FFSAR - COASTAL

Fully Focused SAR Altimetry and innovative river level gauges for Coastal Monitoring

Application Road Map
Deliverable D1.1

Fully Focused SAR Altimetry and innovative river level gauges for Coastal Monitoring

ESA Contract 4000136960/21/I-DT-Ir

Project Reference FFSARCOASTAL_ESA_ D1.1
Issue:1.1

This page has been intentionally left blank

Change Record

Date	Issue	Section	Page	Comment
17/08/2023	1.0	all	all	1st version

Control Document

Process	Name	Date
Written by:	David Cotton, Jean-Christophe Poisson, Mikkel Kruse, Karina Nielsen, Ole Andersen, Charlie Thompson, Amani Becker.	17/08/2023
Checked by	David Cotton	
Approved by:	David Cotton	

Subject	Fully Focused SAR Altimetry and Innovative River Level Gauges for Coastal Monitoring	Project	FFSARCOASTAL
Author		**Organisation**	**Internal references**
David Cotton		SatOC	FFSARCOASTAL_ESA _D1.1

	Signature	Date
For FFSARCOASTAL team		25/08/23
For ESA	Date: 2023.10.05 '13:42:57 +02'00 Digitally signed by Jérôme Benveniste	

Table of Contents

1 Introduction

1.1 The FFSAR Coastal Project

The project has applied the Fully Focused (FF) SAR altimetry processor to Sentinel-3 data and evaluated its potential to make a significant new contribution to coastal and estuarine monitoring systems, when coupled with innovative water level gauges for validation.

The team has investigated the potential benefits to applications that can take advantage of the very high along-track resolution in water level and backscatter that can be provided through Fully Focused SAR processing. The FFSAR processing has been applied to Sentinel-3 tracks in the two study regions: The Severn Estuary in the UK and the Rhône River in France. User agencies and groups from the two regions have been consulted to identify gaps and priorities for monitoring requirements.

Innovative in-situ water level gauges have been used to validate the satellite data. Time series have been provided by autonomous gauges placed at fixed locations, and gauges mounted on drones were used to provide water level profiles between the fixed locations and satellite tracks.

1.2 Scope of this Document

The purpose of this Application Road Map is to provide recommendations for future development and implementation of Fully Focused SAR altimeter processing, and innovative water level gauges for applications in coastal monitoring systems, within the areas studied (Rhône delta and Severn Estuary) and more widely.

1.3 Applicable Documents

AD-01: Fully Focused Sar Altimetry and Innovative River Level Gauges For Coastal Monitoring (FFSAR-Coastal) - ESA Contract No. 4000136960/21/I-DT-Ir

1.4 Reference Documents

RD-01 FFSAR-Coastal Proposal. V1.1 29/07/21, SatOC and FFSAR-Coastal team.
RD-02 FFSAR-Coastal Product Validation and Evaluation Report V2.0, 06/07/23

1.5 Overview of this Document

This deliverable is organised into the following sections:

Section 2: Summary of key users' requirements and gaps
Section 3: Recommendations for Fully Focused SAR processing
Section 4: Recommendations for innovative water level gauges.
Section 5: Recommendations for coastal monitoring applications

2 Summary of key users' requirements and gaps

This section summarises the key user requirements, and gaps in data provision, that were identified by users in workshops.

2.1 Severn Estuary, England

2.1.1 Requirements

Workshops were held with UK users from a range of organisations, including national agencies (Environment Agency, Natural Resources Wales, UK Hydrographic Office), local agencies and authorities, universities, and research organisations.

In general, the UK users require coastal water level data for flood and erosion modelling and planning coastal developments, and for improving interpretation and prediction of sea level trends or significant coastal flooding events.

Sea level rise and climate change are already being considered in construction projects and it is hoped that Fully Focused SAR altimeter data could be useful in planning future developments.

The UK users currently use in-situ data from a network of tide gauges, but additional data is needed to fill gaps between gauges and to provide sea level information away from the shore and improve models of sea level. They do not currently use sea level data from satellite altimetry and would like more information on availability, locations and frequency of these data.

It is hoped that the use of Fully Focused SAR altimeter data could lead to improvements in modelling by filling some of the gaps in availability identified above and that Micro-gauges could be used to improve tidal prediction where they are installed.

