CryoTEMPO-EOLIS

Elevation Over Land Ice from Swath

Validation Report

Land Ice Elevation Thematic Point Product

Land Ice Elevation Thematic Gridded Product

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Approval

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1. Introduction

1.1. Purpose and Scope

The purpose of this document is to report the validation results for the operational EOLIS Land Ice SWATH CryoSat-2 Thematic Products over Greenland.

1.2. Applicable and Reference Documents

Table 1: Applicable Documents

	Document Name	Source
AD1	D4.1_UE-ESA-STSE_CryoTop_ATBD_02_signed	UoE
AD2	CryoSat-2 ThEMmatic PrOducts SWATH Cryo-TEMPO Statement of Work, Issue Date 09/07/2018 Issue 3 Rev 3	ESA
AD3	CryoSat-2 ThEMmatic PrOducts SWATH Cryo-TEMPO Proposal, Issue: 1.c, 6 May 2019	SWATH Team

Table 2: Reference Documents

	Document Name
RD. 1	CryoTop Product Validation Report, UE-ESA-STSE_CryoTop_PVR v0.4
RD. 2	CryoVEx campaign data sets: https://earth.esa.int/web/guest/campaigns
RD. 3	IceBridge ATM data sets http://nsidc.org/data/docs/daac/icebridge/ilatm2/index.html
RD. 4	GLAS/ICESat 1 km Laser Altimetry Digital Elevation Model of Greenland, http://nsidc.org/data/nsidc-0305
RD. 5	ATLAS/ICESat-2 L3A Land Ice Height, Version 1 https://nsidc.org/data/atl06
RD. 6	GIMP Digital Elevation Model http://bprc.osu.edu/GDG/gimpdem.php
RD. 7	Krabill, W. B.: IceBridge ATM L1B Qfit elevation and return strength, (23 March 2009 – 21 April 2010), Digital Media, National Snow and Ice Data Center, Boulder, Colorado USA, 2009.
RD. 8	Krabill W.B., W. Abdalati, E.B. Frederick, S.S. Manizade, C.F. Martin, J.G. Sonntag, R.N. Swift, R.H. Thomas, J.G. Yungel Aircraft laser altimetry measurement of elevation changes of the Greenland Ice Sheet: technique and accuracy assessment. J. Geodynamics 34, 357-376. 2002
RD. 9	Schenk, T., B. M. Csatho and D-C. Lee, Quality control issues of airborne laser ranging data and accuracy study in an urban area. International Archives of Photogrammetry and Remote Sensing, 32(3W14), 101-108, 1999.
RD. 10	Martin, C. F., Krabill, W. B., Manizade, S., Russell, R., Sonntag, J. G., Swift, R. N., and Yungel, J. K.: Airborne Topographic Mapper Calibration Procedures and Accuracy Assessment, NASA Technical Reports, Vol. 20120008479(NASA/TM-2012-215891, GSFC.TM.5893.2012), http://hdl.handle.net/2060/20120008479, 32 pp., Natl. Aeronaut. and Space Admin.,Washington, D. C, 2012.
RD. 11	Kurtz, N. T., Farrell, S. L., Studinger, M., Galin, N., Harbeck, J. P., Lindsay, R., Onana, V. D., Panzer, B., and Sonntag, J. G.: Sea ice thickness, freeboard, and snow depth products from Operation IceBridge airborne data, The Cryosphere, 7, 1035-1056, doi:10.5194/tc-7-1035-2013, 2013.
RD. 12	Dimarzio, J. P.; Brenner, A. C.; Fricker, H. A.; Schutz, B. E.; Shuman, C. A.; Zwally, H. J. Digital Elevation Models of the Antarctic and Greenland Ice Sheets from ICESat, American Geophysical Union, Fall Meeting 2005
RD. 13	Zwally, H. J. and A. C. Brenner. 2001. "Ice sheet dynamics and mass balance." In: Satellite Altimetry and Earth Science, L-L. Fu and A. Cazenave, Eds., Academic Press, Ch. 9, 351-369

RD. 14	ICESat-2 Algorithm Theoretical Basis Document for Land Ice Along-Track Height (ATL06) https://icesat-2.gsfc.nasa.gov/sites/default/files/page_files/ICESat2_ATL06_ATBD_r001.pdf
RD. 15	Anna E. Hogg, Andrew Shepherd, Noel Gourmelen, Marcus Engdal (2016). "Grounding line migration from 1992 to 2011 on Petermann Glacier, North-West Greenland" (PDF). doi:10.1017/jog.2016.83
RD. 16	Joughin I.; Abdalati W.; Fahnestock M. (2004). "Large fluctuations in speed on Greenland's Jakobshavn Isbrae glacier". Nature. 432 (7017): 608–610. Bibcode:2004Natur.432..608J. doi:10.1038/nature03130. PMID 15577906
RD. 17	"History Repeating Itself at Antarctica's Fastest-Melting Glacier". LiveScience. 2014.
RD. 18	Rignot, E. (2008). "Changes in West Antarctic ice stream dynamics observed with ALOS PALSAR data". Geophysical Research Letters. 35 (12): L12505. Bibcode:2008GeoRL..3512505R. doi:10.1029/2008GL033365.
RD. 19	Howat, I. M., Porter, C., Smith, B. E., Noh, M.-J., and Morin, P.: The Reference Elevation Model of Antarctica, The Cryosphere, 13, 665-674, https://doi.org/10.5194/tc-13-665-2019, 2019.
RD. 20	Gourmelen, N, Escorihuela, M, Shepherd, A, Foresta, L, Muir, A, Garcia-Mondejar, A, Roca, M, Baker, S & Drinkwater, MR 2017, 'CryoSat-2 swath interferometric altimetry for mapping ice elevation and elevation change', Advances in Space Research. https://doi.org/10.1016/j.asr.2017.11.014

1.3. Acronyms and Abbreviations

DEM – Digital Elevation Model
ESA – European Space Agency
InSAR – Interferometric Synthetic Aperture Radar
OIB – Operation IceBridge
POCA – Point of closest approach
RMSE – Root Mean Squared Error
STSE – Science, Technology, Society and Environment education
UTC – Coordinated Universal Time

2. Strategy

2.1. Overview

The verification and validation activity has been designed in two different steps. First the verification process consists on a comparison between the Swath Thematic product L2S and a development independent implementation is performed. Breakpoint products may be needed in the cases where internal parameters need to be cross compared.

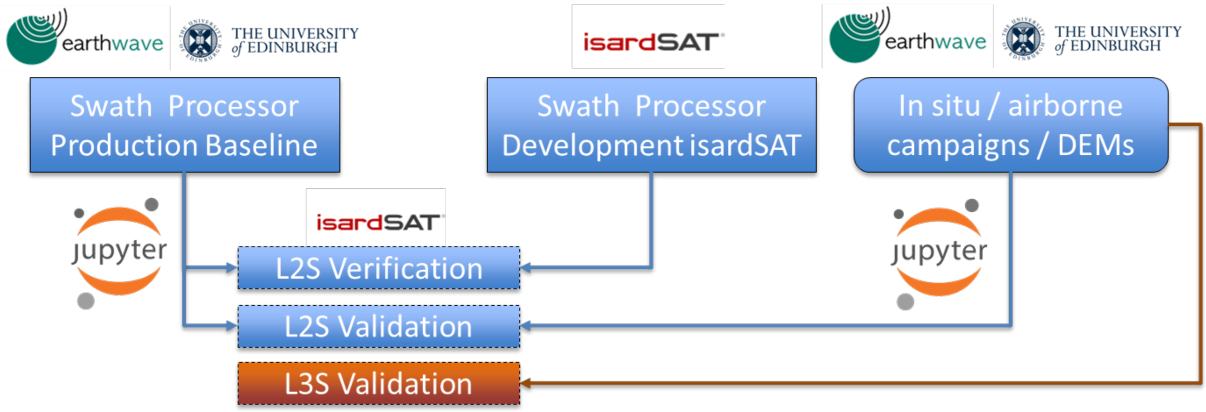


Figure 1: Verification and validation system overview

Secondly, the L2S and the L3S gridded products will be compared against in-situ, airborne and other datasets derived in the dataset survey. The validation exercise is an updated version of the one designed for the CryoTop project (RD. 1) including new validation datasets from ICESat-2 and new airborne campaigns and also new location areas.

