CASE-STUDY OF THE BALTIC, GERMAN BIGHT and ELBE ESTUARY

HYDROCOASTAL PROJECT

SUB-CONTRACT [SATOC-CNR] TO RACZIW CONTRACT N. [4000129872/20/I-DT]

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1. Introduction

Estuaries - water bodies where freshwater from rivers and streams mixes with oceanic salt water under the influence of tides - are among the world's most productive but also delicate ecosystems. They are a geographically well-defined typology.

Riverine estuaries, including surrounding salt marshes, lagoons and wetlands, provide animals with food, places to breed, and migration stopovers, and they create hotspots of biodiversity. Yet with rising sea levels and long-term changes in river discharge in many regions of the world, and a likely increase of extreme events, estuaries are threatened by erosion and other factors (IPCC,

These areas are exposed to sea level rise and storm surge related risks (Fenoglio et al., 2015). The surface level variability is an important driver of the salinity variability from the coast to upriver (Nienhuis et al., 2023). The HydroCoastal project provides for the first time a joint coastal zone and river data set that will permit to relate coastal sea level and river water surface levels and discharge. The Hydrocoastal impact studies study the impact of improved altimetry data to monitor the ocean-to-river continuum. 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. In the following sections the words "ESTUARY" and "SEA" are used to distinguish results pertaining to the estuary areas from those valid in the offshore coastal zone. The regional and estuarine model included in this study is the Semi implicit Cross-scale Hydroscience Integrated System Model (SCHISM)), which is coupled with a wave and 3D sediment model and simulates tidal dynamics in the entire area and salinity fronts and estuarine turbidity maxima in the Estuary.

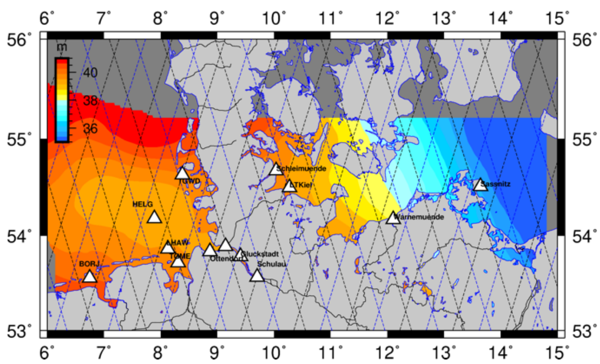

Figure 1.1. CZ validation test site over the German Bight and Baltic Sea with Sentinel-3A ground tracks and locations of fiducial reference data from operational tide gauges of the BfG network (green triangle) and wave buoys (squares) and GPS stations (red dots).

