HYDROCOASTAL

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

Scientific Road Map
Deliverable D4.1

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 HYDROCOASTAL project was funded under the ESA EO Science for Society Programme and aimed to maximise the exploitation of SAR and SARin altimeter measurements in the coastal zone and inland waters, by evaluating and implementing new approaches to process SAR and SARin data from CryoSat-2, and SAR altimeter data from Sentinel-3A and Sentinel-3B.

One of the key objectives is to link together and better understand the interaction processes between river discharge and coastal sea level. Key outputs are global coastal zone and river discharge data sets, and assessments of these products in terms of their scientific impact.

1.2. Scope of this Report

This is the Scientific Road Map for HYDROCOASTAL and represents D4.1 of the project. The document has considered all the project outcomes and deliverables to provide recommendations in 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.

A number of similar recommendations have been identified at different stages of the project. The final summary section of this document brings together the different recommendations and compiles them into a smaller number of major recommendations.

1.3. Applicable Documents

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

1.4. Reference Documents

RD-01 HYDROCOASTAL Technical Proposal. V1.1 28/11/2019, SatOC and HYDROCOASTAL team.
RD-02 HYDROCOASTAL Algorithm Theoretical Basis Document.
RD-03 HYDROCOASTAL Product Validation Report.
RD-04 HYDROCOASTAL Assessment of Tidal Models in Coastal Regions.
RD-04 HYDROCOASTAL Impact Assessment Report – Coastal Zone.
RD-05 HYDROCOASTAL Impact Assessment Report – Inland Water.
RD-06 HYDROCOASTAL Impact Assessment Report – Processing.
RD-07 HYDROCOASTAL_MSS_TechNote_V4_2030501.docx.
RD-08 HYDROCOASTAL Product Validation Plan Issue 3.1b

1.5. Document Organisation

After the introduction section, the Road Map includes the following sections:

2. Technical Note 1 – State of the Art Review – Summary and recommendations from the initial State of the Art review on SAR Altimetry.

3. Recommendations on implementation of SAR and SARin Altimeter Processing– Based on experience during HYDROCOASTAL.

4. Issues for Final Global Products – Recommendations for the generation of large scale, global, coastal, and inland water SAR, and SARin altimeter products.

5. Recommendations for Validation Activities – Based on experience in HYDROCOASTAL from the validation exercise to evaluate the different processing algorithms.

6. Key Findings from the Impact Assessment Studies. Key highlights and Recommendations from the Impact Assessment Case Studies carried out for HYDROCOASTAL.

7. Additional Recommendations – Further recommendations for future work from HYDROCOASTAL partners.

8. Summary

2. Technical Note 1 – Main recommendations

HYDROCOASTAL Technical Note 1 presented a state of the art review of SAR altimetry and its importance in coastal and inland water applications. The study provided the context and technical background for the new SAR altimeter processing algorithms that were tested in the first phase of the project. We list the main recommendations from this review below:

R2.1. There remains a problem with contamination of SAR altimeter waveforms with echoes from off nadir reflections. This mostly affects inland waters, but also some coastal regions. Approaches should continue to be developed that can successfully identify the nadir reflection and sub-sample or clean the waveform to remove contamination from off nadir reflections.

R2.2. Fully Focused SAR altimeter processing has shown its potential to improve precision to the cm-scale for measuring levels of small water bodies, especially for inland waters. This technique has reached maturity to be implemented as part of the baseline processing. A number of HYDROCOASTAL Case Studies evaluated Fully Focused SAR processing over inland water and coastal targets. Also a parallel ESA project – FFSAR-Coastal - funded under the EO4Society Open Call, implemented, and evaluated data from the CLS/ESA/CNES SMAP (Standalone Multi-mission Altimetry Processor) fully focused SAR processor, as well as the VALERIA project (Molina et al., 2023), funded by isardSAT as part of the Sentinel-6 Validation Team. A feasibility study should be dedicated to evaluate the computational effort and parametrisation required, within a dedicated mask over some regions of interest, combined with a cross-comparison and validation of the FF-SAR processing results, as done for the UFSAR.

R2.3. The limitations of Closed Loop retracking in mountainous areas was noted. A HYDROCOASTAL Case Study has investigated this issue.

R2.4. The need for seasonal water masks was noted, as the use of static masks results in over (or under) estimates of the area covered by water, and so limits the accuracy of derived water discharge measurements.

R2.5. It is important to evaluate retracking algorithms over a substantial number of inland water bodies to quantify the quality of the algorithms as a function of the water condition and other parameters (area, elevation, seasonal ice cover, ...), as any single re-tracker may not provide the best results for all environments. Such information may help the user to apply the most optimal product for a certain target type.

R2.6. Improved geophysical corrections at the same spatial resolution of the SAR altimeter products are needed.

R2.7. The accuracy of tidal models is dependent on bathymetric data, which remains sparse in many areas.

R2.8. One of the biggest remaining challenges in ocean tide modelling is the accurate modelling of shallow waters where non-linear interactions play a role (includes estuary regions). Global or regional models do not take account of the interactions between tides and other contributors to the water level variability such as winds and river flow.

R2.9. At the coast / river interface, a major challenge is the decomposition of a combined water level signal into its different components (discharge induced signal, tidal signal, surge component).

R2.10. It will be important to compare results and evaluate new approaches to estimate river discharge from the SWOT mission. HYDROCOASTAL was not able to carry out any direct comparisons because of the timing of the project.

R2.11. A processing approach is needed to produce a "seamless" data set across the boundary between river mouths and tidal estuaries.

3. Processing Recommendations

3.1.Introduction

In this section we list recommendations for implementation of SAR altimeter processing, gained during the experience of establishing the HYDROCOASTAL L1b to L2 processing chain, and subsequently to L3 (water level time series) and L4 (River Discharge Time Series) for the Test Data Set and for the Final Product.

The processing chain and algorithms incorporated within it are described in the HYDROCOASTAL Algorithms Theoretical Basis Document (RD-02).

3.2.Acquisition

For hydrological targets in mountainous areas the baseline for the acquisition mode should follow the Open Loop Tracking Command (OLTC) already implemented within the Sentinel-3 and Sentinel-6 missions. For hydrological targets in flat areas the baseline for the acquisition mode should follow the Closed Loop Tracking Command.

A dynamic OLTC could also solve this problem but might be difficult to implement as not all the targets will have the transition period at the same moment of the year and some of them, for instance water reservoirs controlled by dams, will not be easy to predict.

Moreover, the water level variability of the targets can be too large to be able to use a reference elevation level in the OLTC instruction. This will depend on the length of the window for each specific mission and mode. For Sentinel-6, we recommend avoiding Range Migration Correction (RMC) mode in these cases.

Sentinel-6 uses a 66 pulse repetition chronogram (64 Ku, + 1C +1 CAL) with a Pulse Repetition Frequency (PRF) and pulse length that enable receiving each pulse within the transmitted ones. This allows an almost continuous observation of the hydrological targets (there is a 2 pulse gap due to C and CAL pulses), and the capability to perform Fully Focused processing with enhanced along track resolution. The recommendation for future missions is to retain this Open Burst acquisition strategy but to move the “auxiliary” pulses out of the main Ku chronogram so we can get the full observation of the targets and perform Fully Focused without any replicas (Amraoui et al, 2022).

For interferometric missions such as CryoSat-2 or the future CRISTAL, the recommendation is to use the interferometric capabilities so that water level measurements can be made in the across track direction (over multiple targets if needed) in order to maximise the number of measurements and different targets.

R3.1 Recommendations for SAR Altimetry signal acquisition:

- *Open Loop Tracking Command preferred over closed loop tracking in mountainous areas.*
- *Closed Loop Tracking Command preferred over open loop tracking in flat areas.*
- *Avoid Range Migration Correction onboard truncation.*
- *Implement Interferometry mode when available.*

3.3. L1A to L1B

Download of Sentinel-3 L1A data from the access sites for processing was problematic and time consuming in the initial phase. The implementation in the second phase of the processor on the G-BOX virtual machine with direct access to input data, provided by Earth Console, significantly improved the situation.

R3.2 Processing platform - reducing data access limitations.

- *Avoid the transfer of large amounts of data by gathering the different processors in a platform with direct access to the raw data.*
- *Implement the capability to download sub-products based on the definition of geographical areas (e.g. using kml files).*

3.4.L1B to L2

3.4.1. Processing Set Up

The individual innovative processor software implementations provided by partners were not initially designed to generate global data sets. Processor failures occurred for certain input products, leading to empty output L2E products – the robustness of implemented processors was improved during the project.

ESA L2 variables merged in the HYDROCOASTAL L2E were taken from Sentinel-3 L2 LAND products for Sentinel-3A/Sentinel-3B and from CryoSat-2 L2 Ice for CryoSat-2. Sentinel-3 L2 LAND products cover inland waters and coastal areas close to the coast and the variables interpolated from ESA L2 are not accurate outside the S3 L2 LAND coverage. Some variables useful for coastal areas are not available in CryoSat-2 L2 Ice and thus were missing in CryoSat-2 L2E (e.g. atmospheric attenuation).

The L1A to L1B processing resulted in a new along-track datation for the L1B product, and re-tracked L2 values, different from the standard ESA/EUMETSAT products. The L2 parameters from the standard ESA products (sea surface height – and derived parameters, significant wave height, nadir backscatter (s0) and surface wind speed) were effectively smoothed as they were interpolated onto the new datation created. This meant that the results from the ESA L2 product and the output of the HYDROCOASTAL re-tracker algorithms cannot be directly compared.

Future processing should bear this in mind to allow direct comparisons between the new and original products, which leads to the following recommendation.

R3.3 Compute the geophysical correction from the geophysical models at the along-track time stamp and geographical position of the measurements to provide more accurate information than when interpolating correction recorded in the operational L2 products.

The U Bonn retracker relies on a mean sea surface (mss) to derive its first guess results. For this, the processor used the value provided in the ESA L2 input data file. As long as the same mss is used at all stages, the result will not be significantly affected. However, if there are differences, there may be an impact on the re-tracker output.

R3.4 A large-scale study is recommended to understand the impact of different mss on the output of re-trackers that use an input mss as part of the processing.

3.4.2. Inland Water

The results from the validation of the different re-trackers showed that different re-trackers performed best in some situations (e.g. frozen water, rivers during the ice melt season, multi-branched rivers with nearby lakes and lagoons, narrow rivers in steep topography, rivers where the satellite altimeter tracks are almost parallel to the direction of the river).

The algorithm selected to generate the final data set was the one that performed best across all circumstances, even if it resulted in poorer results in some situations.

Algorithms could potentially be “tuned” to suit these individual situations, but then they would not perform as well in other situations. One approach could be to categorise inland waters into different types and then apply different re-tracking algorithms to different categories.

R3.5 We recommend the trial development of an “intelligent” retracker for inland waters, that applies different re-tracking algorithms to different types of inland water environment and different characteristics of waveform.

3.5. L2 to L3

3.5.1. Inland Water Time Series and its relation to the validation results

Overview
This section discusses the improvements that could be achieved by agreeing on common best practices at each step of the production of River/Lake Water Level time series (L3) over inland waters.

