HYDROCOASTAL

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

Impact Assessment Report Coastal Zone

Deliverable D3.1

Sentinel-3 and CryoSat-2 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/B (S3A/B) and CryoSat-2 (CS2) 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 UBonn STARS type re-tracker 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, used 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 individual Coastal Zone 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 Case Study: Impact Assessment Report of the Bristol Channel and Severn Estuary (SYMAT/NOC/SatOC).
RD-09 HYDROCOASTAL Case Study of the Baltic, German Bight and Elbe Estuary (University of Bonn).
RD-10 HYDROCOASTAL Case Study of the Northern Adriatic Sea (CNR-IBF, CNR-ISP).
RD-11 HYDROCOASTAL Case study: Saline intrusion in the Ebro Delta (isardSAT).
RD-12 HYDROCOASTAL Impact Assessment Report - Data Assimilation. Ref: HYDROCOASTAL_ESA_IAR_D2.7. Issue: 1.0 (TU Delft, Deltares).

1.6. Document Organisation

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

2. Case Study 1: Bristol Channel and Severn Estuary (SKYMAT/NOC/SatOC)

2.1. Overview of Case Study

This case study examines the Bristol Channel and Severn Estuary, which have one of the largest tidal ranges in the world, ranging between 10 m at the entrance to the channel, to approximately 14 m at the eastern end of the channel (RD-08). The key objective of this impact assessment report is to establish if the new re-trackers improve the satellite's performance compared with what is otherwise available. The outcome of this analysis will determine if more valid data points are captured closer to the coast, and if the accuracy of the observations close to the coast has improved. In a wider context, the satellites' improved performance will enable a better understanding of interactions and processes between river discharge and coastal sea level. Three re-trackers are assessed: UBonn, DTU and operational ESA for S3A/B and CS2 by validating these satellite observations against tide gauge measurements. The outcome of this validation will enable us to assess the potential beneficial impact of these new datasets, compared to what is otherwise available.

The noise is defined as the absolute successive differences in Uncorrected Sea Surface Height (USSH = Altitude - Range) along each track. The USSH noise is then binned at 1 km resolution as a function of distance to the coast. The noise level from USSH for S3A/B and CS2 is shown in Table 2.1.

2.2. Main Scientific Findings

- Data not usable in the [0 - 1] km of track segment (first column of results in Table 2.1).
- In terms of noise (S3A/B and CS2): UBonn shows lower noise level (apart from the spike at 10 km from the coast) (Table 2.1).
- In terms of validation:
  TWLE (Total Water Level Envelope): DTU outperforms UBonn and ESA (S3A/B and CS2). (Figure 2.1).
  SLA (Sea Level Anomaly): Although the UBonn re-tracker had the overall best SLA performance (Figure 2.1), DTU re-tracker did perform better from five out of seven tide gauges.
- Tidal model for SLA validation (S3A/B): FES2014 was used to estimate SLA, but this model (with 34 components) could not reproduce the entire tidal regime in the study area.
- Tidal model for SLA validation (CS2): FES2004 has fewer constituents than FES2014.

2.3. Main Recommendations

- Use of Sea State Bias Correction (SSB), WTC/DTC (Wet and Dry Troposphere Corrections) from UPorto to estimate TWLE and SLA.
- Tidal removal from the tide gauges using the same constituents as in FES2014 (S3A/B) has to be made with caution for the SLA validation. The number of constituents in FES2004 (CS2) is not appropriate to remove tides from tide gauges for the Bristol Channel / Severn Estuary region.
- Given the similarity in performance in the DTU and UBonn re-trackers, we recommend use of the DTU re-tracker close to the coast to provide continuity with the water levels for the inflowing rivers (which are also provided by the DTU re-tracker).
- For future work, the DTU re-tracker should be implemented into new datasets in the coastal and inshore regions.

Table 2.1. Summary of Sentinel-3A, Sentinel-3B and CryoSat-2 noise level (m) from Uncorrected Sea Surface Height (USSH) observations as a function of distance to the coast.

Sentinel-3A

	Distance to the Coast (km)			
	1 km	2 km	Varied Distance (specified below)	
ESA	0.18	0.05	0.03 (4 to 10 km)	
U. BONN	0.05	0.03	0.02 (3 to 9 km)	0.01 (10 km)
DTU	0.12	0.07	0.06 (3 to 9 km)	0.07 (10 km)

Sentinel-3B

	Distance to the Coast (km)					
	1 km	2 km	Varied Distance (specified below)			
ESA	0.20	0.07	0.08 (3 to 4 km)	0.06 (5km)	0.04 (6km)	0.03 (7 to 18 km)
U. BONN	0.04	0.03	0.02 (3 to 9 km)	0.02 (4 to 9km)	0.03 (10 km)	0.01 (11 to 18 km)
DTU	0.12	0.06 to 0.07 (2 to 18 km)				

CryoSat-2

	Distance to the Coast (km)			
	1 km	2 km	Varied Distance (specified below)	
ESA	0.21	0.07	0.04 to 0.05 (3 to 18 km)	
U. BONN	0.05	0.04	0.03 (3 to 10 km)	0.02 (11 to 18 km)
DTU	0.12	0.06 to 0.07 (2 to 18 km)		