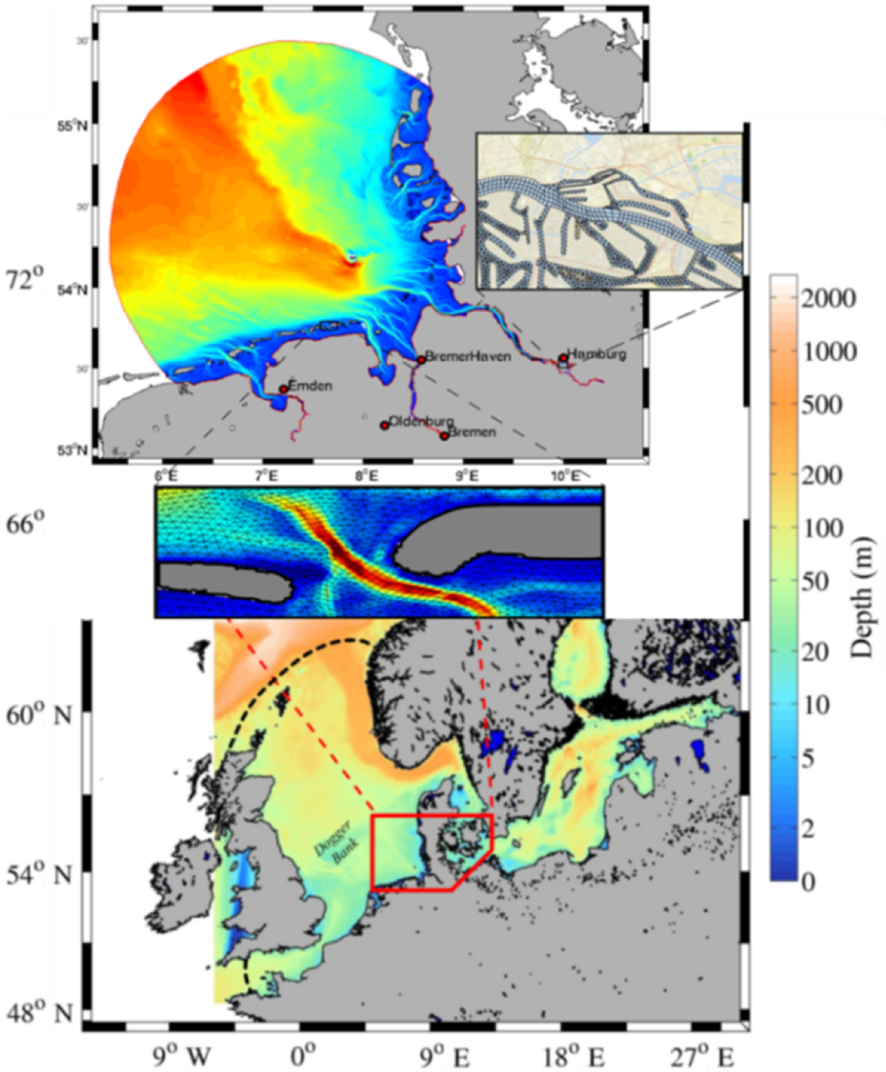

Figure 1.2. German coast of the North Sea and Elbe estuary

2. German coast and estuary

The region is of interest for validation of altimetry because of the large network of fiducial reference measurements and model data made available by the german national agencies (BfG, BKG, and BSH). The location of in situ measurements is shown in Figure 1.1

The goal is to evaluate the performance of the product. Firstly by estimating accuracy and precision, with additional analysis to the validation phase, and then to apply the data to study sea level change and extremes. This is the same study area used in Fenoglio et al., 2015, 2019 and in Dinardo (2018).

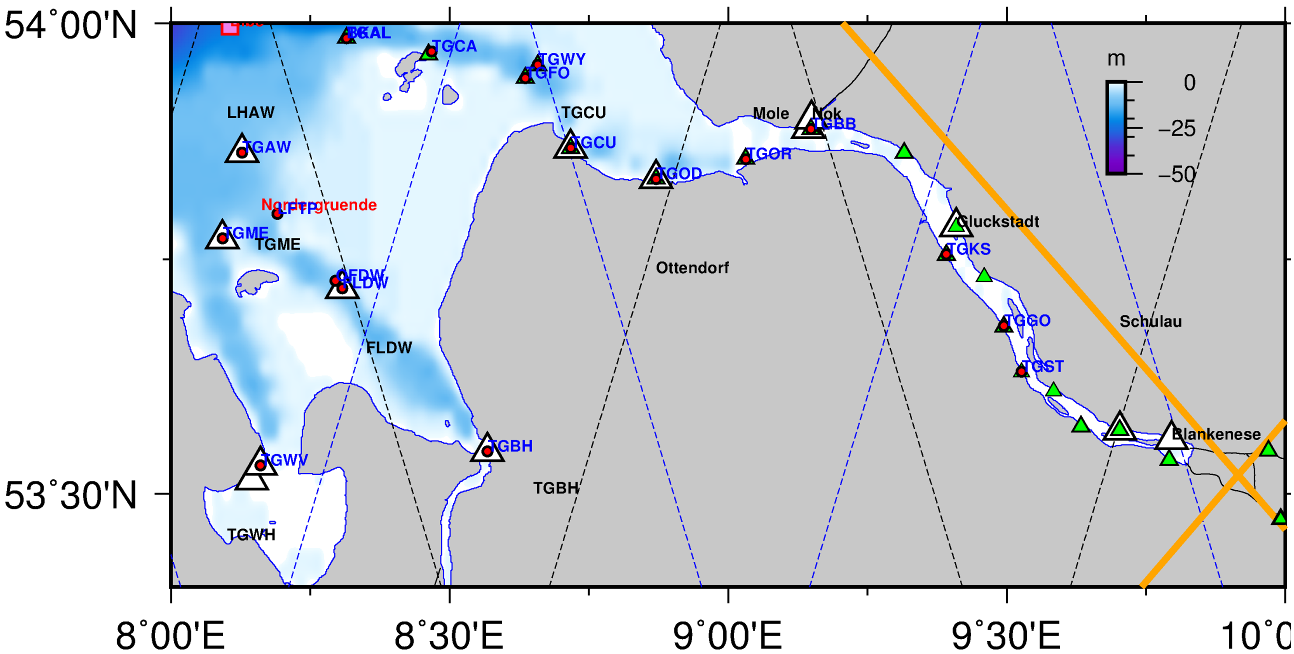

Figure 1.3. Elbe Estuary West of Hamburg with in-situ gauge in pegelonline (white triangle) and from BFG (green triangle), GPS stations (red circle), Sentinel-3A (dashed black), Sentinel-3B (dashed blue), Sentinel-6A (orange line).