The issue of getting reliable data from satellite altimetry in the coastal zone has been a problem in the past. In the future, coastal tailored data products should be provided, based on processing of all available SAR altimeter missions. The processing should account for the impact of land contamination on the reflected signal and provide flags for possibly contaminated data.

2.1.2 Gaps

We list additional data needs below, grouped by category:

Locations

- Water level measurements away from the shore / in the middle of the estuary. For example, to understand water level gradients across estuaries, in particular for extreme flood events.
- Water level data for locations without tide gauges, and data that would enable verification of tidal predictions from models.
- Bathymetry data at the coast (water depths under 5m are often not surveyed) and topographic data for the intertidal zone. This is especially needed for overtopping calculations.
- Data are also needed for the East coast of England for surge modelling, modelling flood severity and for planning.
- On the Severn there are some large gaps in in situ water level data (one specific area of interest is the stretch of coast between the Severn Bridge and Port Isaac on the North Cornish coast).
- There are gaps in water level data for navigational products and an interest in improving the UKHO Vertical Offshore Reference Frame (VORF) to bring it closer to the coast and remove the steps in the model at estuary mouth.

Data Characteristics

- Higher spatial resolution data are required to calibrate models (requires a homogenous data set, which cannot be provided from tide gauges).
- A high resolution (in time and space) gridded coastal sea level product. Gridded products would be preferred to along-track data (based on multi-mission data). Such data could be used to calibrate / validate hydrodynamic models.
- Data for extreme events. Such events are difficult to capture, but data is necessary particularly during storms. Data are also required for long period wave events that may not be identified as storms.
- In addition to measurements of sea surface height, the timing of peaks is also important in particular when related to surges.

Drone data

- Drone data are also of interest as a stand-alone method for areas without a fixed gauge. Users were impressed with the range of the drone used for the project and are interested in repeatability. If a drone can be deployed wherever/whenever it is needed, this would give data on the general tidal regime when setting up a new infrastructure or coastal defence project.

It was also suggested that suitable regions should be identified as “laboratories” to further test and demonstrate use of satellite data. These regions would need to have a good provision of in-situ data and high-resolution models.

2.2 Rhône River, France

Workshops were also held with French users, including agencies responsible for flood management and defence, environmental protection and education, and hydrological monitoring.

Coastal data needs

Similar to the UK, French users are currently mostly reliant on in-situ data and are less familiar with satellite products.

Engineering work on the riverbanks means there is less concern about the flooding of the Rhône River as a result of precipitation and resultant high river flows than there has been previously. At the coast however, particularly in the Camargue area, there are major issues in terms of risks of coastal flooding and coastal erosion. In this context, Fully Focused SAR altimeter data could be very useful.

River water level data needs

There is great interest in data on the Rhône River discharge in connection with the high level of agricultural activity on the Rhône Delta. In particular there are concerns around future water quality and the possible salinisation of the Rhône Delta.

Data on the level and flow rate of rivers and flood extent is used in protecting people and property, but also for calibrating small-scale models. This hydrological monitoring then enables them to implement sector-based actions to better manage resources, protect aquatic environments, inform government departments of the need to lift drought orders, etc.

There is interest in satellite measurements for monthly monitoring of water levels (and therefore flows) on all rivers, and for mapping flooded areas during a flood. However, the issue of getting the data in at the right time can be problematic in the case of rapid flooding, as occurs in the south of France.

In terms of missing data, there is a need to increase the number of hydrometric stations in order to have more measurements of levels and flows on the River Argens' many tributaries. It is also difficult for them to survey the 2750km² catchment area after a flood, and satellites could help to provide wider spatial coverage.

3 Recommendations for Fully Focused SAR processing

This section provides recommendations for the implementation of Fully Focused SAR altimeter processing in coastal regions with different characteristics, and for future work to achieve further improvements.

The project has demonstrated that FFSAR processing is a valuable technique to obtain a high along-track resolution. There are a number of options that can be selected in the processing to maximise performance, the best choices may vary from location to location.

The FFSAR Processing Technical note (RD-02) details studies carried out within this project to identify the preferred processing choices for the regions studied.

