HYDROCOASTAL

SAR/SARin Radar Altimetry for Coastal Zone and Inland Water Level

Impact Assessment Report Processor Case Studies

Deliverable D3.1b

Sentinel-3 and Cryosat SAR/SARin Radar Altimetry for Coastal Zone and Inland Water

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1. Introduction

1.1. The HYDROCOASTAL Project

The objectives of the HYDROCOASTAL project, funded by the European Space Agency under the EO Science for Society programme, were to enhance the understanding of interactions between the inland water and coastal zone, between the coastal zone and the open ocean, and the small scale processes that govern these interactions. The project also aimed to improve the capability to characterize the variation at different time scales of inland water storage, exchanges with the ocean and the impact on regional sea-level changes.

To achieve these aims, the HYDROCOASTAL project team has developed and implemented new SAR altimeter processing algorithms for the coastal zone and inland waters, and with these processed Sentinel 3A, 3B and Cryosat-2 data to generate an initial 2-year Test Data Set for selected regions. The performance of these new algorithms was evaluated by statistical analyses and comparison against in situ data. From this analysis, the best performing algorithms were identified and a processing scheme implemented to generate a global scale coastal zone and inland water altimeter data set (described below).

In the final stage of the project, a series of case studies were implemented to assess these products in terms of their scientific impact on coastal and inland water studies. From these results, and other experience gathered during the project, a Scientific Road Map has been developed which contains a series of recommendations terms of priorities for further development of processing algorithms, recommendations for further SAR and SARin altimeter missions, priorities for further scientific research in the coastal zone and inland waters, to maximise the use and benefit of data from SAR and SARin altimeter missions.

1.2. HYDROCOASTAL Final Product

The HYDROCOASTAL final product was produced using innovative retracking algorithms for the coastal zone (UBonn Statistical STARS type: Buchhaupt et al, 2018, Roscher et al, 2107) and inland waters (DTU: Multiple Waveform Persistent Peak, MWaPP: Villadsen et al, 2016), which were selected as the best performing algorithms tested earlier in the project. The results of the evaluation of the performance of the algorithms are reported in the HYDROCOASTAL Product Validation Report (RD-08). The algorithms are fully described in the HYDROCOASTAL ATBD (RD-06).

To provide continuity between river and coastal water levels, the DTU MWaPP algorithm was applied to all regions, coastal and inland waters. The U Bonn STARS type retracker was applied only to Coastal Zone data. The product is provided at 3 levels:

- **L2E: Level 2 Extended Product**. Along track L2 product for all regions.
- **L3: Inland Waters, Water Level Time Series**. For all inland water regions.
- **L4: Inland Waters, River Discharge Time Series**. For selected inland water regions.

The source data are Sentinel 3A and Sentinel 3B SRAL L1a data, for all the operational mission to 30/09/2022 (S3A from 01/04/2016 to 30/09/2022, S3B from 11/05/2018 to 30/09/2022; South Australia starting from 01/01/2017) and Cryosat-2 SAR mode FBR data, for all the operational mission available in Baseline D (from 06/09/2010 to 21/08/2021). The format of the HYDROCOASTAL products is described in RD-07

The processor to L2 was implemented by isardSAT on a parallel processor virtual machine, with 64 threads, through a GBOX algorithm development and execution environment provided by EarthConsole (https://earthconsole.eu), funded by ESA Network of Resources sponsorship. In addition, the ESA Altimetry Virtual Lab on EarthConsole (https://earthconsole.eu/altimetry-virtual-lab/) SARvatore for Sentinel-3 service has been extensively used during the project for producing additional data sets with specific processing requirements, for comparison against the HYDROCOASTAL product. The Team is pleased to acknowledge the importance of this service for the altimetry community.

1.3. Impact Assessment Case Studies and the Scope of this Document

An important part of the HYDROCOASTAL project was a series of Impact Assessment Case Studies, the objective of which was to evaluate and report on the potential benefits offered by the new coastal zone and inland water processors, as implemented to generate the HYDROCOASTAL Final Product.

In total 13 Impact Assessment Case Studies were carried out, to investigate the capabilities of the HYDROCOASTAL product in a range of different inland water and coastal environments, and to investigate the potential improvements and benefits of possible further developments in SAR and SARin altimeter processing approaches.

This report summarises the key points of the five Processor case studies, highlights the major findings and summarises key recommendations.

1.4. Applicable Documents

AD-01: Sentinel-3 and CryoSat-2 SAR/SARin Radar Altimetry for COASTAL ZONE and INLAND WATER – Statement of Work, V1.0 10/01/2019 Ref: EOP-SD-SOW-2018-089.

1.5. Reference Documents

RD-01 HYDROCOASTAL Technical Proposal. V1.1 28/11/2019, SatOC and HYDROCOASTAL team.
RD-02 HYDROCOASTAL Implementation Proposal. V1.1 28/11/2019, SatOC and HYDROCOASTAL team.
RD-03 HYDROCOASTAL Management Proposal. V1.3 26/11/2019, SatOC and HYDROCOASTAL team
RD-04 HYDROCOASTAL Financial Proposal. V1.2 28/11/2019, SatOC and HYDROCOASTAL team
RD-05 HYDROCOASTAL Contractual Proposal. V 1.2 26/11/2019, SatOC and HYDROCOASTAL team
RD-06 HYDROCOASTAL Algorithm Theoretical Basis Document. V2.1, 23/06/2023. HYDROCOASTAL_ESA_ATBD_D1.3 HYDROCOASTAL Team
RD-07 HYDROCOASTAL Product Specification Document, V2.0, 20/06/23, HYDROCOASTAL_ESA_PSD_D2.3, HYDROCOASTAL Team
RD-08 HYDROCOASTAL Product Validation Report, V2.0, 25/07/22, HYDROCOASTAL_ESA_PVR_D2.5, HYDROCOASTAL Team
RD-09 Processor Case Study Report, L Recchia, Aresys 31/05/23. (Available on the HYDROCOASTAL Project web site)
RD-10 FFSAR Case Study Summary, P Garcia, isardSAT, 15/06/23. (Available on the HYDROCOASTAL Project web site)

RD-11 Coastal and FF-SAR processing of S6 data *Technical Note,* CCN#2, deliverable D2 P Garcia, F Gibert, A Granados, isardSAT. 25/07/23 Ref: HYDROCOASTAL_ESA_TN_CCN2_D2 (Available on the HYDROCOASTAL Project web site)
RD-12 Assessment of Closed Loop Mode Performance and Feasibility of an Open Loop Mode for SARin missions, A Homerin, Noveltis. April 2023 Ref: NOV-FE-0747-NT-013_Task_3_OLTC_SARin. (Available on the HYDROCOASTAL Project web site)

1.6. Document Organisation

After the introductory section 1, the next sections provide summaries of each of the processor case studies, and conclusions and recommendations are given in the final section.