2.1 Objectives

The main objectives of the impact assessment are:

- to assess the HydroCoastal products;
- to demonstrate benefits and scientific value of an improved coastal altimetry product.

2.2 Methodology / Data Processing

A land-sea processor for Sentinel-3 was coded in Matlab to assess the performance of the HydroCoastal product. The main functionalities of the processor are: a) read the HydroCoastal product and prepare a mat file with relevant parameters; b) create time series of sea level anomalies, sea surface heights and heights above the geoid for comparison with tide gauges (TG) or for other scientific exploitation; c) inter-compare the HydroCoastal products (UBonn, DTU and official ESA products) and compare them to two external products using the SAMOSA+ re-tracker: the unfocused SAR (USAR) Versatile Altimetric TOolkit for Research and Exploitation (SARvatore) of the EarthConsole platform (Dinardo et al., 2016) and the in-house FFSAR-UBonn processor.

2.2.1 Quality flags

Values retained for the HydroCoastal data are those with flag set as good. They are:

- flags_ubo_swh — quality flag SWH — [**0** success, 1 failed] — for UBONN SWH
- flags_ubo_sig0 — quality flag sigma0 — [**0** success, 1 failed] — for UBONN σ_0
- flags_ubo_range — quality flag range — [**0** success, 1 failed] — for UBONN range
- flags_dtu — Use data with flags — [**0** and 1] — for DTU range

rain_flag and rad_surf_type were not used. For the ESA range, σ_0 and SWH no flag where considered. Only altimetry measurements collocated on water were considered:

- surf_type Surface Type Flag [**0** ocean, **1** enc.seas/lakes, 2 ice, 3 land]

2.2.2 Methodology for building time-series

The accuracy is evaluated slightly differently than in the validation assessment to better account for the variability of sea level along track. The same corrections as in the validation are applied, the time-series are built differently. As from the below equation:

corr_tot-DAC=+dry_tropo + wet_tropo + GIM_iono + solid_earth_tide + geocentric_polar_tide + ocean_tide + load_tide.

the DAC correction is not applied to both altimeter and gauge. The altimetric SSH is corrected for the ocean tide using a tidal model, while the gauge time-series is de-tided with the t-tide program, as in Hydrocoastal validation methodology. Finally the altimetric SSH are binned in time-series along-track. The binning strategy is as follows for a given track. Firstly the cycle with the maximum number of points is selected as reference. Secondly, the data of all the other cycles are interpolated to the reference track. Thirth, a time series is created at each 20 Hz binned location retaining the SSH without NaN in corrections and re-tracked range. The time-series of the difference between the altimetric and gauge series is constructed applying an outlier test with sigma factor 3 and the Standard Deviation Difference (STDD) of the time-series is retained. Finally, we select the binned location with smallest stdd. Here the data along-track are binned at 20 Hz.

All the tide gauge data used in this study are referenced to the same local datum, with is the Amsterdam reference gauge

2.2.3 Methodology for comparing time-series with statistical indicator

We evaluate the standard deviation difference between binned altimetry and in-situ data. We then take for each station one of the two options:

- minimum STDD along the track
- median STDD along the track

  with STDD= $\sqrt{\frac{1}{N-1}\sum_{n=1}^{N} \left[(X_i - \underline{X}) - (Y_i - \underline{Y})\right]^2}$, $\underline{X} = mean(X)$

and we compute mean and the median of each of the options over the in-situ stations.

2.3 Results

In the coastal zone we consider ten in-situ locations, six in the German Bight (BORJ, LHAW, HELG,TGME,TGWD, TGW2) and four in the Baltic (LTKI, SASS, SCHL, WARN). Standard deviation increases near to coast increases in the last 4-5 kilometers, see below for Borkum Fischerbay. By choosing the minimum STDD along the track, and averaging with both mean and median) over the stations, the smallest values are found for the DTU re-tracker (0.112 m in Table 1). Choosing the median STDD the smallest values are found for the STARS re-tracker (0.172 in Table 2). In all cases the corrections of Uni.Porto and FES are superior.

