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List of Acronyms	
ALES	Adaptive Leading Edge Subwaveform
ATBD	Algorithm Theoretical Basis Document
CCI	Climate Change Initiative
CTOH	Centre of Topography of the Oceans and Hydrosphere
ESA	European Space Agency
GDR	Geophysical Data Record
GPD	GNSS Path Delay we troposphere correction
Level 2P	Level 2 Plus altimeter data (after editing and validation)
RADS	Radar Altimeter Database System
SLA	Sea Level Anomaly
SSH	Sea Surface Height
X-TRACK	Altimeter production system developed by CTOH for coastal areas

1. Introduction

This document specifies the characteristics of the SL_CCI+ production system. The aim is to satisfy the scientific requirement of the SL_CCI+ project: produce regional sea-level products in coastal areas to better understand the climate processes at the coast and their societal impacts. The SL_CCI+ production system integrates retracked data (Level 2) from different LRM and SAR altimetry missions, as well as dedicated geophysical corrections in order to compute a database of Level 3 coastal sea level products in several world coastal zones selected for their vulnerability to global warming and sea level rise.

The processing system used in this project is built on existing algorithms, called X-TRACK and ALES, previously developed and validated in the context of projects funded by space agencies (CNES, ESA) and national research programs. They have been chosen because they have shown their efficiency through different publications (for example *Passaro et al.*, 2014; *Passaro et al.*, 2018; *Gomez-Enri*, 2019; *Jebri et al.*, 2016; *Cipollini et al.*, 2016; *Birol et al.*, 2017) and have already been adopted by a significant part of the coastal altimetry community (https://www.coastalaltimetry.org/, history section). In the SL_CCI+ production system, the coastally-oriented X-TRACK and ALES algorithms have been combined for the first time in order to form homogeneous sea level products from a wide number of altimetry missions on the selected coastal areas. The geophysical corrections integrated in the system are selected as a function of their respective performance in coastal ocean areas. This project build on the work done in the SL CCI 'Bridging Phase' project, itself based on the large experience in coastal altimetry processing of the TUM, CLS and CTOH/LEGOS teams.

The system's objectives are:

1) Implementing a processing and post-processing strategy that, as far as possible, ensures continuity of the sea level information from LRM to SAR altimetry missions.
2) Producing a homogeneous and long-term sea level time series providing valuable information as close as possible to the coastline (i.e a few kilometers instead of > 10 km), including estimations of data uncertainties.
3) Creating distributable CF-compliant products of the sea level time series, and the trends computed from this time series.

It is important to notice that, producing climate change products, the system is an offline processing system, with no automatic data ingestion nor updates, because of the strict quality controls applied on each processing step.

2. System Overview

The SL CCI+ processing system has a general entry point for data, the general database of the *Centre de Topographie des Océans et de l'Hydroshere* (CTOH), French National Observation Service for satellite altimetry funded in 1989 by the CNRS/INSU. The CTOH is hosted at LEGOS (http://www.legos.omp.eu/), Toulouse. Standard Geophysical Data Records (GDRs) data provided by Space Agencies (ESA, CNES and others) are routinely ingested into this database, which is the central workspace for CTOH. Contributions by partners for data processing are mainly made through dataset provisioning. As such, they are easily included in the CTOH database, as is the case of the ALES altimetry products which are provided to CTOH by TUM. The overview of the system is given in Figure 1. Some pre-processing (such as the conversion of TUM-provided Matlab ALES files to the standard NetCDF data format and co-registration with GDR files) can also be done by CTOH before ingestion in the database but is not shown here.

Once the inputs are consolidated (GDR, Geophysical corrections, ALES data), the extraction of all the parameters needed for the computation of the SL_CCI+ product can take place and processing for high-resolution data (i.e. 20/40 Hz for the Jason/SARAL mission, respectively) can begin with the X-TRACK post-processing software. This process produces the sea level time series for the different altimetry missions. To ensure the accuracy of the long-term sea level estimates of the successive Jason missions, inter-mission biases (i.e. relative measurement biases) are computed during the calibration phases between successive missions, and then applied to the sea level estimates. At this point of the processing, we obtain regional sea level coastal products, which are also used to calculate regional trends and create regional sea level trend indicator products.

