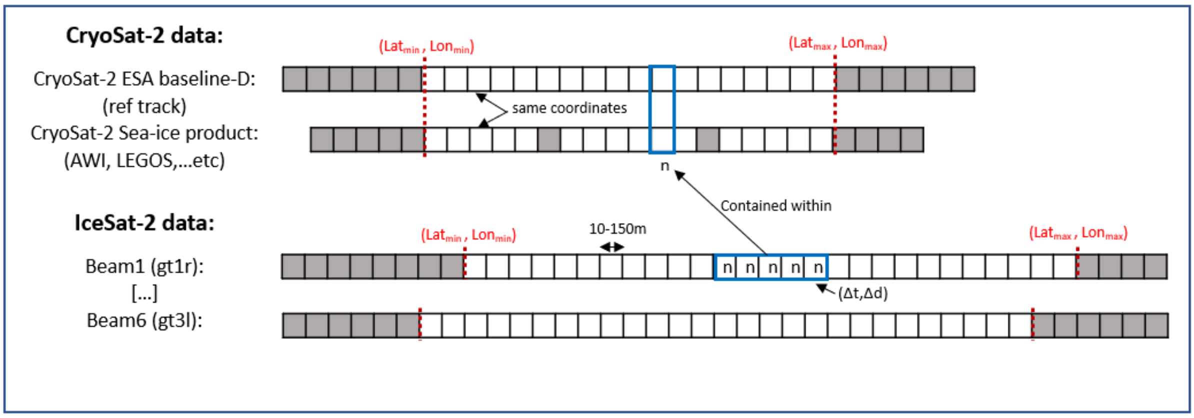


Fig 7.

Algorithm step4

5/ Sorting of IS2 data

For each CS2 data points (Doppler beams) of the reference track, the corresponding data points in IS2 (all beams included) are store and sorted by order of Δd in the matrix M in the corresponding CS2 ref track index column. Each recorded point is associated with a set of parameters listed in Table 3 (mainly: lat, lon, time, Δd , Δt, …) and any other wanted parameters listed in an external dictionary file.

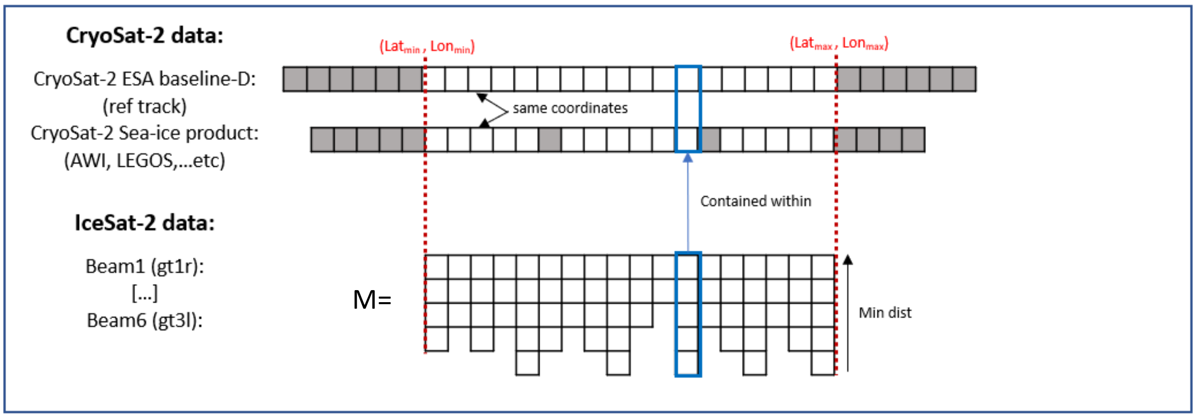


Fig 8. Algorithm step5

6/ Computing IS2 beamwise mean values

In this last step we calculate the weighted mean (Eq. 2) and standard deviation (Eq. 3) of IS2 measurements corresponding to each reference track CS2 beams (each column of the matrix M). The mean is weighted by the IS2 granule segment length L_i to account for non-uniform and variable length sampling of height estimates. Also, a Gaussian weight W_i depending on the distance Δd of each IS2 granule to the corresponding CS2 beam centre is also applied following Eq. 1.