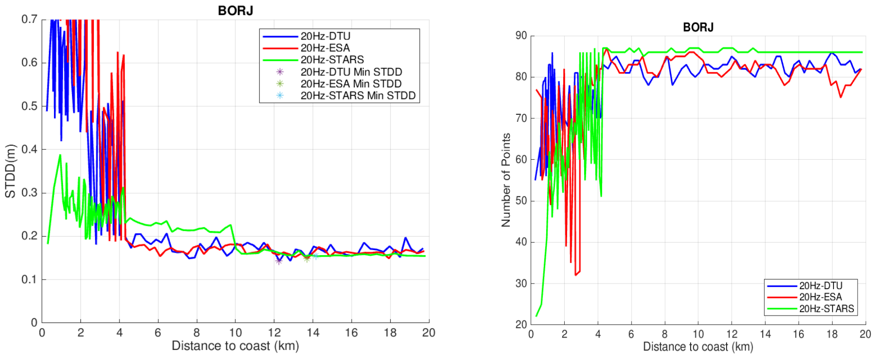

Figure 2.1 STDD and correlation at Borkum Fischerbay

Moreover at most stations, STARS has for the selected point the higher number of observations and also the minimum distance to coast compared to the DTU and ESA re-trackers. Also median and mean of all STDD along track are the smallest for STARS at most stations. STARS has also the highest number of observations at each binned point, except for the coastal area between 0-5km, where land contamination exist.

Table 1. Median and mean accuracy over the 10 stations selecting the minimum STDD method

Min std	dtu ecmwf-fes	esa ecmwf-fes	Stars ecmwf-fes	Dtu Uporto-fes	Esa Uporto-fes	Stars Uporto-fes
Median	0.112	0.121	0.118	**0.112**	0.120	0.116
Mean	0.122	0.127	0.130	0.121	0.126	0.129

Table 2. Median and mean accuracy over the 10 stations selecting the median STDD method

Median std	dtu ecmwf-fes	esa ecmwf-fes	Stars ecmwf-fes	Dtu Uporto-fes	Esa Uporto-ges	Stars Uporto-fes
Median	0.178	0.175	0.173	**0**.177	0.175	**0.172**
Mean	0.199	0.194	0.198	0.199	0.194	0.198

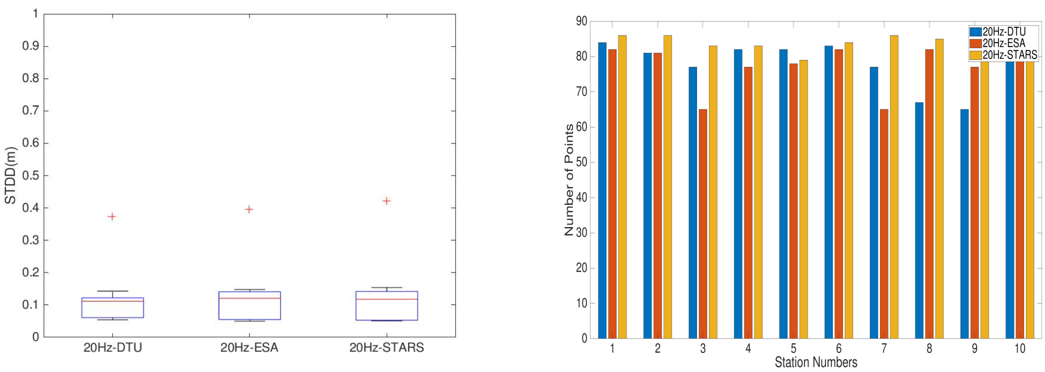

Figure 2.2 Boxplot and number of points for selection of minimum standard deviation and median over the ten stations

In estuaries and tidal rivers, we find high STDD between binned altimeter values and gauges, caused by land contamination, currents and river flow. Fig. 2.3 shows for four stations in the Elbe boxplot and retained number of points. Represented is the median over the stations of the minimum STDD along-track for each station obtained by binning. Figs. 2.4 and 2.5. give the STDD along-track of the binned DTU and UBonn time-series. The DTU re-tracker is performing at best, with STDD rarely smaller then 50 cm. With two external products, the 20 Hz UFSAR product generated by the SARVatore processor with re-tracker SAMOSA+, available from Earth Console and the 20Hz fully-focused (FFSAR) UBonn processor with re-tracker SAMOSA+, the STDD is smaller but still around 50 cm, the same for FFSAR at 80 Hz. Finally, we examine in Fig.2.7 the tide-uncorrected SSH along a single pass near Ottendorf at two epochs. DTU and ESA SSHs are unrealistic and UBonn SSH more realistic at the first epoch, the variability along track is within few centimetres for all re-trackers at the second epoch. The radargrams in Fig. 2.8 show contamination at the correspondent locations.