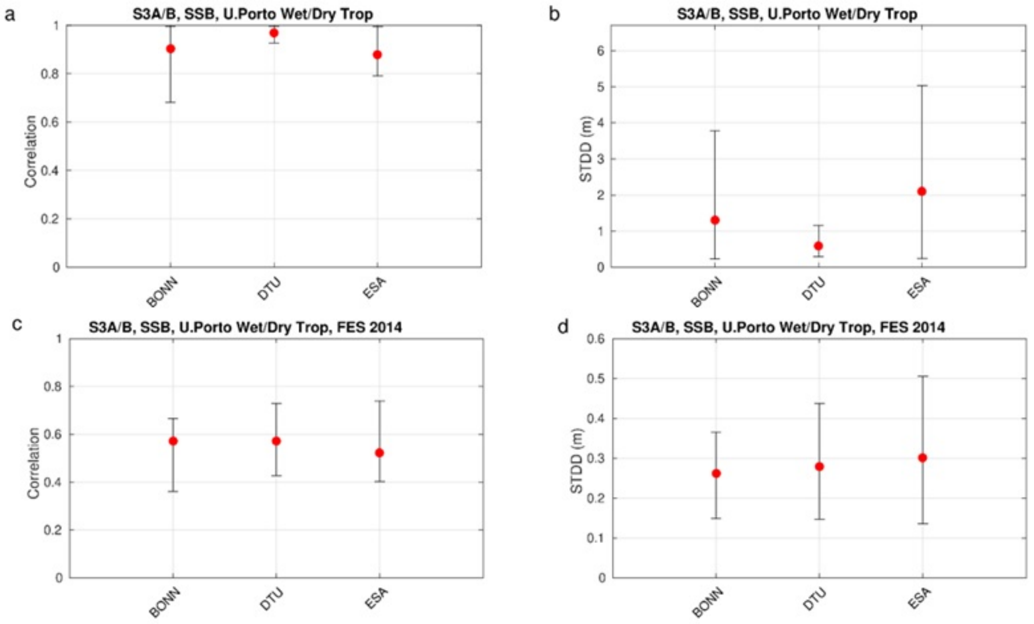

Figure 2.1. Correlation (a) and STDD (Standard Deviation of Differences) (b) between tide gauge and S3A/B TWLE measurements (SSB, DTC/WTC from UPorto corrections) averaged over 2-15 km from the coast. Red filled in circles denote average over the seven tide gauges while the whiskers represent the range of values. Here, no FES2014 ocean tide correction was applied. Correlation (c) and STDD (d) between tide gauge and S3A/B SLA measurements (FES2014 applied).

3. Case Study 2: Baltic, German Bight and Elbe Estuary (University of Bonn)

3.1. Overview of Case Study

This case study investigates the impact of improved altimetry data in monitoring the ocean-to-river continuum (RD09). The selected region, the German coast of the Baltic and North Sea with the Elbe Estuary, offers a dense network of in situ data and model simulations. The results of the analysis presented in this study are separated for the Elbe Estuary and for the coastal zone. The goal is to evaluate the performance of UBonn, DTU and operational ESA products for S3A/B and CS2. Firstly, by estimating accuracy and precision, with additional analysis to the validation phase, and then going to a possible application of the data, here towards sea level change and extremes. These data were compared to two external products: An unfocused SAR altimeter Sentinel 3 product produced by the SARVATORE for Sentinel-3 service part of the ESA Altimetry Virtual Lab (https://earthconsole.eu/groups/altimetry/), using the SAMOSA+ re-tracker (Dinardo et al., 2020), and a fully focused SAR altimeter Sentinel 3 product, produced by a UBonn implementation of the CLS FFSAR processor (https://github.com/cls-obsnadir-dev/SMAP-FFSAR), also using the SAMOSA+ re-tracker.

3.2. Main Scientific Findings

The case-study in coastal zone and estuary shows that altimeter data exploitation is possible very near to coast. Contamination by land can however not be eliminated either by Unfocused SAR or in Fully Focused SAR altimeter processing. Accuracy (SLA) found in the Baltic was: 5 - 10 cm, German Bight: 20 - 40 cm, and Elbe Estuary: 50 - 100 cm (Figure 3.1). There is a clear consistency between the three satellite-based independent products. UBonn and DTU comparisons against tide gauge are in a very good agreement (Table 3.1). Some interesting findings are found:

- Binned method is the preferable method in the construction of the time-series.
- FES 2014 is the best tidal model in the region.

Satellite altimetry in such an environment gives continuity of observations from open ocean through the coast and inland. The comparison of results over different estuaries can give a better understanding. Working with ocean models for estuaries is mandatory.

3.3. Main Recommendations

- Further investigation of Fully Focused SAR capability.
- To take into account the difference of FFSAR results in sea and river, bays, lakes, carry out a detailed analysis of the waveform contamination in all cases.
- To investigate results from SWOT.
- Elbe is a good cal/val test area for the 1-day SWOT, and all Sentinel-3/6 missions.
- For investigation of absolute SSH, accurate bathymetric information is required.
- To consider river discharge and tidal discharge, wind, currents in further studies.

Table 3.1. Summary of Sentinel-3A median and mean accuracy over 10 stations (coastal zone: German Bight) selecting the minimum and mean STDD methods. Values are in metres.

Minimum std	DTU: UPorto-FES	ESA: UPorto-FES	U.Bonn: UPorto-FES
Median	**0.112**	0.120	0.116
Mean	0.121	0.126	0.129

Median std	DTU: UPorto-FES	ESA: UPorto-FES	U.Bonn: UPorto-FES
Median	0.177	0.175	**0.172**
Mean	0.199	0.194	0.198