To generate altimetry-based lake and river time series, auxiliary data in terms of raster or vector water masks are needed. In the HYDROCOASTAL project the Global Surface Water Occurrence product (Pekel, et al., 2016) and the SWORD product (Altenau et al., 2021) were used to extract L2 observations over a given target. Additionally lake masks were used. For small targets e.g. narrow rivers it is beneficial to also include measurements in the vicinity of the river simply to enhance the number of measurements. In cloudy regions such as the “White Nile River”, the occurrence product should not be used to identify the location of water bodies.

The extracted data may still contain outliers as the echo does not necessarily originate from the nadir water surface. In the HYDROCOASTAL project the included retrackers were provided with flags to help discard measurements of a poor quality. In many cases discarding data flagged as poor resulted in a pronounced data loss. Hence, it would be beneficial to invest resources in providing improved quality flags that could be applied when reconstructing the time series.

Providing time series to end-users as in HYDROCOASTAL requires a strict quality assessment to assure a good quality. In the case where only a few measurements are available for time series reconstruction (1 measurement or time on average) a time series should not be provided even though the measurement may be valid. In the DTU time series solution, a number of restriction criteria were applied to ensure the quality, which resulted in fewer available resulting time series.

A difference in approach is appropriate when generating a standard global solution and a detailed study of a single area, where additional knowledge is available. However, to improve global products further work is needed to ensure better quality control.

River Water Level (RWL) Time Series
In the repeat orbit case or after the adequate migration of Once Per Crossing (OPC) measurements in a non-repeat orbit case, time series are obtained after filtering the series of OPC measurements to remove their outliers. This can be done in several ways; for example through a recursive 3 sigma rejection filter.

The selected outlier removal method will impact the final products and therefore the validation exercise with respect to some gauging stations. For the sake of clarity the exact method that is used to reject the outliers should be detailed and known to the validation teams, as the validation results and their interpretation depends on the method used to obtain the RWL time series.

The full detail on the method used to produce the OPC RWL and then the method used to produce the time series should be specified, especially if the same team is running the full processing chain (producing the OPC RWL, producing the time series by filtering the outliers, and running the validation against gauging station). Without the detailed information on the whole processing chain it may become impossible to compare the validation results from different teams.
Ideally the validation team should agree on:

- a common and unique method to produce OPC measurements,
- a set of methods to produce the L3 time series from the very same L2 measurements.

3.6. Geophysical Corrections

3.6.1. Wet and Dry Troposphere Corrections

U Porto generated improved “GPD+” Wet and Dry troposphere corrections for the HYDROCOASTAL data sets (Ref RD-02 - HYDROCOASTAL ATBD). Analysis for the HYDROCOASTAL Production Validation Report (RD-03) leads to some specific recommendations.

The Dry Troposphere Corrections (DTC) present in current products may still induce significant errors in the altimeter derived water surface heights, in particular over regions at high altitudes, where the DTC should be correctly referred to the actual surface height, using the best available topographic information.

R3.6 The reference height at which the tropospheric corrections (DTC and WTC) have been computed should be provided in the altimeter products, to allow for the application of corrective terms, in case more accurate re-tracked heights become available and these differ from the reference heights by more than 40 m.

R3.7 Icesat-2 data should be exploited to derive and improve Digital Elevation Models (DEM) over Inland Water (IW) regions, similar to what was achieved in ACE2.

R3.8 Due to the land contamination, MWR-derived WTC observations cannot be used near the coast nor over IW regions.

Although the differences between the model-derived WTC and those based on observations, such as GPD+ are statistically small, at small scales, these can still be significantly different.

R3.9 The ECMWF Operational model is not stable and should not be used before 2004. For climate studies, the use of ECMWF operational model derived WTC may introduce significant trend errors at time scales of 5-10 years, as e.g., for the Sentinel-3 time span. ERA5 is the most stable model with respect to the SSMI/SSMIS imaging sensors, considered a radiometric reference.

R3.10 ERA5 derived WTC should be provided in the altimeter products.

R3.11 For coastal and IW regions, neither the MWR nor the model-derived WTC should be adopted. The adopted WTC should be an improved and continuous WTC such as GPD+, based on observations when they exist and calibrated against a stable source such as SSMI/SSMIS.

3.6.2. Improved Retrieval of the Atmospheric Attenuation on Sigma0

Over the open ocean, both WTC and atmospheric attenuation corrections for sigma0 are computed from MWR measurements (as e.g. on Sentinel-3).

The retrieval of the geophysical parameters from the MWR measurements is difficult, due to the nonlinearity of the relation between these parameters and the measured Brightness Temperatures (TB) and due to the difficulty in designing retrieval algorithms able to produce valid observations over all radiometric conditions. This raises problems over regions such as coastal and inland waters, leading to invalid measurements for the MWR-derived WTC and atmospheric attenuation. For these cases, the atmospheric attenuation can be computed from atmospheric model parameters.

There are some simple alternative approaches, where the atmospheric attenuation correction for sigma0 is a function only of the WTC, usually derived from atmospheric models. This approach can be investigated to get enhanced retrievals over coastal and inland water regions, using improved WTC retrievals over these regions such as:

i) GPD+ WTC.
ii) Improved MWR-derived WTC either from the measured TBs and/or from additional parameters such as the Sea Surface Temperature (SST), where available.

3.6.3. Ocean Tide Corrections

Noveltis carried out an assessment of tidal models in coastal regions as part of the HYDROCOASTAL project (RD-04).

It was concluded that the most recent global models generally perform better than the older and coarser solutions. In the case of the hydrodynamic models (TPXO and FES families), this is due to higher-resolution grids, improved modelling schemes and more accurate observations for the data assimilation process. In addition to the improvements brought by more accurate observations in the optimal interpolation process, the empirical models (DTU and EOT families) directly benefit from the improvements in the hydrodynamic models, which are used as prior solutions.

In general, the regional tidal models were found to show much lower differences with the shelf and coastal observations than the global models. This is mainly due to their even higher-resolution grids and to the possibility to locally tune the hydrodynamic model and pay specific attention to bathymetry details and other local features, which is not possible in the case of a global model. The regional approach is thus of high interest as it brings more details and reduces the errors in the tidal models, which consequently leads to more accurate coastal altimetry SSH estimates (corrected for tides). We also note the recommendations R2.7 and R2.8 from the state of the art review.

Users are advised to be cautious when considering the use of alternative tidal corrections for satellite altimetry observations, especially if they also want to remove the high-frequency sea surface height variations due to the wind and atmospheric pressure (DAC-HF correction), as the compatibility between the two corrections must be ensured in order to properly remove all these signals.

3.6.4. Recommendations regarding ESA and EUMETSAT products

When investigating the potential impact of different corrections, HYDROCOASTAL partners identified that the use of different L1A, FBR source products (Land, Ice Ocean) introduced some complications on L2 parameters that were interpolated into the L2E products. Also it was noted that the ESA/EUMETSAT data access platforms for L1A/FBR data included products from different processing baselines, which was the source of some confusion. In addition it was found that changes had been made to some products that were not documented or explained (e.g. to the sigma0 scale factor in the EUMETSAT and ESA Sentinel-3 SRAL L1A product, early in 2020)
Therefore we offer recommendations to improve the situation:

R3.12 - Recommendations for presentation of ESA Altimeter products
It is recommended that ESA should:

- Include a flag to select the processing baseline of products in the interface (SciHub - https://scihub.copernicus.eu/ which is migrating to dataspace.copernicus.eu).
- Consider why old baselines are still the only available option for very old products.
- Provide/update resources to detail the differences between baselines. (We note that the following resource is outdated: https://sentinels.copernicus.eu/fi/web/sentinel/technical-guides/sentinel-3-altimetry/processing-baseline)
- All changes in data processing applied to products made available on distribution platforms should be fully documented and explained.

4. Issues for Final Global Products

4.1. Introduction

In this section we identify key issues to be addressed to enable the production of accurate and reliable global products.

The implementation in the second phase of the processor on the Earth Console G-BOX virtual machine, with direct access to Sentinel-3 input data, has largely improved the issues related to the download of S3 L1A data, which was problematic and time consuming in the initial phase. The UBonn STARs retracker has very high CPU consumption with respect to standard SAR retrackers, and the Earth Console solution including 64 cores was used with success to perform the processing of the limited set of areas defined for the final products within the time frame of the project. Globally the Earth Console G-BOX virtual machine was found easy to set-up and to use and can be recommended for uses such as the generation of the final Hydrocoastal products.

Due to the high CPU consumption of the UBonn STARS retracker, the 64 cores of the G-BOX virtual machine would not have allowed the generation of truly global products in the given limited time frame of the project. The DTU retracker, selected for Inland Water areas, had low CPU consumption, and was found easier to use for a very large scale of data.

For sake of efficiency, algorithms dedicated to a specific kind of area and requesting high CPU consumption should not be activated globally. If the performances cannot be improved, then a processing on demand using solutions like the Altimetry Virtual Lab (provided by Earth Console) can be recommended.

4.2. L2 Coastal Zone

4.2.1. Expanding Coverage

Due to time and resource constraints, the geographic coverage of the final HYDROCOASTAL coastal zone output product was limited to those areas required for the case studies. When considering expansion of this coverage we recommend making a distinction between coastal zones and transition zones between inland and coastal (estuaries, river mouths, coastal lagoons). There is a further strong argument that Coastal Lagoons could form a category in their own right, as they form a specific type of target that share similar characteristics (see e.g. Barnes, 1980), potentially exploitable through satellite altimetry. Thus we could envisage the development of a plan to expand coverage in the following sub-categories:

- Coastal zones (not closely affected by the dynamics of estuarine and river mouth zones)
- Transition regions (estuaries and river mouths)
- Global Coastal Lagoons

It is likely that different processing approaches would be relevant to these different categories and some more investigation is required to identify the best approaches. The Altimeter Virtual Laboratory offers a convenient platform for implementation. Alternatively a new solution could be implemented via the G-BOX option used in HYDROCOASTAL.

R 4.1 We recommend development of an incremental processing scheme to generate a coastal altimetry data set to provide global coverage in the three identified categories: Coastal Zones, Transition Regions, Coastal Lagoons. Different processing options should be considered for the different categories. This may involve the use of more than one processing approach per category. (see also discussion of "Next Generation" Coastal products in the section below).

4.2.2. "Next Generation" Coastal Products

A number of factors combine to make it difficult to provide a consistent global along-track product for the coastal zone, even if a single re-tracker is used. This is due to the fact that different factors impact the accuracy of each individual track when it approaches (or leaves) the coast. These factors include the angle of approach of the track with respect to the coast, the land topography, the hydrodynamic conditions, etc. Together, these (and other) factors result in a segment of the track which might range between 1 to 10 km from the coast where the processor fails to retrieve a measurement or provides an inaccurate measurement.