In this project an illumination time of 2.3s together with a posting rate of 1000Hz was selected as the FFSAR processing options for both Severn and Rhône locations. The tests with different posting rates identified this option as giving the best along track resolution together with a low root mean square error. Note that the choice of posting rate will also depend on the size of the water body being monitored. Hence, whilst a high posting rate is necessary for small targets, for larger targets a higher posting rate may not be necessary.

The DTU MWaPP (Multiple Waveform Persistent Peak) re-tracker was identified as giving the best results amongst the four options tested. It was able to provide stable measurements where other re-trackers were more impacted from increased noise in measured water level and erroneous measurements from off-nadir reflections ("snagging").

The use of ICESAT-2 data to provide a reference water level, not originally planned, was found to be especially important. These data were used to help identify outliers and support the assessment of performance of the different retracking options.

Recommendation 1 – FFSAR-Coastal Processing "Recipe"
The combination of MWaPP retracker, 2.3s illumination time, and 1000 Hz posting rate was able to provide stable and reliable measurements of water levels in both regions, on narrow (~60m wide) channels and on open coastal locations.

RD-02 reports that Fully Focused SAR altimeter processing provides a high along-track resolution (order 10m resolution) which is essential to monitor small targets such as small canals within harbour areas. The FFSAR measurement also provides a more detailed representation of the time-changing slopes related to the tides in the Severn estuary. The information is not available in the standard 20 Hz SAR data due to its lower along-track resolution (350m). Hence, FFSAR is ideal for rivers and other narrow targets e.g. small lakes. FFSAR also enables a better representation of slopes.

Therefore, this general "recipe" is recommended for initial wider scale processing.

However, this project has only considered two locations and a limited range of environmental conditions, so it is recommended that further research is carried out to establish the best processing options for a wider range of locations and environments.

Recommendation 2 – Further FFSAR Processing Research – Different coastal locations and environments.
There should be more extensive studies over a wide range of locations to understand if there is need for / possibility to develop an adaptive re-tracker system. This could use information on the type of environment under the satellite track and also / alternatively a waveform classification system.
The study area should be well monitored with a range of in situ instrumentation.
Operational ocean model data should be used to support validation and assessment (originally planned for the FFSAR Coastal project). These data could also be used to support case studies of individual storm events.

Aspects to consider include:
- *Track orientation with respect to river/ coastline*
- *Time of pass with respect to tidal condition (high, low, drying,…)*
- *Topographic characterisation*

Recommendation 3 - Multi-Satellite Study – Sea State impact on FFSAR
To investigate the effects of sea state on FFSAR measurements there should be a regionally focused study at a suitable well instrumented location (with e.g. wave buoys, water level / tide gauges, coastal radar,….). It is recommended to bring together satellite information from different missions, such as fully focused SAR altimeter data from Sentinel 3A, 3B, Sentinel 6, and SWOT, and wave spectrum information derived from Sentinel-1 and CFOSAT.
Wave spectrum data from wave models should be also used in this study.
This would investigate a range of issues including further investigation of Sea State Bias corrections for SAR altimeter data (fully focused and unfocused) and also the potential impact of swell on SAR altimeter data.

Recommendation 4 - Isolating Nadir Reflections
Another line of research could investigate how to isolate the part of the return waveform that relates to the reflections from nadir. Reflections from off-nadir will give incorrect (low) estimates of water level, as the echo will have travelled a longer path.

4 Recommendations for innovative water level gauges

This section provides recommendations for the implementation of the vortex.io micro-gauges as part of coastal monitoring systems, and for the validation of satellite-derived water levels.

The vorteX-io Micro-gauge is an innovative solution for monitoring water levels, with features that are ideally suited to satellite Cal/Val activities. It is in this framework that the micro-gauges have been installed and used in this FFSAR-Coastal project.

Based on the project results and feedback, we have seen that the vorteX-io Micro-gauges are easy to install only taking 1 hour each to fix in place. This installation has been possible after requesting permissions to install on the different structures selected for the project (bridges, grand pier, etc…). It is important to note that although we have never been refused permission to install the gauges, it has taken us a certain administrative time (from 1 month to 3 months) to obtain these authorisations for both UK and France. And these administrative procedures were made easier because the members of the project are from both countries. This is something that must be accounted for when installing new in-situ stations.

