DeDop

Fully Adaptable and Configurable Altimeter Delay Doppler Processor

Sentinel 3 For Science – SAR Altimetry Studies

SEOM Study 8. SARAE

DeDop Case Study Report
Polar Ocean

WP6800

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1 Introduction

1.1 Purpose

Cryosat-2 is the first altimeter to operate in three different modes over the ocean. Over most of the open ocean it operates in the classical pulse limited mode (PLM) and switch to Delay-Doppler Altimeter (DDA) or SAR mode near the sea ice edge. The advantage of using SAR mode is much greater spatial resolution of only 300m when comparing to the PLM resolution of 7km. This significant increase of the resolution can be of great advantage for the oceanographic applications. For example, much greater spatial resolution of the mode could resolve much smaller spatial scales of the ocean circulation like narrow currents, ocean eddies and coastal currents. Another advantage of using SAR-mode altimetry is to gather measurements much closer to the coast and ice-edge.

The aim of this case study is to check if different processing of the lower-level altimetry of the (1A to 1B Level) possible in the DeDop tool impact the output of the SSH (Level 2) and its relationship with in situ observations of temperature and salinity in the sub-polar Arctic along the West Spitsbergen Current. The WSC consists of the two branches, one core branch located more inshore in the shallower waters between 500-900m and the wider offshore branch located in deeper waters between about 1000-1500m. The core branch is only 15km wide and normal PLM altimetry does not resolve such narrow current. The objective of the case study is to check if the sea surface height close to Svalbard archipelago can be used to predict the temperature of AW inflow or the SST.

1.2 Document structure

The first section of this document presents the purpose of this case study. The second section presents the data sets used for the case study and the processing and methods used. The third section presents results. The fourth section gives some recommendations for the processor's improvements.

1.3 Acronyms

AD	Applicable Document
DDP	Delay-Doppler Processor
ESA	European Space Agency
HRM	High Resolution Mode
L1A	Input file with geo-located bursts of Ku echoes. The calibrations are not applied. Each record contains 1 SAR burst of aligned but not-calibrated echoes
L1B-S	Output file with fully processed and calibrated SAR complex echoes, arranged in stacks after slant range correction and prior to echo multi-looking.
L1B	Output file with fully calibrated multi-looked power echoes (SAR)

RD	Reference Document
SAR	Synthetic Aperture Radar
WSC	West Spitsbergen Current
IO PAS	Institute f Oceanology Polish Academy of Sciences
CTD	Conductivity, temperature, depth profiler
SSH	Sea Surface Height
SST	Sea Surface Temperature
SPICE	The Sentinel-3 Performance improvement for ICE sheets
SCOOP	SAR Altimetry Coastal & Open Ocean Performance
SHAPE	The Sentinels Hydrologic Altimetry PrototypE

1.4 References

1.4.1 Applicable Documents

AD.1 Invitation to Tender AO/1-8080/I-BG Sentinel 3 For Science – SAR Altimetry Studies (S3 4 SCI – SAR Altimetry Studies), 13 October 2014

AD.2 Scientific Exploitation of Operational Missions (SEOM). Sentinel-3 SAR Altimetry Statement of Work (SEOM S3-4SCI SAR Altimetry). Issue 1, 27/09/2014

1.4.2 Reference Documents

RD.1 AREX 2011 Cruise Report, http://www.iopan.gda.pl/hydrodynamics/po/Oceania_2011_report.pdf

RD.2 Ray, C.; Roca, M.; Martin-Puig, C.; Escola, R.; Garcia, A., "Amplitude and Dilation Compensation of the SAR Altimeter Backscattered Power," in IEEE Transcations on Geoscience and Remote Sensing Letters, vol.12, no.12, pp.2473-2476, Dec. 2015, doi: 10.1109/LGRS.2015.2485119.

RD.3 Makhoul et al, 2017, Mid-Term-Review meeting of the SHAPE project

RD.4 Beszczynska-Moller A. and Walczowski W. 2013, presentation at ASOF annual meeting

RD.5 SHAPE Project, https://projects.along-track.com/shape/

2 Case Study Description

2.1 Scientific / Technical Context

The case study concerns seven Cryosat-2 orbits in SAR mode located in the south-western Svalbard in the West Spitsbergen Current (WSC) region between 75°N-78°N latitudes and 16-18°E longitudes, between 20th June and 2nd July of 2011 (Figure 1). The spatial resolution is 300m. The length of each track is between 45km (track 5) to 270km (Track 7). The Cryosat-2 FBR were adapted to Sentinel-3 L1A format.

More data in the region could be used but only those seven orbits were acquired in the SAR-mode over the region of CTD in situ measurements of IO PAS in that time. It can be seen in Fig 1 that the SAR data provides greater coverage in the WSC region, and much greater spatial resolution.

The seven orbits shown in Fig 1 were converted to Sentinel-3 like data and used in the DeDop tool to process from Level 1A to Level 1B using a two configurations. Then the output from DeDop was further processed.

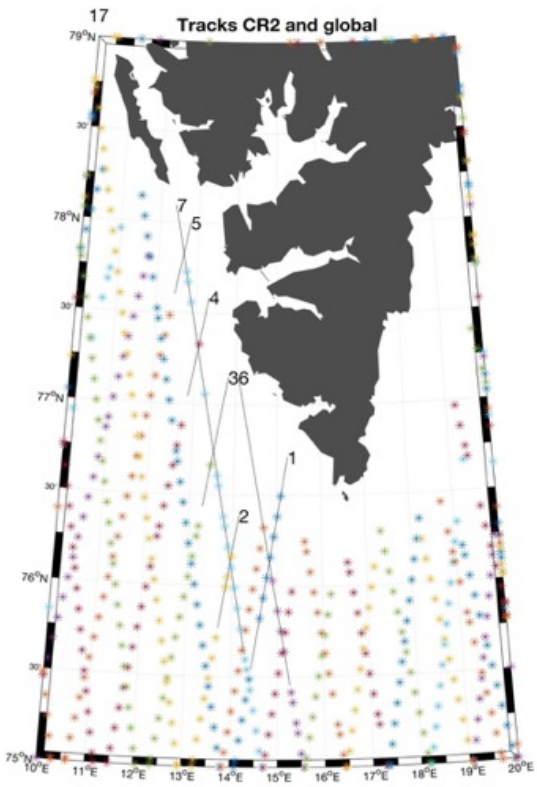


Figure 1: The orbits of SAR mode altimetry used in the case study. In colour the CryoSat 2 PLM altimetry available from CMEMS.

2.2 Objective / Purpose of Case Study

The main technical objective of the study is to investigate whether SAR altimeter data can be used to extend the observations of SSH in the coastal and polar regions and for the narrow currents. The scientific objective of the research is to find out if the high resolution SSH next to the south-western Svalbard, in the WSC region, relates to the in situ temperature and salinity, or to SST.

The aim of the case study for the DeDop project is to investigate if different configurations of the lower level altimetry processing from level 1A to level 1B, available in the DeDop processor, impact Level 2 output of SSH and relationship to the in situ temperature and salinity. The improvement in the relationship with the in-situ data may demonstrate which configuration is better and support recommendations for future studies.

2.3 Input Data Sets (including auxiliary and validation data sets)

Seven orbits, shown in Fig 1, are used:

1. CS_LTA__SIR1SAR_FR_20110620T195019_20110620T195039_C001.DBL.nc
2. CS_LTA__SIR1SAR_FR_20110622T194758_20110622T194808_C001.DBL.nc
3. CS_LTA__SIR1SAR_FR_20110624T194519_20110624T194531_C001.DBL.nc
4. CS_LTA__SIR1SAR_FR_20110626T194245_20110626T194254_C001.DBL.nc
5. CS_LTA__SIR1SAR_FR_20110628T194011_20110628T194018_C001.DBL.nc
6. CS_LTA__SIR1SAR_FR_20110630T061640_20110630T061709_C001.DBL.nc
7. CS_LTA__SIR1SAR_FR_20110702T061416_20110702T061458_C001.DBL.nc

Both L1B and L1BS data are used. The tracks are located in the south-western Spitsbergen, in the close proximity of the coast. Tracks 1-5 are located in the north-eastern direction towards land and tracks 6-7 from the south to north. The distance of each track is 45km for Track 5 and 270km for Track 7, and spatial resolution is 300m.

For the in-situ data we use temperature and salinity profiles (CTD) gathered by the Institute of Oceanology, Polish Academy of Sciences (IO PAS) between June 20th and July 2nd 2011 during AREX2011 oceanographic cruise (RD1). The map of the CTD stations is shown in Fig 2. The distances between CTD profiles are about 10-30km at cross-sections and 50-100km between the sections. For the regression between satellite SSH and in-situ temperature and salinity we use interpolated values (optimal interpolation) at the SSH positions at 1m and 100m depths (Figs 3 and 4).