$$W_i = e^{-\frac{\Delta di^2}{D^2}} \quad (1)$$

$$\overline{h} = \frac{\sum_i^N L_i W_i h_i}{\sum_i^n L_i W_i} \quad (2)$$

$$\sigma^2 = \frac{\sum_i^N L_i W_i \left(h_i - \overline{h}\right)^2}{\sum_i^N L_i W} \quad (3)$$

The outcome of this last step is an array filled with averaged IS2 data points with the exact same size of the reference CS2 track array, thus enabling direct comparison.

Recorded parameters	**description**
lat	latitude
lon	longitude
Δd	Distance separating IS2 segment to associated CS2 beam center
weight	Gaussian weight coefficient function of Δd and averaging radius (usually 4.5 km)
time	Time in UTC of IS2 segment
delay	Time delay

id	Beam identification number respecting 'gt1r': 11, 'gt1l': 12, 'gt2r': 21, 'gt2l': 22, 'gt3r': 31, 'gt3l': 32,
param	IceSAT-2 recorded parameters

Table 3. List of parameters recorded in each cell of M matrix

3.4 Crossover data

In order to increase the amount of information along the collocated track route, we have added measurements from other missions at cross-over points. All other mission data crossing over the reference track during the required period (+- 10 days) are recorded and the associated distance, delay and measurements are stored in matrix C.

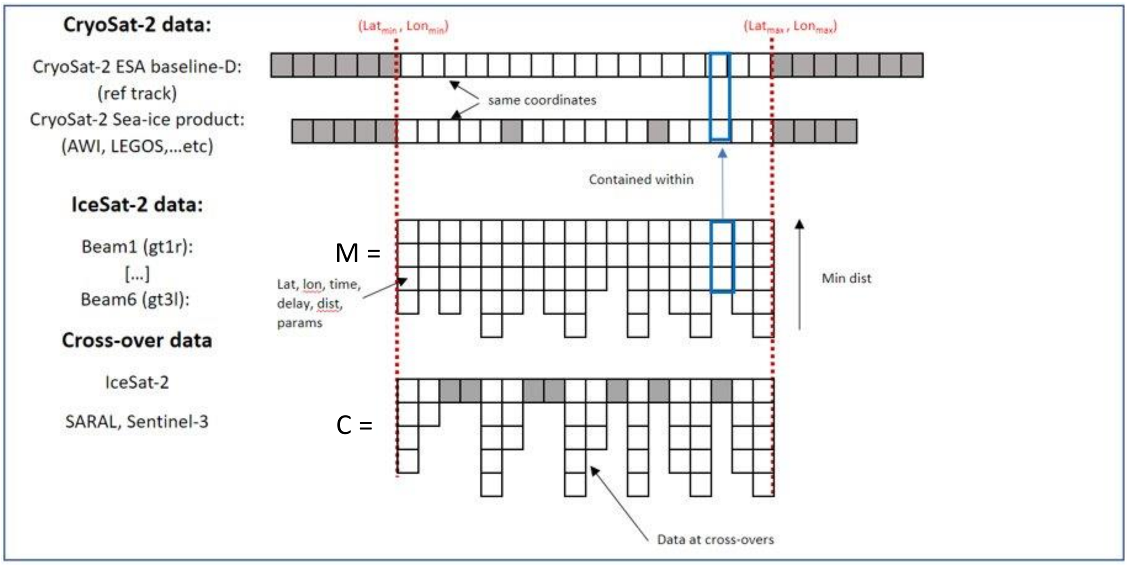


Fig 9. Cross-over matrix

3.5 Animation

For outreach purposes an animation showing various parameters (freeboard, sea surface anomaly, surface type) from both missions over collocated tracks was developed. A tweet was posted to communicate on the CRYO2ICE project:

https://twitter.com/esa_cryosat/status/1359446279210827777

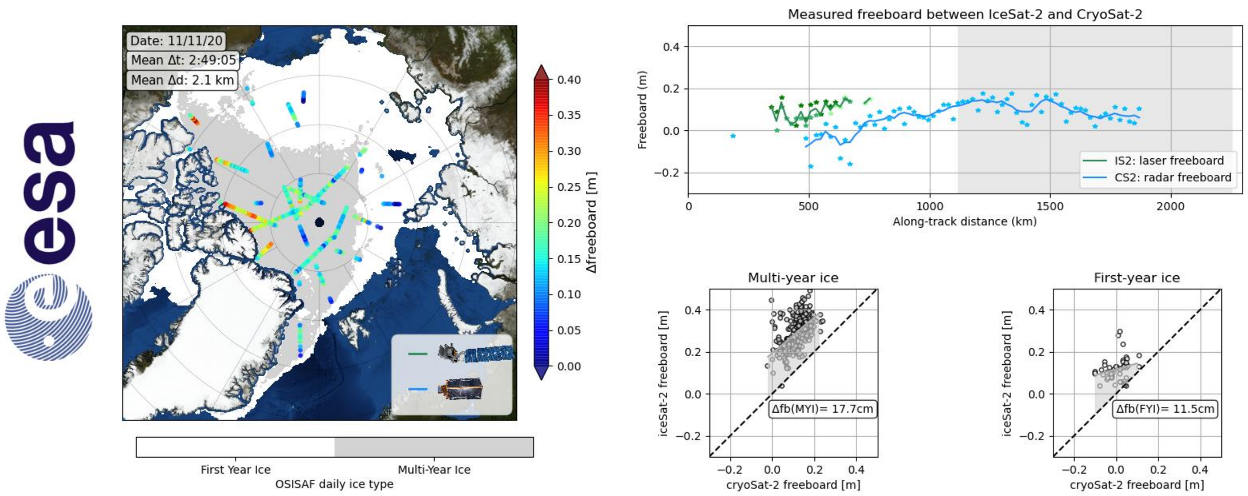


Fig 9. Last frame of an animation showing the map of freeboard elevation difference between IceSat-2 and CryoSat-2 for the period 28/10/20 to 11/11/20. The distinction is made between Multi-Year Ice and First Year Ice in the scatter plot.

4 Along-track comparisons: towards snow depth?

In this section, we show an application of the methodology by looking at the freeboard elevation difference between CS2 and IS2 over coincidental tracks and comparing it to snow-depth products.

4.1 Methodology

Assuming a full penetration of Ku-band wave in the snow layer above sea-ice, and reflection of IS2 laser beam at the snow surface, the difference of the elevations between the 2 missions should provide the snow thickness.

In this section we estimate this snow depth using this hypothesis.