2. Case Study 1: FFSAR Processing (Aresys)

2.1. Overview of Case Study

Aresys has developed its own in house Fully Focussed SAR processor which operates in the frequency domain, as an alternative to the more computationally expensive “Back-Projection” approach used by others.

In the Case Study for HYDROCOASTAL (RD-09) they investigated options for implementation in the multi-looking processing step, and also investigated different strategies to mitigate the impact of grating-lobes on the FFSAR waveforms (particularly over inland waters).

2.2. Main Scientific Findings

Multi-Looking

- A high posting rate will offer higher along-track resolution but averages fewer single waveforms so results in increased speckle noise.
- A new theoretical model has been developed which describes the standard deviation of noise reduction as a function of the number of samples averaged.
- A practical procedure has been developed to select the multi-looking step in function of the desired reduction in the noise standard deviation proposed.
- Figure 2.1 illustrates the model and can be used to select the posting rate required in order to meet a specified noise reduction.

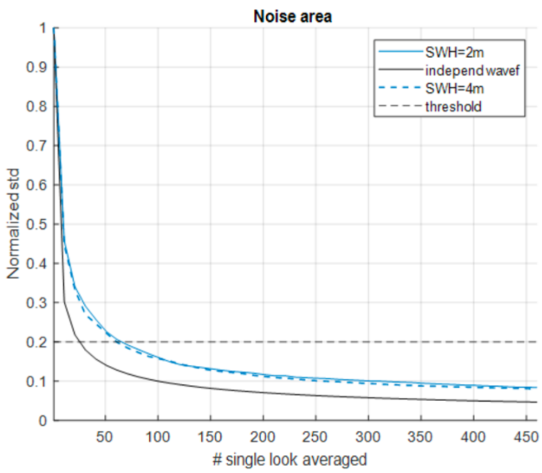


Figure 2.1 FFSAR processing, multi-looking analysis. Behaviour of two real data cases: To achieve a noise reduction of 80%, a posting rate of 151hz need to be employed for SWH about 2m (blue solid line) and a posting rate of 140hz for SWH about 4m (blue dashed line). It corresponds to 60 and 65 single-looks averaged respectively.

Grating Lobes Mitigation

- When a SAR altimeter operates in closed burst configuration (as for CryoSat-2 and Sentinel-3), the impulse response of the system includes replicas of the main signal – or grating lobes.

These replicas can create difficulties in FFSAR processing of waveforms, especially over inland water regions.

- A prototype approach is being developed to mitigate the impact of these “grating lobes” on the accurate retrieval of inland water levels. Figure 2.2 shows results achieved for a modelled example. An initial version of this approach has been included in an FF-SAR service developed for the ESA Altimetry Virtual Laboratory. The approach described here is a more robust implementation of that initial version. Further development and testing are still needed.

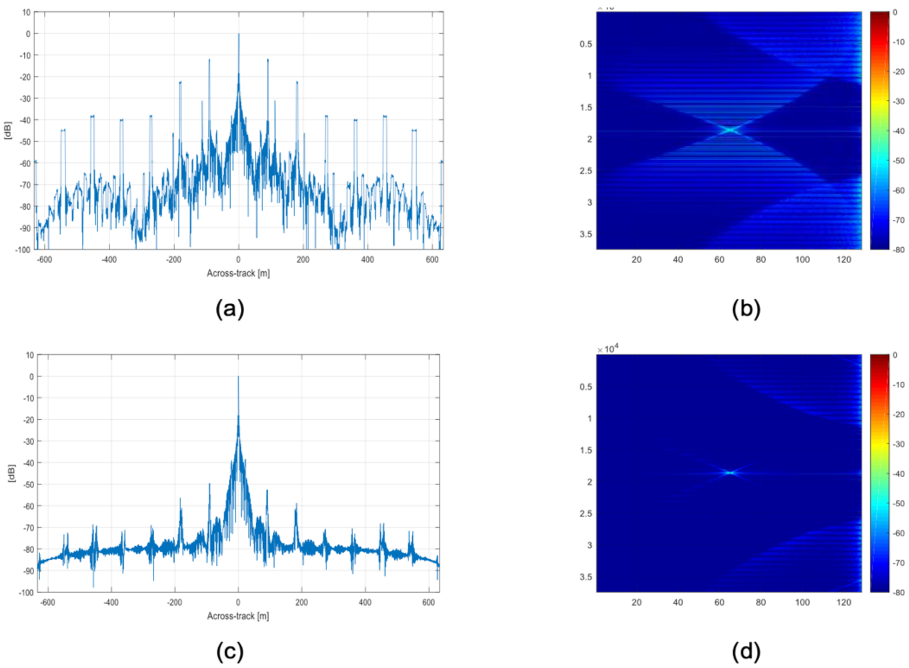


Figure 2.2 Visual impact of the application of the method proposed by Aresys for grating lobes mitigation. (a): azimuth cut of the point target shown in (b) in the 2D image. (c) Azimuth cut of the same point target after mitigation and (d) the 2D image

2.3. Main Recommendations

1. Recommend a systematic study for Fully Focussed SAR processing into the best processing options for different target areas, in terms of waveform identification / pre-processing, retracker selection, posting rate, illumination time.
    - Should include investigation of different inland, coastal and offshore target areas and include different sea-states (high wind / low wind, high SWH / low SWH, high tide / low tide), also off- nadir angle to target.
    - Output would be a matrix of processing recommendations for different targets and a “recipe” for FFSAR processing.
    - Should be based on a fast processor in the frequency domain.
2. The grating lobes study should be extended to provide specific recommendations for processing, considering e.g. the sizes of target that are affected.

3. Case Study 2: Attitude Errors and Along / Across Track Slope (Aresys)

3.1. Overview of Case Study

Precise attitude information is crucial for satellite altimetry, mispointing along-track and across-track results in errors in the estimated measurements. Aresys carried out a study to investigate attitude (roll and pitch errors) in the CryoSat-2, Sentinel 3A and Sentinel 3B altimeters (RD-09).

For CryoSat-2 roll errors can be estimated making use of the Interferometric SAR (SARin) capabilities of the SIRAL instrument and the results from the roll campaigns. Further estimates were made from data acquisitions over the Aegean Sea. However, the results were different from those acquired from the roll campaign, so it was concluded a longer acquisition period was necessary.

