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Improved retrieval of land ice topography from CryoSat-2 data and its impact for volume-change estimation of the Greenland Ice Sheet

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S1 – Phase filtering and ambiguity corrections

To determine the effects of the phase filtering and phase ambiguity corrections steps in the SIN-processing on accuracy and precision, a case study was performed over Barnes Ice Cap, Nunavut, Canada. The Barnes Ice Cap was chosen as there was an extensive IceBridge ATM campaign flown there in 2011. The analysis was divided up into four parts. First, both corrections were applied in the processing and compared to ATM elevations within 50 m of each ATM point; second, the phase ambiguity correction was omitted; third, the phase filtering was omitted; and fourth, both corrections were omitted.

The case study was carried out using five months of CryoSat-2 data between February and June 2011. The number of months was selected to maximize the number of comparison samples on this relatively small ice cap. From the statistical analysis (Table S1), we observed that the phase-filtering step accounted for most of the improvement, followed by the phase ambiguity correction.

S2 – Implementation and selection of surface-fit algorithm

For this study a point-by-point (PP) elevation changes estimation procedure was used to derive elevation changes following the approach of Wouters et al. (2015). This solution produced significantly better results than solving for the elevation change rate on a regular grid (RG), as employed by McMillan et al. (2014). The two methods were contrasted by gridding the PP estimated elevation changes onto a regular grid with 1 km resolution and comparing to RG-derived changes of the same resolution. The quality of the solutions was then estimated by comparing to ATM elevation changes over the same time period by means of bilinear interpolation. This produced agreements of 0.09 ± 0.13 m a^{-1} and 0.14 ± 0.21 m a^{-1} for the PP and RG methods respectively, producing a difference in RMSE of 36%. The PP method further exhibited an 80% lower sensitivity to surface slope compared to the RG method.

The higher locality of the solution in the PP method allows for a locally- and globally-higher SNR compared to the RG method. This is due to the fact that the PP method captures the local underlying topography in the solution to a higher degree, making it less sensitive to small-scale surface undulations. In comparison, the grid-based methods solve for the local topography over the entire grid cell area (1 km in this case). Statistically, one might argue that the PP approach has the potential to introduce spatial correlations into the solution; however, studies of the correlation length between the two products compared to ATM elevation change residuals, does not support this argument.

In conclusion, we recommend the use of the point-based solution method (PP) over the grid-based methods (RG), as they provide better agreement with ATM-derived elevation changes, despite the drawback of higher computational cost.

S3 – Validation of surface elevations

We used ATM data spanning four separate years of spring campaigns, largely in the month of April. The estimated surface elevations from the CryoSat-2 mission for both the ESA L2 product and our processing was compared using a search radius of 50 m around each ATM location. The difference between the two measurements was computed as CryoSat-2 minus ATM-formed elevation residuals. The residuals were then edited for outliers using an iterative 3-sigma filter, which stopped once the difference in standard deviation was less than 2%. The results of the surface validation procedure are provided in Tables S2 and S3 and are separated according to their individual modes.

The quality of the four DEMs used in our study (Table S4) was estimated in approximately the same manner as the individual point observations described above, although bilinear interpolation was used instead to estimate the DEM surface elevation at each ATM location. Statistics were then computed for each ATM campaign (Table S4).

S4 – Validation of surface elevation changes

Due to the different time periods used the elevation change errors were multiplied with their individual time spans as elevation change errors should be proportional to the uncertainty in the repeat elevation measurements divided by the time between acquisitions. For the surface-fit method a search radius of 175 m was used which is similar resolution as the ATM elevation changes of 250x250 m (Krabill, 2014a) (product IDHDT4.001). The surface-fit method produces the largest number of validation samples for all time periods. Comparing these results with the crossover method, which used the same search radius for the validation, we found a lower number of validation samples due to the lower spatial coverage produced by this method, further aggravated by the availability of only one time-period for the validation procedure and spatial sampling.

S5 – Determination of correlation length using semi-variogram analysis

To determine the correlation length of the estimated surface elevation changes to compute the error budget we computed semi-variograms for both the LRM and SIN-mode for both products, as seen in Figure S1. The semi-variogram was estimated from the elevation change residuals between CryoSat-2 derived elevation changes and ATM. To merge residuals estimated from many different time periods (2011-2013, 2011-2014, 2012-2014) each residual dataset was multiplied with its corresponding time span. The merged dataset was then used to compute the overall semi-variogram, which is seen in Figure S1. As spatial patterns of elevation change are variable (i.e. topography dependent) the semi-variogram was computed separately for the SIN and LRM-mode. From the individual semi-variograms we estimate a correlation length for the LRM data of ~75 km and for SIN ~100 km.