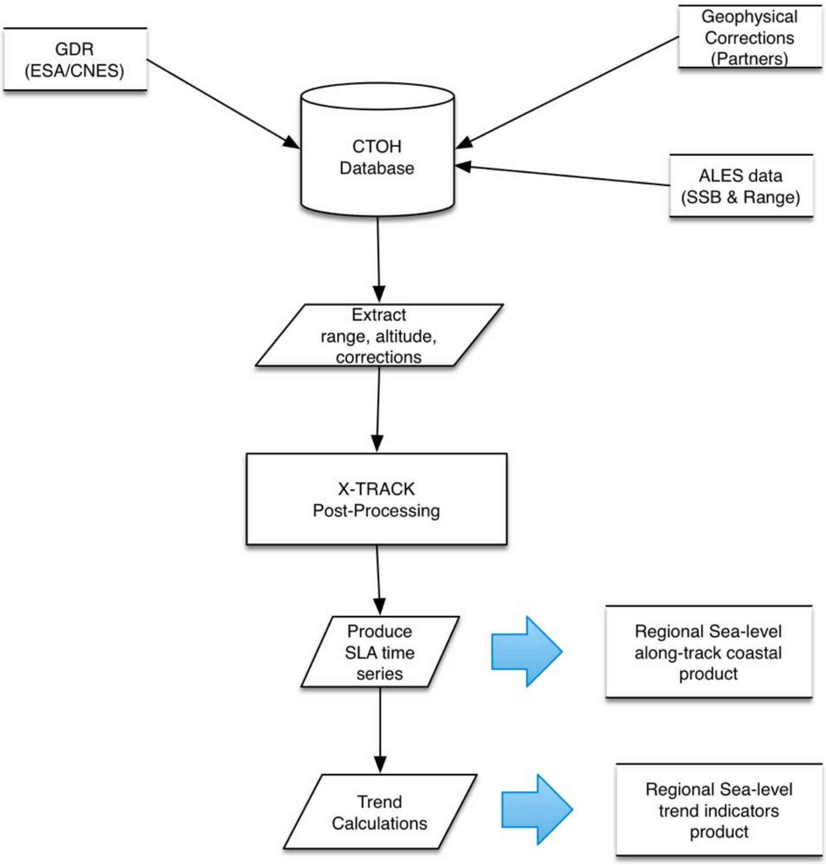

Figure 1 - System Overview

3. System description

3.1. Development rationale and constraints

The SL CCI+ project fosters reuse of existing algorithms and processors. The production of new sea-level products, however, does not require the integration of all algorithms and processors on the same premises – as it would be cumbersome and have some intellectual property rights issues (as many of these algorithms were developed out of the SL CCI+ project).

3.1.1. Algorithm and processor interfaces

The main design decision is thus to interface the algorithms and processors of different partners through datasets, to be ingested at LEGOS through the CTOH database. All datasets provided by the partners must be versioned so as to ensure traceability.

Ideally, each partner providing a dataset must have its own versioning scheme and ensure traceability and reproducibility of each data provision. However, if they were developed outside of this project, the producing systems are out of the scope of this project and such requirements cannot be guaranteed. For these situations, we require that all datasets to be ingested by CTOH be given an identifier which will be the versioning tag of the dataset, and that can be used to trace its provenance and history. This identifier will be given using the standard dataset identification of the CTOH database.

3.1.2. Algorithm improvements

On the case of an improvement of a partner algorithm or processor, a new dataset delivery can be scheduled, and hence a new dataset identification and ingestion should take place, in coherence with what has been specified in §3.1.1.

3.2. Production and reprocessing with reproducibility

As natural continuation of the requirements for dataset ingestions of the previous section, the development should use source code control and product versioning, ensuring reproducibility of data generation.

3.2.1. Processing components

For all developments taking place at LEGOS, mercurial (http://mercurial-scm.org) will be used as the standard source code management tool. All components used in the SL CCI+ processing chain should exist and be traceable at the mercurial repository level.