Our main validation test sites are located in the ice margins of Greenland and concern the glaciers of Petermann [79° to 81.3° N; 60° to W49° W] and Jakobshavn [68.8° to 69.6° N; 51 to 47° W].

2.2. Methodology

The main validation dataset is for swath data is composed of data provided by the IceBridge airborne campaigns and ICESat-2 satellites data.

Gridded products will be validated against most actual DEMs available, currently GLAS DEM and Artic DEM for Greenland and REMA for Antarctica.

In all cases, we have built a SWATH match-up database with the validation data. Elevations have been considered to match if their respective pixel's centres were within +/- 50m for the validation data. We have computed the difference between the Swath and the validation collocated points and performed a statistical analysis of the distribution of the differences computing the mean, sigma and root mean squared error (RMSE).

2.3. Validation datasets

2.3.1. IceBridge airborne campaigns

The IceBridge campaigns are a series of airborne missions to map Arctic and Antarctic ice sheets with laser altimetry since 2009 (filling the gap between ICESat and ICESat-2) (see Figure 2 for the Arctic campaigns). We have used the IceBridge ATM L2 Icessn Elevation, Slope, and Roughness product, Version 1. The data set contains resampled and smoothed elevation acquired using the NASA Airborne Topographic Mapper (ATM). The ATM is a 532 nm wavelength conically scanning laser altimeter, combined with a differential GPS system for aircraft positioning and an inertial navigation system (INS) to measure aircraft orientation (Figure 3). The laser range, GPS position, and INS orientation measurements are used to assign three-dimensional geographic coordinates to the point where each laser pulse reflects from the surface. The ATM data are referenced to the ITRF-2005 reference frame and projected onto the WGS-84 ellipsoid.

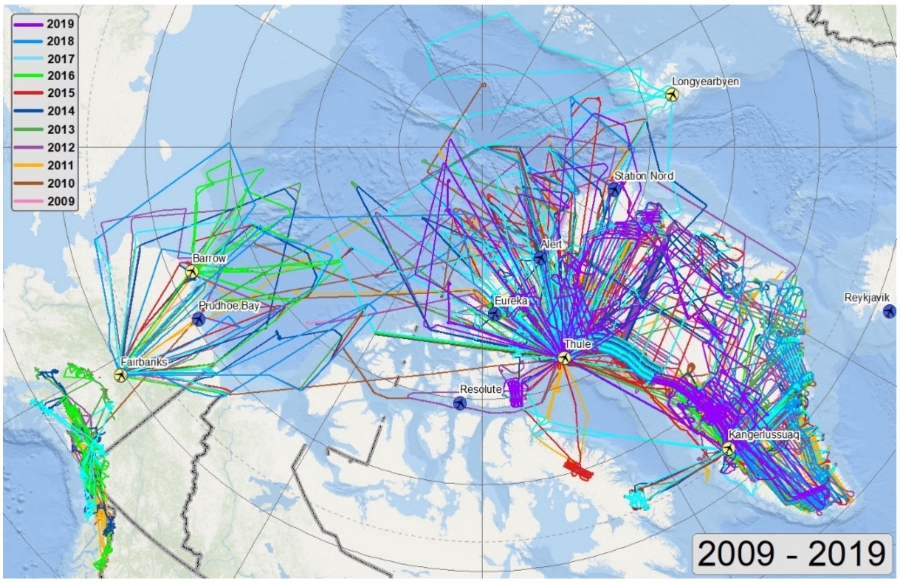


Figure 2: Icebridge airborne flights over Greenland and Alaska between 2009-2019

The 15-degree scanner used during the missions yields a measured swath width of approximately half of the aircraft's altitude above the surface. The footprint size of each individual elevation measurement is 1 m, which is set by the laser beam divergence [RD. 7]. The spatial resolutions of the ATM laser footprint and leading edge detection steps are ~1 m for the nominal flight altitude (460 m) of the IceBridge data set. ATM L2 is gridded at a sample width of 80 m with a 40 m spacing along track.

The system is calibrated using independent ranging measurements with the system on the ground, and by overflights of pre-surveyed ground areas. Absolute elevation accuracy from the ATM is usually about 10 cm or better [RD. 8] with geolocation accuracies of better than 1 m [RD. 9]. Specifically, for the IceBridge campaigns, RD. 10 estimate the parameters of the ATM system to be (1) 74 cm horizontal accuracy, (2) 6.6 cm vertical accuracy, and (3) 3 cm vertical precision [RD. 11]. Further documentation and data are available at RD. 3.

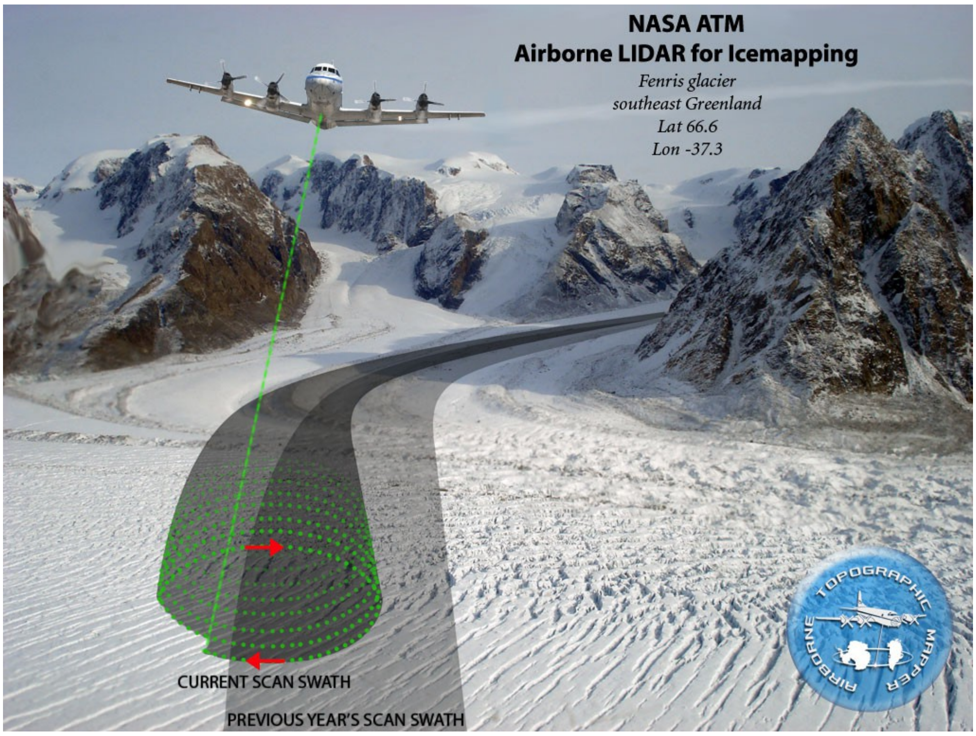


Figure 3: ATM laser operation example over the Ferris Glacier, Alaska.