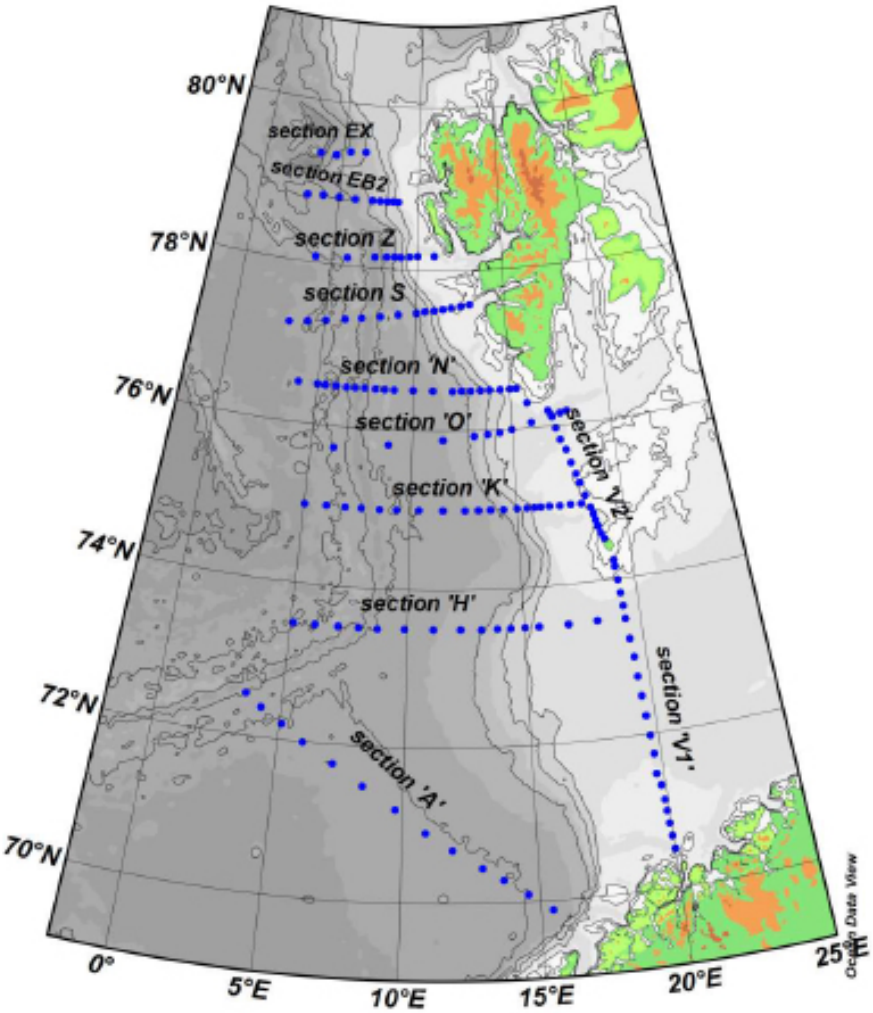


Figure 2: Locations of the IO PAS CTD stations.

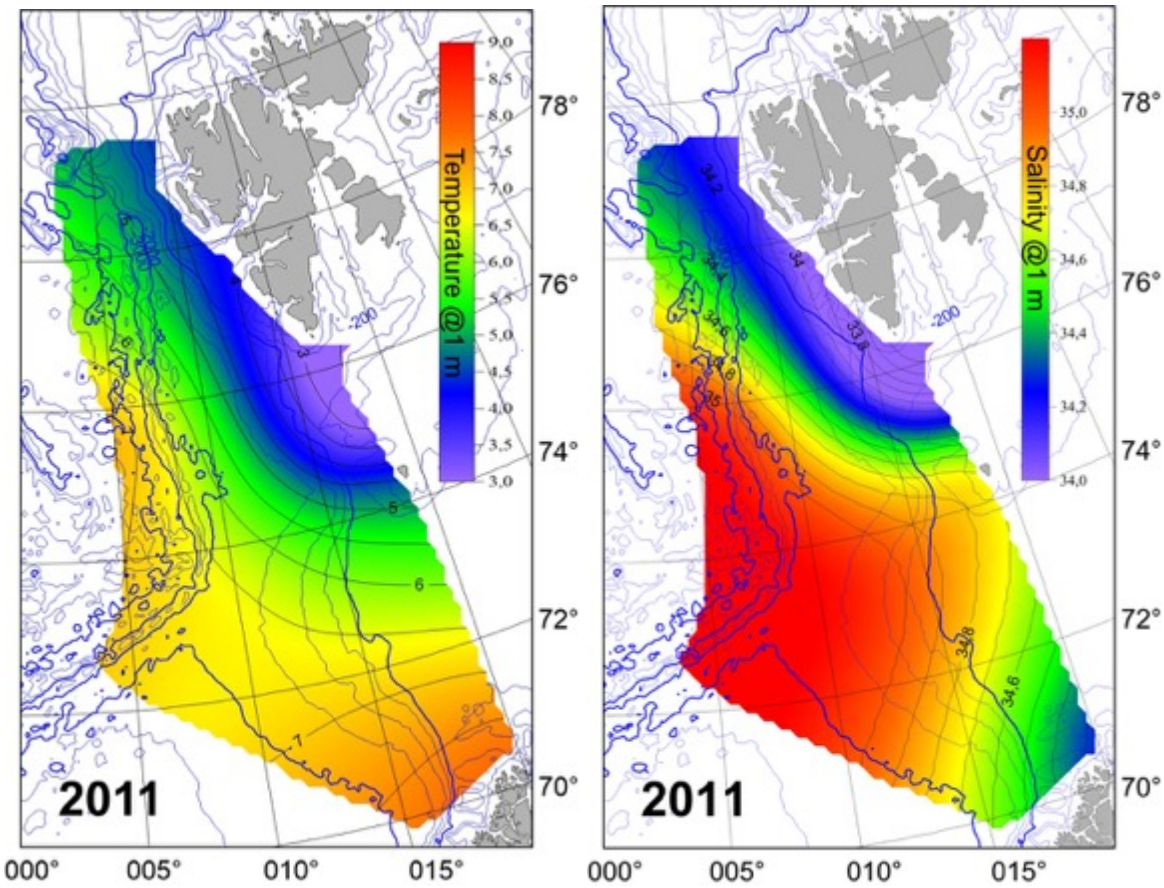


Figure 3: Interpolated fields of Temperature and Salinity at 1m depth, 20th June -2nd July 2011.

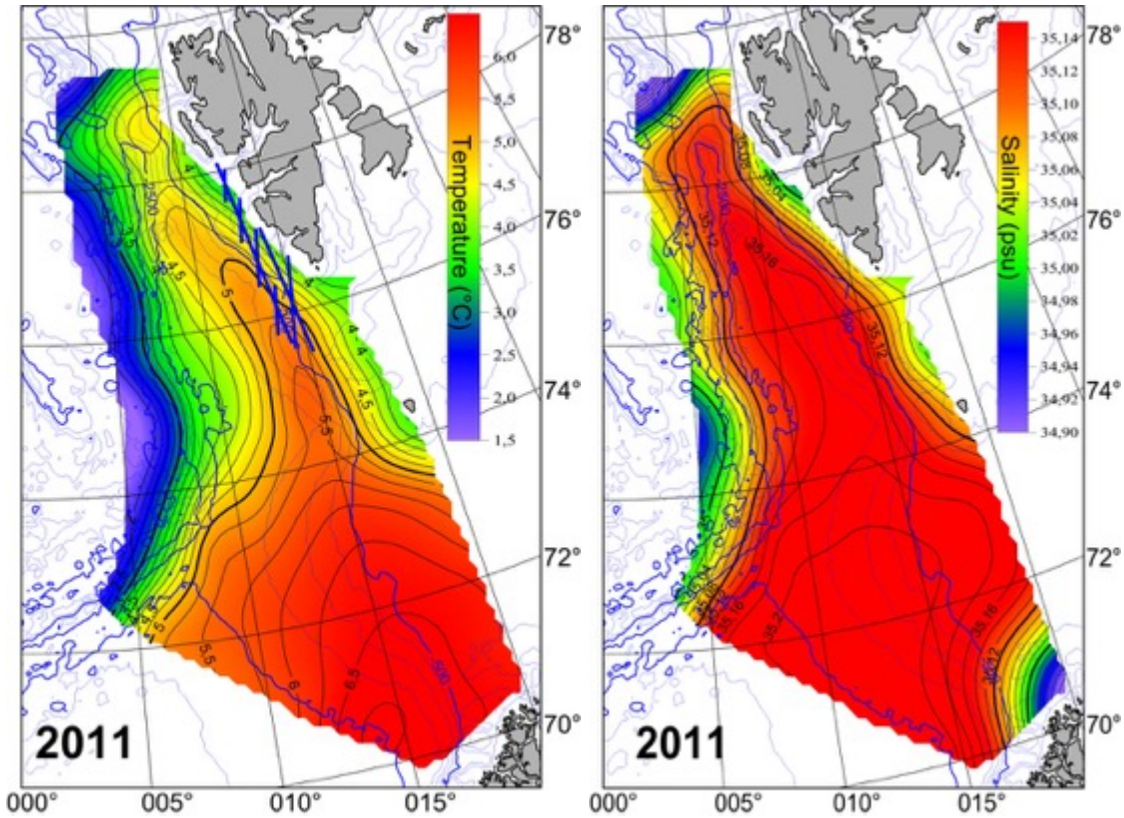


Figure 4: Interpolated fields of Temperature and Salinity at 100m depth.