Thus, an important consideration for the "Next Generation" of coastal products is whether it is best to implement a single consistent global processing scheme, or if a combination of outputs from different processing approaches could provide a better product. For the latter one could consider the use of unfocussed and fully focussed SAR altimeter processing, and the implementation of different retrackers depending on the characteristics of the situation. The difficulty in this case is how to provide a consistent product from different processing approaches.

Thus questions to address include:

- How / whether to truncate the product close to the coast. General opinion is to flag the products according to the re-tracking results.
- Where / if to implement a transition to fully focussed SAR altimeter processing.
- A single re-tracker or choice of re-trackers?
- Single or variable posting rate? General opinion from HYDROCOASTAL partners is that the best option is a single rate of 80Hz, see also Egido et al. (2021).
- How / whether to include the specularity degree of the surface in identifying the best processing options

The use of statistical parameters to quantify the quality of the products could be proposed to identify the preferred processing option and the point at which data become unreliable on approaching the coast.

4.3. L2 Inland Water

4.3.1. Expanding Coverage

Having dedicated inland water products is essential to reach more end users, who can apply the altimetry products in modelling and further analysis. Time series of lake and river levels can be acquired from several services such as DAHITI[1], Hydroweb, Copernicus. However, this is not the case for along-track products, which currently, are difficult and time consuming to acquire especially

[1] DAHITI (Database for Hydrological Time Series of Inland Waters) is a DGFI-TUM initiative, and is based on inputs from the DGFI-TUM Open Altimeter Database (https://openadb.dgfi.tum.de/en/) which provides along-track multi-mission data (Schwatke et al, 2015)

if different missions are needed. Along-track products of several altimetry missions, which are extracted over lakes, rivers, and estuaries would be a user attractive supplement to the already existent services. The different products could be provided in basin files enabling the user to easily acquire the data needed. Such products would naturally be limited by the applied masks, but the benefits for most users will be large.

R4.2 The initial geographic coverage of the final HYDROCOASTAL inland water output product was limited to the areas required for the case studies. Now that the improvements in accuracy and precision of the final products have been demonstrated, we recommend that the coverage of the HYDROCOASTAL product is expanded, starting with the following regions:

- *Global lake product*
- *Global river product*
- *Global Estuary product*

(For the lake and river products, we recommend expanding coverage starting from arid and arctic regions as the existing altimetry-based databases targeted mostly temperate (easy to validate) and equatorial (easy to process altimetry data) rivers and lakes.
Also, as the ongoing CCI-Lakes+ project is producing a global lake water level time series in all climates, the best value of future HYDROCOASTAL-based products could be achieved by focussing on small to medium sized lakes lakes.)

4.3.2. “Next Generation” Inland Water Products

The experience of processing data for the Yangtze River, identified that urban rivers provide a particular challenge, with complex topography, river traffic and off nadir echoing. Monitoring of these areas from space is important, and of potentially high value, especially when other sources of water level information may be restricted / classified.

A major processing challenge is the presence of multi-peaked waveforms including echoes from non-nadir reflectors. Some re-tracking approaches may not adequately track the nadir echo and so return highly variable values of water level which may not be usable.

Therefore more adaptive re-trackers (which can track the nadir echo peak) or fully focussed SAR processing may be more appropriate. However, this can be more difficult in terms of setting up a routine processing approach. In a future product different retracker-based elevations could be provided accompanied with flag information about which surfaces they should be applied to. As one retracker will not be ideal for all inland water surfaces.

The challenge with 20Hz UFSAR over narrow rivers and small lakes is the often limited number of measurements over the given target, which makes it challenging to identify outliers and provide reliable time series. Hence, increasing the along-track resolution via 80Hz or FFSAR processing over small targets (width less than 300 m) would be of high value as more independent measurements along-track would be available.

Processing with FFSAR, as shown in a dedicated Impact Assessment study and also in Molina et al 2023, allows the number of independent looks over small targets to be increased, and the precision is improved to the cm-scale. Nevertheless, time-domain based FFSAR processing is challenging in terms of computational effort, and in order to develop operational products a dedicated mask should be defined to reduce the processing only over the regions of interest. Although efforts are being taken to speed up the time-domain classic algorithms, alternative FFSAR options based on frequency-domain computing, which are faster but rely on some additional assumptions, should be extensively tested first to assess their precision.

In the HYDROCOASTAL project only the CryoSat-2 SAR and Sentinel 3A / 3B missions were used to construct water levels and discharge at virtual stations. Currently, with several missions operating simultaneously, it would be worthwhile to allocate research activities to create improved water level and discharge products based on multiple missions, in addition to the classical virtual station approach. Initial studies of such activities were conducted in the frame of the ESA RIDESAT and STREAMRIDE projects, where densified water level time series were reconstructed from multiple altimetry missions covering a river reach via different time-space state-space models. Additionally, now methodologies are needed to combine the nadir altimetry with the newly launched SWOT missions where the water level is provided as a spatial field.

Note that in the validation activities it was found that different re-trackers provided the best performance in different environments (See section 5.3). This leads to a recommendation to develop an adaptive or intelligent re-tracker approach, where different re-trackers are implemented for different environmental situations. The challenge is then to provide a continuous product from different re-trackers.

R4.3 We recommend further research to identify the best approach to construct a “next generation” inland water product:

- *Study feasibility of operational FFSAR products over regions of interest.*
- *Investigation into the options of implementing a single re-tracker or choice of retrackers – is the best choice dependent on classification of environment and/or the nature of the waveform?*

4.4.L3 River Level Time Series

To provide river level time series on a global scale, accurate information regarding the location of the rivers is necessary. This is provided in the SWORD database together with important auxiliary information (e.g. river width and elevation). In the HYDROCOASTAL project the SWORD database was used in combination with the Global Surface Water occurrence product to extract data over the rivers and link the altimetry to a location on the river centre lines to identify all the potential virtual stations. The approach developed in HYDROCOASTAL can be upscaled to a global product.

For rivers located in areas subjected to seasonal freezing a flag related to the ice conditions is indispensable as many currently available retrackers may fail or retrack different surfaces (ice top/ice bottom). Users should be warned which waveform peak was retracked in the case of adaptive retrackers.

The sampling provided by CryoSat-2 and Sentinel 3A / 3B is not sufficient spatially to capture small water bodies, or temporally to capture short term, episodic, flooding events. This will impact estimates of seasonal / annual flow and, depending on the situation, could result in significant over or under-estimates of river flow.

As mentioned above, one solution to improve the sampling would be to include more missions to obtain a higher resolution time series which can then capture river water level variations at a higher temporal scale. Another approach could be to carry out a spectral analysis on river flows.

4.5. L4 River Discharge

4.5.1. Overview

Three methods can be used for river discharge estimation from altimetry-derived River Water Level (RWL) time series:

- Rating Curve (RC) methods based on establishing an empirical relation between RWL and gauged (or modelled) river discharge.
- Manning equation based methods (ME) relying on hydraulic laws.
- Merging approach that uses RWL from altimetry data and reflectance indices from multi-spectral band images.

The first method is based purely on altimetry measurements, while the second method requires an estimation of additional hydraulic parameters, such as a river width and a river slope at each individual Water Level (WL) observation retrieval point from, for example, remote sensing measurements. However, it is necessary to make some assumptions for the slope parameter (constant slope over quite a long river section) which may not hold, and there are uncertainties in the width parameter (caused by asynchrony of width and WL observation), both of which may increase errors in the final L4 product using Manning equation based approaches. Another crucial information requirement for the ME methods is a mean river depth for the location of the Virtual Station (VS), which can be obtained from ground profiling (data could be requested from navigation authorities or teams running basin hydraulic models) or from an inversion of the RC method.

The third method requires the auxiliary files from multi-spectral satellite sensors. These datasets can be released to different spatial resolutions (250 m or 20 m) and are characterised by high temporal resolution (nearly daily). Because they are derived by passive sensors, they have problems linked to cloud coverage. Therefore, their efficiency can be limited in tropical areas.

It is important to note that the discharge calculated using altimetry measurements is always referenced to the location of a ground station whose data are used for calibration of RC or ME methods. Similarly, the reflectance indices need in-situ measurements or other auxiliary data (for example altimetry time series) to calibrate the location of the sensitive pixels. The uncalibrated procedure is being investigated.

4.5.2. River Discharge

In the standard practice of National Hydrological Agencies, the RC method underlies the production of all daily discharges from ground WL measurements at gauging stations. Several times per year the agencies should measure discharge using current meters for re-calibration and verification of the existing "stational" rating curves. The RC are usually stable if no changes in fluvial morphology (erosion, accumulation) occur within a reasonable distance up- and down-stream of the gauging station (GS). The RC method also provides the most accurate estimates of the river discharge from RWL time series retrieved for a broad range of altimetry missions including the Sentinel-3 SAR mission. The results of HYDROCOASTAL project demonstrated that for the tested locations the ME method can provide discharge estimation accuracy comparable with the RC method. Regarding the merging method based on the RIDESAT approach, it was shown in the project that this can produce improved estimates over the rating curve for some stations, where the contribution of the multispectral analysis is robust and consistent with the altimetric time series.

All the methods are sensitive to the RWL outliers. Their identification is crucial for the overall accuracy of produced discharge time series.

For RC method in cases 1) of rivers with seasonal ice cover or 2) when the distance between VS and GS is more than 100 km, 3) in presence of tributary downstream to VS, two or more distinct seasonal or flow dependent relationships between altimetry RWL and in-situ discharge may occur due to backwater effect or unknown flood wave travelling time, as well as due to changing flow resistance parameters and area geometry. Other potential cases of non-unique Q-WL relationship (e.g. a tributary effect) have not yet been investigated. An identification of reasons and separation of RWL time series (L3 product) based upon objective criteria (e.g. ice/water flag) can improve the accuracy of the satellite altimetry-based discharge products.

The current frequency of the Sentinel-3 observations is insufficient for the discharge product to be used in operational or even in climate-related tasks, as the repeat sampling is too infrequent to capture critical hydrological events even in large rivers with long flow integration timescales. Increased temporal resolution of the records in the L4 product can be made using a multiple VS approach whereby specific Q-WL relations are developed for several nearest VSs of the same and / or a range of different altimetry missions. For many big rivers a discharge product fulfilling the requirements related to climate change monitoring can be produced using such an approach. However, the success depends on configuration of satellite orbits, latitude, and river channel orientation (zonal or longitudinal). For middle and small size rivers, nevertheless, the densification of altimetry-built L4 product allows for adequately recording only the seasonal variability of the flow and not the individual synoptic-scale flow events such as individual floods.

4.5.3. Recommendations

R4.4. Ice period and especially melting identification and flagging for arctic and boreal rivers is crucial for accuracy of any satellite altimetry based discharge product.
A development of specific approaches for melting/freezing periods when the snagging is often observed should be considered for any global L4 product. It may include the application of specific retrackers (at L2 product level), OPC measurement selection (at L3 product level) as well as flagging the ice periods in the L3 and L4 products.

R4.5 Improving the water masks for mid-size/small rivers in braiding reaches or adaptation /development of the WL time series construction algorithm for such reaches would allow future applications to significantly enlarge the area of successful production of L4 products.
This is especially critical for high latitudes, where the channel braiding is a typical fluvial landscape.