2.3.2. Artic DEM Greenland

ArcticDEM is a National Geospatial-Intelligence Agency (NGA) and National Science Foundation (NSF) public-private initiative to automatically produce a high-resolution, high-quality digital surface model (DSM) of the Arctic using optical stereo imagery, high-performance computing, and open source photogrammetry software. The product is a collection of time-dependent DEM strips and a seamless terrain mosaic that can be distributed without restriction.

The mosaic product version 5 of ArcticDEM (Porter et al., 2018) covers most of the GrIS. The mosaic is constructed from Digital Globe's WorldView stereoscopic images, with images acquired between 2008 and 2016. IceSat-2 elevation are used to improve the absolute vertical accuracy of the product. The finest resolution of the mosaic product is 2m.

2.4. Validation areas

2.4.1. Peterman Glacier

Peterman glacier (80°45′N 60°45′W, Figure 5) consists of a 70 km long and 15 km wide floating ice tongue whose thickness changes from about 600 m at its grounding line to about 30–80 metres at its front. The grounding line is relatively stable with on average 470 m variation over the period 1992 to 2011. This indicates that the glacier was dynamically stable [RD. 15].

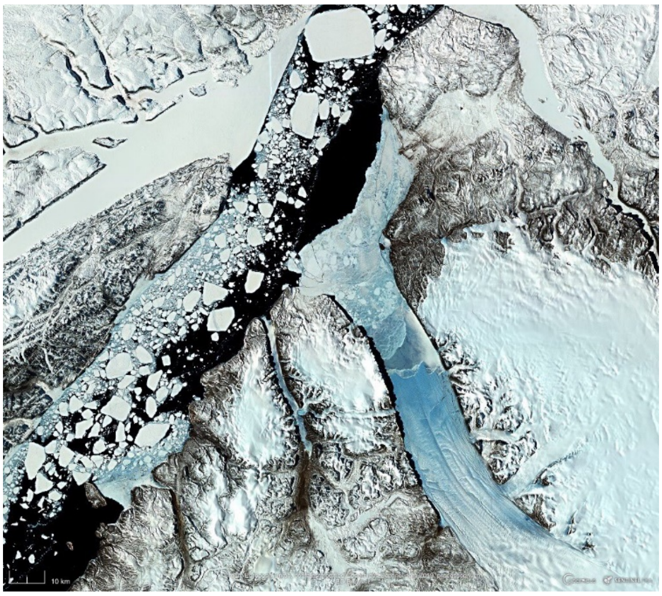


Figure 4: Sentinel 2 image of the Petermann glacier (at the bottom right side), 23/05/2019

The iceBridge airborne campaigns in the las 9 years are depicted in Figure 5.

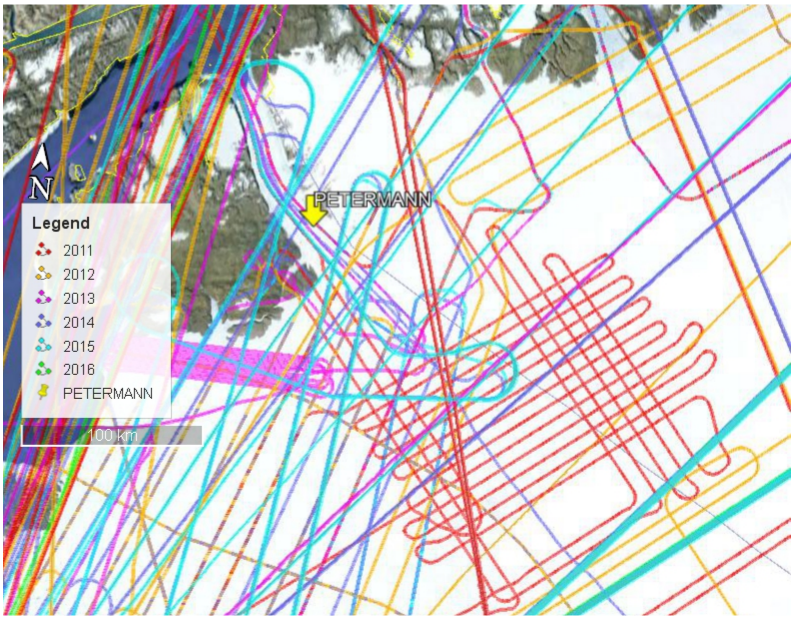


Figure 5: IceBridge campaigns over Petermann glacier.

2.4.2. Jakobshavn Glacier

Jakobshavn Glacier (69°10'N 49°50'W, Figure 6) drains 6.5% of the Greenland ice sheet [RD. 16] and produces around 10% of all Greenland icebergs. Some 35 billion tonnes of icebergs calve off and pass out of the fjord every year. Icebergs breaking from the glacier are often so large (up to 1 km in height) that they are too tall to float down the fjord and lie stuck on the bottom of its shallower areas, sometimes for years, until they are broken up by the force of the glacier and icebergs further up the fjord. Studied for over 250 years, the Jakobshavn Glacier has helped develop modern understanding of climate change and icecap glaciology. It is greater than 65 km

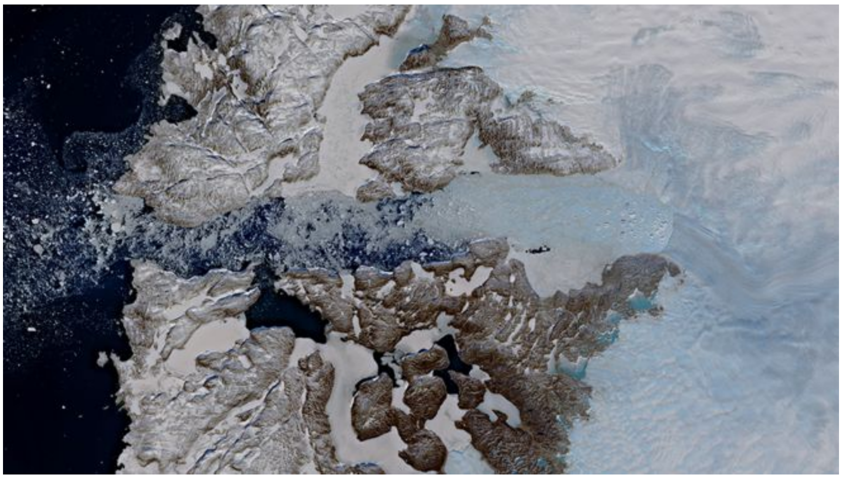


Figure 6: Sentinel 2 image of the Jacobshavn glacier, April 2019

The iceBridge airborne campaigns in the las 9 years are depicted in Figure 7.

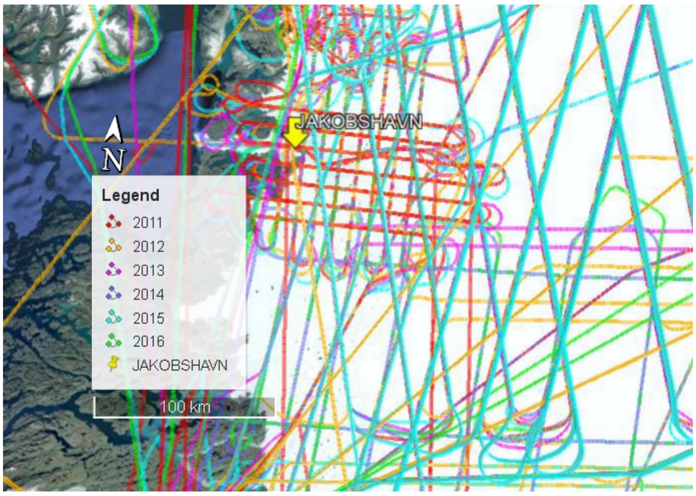


Figure 7: IceBridge campaigns over Jacobshavn glacier.

