FFSAR - COASTAL

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

Data Set of SAR processed altimeter data

Deliverable D2.1

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

ESA Contract 4000136960/21/I-DT-Ir

Project Reference FFSARCOASTAL_ESA_MTR _D2.1
Issue:2.2

This page has been intentionally left blank

Change Record

Date	Issue	Section	Page	Comment
21/09/2022	1.0	all	all	1st version
26/06/2023	2.0	all	all	2nd version
10/07/2023	2.1	various	various	Minor updates by DC
14/08/2023	2.2	various	various	Updates following ESA review

Control Document

Process	Name	Date
Written by:	Heidi Ranndal Mikkel Aaby Kruse	21/09/2022 26/06/2023
Checked by	David Cotton	10/07/23
Approved by:		

Subject	Fully Focused SAR Altimetry and Innovative River Level Gauges for Coastal Monitoring	Project	FFSARCOASTAL
Author	**Organisation**	**Internal references**	
Heidi Ranndal, Mikkel Aaby Kruse, Karina Nielsen	DTU	FFSARCOASTAL_ESA_MTR_D2.1	

	Signature	Date
For FFSARCOASTAL team	David Cotton	22/07/23
For ESA	Date: 2023.10.05 '14:11:13 +02'00	Digitally signed by Jérôme Benveniste

Table of Contents

1 Introduction

1.1 The FFSAR Coastal Project

In this project, Fully Focussed (FF) SAR altimetry processing was applied to Sentinel-3 data, and its potential to make significant new contributions to coastal and estuarine monitoring systems was evaluated using innovative water level gauges.

FFSAR processing was performed using the open-source processor called the Standalone Multi-mission Altimetry Processor (SMAP). Autonomous gauges (micro-gauges) placed at fixed locations provided high-resolution time series, and gauges mounted on drones provided water level profiles between the fixed locations and satellite tracks.

Specific focus was put on applications that benefit from the high along-track resolution in water level offered by Fully Focussed SAR processing. The FFSAR processing was conducted for three Sentinel-3 reference ground tracks in the two study regions: The Severn Estuary in the UK and the Rhône River in France. User agencies and interest groups from the two regions were consulted to identify gaps and priorities for monitoring requirements.

1.2 Scope of this Document

The purpose of this document is to present the workflow of the FFSAR processing carried out for the two study regions within the project. The document presents the two study regions, the SMAP setup, and the output data format.

1.3 Applicable Documents

AD-01: Fully Focussed 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.

1.5 Overview of this Document

This deliverable is organised into the following sections:

Section 2: Study areas
Section 3: Data processing
Section 4: Output data

2 Study areas

This section describes the two study areas as well as the available and processed data from Sentinel-3A (S3A) and Sentinel-3B (S3B).

2.1 Severn Estuary, United Kingdom

The Severn Estuary is an area spanning up to 200 km from east to west. Due to the size of the input data required for the FFSAR processing (Sentinal-3 L1a files of 2.5 GB each), the scope of analysis for this area was initially limited to a few select reference ground tracks. As the project progressed it became evident that a further decrease in scope was needed to carry out a meaningful analysis.

As only one of the selected reference ground tracks intersects the location of any of the previously mentioned stationary micro-gauges (S3B 265), the analysis was refocused on this specific reference ground track. The reference ground track in question crosses the estuary's southern bank close to Weston-super-Mare and the northern bank in Newport (Wales). Any results for the Severn presented in this document thus originate from data extracted close to this specific reference ground track. All the analysed reference ground tracks and their respective processed data can be seen in Table 1 and are visualized in Figure 1 on the following page.