Table 3. Estuar. Median and mean accuracy over the 4 stations selecting the minimum STDD method

Min std	dtu Uporto-fes	esa Uporto-fes	Stars Uporto-fes
Median	0.862	1.2595	1.401
Mean	0.953	1.2635	2.838

Table 4. Estuar. Median and mean accuracy over the 4 stations selecting the minimum STDD method

Median std	dtu Uporto-fes	esa Uporto-fes	Stars Uporto-fes
Median	1.3315	1.4635	1.8155
Mean	1.2592	1.4765	3.6192

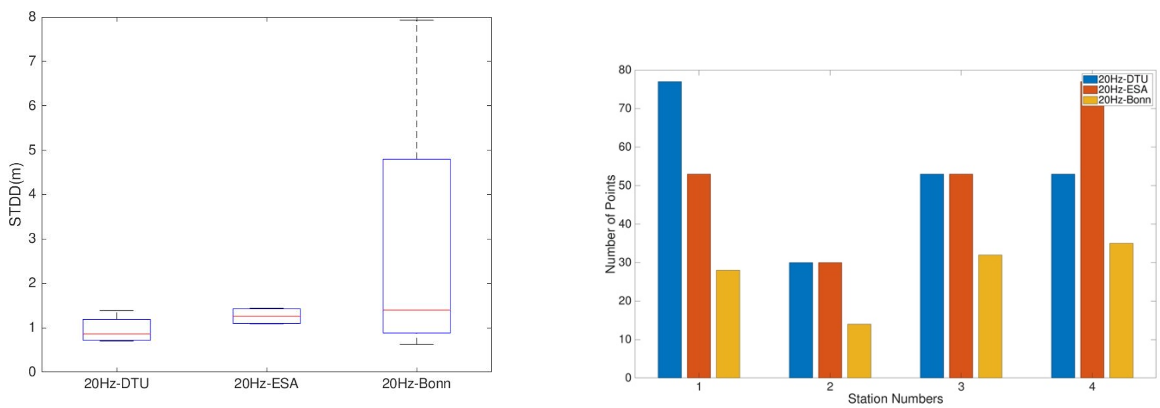

Figure 2.3 For Hydrocoastal products DTU, UBonn and ESA in the Elbe Estuar at four gauges: Boxplot and number of points for selection of minimum standard deviation and median over the four stations