3. Results

3.1. L2Swath Point verification

Single swath point products over the validation areas have been compared with alternative products created by isardSAT swath development processor.

In Figure 8 and Figure 9 a comparison of the output for both processors is presented. As the processors are not identical, some small differences can be seen. The elevations from the official processor are smoother and in some areas a bit more populated. The collocated comparison shows a good agreement and the differences are mainly related to the phase model correction not implemented in the alternative processor and outlier rejection. The mean bias for Petermann is 1.95 meters.

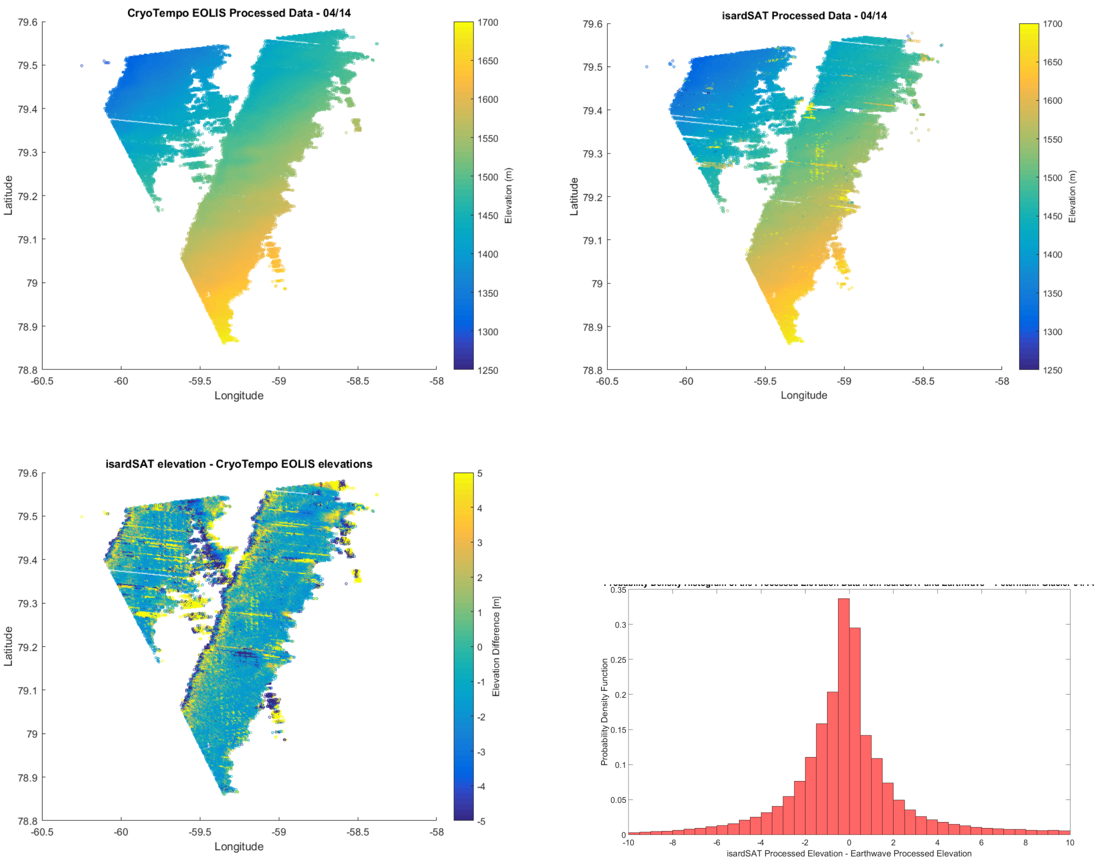


Figure 8: Official and alternative Swath products over the Peterman glacier area and their difference

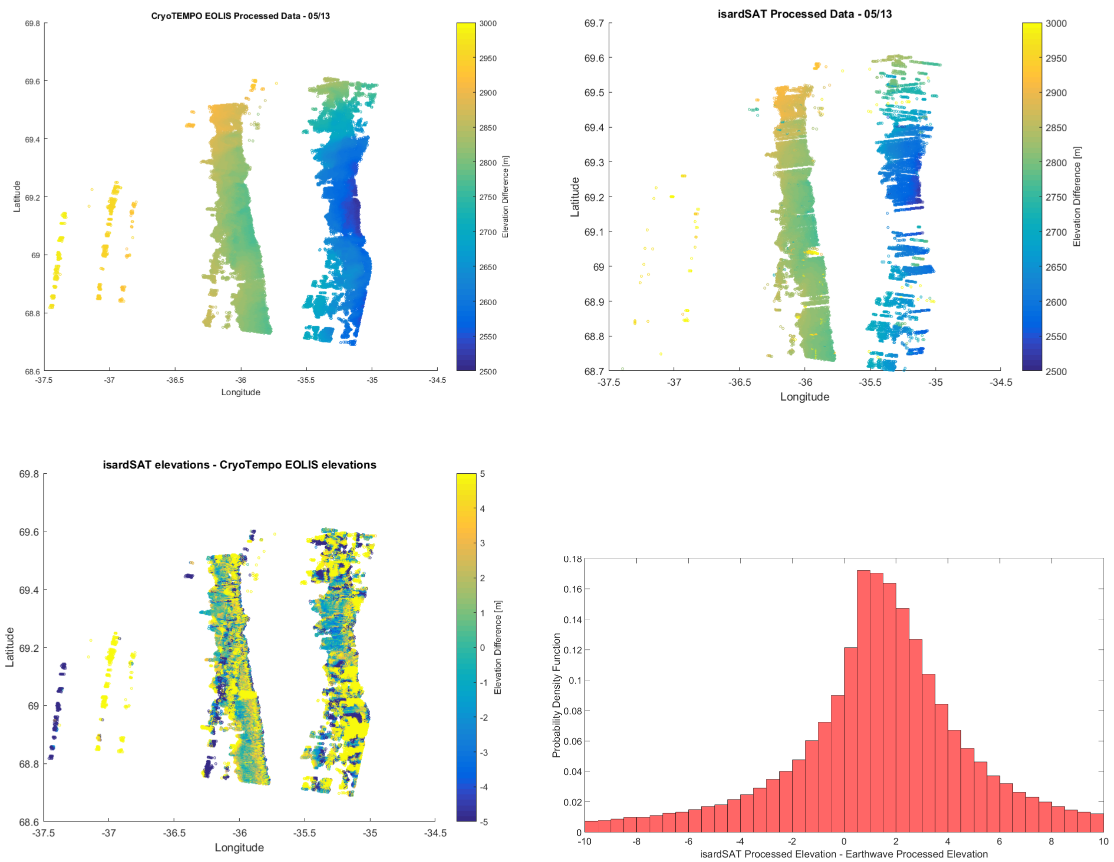


Figure 9: Official and alternative Swath products over the Jacobshavn glacier area and their difference

3.2. L3Swath Gridded validation

3.2.1. Comparison with OIB

The Swath gridded products have been compared with Operation IceBridge (OIB) airborne campaign elevation. The difference is shown in Figure 10 and Figure 11 and the numerical results are summarised in Table 3 and Table 4.