R4.6 To improve the temporal sampling of the records in the satellite discharge products the approach of multiple VS merging should be undertaken.
This may be achieved both at the level L3 (merging the WL time series) and at the level L4 (merging the discharge time series) processing steps. However, existing merging techniques at both levels currently are underdeveloped and lack necessary verification of efficacy across a broad range of application areas. Studies and tests on extensive datasets are required potentially leading to further development of such approaches.

R4.7 When taking a decision on use of the VS for L4 production, an investigation of the Q-WL relation for presence of non-unique Q-WL relationship (in case of high scattering of points around the rating curve) should be envisaged before rejection of VS-GS pair, especially when considering efforts to increase the temporal resolution of records at the L4 step.

R4.8. All the methods for the river discharge estimation, RC, ME and RIDESAT methods, require a calibration against in situ discharge, measured at a nearest gauging station (GS) or modelled.

In this context:
D4.9 We recommend, to achieve continuity of L4 production, a continuation of ongoing satellite missions on the same orbit and with sufficient calibration periods. This is important if we want, in the long perspective, to reduce the dependence of satellite discharge products and processing schemes on ground observations (especially in remote areas).

5. Recommendations for Validation Activities

5.1. Introduction

The HYDROCOASTAL Product Validation Plan and Report (RD-08, RD-03) detail the methodology and results from the validation analyses applied to the HYDROCOASTAL Test Data Set, which included output from all the candidate new re-trackers.

The following high-level recommendation(s) is / are derived from this report:

R5.1. A consistent methodology should be applied a for validating the different products in coastal zones/transition regions/coastal lagoons. Aspects to be considered are: method for the outlier detection, the need of geophysical corrections at the same position / datation of the re-tracked range measurements. Other questions should be taken into account, such as the distance of the track to the in-situ measurements (coastal zones), the length of the track segment analysed, the best posting rate for the construction of the time series (80 Hz or a binned method).

The methodology used for HYDROCOASTAL is defined in the Product Validation Plan (RD-08). Readers are referred to that document for details.
When comparing altimeter sea level measurements to tide gauge measurements, the sea level anomaly was averaged over a distance of 2-20 km to the coast. For future studies we recommend considering reducing this distance according to the location. In estuaries or lagoons, the averaging distance should be less than the width of the feature and reduced further (to 300 m) if spatial details are of interest.

5.2.Coastal Zone

5.2.1. General Issues

The coastal zone SAR Altimeter re-trackers implemented by HYDROCOASTAL did not improve on the ESA product for wind speed. Wind speeds close to the coast, co-located with wave height measurements are important.

R5.2 It is recommended that further work is carried out to improve SAR Altimeter estimates of wind speed in the coastal zone. This will require a consistent and validated estimate for nadir radar-backscatter.

5.2.2. Recommendations from The Product Validation Report

The validation exercise for the coastal zone concluded that, based on the superior performance of the U Bonn re-tracker in retrieving SWH and U10, and the fact that it also retained a higher percentage of valid data closer to the coast, the UBonn re-tracker should be used to generate the coastal zone data set. An issue with a discontinuity in performance at 10km from the coast was noted.

R5.3. It was recommended that U Bonn investigates an improved implementation of the STARS retracker to provide a product without discontinuity at 10 km from coast. It is expected that this change could require a longer computation time. The performance of the revised algorithm will need to be evaluated.

R5.4. It was also recommended that the coverage of the selected re-tracker for inland waters (DTU) is extended to cover tidal estuaries close to the coast to provide continuity with inland water products.

It is important to note in assessing the validation results that the processing of data for HYDROCOASTAL has generated a data set with a different datation to the original input Sentinel 3A, 3B and Cryosat-2 data (Section 3.3). To match this datation, the ESA product L2 data were interpolated to the new locations, resulting in a certain amount of smoothing. This meant that in the analyses the ESA data may demonstrate a lower along track noise and apparently lower variability, so the results of the analyses for the ESA data were not directly comparable to those of the data from the new HYDROCOASTAL re-trackers.

Nonetheless, none of the new re-trackers was found to perform significantly better than the original ESA product, therefore from the results of the HYDROCOASTAL validation study, there was not sufficient evidence to support any recommendation that another re-tracker should be implemented on the satellite ground segment processing chains.

5.2.3. Other Recommendations

R5.5. Validation in Transition Zones
There is an interesting point regarding the transition zones between estuary mouths of river systems and their surrounding coastal waters. The impact of strong freshwater river discharges in the nearshore coastal waters, in terms of sea level variations, is still not clear (or not fully analysed). This bulge (or even ballooning if the bulge grows offshore under some conditions) of less dense water could be analysed with the HYDROCOASTAL final product in some specific areas with in-situ information (basically, discharge and sea/river water levels, but not only). This could allow a kind of validation of the product in these transition zones, but it could be also considered as an application activity. The use of HF radars could be of interest to validate geostrophic currents from along track data. Close to the coast, the ageostrophic components (wind effect and bottom-friction) can be added to the geostrophic currents in order to make a better comparison against HFR total currents. This is also particularly interesting for a validation strategy of SWOT data.

R5.6. The Distance to the Coast Parameter
For the development of the different diagnosis of the geophysical retrievals in the coastal Ocean scenario, the distance to the coast (d2c) is a key element.

The official L2 product contains information of this parameter, which is computed from a GSHHS solution. We have observed that the lack of accuracy of the d2c L2 field causes a general inconsistency in the analysis of the results, making it difficult to extract sound conclusions when this parameter is involved.

isardSAT has developed a d2c solution with a much higher resolution and an almost exact match with the georeferenced maps (García, 2018). This solution is based on a processing of the coastline polylines included in a collaborative open-source platform: the Open Street Map (OSM). Coastline polygons are closed forming a global database. This database can be easily scalable to a specific area of study, in order to reduce the computational effort when retrieving the d2c from every science product record to the closest OSM polygon.

We recommend using an enhanced land-sea mask solution (such as the previously exposed) that gives us a d2c parameter able to be used for more reliable coastal ocean validation exercises.

5.3.Inland Water

5.3.1. General Issues

Validation of lake and river levels is typically done based on the time series and not the L2 products. In this sense the validation results will in some degree depend on the method used to reconstruct the water level time series. To separate the value of the data and the time series method the following should be considered.

- When evaluating the data, the same approach to construct the time series should be used for all data types.
- When evaluating the method, the same L2 data should be used as input. In addition to the output time series the number of discarded measurements should also be reported

There is a problem in accessing river gauge data from some countries, where the data are regarded as proprietary (and related to national security). This reduces the effectiveness with which water resources can be monitored on a basin scale.

R5.7. We recommend that WMO and IHO work to improve access to water level data as an important international water management and supply security measure.

5.3.2. L2 and L3 - From Product Validation Report Recommendations

Note that only products generated from Sentinel-3A and Sentinel 3B data were evaluated.

Sentinel 3A and Sentinel 3B data
There was a consistent finding across the evaluations with larger data sets that the DTU re-tracker was on average found to be the best performing, in terms of accuracy of data retrieved (lowest NRMSE, RMSD) and the number of valid points retrieved.

However, there were some locations and types of river topography (complex geomorphology) in which the DTU retracker was not found to provide good estimates. In cases of complex relief the TUM and isardSAT re-trackers gave better results, and the TUM re-tracker provided better results than other re-trackers during ice melt. Therefore, different re-trackers may be preferred for different types of inland water topographies and environments.

Therefore, the main recommendation from the validation was that the DTU re-tracker should be implemented to generate the global scale data set from Sentinel 3A and 3B data.

R5.8. For future implementation, different re-trackers could be used to provide coverage in specific types of topography and environment where the DTU re-tracker did not perform well (for instance in complex terrain and during ice melt).

R5.9. Recommend the development of a classification scheme for inland waters, and the selection of different re-trackers most suitable for different situations. This could also involve the tuning of current re-trackers for these different classifications.

Cryosat-2 Data

Cryosat-2 data were not evaluated as part of the validation exercise (SAR or SARin mode). There is extensive coverage of the Amazon basin in the SARin mode, and it is anticipated that re-tracked SARin mode data could be effective in regions to enable the selection of the desired target where there are a number of reflecting sites close to the satellite track. CryoSat-2 SARin mode covers the Rhine river since 2017 and L3 time-series built at UBonn using the data processed by the SAMOSA+ retracker at G-POD/Earth Console are available for comparison for the interval 2017-2021.

5.3.3. Further Recommendations

Results from validation against tide/river gauges in estuaries show very large STDD when averaging along track (e.g. Bonn results for Elbe, FFSAR results for Severn). Inspection of along-track data shows very large variability in water level profile, different at different times. A different approach to validation is required to take this characteristic into account, but also other physical parameters, such as wind and waves, need to be accounted for to understand the signal. Early results from SWOT low resolution data show a good agreement of the altimeter with gauges in the same region. Studies are needed to investigate the new results.

The question is relevant as it may strongly impact the result of any validation exercise. It is not only important to agree on a validation method and on validation criteria, but also to agree the methods to be employed in the preliminary steps to produce the River/Lake Water Levels that are inputs to the validation exercise.

Some validation methods may only use the One Per Crossing (OPC) measurements (the selected or computed measurement at the intersection of a water body mask and the altimeter single pass ground track, also called a Virtual Station (VS) or a Virtual Gauge (VG)) while others may generate and use a time series built from these single pass measurements after detecting and removing the outliers.

Producing a time-series is also possible in the case of a geodetic orbits if the OPC measurements are migrated along the river profile to artificially increase (in the time domain) the number of measurements near a selected gauging station and therefore obtain time series to compare with those of the gauging stations. All of the methods that are necessary to produce the OPC and the time series should be agreed by the validation teams and at least specified to permit the comparison of differing validation results.

River Water Level (RWL)
In the HYDROCOASTAL L3 production/validation team there were different approaches to produce the OPC measurements:

- Use the median value (retracked_epoch) of all of the measurements within a given water body crossing.
- Compute the mean value (retracked_epoch) of all records within a given water body crossing.
- Use a robust state-space model to reconstruct the water level time series based on all measurements extracted using the SWORD centre lines and river width information accompanied with the Global Surface Water occurrence value (Pekel et al., 2016).

The first method is expected to provide less noisy results as it ignores the outliers that may be due to islands, bridges, or buildings at the riverbanks or even water ponds that may cause snagging of the radar altimeter. However, it is not possible to retrieve an error estimate with this approach. The second method merges all types of surfaces found within the water body crossing into a single “water height measurement” (whether they are water man-made structures or snagging) and so may be expected to provide noisier results and lead to higher errors when assessing the performance of a retracker. These methods must also take into account any editing that is performed with respect to the retracker flags. The selected flags should clearly be associated to the figures obtained in the validation exercise.

All of these experimental conditions during validation should be clearly identified and reported in order to progressively build a sound scientific knowledge on the performance of the altimetric chain at each step. Without a normalisation of the initial steps it becomes impossible to compare validation results.