RON	Sentinel-3A period (cycles)	Sentinel-3B period (cycles)
265	Apr 2016 (cycle 3) – May 2022 (cycle 85)	**Dec 2018 (cycle 19) – April 2023 (cycle 78)**
299(300)	Apr 2016 (cycle 3) – May 2022 (cycle 85)	Feb 2018 (cycle 21) – June 2022 (cycle 66)
208	May 2016 (cycle 4) – June 2022 (cycle 86)	Dec-2018 (cycle 19) – June 2022 (cycle 66)

Table 1: Downloaded and processed data for Sentinel-3A and Sentinel-3B in the Severn Estuary. The data series highlighted in bold letters are the data originating from the specified reference ground track in focus. RON = Relative Orbit Number

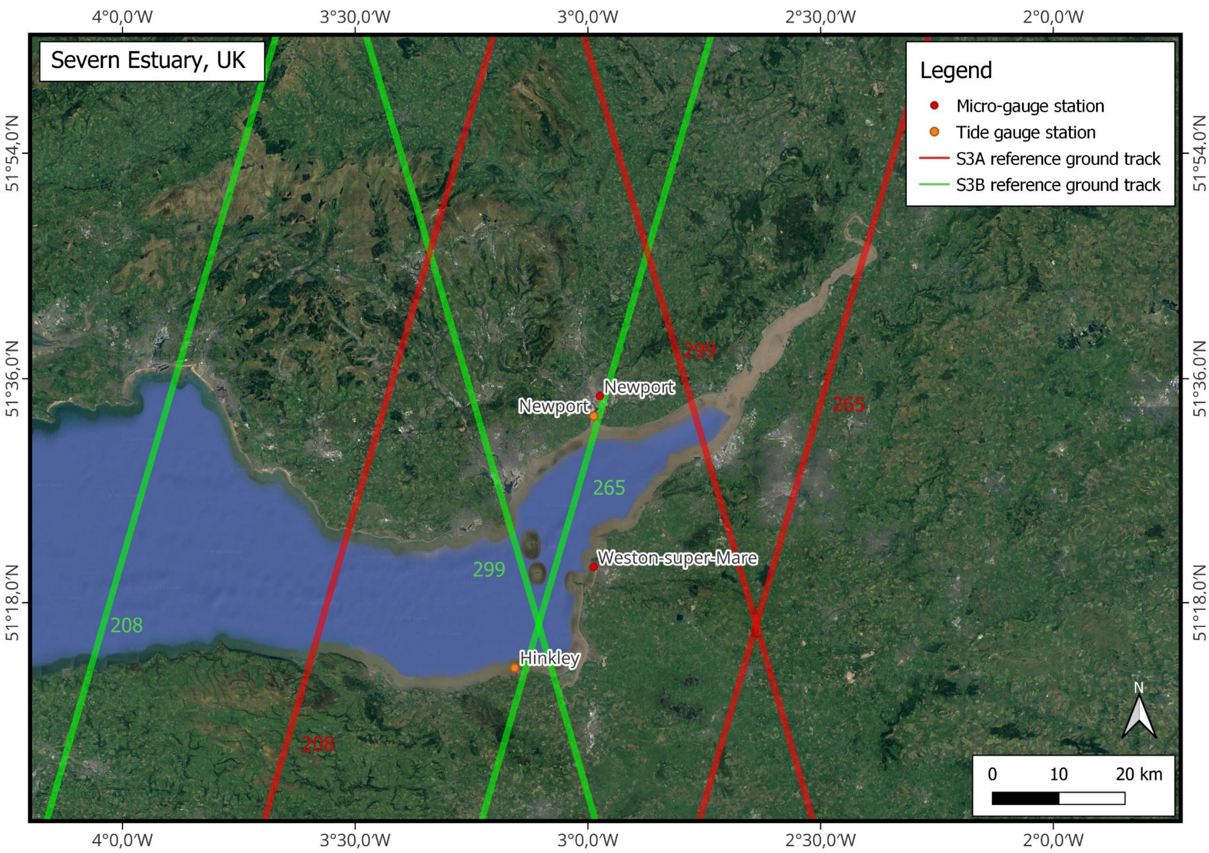

Figure 1: A map showing the Severn Estuary along with the S3A and S3B reference ground tracks that FFSAR altimetry processing was applied to in the presented analysis. The locations of the micro-gauge stations installed by vorteX-io and the NOC two tide gauge stations used in the presented analysis are marked as red and orange dots respectively. [Imagery © TerraMetrics 2023, Map data © 2023 Google]

2.2 Rhône River, France

The Rhône River is located in a low-lying river delta in southern France, primarily consisting of wetlands. The river is quite narrow and has many tributaries and manmade canals feeding into and stretching out from it. This means that the standard 20Hz OCOG re-tracker applied to Sentinel-3 data to retrieve water surface level heights only provides a few or a single estimate for parts of the river. Furthermore, the heterogeneous nature of the area means that any returned waveforms will very likely be contaminated, making it even more difficult to obtain a stable set of water surface level heights for the river.