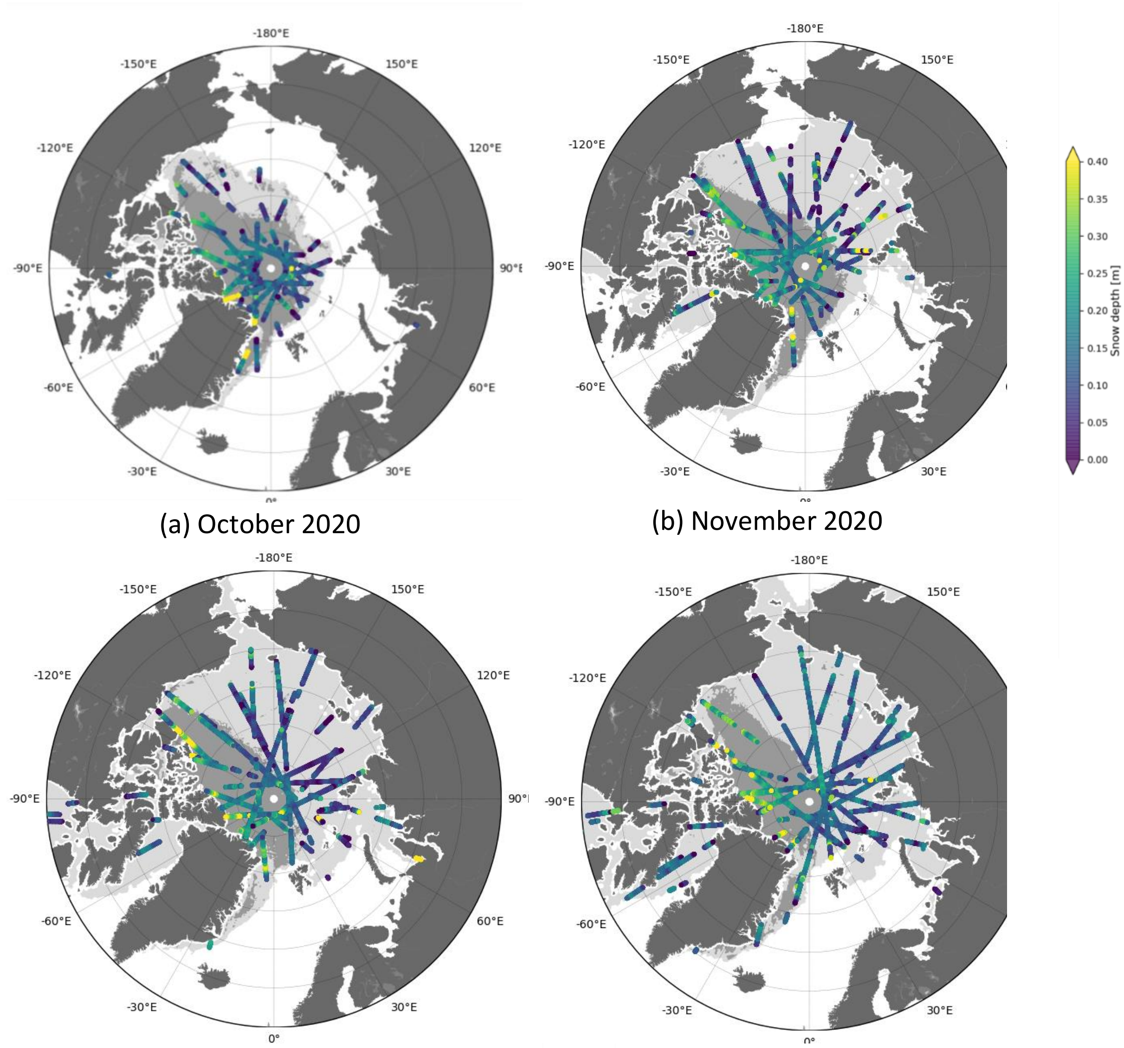
The elevation difference between IS2 and CS2 is measured through the differences of freeboard to limit the impacts of the geophysical corrections between the different products:

$$\Delta fb = fb_{la} - fb_{ku} \qquad (4)$$

If we assume that the freeboard elevation difference is only impacted by the Ku-band penetration within the snow layer and that the main scattering horizon is the snow/ice interface, we can estimate snow depth with the following formula:

$$SD = \Delta fb \times (1 + 0.51\, \rho_s)^{-1.5} \qquad (5)$$

We apply a 75km smoothing to eliminate random noise.



(a) October 2020 (b) November 2020

(c)December 2020 (d) January 2021

Fig 10. Monthly LaKu snow depth estimation measured from freeboard elevation differences for the collocated tracks

4.2 Comparison with other snow depth products

The resulting snow-depth product is compared to existing monthly snow-depth product for the period 1st of October to the 31st of January 2021. The product used in the comparisons are:

- The ASD products which used Ka-Ku elevation differences between Saral/AltiKa and CryoSat-2 (pLRM) to estimate snow-depth (Garnier et al, 2021).
- The Warren modified climatology is based on the work by Warren et al 1999.
- The AMSR product, distributed by NASA, uses the brightness temperature differences between the sea-ice and the covering snow layer to estimation snow-depth. It is only available over First-year ice.
- The PIOMAS model is a numerical model of reanalysis developed by University of Wahington

The purpose of this document is not to analysis these comparisons but to show the possible application and its potential to serve scientific objectives.