It was suggested by some partners that the method used to produce Once Per Crossing measurements should be unique, even in a project with several validation entities.

It is recommended that the editing of the re-tracked epochs (flags used to select the record per record measurements) should be reported when producing OPC values and time series.

RWL Time Series

In the repeat orbit case or after the adequate migration of OPC measurements in a non-repeat orbit case, time series are obtained after filtering the series of OPC measurements to remove their outliers. This can be done in several ways, for example through a recursive calendar 3 sigma rejection filter.

The selected outlier removal method will impact the final products and therefore the validation exercise with respect to some gauging stations. For the sake of clarity, the exact method that is used to reject the outliers shall be detailed and known to the validation teams as the validation results and their interpretation depends on the method used to obtain the RWL time series.

The full detail on the method used to produce the OPC RWL and then the method used to produce the time series shall be specified, especially if the same team is running the full stack (producing the OPC RWL, producing the time series by filtering the outliers, and running the validation against gauging station). Without the detailed information on the whole processing chain, it may become impossible to compare the validation results from different teams. This has been observed during the HYDROCOASTAL project. Ideally the validation team should agree on:

- a common and unique method to produce OPC measurements,
- a set of methods to produce the L3 time series from the very same OPC measurements.

A set of recognized validation methods (outlier rejection, densification through spatial migration of measurements) should be agreed and specified by the quorum of the validation teams.

A single entity in such a project should be in charge of producing at least the OPC measurements and possibly up to the L3 time series. The time series should then be provided to all of the validation teams that would then be in charge of comparing them with their own levelled reference gauging data.

The density of measurements or Sampling Loss Rate should be part of a validation exercise as various re-trackers may have relaxed or strict flagging resulting in different performances and coverage. A global ranking mark could be obtained by the proper combination of all validation criteria to be agreed.

Having a standard method for ranking the validation results and taking into account all of its aspects (criteria) is essential to be able to compare different processing chains. There could be several flavours of such a global ranking method and the results should be attached to the ranking method.

6. Key Findings from Impact Assessment Studies

6.1. Introduction

In the final phase of the HYDROCOASTAL project, a series of Impact Assessment Case Studies were carried out 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.

The three Impact Assessment Reports (RD-04, RD-05, RD-06) summarise the key scientific findings and the main recommendations from the Impact Assessment Case Studies. We provide the main recommendations in the sections below:

6.2.Coastal Zone

6.2.1. Overview

The Impact Assessment Report for the Coastal Zone (RD-04) 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 and CryoSat-2 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 Sentinel 3A/B and CryoSat-2; 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 (Sentinel 3A/B and CryoSat-2).
- 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 Sentinel 3A.
- 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).

6.2.2. Summary

The precision of the re-trackers has been assessed in four locations: Bristol Channel and Severn Estuary (U.K.), Marano-Grado lagoon (Italy), Ebro Delta (Spain), German Bight and Baltic (Germany). The UBonn re-tracker gives the best performance in the U.K. coastal area (in comparison to DTU and ESA) and in the Spanish coastal areas (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. Along the German coasts UBonn is more precise.

The accuracy of the re-trackers was also quantified in most of the study areas using times series of Sea Level Anomaly, Total Water Level Envelope and Absolute Dynamic Topography. 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 the Elbe estuary, DTU data have the highest accuracy.

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.

The impact of the improved coastal products in sea level rise estimation could not be properly evaluated due to the relatively short time series duration (it was estimated that at least 10 years are needed to get estimations with acceptable levels of uncertainty). With the current length of data records, SLR derived from Hydrocoastal products seem to diverge from baseline products and literature even at relatively large distances from the coast.

6.2.3. Recommendations

The findings of the Coastal Zone Case Studies lead to the following recommendations:

R6.1 The use of WTC/DTC from UPorto to estimate sea level parameters is strongly recommended.

R6.2 Further studies are recommended to develop an accurate Sea State Bias correction for SAR altimeter data.

R6.3 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.

R6.4. Further detailed studies of Unfocused SAR and Fully Focused SAR altimeter processing in estuary environments are recommended.
These should 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.

R6.5 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.

R6.6 We recommend a specific activity to investigate storm surge events.
TWLE, wind speed and SWH are important for many applications in coastal zones (e.g. storm surges). TWLE has improved thanks to better re-tracking strategies. SWH and wind speed are not mature enough for exploitation, so we recommend more work to improve their precision and accuracy.

R6.7 The use for exploitation of the new HYDROCOASTAL re-trackers are recommended for coastal zones, with accurate mean sea surface.
We note that UBonn includes SWH and U10 as output products that need more work in terms of validation.

R6.8. In estuarine areas, the use of the DTU re-tracker is recommended to provide continuity with the water levels for the inflowing rivers (which are also provided by the DTU re-tracker).

R6.9 We recommend 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.

R6.10 Longer time series of altimeter data are needed in order to analyse the benefits of HYDROCOASTAL products in terms of ocean variability of lower frequency: e.g. Sea Level Rise.

R6.11 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.

R6.12. Assess the potential of SAR altimeter data processed at higher posting rates. More research is needed to determine whether usage of higher posting rates generally results in more data.

6.3.Inland Water

6.3.1. Overview

The Impact Assessment Report for Inland Waters (RD-05) summarises the results from Four Case studies:

- UBonn evaluated the quality of the HYDROCOASTAL product against official and other specialised products and gauge data. The evaluation was conducted over the Rhine River and Lake Constance.
- CNR/IRPI validated the HYDROCOASTAL discharge product which is primarily based on the approaches from the ESA RIDESAT project. Additionally, the interaction between the Po river outlet and coastal zone was investigated in relation to flood and drought events in 2022. Also, the influence of river floods and drought was studied from the ocean side.
- NUIM validated the HYDROCOASTAL products over lakes and rivers in Ireland. Additionally it was shown that the use of altimetry provided promising results over peatlands.
- DTU developed a hydraulic model informed with river cross section profiles based on ICESat-2. The model can simulate water level and discharge at any location along the river.

6.3.2. Summary

In the projects several inland water relevant retracts were evaluated but the DTU MWaPP retracker was selected for the production of the final global products. The performance is in general good, and it is the only retracker that was used for both inland water and the coastal zone. Being able to apply the same retracker in this transition zone is important for consistency to avoid an elevation bias.

When compared to other altimetry products and gauge data the quality of the MWaPP retracker was in the high to medium performance range depending on the specific study (as demonstrated by NUIM and CNR IRPI). The UBonn case study showed that the use of FFSAR may provide improved results, but simply increasing the resolution of unfocused SAR to 80Hz could lead to improved results, and also the retracking used is relevant (80Hz and SAMOSA+ re-tracker provided the best solution in this study).

Another result that was gained from the project is the role of generating time series and critical data and result filtering. UBonn demonstrated that for lakes one simple virtual station time series may not be ideal, whereas a better solution is to generate several time series along the tracks representing the virtual station. NUIM demonstrated that the HYDROCOASTAL approach to generate time series improved the RMSE by several cms compared to the simpler approach also used in the case study. In the case study regarding the Amur river, DTU showed that the HYDROCOASTAL L3 product is of similar quality as the HydroWeb products. The HYDROCOASTAL product provided approximately 50 % more virtual stations but some were of reduced quality, indicating that a more severe quality assurance is necessary.

River discharge was produced on the basis of the L3 water level time series via the rating curve approach and the RIDESAT algorithm (CNR IRPI). Rating curves were produced based on altimetry and reflectance indices obtained from imagery. From the study by CNR IRPI it was demonstrated that the RIDESAT algorithm outperformed the other methods. This study further highlighted the necessity of an increased temporal resolution of altimetry to improve discharge and the issues of spectral data loss in tropical and arctic areas due to cloud cover.

Sentinel-3 SAR altimetry demonstrated good potential for monitoring the WL regime over medium and small size lakes (area between 1 and 115 km2) and small rivers (width < 100 m). The method used for construction of the L3 HYDROCOASTAL product over several big Irish lakes (TsHydro) provided WLTS with better accuracy than an alternative method based on a simple statistical filtering approach and an adaptation and testing of the TsHydro approach over smaller water objects in other case study regions may be valuable.

The HYDROCOASTAL project has fostered several new scientific applications of altimetry. NUIM demonstrated that altimetry (here the HYDROCOASTAL product) can be used to monitor water level change in peatlands. Peatlands represent potentially millennial scale carbon storage as noted in the IPCC Special Report on Climate Change and Land. Efficacy of this storage is related to the stability of their water regime.

CNR IRPI showed that the HYDROCOASTAL products (L3 and L4) were able to map the extreme 2022 drought event of the Po River. The study further showed that the intrusion of seawater could be detected in the downstream part of the river. Additionally, the HYDROCOASTAL L2 (MWaPP) sea levels could detect both floods and droughts near the mouth of the Po River. DTU developed a hydrodynamic model which is informed by ICESat-2 based river cross sections. The benefit of such a model is that it will allow the prediction of water level and discharge along the river reach included in the model.

In summary the HYDROCOASTAL project has fostered many new products and scientific results that will be a stepping stone for several new products and studies.

6.3.3. Recommendations

The Inland Water Case Studies led to the following recommendations.

R6.13 For smaller targets it would be beneficial to increase the resolution to 80Hz for unfocused SAR or apply the FFSAR technique to increase the along track resolution.

R6.14 Ensure consistency of the river and sea level by having a common retracker such as the MWaPP retracker. In addition, a consistent reference surface in this zone is equally important.

R6.15 The methodology to generate time series from L2 water levels may influence the results and should be further investigated.

R6.16 An adaptation and testing of the TsHydro approach over smaller water objects in other case study regions is recommended.

R6.17 The development of specific water mask products based on high resolution optical/SAR images or altimetry-based methods for OPC selection of radar measurement over small inland water bodies and courses would permit the application of TsHydro at smaller scales.

R6.18 Develop a sand-box model to simulate the impact of the flooding and drought extreme events with the aim of providing scenarios to local stakeholders from the integration of river discharge and coastal circulation and facilitate the interpretation of the radar altimetry product.

R6.19 To improve discharge estimation and the study of extreme events it is critical to improve the temporal resolutions of altimetry (e.g. with constellations of small satellites).
The current configuration of orbits of altimetry missions (Sentinel-3A, 3B and Sentinel-6) means that many important middle-size lakes and smaller water bodies are not adequately sampled, or indeed in many cases sampled at all. This requires both more missions but also careful orbital configuration design decisions to maximise the chances of covering as many inland water bodies as possible with a minimisation of repeat sampling times.

R6.20 In relation to the recent launch of SWOT it will be important to investigate the benefits of combining SWOT and the nadir altimetry.
This recommendation is expanded in Section 7.

R6.21 Expand the use of satellite altimetry, one example could be over peatlands, which are important reservoirs of carbon dioxide which depending upon their health can act as sinks or sources.
A dedicated study will be helpful for more accurate retrieval of the height of water table. This has enormous potential applicability in terms of accurately accounting for Land Use, Land Use Change and Forestry (LULUCF) emissions at territorial and pan-European levels which will be key in verifying net-zero emissions attainment over coming decades.