3.2.2. Production control

Products will be generated as outputs of the processing chain by executing the X-TRACK processor which handles parallel execution of the processing jobs (1 job per track). In case of error while processing a track, error logs indicate what went wrong (missing file, incomplete data…) and when corrective action is taken, reprocessing of selected tracks can be done.

The processing chain as a whole has a version number which is part of the metadata included in the NetCDF product files. With this version number, at CTOH we are able to trace the datasets that were used for each particular version. However, the individual dataset identifiers will not be included in the NetCDF file, since the datasets they refer to are in general not publicly available.

3.2.3. Product quality checks

Basic quality checks are made in the SL CCI+ system, and are limited to technical details:

- Every file to be processed is defined by a track and cycle number. After a first processing step for altimetry correction post-processing, each file is saved as an intermediate file. This file contains the edited altimetric range, and the reprocessed altimetric corrections (edition, filtering and interpolation). The number of intermediate files, before the creation of the time-series, should equal the number of input track files.
- Check of the number of cycles present in the final time-series products, which must be the same as the number of cycles given as input.
- Control of the spatial coverage of the product by generation of maps, checking the continuity of products, and calculating regional statistics (min/max/standard deviation/percentage of valid data), as shown in Figure 2 and Figure 3 below. Four regions are shown: Mediterranean Sea, South East Asia, North Eastern Atlantic and South Australia, they show the processed SLA records for the multi-mission Jason-1, Jason-2 and Jason-3 product. Please note that the full dataset spans 13 zones covering most of the Earth's coastal areas between latitudes -66° and 66°. The same quality checks are provided to all zones.
- Regional maps of sea level trends are also computed to check the product's stability over time.