Pitch errors can be estimated based on an analysis of the L1B-S data stack, by analysing single look waveforms that should be illuminating the same ground location. Data from passes over the Aegean sea Again, high variability in results indicated a longer acquisition time period was required to provide more accurate results.

3.2. Main Scientific Findings

The estimate of bias in the roll estimate for CryoSat-2 was -0.1145 degrees, which is increasing in magnitude, in time by -53.85 mdeg / year. This results in a mean across-track slope error of 12.48 microradians, with a precision of 27.19 microradians.

Tables 3.1 and 3.2 summarise the results of pitch / slope correction bias analysis.

Mission	Pitch bias mean [deg]	Pitch bias standard deviation [deg]
Sentinel 3A	0.0088	0.0034
Sentinel 3B	-0.0079	0.0033
CryoSat-2	0.0109	0.0127

Table 3.1 Mean and standard deviation in pitch bias.

Mission	Slope correction mean [deg]	Slope correction standard deviation [deg]
Sentinel 3A	0.00015	0.00099
Sentinel 3B	0.00051	0.00189
CryoSat-2	-3.1e-17	0.00454

Table 3.2 Mean and standard deviation in slope correction

3.3. Main Recommendations

- A longer data acquisition period is required to provide more accurate estimates of along and across track slope errors in CryoSat-2, Sentinel 3A and Sentinel 3B.

4. Case Study 3: FFSAR Processing (isardSAT)

4.1. Overview of Case Study

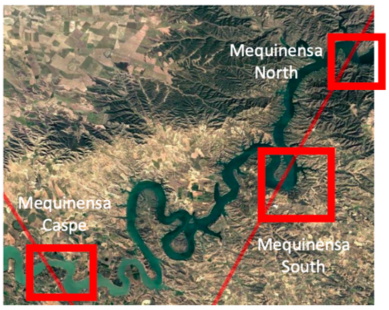
isardSAT carried out an investigation into Fully Focussed SAR processing by implementing an in-house isardSAT FFSAR processor to 1 year's (08/08/2021 – 16/08/2022) Sentinel-6 data over 4 targets in the Ebre Basin in northern Spain (Figure 4.1). (RD-10)

Sentinel-6 operates in an open burst mode, and so is better suited to FFSAR processing as it does not suffer from the same grating-lobe / replica problem of CryoSat-2 and Sentinel 3A/3B, investigated by Aresys.

The isardSAT Fully Focussed SAR processor is based on the back projection algorithm first developed by Egido and Smith (2017). The integration time was set to 3s, giving a single look spacing of 0.6m and a multi-look spacing of 5m. A simple re-tracker was used which was based on a Gaussian fit over the maximum power of the waveform. Initial waveform filtering was carried out to discard waveforms from non-nadir scatterers and waveforms with high peakiness.

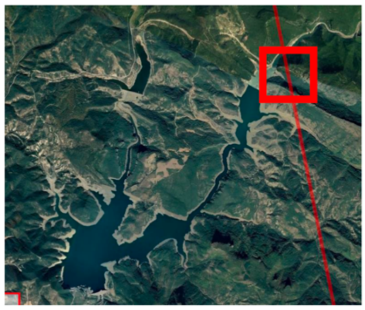
The water levels retrieved from FFSAR processing were compared to in-situ water level data, also to S6 level 2 products from ESA, and to results from a validation of the Sentinel-3 HYDROCOASTAL product for the same region.

Mequinensa



Pass	Track num.	Coordinates	Track length
Mequinensa – North	111	[41.4, 0.172]	700 - 1000 m
Mequinensa – South	111	[42.32, 0.114]	800 - 2000 m
Mequinensa – Caspe	248	[41.27, -0.08]	450 m

Itoiz



Location	Track number	Coordinates	Track length
Itoiz	248	[42.872, -1.331]	100 – 125 m

Figure 4.1 Images and coordinates of the isardSAT FFSAR study targets within the Ebre Basin, Sentinel 6 ground track overlaid in red.

The results of the comparisons are given in Table 4.1 and show a very large reduction in error bias and standard deviation. The average error standard deviation between the FFSAR processed data and the in-situ water level data was 4.5 cm, with a mean error bias of 2.5cm. The error std for the OCOG retracked unfocused SAR processed data ranged from 19cm to 1.09m.

The HYDROCOASTAL S3A product, with the DTU MWaPP retracker, showed rmse of 0.48 and 1.01m for Itoiz and Mequinaenza respectively (though not exactly the same locations).

Target	Method	Error bias [cm]	Error std [cm]	Avg number of waveforms per pass
Itoiz	FF-SAR	-0.1	3.7	20.3
	L2 OCOG	77.5	109	1.7
	L2 Ocean	-115	911	1.7
Mequinaenza-North	FF-SAR	1.2	4.9	100.1
	L2 OCOG	23.2	19	4.4
	L2 Ocean	32.3	18.3	4.4
Mequinaenza-South	FF-SAR	1.3	4.1	95
	L2 OCOG	48.2	57.7	3.3
	L2 Ocean	49	60.4	3.3
Mequinaenza-Cape	FF-SAR	7.5	5.15	103.3
	L2 OCOG	44.9	102	2.6
	L2 Ocean	44.5	118.5	2.6

Table 4.1 Results from the comparison of 1 year's Sentinel 6 data (FFSAR, L2 OCOG, L2 Ocean), against in-situ water level data for 4 targets in the Ebre basin

4.2. Main Scientific Findings

- Fully Focussed SAR processing of Sentinel-6 data over 4 small (< 2km) inland water targets, gave an average water level measurement accuracy of under 5cm, when compared to in situ data. This is a greater than 10 factor of improvement on data produced by unfocussed SAR processing.
- Fully Focussed SAR processing is a very promising technique for inland water monitoring, offering a very significant improvement in accuracy.

4.3. Main Recommendations

- It is recommended to carry out a similar, scale study, with an increased number and variety of targets included in the analysis to confirm its feasibility at a larger/global scale. Other processing options (e.g. illumination time) should also be considered.
  - A frequency domain ($\omega\kappa$) FFSAR processor should be implemented to reduce processing time
- It is recommended that future radar altimeters operate at open burst over inland waters to optimize the FFSAR performance and avoid undesired along-track replicas. Though current plans for S3-NG over inland is to operate at open burst, current plans for CRISTAL over land is to operate at close burst.

5. Case Study 4: CORS/ FFSAR with Sentinel-6 (isardSAT)

5.1. Overview of Case Study

This Case Study (RD-11_, carried out under HYDROCOASTAL CCN2, isardSAT, was composed of two parts:

- Implementation and assessment of the isardSAT CORS (Coastal Ocean Retracker for the Sentinels) processor on Sentinel-6 data over the Baltic Sea, California Coast and Aegean Sea.
- Implementation and assessment of the isardSAT FF-SAR processor to Sentinel-6 data over one specific track of interest on the coasts of the Aegean Sea islands.