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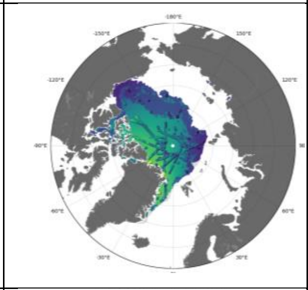
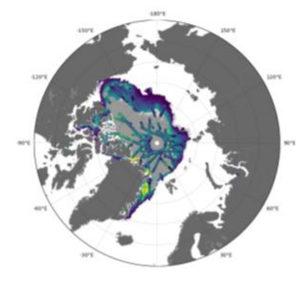
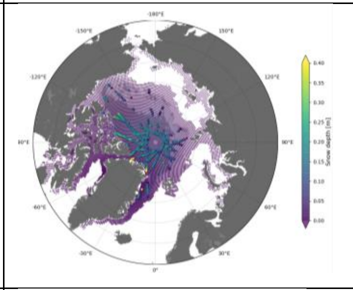
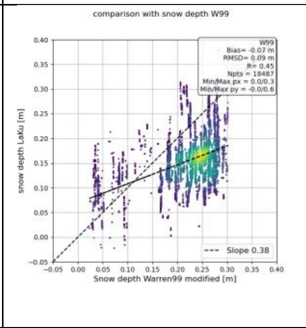
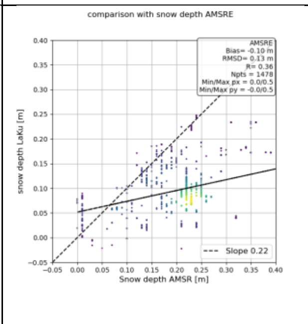
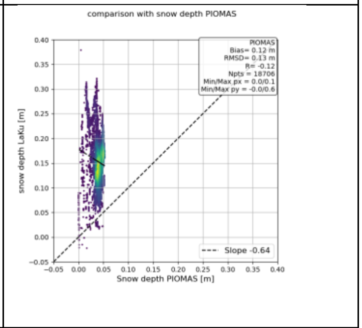
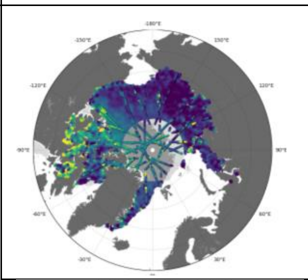
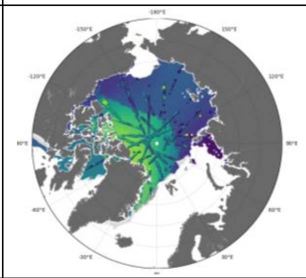
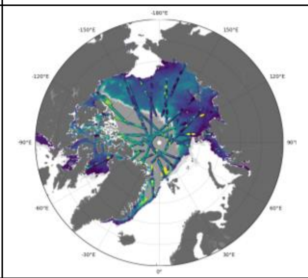
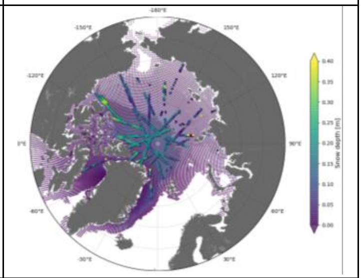
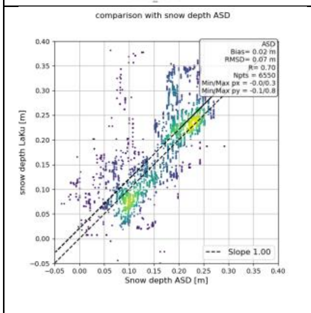
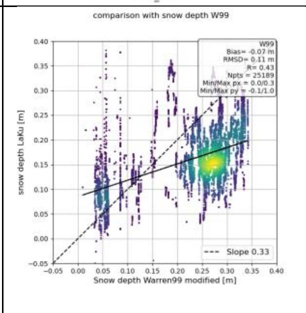
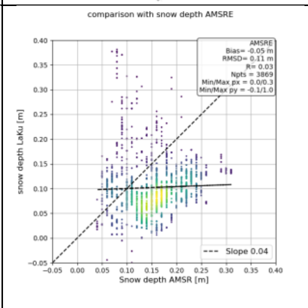
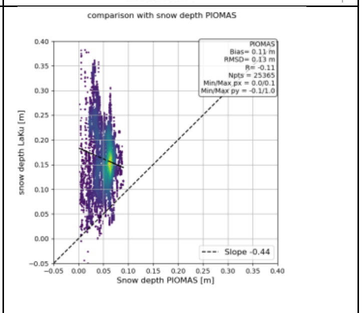
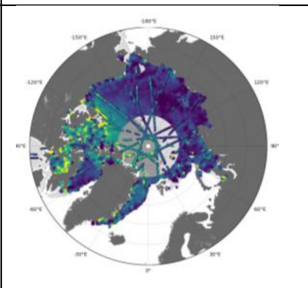
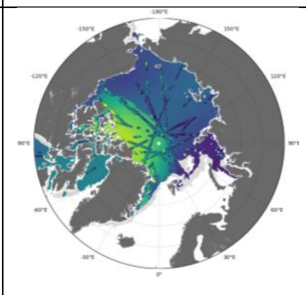