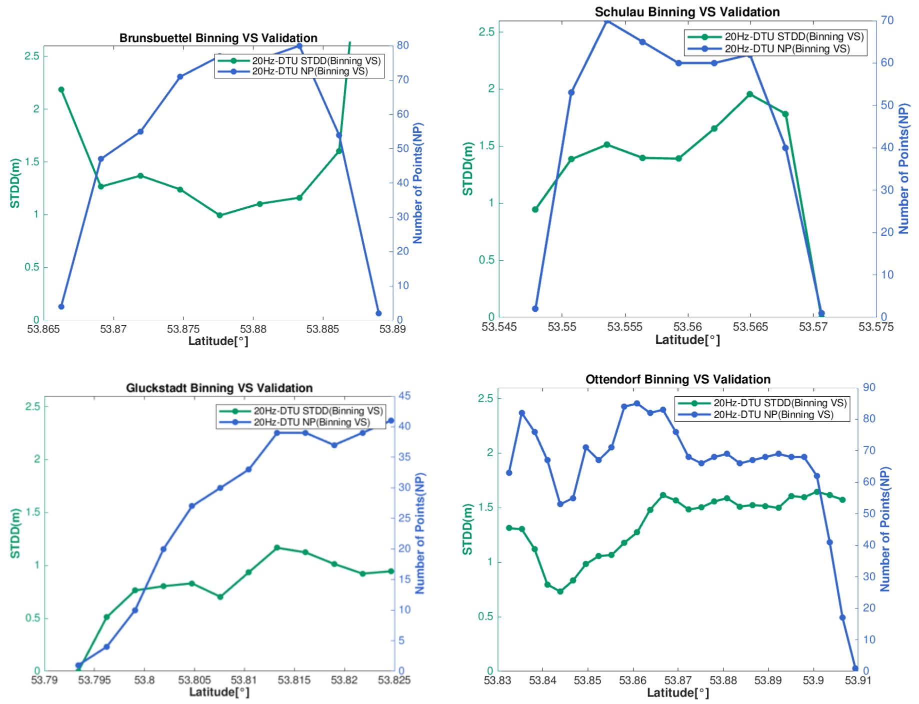

Figure 2.4 STDD from Hydrocoastal DTU UFSAR product at the four stations

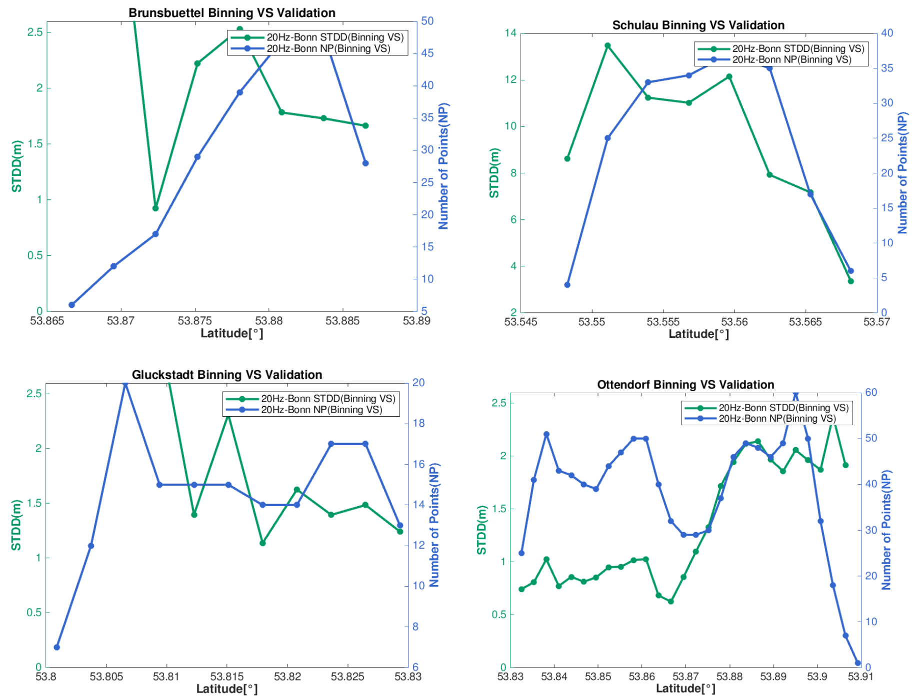

Figure 2.5 STDD from Hydrocoastal UBonn product with UFSAR processing and re-tracker STARS

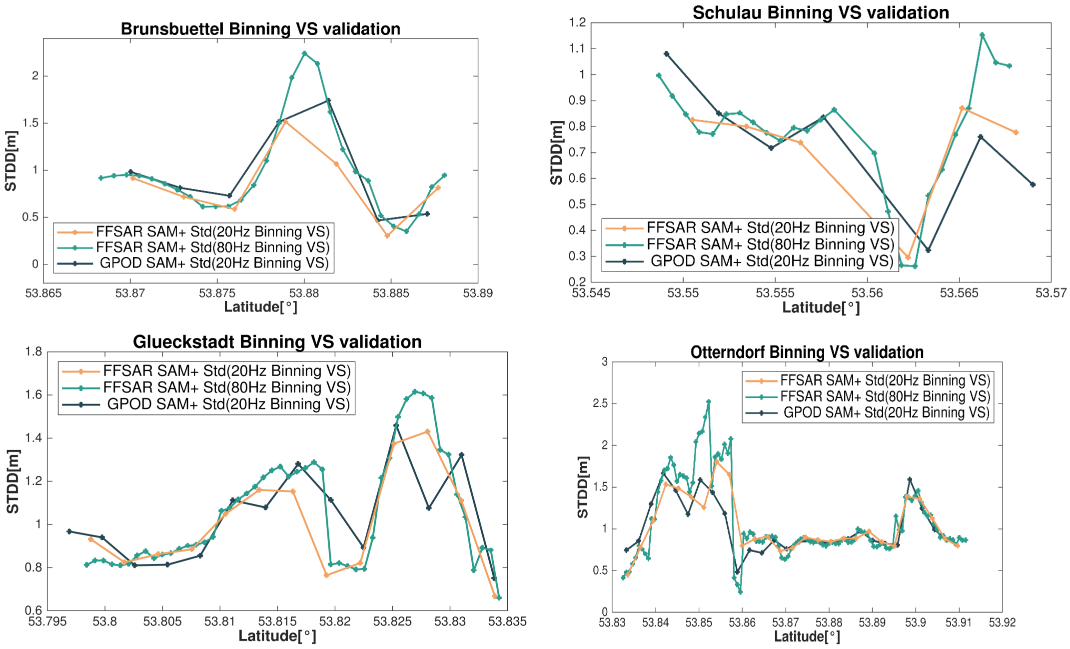

Figure 2.6 STDD from non-Hydrocoastal with FFSAR and UFSAR processing and re-tracker Samosa+