Monthly mean maps of remotely sensed SST were used for comparison with in situ and SSH (15th May, 15th June, 15th July).

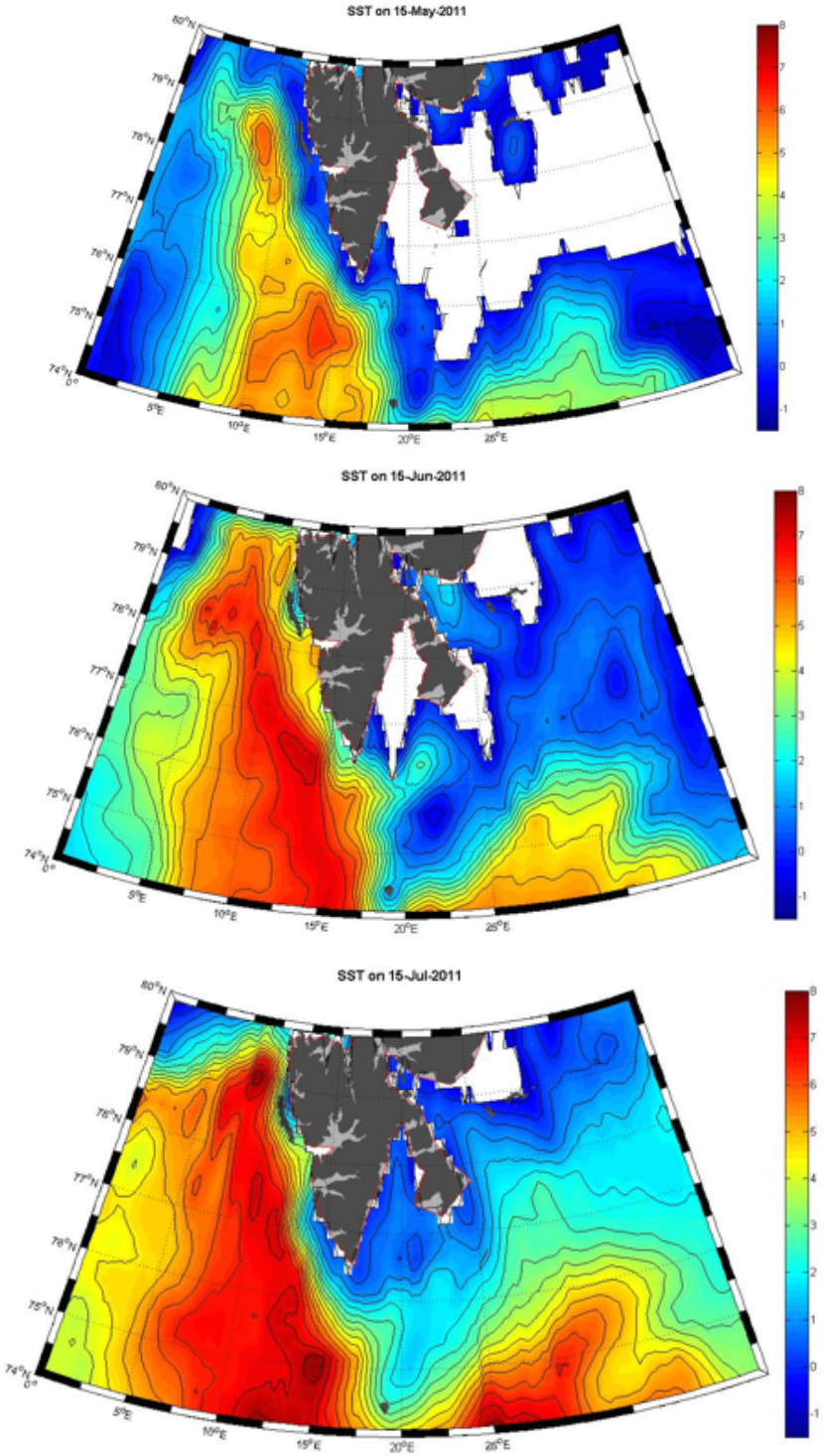


Figure 5: Monthly means of remotely sensed sea surface temperature in May-July 2011. The sea ice is shown in white.

2.4 DeDop Tool Processing Specifications and Description

Two configurations are used to test mainly the impact of zero padding and hamming filtering on the noise level of the of waveforms

1. Default (Sentinel-3 like baseline): no zero padding, no Hamming intra-burst,
2. Cryosat-2 baseline: zero-padding, Hamming intra-burst filtering

Flag_"avoid_zeros_in_multilooking_cnf" set to false was used in both configurations

2.5 Additional Post DeDop Processing

The tracks were retracked using an in-house L2 processor exploiting an implementation of the SAR ocean retracker based on the model proposed by Chris Ray in TGRS Ray et al. (2015). Two different re-tracking options have been considered: in one retracker the SWH is being fitted and MSS[1] is fixed (ocean-like waveforms), while the second one (more specular-like scenarios) the MSS is being fitted, fixing the SWH. For the case of fitting the SWH: the retrieved geophysical parameters are SSH, sigma0 and SWH; when fitting the MSS, the retrieved parameters are SSH, sigma0 and MSS.

The block diagram of the ocean retracker is depicted in Figure 6. The main steps are:

- Pre-processing (or filtering)
- Waveform modelling
- Fitting procedure
- Geophysical corrections

In this block diagram a 2-step retracking procedure is shown, i.e., first an ocean like waveform fitting is used (where MSS is fixed) and if the correlation coefficient is below a threshold a second fitting (specular-like waveforms) is performed fixing the SWH and fitting the MSS. However, for this case study we have taken the option to provide independently the two types of retracking.

[1] MSS refers to mean-squared slopes and are related to the roughness of the Surface.

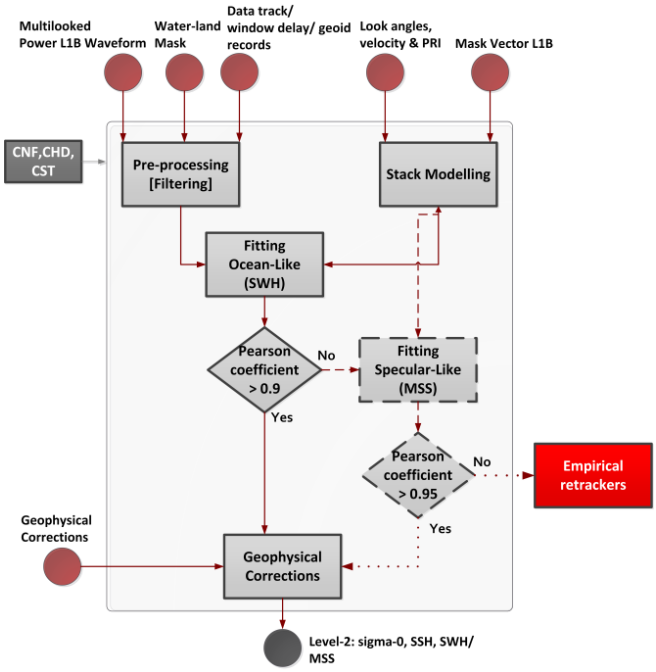


Figure 6: Physically-based SAR ocean retracker block diagram. (CNF, CHD and CST stand for configuration, characterization and constants' files provided as inputs to the L2 processor) (credit: isardSAT).

The geophysical corrections were applied to correct the SSH – we have used a Dedop version the same as for SPICE, SCOOP and SHAPE isardSAT projects, where geophysical corrections are directly included in Level 1B (Makhoul et al, 2017, MTR SHAPE). An example of output of the L2 processing is shown in Figure 7. The goodness of the fitted model for the first retracker is measured by the Pearson correlation (r) between the original and analytical waveform. The results of the two retracked SSH are shown in Fig 8.