R6.22 A tighter control of cross-track orbit deadband is recommended to support repeat monitoring of inland water bodies with small scale cross-sections.
In areas of more complex topography the cross-track orbit variation was found to be a critical limitation to the construction of meaningful water level time series. A reduction of the satellite orbit cross-track oscillation is thus necessary for monitoring small water bodies and streams in more complex topography.

R6.23 A more accurate DEM is recommended.
Over small lakes in Central Yakutia (e.g. the Aldan and Lena rivers interfluvial area) the on-board DEM on Sentinels-3A and 3B is still not sufficiently accurate. This region is important for understanding the effect of rapid degradation of permafrost on surface water balance and associated implications for natural sources and sinks of GHGs. We note also that it was not possible to generate Water Level Time Series for some Greenland rivers due to an inaccurate DEM in the ice-free zone. These rivers are interesting in their own right as a technically challenging target.

R6.24 To ensure the value of products such as HYDROCOASTAL, a strategy for continuation and easily accessible via a web interface is important.

R6.25 A strict quality assessment is important before public release.

R6.26 In view of a potential global application of the hydrodynamic workflow a focus on a calibration-free cross section delineation workflow is important.

6.4. Processor Case Studies

6.4.1. Overview

Six Processing Case studies were carried out for HYDROCOASTAL and are reported in the Impact Assessment Processing Case Study Report (RD-06):

- 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.
- 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.
- isardSAT applied the Sentinel-6 GPP FFSAR processor to data over inland water targets and analysed by validation against in-situ data.
- isardSAT applied their coastal and FFSAR processors to Sentinel-6 data over coastal regions.
- 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.

6.4.2. Summary

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 100s m 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 again at higher along-track resolution, what allows to improve the measurement precision to the cm-scale. 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.

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). In addition to that, the analysis of an FFSAR reduced dataset points to a clear improvement with respect to the DDP products, which should be further investigated.

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.

6.4.3. Recommendations

The full focusing of radar altimeter data, a new concept proposed by Egido and Smith (2017), works under the assumption that the instrument maintains the signal coherency by, at least, a full illumination time. By processing all the bursts illuminating a scatterer on the surface, it is possible to complete the coherent focusing in the along-track over the entire illumination time. The main advantage of this processing is a high resolution in along-track or a higher number of equivalent looks.

Fully focused back-projection algorithm has shown to be a robust way to focus altimeter data, at least in closed burst configuration. However, the processing is computationally heavy. Currently, efforts are underway to accelerate the processing by means of code simplification while preserving the good quality of the Impulse Response Function, as well as with GPU implementation.

The improvements in terms of water level precision to the cm-scale reported by isardSAT using the S6-GPP FFSAR processor are based on a small set of targets [Molina et al 2023].

R6.27. It is recommended to extend the study of FFSAR performance over a more general collection of inland targets, including a larger variety in terms of size, in order to get a more general idea of the FFSAR improvements in terms of accuracy and precision over inland targets with respect to Delay-Doppler results.

Regarding the FFSAR coastal analysis, the improvements observed are based on multiple observations of the same area using few tracks.

R6.28. It is recommended to extend the evaluation of benefits in terms of performance of FFSAR processing on coastal areas over a larger dataset and with different coastal topography and ground track orientations, and with different sea states.

Aresys investigated processing algorithms in the frequency domain for high PRF radar altimeters. It has been demonstrated that the in-house Fully Focussed SAR processor [Guccione et al., 2018], operating in the frequency domain, is a valid alternative with respect to the back-projection processing. In particular, the Aresys processor showed to be about 450 times less expensive (in terms of computational time) than the back-projection while preserving a good quality of the Impulse Response Function.

R6.29. It is recommended that Fully Focused processors working in the frequency domain be further developed, to take advantage of the more efficient computational capabilities.
The Full Focusing processing allows to increase the along-track resolution up to its theoretical limits, i.e. half the antenna length, and can potentially lead to more accurate estimation of geophysical parameters than those obtained from unfocused SAR processing. In addition, the increment in along-track resolution allows for a better isolation and removal of corrupted waveforms due to small off-nadir scatters without significant loss in the total number of observations. In order to fully exploit the potentiality of this new processing technique however, a systematic study into best processing options for different sensors and target areas is needed. The analysis should investigate different inland, coastal and offshore target areas and include different sea-states (high wind / low wind, high SWH / low SWH, high tide / low tide) in order to identify the optimal parameters in terms of waveform identification / pre-processing, retracker selection, posting rate and illumination time. An extensive study of this kind would highly benefit from the reduced computational time of operating in the frequency domain with respect to the Back Projection algorithm, though it would be worth assessing the differences in terms of performance between the different available algorithms.

R6.30. It is recommended to investigate algorithms and procedures to optimise the filtering of corrupted waveforms in FFSAR observations over inland targets.

R6.31. 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.
- The different FFSAR processing algorithms (classic back projection, accelerated back projection, and frequency-domain) should be considered and compared in terms of performance.

In the Case Study for HYDROCOASTAL, Aresys investigated some options in the multi-looking output step according to the different kind of target; moreover, different strategies have been investigated to mitigate the impact of the grating-lobes on the FFSAR waveforms (particularly over inland waters).

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, attenuated by the antenna envelope. These replicas can create difficulties in FF-SAR processing of waveforms, especially over inland water regions. Here, due to the presence of high reflecting targets, the replica can produce artefacts and false peaks, cheating the retracker. A proper mitigation strategy must be applied. A prototype approach is being developed to mitigate the impact of these “grating lobes” on the accurate retrieval of inland water levels. The most delicate part of the algorithm is the identification of the point targets that generate the grating lobes. For this reason, further development and testing are needed.

R6.32. The (Aresys) grating lobes study should be extended to provide specific recommendations for processing, considering e.g. the sizes of target that are affected.

In a prototype algorithm, the impact of the grating lobes has been reduced by replacing the target acquisition with an open-burst configuration and subtracting the grating lobes on the strongest targets only. Another approach would remove the low-coherence areas, since the grating lobes are not focused. Since a proper identification of the point target is necessary, the algorithms still need further refinement and testing.

R6.33 A recommendation for future missions in closed-burst configuration (such as CRISTAL) intended to process FF-SAR data, is to design, where possible, the antenna pattern so to place the pattern notches close to the grating lobes replicas. This would naturally mitigate the effect of the lobes.

R6.34. 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.

R6.35. It is recommended that future radar altimeters operate at open burst over inland waters to optimise 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.

R6.36. 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.

R6.37. 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.

R6.38. It is recommended that an Open Loop Tracking Mode is considered for the CRISTAL mission over mountainous inland water bodies, over flat areas the Close Loop Tracking Mode is preferred.

- 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.

7. Additional Recommendations

7.1.Mean Sea Surface Improvements

Now, through the availability of SAR altimetry and new re-trackers, it is possible to retrieve valid altimeter data at high frequency very close to the coast. These products could be used to improve Mean Sea Surface products close to the coast.

R7.1 It is recommended to recalculate average MSS profiles from missions in repetitive orbits using the new data sets and:

- *compare them with MSS gridded products in order to precisely quantify the errors near the coast.*
- *use these data to recompute new gridded MSS products that meet the needs of coastal applications.*

7.2.SWOT Studies

Contribution of the EO satellite missions to the assessment of coastal and Estuarine hydrodynamics in response to multi-drivers: New SWOT mission. In this action, we would like to explore our works (previous and in progress) to include activities related to the new SWOT products and their contribution in the improvement of numerical models and to higher quality in observations. We think investigations should focus in particular on rapid changes and inundation events causing large disasters.

Contribution of the EO satellite missions to the assessment of glacial lakes change in response to multi-drivers: New SWOT mission. In this action, we would like to explore our works (previous and in progress) to include activities related to the new SWOT products and their contribution in the improvement of detection of water level and water storage change at small scales in the Alpine lakes and reservoirs.

R7.2 Investigation into the benefits from a 2D complete coverage
We recommend an assessment of the potential contribution of the EO satellite missions to the analysis of coastal and Estuarine hydrodynamics in response to multiple inputs, to include data from the new SWOT mission in the nadir multi-mission coverage. In this action, previous and in progress activities would be extended to merge the new SWOT products with data from nadir altimeters into 2D maps, including AI techniques for reconstruction of heights. The potential of these maps to detect sea level change and to improve the performance of numerical models would be assessed. The ultimate goal is to detect rapid water level change in extremes and inundation events.

A second task would be to investigate the contribution of EO satellite missions to the analysis of changes (level and storage) in glacial lakes in response to multiple drivers. Data from the new SWOT mission would again be added to that from the nadir altimeter constellation. FFSAR processing of past SAR nadir altimetry could be included. In this action, previous and in progress activities would be extended to include the new SWOT products. The changes in Alpine lakes and reservoirs due to glaciers melting would be assessed.

Finally earlier and ongoing work would be further developed to investigate the contribution of the EO satellite missions to the assessment of changes in river discharge in response to multiple drivers.

Again, data from the SWOT mission and from nadir altimeter data would be merged, and FFSAR processing investigated. The goal of this work would be to improve measurements of river discharge.

7.3. Machine Learning-Based Gridding

The current HYDROCOASTAL coastal product is along-track. This limits its uptake by the users. Traditional gridding of altimetry data is based on optimal interpolation and has a very different primary objective than this project, i.e. identification of circulation features, rather than sea level monitoring.

R7.3 We recommend an activity to investigate data-driven methodologies to provide sea level measurements on a grid.
In particular, a training dataset would be generated based on the HYDROCOASTAL product, or on the standard CMEMS L3 product, and used to feed a machine-learning regression (Random Forest Regression, Support Vector Machines). Likely features to be used are weighted neighbouring points. The regression routine would be used to generate daily sea level data, which may be averaged on a monthly basis and used to compute sea level trends. The procedure would be applied to a test area and the daily product validated by means of tide gauges.

8. Summary

8.1. Introduction

In this summary section we have taken the various recommendations from the different phases of the project, as presented in the earlier sections and compiled them into combined recommendations under 8 headings:

- For Operational Processing and Products (OPP)
- For Corrections and Auxiliary Data (CAD)
- For Generating a Global Product (GP)
- For Processor Development (PD)
- For Validation Studies (VS)
- For Scientific Investigations (SI)
- Satellite Mission Recommendations (SM)
- General Recommendations (G)

8.2. Recommendations for Operational Processing and Products (OPP)

OPP.1 Wet and Dry Troposphere Operations options and usage - Recommendation to use GPD+

R6.1 The use of WTC/DTC from UPorto to estimate sea level parameters is strongly recommended.

R3.8 Due to the land contamination, MWR-derived WTC observations cannot be used near the coast nor over IW regions.

R3.9 The ECMWF Operational model is not stable and should not be used before 2004. For climate studies, the use of ECMWF Op derived WTC may introduce significant trend errors at time scales of 5-10 years, as e.g., for the S3 time span. ERA5 is the most stable model wrt the SSMI/SSMIS imaging sensors, considered a radiometric reference.