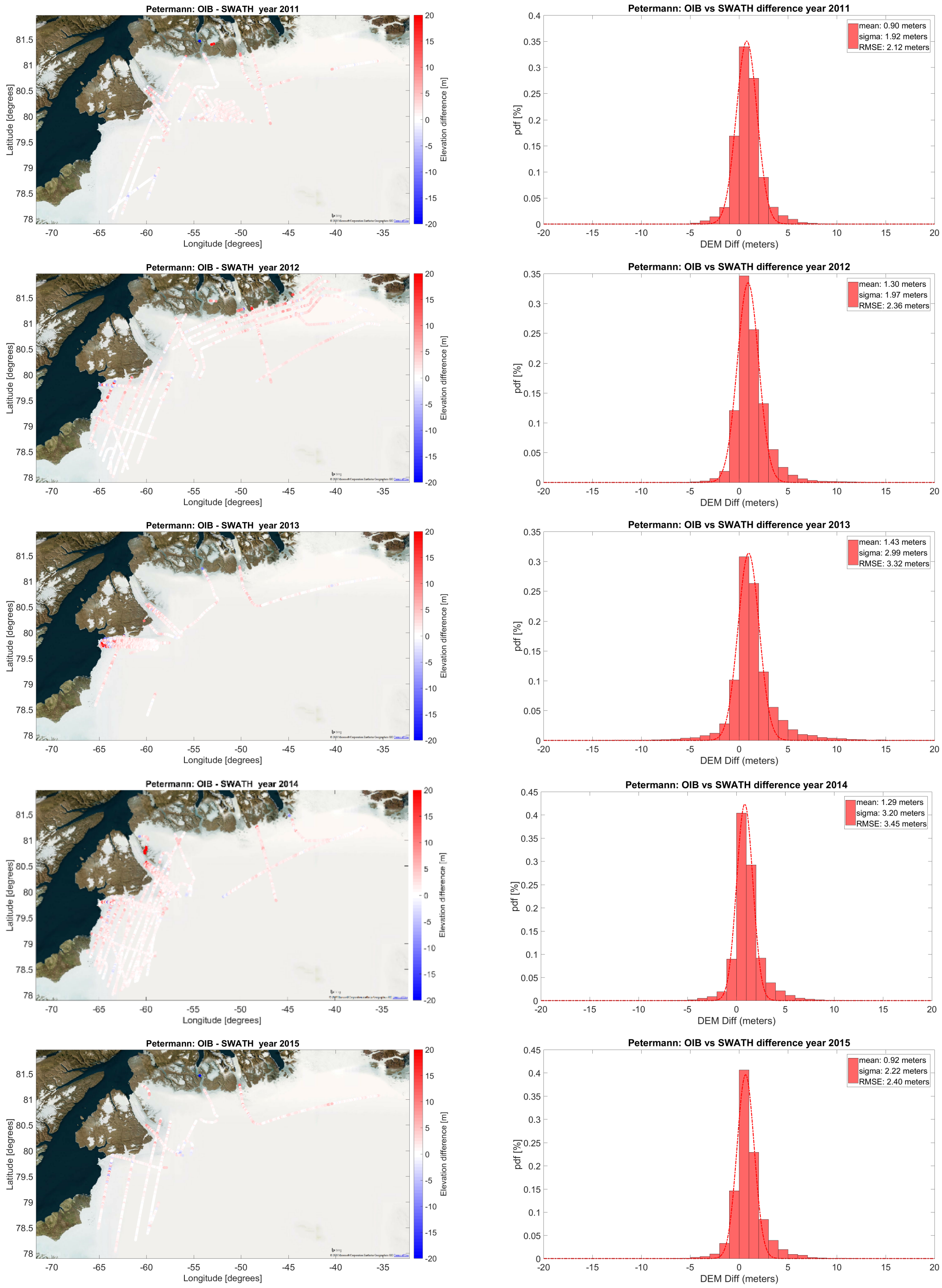


Figure 10: OIB difference evolution 2011-2015 for the gridded products over Petermann glacier.

Table 3: Petermann numerical results

Year	OIB points	OIB diff mean [m]	OIB diff sigma [m]	OIB diff RMSE [m]
2011	72258	0.90	1.92	2.12
2012	62500	1.30	1.97	2.36
2013	37033	1.43	2.99	3.32
2014	87128	1.29	3.20	3.45
2015	31883	0.92	2.22	2.40
Mean [m]		**1.17**	**2.46**	**2.73**

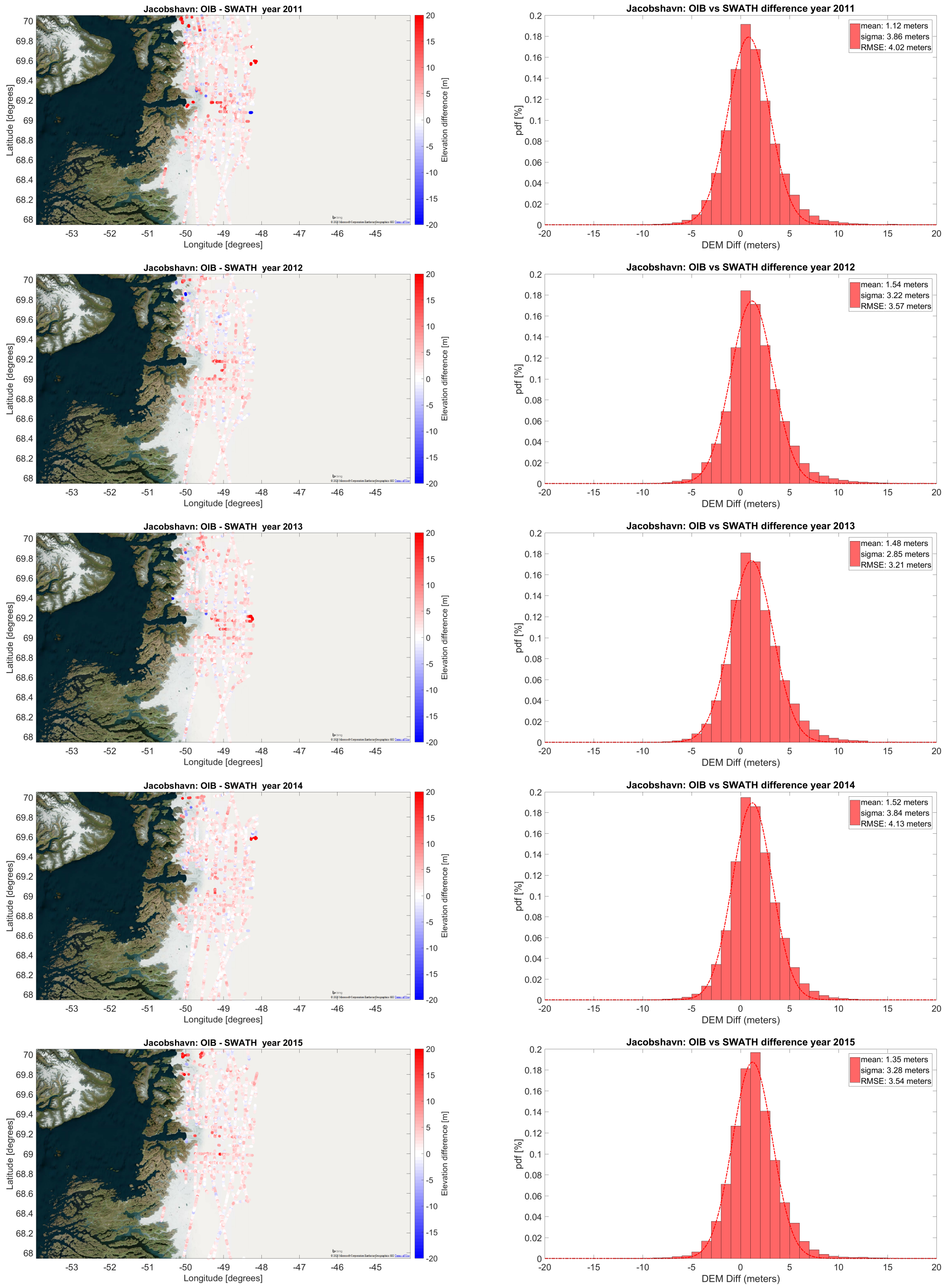


Figure 11: OIB difference evolution 2011-2015 for the gridded products over Jacobshavn glacier.