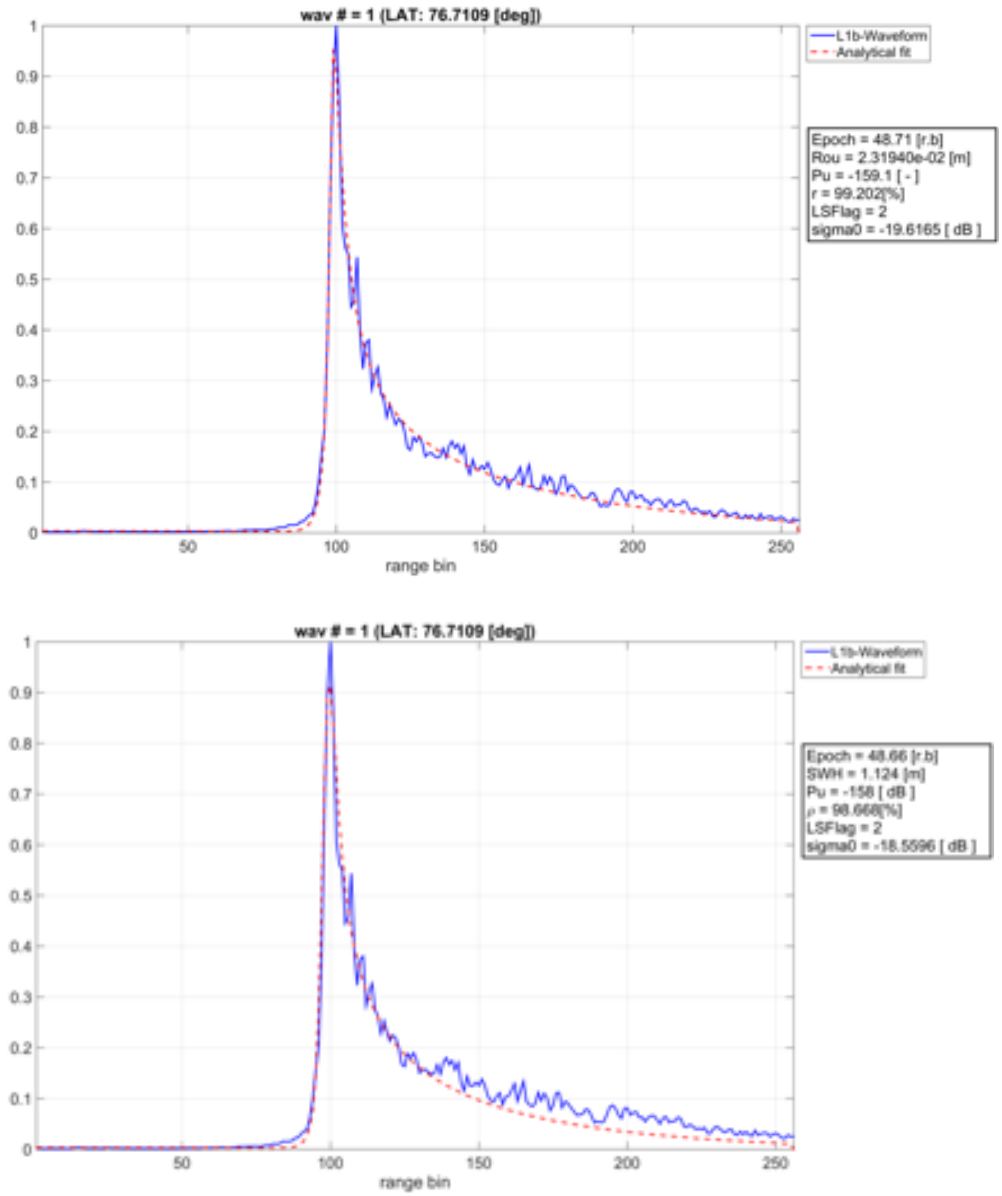


Figure 7: An example of the output of L2 processing showing the results of the two retrackers. In the top SWH is being fitted and MSS is fixed (ocean-like waveforms), in the bottom (more specular-like scenarios) the MSS is being fitted, fixing the SWH.

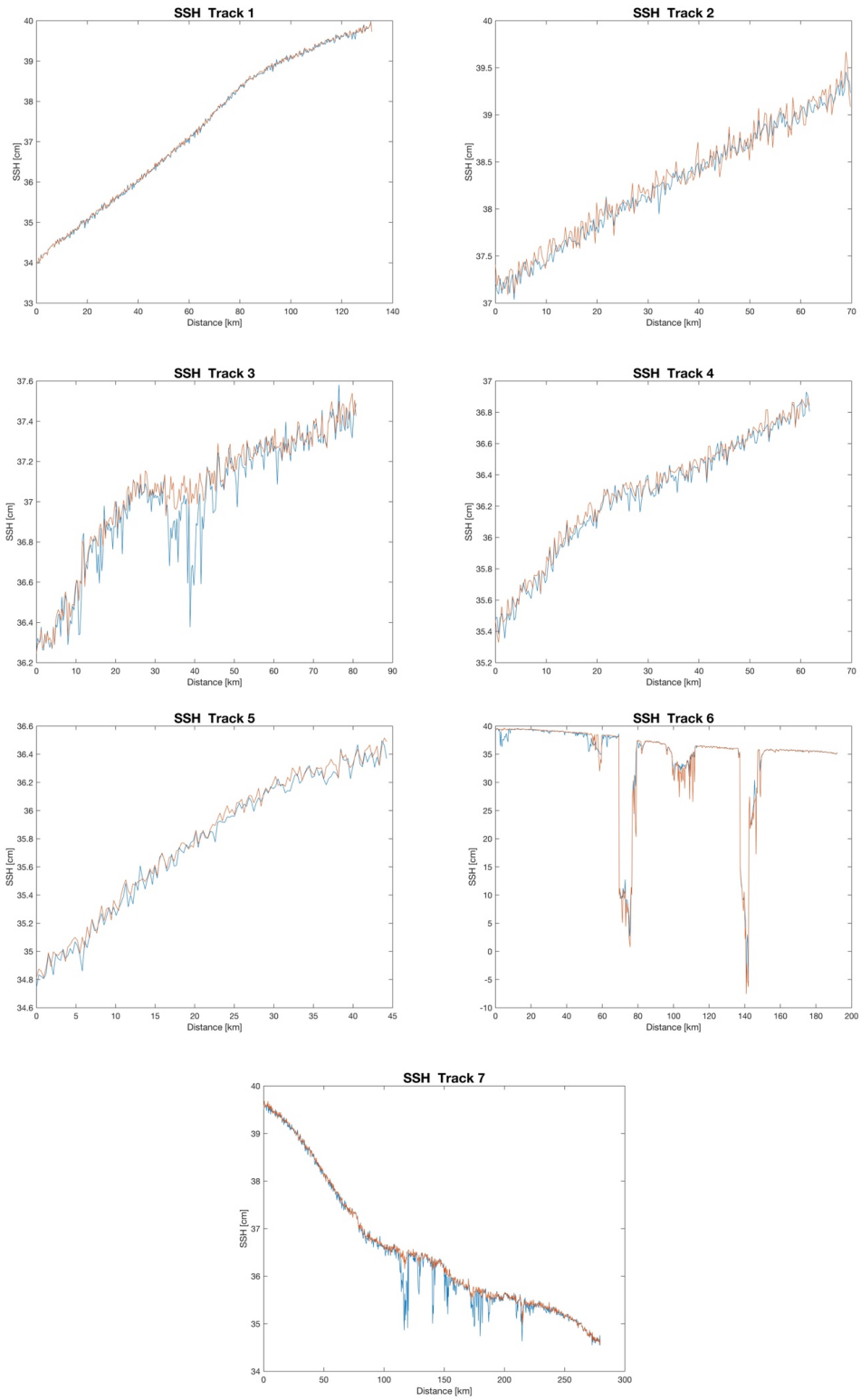


Figure 8:. SSH otputs from two retracked models for all 7 tracks. In blue SWH is being fitted and MSS is fixed, in red MSS fitted and SWH is fixed.

The dynamic height at 100 m was calculated using in situ salinity and temperature. The regression between the SSH and in situ salinity, temperature and dynamic height was performed for two depth levels: 1m and 100 m.