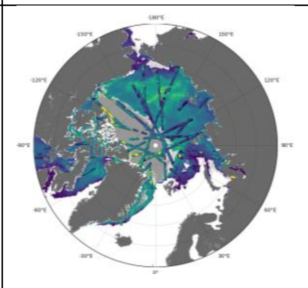
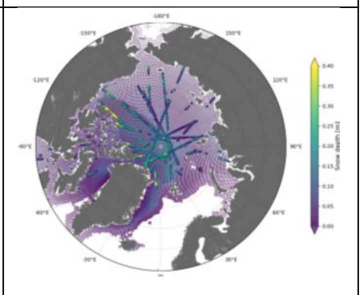
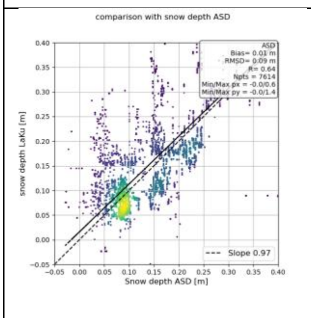
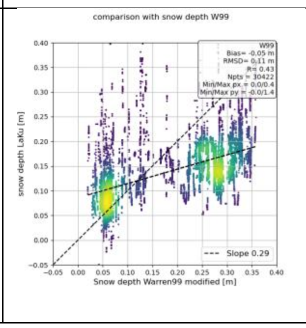
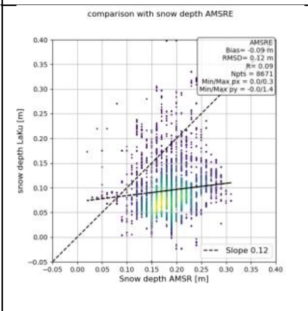
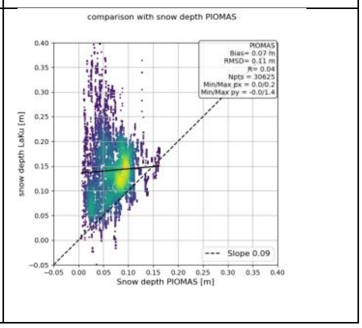
<tr><td rowspan="2">October</td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td rowspan="2">November</td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td rowspan="2">December</td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
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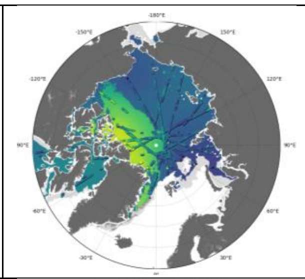
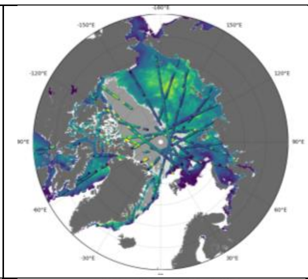
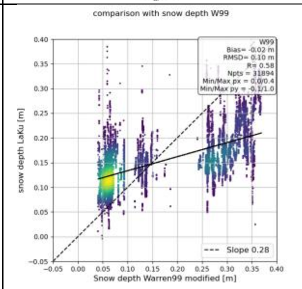
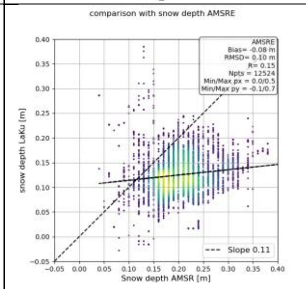
January				
				