Table 4: Jacobshavn numerical results

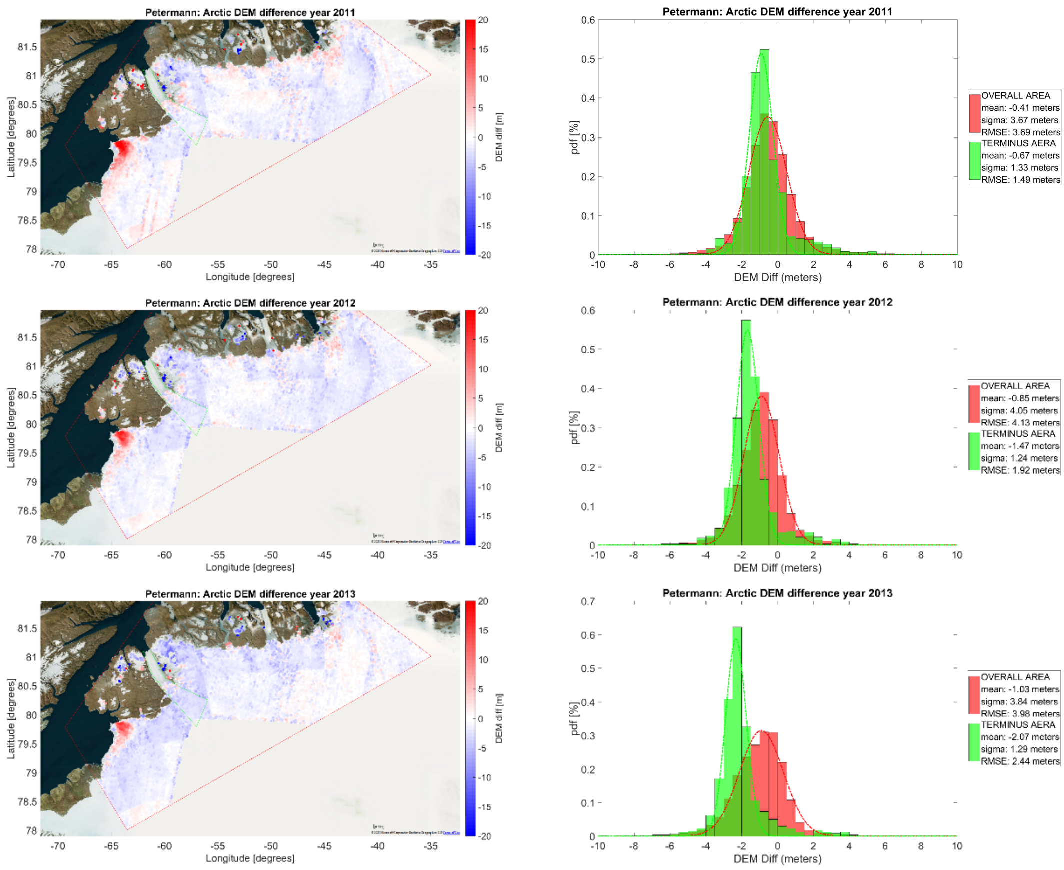
Year	OIB points	OIB diff mean [m]	OIB diff sigma [m]	OIB diff RMSE [m]
2011	182858	1.12	3.86	4.02
2012	122219	1.54	3.22	3.57
2013	95834	1.48	2.58	3.21
2014	124329	1.52	3.84	4.13

Year	OIB points	OIB diff mean [m]	OIB diff sigma [m]	OIB diff RMSE [m]
2015	112722	1.35	3.27	3.54
Mean [m]		1.40	3.41	3.69

3.2.2. Comparison with ArcticDEM

The Swath gridded products have been compared with the Arctic DEM after resampling and collocating it to 2km. The DEM difference evolution between 2011 and 2015 is shown in Figure 12 and Figure 13 for Petermann and Jacobshavn glaciers. The results have been split in the particular ones close to the terminus of the glacier (presented in green) and the overall ones (in red). Two different effects can be appreciated. The first one are the stripped lines in the south west section of the image. The second one is the "patched" bias caused by the Arctic DEM tiling residual effect.

The 2011 to 2015 change in elevation difference is explained by the fact that Arctic DEM elevation is representative of ice conditions in 2015, due to the timing of WorldView data acquisitions. It is also interesting to note that despite CryoSat data being used for vertical coregistration of the ArcticDEM strips, we observe elevation bias between the EOLIS DEMs and ArcticDEM.



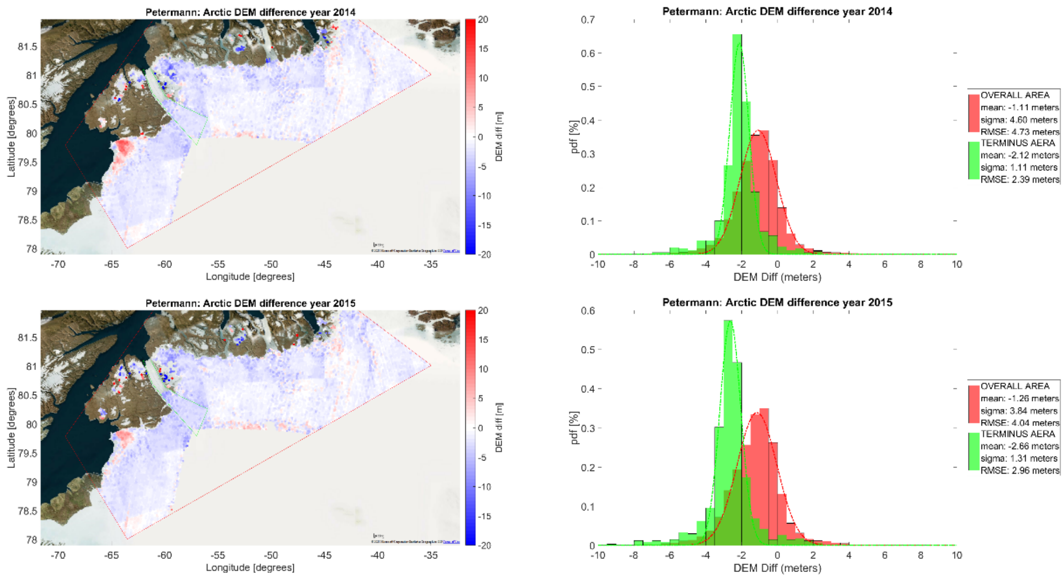
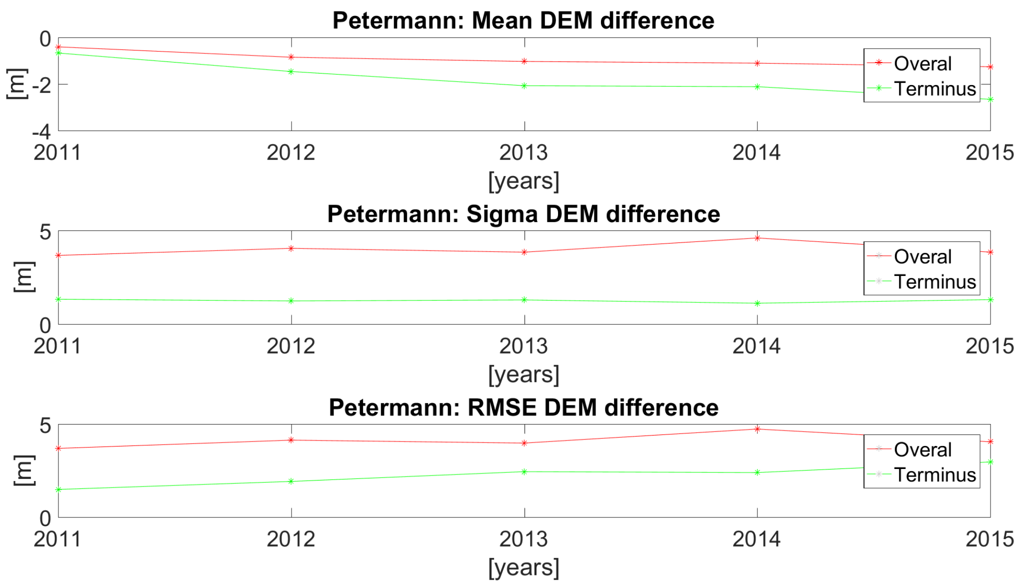