The isardSAT CORS processor

The isardSAT CORS processor was initially developed in the CP4O project and has been developed since then. It works on the basis that sea surface elevations are not expected to vary considerably between consecutive records along track, using a refence range window location to set the initial tracking point, based on the mean sea surface for the location of the echo waveform. The waveform is then truncated around that range window reference location and re-tracked.

The CORS processor outputs of Sea Surface Height (SSH), Significant Wave Height (SWH) and sigma0 were assessed in terms of the noise level as a function of distance from the coast and compared to values calculated for the EUMETSAT L2 product. Because of some inaccuracies identified in the GSHHS coastline, previously used to calculate the distance to coast, the open source Open Street Map (OSM) coastline was instead used. The results of the analysis are summarised in Table 5.1. The results for Greece and California are illustrated in Figure 5.1

Area	SSH	SWH	Sigma0
Greece	81.51 %	36.5 %	25.97 %
Baltic	76.51 %	12.76 %	2.6 %
California	59.34 %	-21.18 %	-148.75 %

Table 5.1 Noise improvement ratio of the SSH, SWH and sigma0 from the isardSAT CORS processor compared to the EUMETSAT L2 product, for each of the three areas considered.

Typically, the noise level tends to increase at around 8 km from the coast, where the tracking window starts to show the impact of interferences from coastal environments. These interferences are originated usually by land bright targets or specular coastal waters. Some of these targets are sufficiently bright to cause the retracker to follow them for several consecutive records

The noise improvement ratio for SSH is over 50% for all 3 areas, and close to 80% for Baltic and Greece. In the SSH plots in Figure 5.1 (top row) the wide margin of SSH noise improvement is clearly evident for distances close to the coast (within 7km).

The greatest improvements, in terms of noise, are observed in the retrieved Sea Surface Height and the best improvements are seen in the Greece region. Improvements in SWH and Sigma0 were also seen for the Greece region, with smaller improvements in the Baltic, and apparent reductions in performance for the California region.

Further analysis indicates that the SWH from the CORS processor shows lower noise (than the EUMETSAT data) to within 2-3km of the coast. Closer to the coast, SWH becomes very noisy in both EUMETSAT and CORS data. It was concluded that it was difficult to retrieve valid sigma0 values close to the coast from both EUMETSAT and CORS data.

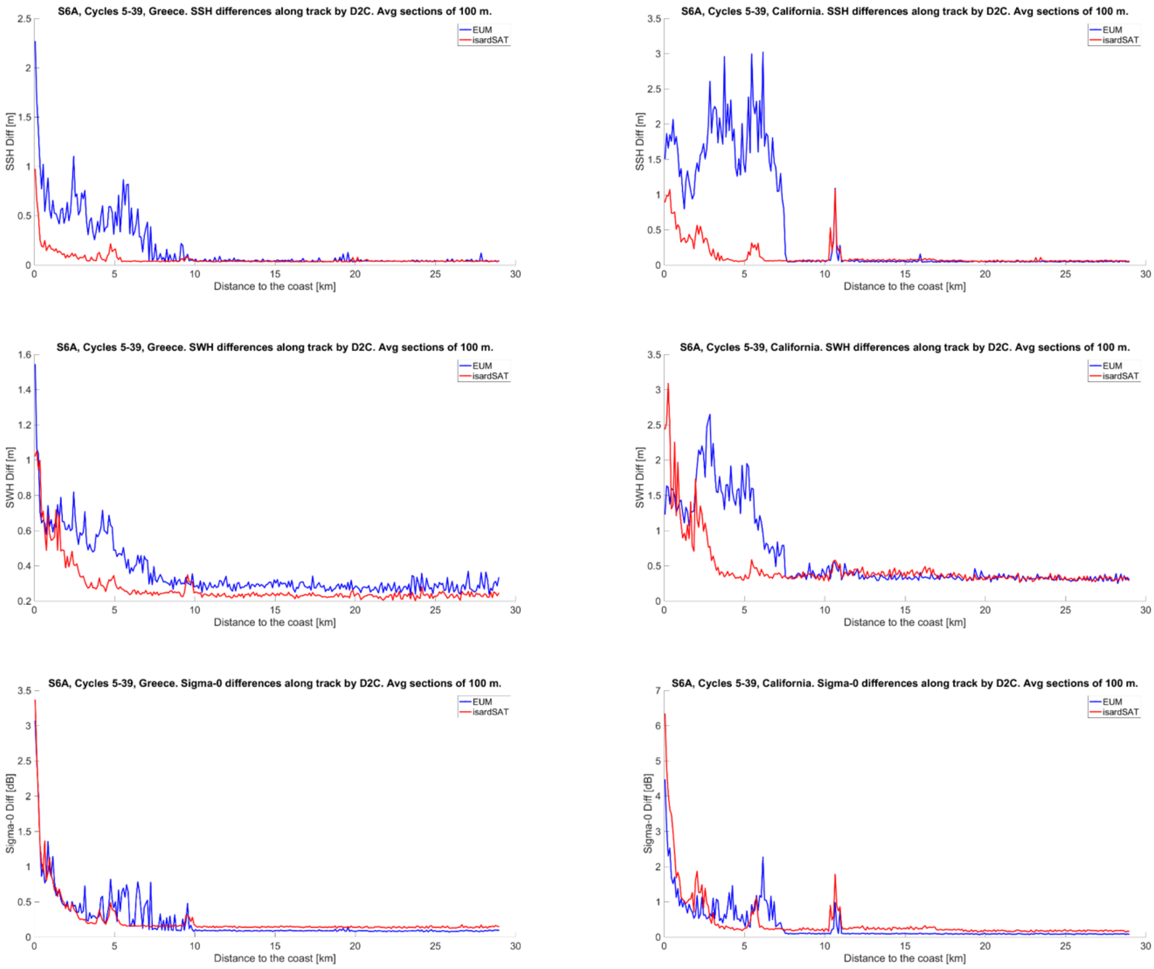


Figure 5.1 SSH / SWH / Sigma0 noise along track versus distance to the coast. Left Column Greece Area of Interest, Right Column, California Area of Interest.

Power Spectral Density (PSD) plots show the amount of energy of the measured science altimeter signal at different ocean spatial scales (Figure 5.2). The plots in Figure 5.2 were produced after filtering for avoiding anomalous Sea State conditions, which adds a considerable amount of noise to the PSD figure in form of oscillations or inconsistencies.