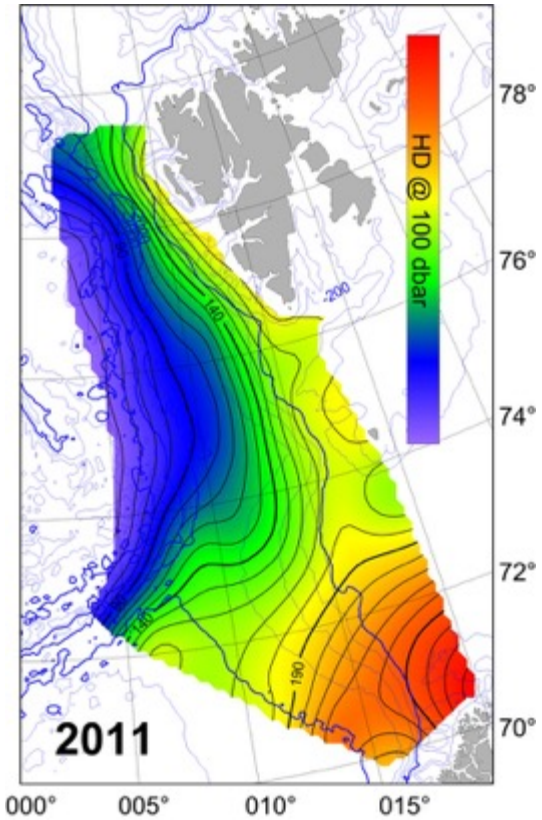


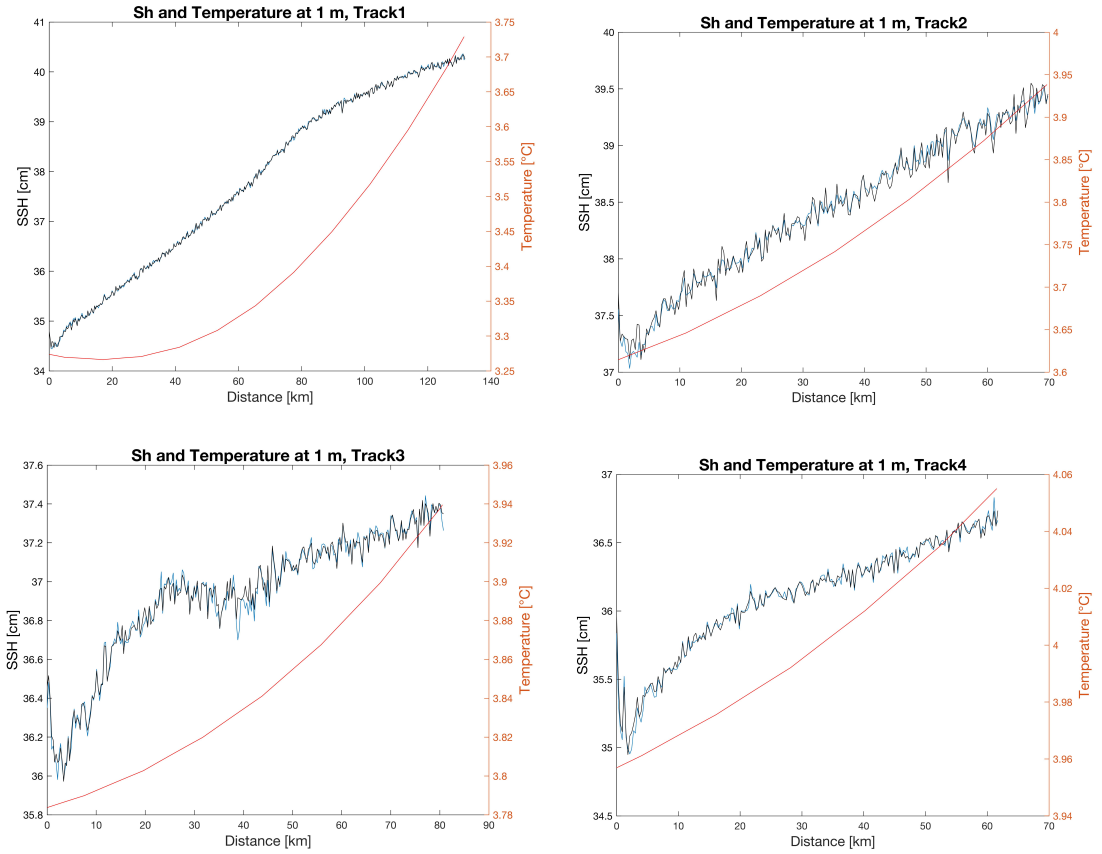
Figure 9:. Dynamic height at 100 m depth calculated using in situ temperature and salinity.

3 Analysis of Case Study Output

3.1 Technical / Scientific Results

3.1.1 Relationship of SSH and in situ temperature and salinity at 1m depth

Along-track SSH and subsurface (1m) in situ temperature are shown for each track in Fig 10. Positive correlations of 0.9 were obtained for tracks 1-5. No correlation was found for Track 6 and negative for Track 7. It was not possible to derive a model relationship for all tracks and subsurface Temperature (the same for SST). It is very likely that subsurface temperature in June 2011 is not typical due to activity of the Sørkapp Current that outflowed from the Stortfiord into western Spitsbergen waters, which then caused surface temperature to increase northwards and therefore large differences between the correlations for individual tracks occur.



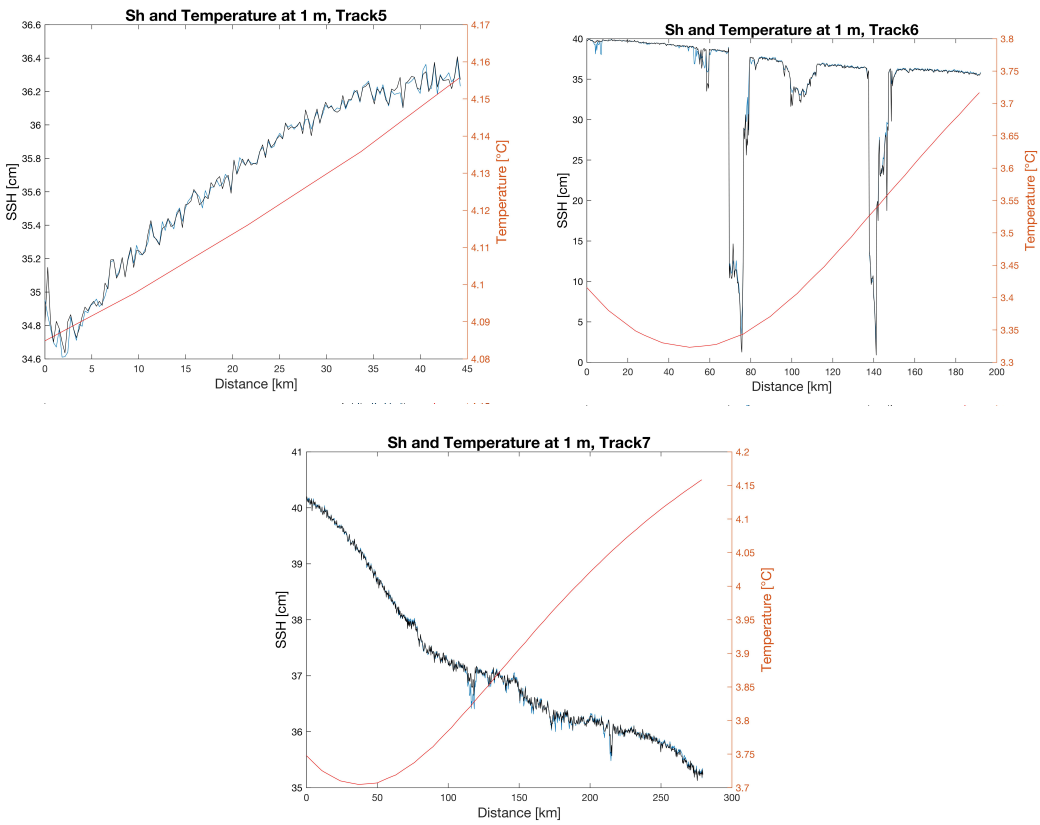
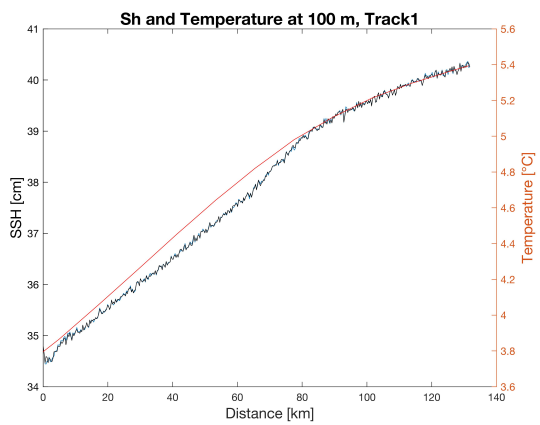


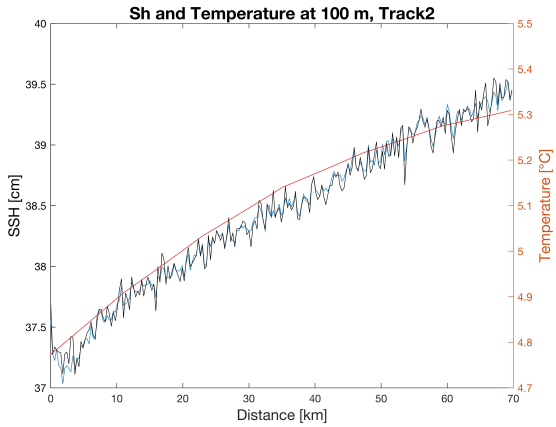
Figure 10:. Along-track SSH and interpolated in situ Temperature at 1m depth.