For the analysis presented here, two regions of interest (ROI) were chosen in the Rhône River area, both very close to the mouth of the river. Each of these ROIs has a micro-gauge present in them and is intersected by a single reference ground track. The ROIs are located at the Fos-Sur-Mer harbour (S3B 179) and Port-Saint-Louis-du-Rhône (S3B 199) slightly inland from the mouth of the Rhône. The analysed reference ground tracks and their processed data can be seen in Table 2 and are visualized in Figure 2.

RON	Sentinel-3B period (cycles)
179	March 2019 (cycle 23) – May 2023 (cycle 79)
199	Dec 2018 (cycle 19) – May 2023 (cycle 79)

Table 2: Downloaded and processed data for Sentinel-3A and Sentinel-3B in the Rhône River, France. The data series highlighted in bold letters are the data originating from the specified reference ground track in focus. RON = Relative Orbit Number

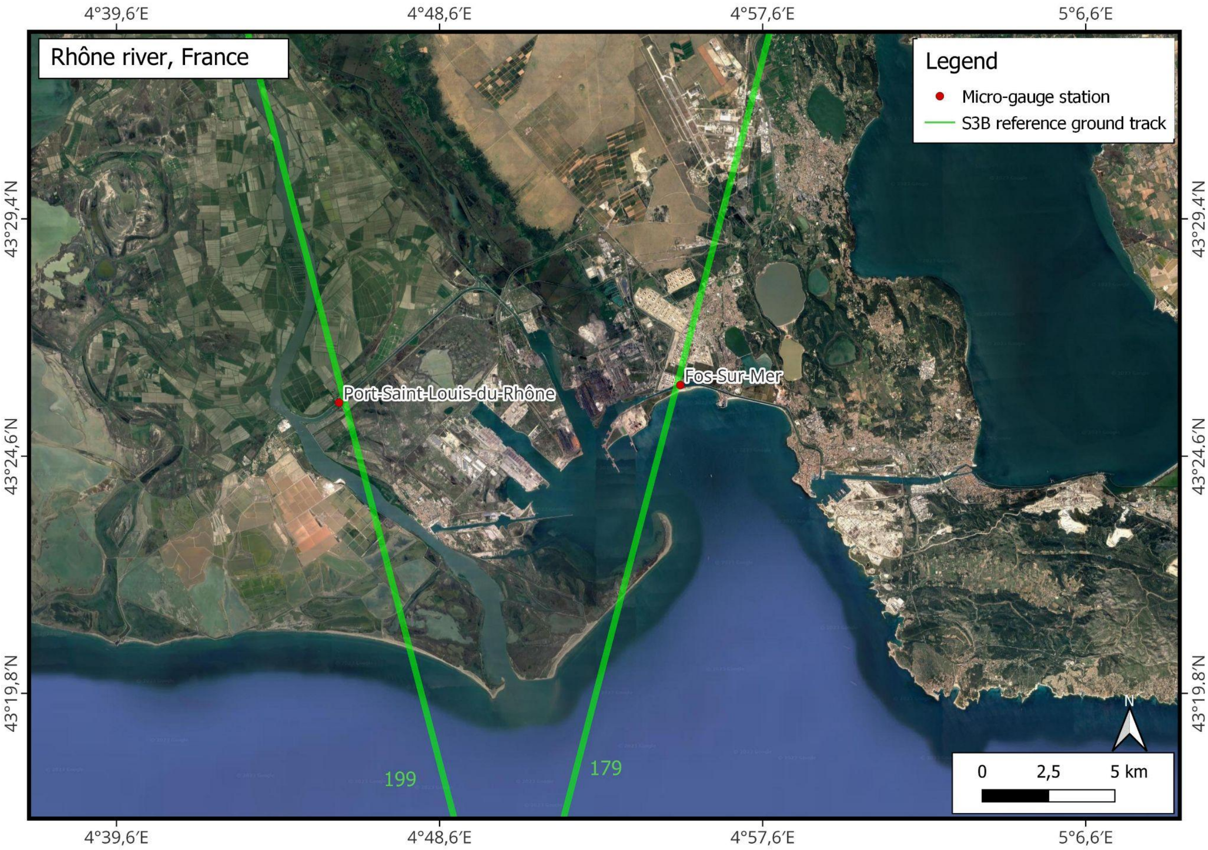

Figure 2: A map of the Rhône River along with the S3B reference ground tracks that FFSAR altimetry processing was applied to in the presented analysis. The locations of the two micro-gauge stations installed by vorteX-io are also shown as red dots. [Imagery © TerraMetrics 2023, Map data © 2023 Google]

3 Data Processing

This section describes the data processing performed during the presented analysis. An overview of the FFSAR SMAP setup is first given, followed by a description of the applied re-tracking and post-processing of the SMAP output.

3.1 SMAP setup

The SMAP was developed by the CLS Group (Collecte Localisation Satellites) in collaboration with the European Space Agency (ESA) and The National Centre for Space Studies (CNES) for the SMAP FFSAR CLS/ESA/CNES project. The data processor is open source and is available on GitHub from the following link (https://github.com/cls-obsnadir-dev/SMAP-FFSAR). The SMAP processing chain consists of three blocks running sequentially that each generate an output at different data levels. The first two blocks collectively generate a set of fully-focused and multi-looked waveforms (L1b), and the third block performs the re-tracking on the previously computed waveforms (L2). Each of these blocks requires a set of input data and processing parameters.

3.1.1 L1b processing

The SMAP takes as input L1a files from the Sentinel-3 satellites which can be obtained from Copernicus (scihub.copernicus.eu) using a wget script in the format described in the “Batch Scripting” user guide on the website. To run the SMAP after several input files have been obtained, a number of processing parameters must be specified by the user in a configuration file and passed on to the SMAP. The different L1b parameters used in this analysis of the two study regions are listed in Table 3. More information about these parameters can be found in the SMAP documentation or Egido et al. (2016) or Guccione et al. (2018)