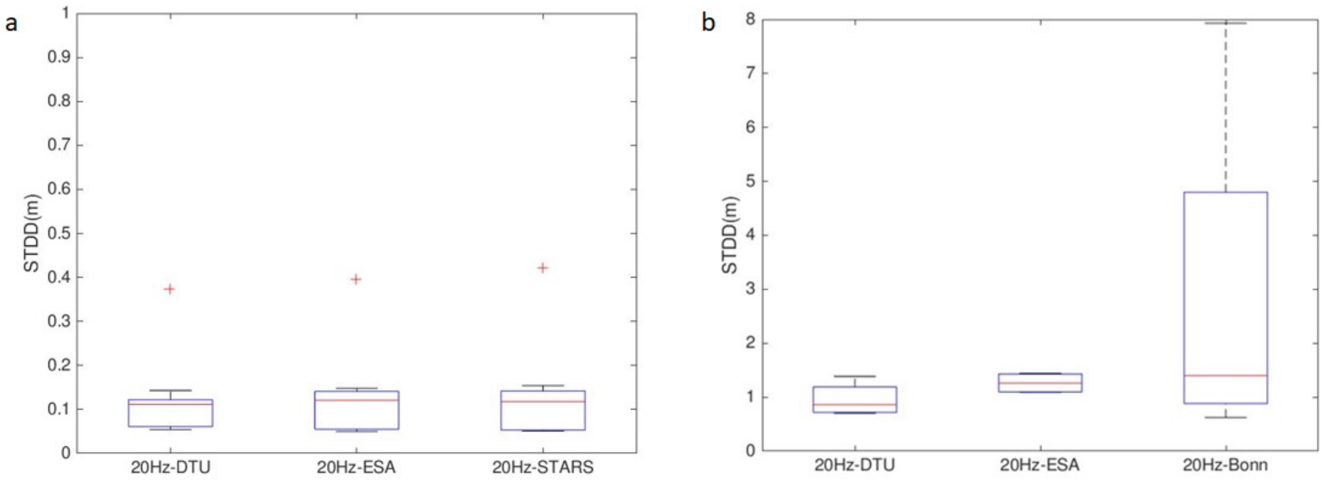

Figure 3.1. Boxplot for selection of minimum standard deviation and median over the coastal zone (a) and estuary (b).

4. Case 3: Northern Adriatic Sea (CNR-IBF, CNR-ISP)

4.1. Overview of Case Study

The Northern Adriatic Sea, with Veneto and Friuli-Venezia Giulia regions has about 2.400 km^2 of low-lying areas along 300 km of coast. Some important inland water basins are found in this coastal zone: The lagoons of Marano-Grado and Venice, and the Po River with its delta. These areas are exposed to sea level rise and storm surge related risks. Coastal lagoons are similar to lakes but connected to the ocean. Coastal lagoons are a geographically well-defined typology, possibly protected from wave action and exposed to weaker and less persistent winds. The results of the analysis presented in this study (RD-10) are separated for the lagoon areas and for the coastal zone. The main objectives of this study are (i) to assess the HYDROCOASTAL products (generated by the UBonn, DTU and ESA "standard"-SAMOSA2 re-trackers) and a data set generated by the P-PRO (former G-POD) service using the SAMOSA+ re-tracker, in the lagoons and the adjacent coastal areas (S3A/B and CS2); (ii) to show that coastal lagoon altimetry can be more accurate than coastal offshore altimetry; (iii) to demonstrate the benefits and the scientific value of an improved lagoon altimetry product, also for storm surge monitoring and forecast applications; and (iv) To investigate the limits and the potential of novel altimetry products in a complex yet fragile environment, subject to profound and sudden developments led by anthropic drivers (tourism, commerce, navigation, industry and fishery).

4.2. Main Scientific Findings

Marano-Grado Lagoon:

- Altimeter data can be exploited in the lagoon.
- DTU2018 MSS performs better. Interpolation from gridded MSS is better than from 1 Hz along-track products (De Biasio and Vignudelli, 2023).
- FES2014 in the lagoon showed good agreement with Tide Gauges.
- Inside the lagoon, DTU gives lower levels of noise respect to UBonn and ESA re-trackers, even if UBonn has a much lower bias than DTU (Table 4.1). On the seaside, UBonn and DTU have similar performance, which are better than GPOD and standard ESA product.
- 80 Hz along-track data instead of 20 Hz might be more appropriate in lagoons to better mask land / water surfaces. The improvements of using the 80 Hz posting rate have been analysed in terms of precision in Egido et al. (2021) and accuracy in Aldarias et al. (2020).

Venice Lagoon:

- TWLE: Storm surge events were used to analyse the performance of the re-trackers. UBonn and DTU re-trackers perform well in the lagoon during the events and much better than ESA. DTU and UBonn re-trackers give better results also closer to land in the coastal zone, with respect to ESA (Figure 4.1).
- The MSS vertical references might play a key role in both lagoon and coastal zones (De Biasio and Vignudelli, 2023).
- More work is needed for wind speed. The wind speed calculated from the S3A/B normalised radar backscatter values has to be considered as indicative using Abdalla's algorithm (Abdalla, S., 2007). Moreover, CS2 files do not contain the field: *atm_cor_sig0*, needed to compute the wind speed using Abdalla's algorithm. Thus, the wind speed could not be derived at all for the CS2 mission. In addition to this, the Abdalla algorithm was intended for open ocean and tuned with buoys and ECMWF TL511 model wind at global scale. These are some of a few constraints that could not be adopted in our test study site, where the measurements were over the coastal zone/lagoon, no buoys were available, and the sampling was at 20 Hz.