R3.10 ERA5 derived WTC should be provided in the altimeter products.

R3.11 For coastal and IW regions, neither the MWR nor the model-derived WTC should be adopted. The adopted WTC should be an improved and continuous WTC such as GPD+, based on observations when they exist and calibrated against a stable source such as SSMI/SSMIS.

OPP.2 Presentation / availability of ESA products on distribution platforms

R3.12 - Recommendations for presentation of ESA Altimeter products

It is recommended that ESA should:

- Include a flag to select the processing baseline of products in the interface (SciHub & dataspace.copernicus.eu).
- Explain why old baselines (003) are still the only option for very old products.
- Provide/update resources to detail the differences between baselines.

8.3. Recommendations for Corrections and Auxiliary Data (CAD)

CAD 1. Seasonal / dynamic water masks

R2.4 The need for seasonal water masks was noted, as the use of static masks results in over (or under) estimates of the area covered by water, and so limits the accuracy of derived water discharge measurements.

R4.5 Improving the water masks for mid-size/small rivers in braiding reaches or adaptation /development of the WL time series construction algorithm for such reaches would allow future applications to significantly enlarge the area of successful production of L4 products.

CAD 2. Geophysical corrections at same resolution and datation as re-tracked data.

R2.6. Improved geophysical corrections, at the same spatial resolution of the SAR altimeter products are needed.

R3.3 Compute the geophysical correction from the geophysical models at the time stamps of the measurements to provide more accurate information than when interpolating correction recorded in the operational L2 products.

CAD 3. Improved (Coastal) Bathymetries

R2.7. The accuracy of tidal models is dependent on bathymetric data, which remains sparse in many areas.

CAD 4. Improved Regional and Coastal Tidal Models

R2.8. One of the biggest remaining challenges in ocean tide modelling is the accurate modelling of shallow waters where non-linear interactions play a role (includes estuary regions). Global or regional models do not take account of the interactions between tides and other contributors to the water level variability such as winds and river flow.

R6.3 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.

CAD 5. Mean Sea Surface. Develop new improved mss with implementation recommendations.

R3.5 A large scale study is recommended to understand the impact of different mss on the output of re-trackers that use an input mss as part of the processing.

R6.5 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.

R7.1 It is recommended to recalculate average MSS profiles from missions in repetitive orbits using the new data sets and:

- *compare them with MSS gridded products in order to precisely quantify the errors near the coast.*
- *use these data to recompute new gridded MSS products that meet the needs of coastal applications.*

CAD 6. Improvements to Wet and Dry Troposphere Corrections

R3.6 The reference height at which the tropospheric corrections (DTC and WTC) have been computed should be provided in the altimeter products, to allow for the application of corrective terms, in case more accurate re-tracked heights become available and these differ from the reference heights by more than 40 m.

R3.7 Icesat-2 data should be exploited to derive and improved DEM over IW regions, similar to what has been done in ACE2.

CAD 6. Inland Water: Flags for river characteristics / season

R4.4. Ice period and especially melting identification and flagging for arctic and boreal rivers is crucial for accuracy of any satellite altimetry based discharge product.

CAD 7. SAR Altimeter Sea State Bias Correction

R6.2 Further studies are recommended to develop an accurate Sea State Bias correction for SAR altimeter data.

CAD 8. Dynamic Coastal Zone Water Masks

R6.9 We recommend 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.

CAD 9. Tide-Surge Water Level Corrections

R6.11 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.

CAD 10. Improved Digital Elevation Model

R6.23 A more accurate DEM is recommended. Over small lakes in Central Yakutia (e.g. the Aldan and Lena rivers interfluvial area) the on-board DEM on Sentinels-3A and 3B is still not sufficiently accurate. This region is important for understanding the effect of rapid degradation of permafrost on surface water balance and associated implications for natural sources and sinks of Greenhouse Gases.

8.4. Recommendations for a Global Product (GP)

GP.1 Processing Platform Design

R3.2 Processing platform - reducing data access limitations.

- *Avoid the transfer of large amounts of data by gathering the different processors in a platform with direct access to the raw data.*
- *Implement the capability to download sub-products based on the definition of geographical areas (e.g. using kml files).*

GP.2 Coastal Zone Global Products

R 4.1 We recommend development of an incremental processing scheme to generate a coastal altimetry data set to provide global coverage in the three identified categories: Coastal Zones, Transition Regions, Coastal Lagoons. Different processing options should be considered for the different categories. This may involve the use of more than one processing approach per category.
R5.4. Recommended that the coverage of the selected re-tracker for inland waters (DTU) is extended to cover tidal estuaries close to the coast to provide continuity with inland water products.
R6.7 The use for exploitation of the new HYDROCOASTAL re-trackers are recommended for coastal zones, with accurate mean sea surface.
R6.8. In estuarine areas, the use of the DTU re-tracker is recommended to provide continuity with the water levels for the inflowing rivers (which are also provided by the DTU re-tracker).
R6.14 Ensure consistency of the river and sea level by having a common retracker such as the MWaPP retracker. In addition, a consistent reference surface in this zone is equally important).
R6.24 To ensure the value of products such as HYDROCOASTAL, a strategy for continuation and easily accessible via a web interface is important.
R6.25 A strict quality assessment is important before public release.

GP.3 Inland Water Global Products

R4.2 The initial geographic coverage of the final HYDROCOASTAL inland water output product was limited to the areas required for the case studies. Now that the improvements in accuracy and precision of the final products have been demonstrated, we recommend that the coverage of the HYDROCOASTAL product is expanded, starting with the following regions:

- *Global lake product*
- *Global river product*
- *Global Estuary product*

(For the lake and river products, we recommend expanding coverage starting from arid and arctic regions as the existing altimetry-based databases targeted mostly temperate (easy to validate) and equatorial (easy to process altimetry data) rivers and lakes.
Also, as the ongoing CCI-Lakes+ project is producing a global lake water level time series in all climates, the best value of future HYDROCOASTAL-based products could be achieved by focussing on small to medium sized lakes lakes.)

R6.14 Ensure consistency of the river and sea level by having a common retracker such as the MWaPP retracker. In addition, a consistent reference surface in this zone is equally important).
R6.24 To ensure the value of products such as HYDROCOASTAL, a strategy for continuation and easily accessible via a web interface is important.
R6.25 A strict quality assessment is important before public release.

8.5.Recommendations for SAR /SARin Altimeter Processor Development (PD)

PD.1 Off nadir echoes

R2.1. There remains a problem with contamination of SAR altimeter waveforms with echoes from off nadir reflections. This mostly affects inland waters, but also some coastal regions. Approaches should continue to be developed that can successfully identify the nadir reflection and sub-sample or clean the waveform to remove contamination from off nadir reflections.

PD.2 Development and Implementation of Fully Focussed SAR Processing

R2.2 Fully Focused SAR altimeter processing has shown its potential to improve precision to the cm-scale for measuring levels of small water bodies, especially for inland waters.

PD.3 Next Generation Inland Water L2 Products: Inland Water categorisation and "intelligent" re-tracker selection

R4.3 We recommend further research to identify the best approach to construct a "next generation" inland water product:

- *Study feasibility of operational FFSAR products over regions of interest.*
- *Investigation into the options of implementing a single re-tracker or choice of retrackers – is the best choice dependent on classification of environment and/or the nature of the waveform?*

R2.5. It is important to evaluate retracking algorithms over a substantial number of inland water bodies to quantify the quality of the algorithms as a function of the water condition and other parameters (area, elevation, seasonal ice cover, braiding...), as any single re-tracker may not provide the best results for all environments. Such information may help the user to apply the most optimal product for a certain target type.

R3.5 We recommend the trial development of an "intelligent" retracker for inland waters, that applies different re-tracking algorithms to different types of inland water environment and different characteristics of waveform.
R5.8. For future implementation, different re-trackers could be used to provide coverage in specific types of topography and environment where the DTU re-tracker did not perform well (for instance in complex terrain and during ice melt).
R5.9. Recommend the development of a classification scheme for inland waters, and the selection of different re-trackers most suitable for different situations. This could also involve the tuning of current re-trackers for these different classifications.
R6.12. Assess the potential of SAR altimeter data processed at higher posting rates. More research is needed to determine whether usage of higher posting rates generally results in more data.
R6.13 For smaller targets it would be beneficial to increase the resolution to 80Hz for unfocused SAR or apply the FFSAR technique to increase the along track resolution.

PD.4 Next Generation Coastal Products
R2.11. A processing approach is needed to produce a "seamless" data set across the boundary between river mouths and tidal estuaries.
R 4.1 We recommend development of an incremental processing scheme to generate a coastal altimetry data set to provide global coverage in the three identified categories: Coastal Zones, Transition Regions, Coastal Lagoons. Different processing options should be considered for the different categories. This may involve the use of more than one processing approach per category.
R6.12. Assess the potential of SAR altimeter data processed at higher posting rates. More research is needed to determine whether usage of higher posting rates generally results in more data.
R6.13 For smaller targets it would be beneficial to increase the resolution to 80Hz for unfocused SAR or apply the FFSAR technique to increase the along track resolution.

PD.5 Inland water L3 Improvements
R4.6 To improve the temporal sampling of the records in the satellite discharge products the approach of multiple VS merging should be undertaken.
R6.15 The methodology to generate time series from L2 water levels may influence the results and should be further investigated.
R6.16 An adaptation and testing of the TsHydro approach over smaller water objects in other case study regions is recommended.
R6.17 The development of specific water mask products based on high resolution optical/SAR images or altimetry-based methods for OPC selection of radar measurement over small inland water bodies and courses would permit the application of TsHydro at smaller scales.
R6.26 In view of a potential global application of the hydrodynamic workflow a focus on a calibration-free cross section delineation workflow is important.

PD.5 Inland water L4 Improvements
R4.7 When taking a decision on use of the VS for L4 production, an investigation of the Q-WL relation for presence of non-unique Q-WL relationship (in case of high scattering of points around the rating curve) should be envisaged before rejection of VS-GS pair, especially when considering efforts to increase the temporal resolution of records at the L4 step.
R4.8. All the methods RC, ME and RIDESAT methods require a calibration against in situ discharge, measured at a nearest gauging station (GS) or modelled.

PD.6 Sigma-0, Wind Speed and SWH from SAR altimetry

R5.2 It is recommended that further work is carried out to improve SAR Altimeter estimates of wind speed in the coastal zone. This will require a consistent and validated estimate for nadir radar-backscatter.

R6.7 The use for exploitation of the new HYDROCOASTAL re-trackers are recommended for coastal zones, with accurate mean sea surface. We note that UBonn includes SWH and U10 as output products that need more work in terms of validation.

PD.7 Development of U Bonn STARS re-tracker

R5.3. It was recommended that U Bonn investigate an improved implementation of the STARS retracker to provide a product without discontinuity at 10 km from coast.

PD.8 Further development of fully focused SAR processing

R6.29. It is recommended that Fully Focused processors working in the frequency domain be further developed, to take advantage of the more efficient computational capabilities.

R6.30. It is recommended to investigate algorithms and procedures to optimise the filtering of corrupted waveforms in FFSAR observations over inland targets.