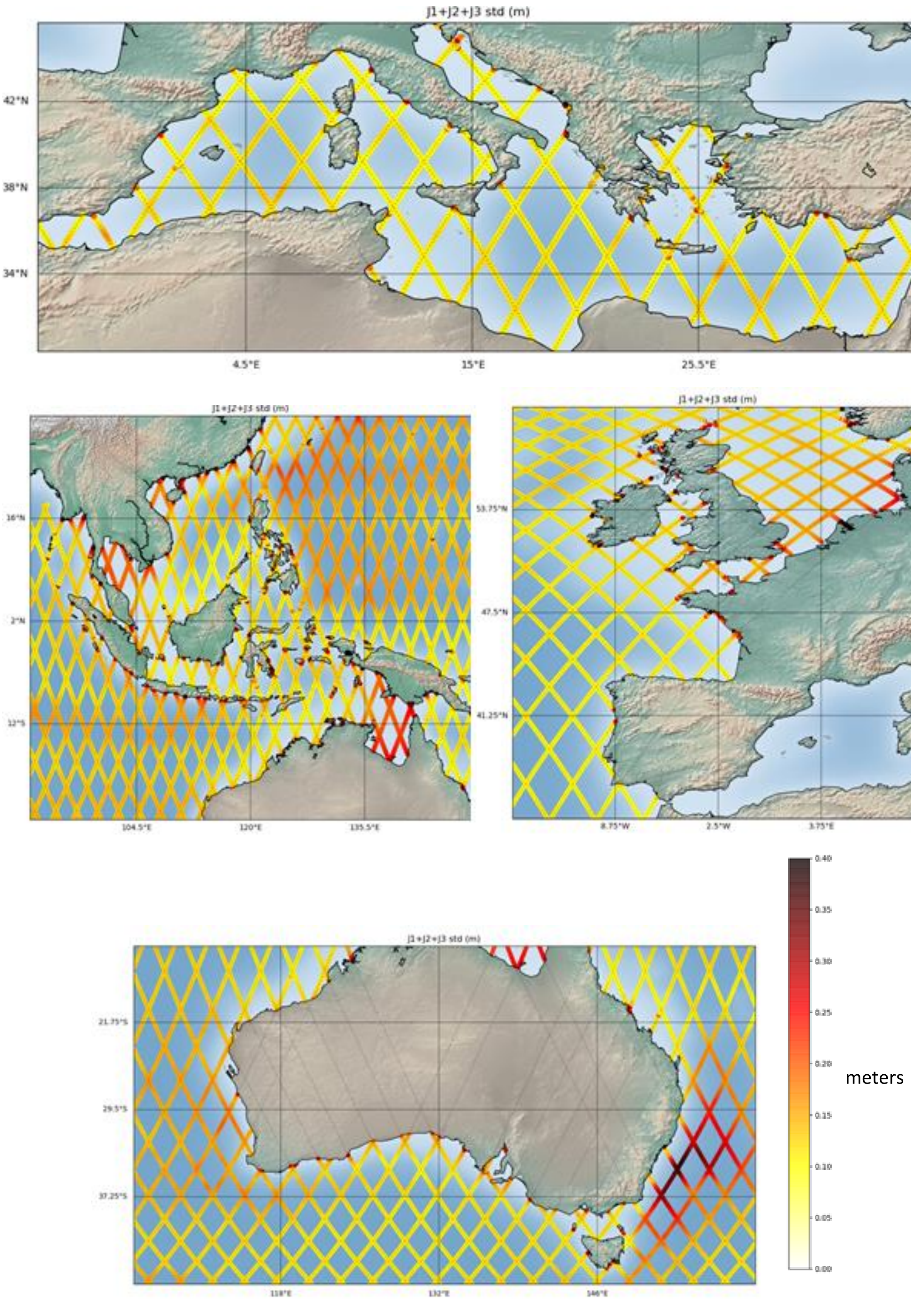

Figure 2 - Standard deviation of SLA (in m) for 4 regions in CCI+ (J1+J2+J3)