4.3. Main Recommendations

- Specular and quasi-specular echoes are seen as recurrent and precious for lagoon altimetry; they can be the key for bringing altimetry further inside sheltered areas (e.g., bays) than ever before. It is recommended to extend the analysis to other lagoons.
- Specular echoes in lagoons could be used for calibration of radar altimetry, as they can be seen as a handy laboratory for understanding the interaction of active microwaves, water, and land.
- Marano-Grado Lagoon suggested as cal/val area for the S3B, Sentinel-6 and ICESat-2 missions, a laboratory where a better understanding of radar reflectance at the sea is facilitated, thanks to existing infrastructures and easy logistics.
- Further analyses are recommended to investigate the physics of echoes and how they relate to surface types and wind conditions.
- Regionalization of range, wind, and significant wave height algorithms, as the interface of sea and land, the coastal zone, has different characteristics than global ocean, and is also of paramount interest for the monitoring of sea level rise and for storm surge applications.
- An improved MSS is necessary and should be computed using the new reprocessed 20/80 Hz data.
- Consistent MSS and geoid are necessary to join sea and land properly. We recommend a dedicated study to assess MSS and geoid and the northern Adriatic Sea is a good laboratory to test with the local ITALGEO geoid.
- We need all the parameters (TWLE, wind and waves) for storm surge applications. TWLE improved thanks to retracking. Wind amplitude and SWH (Significant Wave Height) are not mature for exploitation yet.
- Establishing a common vertical datum (geoid) for storm surge studies at regional level to integrate all height measuring systems and exploit satellite radar altimetry for inundation assessments.
- Re-computing a coastal MSS with high-resolution SSH for better understanding ocean dynamics and for non-repeating tracks. Examining the effects of different MSS references and the opportunity of defining an MSS tuned for storm surge applications.
- Exploiting novel methodologies for sea surface height determination, based on specular reflection, as they can be more accurate for geodetic and cal/val applications in the coastal zone.
- Exploiting the extra resolution (80 Hz or less) possible by reprocessing individual echoes.
- Improving the revisiting and exploring the possible advantage of a constellation of small altimeters, as the storm surge signal is much higher than the background level and therefore might require a reduced radar payload.
- Investigate how the new HYDROCOASTAL product could be optimally exploited in the reanalyses of storm surge events and in the operational context if the satellite is flying at the time of the event.
- Stimulate the development of new high-resolution land-sea masks, possibly with a dynamic approach that could account for the tidal dynamics in the coastal strip and in coastal lagoons.

Table 4.1. Statistical indicators for TWLE anomaly from S3B (Lalt-Ltg) in the Marano-Grado lagoon region. Values are in metres.

LAGOON	ESA	UBONN	DTU	GPOD
BIAS	-0.56	0.06	-0.37	0.09
MAE	0.70	0.09	0.37	0.07
MAD	0.14	0.08	0.03	0.05
CRMSD	0.45	0.14	0.06	0.14
RMSD	0.72	0.15	0.37	0.17

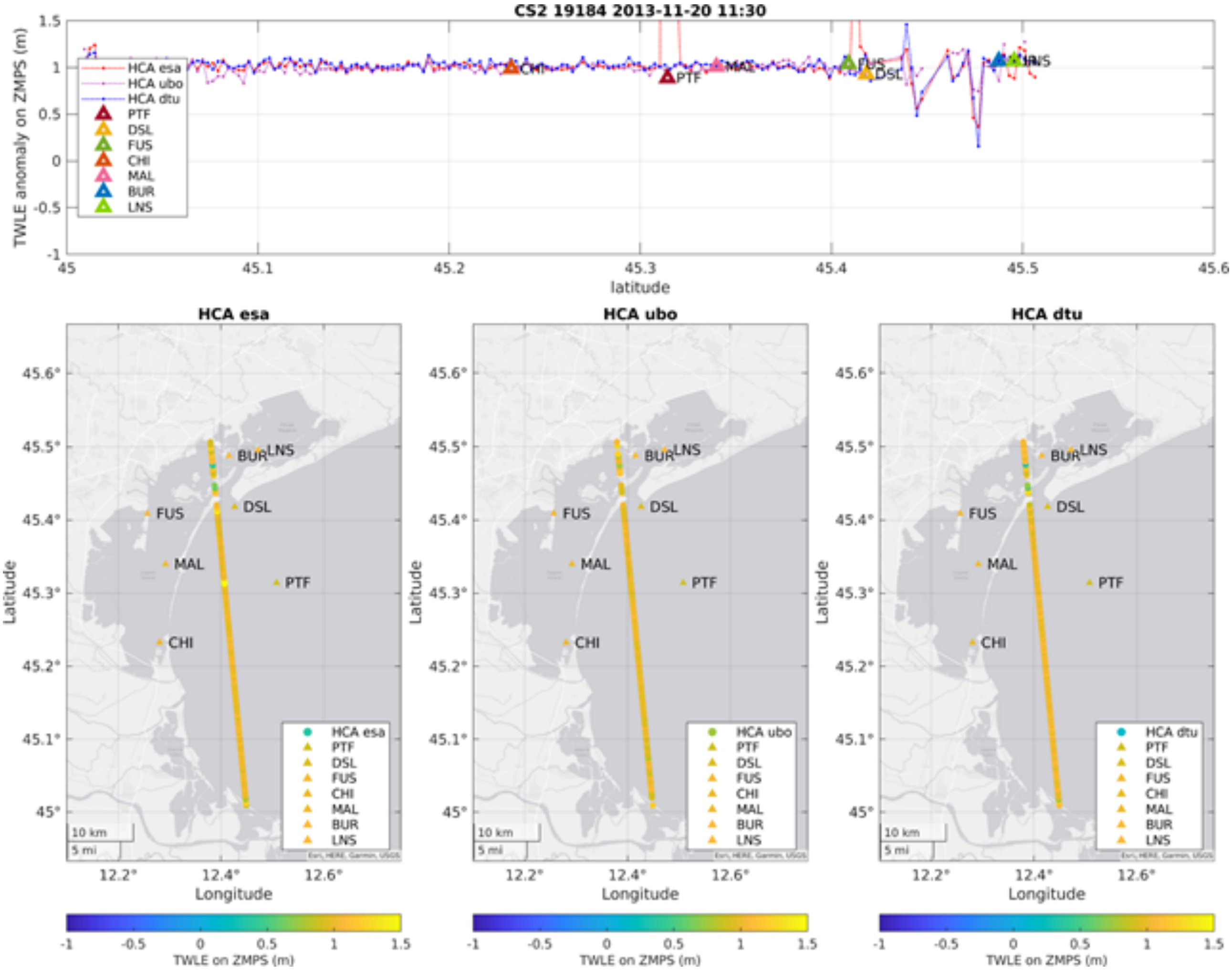

Figure 4.1. Total water level envelope anomalies as seen by CS2 orbit 2464 over the Venice Lagoon and the coastal zone, and by several tide gauges and weather stations. Upper panel: plot of the TWLE from the three re-trackers (ESA, UBONN, DTU) versus latitude. Bottom panels: same as above but geolocated on the map.