Parameter	Value Severn Estuary	Value Rhône River
Illumination time	2.3 s	2.3 s
Hamming range	Yes	Yes
Hamming azimuth	Yes	Yes
Zeropadding	2	2
Posting rate	1000 Hz	1000 Hz
Range extension factor	1	1

Table 3: L1b processing parameters used in the application of the SMAP for the two study areas.

In addition to the processing options specified in Table 3, the user can also specify by what mean(s) the SMAP should obtain the range to target in the scene of interest.

The SMAP can obtain this range using two built-in re-tracking methods, the classical Offset Centre of Gravity (OCOG) re-tracker, and a peak re-tracker. The peak re-tracker has the option of either re-tracking a single dominant peak called the Point Target Response (PTR) re-tracker or to re-track a user-define number of peaks to a maximum of 10 called the Multiple Point Target Response (MultiPTR) re-tracker. The user can specify which of these re-trackers should be employed by the SMAP during a processing run in any combination of the three that is desired. For the analysis performed on the two study areas, all three of these re-trackers were employed to test their capabilities. Lastly, a shapefile and or bounding box for a ROI can be defined in the configuration file, specifying what parts of a satellite track should be processed. A custom shapefile for each of the study areas was defined during this analysis to speed up processing.

The program files included in the processor package were used in the manner described in the GitHub documentation, with one exception being a minor change to the program file “l1b_processing.py”. The version of the code file available when the project started consequently terminated due to an error when reading the needed input files. The error was due to a format change in the input data files, occurring sometime at the end of 2022. The lines of code causing this problem were stated as:

```
self.burst_power[:]=self.file_l1a["burst_power_cor_ku_l1a_echo_sar_ku"][index_start]
self.burst_phase[:]=self.file_l1a["burst_phase_cor_ku_l1a_echo_sar_ku"][index_start]
```

These lines were changed to:

```
try:

self.burst_power[:]=self.file_l1a["burst_power_cor_ku_l1a_echo_sar_ku"][index_start]

self.burst_phase[:]=self.file_l1a["burst_phase_cor_ku_l1a_echo_sar_ku"][index_start]

except:

self.burst_power[:]=self.file_l1a["burst_power_cor_ku_l1a_echo_sar_ku"][:]
self.burst_phase[:]=self.file_l1a["burst_phase_cor_ku_l1a_echo_sar_ku"][:]
```

3.1.2 L2 processing - SMAP

The user may additionally pass on a number of processing options in the SMAP configuration file, defining how the chosen re-trackers should be used. The processing options for the different build-in re-trackers that were used in the presented analysis can be seen in Table 4.