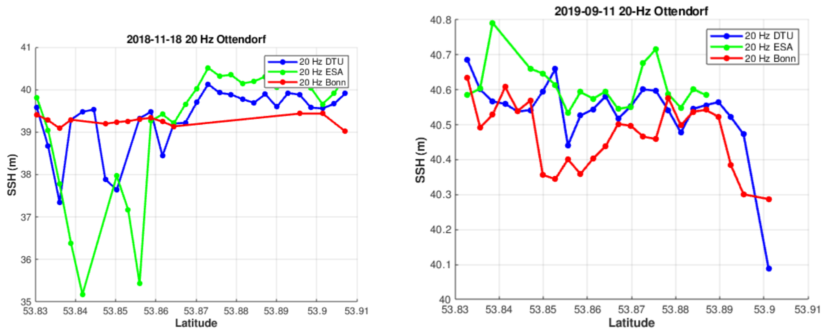

Figure 2.7 Along-track water height (no tide corrected) from Hydrocoastal UBonn products in Figure 2.5

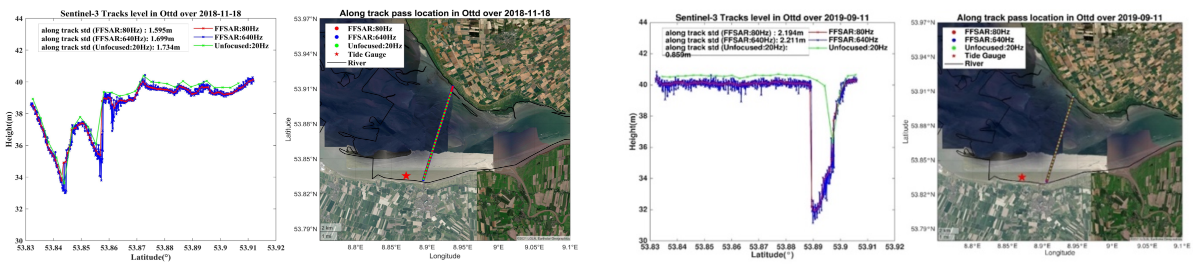

Figure 2.8 Along-track water height (no tide corrected) from non-Hydrocoastal products as in Fig. 2.6

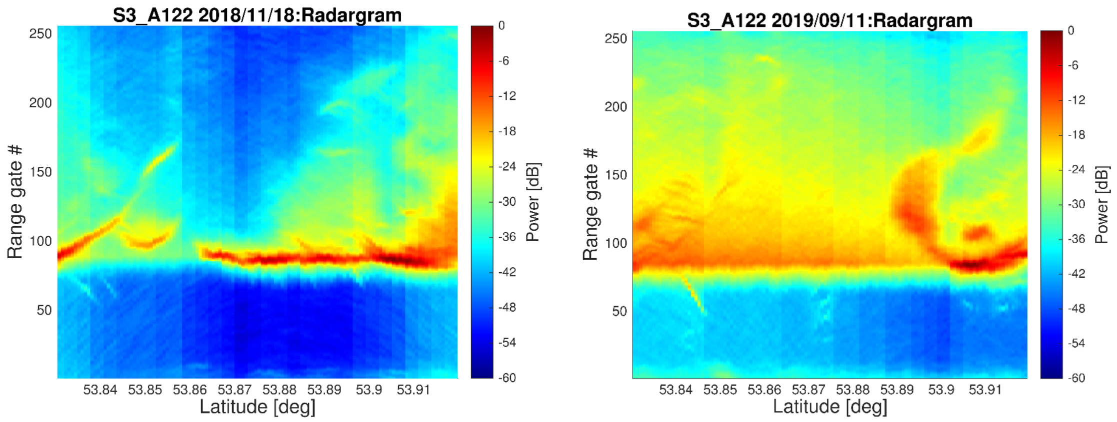

Figure 2.9 Radargram from FFSAR at same epochs as Figs. 2.7, 2.8 with contaminated waveforms