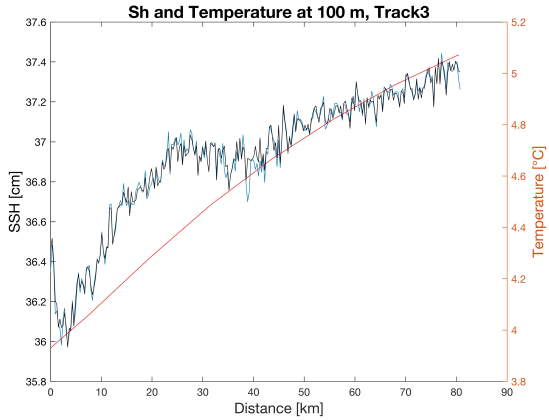
3.1.2 *Relationship of SSH and in situ temperature, salinity and dynamic height, at 100 m depth*

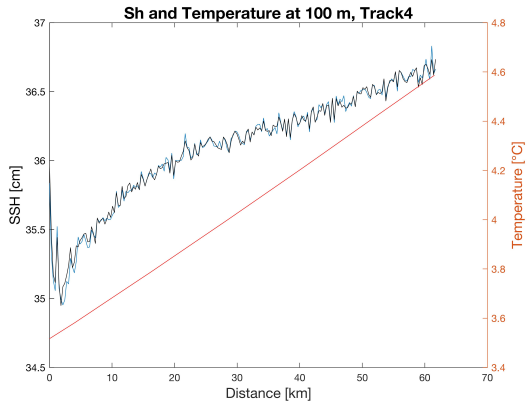
The along-track values of SSH and temperature at 100 m are shown in Fig 10. One can see that for track 6 large negative deviations in SSH occurred. The model analytical waveforms were not able to fit the received waveform well (low Pearson correlations were observed for both retrackers). Overall, the Temperature at 100 m and SSH have very similar spatial variability in the region (Fig 12). Therefore, it was possible to derive a universal regression model where the in-situ temperature at 100 m can be used to forecast the SSH, and vice versa with a good accuracy of R=0.879 (77%), and significance of 99% (Fig 11). In Fig 13 one can see that also in situ salinity at 100m shows very similar relationship to the SSH. Very similar relationship can be also obtained for the dynamic height, although with some weaker explained variance (70%). However, the greater salinity does not cause an increase of SSH, rather the variability and pattern of salinity of AW inflow is coherent with AW temperature what was demonstrated by the high correlations (0.9) between those two hydrological values (RD4). It is known that an increase of salinity causes an increase of density and therefore decrease of SSH. The analysis proves that the Atlantic Water temperature drives the SSH in the region. The higher the steric height and steric volume, the greater the SSH. In the past temperature and salinity of AW inflow were closely correlated showing simultaneous increases and decreases,

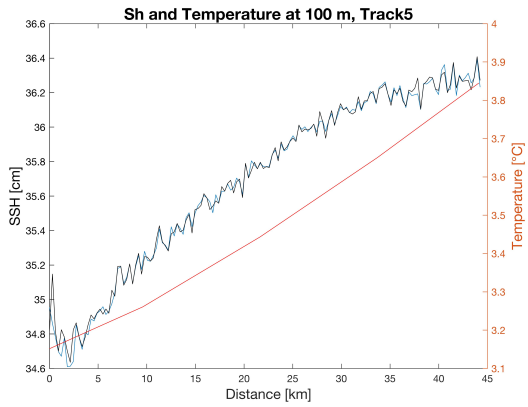
however in the recent years the observations show different incoherent variability of temperature and salinity of AW inflow, especially at the northern part of WSC (RD4). Therefore, it would be interesting to see whether the obtained relationship changes in time, considering different seasons and years and also position to find out what is causing the observed recent changes in the relationship of temperature and salinity.

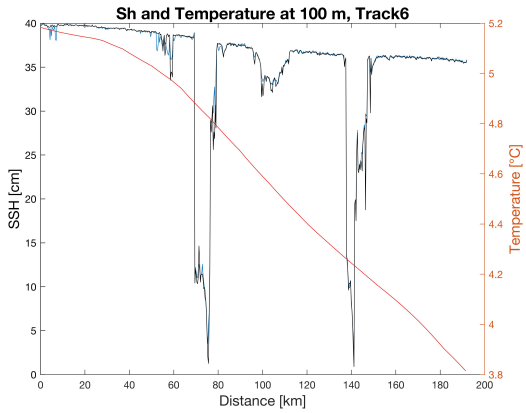












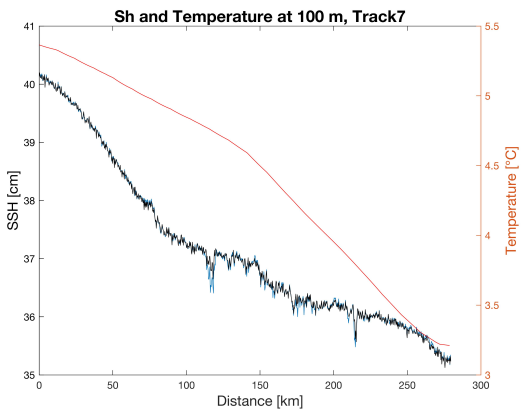


Figure 11:. Along-track SSH and interpolated in situ Temperature at 100 m depth.

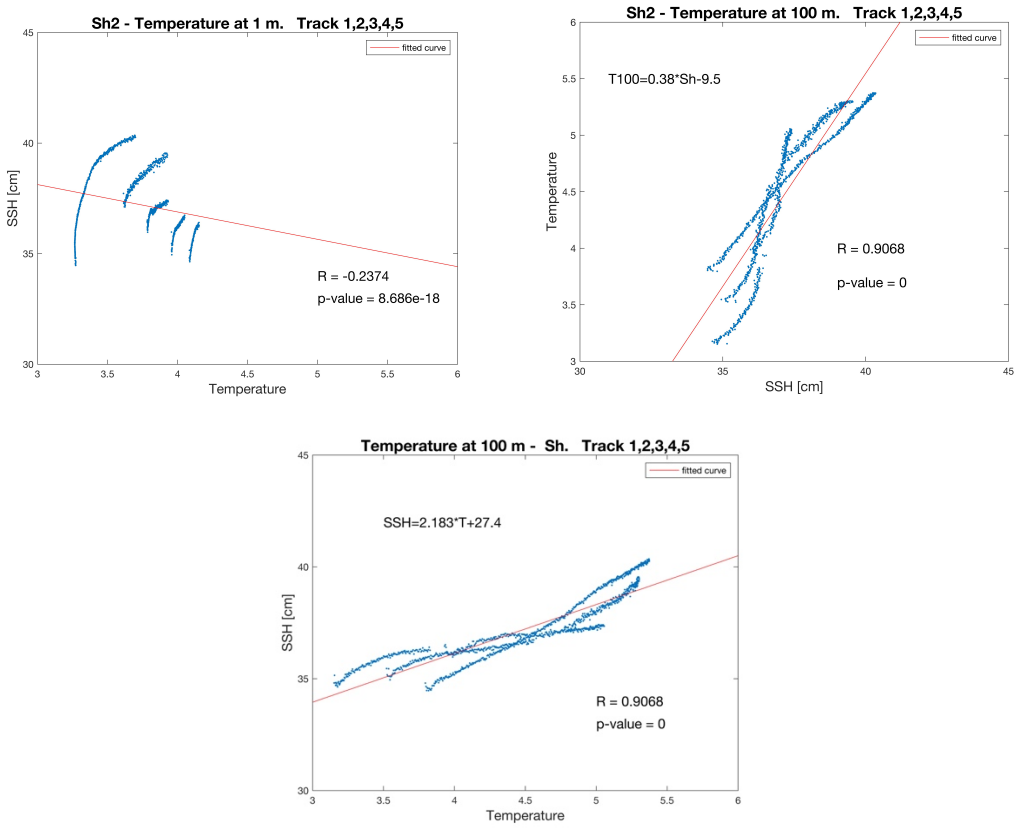


Figure 12:. Regression results for the along-track SSH and interpolated in situ Temperature at 1m and 100 m depth.