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Figures

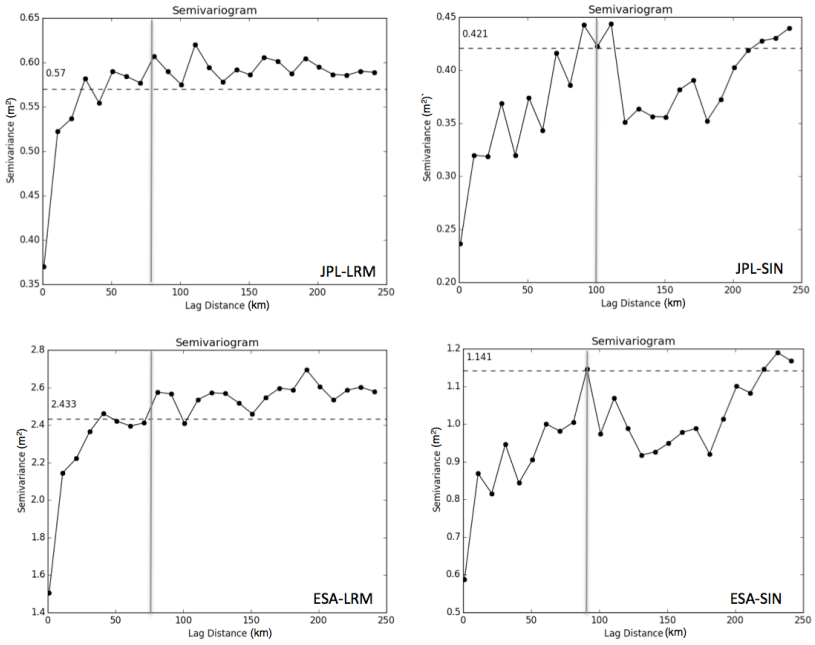

Figure S1: Semi-variograms estimated from CryoSat-2 and ATM residuals of elevation change from all three ATM data sets. The correlation length has been determined for each mode for both the JPL and ESA product, indicated by the grey vertical line. From these figures an approximate correlation length of 75 and 100 km was estimated for the LRM and SIN mode respectively.

Tables

Table S1: Effects on accuracy and precision when omitting SIN-processing steps over Barnes Ice Cap. Four test cases were completed to determine the influence of the different processing steps (phase-filtering and phase ambiguity correction) on the quality of the retrieved observations. Case-1 both the phase-filtering and ambiguity correction applied; Case-2 the ambiguity correction omitted; Case-3 the phase-filtering step omitted; Case-4 both steps have omitted. Statistics were calculated by comparing CryoSat-2 elevations with IceBridge ATM elevations. Here the Mean is the average of the residuals, SD is the standard deviation, RMSE the Root-Mean-Square-Error and N the number of observations.

Case	Mean (m)	SD (m)	RMSE (m)	N
1	-0.36	0.61	0.71	282
2	-0.37	0.62	0.72	279
3	-0.42	0.70	0.82	241
4	-0.43	0.69	0.82	266

Table S2: Validation of LRM surface elevations from CryoSat-2 compared to ATM surface elevations. The "Average" row shows the weighted mean-value (using the number of observations) of values. SD is the standard deviation*, RMSE the Root-Mean-Square-Error and N the number of observations.*

LRM	Mean (m)	SD (m)	RMSE (m)	N
JPL - 2011	-0.18	0.30	0.35	2035
JPL - 2012	-0.06	0.60	0.60	2443
JPL - 2013	0.26	0.50	0.57	1054
JPL - 2014	0.09	0.35	0.36	3025
Average:	**0.00**	**0.43**	**0.45**	**N/A**
ESA - 2011	-1.36	0.91	1.64	2818
ESA - 2012	-1.45	1.17	1.87	2874
ESA - 2013	-0.56	0.71	0.90	1236
ESA - 2014	-0.70	0.72	1.01	3713
Average:	**-1.06**	**0.89**	**1.40**	**N/A**

Table S3: Validation of SIN surface elevations from CryoSat-2 compared to ATM surface elevations, using CryoSat-2-data from the month of April. The "Average" row shows the weighted mean-value (using the number of observations) of values. *SD is the standard deviation, RMSE the Root-Mean-Square-Error and N the number of observations.*