We calculated the total water level envelope (TWLE) anomalies for both the altimeter and the tide gauge and we verify that all the re-trackers find extremes. TWLE is the geocentric sea level height measured by the altimeters, i.e. the sea level inclusive of ocean, polar, load and solid earth tides, atmospheric forcing, wave setup, etc. As the relative sea level height measured by tide gauges does not include the solid earth tide, the load tide and a fraction of the geocentric polar tide, such terms are subtracted from the altimetric TWLE (Fenoglio-Marc et al., 2015). Finally, also the MSS is subtracted from altimetric TWLE. Tide gauge observations are transformed to TWLE anomalies by subtracting the local MSS obtained by averaging the TG sea level signal over the same time period used to obtain the altimetric MSS. This procedure permits to compare the two anomalies in a consistent way, despite the fact that only relative measurements are used, instead of absolute ones. In terms of HydroCoastal L2 product parameters, the formulas for obtaining the altimetric and the tide gauge TWLE anomalies are given below.

TWLE anomaly for altimetry:

$$L_{alt} = altitude \; - \; range_{uncorr} - atmospheric_{corr} - tide_{land} - MSS_{alt}{}^{(time\ span)}$$

$$atmospheric_{corr} = tropo_{wet} + tropo_{dry} + iono_{gim}$$

$$tide_{land} = tide_{solid\ earth} + tide_{load\ fes} + 0.468 * tide_{geo\ polar}$$

TWLE anomaly for tide gauge:

$$L_{tg} = level_{tg} \; - MSS_{tg}{}^{(time\ span)}$$

2.4 Summary

The quality and quantity of the altimeter data exploitable close to the coast can be enhanced by dedicated processing.

The agreement with tide gauges, in terms of STDD, is an indicator of the accuracy of the altimeter data. The value found for STDD depends on the frequency of data used in the comparison (annual, monthly or instantaneous), on the chosen averaging area for the altimetry data and minimum distance to coast, on the region investigated and its geophysical characteristics. Therefore results found in the literature are difficult to compare. Typical values for accuracy are in the range 10-20 cm in Australia (Peng et al., 2021), 5-15 cm in West Africa, North East Atlantic and Mediterranean (Birol et al., 2021, Bruni et al. 2022, Fenoglio et al., 2021), 30-40 cm in the 0-3 km along track coastal segment and many stations were found in the Baltic Sea (Passaro et al., 2022).

This study finds with the HydroCoastal product a lower STDD in Baltic (5-10 cm) than in the German Bight (20-40 cm). 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, The accuracy from Samosa+ Earth Console and are comparable and even higher. In the estuary the accuracy is worst and between 0.5 and 1 meter.

In addition to the Unfocused SAR we have used also the Fully Focused processing. This gives better spatial resolution along-track, results are good comparable to Samosa+ Earth Console as the same re-tracker is used, but the accuracy is not considerably improved.

2.5 Highlight main 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 neither in USAR or in FF-SAR. Particularly in the sea, with tide and circulation, and probably due to the rough surface, the accuracy compared to the tide gauge is low (0.5-1 meter).

Some interesting findings that we mention hereinafter.

- Radargrams can be used to identify waveforms to be discarded
- Binned method is the preferable in the construction of the time-series
- FES is the best tidal model in our region
- Use of 80 hz instead than 20 hz is preferable in coastal and estuary

2.6 Potential Scientific / Operational Impact (“Benefit and unique value”)

Satellite altimetry in such an environment gives continuity of observations from open ocean through the coast and inland.

Comparison of results over different estuaries can give a better understanding. Working with ocean models for estuary is mandatory.

2.7 Recommendations

The altimeter data analyses outlined a number of topics to be addressed, including specific R&D investigations that deserve further consideration, with future projects to be implemented. Hereinafter some recommendations:

- Further investigate FFSAR capability

- Consider difference of FFSAR results in sea and river, bays, lakes, contamination in all cases
- Investigate results from SWOT to study small scale of wavelength < 50 km and 2D grids
- Reconstruct 2D grids from altimeters and compare with ocean models to detect observed and modelled small spatial and temporal scales, investigate reconstruction methods included Optimal Interpolation (OI) and Artificial Intelligence (AI)
- Elbe is a good cal/val test area for the 1-day SWOT, and all Sentinel-3,6 missions
- Investigation of SSH absolute, bathymetric information need to be added
- Consider discharge and tidal discharge, wind, currents effects in the estuarine region

3. Acknowledgments

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4. References

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