Fig 11. Monthly comparisons of the LaKu CRYO2ICE snow-depth product with ASD, W99m, AMSR and PIOMAS.

5 Conclusions

The alignment algorithm presented here allows to gather all colocalised points between CryoSat-2 and IceSat-2 in a unique matrix and to make along-track comparison of their measurements or any required parameter. This methodology is generic and particularly well suited for the Cryo2Ice project and the numerous collocated tracks it offers between these two. The coherence of the obtained outputs is shown by means of the animation produced for outreach purpose (Fig. 9), as well as by the realistic estimation of the snow depth obtained by difference of the freeboards (Fig. 10). However, improvement can still be made in order to extend the methodology to near collocated track that can be find between most polar orbit missions (S3 series, Saral).

References

Garnier, F.; Fleury, S.; Garric, G.; Bouffard, J.; Tsamados, M.; Laforge, A.; Bocquet, M.; Fredensborg Hansen, R. M. & Rémy, F.Advances in altimetric snow depth estimates using bi-frequency SARAL/CryoSat-2 Ka/Ku measurements,The Cryosphere Discussions, Copernicus GmbH, 2021, 1-40

Hendricks, S.; Ricker, R. & Helm, V. User Guide-AWI CryoSat-2 Sea Ice Thickness Data Product (v1. 2) 2016

Laforge, A.; Fleury, S.; Dinardo, S.; Garnier, F.; Remy, F.; Benveniste, J.; Bouffard, J. & Verley, J.Toward improved sea ice freeboard observation with SAR altimetry using the physical retracker SAMOSA+ Advances in Space Research, Elsevier, 2020

Landy, J. C.; Tsamados, M. & Scharien, R. K.A facet-based numerical model for simulating SAR altimeter echoes from heterogeneous sea ice surfaces IEEE Transactions on Geoscience and Remote Sensing, IEEE, 2019

Maneewongvatana, S. & Mount, D. M.It’s okay to be skinny, if your friends are fat Center for geometric computing 4th annual workshop on computational geometry, 1999, 2, 1-8

Ricker, R.; Hendricks, S.; Helm, V.; Skourup, H. & Davidson, M.Sensitivity of CryoSat-2 Arctic sea-ice freeboard and thickness on radar-waveform interpretation The Cryosphere, Copernicus Publications, 2014, 8, 1607-1622

Tilling, R. L.; Ridout, A. & Shepherd, A.Estimating Arctic sea ice thickness and volume using CryoSat-2 radar altimeter data Advances in Space Research, Elsevier, 2018, 62, 1203-1225

Wang, X.; Key, J.; Kwok, R. & Zhang, J.Comparison of Arctic sea ice thickness from satellites, aircraft, and PIOMASdata Remote Sensing, Multidisciplinary Digital Publishing Institute, 2016, 8, 713

Warren, S. G.; Rigor, I. G.; Untersteiner, N.; Radionov, V. F.; Bryazgin, N. N.; Aleksandrov, Y. I. & Colony, R.Snow depth on Arctic sea ice,Journal of Climate, 1999, 12, 1814-1829