Re-tracker parameter	Value (Severn Estuary / Rhône river)
OCOG SAR threshold	0.8

MultiPTR # of estimates	10

Table 4: L2 processing parameters used in the application of the SMAP for the two study areas.

3.1.3 L2 processing - MWaPP

In addition to the build-on re-trackers available for the SMAP, the FFSAR waveforms produced by the SMAP processor were also retracted using the Multiple Waveform Persistent Peak (MWaPP) re-tracker described in Villadsen et al. (2016). In short, the MWaPP re-tracker looks at adjacent waveforms to determine the best sub-waveform for re-tracking. In this way, it is possible to identify persistent peaks, which are expected to represent the underlying water body of interest. Looking at neighbouring waveforms can help alleviate snagging issues, where a waveform is dominated by reflections from points off-nadir.

3.2 From range to height

The L2 output obtained from the SMAP and MWaPP re-trackers as previously mentioned, holds the range to target measurements obtained from the different re-trackers. These ranges were converted to water surface level heights using a set of matching ESA L2 correction files also obtained from Copernicus (scihub.copernicus.eu). The water surface level heights were computed in terms of an absolute altitude reference i.e. relative to the WGS84 reference ellipsoid, using the following equation:

$$WL = altitude - range - geocorr \,, \qquad (1)$$

wherein *altitude* is the altitude of the satellite platform, *range* is the estimated range to target from a given re-tracker and *geocorr* is a set of atmospheric and geophysical corrections computed as:

$$geocorr = iono + gpt + dry + wet + set + lt \,, \qquad (2)$$

The individual terms in the above expression are here given in shorthand names applied during the computation, and their full names as given in the L2 files are specified in Table 5 on the following page. All corrections included in the L2 files were provided in 1 Hz resolution and were therefore linearly interpolated to coincide with SAR positions along the reference ground tracks. The water surface level was chosen to be outputted in an absolute altitude reference to make it easier for the end user to realign the estimates to whatever frame of reference is needed for their specific case e.g. mean sea surface or local geoid.

A set of water surface level heights were computed for the two study areas in the period specified in Table 1 and Table 2 respectively, using all three re-tracking methods. All heights extracted from a specific satellite track using the same tracker were collected and saved as an individual data set before being post-processed.

Correction	Variable name in Copernicus L2 file
(iono) Ionospheric correction	iono_cor_gim_01_ku
(dry) Dry tropospheric correction	mod_dry_tropo_cor_meas_altitude_01
(wet) Wet tropospheric correction	mod_wet_tropo_cor_meas_altitude_01
(gpt) Geocentric polar tide	pole_tide_01
(set) Solid earth tide	solid_earth_tide_01
(lt) Loading tide	load_tide_sol2_01

Table 5: Naming of geophysical and atmospheric corrections from Copernicus L2 files.

3.3 Post-processing

The water surface level heights from the different reference ground tracks estimated by the different re-trackers were post-processed for outlier values according to a MAD criterion. ICESat-2 data with the same spatial and temporal origin as the L1a input files were downloaded from the National Snow and Ice Data Centre (NSIDC) (nsidc.org/data/icesat-2/data), and were used as reference data to remove outliers in the re-tracked heights using a Median Absolute Deviation (MAD) criterion. All re-tracked heights outside a +-2 MAD interval of the ICESat-2 median height value were deemed to be statistical outliers and set equal to NaN. The resulting dataset of this post-processing thus all have a narrower spread around what was deemed to be a reliable median value of the local water surface level height.

4 Output data

The processing steps described in the previous sections all culminate in a set of water surface level height estimates for the two study areas, each obtained using a different re-tracker. At the end of the analysis, the estimates obtained from the MWaPP re-tracker were chosen as the best estimates, and all output height estimates mentioned in the remainder of this document will have been estimated using this re-tracker. A detailed description of the reasoning behind this decision can be found in the companion deliverable “Product Validation and Evaluation Report - Deliverable D2.2”.