Figure 12: DEM difference evolution 2011-2015 for the gridded products over Petermann glacier. The overall results are shown in red and the ones around the terminus in green.

Table 5: Petermann numerical results

Year	Overall area			Terminus area		
	DEM diff mean [m]	DEM diff sigma [m]	DEM diff RMSE [m]	DEM diff mean [m]	DEM diff sigma [m]	DEM diff RMSE [m]
2011	-0.41	3.67	3.69	-0.67	1.33	1.49
2012	-0.85	4.05	4.13	-1.47	1.24	1.92
2013	-1.03	3.84	3.98	-2.07	1.29	2.44
2014	-1.11	4.60	4.73	-2.12	1.11	2.39
2015	-1.26	3.84	4.04	-2.66	1.31	2.96
Mean [m]	-0.93	4.00	4.12	-1.80	1.25	2.24
Trend [m/y]	-0.19	0.09	0.13	-0.46	-0.02	0.34



Petermann glacier swath gridded products show a very good agreement with Arctic DEM, with a uniform RMSE of 4.12 meters and a very small variation over time.

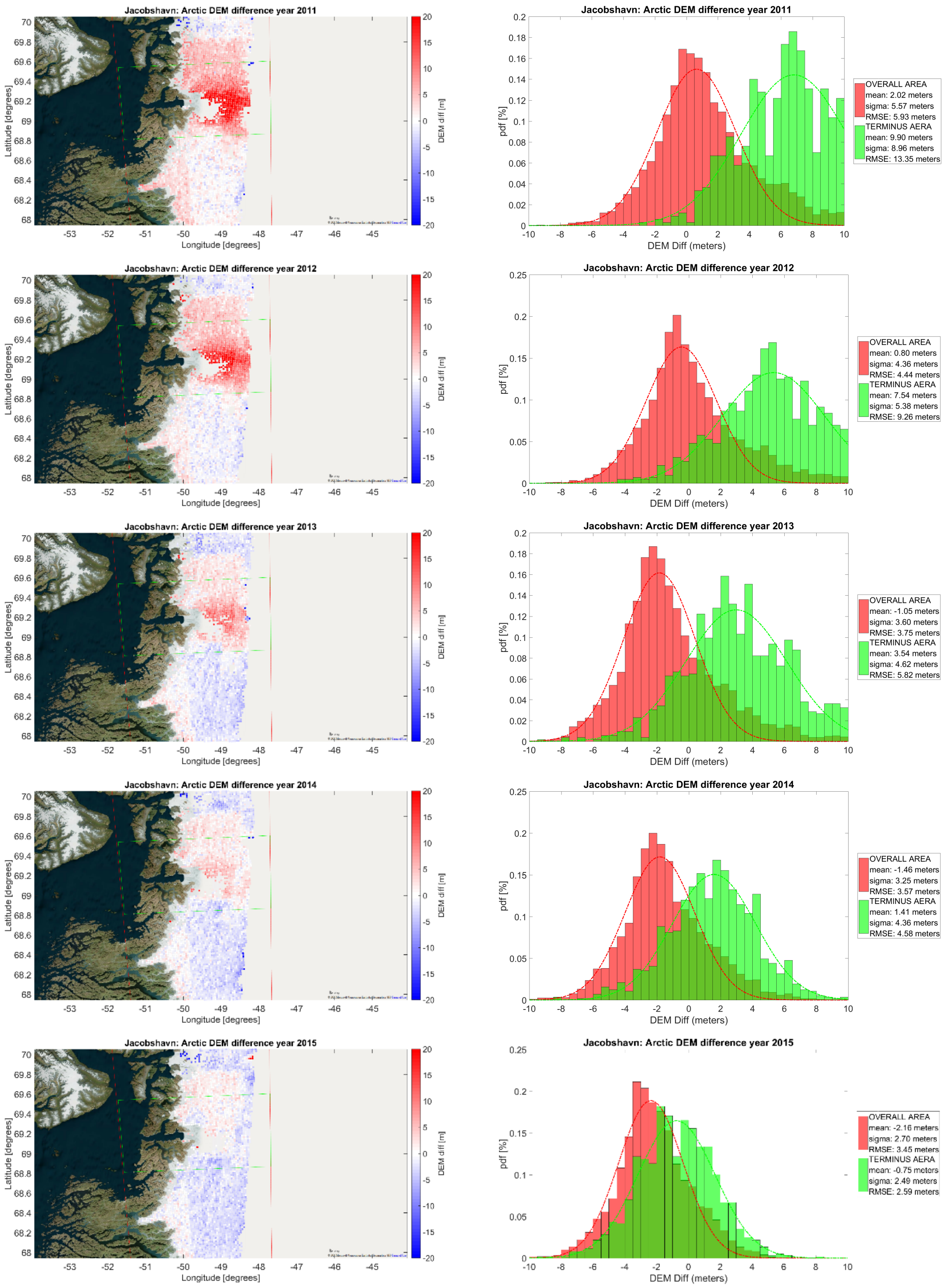
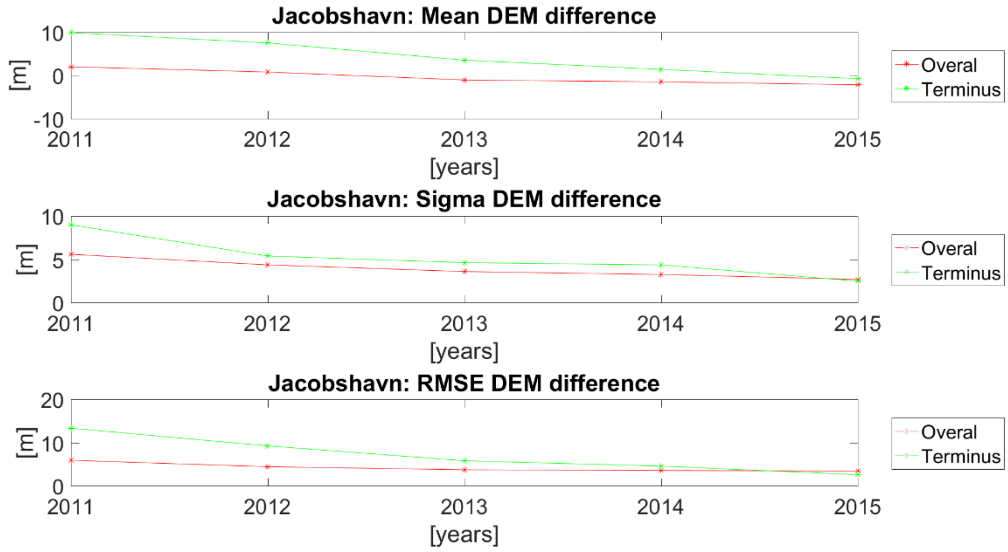