The most important information we can extract from these plots is the reduction of noise along all the wavelengths of the CORS processor with respect to the EUMETSAT solution.

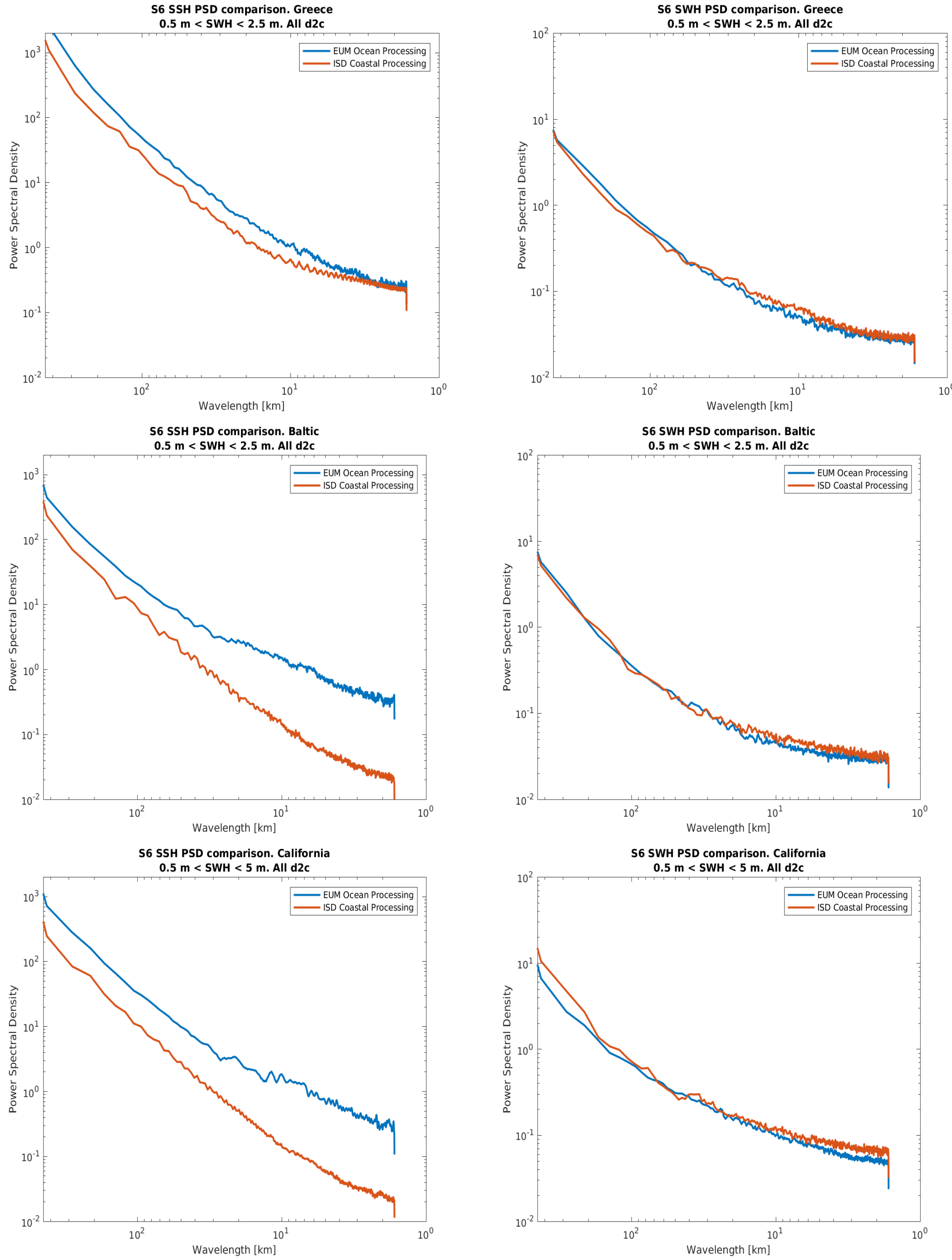


Figure 5.2 Power Spectral Density plots for Greece, Baltic, and California areas of interest. Left Column SSH, Right Column SWH

Usually, when analysing PSD plots, we can observe the following:

- In the longest wavelengths the different solutions lines tend to similar values, representing the true large scale ocean dynamics signal.

- In very small scales the figures also converge, as the noise represented is related to the intrinsic instrument speckle noise.
- The larger differences are usually located in the mesoscale area of the plot (5 km to tenths of kms).

The results we observe from the CORS and EUMETSAT plots in Figure 5.2 are generally in agreement with the above three points. But there is a fundamental difference in the current analysis: we are observing Coastal Ocean signals, and the level of reduction of noise, especially in the SSH series, is also represented in the figures. This is why we see in the Baltic and Greece zones at almost all wavelengths a very high amount of SSH improvement in the spectra behaviour of the CORS with respect to the EUMETSAT one, a kind of result that is difficult to observe in Open Ocean analysis.

Another conclusion we can extract is that the level of improvement of the SSH noise is not that high when the SWH retrievals are higher (California). This coincides with observations in other coastal processor studies. The CORS performance over Sea Ice surfaces (Baltic in winter) is not degraded.

Also, and in agreement with the results shown in Table 5.1 the PSD observations of noise improvement are much better for the SSH series than for the SWH series. In the SWH case, the higher improvement is observed specifically at mesoscale regions, and proportional to the SWH: better results in higher spatial scales for higher SWH (California), and better results in lower spatial scales for lower SWH (Greece).

The isardSAT FFSAR processor

The isardSAT FFSAR processor was applied to Sentinel-6 data for a track (pass 94) across the Aegean Sea and compared to output from unfocused (Delay Doppler) SAR processing. Figure 5.2 shows the differences in the radargrams from the two processors.