Due to the ease of installation of the Micro-gauge systems, it was relatively simple to find a suitable location close to the satellite ground track. However, with tidal effects (and especially with strong tides as the one encountered in the Severn estuary), it is very important to find a location very close to the satellite ground track. We observed in the project that the micro-gauge installed in Weston is far from the satellite track (~5.5 km) which makes the comparison very challenging. In addition this micro-gauge dries out at low tide, which makes the comparison between the satellite measurements and the in-situ data even more challenging at this location (the satellite measures the water surface whereas the micro-gauge measures the intertidal seabed – which in this location is mudflat). This illustrates how complex it is to find a good location to install an in-situ system to validate satellite data, especially in coastal areas (it is more simple for inland waters), even if these bathymetry measurements can be useful for coastal applications. The ease with which micro-stations can be installed makes it possible to mitigate these issues. One final point to note about the installation of the micro-gauge is the logistical problems we had to deal with. We faced an issue with the courier when a micro-gauge arrived damaged at the installation point. This logistics issue raises potential concerns in case of installation in remote countries and must be anticipated. Note that it is also important to accurately geo-reference the gauges against a standard reference level.

Concerning the micro-gauge measurements, it has been demonstrated how easy it is to access the data, either through the web platform MAELSTROM or using the web API for the automatic extractions. One of the strengths of the Micro-gauge system for satellite Cal/Val activities, is the possibility to synchronise the micro-gauge measurements with satellite measurements, minimising the time difference between the two measurements (in-situ and from the satellite). This is important especially in coastal areas with strong tide signals. It is important to note that the micro-gauges have been installed in this project to validate satellite measurements. In this context, the micro-gauges have been configured to work on an hourly basis synchronised with satellite measurements. It appears that this frequency is too low for users who want to use the micro-gauge data directly. It is then recommended to increase the measurement frequency for any in-situ station installed in coastal areas in order to properly sample the tide signals for users. It is possible to increase the measurement frequency of the Micro-gauge systems up to 1 measurement every 15 minutes (and temporarily, up to 1 every 5 minutes). However, users are used to having

measurements more frequently (1-10 minutes), which is too frequent for the power capacity of the existing Micro-gauge system. Based on user feedback, it appears that more information should be extracted from the images taken by the Micro-gauge system (wave analysis, surface roughness ,etc…). In this project, users are more interested in LiDAR measurements than in images, but this can change if we can process and extract more information from these images.

In terms of Cal/Val activities, the most important recommendation is that long time series of in-situ measurements are mandatory to validate satellite data (at least 1 year), due to the 27-day orbit of Sentinel-3 satellites. Otherwise, only a few points are available for validation. We also strongly recommend increasing the number of in-situ micro-gauge under different satellite tracks or finding installation locations at crossovers in order to increase the number of validation points.

Recommendation 5 – Micro-gauges for satellite data validation
The vortex.io micro-gauges have been found to be highly suitable instruments for providing ground truth to satellite water level measurements. Key considerations are:

- *Suitable locations close to the ground-track should be chosen, based on a number of considerations. Consider more than one location per ground track, and use of cross-over locations where possible.*
- *Long time series of in-situ measurements are necessary to validate satellite data (at least 1 year).*
- *Measurements should be made at the highest frequency possible within power / energy constraints.*
- *Subsidiary information from images is of potential value.*

Finally, drone campaigns have been performed in this project, using the vortex-io lightweight LiDAR altimeter to measure water surface height all along the drone flight. Drone campaigns are very useful for satellite validation for inland waters. However, it can be challenging to use this data effectively in coastal areas where tidal signals are strong unless we can properly correct the tidal signal in both the drone data and satellite data. Because these regions are highly dynamic, the height of the water surface measured changes rapidly during the drone campaign, which can last several hours, whereas satellite data is more instantaneous. It is therefore mandatory to correct tidal signals when comparing satellite and UAV data. Nevertheless, users are very interested in drone data because of the flexibility of the drone, which can be deployed wherever and whenever it is needed, whereas satellite data is only available according to its orbit.

Another very interesting application of drone data in coastal areas is the observation of tide signals along the satellite track. It can be used to validate the tidal correction of satellite data. Waves signals are also well measured by the drone LiDAR altimeter. It is therefore very interesting to exploit these data for coastal application. It is worth noting that specific processing algorithms have been developed to compute the

directional swell power spectrum from drone LiDAR data. In this framework, computing the wave properties at different locations and distance from the coast in coastal areas is a very interesting feature for future studies.