5. Case Study 4: Saline intrusion in the Ebro Delta (isardSAT)

5.1. Overview of Case Study

The objective of this study (RD-11) is to assess the possibility of calculating the Sea Level Rise (SLR, henceforth) close to the Ebro River Delta using altimetry data from Sentinel-3, in order to improve saline intrusion empirical models which only consider the river discharge.

Two S3A tracks were analysed to determine the sea level close to two coastal regions of interest, specifically, the bays surrounding the Ebro Delta (Fangars and Alfacs bay). In addition to the aforementioned S3A tracks, two S3B tracks were used to study how the proximity to the coast (up to 30 km) influences the sea level measurements. The validation was performed using the data from a buoy located 50 km away from the delta. The products used in the analysis were: UBonn, ESA SAMOSA2.5 and OCOG from Sentinel-3A. The UBonn re-tracker was officially accepted as the more effective retracker in coastal regions. This was also supported by an internal study, where UBonn and DTU were compared in the Ebro Delta region. The results indicated that the noise level generated by UBonn re-tracker was significantly smaller than DTU's The data were binned in space (1 km) for noise quantification and in time (monthly averages) for SLR determination. Time span for analysis: 7 years. Note that SWH and U10 are not used in the impact assessment study. Two analyses were made:

- Level of noise from water level time series.
- Sea Level Rise determination (three methods were applied).

Statistical approach: Average of the absolute water level differences (noise) and three methods for SLR.

5.2. Main Scientific Findings

In terms of noise:
- UBonn shows lower noise level and greater number of valid points (both study areas) (Table 5.1).

In terms of SLR:
- More time is needed to accurately estimate SLR (at least 10 years) (Figure 5.1). The third method to estimate SLR (low pass filter after linear regression) shows the lowest uncertainty.

5.3. Main Recommendations

- The impact of the improved coastal products in SLR estimation could not be properly evaluated due to the relatively short time series duration. At least 10 years are needed to get estimations of SLR with acceptable levels of uncertainty.
- With the current length of data records, SLR derived from HYDROCOASTAL products seem to diverge from baseline products even at relatively large distances from the coast. It would be recommended to assess the impact of the improved products in SLR estimations in other areas to confirm these preliminary results and revise them when longer datasets are available.

Table 5.1. Noise measurements of the sea level time series close the Ebro Delta.

	AASLD (m) – Number of points		
Retrackers	Alfacs bay (inside)	Alfacs bay (outside)	Fangars bay
UBO	0,16 – 173	0,11 – 174	0,20 – 86
ESA OCEAN	1,67 – 172	0,76 – 172	0,55 – 84
ESA OCOG	2,22 – 172	1,43 – 172	1,45 – 84

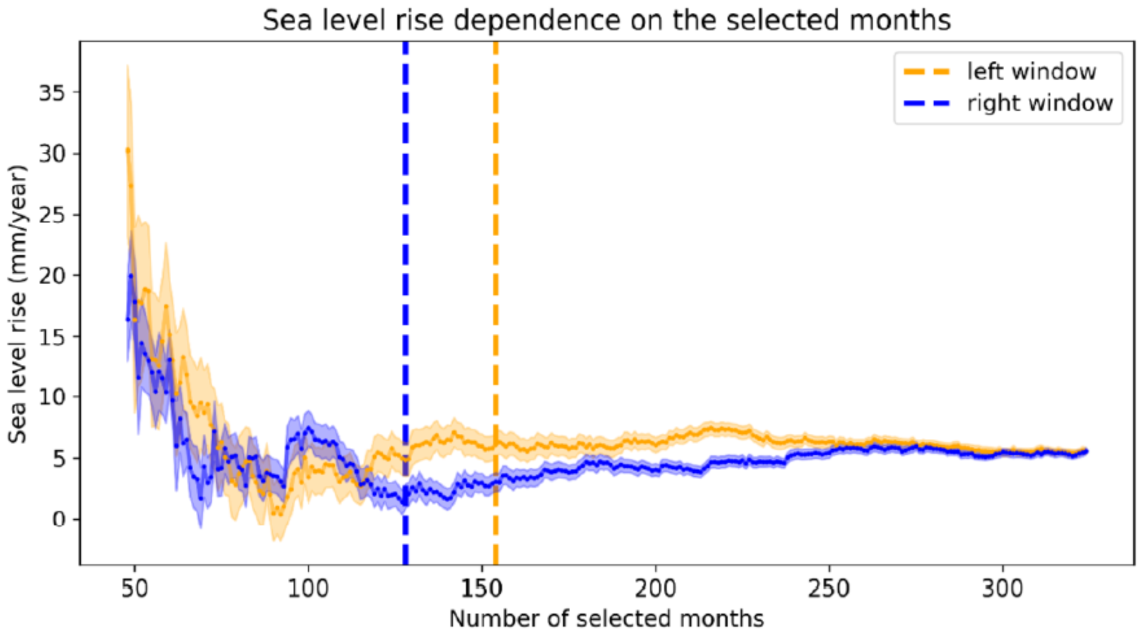

Figure 5.1. Sea Level Rise dependency on the time span measured for the data from the buoy of Tarragona. The dashed lines indicate the number of months at which the uncertainty (the shadow) reached a value below 1 mm. AASLD – Average of Absolute Sea Level Difference (measure of noise).