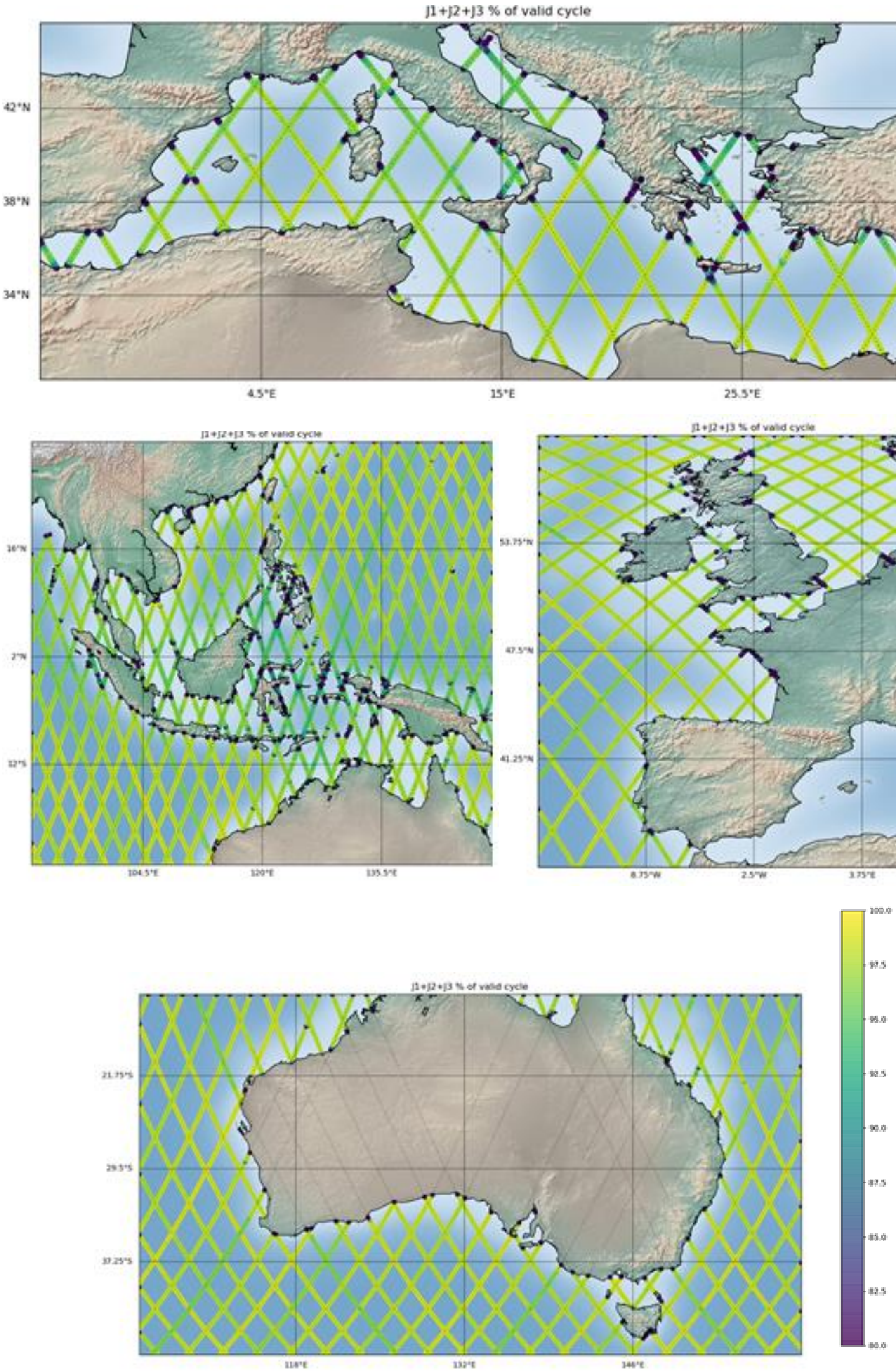

Figure 3 - % of valid cycles for 4 regions in CCI+ (J1+J2+J3)

3.3. CTOH database

A pre-existing asset of the French National Observations Service for altimetry, CTOH, has as main functionalities:

- ingestion of altimetry datasets
- indexing of these datasets in the database catalogue
- access and subsetting of datasets by spatiotemporal criteria (lat/lon/shapefile, cycle/dates)

The input datasets are expected in NetCDF format and must include all necessary information for processing X-TRACK: retracker, and complete altimetric corrections. For the case of a *partial* dataset in which not all altimetric corrections are delivered, we require for ingestion that it should include at least 3 fields which should be strictly equal to the dataset it will complement: time, latitude and longitude (in low and high resolutions).

The ALES retracker is expected to be delivered in MATLAB format, and a specific converter is necessary. However, we expect the matlab dataset to conform to the above requirement. Namely:

- Provide 1 file per track and per cycle
- For each data point, include time, latitude and longitude in addition to the new information.
- Each time/latitude/longitude triplet should be exactly equal to that of a reference dataset.

For example, if the system is to accept new information for the ALES retracker of Sentinel-3A data, the reference dataset should be exactly the same (e.g. using dataset REP 004 from the CODAREP archive) and matching time/latitude/longitude information. Otherwise, merging the two datasets will not be possible.

Subsetting output is always done in NetCDF format.

3.4. The X-TRACK/ALES processing system

The X-TRACK/ALES processing system is largely built on the X-TRACK processing system, adapted to the ingestion of ALES altimetry data and extended to the processing of high-rate altimetry measurements (20/40Hz) instead of the standard 1-Hz data.

The X-TRACK processing system is described in detail in Vignudelli et al. (2005), Roblou et al. (2011) and Birol et al. (2017). It is summarized in the scheme below. Here we will only provide a brief description. The resulting R&D products (that are delivered today by the AVISO+ operational centre) are fully documented at https://www.aviso.altimetry.fr/index.php?id=3047.