Finally, it is important to keep in mind the weather and wind limitation to safely deploy drones in such areas. Also, local regulations and permissions for flying drones must be observed.

Recommendation 6 – Drones with lidar for research and satellite data validation
The use of drones equipped with lidar to provide a geo-referenced baseline was essential for this study. A wider research use should be considered. High resolution water level profiles, together with video images, could be used to investigate water levels and directional wave fields at the coast and in shallow inter-tidal regions.

5 Recommendations for Coastal Monitoring Applications.

This section provides recommendations for the use of fully focussed SAR altimeter data in coastal monitoring systems.

At this stage, direct use of FFSAR altimetry data for monitoring may be limited due to the relatively low repeat frequency of the data, but there is potential for the data to improve modelling, in particular where there are fewer in situ tide gauges, and for increasing understanding of tidal variability across water bodies. While initial analysis provides promising results, these will need to be scaled up and tested in a wider range of environments and tidal conditions, to increase user confidence in the techniques.

A number of “laboratory” sites within the UK could be chosen to facilitate this, where there is good coverage of both existing satellite missions and in situ data, as well as well-developed operational high-resolution coastal models. This can be used to assess a wider range of environments, determine the context-specific considerations of processing methods, and quantify the potential improvements to coastal models that may be possible from inclusion of FFSAR altimetry data.

This provides further justification and background for **Recommendation 2,** above.

A hackathon type event may be a way to facilitate this type of investigation, whereby a number of data sets and processing options are made available to a group of researchers who can directly interact with each other to compare and assess results.

Coastal monitoring is often used to inform the impact of storms, both observationally and through analysis of joint probability. An assessment of the suitability of FFSAR altimetry for events such as storms, surges and overtopping is essential, but was beyond the scope of the initial analysis. A list of events that have occurred during satellite passes processed as part of this project has been identified by the project team, and could be used for further study.

Recommendation 7 – Extreme Events study
A series of extreme water level events should be identified for a selected location and cross referenced against available SAR altimeter data, which is then processed and analysed alongside storm surge model output. This would assess the potential of FFSAR altimetry to provide additional capability to operational models, to support assessment of vulnerability of coasts and to contribute to long-term planning of coastal defences.

Beyond the UK, a number of priority areas can be identified for scaling up of the FFSAR processing. This includes small island nations which are vulnerable to sea level rise (Martyr-Koller et al., 2021), countries in the global south with a limited number of tide gauges (e.g. Mozambique, Nehama et al, 2022) and regions identified by the ESA Climate Change Initiative (CCI+) where there are gaps because of limitations in routine (SAR) altimeter coastal processors. Focus on this scaling could be limited to a near-coastal strip (~5-10km) to reduce effort, but the optimum distance would need to be assessed based on the largest benefits over routine processing.

Recommendation 8 – Priority Areas for FFSAR (and improved unfocused SAR) altimeter processing.
It is recommended that a costed proposal be put together to generate a new coastal SAR altimeter product (using Fully Focused and unfocused SAR processing) for priority coastal / island locations, for which improved sea level products close to the coast (e.g. 0 - 10km) are a key requirement and where routine altimeter processing is not able to provide reliable data.

There was an interest from UK users for an improved coastal product, that would fill in the gaps between in-situ data at coast, and also provide measurements offshore that could be used to validate models. The UK Hydrographic Office in particular has an interest in a national coastal sea level product, to support a planned development to the UKHO Vertical Offshore Reference Frame (VORF) to bring it closer to the coast and remove the steps in the model at the mouth of the Severn Estuary.

Recommendation 9 –FFSAR Altimeter Products – Coast
It is recommended to develop a costed proposal for a national UK coastal altimeter product which would combine unfocused and fully focussed SAR altimeter data.
This could use processors implemented on the Altimeter Virtual Laboratory and would need associated geophysical correction fields at the same resolution. Users have identified that a gridded product is preferred, so research would also be needed to identify the optimum characteristics for such a product.

Following the above recommendation to generate a more general FFSAR altimeter product, it is important to recognise that the format of the supplied data will influence the uptake from the user community, due to IT, software and resource limitations.