6. Case Study 5: Impact Assessment Report - Data Assimilation (TU Delft - Deltares)

6.1. Overview of Case Study

The main objective of this impact study is to explore whether satellite altimeter data can be used to improve storm surge models for operational forecasting of water levels (RD-12). Doing so would largely increase the number of locations for which data are available. Specifically, we aim to improve the low-frequency water level variability of the regional, high-resolution, 2D tide-surge Dutch Continental Shelf Model version 7 (DCSM) in Dutch coastal waters by the assimilation of Topex-Poseidon, Jason (TPJ)-derived low-frequency water levels and to validate the approach by using S3 water levels. The added value of using S3 water levels as control data is that these data allow us to get much closer to the coast. The S3 data being used in this study are produced in the context of the HYDROCOASTAL project. A secondary objective is to assess the performance of i) the DCSM-derived tide-surge water levels compared to the FES tidal and DAC surge water levels, ii) the various re-tracker products included in the HYDROCOASTAL data product (UBonn, DTU and ESA SAMOSA2.5), and iii) an in-house developed unfocussed SAR product produced at a posting rate of 80 Hz (Guameri et al., 2023).

6.2. Main Scientific Findings

- Computing sea level anomalies (i.e., water levels corrected for tides and surge) requires consideration of the nonlinear tide-surge interactions. Over the North Sea, well known for the nonlinear interactions between tides and surge, we observed a 10 cm (i.e., more than 50%) reduction of the median SD when using the DCSM-derived tide-surge water levels compared to the use of the FES tidal and DAC surge water levels included in the HYDROCOASTAL product (Figure 6.1).
- In the coastal waters of the southern North Sea, the UBonn re-tracker provides the lowest median SDs of the residual water level time series up to 1.5 km off the coast (differences in median SD reach approximately 7.5 cm) and beyond 10.5 km off the coast (differences in median SD compared to the ESA re-tracker are on the order of 1–2 cm). Between 1.5 and 10.5 km it is the ESA re-tracker (differences in median SD reach approximately 6.5 cm). In the coastal waters, the UBonn re-tracker provides the lowest number of water levels.
- Outside the area covered by the Sentinel-3 L2 LAND product, the results of the ESA re-tracker in the HYDROCOASTAL product are in many cases unreliable. Water levels gradually rise to tens of metres. The quality flag included in the product does not label these data as unreliable.
- Processing SAR data at higher posting rates may allow more data to be retrieved in coastal waters. In this study, we analysed the potential of an in-house developed unfocussed SAR product generated at a posting rate of 80 Hz. In doing so, we used all data acquired along the track with relative orbit number 370. The median SDs as a function of distance to the coast are comparable to the ones obtained with the ESA re-tracker. We do, however, obtain significantly more data.

6.3. Main Recommendations

- Provide tide-surge water level corrections in future (coastal) altimeter products obtained from a model considering the nonlinear interactions.

- Assess the potential of SAR altimeter data processed at higher posting rates. In this study, we only considered one track. More research is needed to determine whether usage of higher posting rates generally results in more data.
- Assess the performance of assimilating TPJ-derived low-frequency water levels compared to the performance of the approach that relies on coastal tide gauges.