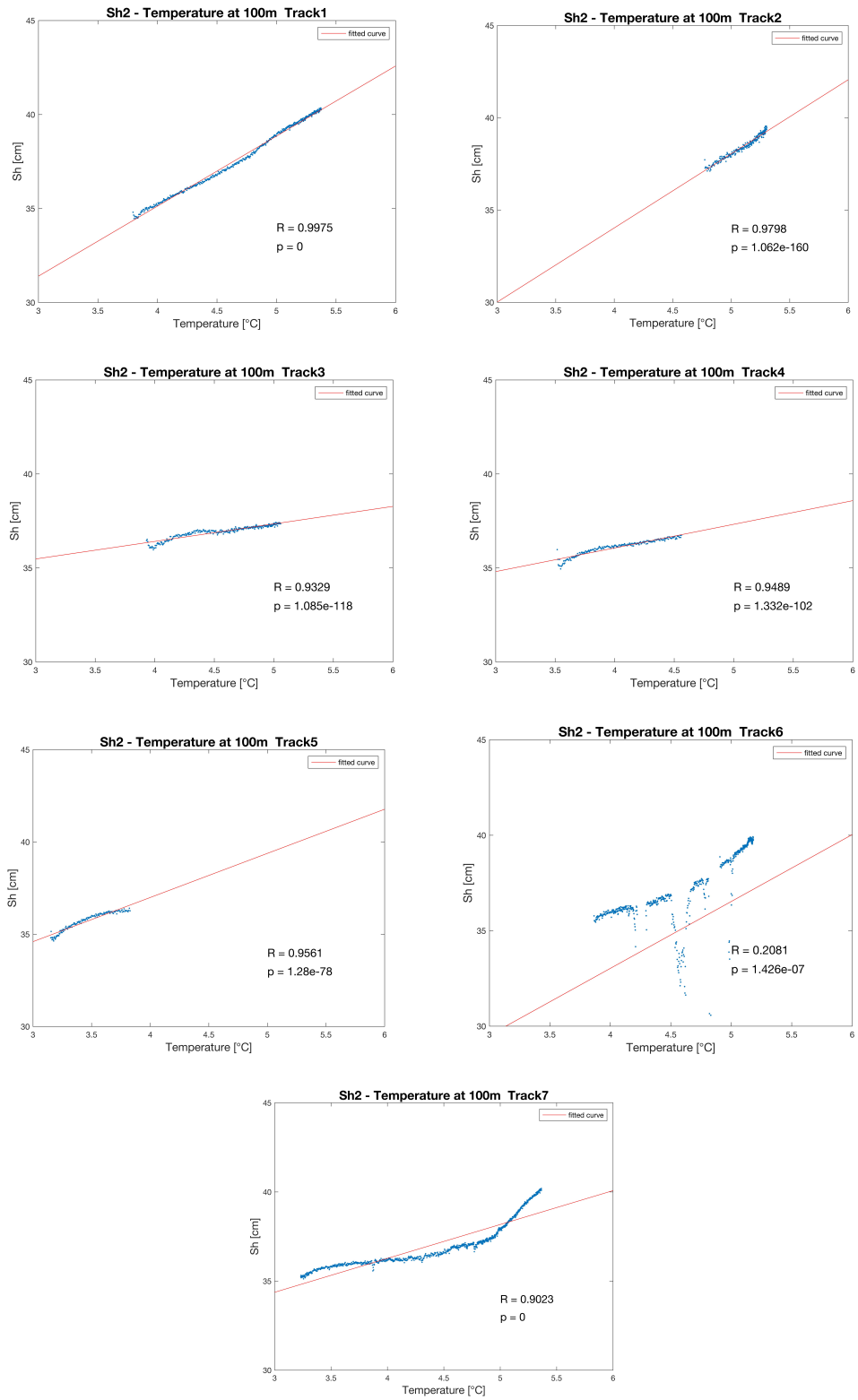


Figure 13:. Regression results for the Along-track SSH and interpolated in situ temperature at 100m depth.

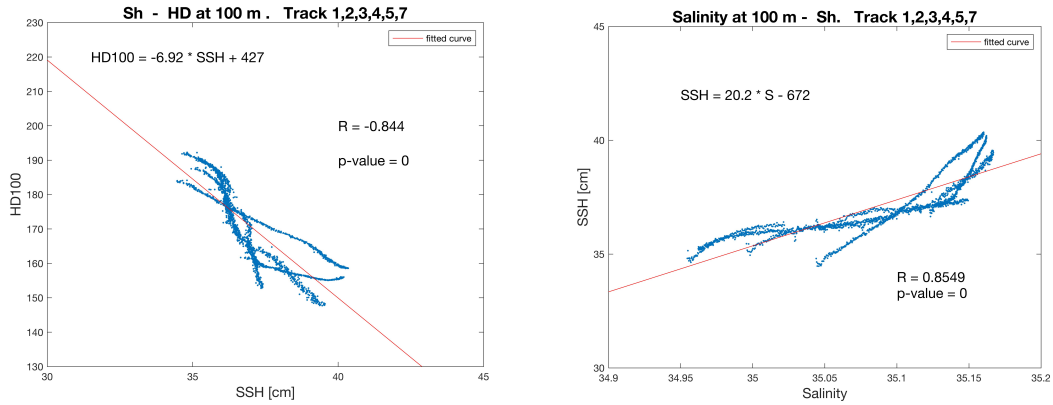


Figure 14:. Regression results for the along-track SSH and dynamic height and salinity at 100m depth.

3.1.3 *Scientific Conclusions*

Positive significant correlation exists between sub-surface Temperature at 1m depth and SSH, showing overall god fit (R=0.9) but not for all tracks (mainly only those located along East-West direction). This could be explained by the increased activity of the freshwater current flowing from the Storfiord into western Svalbard, causing unusual pattern of SST characterized by the SST increasing northwards- This pattern causes a negative correlation with the SSH track 7 located along North-South direction.

There is a significant relationship between the Atlantic Water temperature and salinity and SSH, that means that those two values are in good agreement and show the same pattern. It is possible to use the derived empirical relationship to predict the Temperature of AW at 100m using SSH and vice versa.

The 2 DeDop configurations produced SSH values that were **not on average different** from each other for the 7 orbits considered, but their differences range was about 20 cm and their standard deviation was about 5cm. The comparison with in situ data produced similar results. This could be caused by the low spatial resolution of in situ data.

3.2 Impact of Different DeDop Processing Configurations

The results presented in Section 3.1 in Figs 10-14 were obtained with the CryoSat-2 baseline configuration.

The flag ”avoid_zeros_in_multilooking_cnf” was set to *false* in both configurations. If this flag was set to ‘*true’* in DeDop this would avoid considering the samples set to zero in the stack and L1B waveform will have a higher trailing edge (as zero samples are not considered in averaging), but the retracking model in Level 2 processing assumes that these samples shall be accounted in the

averaging leading to smaller trailing edge causing a bias the retracked SSH and a mismatch between SSH and the Mean Sea Surface and in situ temperature. After setting the flag to false an increase of the correlation between SSH and in situ Temperature at 100 m slightly increased from 0.88 to 0.91.

The results of the regression between SSH obtained using Sentinel-3 like baseline configuration in DeDop and in situ temperature, salinity and dynamic height are shown in Fig 15. There is no significant difference between the SSH outputs obtained by using 2 different DeDop configurations at least for all the considered tracks. The greatest impact on the resultant regression was found between temperature and SSH, the Pearson correlation coefficient increased slightly for the Sentinel-3 like configuration from R=0.9046 to R=0.9068, this demonstrates only a very small insignificant increase in the explained variance between the two variables. When inspecting the differences for each track separately a slightly greater changes about reaching about 0.01 between the individual correlation coefficients, this is still too small to be significant. The differences of SSH resulted from two different DeDop processor configurations are shown in Fig 15. The differences are significant ranging usually around +-20 cm, however their distribution is close to normal for all tracks and the mean difference for each track in close to zero (Fig 17, Table 1). The standard deviation of the SSH difference is around 5 cm for all tracks, except for track 6 that has large errors.

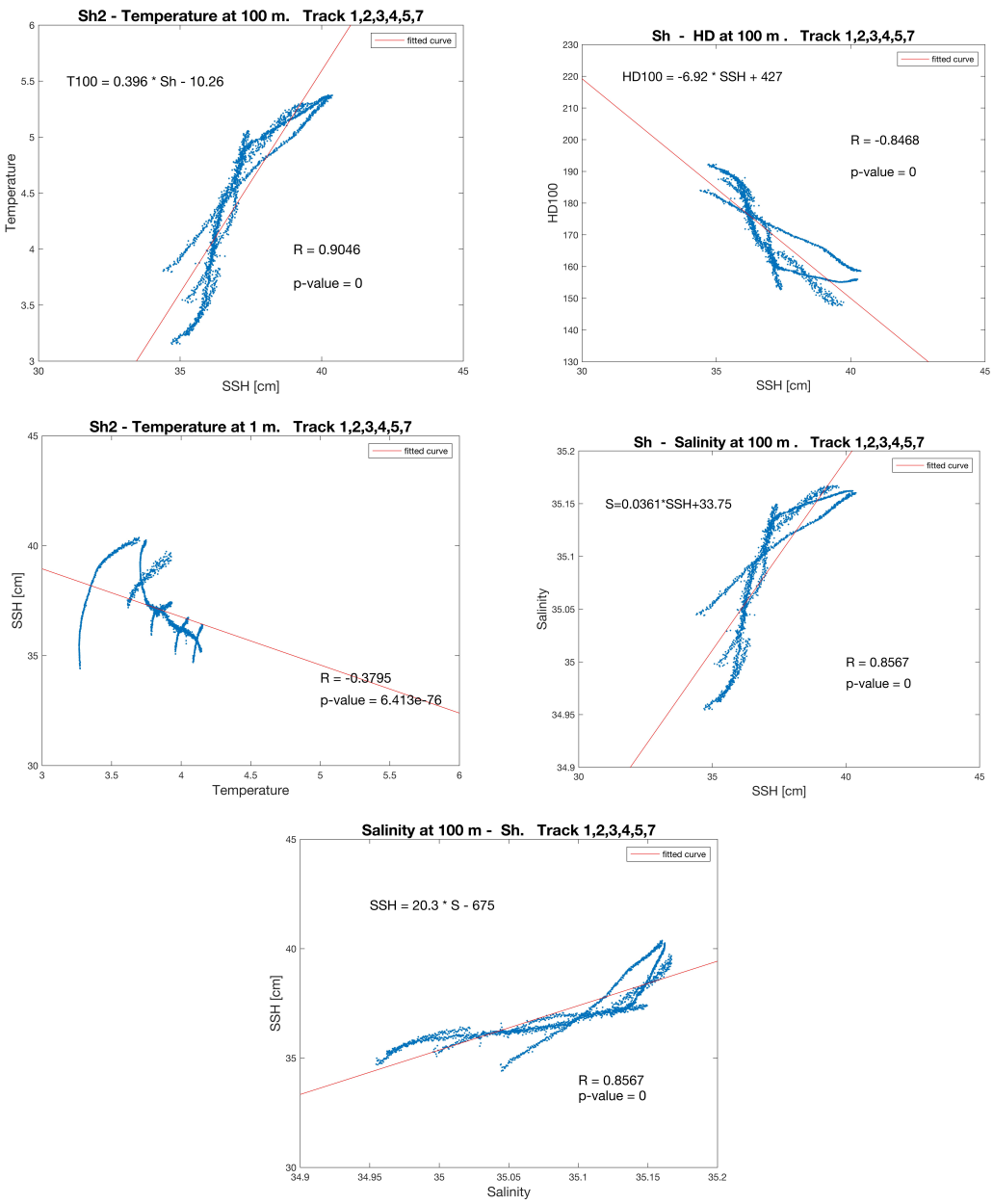


Figure 15:. Regression results with Sentinel-3 like baseline configuration used in DeDop.