Figure 13: DEM difference evolution 2011-2015 for the gridded products over Jacobshavn glacier. The overall results are shown in red and the ones around the terminus in green.

Table 6: Jacobshavn numerical results

Year	Overall area			Terminus area		
	DEM diff mean [m]	DEM diff sigma [m]	DEM diff RMSE [m]	DEM diff mean [m]	DEM diff sigma [m]	DEM diff RMSE [m]
2011	2.02	5.57	5.93	9.90	8.96	13.35
2012	0.80	4.36	4.44	7.54	5.38	9.26
2013	-1.05	3.60	3.75	3.54	4.62	5.82
2014	-1.46	3.25	3.57	1.41	4.36	4.58
2015	-2.16	2.70	3.45	-0.75	2.49	2.59
Mean [m]	**-0.37**	**3.90**	**4.23**	**4.33**	**5.16**	**7.12**
Trend [m/y]	**-1.06**	**-0.68**	**-0.58**	**-2.74**	**-1.39**	**-2.61**



Jacobshavn glacier swath gridded products show a very good agreement with Arctic DEM overall. Looking at the terminus area, the best agreement is found in year 2015 and a RMSE trend of 2.61 meters/year. The RMSE overall is 4.23 meters (quite similar with the 4.13 meters from Jacobshavn).

These ratios are well aligned with other studies presented (Helm 2014[1], Simonsen 2017[2])

3.2.3. Additional analysis

Small non-uniformities can be seen when computing the differences of the Swath gridded products and the DEM diff over time (2011-2012, 2012-2013, and so on). In Figure 14, for the Petermann area, it can be appreciated a few strip lines in the south west section . On the contrary , for the Jacobshavn area, in Figure 15, the evolution of the gridded product doesn't seem to have any kind of unreasonable singularity that cannot be associate to the dynamics of the region.

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[1] Helm, V., Humbert, A., and Miller, H.: Elevation and elevation change of Greenland and Antarctica derived from CryoSat-2, The Cryosphere, 8, 1539-1559, doi:10.5194/tc-8-1539-2014, 2014

[2] Simonsen, Sebastian B., and Louise Sandberg Sørensen. "Implications of changing scattering properties on Greenland ice sheet volume change from Cryosat-2 altimetry." Remote Sensing of Environment 190 (2017): 207-216.

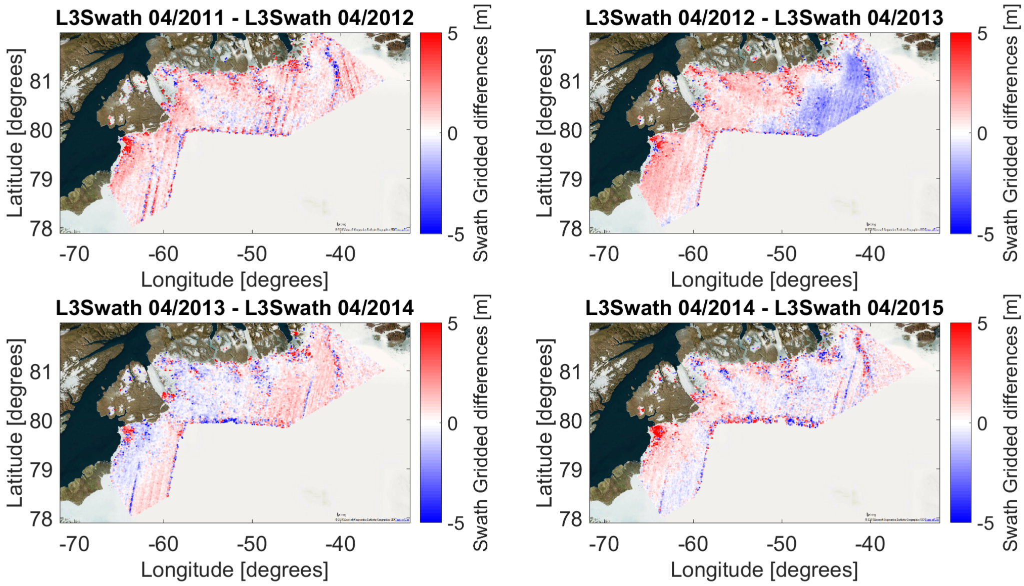

Figure 14: Petermann glacier Swath gridded differences between each year.

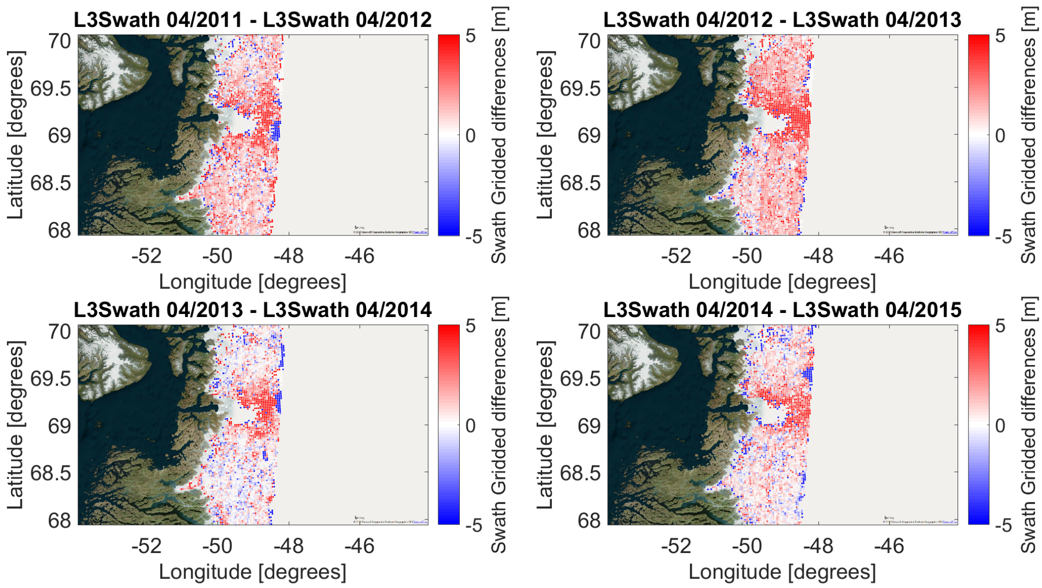

Figure 15: Jacobshavn glacier Swath gridded differences between each year.

4. Contacts

Feedback or questions about the CryoTEMPO-EOLIS Thematic Products is welcomed. Please use the following contact details:

e-mail: support@cryotempo-eolis.org

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