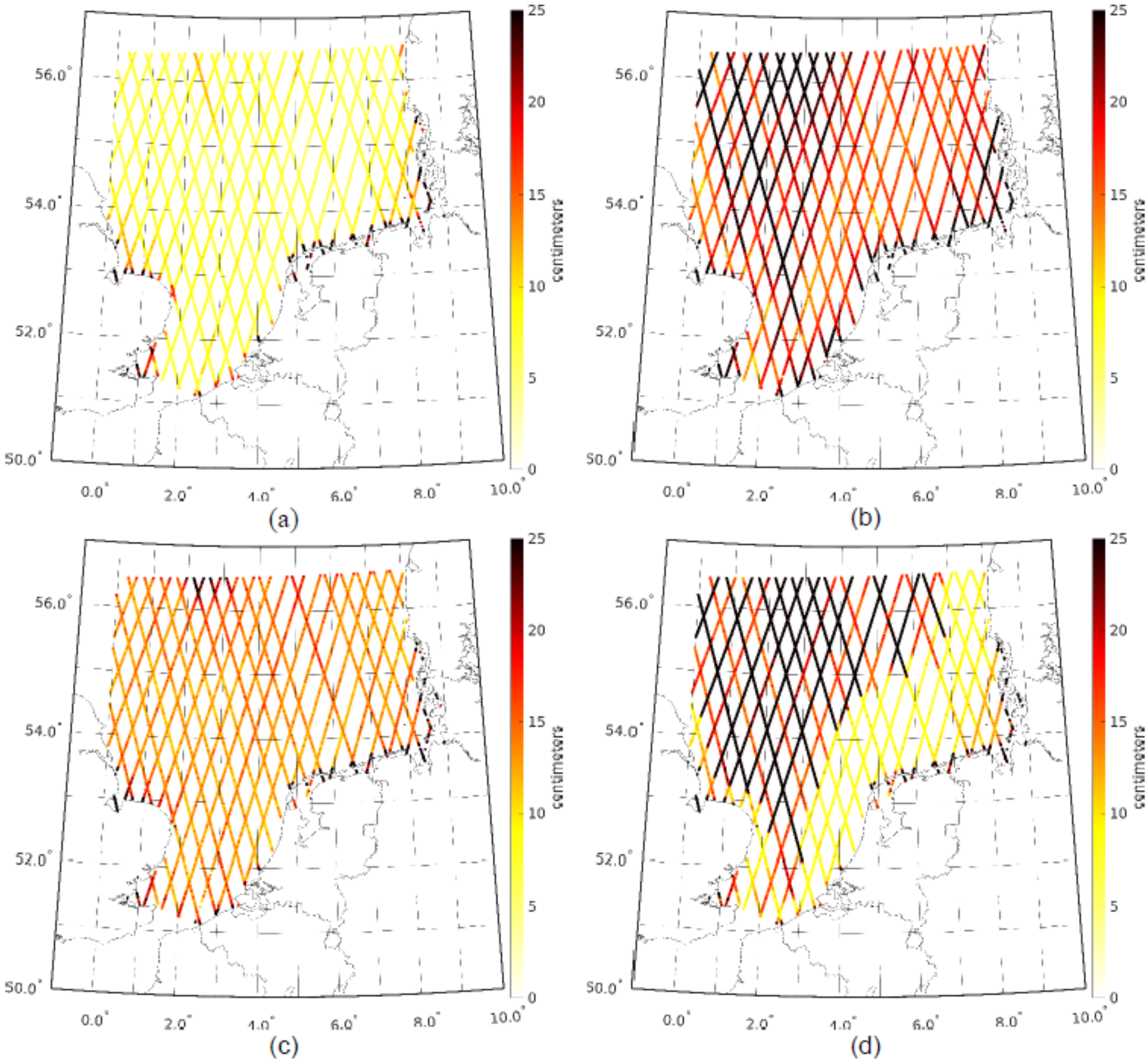

Figure 6.1. Standard deviations of the S3 residual water level time series covering the period 2017 to 2021. The S3 sea surface heights were obtained with the UBonn re-tracker ((a) and (b)), the DTU re-tracker (c), and the ESA re-tracker (d). In (a), (c), and (d) the residual water levels were computed by removing the DCSM tide-surge water levels obtained with the 'model-only' simulation. In (b), we removed the FES tidal and DAC surge water levels. Note that we only included the time series for which the number of points ≥ 30.

7. Summary and Conclusions

7.1. Overview of Case Studies

The Impact Assessment Report covered 5 study zones with different tidal regimes, hydrodynamic conditions, and sea-land interactions:

- Bristol Channel and Severn Estuary (SKYMAT / NOC / SatOC): Three re-trackers were assessed: UBonn, DTU and operational ESA for Sentinel 3A/B (S3A/B) and CryoSat-2 (CS2) by validating these satellite observations against tide gauge measurements.
- Baltic, German Bight and Elbe Estuary (University of Bonn): The goal was to evaluate the performance of UBonn, DTU; operational ESA products for S3A/B and CS2; and Fully Focussed SAR altimeter products.
- Northern Adriatic Sea: Marano-Grado and Venice lagoons (CNR-IBF / CNR-ISP): To assess the HYDROCOASTAL products (UBonn, DTU, ESA standard product) and P-PRO SAMOSA+ in the lagoons and the adjacent coastal areas (S3A/B and CS2).
- Ebro Delta (isardSAT): The objective was to assess the possibility of calculating Sea Level Rise close to the River Ebro Delta. The products analysed were: UBonn, ESA SAMOSA2.5 and OCOG from S3A.
- Wadden Sea (TU Delft / Deltares): The main objective of this study was to explore whether TOPEX/Jason-derived low-frequency water levels can be used to improve the low-frequency water level variability in a tide-surge model. The Sentinel-3 data being used in this study to assess the impact are produced in the context of the HYDROCOASTAL project (UBonn, DTU and ESA SAMOSA2.5).

7.2. Major Scientific Findings

Here, a summary of the major findings is provided:

- Precision (noise level):
  - Bristol Channel and Severn Estuary: UBonn shows lower noise level in comparison to DTU and ESA re-trackers.
  - Marano-Grado lagoon: UBonn and DTU give lower levels of noise with respect to ESA re-tracker.
  - Ebro Delta: UBonn shows lower noise level in comparison to ESA Ocean (SAMOSA 2.5) and ESA OCOG re-trackers.
- Accuracy (comparisons against tide gauges):
  - Bristol Channel and Severn Estuary:
    TWLE: DTU outperforms UBonn and ESA.
    SLA: UBonn re-tracker had the overall best SLA performance, DTU re-tracker did perform better for five out of seven tide gauges.
  - Baltic, German Bight, Elbe Estuary:
    SLA: UBonn and DTU comparisons against tide gauges are in a very good agreement.
  - Marano-Grado lagoon:
    TWLE offshore: DTU and UBonn re-trackers show similar accuracy, though DTU performs better than UBonn but with a higher number of outliers.
    TWLE inside the lagoon: UBonn and GPOD SAMOSA+ perform similarly. However, if DTU MSS had been used for DTU and ESA ranges, their bias and

RMSD would have been much lower, and the DTU re-tracker would have produced at least similar global performance (accuracy and precision) to that of UBonn.
- Wadden Sea (not a comparison against tide gauges):
  ADT: UBonn outperforms DTU and ESA in the [0 - 1.5] km and >= 10 km offshore. ESA shows the best performance between 1.5 and 10 km off the coast.

- Venice lagoon: TWLE (UBonn and DTU) at the time of storm surge events is often comparable to the tide gauge measurements and also much improved with respect to the state-of-the-art ESA product.
- Wadden Sea: The DCSM-derived tide-surge water levels outperform the water levels obtained with the FES and DAC corrections.

7.3. Impact Assessment from Coastal Zones 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 precision of the re-trackers has been assessed in three locations: Bristol Channel and Severn Estuary (U.K.), Marano-Grado lagoon (Italy) and Ebro Delta (Spain). The UBonn re-tracker gives the best performance in the U.K. coast (in comparison to DTU and ESA) and in the Spanish coast (in comparison to ESA SAMOSA 2.5 and ESA OCOG re-trackers). In the Marano-Grado lagoon, DTU is comparable to UBonn, if not better, as long as DTU-2018 MSS is used.