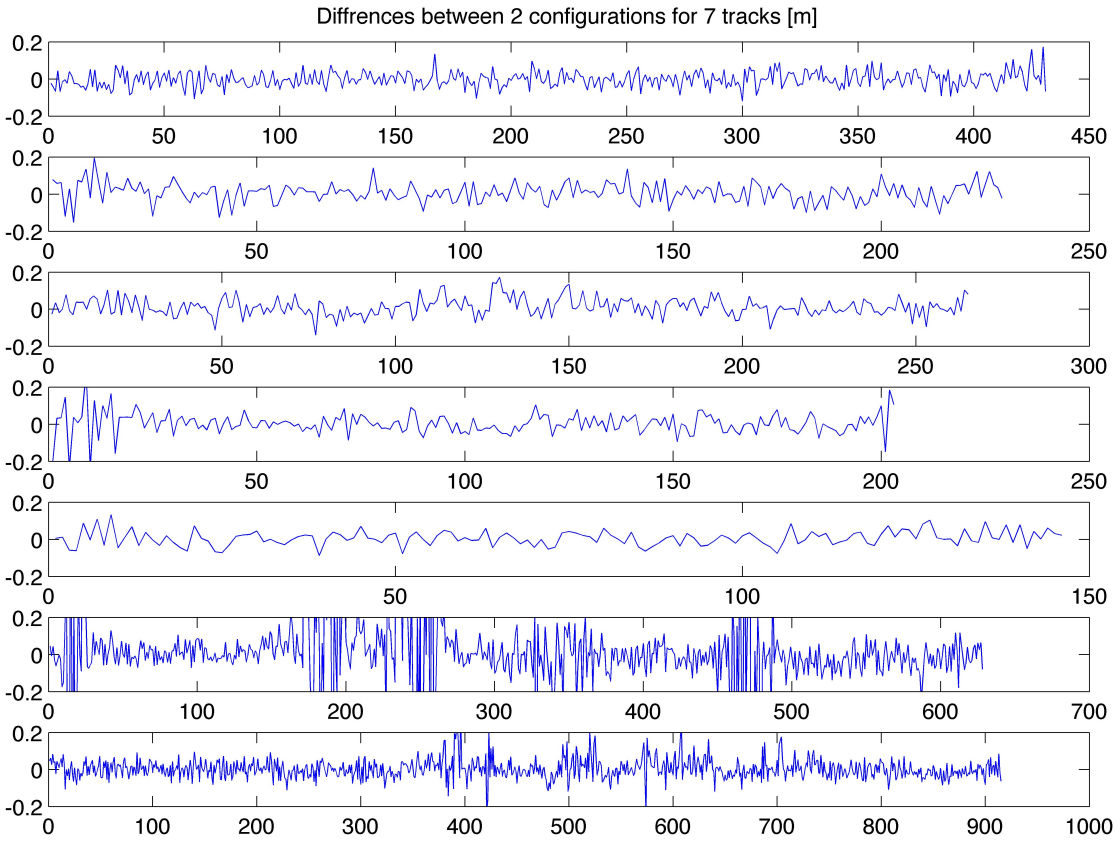


Figure 16:. Differences between the 2 DeDop configurations for all 7 tracks, track 1 at the top to track 7 at the bottom.

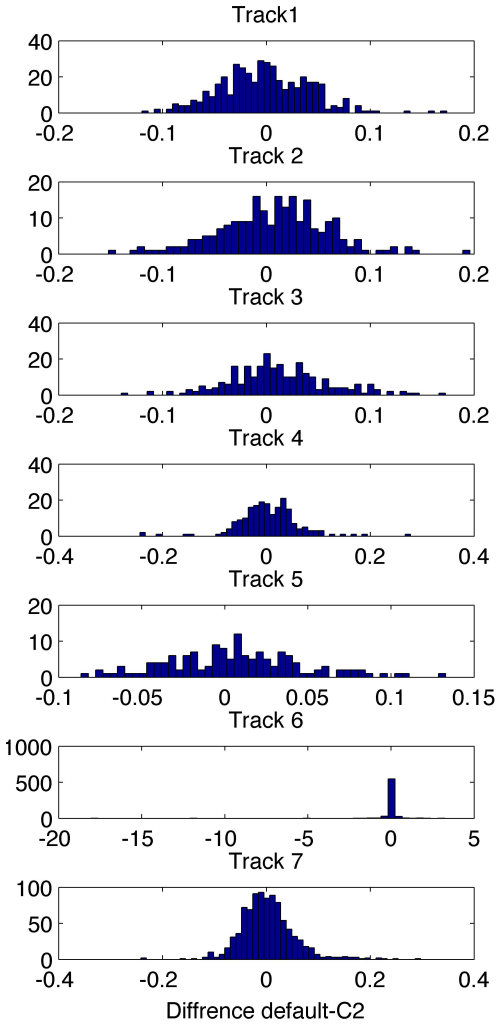


Figure 17:. Distribution of the SSH differences between the 2 Dedop configurations for all tracks.

Track no.	Mean difference [cm]	Standard deviation [cm]	Range [cm]
1	-0.2	4.2	29.3
2	0.8	5.2	34.8
3	1.2	4.8	31.2
4	0.3	6.0	52.1
5	0.6	4.1	21.9
6	-3.7	94.4	2128.0
7	0.2	5.2	53.9

Table 1: Statistics for SSH differences between the 2 Dedop configurations for all tracks.

3.3 DeDop Processor and Tool Performance

The DeDop processor was used to process the input 1A orbits into Level 1B and 1BS outputs. Two configurations were used in this process: The “default” Sentinel-3 like baseline, with no Hamming windowing or zero padding, and then more aligned with the CryoSat processor with Hamming Windowing and Zero Padding.

The reason why those 2 configurations were investigated is that the Cryosat-2 configuration can have following advantages for the noise reduction:

- Zero-padding helps in the retracking as there are more samples in the waveform, specially for those peaky waveforms at low SWH. We have observed that zero-padding provides improved noise in SSH and SWH retrieval for low SWH (below 2 m).
- Hamming intra-burst (reducing the impact of azimuth or along-track sidelobes produces a cleaner stack specifically in the noise area, removing the interferences of along-track sidelobes folding back after geometry corrections that results in the cleaner waveforms in the noise area before the leading edge) is helping to reduce the error in estimation of SSH and SWH for higher SWH above 4-m.
- The noise in sigma0 is improved over the different SWH compared to processing with Sentinel-3 configuration.

Considering the above advantages, it was expected that Cryosat-2 baseline will result in a better retracking and more accurate estimation of geophysical parameters such as SSH and SWH.

Those Level 1B outputs were then processed further with the extended DeDop Level 2 SHAPE processor and the outputs SSH values were compared and analysed. For this study it was important to have a full chain of processing from Level 1A up to level 2, that produces geophysical variables such as SSH. The results showed that two different DeDop configurations impact the output SSH, the differences are significant and range about 20 cm and their standard deviation is about 5 cm, however the two configurations produced similar orbit averages in the region of interest. Comparison with the in situ measured temperature and salinity did not allow to choose any ‘better’ configuration. This could be caused by the low spatial resolution of the in-situ data which is between 10-50 km (see Section 2.3 for more information).

It is recommended to compare the high-resolution SAR altimetry outputs with the high resolution CTD that is of similar spatial resolution, this could be possible with other in situ data bases or different regions e.g. in the fjords of Svalbard.

4 Conclusions/Recommendations

Dedop tool is very useful to try different processing configurations and testing the effects on the waveform outputs (L1B). It allows for the assessment and comparison of the different processing options when processing the altimetry data from the Level 1A to Level 1B and 1BS.

We greatly recommend to extend the DeDop toolbox by the inclusion of Level 2 processing: retracking and geophysical corrections. It is not possible to assess the impact of different lower-level processing without analysing it impacts on the final output geophysical parameters such as SWH or SSH.

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