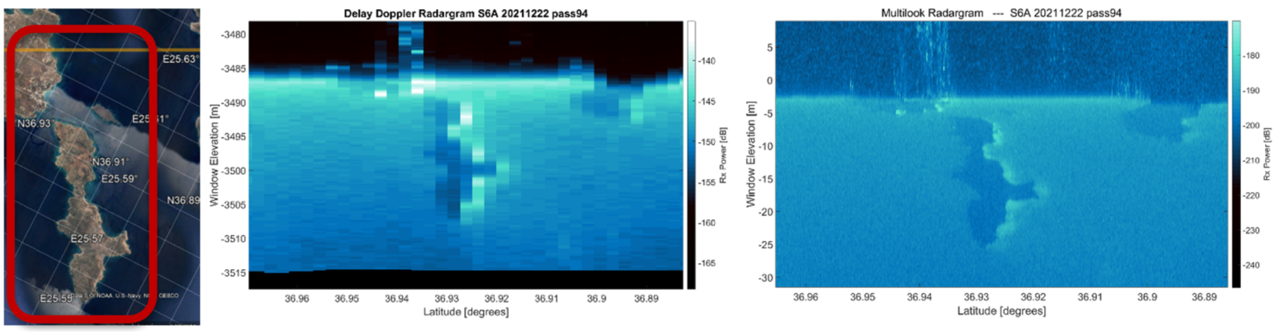


Figure 5.3 Image of an island in the Aegean Sea close to the Sentinel-6 pass, and examples of the associated radargrams from unfocused delay Doppler processing (left) and fully focused processing (right)

For the fully focused processing an integration time of 4.75s, factor of 2 in zero-padding (range direction), 0.4m single look spacing, and 10-300m multi-look spacing were applied. The FF processed waveforms were re-tracked with an ocean re-tracker and the coastal re-tracker. Results were compared to the EUMETSAT unfocused L2 data, and to isardSAT L2 unfocused processing using its in house ocean and coastal re-trackers. Results are summarised in table 5.2.

	Products	Std SSH [m]	Std σ^0 [dB]	Std SWH [m]
Open Ocean with Ocean re-tracker	DD L2 EUM	0.0249	0.0753	0.2269

	DD L2 ISD	0.0245	0.0754	0.2174
	FF L2 ISD SL=0.4 ML=300	0.0220	0.0976	0.1933
Coastal with Ocean re-tracker / Coastal re-tracker	DD L2 EUM	0.1962	0.4711	0.3819
	DD L2 ISD	0.0646 / 0.0349	0.4479 / 0.4772	0.3970 / 0.2755
	FF L2 ISD SL=0.4 ML=300	0.0583 / 0.0571	0.4268 / 0.4557	0.1870 / 0.1543

Table 5.2. Summary of performances over open ocean with the analytical ocean retracker and over a coastal area retracked with either the same analytical ocean retracker and with the coastal retracker, both for DD and FF-SAR.

Thus fully focused SAR processing provides similar noise performance to the L2 data in open water for SSH, sigma0 and SWH. At the coast the isardSAT coastal re-tracker provided the best results for SSH.
A further analysis looked at fully focused SAR processing to higher along track resolutions of 100m and 50m and showed similar performances for SSH at the higher resolutions, but an increase in noise in retrieved sigma0 and SWH.

5.2. Main Scientific Findings

The isardSAT CORS processor

- The isardSAT CORS processor, applied to Sentinel-6 data, provides significant reduction (60%-80%) in noise in retrieved SSH. At less than 0.5km from the coast it shows less noise in SSH than the EUMETSAT solution at 7km.
- For SWH the CORS data show an improvement up to 2-3 km offshore, while from that point to the coast, it starts showing a worse behaviour.
- For sigma0 it is hard to extract valid conclusions, due to the high amount of invalid data.

The isardSAT FFSAR processor

- FF-SAR processed data over coastal areas, processed at a resolution of 300m and re-tracked with dedicated coastal re-trackers, exceeds the current performances achieved by operational Delay-Doppler processing,
- A further analysis looked at FF-SAR processing to higher along track resolutions of 100m and 50m and showed similar performances for SSH at the higher resolutions, but an increase in noise in retrieved sigma0 and SWH.
- In terms of along-track noise, FF-SAR data retracked with the coastal re-tracker reports improved results for SSH and SWH with respect to any L2 DD-based solution.
- The FF-SAR data retracked with the isardSAT coastal re-tracker improves retrievals up to about 36% in SSH and 65% in SWH at an improved along-track resolution of 50 m.

5.3. Main Recommendations

- Further developments to the CORS processor are recommended, to improve the performance for SWH and Sigma0, and to understand sea state impacts on the performance of the processor.

- A further analysis is required to develop recommendations for the best option in terms of unfocused and fully focused processing at the coast, this should include an analysis on the effect of sea state, swell, and the relative angle of swell propagation and ground track orientation.

6. Case Study 5: Assessment of Closed Loop Performance and Assessment of Open Loop Tracking (Noveltis)

6.1. Overview of Case Study

In this study Noveltis analysed the performance of CryoSat-2 data over the European Alps, in terms of retrieval of water levels from inland waters (RD-12). For SARIN operations, Cryosat-2 operates in “closed loop” mode, where the initial tracking point is based on previously retrieved heights and height rate. The “Open Loop” tracking mode instead uses an on-board digital elevation model to provide an ‘a priori’ estimate of the expected height.

Noveltis analysed CryoSat-2 SARin data over rivers and lakes in mountainous and level terrain.

A reference elevation model from (GDEM) ACE2 was used to derive levels at virtual stations for water bodies under the CryoSat-2 satellite track using a specially derived water mask. These heights were references to WGS84. A number of case study areas were considered (Lake Garda, Lake Geneva, Lake Victoria, W Siberian Lakes) to allow a comparison of terrain with different morphology.

It was clearly shown that whilst accurate water level estimates could reliably be retrieved from inland waters in more level terrain (e.g. W Siberia), accurate water levels could not be reliably retrieved in mountainous areas (see Figures 6.1 and 6.2).

To investigate biases, the height of the ACE2 reference DEM was sampled under each point of closest approach, and the difference calculated between this reference and the measured height. The distribution and magnitude of the biases between both datasets was then compared, after filtering out the points flagged with height errors (Figure 6.3). In the Alps zone, even though the points with height errors have been filtered out, 22% of the points in the Alps still show a bias of more than 50 meters, whereas more than 98% of the points from the Siberian Lakes dataset show biases under 20 meters.