The estimated heights have been exported in two distinct data sets for each of the three reference ground tracks in focus. The first is a dataset containing all the extracted and post-processed water surface level heights for the given scenes, and the other is a time series containing the sampled data from select ROI's within each of the different scenes.

All of the different output data are exported in a NetCDF format and are available on the project google drive folder under /Data Sets/FFSAR Data Deliverables.

These data are also publicly available for download on the Channel Coast Observatory website (www.coastalmonitoring.org/ccoresources/FFSAR-Coastal/)

4.1 Full data files

The NetCDF files containing the full dataset of height estimates acquired from the various re-trackers are arranged according to the sensing times of the SAR. This means that all data acquired from the first orbital cycle in the analysed period appear as the first X number of rows in the data set, followed by all data acquired at the next occurring sensing date. The columns in the dataset are arranged in the order shown in Table 6 on the following page along with a detailed description of the format of included variables. Some of the variables included in the output files (various height corrections) have been copied from the input L2 correction files, wherein no description of their exact origin is given. The reader is thus referred to literature describing the underlying models used in acquiring these estimates, but no further information about their origin is available.

The name of the full data set output files is defined from the following naming convention:

FFSAR**_MMM_GGG_yyyymmdd_YYYYMMDD.**nc

- **MMM**: mission ID: (e.g. S3A for SENTINEL-3A mission, S3B for SENTINEL-3B mission).
- **GGG**: Reference ground track number
- **yyyymmdd:** Start date of processed time period
- **YYYYMMDD:** End date of processed time period

Variables	Description
time	Time [UTC time as decimal years]
date	Date and time [UTC time as a date string in the format yyyy-MM-dd HH:mm:ss]
water_height	Water height relative to the WGS84 reference ellipsoid estimated by the MWaPP retracker [m]
geoid_height	Geoid height above the WGS84 reference ellipsoid [m], Pavlis et al. (2012)*
mss_height	Mean sea surface height above the WGS84 reference ellipsoid [m], Andersen et al. (2018)*
lat	Latitude [decimal degrees]
lon	Longitude [decimal degrees]
ocean_tide	Sea surface height amplitude due to geocentric ocean tide [m], Lyard et al. (2016)*
pole_tide	Geocentric tide height [m], Wahr (1985)*
solid_earth_tide	Solid earth tide height [m], Cartwright and Edden (1973)*
load_tide	Load tide height for geocentric ocean tide [m], Lyard et al. (2016)*
polygon_id	Integer specifying polygon of origin ID in custom shapefiles used in extraction

*Table 6: The variables included in an output data file containing the post-processed data set from a given reference ground track, along with a detailed description of the variables. Variables marked with a * at the end of their description have been extracted from Copernicus L2 files. No information on the exact origin of these data is provided by Copernicus, and the reader is thus referred to general literature describing their various underlying models.*

Three files with along-track FFSAR processed data are provided as the deliverable data set:

- FFSAR_S3B_265_20181208_20230419.nc (Severn Region)
- FFSAR_S3B_199_20181203_20230414.nc (Rhône Region)
- FFSAR_S3B_179_20190320_20230413.nc (Rhône Region)

In addition to these FFSAR processed data, three accompanying auxiliary shape files are available that may be used to extract data originating from a number of ROI's in each study area. These are:

- severn_S3B_265.shp (ROI's in Severn Estuary and mouth of River Usk)

- rhone_S3B_199.shp (ROI's near Port-Saint-Louis-du-Rhône)
- rhone_S3B_179.shp (ROI's near Fos-Sur-Mer)

4.2 Time series files

The columns in the time series dataset are arranged in the following order:

Variables	Description
time	Time [UTC time as decimal years]
wl	Water surface level heights wrt the WGS84 ellipsoid [m]
wlsd	Standard deviations for water surface level height (wl) estimates [m]
date	Date and time [UTC time as a date string in the format yyyy-MM-dd HH:mm:ss]
lat	Latitude [decimal degrees]
lon	Longitude [decimal degrees]
geoid	Geoid height above the WGS84 reference ellipsoid [m], Pavlis et al. (2012)*
mss	Mean sea surface height above the WGS84 reference ellipsoid [m], Andersen et al. (2018)*