R6.31. 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.

PD.9 Grating Lobes Mitigation

R6.32 The (Aresys) grating lobes study should be extended to provide specific recommendations for processing, considering e.g. the sizes of target that are affected.

PD.10 Attitude Errors

R6.34. 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.

PD.11 CORS Processor Development

R6.35. 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.

PD.12 Unfocused and Fully Focused SAR at the Coast

R6.36. 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.

PD.13 Investigating Gridding Approaches for Sea Level Data

R7.3 We recommend an activity to investigate data-driven methodologies to provide sea level measurements on a grid.

8.6.Recommendations for Validation Studies (VS)

VS.1 Validation Studies – General Recommendation

R5.1. A consistent methodology should be applied a for validating the different products in coastal zones/transition regions/coastal lagoons. Aspects to be considered are: method for the outlier *detection, the need of geophysical corrections at the same position / datation of the re-tracked range measurements. Other questions should be taken into account, such as the distance of the track to the in-situ measurements (coastal zones), the length of the track segment analysed, the best posting rate for the construction of the time series (80 Hz or a binned method).*

VS.2 Validation Studies with SWOT data – Coastal
R7.2 Investigation into the benefits from a 2D complete coverage

VS.3 Validation Studies with SWOT data – Inland Water
R2.10. It will be important to compare results and evaluate new approaches to estimating river discharge from the SWOT mission.
R6.20 In relation to the recent launch of SWOT it will be important to investigate the benefits of combining SWOT and the nadir altimetry.
R7.2 Investigation into the benefits from a 2D complete coverage

VS.4 Recommend further validation studies in "transition" zones
R5.5. Validation in Transition Zones

VS.5 Recommend the implementation of an improved distance to coast parameter
R5.6. The Distance to the Coast Parameter

8.7. Recommendations for Scientific Investigations (SI)

SI .1 Decomposition of water level signal into different components
R2.9. At the coast / river interface, a major challenge is the decomposition of a combined water level signal into its different components (discharge induced signal, tidal signal, surge component).

SI .2 Investigation of Extreme Events - Coastal
R6.6 We recommend a specific activity to investigate storm surge events. TWLE, wind speed and SWH are important for many applications in coastal zones (e.g. storm surges). TWLE has improved thanks to better re-tracking strategies. SWH and wind speed are not mature enough for exploitation, so we recommend more work to improve their precision and accuracy.

SI .3 Investigation of Extreme Events – Inland Water
R6.18 Develop a sand-box model to simulate the impact of the flooding and drought extreme events with the aim of providing scenarios to local stakeholders from the integration of river discharge and coastal circulation and facilitate the interpretation of the radar altimetry product.

SI .4 Investigation of long term trends in sea level
R6.10 Longer time series of altimeter data are needed in order to analyse the benefits of HYDROCOASTAL products in terms of ocean variability of lower frequency: e.g. Sea Level Rise.

SI .5 Expansion of the use of satellite altimetry to include peatlands.
R6.21 Expand the use of satellite altimetry, one example could be over peatlands, which are important sources of carbon dioxide. A dedicated study will be helpful for more accurate retrieval of the height of water table. This has enormous potential applicability in terms of accurately accounting for LULUCF emissions at territorial and pan-European levels which will be key in verifying net-zero emissions attainment over coming decades.

SI .6 FFSAR performance investigation over inland waters

R6.27 It is recommended to extend the study of FFSAR performance over a more general collection of inland targets, including a larger variety in terms of size, in order to get a more general idea of the FFSAR improvements in terms of accuracy and precision over inland targets with respect to Delay-Doppler results.

SI .7 FFSAR performance investigation over coastal scenarios

R6.28 It is recommended to extend the evaluation of benefits in terms of performance of FFSAR processing on coastal areas over a larger dataset and with different coastal topography and ground track orientations, and with different sea states.

8.8. Recommendations for Satellite Missions and Operations (SM)

SM1 – SAR Altimeter operation / design: Open Loop Tracking Command, Range Migration Correction, Open Burst / Closed Burst, Interferometric Mode.

R6.34. 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.

R6.38. It is recommended that an Open Loop Tracking Mode is considered for the CRISTAL mission over **mountainous** inland water bodies, over flat areas the Close Loop Tracking Mode is preferred.

R3.1 Recommendations for SAR Altimetry signal acquisition:

- *Open Loop Tracking Command preferred over closed loop tracking in mountainous areas.*
- *Closed Loop Tracking Command preferred over open loop tracking in flat areas.*
- *Avoid Range Migration Correction onboard truncation.*
- *Implement Interferometry mode when available.*

R2.3. The limitations of Closed Loop retracking was noted.

SM2 – Recommendation to improve spatial and temporal sampling of satellite altimetry.

R6.19 To improve discharge estimation and the study of extreme events it is critical to improve the temporal resolutions of altimetry (e.g. with constellations of small satellites). The current configuration of orbits of altimetry missions (Sentinel-3A, 3B and Sentinel-6) means that many important middle-size lakes and smaller water bodies are not adequately sampled, or indeed in many cases sampled at all. This requires both more missions but also careful orbital configuration design decisions to maximise the chances of covering as many inland water bodies as possible with a minimisation of repeat sampling times.

SM3 – A tighter control of cross-track orbit deadband is recommended.

R6.22 A tighter control of cross-track orbit deadband is recommended to support repeat monitoring of inland water bodies with small scale cross-sections. In areas of more complex topography the cross-track orbit variation was found to be a critical limitation to the construction of meaningful water level time series. A reduction of the satellite orbit cross-track oscillation is thus necessary for monitoring small water bodies and streams in more complex topography.

SM4 – Antenna Pattern for SAR Altimeter Missions with Closed Burst Operation

R6.32 A recommendation for future missions in closed-burst configuration (such as CRISTAL) intended to process FF-SAR data, is to design, where possible, the antenna pattern so to place the pattern notches close to the grating lobes replicas. This would naturally mitigate the effect of the lobes.

SM5 – Continuity of ongoing satellite missions and orbits

D4.9 We recommend, to achieve continuity of L4 production, a continuation of ongoing satellite missions on the same orbit and with sufficient calibration periods.

8.9. General Recommendations (G)

G1 – Improved access to Water Level Data

R5.7. We recommend that WMO and IHO work to improve access to water level data as an important international water management and supply security measure.

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10. List of Acronyms

ACE2 Altimeter Corrected Elevations (vers. 2)
AD Applicable Documents
ATBD Algorithm Technical Basis Document
CLS Collecte Localisation Satellites
CMEMS Copernicus Marine Environmental Monitoring Service
CNES Centre Nationale d'Études Spatiales
CNR-IBF Consiglio Nazionale delle Ricerche - Istituto di Biofisica
CNR-IRPI Consiglio Nazionale delle Ricerche – Istituto di Ricerca per la Protezione Idrogeologica
CNR-ISP Consiglio Nazionale delle Ricerche - Istituto di Scienze Polari
CPP CryoSat-2 Processing Prototype (CNES)
CPU Central Processing Unit
CryoSat-2 Altimetry satellite for the measurement of the polar ice caps and the ice thickness
CRISTAL Copernicus polaR Ice and Snow Topography ALtimeter
CRUCIAL CryoSat-2 sUCcess over Inland wAter and Land
DAHITI Database for Hydrological Time Series of Inland Waters (DGFI-TUM)
DEM Digital Elevation Model
DGFI-TUM The Deutsches Geodätisches Forschungsinstitut, Technische Universität München
DTC Dry Tropospheric Correction
DTU Danmarks Tekniske Universitet (Technical University of Denmark)
d2c Distance to Coast
Earth Console Cloud based platform for EO data services.
ECMWF European Centre for Medium Range Weather Forecasting
EO Earth Observation
EOEP Earth Observation Enveloppe Programme
EOT Empirical Ocean Tide. Family of tide models developed by DGFI-TUM
ERA ECMWF ReAnalysis
ESA European Space Agency
EUMETSAT European Organisation for the Exploitation of Meteorological Satellites
FBR Full Bit Rate
FES Finite Element Solution – family of tide models developed by LEGOS, Noveltis and CLS
FTP File Transfer Protocol
G-BOX Algorithm development and execution environment provided by EarthConsole.
GFZ Deutsche GeoForschungsZentrum (German Research Centre for Geosciences)
GNSS Global Navigation Satellite System
GPD GNSS-derived Path Delay
G-POD Grid Processing on Demand
GS Gauging Station
HF High Frequency
Hydroweb Time series of water levels in the rivers and lakes around the world.
IHO International Hydrographic Organisation
IW Inland Water
LULUCF Land Use, Land Use Change, and Forestry.
L1A Level-1A data processing level
L1B Level-1B data processing level
L1B-S, L1BS Level-1B-S (aka, Stack data)
L2 Level-2 data processing level
L2E Level 2 Extended product (product format devised for HYDROCOASTAL).
L3 Level-3 data processing level
L4 Level-4 data processing level
ME Manning Equation
MSS Mean Sea Surface
MWR Micro Wave Radiometer
netCDF Network Common Data Form
NOC National Oceanography Centre, UK
OCOG Offset Centre of Gravity
OLTC Open Loop Tracking Command
OPC One per Crossing
PDF Probability Density Function
PRF Pulse Repetition Frequency
PSD Product Specification Document
PTR Point Target Response
PVP Product Validation Plan
PVR Product Validation Report
Q Discharge rate
RC Rating Curve
RD Reference Document
RIDESAT River flow monitoring and Discharge

Estimation by integrating multiple SATellite data ESA project

RMC Range Migration Correction

RWL River Water Level

SAMOSA SAR Altimetry MOde Studies and Applications

SAR Synthetic Aperture Radar

SARIn SAR Interferometric (CryoSat-2/SIRAL mode)

SARvatore SAR Versatile Altimetric Toolkit for Ocean Research & Exploitation

Sigma-0 Vertical incidence radar backscatter

SMAP Standalone Multi-mission Altimetry Processor

SRAL SAR Radar Altimeter

SSB Sea State Bias

SSMI Special Sensor Microwave Imager - passive microwave radiometer

SSMIS Special Sensor Microwave Imager Sounder - passive microwave radiometer

SST Sea Surface Temperature

STARS Spatio-Temporal Altimeter Retracker for SAR altimetry - UBonn retracker

STD Standard Deviation

STDD Standard Deviation of Differences

STREAMRIDE Extension of SaTellite based Runoff Evaluation And Mapping (STREAM), ESA project

SWH Significant Wave Height

SWORD River data base developed for SWOT mission

SWOT Surface Water Ocean Topography. Swath altimeter mission, launched December 2022

TB Brightness Temperature

TPXO Family of tide models from Oregon State University, using satellite altimetry.

TSHydro Software package (written in “R”) developed by DTU to estimate water level time series from altimeter data.

UBonn University of Bonn.

UFSAR Unfocused SAR processing

U10 Wind speed at 10m above the ocean surface.

WL Water Level

WMO World Meteorological Organisation

VG Virtual Gauge

VS Virtual Station