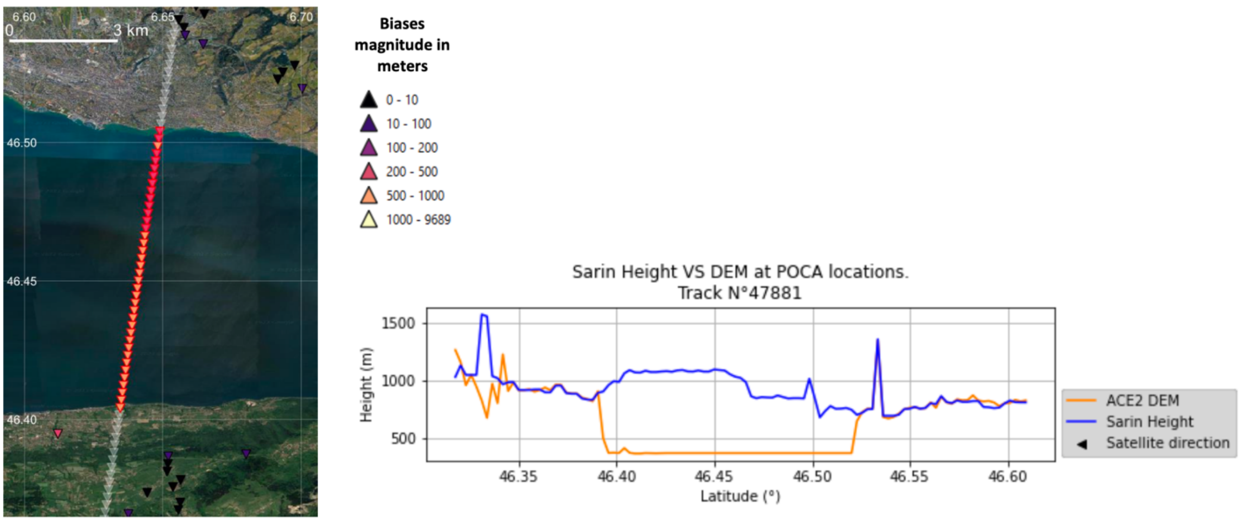


Figure 6.1 Results from Noveltis analysis of CryoSat-2 data (orbit 47881) over Lake Geneva. Left: Coloured triangles indicate the height bias relative to in-situ data, Right: Compares the CroySat-2 SARin retrieved height to the ACE2 DEM height

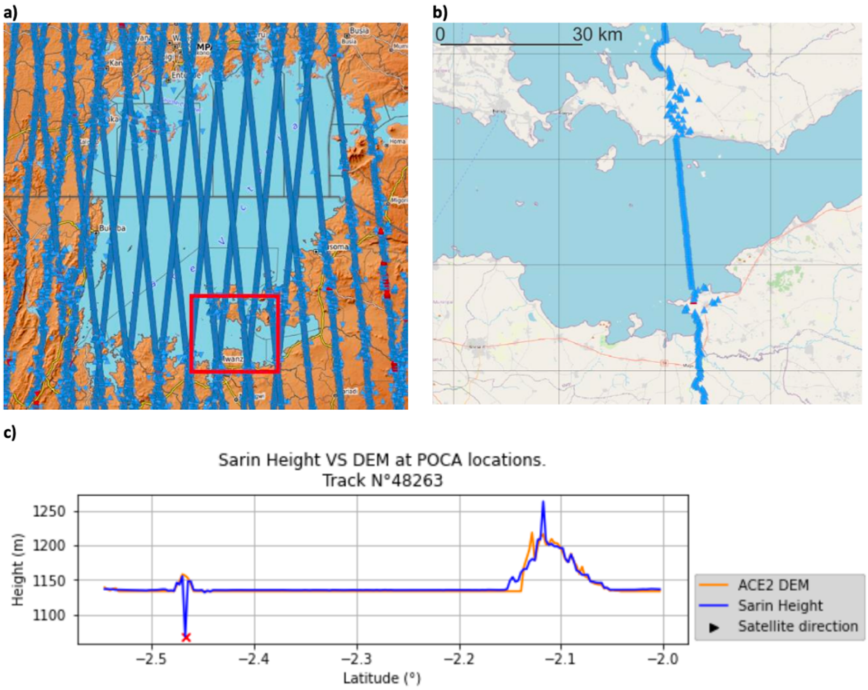


Figure 6.2 (a) Overview of the sub-satellite points of closest approach (POCA) over Lake Victoria. The POCAs are represented by triangles oriented according to the satellite direction. The points flagged with height errors are coloured in red, and the others in blue. The red square shows the area where we focus on orbit N°48263, isolated in b). c) shows its measured elevation profile, compared to the ACE 2 DEM, sampled under the POCAs. The POCAs flagged with height errors are shown by a red cross on the plot.

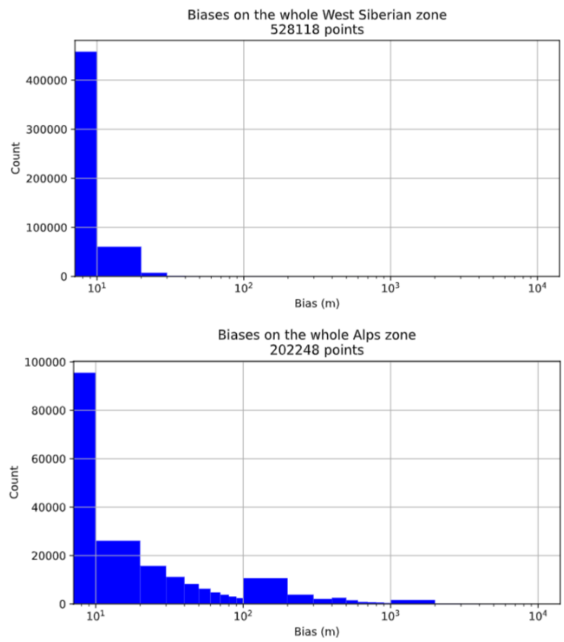


Figure 6.3 Biases in the West Siberian and Alps zones, with the ACE 2 DEM as reference

6.2. Main Scientific Findings

- When in closed loop mode CryoSat-2 SARin data show large errors in retrieving water level for mountainous areas.
- 22% of points in the Alps show a bias of more than 50m, whereas 98% of points in W Siberian lakes show biases of less than 20m.

6.3. Main Recommendations

- Using satellites to monitor inland water heights in mountainous areas is crucial: mountain lakes and rivers supply the downstream hydrographical network and are located in areas that can be difficult to access for in-situ measurements.
- Open Loop Tracking on a SARin altimeter could enhance data acquisition for both lakes and rivers - incorporation of DEM should help centring the radar's reception window and significantly improve the results.
- CryoSat-2's dense coverage offers the potential to monitor a vast number of water bodies.
- It is recommended that an Open Loop Tracking Mode is considered for the CRISTAL mission over inland water bodies.

7. Summary and Conclusions

7.1. Overview of Processing Case Studies

Six Case studies are reported in this document:

1. Aresys has developed and implemented a frequency domain Fully Focused SAR (FFSAR) altimeter Processor, which is more computationally efficient than the previously implemented back projection approach. They proposed a practical approach to determine the optimal posting rate to achieve a specified noise reduction; and have developed a prototype approach to mitigate the impact of replicas or grating lobes on processing waveforms reflected from inland water surfaces.
2. Aresys carried out an analysis to estimate pitch and roll attitude errors and hence along / across track slope errors for the CryoSat2 and Sentinel 3A and 3B missions.
3. isardSAT applied their in-house FFSAR processor to Sentinel-6 data over inland water targets and analysed by validation against in-situ data.
4. isardSAT applied their coastal and FFSAR processors to Sentinel-6 data over coastal regions.
5. Noveltis carried out an assessment of the performance of Cryosat-2 SARIn mode data over inland waters and analysed the impact of the closed loop processing that is operationally implemented.