The accuracy of the re-trackers was also quantified in most of the study areas using times series of SLA, TWLE and ADT. DTU and UBonn have the same level of accuracy, and they are more accurate than the ESA product in most of the locations analysed.

In summary, the HYDROCOASTAL final product was found to provide higher precision and more accurate measurements of sea surface heights, across a range of coastal locations. This was assessed in terms of along-track noise (precision), and in comparisons against in situ measurements (accuracy). The Impact Assessment Reports demonstrate that in most of the cases UBonn outperforms the other re-trackers in terms of precision (in Marano-Grado lagoon UBonn and DTU performs similarly). DTU and UBonn have the same level of accuracy, and they are more accurate than the ESA product.

The DTU and UBonn re-trackers offered similar overall performance, so the DTU re-tracker offers potential to provide continuous water level measurements from rivers to tidal estuaries (an accurate MSS is strongly needed).

The HYDROCOASTAL product gives a higher number of valid observations than the standard ESA product in some locations (Baltic, German Bight, Ebro Delta) and similar percentages in most of the other sites (the only exception is the Bristol Channel and Severn Estuary). The number of valid measurements very close to the shore is still problematic due to land contamination and inaccurate corrections.

7.4. Main Recommendations from the Impact Assessment

From the analysis of the results obtained the team in charge of the Impact Assessment study of the products generated in the HYDROCOASTAL project recommend that:

1. The use of WTC/DTC from UPorto to estimate TWLE / ADT / SLA is strongly recommended.

2. Further studies are recommended to develop an accurate Sea State Bias correction for SAR altimeter data.

3. Global tidal models are the preferred option to remove tides, but caution should be taken in some cases as shown in the Bristol Channel, Severn Estuary and Wadden Sea. The FES2024 tidal model will soon be available and should be assessed in the coastal zones under different tidal regime conditions.

4. Recommend further detailed studies of Unfocused SAR and Fully Focused SAR altimeter processing in estuary environments, to include a range of environmental variables (river discharge, tidal currents, winds, waveform contamination). Higher posting rates (e.g. 80 Hz or even more) should be further investigated. To support this a number of well instrumented “laboratory” sites should be identified (e.g. the Elbe, Northern Adriatic, Severn Estuary). SWOT data should be included.

5. Consistent MSS and geoid are necessary to join sea and land properly. An improved MSS is necessary and should be computed using reprocessed 20/80 Hz data. We recommend a dedicated study to assess MSS and geoid and the northern Adriatic Sea is a good laboratory to test with the local ITALGEO geoid.

6. Recommendation on storm surge studies: TWLE, wind speed and SWH are important for many applications in coastal zones (e.g. storm surges). TWLE has improved thanks to better retracking strategies. SWH and wind speed are not mature enough for exploitation, so we recommend more work to improve their precision and accuracy.

7. In coastal zones, it is recommended the use of the new HYDROCOASTAL re-trackers for exploitation, with accurate mean sea surface. We note that UBonn includes SWH and U10 as output products that need more work in terms of validation.

8. In estuarine areas, it is recommended to use of the DTU re-tracker to provide continuity with the water levels for the inflowing rivers (which are also provided by the DTU re-tracker).

9. Stimulate the development of new high-resolution land-sea masks, possibly with a dynamic approach that could account for the tidal dynamics in the coastal strip and in coastal lagoons.

10. Longer time series are needed in order to analyse the benefits of HYDROCOASTAL products in terms of ocean variability of lower frequency: e.g. Sea Level Rise.

11. Provide tide-surge water level corrections in future (coastal) altimeter products obtained from a model considering the nonlinear interactions. These corrections are a must for anyone interested in sea level anomalies in shallow waters.

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Acronyms

AASLD Average of Absolute Sea Level Difference (measure of noise)
ADT Absolute Dynamic Topography
CLS Collecte Localisation Satellites
CNR-IBF Consiglio Nazionale delle Ricerche - Istituto di Biofisica
CNR-ISP Consiglio Nazionale delle Ricerche - Istituto di Scienze Polari
CS2 CryoSat-2
DAC Dynamic Atmospheric Correction
DCSM Dutch Continental Shelf Model
DTC Dry Troposphere Correction
DTU Danmarks Tekniske Universitet (Technical University of Denmark)
EO Earth Observation
ESA European Space Agency
FES2004 Finite Element Solution Tidal Model developed in 2004
FES2014 Finite Element Solution Tidal Model, developed in 2014-16
FFSAR Fully Focused SAR
G-POD Grid Processing on Demand
MSS Mean Sea Surface
NOC National Oceanography Centre, UK
OCOG Offset Centre of Gravity (re-tracker usually applied to land or ice surfaces)
P-PRO Parallel Processing Service
RMSD Root Mean Square Difference
SARIn SAR Interferometric (CryoSat-2/SIRAL mode)
SAMOSA SAR Altimetry MOde Studies and Applications – a SAR altimeter re-tracker
SAMOSA+ A version of the SAMOSA re-tracker for coastal applications
SAR Synthetic Aperture Radar
SARVATORE SAR Versatile Altimetric Toolkit for Ocean Research & Exploitation
SatOC Satellite Oceanographic Consultants Ltd
SD Standard Deviation
SLA Sea Level Anomaly
SLR Sea Level Rise
SSB Sea State Bias Correction
SSH Sea Surface Height
STDD Standard Deviation of Differences
SWH Significant Wave Height
SWOT Surface Water and Ocean Topography – A satellite altimeter operated by NASA and CNES, launched in December 2022
S3A Sentinel 3A
S3B Sentinel 3B
TG Tide Gauge
TPJ Topex-Poseidon, Jason series of radar altimeter satellites
TU Delft Delft University of Technology
TWLE Total Water Level Envelope
U Bonn University of Bonn
U Porto University of Porto
U10 Wind speed 10m above the ocean surface
WTC Wet Troposphere Correction