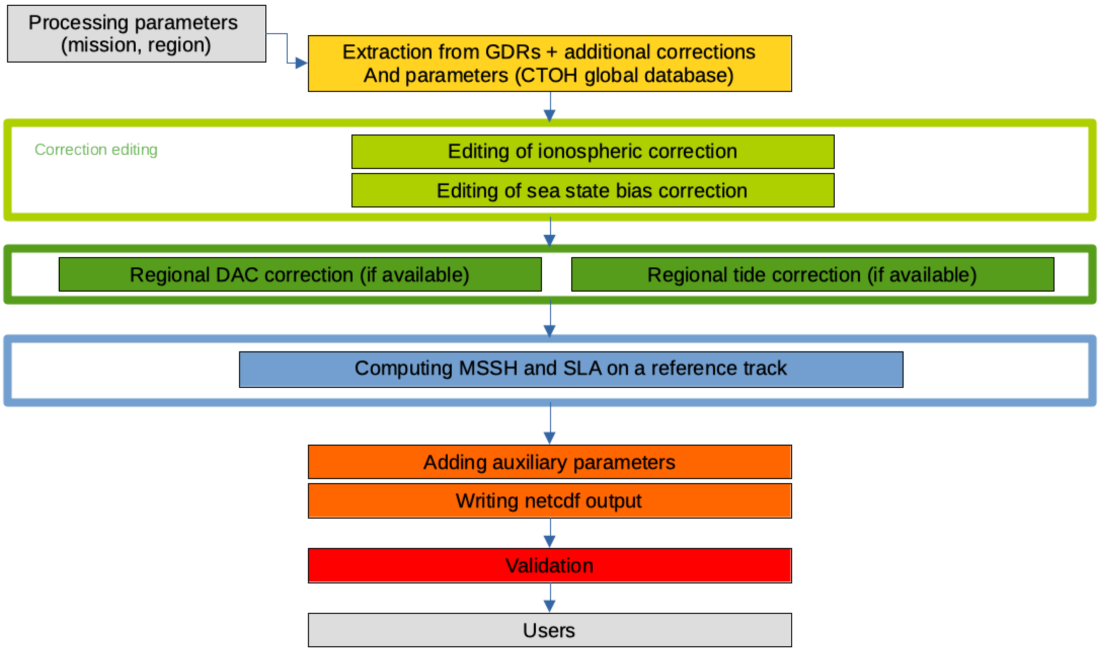

Figure 4 - X-TRACK processing scheme

The X-TRACK processing system works on a regional basis (the regional domain can be easily defined before the processing in a parameter file). It first reads parameters from the CTOH database: information from the L2 Geophysical Data Records (GDRs) products for each altimetry mission plus additional state-of-the-art altimetry parameters, geophysical corrections and auxiliary data.

Since altimetry observations degrade in accuracy near the coast, the algorithm first selects valid ocean data (i.e. non-fill-value altimeter range located over the ocean). Then, a precise land mask and a dedicated editing strategy are used. The latter includes two steps. The first step is to impose editing criteria, both on the altimeter measurements and corrections, designed to be more restrictive than the standard ones (e.g. §3.2.7 Editing Criteria of SALP-MU-M-OP-16118-CN - Aviso, 2018). These threshold criteria have been chosen after series of tests for each parameter, in order to ensure that all outliers are totally removed. The behavior of all corrections is analyzed along the track, taking into account their individual characteristics. Each correction is edited in a different way (Birol el al., 2017). Abrupt changes are assumed to be associated with erroneous data. Outliers are removed. Since the editing process leads to the rejection of all altimeter measurements for which at least one correction is considered as wrong, this method rejects much more data than the classical ones, even if the altimeter measurement is meaningful. Thus, in a second step, all corrections are recomputed using interpolation/extrapolation methods, based on valid data for each correction. This strategy is very efficient in recovering a lot of good altimeter measurements flagged in the standard product because of a deficient correction (Vignudelli et al., 2005; Jebri et al., 2016). Once the corrected sea surface heights (SSHs) are computed, they are projected onto fixed points along the nominal ground track of the altimeter satellite and converted into SLAs (Sea Level Anomalies) by subtracting a precise mean sea surface height. The latter is computed at the fixed nominal points, by inversion of all the available SSH measurements along the repeated ground tracks of the considered altimetry mission. This procedure is important, since in coastal areas where topographic gradients can be large, use of a standard mean sea surface leads to significant errors in SLAs because of poor spatial resolution (Vignudelli et al., 2005). Figure 4 summarizes the different processing steps of the X-TRACK system.