7.2. Major Scientific Findings of Processing Case Studies

FFSAR Processing (Aresys)

- A high posting rate will offer higher along-track resolution but averages fewer single waveforms so results in increased speckle noise.
- When a SAR altimeter operates in closed burst configuration (as for CryoSat-2 and Sentinel-3), the impulse response of the system includes replicas of the main signal – or grating lobes. These replicas can create difficulties in FFSAR processing of waveforms, especially over inland water regions. A prototype approach is being developed to mitigate the impact of these “grating lobes” on the accurate retrieval of inland water levels.

Attitude Errors and Along / Across track slope (Aresys)

- Estimates in roll bias and across track slope error have been calculated for Cryosat-2
- Estimates in pitch bias and along track slope error have been calculated for Cryosat-2, Sentinel 3A and Sentinel 3B.

FFSAR processing – inland waters (isardSAT)

- Fully Focussed SAR processing of Sentinel-6 data over 4 small (< 2km) inland water targets, gave an average water level measurement precision of under 5cm, when compared to in situ data. This is a greater than 10 factor of improvement on data produced by unfocussed SAR processing.
- Fully Focussed SAR processing is a very promising technique for inland water monitoring, offering a very significant improvement in precision.

CORS / FFSAR processing – coastal zone (isardSAT)

- The isardSAT CORS processor, applied to Sentinel-6 data, provides significant reduction (60%-80%) in noise in retrieved SSH. At less than 0.5km from the coast it shows less noise in SSH than the EUMETSAT solution at 7km.
- For SWH the CORS data show an improvement up to 2-3 km offshore, while from that point to the coast, it starts showing a worse behaviour.
- For sigma0 it is hard to extract valid conclusions, due to the high amount of invalid data.
- FF-SAR processed data over coastal areas, processed at a resolution of 300m and re-tracked with dedicated coastal re-trackers, exceeds the current performances achieved by operational Delay-Doppler processing,
- Analysis of fully focused SAR processing to higher along track resolutions of 100m and 50m showed similar performances for SSH at the higher resolutions, but an increase in noise in retrieved sigma0 and SWH.
- In terms of along-track noise, FF-SAR data retracked with the coastal re-tracker reports improved results for SSH and SWH with respect to any L2 Delay Doppler based solution.
- The FF-SAR data retracked with the isardSAT coastal re-tracker improves retrievals up to about 36% in SSH and 65% in SWH at an improved along-track resolution of 50 m.

Assessment of Closed and Open Loop Tracking (Noveltis)

- When in closed loop mode CryoSat-2 SARin data show large errors in retrieving water level for mountainous areas.
- 22% of points in the Alps show a bias of more than 50m, whereas 98% of points in W Siberian lakes show biases of less than 20m.

7.3. Impact Assessment from Processing Case Studies - Summary

A main objective of the Impact Assessment Reports is to summarise the results of the case studies in terms of the impact on scientific and operational applications that the HYDROCOASTAL Final Products can provide.

The Processing Case studies are different from the Coastal Zone and Inland Water Case Studies as they have not assessed the HYDROCOASTAL Final Products directly, but rather considered further improvements that can be made. Therefore, in this section we summarise the potential impact offered by new developments.

The isardSAT CORS processor offers an improvement in noise close to the coastline, particularly in SSH. Its application requires no external information beyond the mean sea surface that is already available in standard L2 altimeter products. Thus applied, it can support improved monitoring of the coastal zone, closer to the coast than was previously possible (to within less than 1km).

Fully Focused SAR altimeter processing offers a major impact both for inland water and coastal zone studies. For the coastal zone it can provide SSH measurements to within 100m of the shore, and SWH to within 0.5km of the shore. It can also provide higher along track resolution, supporting the identification and study of small-scale coastal features. For inland waters FFSAR processing offers the capability to monitor smaller targets than unfocused SAR processing, again at higher along-track resolution. The case studies have demonstrated techniques to identify optimum processing choices, and to minimise the effects of grating lobes for closed burst altimeters. A frequency domain FFSAR processor is recommended to allow faster processing.

Open Loop tracking, if applied to SARIn mode altimeters, will support much enhanced monitoring of inland waters over mountainous terrain. These areas are very important for inland water monitoring. Mountain lakes and rivers supply the downstream hydrographical network and are located in areas that can be difficult to access for in-situ measurements.

7.4. Main Recommendations from Processing Case Studies

1. Recommend a systematic study for Fully Focussed SAR processing into the best processing options for different target areas, in terms of waveform identification / pre-processing, retracker selection, posting rate, illumination time.
    - Should include investigation of different inland, coastal and offshore target areas and include different sea-states (high wind / low wind, high SWH / low SWH, high tide / low tide), also off- nadir angle to target.
    - Output would be a matrix of processing recommendations for different targets and a “recipe” for FFSAR processing.
    - Should be based on a fast processor in the frequency domain.
2. The (Aresys) grating lobes study should be extended to provide specific recommendations for processing, considering e.g. the sizes of target that are affected.
3. The (Aresys) attitude error study should be extended with a longer data acquisition period to provide more accurate estimates of along and across track slope errors in CryoSat-2, Sentinel 3A and Sentinel 3B.
4. It is recommended that future radar altimeters operate at open burst over inland waters to optimize the FFSAR performance and avoid undesired along-track replicas. It is noted that current plans for S3-Next Generation is to operate at open burst over inland waters, the current plan for CRISTAL is to operate at close burst over land.
5. Further developments to the CORS processor are recommended, to improve the performance for SWH and Sigma0, and to understand sea state impacts on the performance of the processor.
6. A further analysis is required to develop recommendations for the best option in terms of unfocused and fully focused processing at the coast, this should include an analysis on the effect of sea state, swell, and the relative angle of swell propagation and ground track orientation.
7. It is recommended that an Open Loop Tracking Mode is considered for the CRISTAL mission over inland water bodies.
    - Using satellites to monitor inland water heights in mountainous areas is crucial: mountain lakes and rivers supply the downstream hydrographical network and are located in areas that can be difficult to access for in-situ measurements.
    - Open Loop Tracking on a SARin altimeter could enhance data acquisition for both lakes and rivers - incorporation of DEM should help centring the radar’s reception window and significantly improve the results.
    - CryoSat-2 and Cristal’s dense orbit coverage offers the potential to monitor a vast number of water bodies.

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