SIN	Mean (m)	SD (m)	RMSE (m)	N
JPL - 2011	-0.63	0.82	1.03	4475
JPL - 2012	-0.55	0.57	0.79	4010
JPL - 2013	-0.37	0.37	0.61	2309
JPL - 2014	-0.47	0.48	0.76	5504
Average:	**-0.52**	**0.58**	**0.82**	**N/A**
ESA - 2011	-0.95	1.20	1.53	4355
ESA - 2012	-1.19	1.31	0.91	4764
ESA - 2013	-0.76	0.95	1.22	2490
ESA - 2014	-0.87	0.73	0.96	5203
Average:	**-0.90**	**1.05**	**1.13**	**N/A**

Table S4: Validation of four DEM's using ATM surface elevations from four different campaigns over the Greenland Ice Sheet. The "Average" row shows the weighted mean-value (using the number of observations) of values. SD is the standard deviation, *RMSE the Root-Mean-Square-Error and N the number of observations.*

DEM	Mean (m)	SD (m)	RMSE (m)	N
AWI - 2011	-2.03	6.48	6.79	4,216,153
AWI - 2012	-1.24	5.93	6.06	4,290,351
AWI - 2013	-0.32	6.74	6.75	2,690,046
AWI - 2014	-1.41	5.13	5.32	5,314,066
Average:	**-1.35**	**5.95**	**6.12**	**N/A**
GIMP - 2011	-1.44	7.89	8.02	4,481,612
GIMP - 2012	-1.35	7.25	7.38	4,427,566
GIMP - 2013	-0.22	7.40	7.40	2,764,105
GIMP - 2014	-1.15	6.56	6.66	5,541,920
Average:	**-1.13**	**7.22**	**7.32**	**N/A**
JPL - 2011	-1.27	6.77	6.89	4,336,066
JPL - 2012	-1.16	6.14	6.24	4,320,667
JPL - 2013	0.07	6.81	6.81	2,682,035
JPL - 2014	-0.79	5.85	5.90	5,443,766
Average:	**-0.87**	**6.31**	**6.39**	**N/A**
ESA - 2011	-3.48	6.75	7.59	4,321,714
ESA - 2012	-2.91	5.87	6.55	4,231,174
ESA - 2013	-2.17	6.80	7.14	2,667,683
ESA - 2014	-2.57	5.50	6.08	5,356,199
Average:	**-2.83**	**6.13**	**6.76**	**N/A**

Table S5: Validation of SF-SIN surface elevation changes from CryoSat-2 compared to ATM surface elevation changes, using CryoSat-2-data from within a search radius of 175 m of the ATM-locations. The "Average" row shows the weighted mean-value (using the number of observations) of values SD is the standard deviation, RMSE the Root-Mean-Square-Error, N the number of observations and SE the residual slope error

SF - SIN	Mean (m)	SD (m)	RMSE (m)	N
JPL – 2011-13	0.36	0.68	0.78	20,051
JPL – 2011-14	0.33	0.57	0.66	102,613
JPL – 2012-14	0.26	0.58	0.64	94,630
Average:	**0.30**	**0.58**	**0.66**	**N/A**
ESA – 2011-13	0.48	1.18	1.26	22,844
ESA – 2011-14	0.33	0.99	1.05	112,091
ESA – 2012-14	0.32	1.10	1.14	101,042
Average:	**0.34**	**1.06**	**1.11**	**N/A**

Table S6: Validation of SF-LRM surface elevation changes from CryoSat-2 compared to ATM surface elevation changes, using CryoSat-2-data The "Average" row shows the weighted mean-value (using the number of observations) of values. SD is the standard deviation, RMSE the Root-Mean-Square-Error and N the number of observations.

SF - LRM	Mean (m)	SD (m)	RMSE (m)	N
JPL – 2011-13	0.32	0.56	0.64	6,639
JPL – 2011-14	0.18	0.69	0.69	14,643
JPL – 2012-14	-0.02	0.70	0.70	18,950
Average:	**0.11**	**0.67**	**0.69**	**N/A**
ESA – 2011-13	0.66	1.56	1.70	8,679
ESA – 2011-14	0.54	1.50	1.59	18,142
ESA – 2012-14	-0.20	1.50	1.50	19,846
Average:	**0.25**	**1.51**	**1.57**	**N/A**

Table S7: Validation of XO crossover surface elevation changes from CryoSat-2 (2011-2014) compared to ATM surface elevation changes. SD is the standard deviation, RMSE the Root-Mean-Square-Error and N the number of observations.

XO - LRM	Mean (m)	SD (m)	RMSE (m)	N
JPL	0.24	0.72	0.78	683
ESA	0.60	1.02	1.20	557
XO - SIN				
JPL	-0.06	1.26	1.26	12,075
ESA	-0.21	1.44	1.44	10,477