Recommendation 10 – Guidelines for use of FFSAR processed altimeter data
An FFSAR altimeter user guide should be created, with clear guidelines for how to use the data, and provision in, or simple guidance for conversion to, local grids and vertical reference datums is essential to maximise useability.
The limitations and applicability of the data, in comparison with more standard and familiar techniques also needs to be carefully communicated. This includes signposting what data is available, along what tracks and at what frequency.

Initial analysis in this project has identified potential for value-added information in the data, such as the identification of intertidal topography during low tide from SAR, drone and micro-gauge data. It is unclear at the moment whether this data would be suitable for monitoring purposes, but there is potential for this to fill a gap in areas where traditional ground-based monitoring techniques are challenging due to either logistical or financial constraints. As such, it would be worth investigating this element of the data further.

Recommendation 11 – FFSAR for inter-tidal bathymetry
Accurate measurements of inter-tidal bathymetry were identified as being important to the coastal user community (needed for overtopping modelling), and difficult to measure through in-situ techniques. The use / interpretation of FFSAR processing to measure inter-tidal bathymetry could be investigated, working with ICESat-2 data, and using available airborne / drone lidar for validation.

Drought monitoring and water availability are very important societal applications, and the analysis of data in the lower reaches of the River Rhône has established that FFSAR processing is able to reliably provide accurate water levels for inland water bodies where other processing fails.

Recommendation 12 –FFSAR Altimeter Products – Inland Waters
We recommend the development of a proposal to further develop the capability of FFSAR processing to accurately measure water levels in narrow rivers and other inland water locations where other SAR altimeter processing fails. The study could involve a round robin exercise to investigate capability of different re-trackers and identification of optimum FFSAR processing options.

Finally, the interface between river outflow and tidal estuary is a key area of high relevance to coastal populations, where there is a lack of data and a need to develop better understanding of physical processes. There are some projects investigating combined river /estuary systems, for instance the “Forth-ERA” project by the University of Stirling (https://www.stir.ac.uk/about/scotlands-international-environment-centre/forth-environmental-resilience-array/about-forth-era/), which is linked to the DANUBIUS-RI pan-European research infrastructure on River-Sea systems (www.danubius-ri.de), as a “super-site.”

Recommendation 13 –FFSAR Altimeter Products – Coast and river interface
We recommend development of further research that brings together hydrologists and oceanographers and focuses on the inland water / ocean interface.

Recommendation 14 –FFSAR Altimeter Products – Small scale Variability in Tides (Currents, slopes and tidal components
Work in other projects (ESA HYDROCOASTAL) has demonstrated that even the most recent tidal models are not accurate in the Severn Estuary. Accurate tidal models are a pre-requisite for scientific studies into the dynamics of estuaries and coast / river interfaces. The results of WP2300 (Detection of small- scale signals) have clearly demonstrated the potential of FFSAR data in studies of tidal characteristics (slopes, currents and tidal components. We recommend further work in this area, including data from other satellite missions to allow investigation of tidal components not-possible from the Sentinel-3 orbit.

6 References

Martyr-Koller, R., Thomas, A., Schleussner F-C., Nauels, A., Lissner T., Loss and damage implications of sea-level rise on small island developing states, Current Opinion in Environmental Sustainability, June 2021, Vol 50, pp 245-259 (https://www.sciencedirect.com/science/article/pii/S1877343521000713

Nehama, F.P.J., Veriua, Z.D.H., Maueua, C., Hibbert, A., Calafat, F., and Cotton, P.D. (2022) Validating Sea-Level Altimetry Data against Tide Gauge for Coastal Risk Analysis in Mozambique. Journal of Marine Science and Engineering. 10(11):1597. (https://doi.org/10.3390/jmse10111597)

7 List of Acronyms

AD	Applicable Documents
CCO	Channel Coastal Observatory
DTU	Danmarks Tekniske Universitet (Technical University of Denmark)
EO	Earth Observation
ESA	European Space Agency
MTR	Mid Term Review
NOC	National Oceanography Centre
RD	Reference Document
RON	Relative Orbit Number
SAR	Synthetic Aperture Radar
SatOC	Satellite Oceanographic Consultants Ltd
SMAP	Stand Alone Multi-Mission Processor
SRAL	SAR Radar Altimeter
S3A, S3B	Sentinel 3A, and Sentinel 3B
TWLE	Total Water Level Envelope