This processing system has been initially designed to provide along-track SLA time series at 1-Hz along the track for different LRM missions (T/P, GFO, Envisat, Jason-1,2,3 and SARAL/AltiKa). In Birol et al. (2014), a version of the X-TRACK algorithm was successfully tested on a sample of original full rate (10/20 Hz) altimetry measurements in the Northwestern Mediterranean Sea, generating more near-shore sea level data. In 2018, during the SL_cci "Bridging phase", all the processing system has been rewritten and adapted in order to compute high-frequency (i.e. 20/40-Hz) altimeter measurements in routine, and to take advantage of the ALES retracker. The version of the X-TRACK/ALES processing system used to produce SL_cci+ data sets have been successfully evaluated and validated (in particular by comparison with tide gauge measurements) during the project (Marti et al., 2019; Léger et al.,2019; Birol et al., 2021).

It is worth noting that the process just described is tackled track by track for each mission (e.g. Jason-2). When creating multi-mission time series (Jason-1, Jason-2 and Jason-3), an inter-mission regional bias is calculated and applied so as that the resulting merged time-series has correct continuity properties. The detailed description of this calculation is given in the ATBD document (SL_CCI+, 2020).

3.5. Product generation

The X-TRACK/ALES software computes along-track sea surface height time series for different altimetry missions using corrections and parameters from delayed-time geophysical data records (GDR) provided by space agencies, ALES products from TUM (range, sigma0 and sea state bias) and additional geophysical corrections provided by the RADS altimeter database (http://rads.tudelft.nl/rads/rads.shtml) and the University of Porto (GPD+). The list, provided in Table 1, is a copy of the table provided in section 2 of the *Product User Guide* SLCCI_PUG_011 (https://climate.esa.int/en/projects/sea-level/key-documents/), which we provide here for convenience for the reader.

parameter	source	Jason-1 / Jason-2 / Jason-3
Altitude	GDR	Altitude of satellite
Range	ALES/TUM	20 Hz ku band ALES corrected altimeter range (Passaro et al.2014)
Ionosphere	GDR	From dual-frequency altimeter range measurement
Dry troposphere	GDR	From ECMWF model
Wet troposphere	University of Porto	GPD+ radiometer correction (Fernandes and Lazaro. 2016)
Sea state bias	ALES/TUM	Sea state bias correction in ku band, ALES retracking (Passaro et al. 2018)
Solid tides	RADS	From tide potential model (Cartwright and Taylor 1971, Cartwright and Eden 1973)
Pole tides	GDR	From Wahr 1985
Loading effect	CNES/CLS database	From FES 2014 (in product versions up to v2.2) and FES 2022 (v2.3)
Atmospheric correction	RADS	From MOG2D-G (Carrere and Lyard 2003)
Ocean tide	CNES/CLS database	From FES 2014 (in product versions up to v2.2) and FES 2022 (v2.3)

Table 1: List of altimetry parameters and geophysical corrections used in the computation of the SL_cci+ coastal sea level product.

After all the processing has been done, distributable NetCDF files are generated, including all the parameters listed in Table 2.

Trend analysis is made as a further step and the generation of another NetCDF product containing trend information is made. The content of this trend product is detailed in a separate Product User Guide.

Names of variables in files	Description
lon	Longitude of the data point at 20 Hz resolution along the mean track
lat	Latitude of the data point at 20 Hz resolution along the mean track
cycle	Mission cycle number
missions_cycles	Original cycle number specific to each mission. It is discontinuous on the date of the change of mission.
sla	Sea Level Anomaly
ocean_tide	Oceanic tide includes the corresponding loading tide and equilibrium long-period ocean tide height from FES 2014 (in product versions up to v2.2) and FES 2022 (v2.3)
dynamic_atmospheric_correction	Dynamic Atmospheric Correction, combining the low and high frequency effect of atmospheric pressure and wind on sea surface height from MOG2D-G
mean_sea_surface	X-TRACK Mean Sea Surface
dist_to_coast_gshhs	Distance to the nearest GSHHS coastline
mdt_cnes_cls_18	Mean Dynamic Topography
Time	Time of measurement at 20 Hz resolution
qual_flag	Quality flag if distance to the coast is lower than 4 km

Table 2: List of the variables stored in **the SL_cci+ coastal sea level product**

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