*Table 7: The variables included in an output data file containing the sampled height time series from a given reference ground track, along with a detailed description of the variables. Variables marked with a * at the end of their description have been extracted from Copernicus L2 files. No information on the exact origin of these data is provided by Copernicus, and the reader is thus referred to general literature describing their various underlying models].*

The time series data has no naming convention, but instead follow the same naming principles: (name of the study area)_(mission ID)_(reference ground track number)_(sampling location within study area).nc

Six files with sampled time series of processed FFSAR data are provided as the deliverable data sets:

- Rhone_S3B_179_open.nc
- Rhone_S3B_179_canal.nc
- Rhone_S3B_199_north.nc
- Rhone_S3B_199_south.nc
- Severn_S3B_265_open.nc
- Severn_S3B_265_tributary.nc

These data sets are also available in .dat format.

The location for which the time series have been calculated, together with the geoid and mean sea surface heights, is given in Table 8.

Filename	Lat (decimal degrees)	Lon (decimal degrees)	Geoid (m)	MSS (m)
Rhone_S3B_179_canal.nc	43.43	4.92	50.12	49.13
Rhone_S3B_179_open.nc	43.41	4.91	50.10	49.12
Rhone_S3B_199_north.nc	43.47	4.75	50.18	49.27
Rhone_S3B_199_south.nc	43.40	4.78	50.12	49.20
Severn_S3B_265_open.nc	51.40	-3.04	51.26	50.85
Severn_S3B_265_tributary.nc	51.56	-2.97	51.31	51.06

Table 8: The latitude, longitude, geoid height(EGM2008: relative to WGS84) and mean sea surface height (DTU2018: relative to WGS84) for the locations of the six sites selected for time series data sets

5 References

[Andersen, O., Knudsen, P., & Stenseng, L. (2018). *A New DTU18 MSS Mean Sea Surface – Improvement from SAR Altimetry*. 172. Abstract from 25 years of progress in radar altimetry symposium, Portugal.]

[Cartwright, D. E., & Edden, A. C. (1973). Corrected tables of tidal harmonics. Geophysical Journal International, 33(3), 253–264.] (https://doi.org/10.1111/j.1365-246x.1973.tb03420.x)

[Egido, A., & Smith, W. H. (2016). Fully focused SAR altimetry: theory and applications. IEEE Transactions on Geoscience and Remote Sensing, 55(1), 392-406.] (https://ieeexplore.ieee.org/abstract/document/7579570)

[Guccione, P., Scagliola, M., & Giudici, D. (2018). 2D Frequency Domain Fully Focused SAR Processing for High PRF Radar Altimeters. *Remote Sensing*, *10*(12), 1943.] (https://doi.org/10.3390/rs10121943)

[Lyard F., L. Carrere, M. Cancet, A. Guillot, N. Picot (2016). FES2014, a new finite elements tidal model for global ocean, in preparation, to be submitted to Ocean Dynamics in 2016.]

[Pavlis, N. K., S. A. Holmes, S. C. Kenyon, and J. K. Factor (2012), The development and evaluation of the EarthGravitational Model 2008 (EGM2008),J. Geophys. Res.,117, B04406] (https://doi.org/10.1029/2011JB008916)

[Villadsen, H., Deng, X., Andersen, O., Stenseng, L., Nielsen, K., & Knudsen, P. (2016). Improved inland water levels from SAR altimetry using novel empirical and physical retrackers. *Journal of Hydrology*, *537*, 234–247.] (https://doi.org/10.1016/j.jhydrol.2016.03.051)

[Wahr, J. (1985). Deformation induced by polar motion. *Journal of Geophysical Research*, *90*(B11), 9363.](https://doi.org/10.1029/jb090ib11p09363)

6 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
MWaPP	Multiple Waveform Persistent Peak
SRAL	SAR Radar Altimeter
S3A, S3B	Sentinel 3A, and Sentinel 3B
TWLE	Total Water Level Envelope
NSICD	National Snow and Ice Data Center
MAD	Median Absolute Deviation