# Round Robin Assessment of altimetry algorithms for coastal sea surface height data : Inter-comparison Protocol

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## 1. Overview

In the coastal ocean, satellite altimetry encounters several specific issues that make more difficult to derive accurate geophysical data than it is for the deep ocean (i.e. land contamination in the radar and radiometer footprints, lack of accuracy in some corrections and auxiliary information when approaching the coast, specific interpretation of the retrieved signal, …). The critical need of monitoring coastal sea level changes at global scale has motivated many efforts to obtain accurate sea level retrievals by satellite altimetry as close as possible to the shore. The result is the availability of new algorithms for retracking radar altimeter data, correcting sea surface heights and, finally, deriving sea level variations.

The main objective of this Round Robin study is the comparison of various algorithms for the generation of sea level anomaly (SLA) data from Low Resolution Mode (LRM) altimetry in coastal zones. It aims to compare the different processing solutions in order to gain insight into their relative capabilities to provide accurate sea level data as close as possible to the shoreline. Even though we compare the algorithms against each other with a set of different performance assessment criteria, we will not identify here the "best" algorithm among all those tested to compute SLA, because the relative weight of each individual criterion depends on user needs and the final choice is always a trade-off of different features (e.g. computational cost, availability of the algorithm, continuity between missions, improvement of long scales over white noise). Thanks to the elements brought forth by this document, colleagues can understand the role and importance of each diagnostic, and use their own expertise to choose the best set of algorithms for their specific needs.

Here, we have chosen to **focus on LRM altimetry only** because it concerns the larger time span and number of altimetry missions as well as the greater number of algorithms available for coastal altimetry. Moreover, LRM observations will remain critical for long-term sea level time series.

The inter-comparison protocol described in this document concerns:

- The definition and the description of the input data used in the round-robin inter-comparison.
- The definition and the description of the diagnostics used for the round-robin inter-comparison: they are based not only on intrinsic characteristics of the altimetry data (availability, noise level), but also on external data such as tide gauges measurements.

An important decision taken by the members of this project at its inception was to work using the CNES altimetry database, as this was the simplest way of integrating the algorithms directly used in operational sea level products and considering them as the reference for evaluating the relative quality and potential improvement of the other algorithms. It was also the only way to evaluate as many algorithms as those presented here. Most of the data in this database are distributed as level 2 Geophysical Data Records by CNES and NASA; however, some project-specific data was also used which is not freely available for distribution (e.g. ALES retracker data, some adaptive retracker data, regional tide solutions; see Table 1 for full information). Nevertheless, we believe their inclusion is important for the community. The performance assessment results in this Round Robin Exercise are available online (see Section 6). A brief analysis of the results is proposed in *Birol et al.*, 2022 (http://dx.doi.org/10.24400/527896/a03-2022.3363). A scientific peer reviewed journal publication is the next objective.

## 2. General specification

This Round Robin exercise was implemented to compare algorithms used to calculate the altimeter SLA. The latter is computed according to the equation:

$$SLA = Altitude\ of\ satellite - Altimeter\ range - Ionospheric\ correction - Dry\ tropospheric\ correction - Wet\ tropospheric\ correction - Sea\ state\ bias\ correction - Solid\ earth\ tide\ height - Geocentric\ ocean\ tide - Geocentric\ pole\ tide\ height - Dynamic\ atmospheric\ correction - mean\ sea\ surface\ height \quad (Eq.1)$$

For the majority of the sea level terms (also called "sea level components" hereinafter) of Eq. 1 (i.e. the range, ionospheric correction, …), different algorithms to compute them exist, derived from numerical or empirical models, or from altimetry or auxiliary observations. When available, we have included solutions developed specifically for the coastal environment. The algorithms for each term will then be inter-compared with standard diagnostics, which also assess their impact on the resulting SLA.

- We will consider **along-track altimetric measurements at the original high-frequency sampling rate (20Hz)** because they provide sea level data closer to the coast and are the raw data from which the widely used 1Hz datasets are obtained.
- We also want to estimate the degree of agreement of our results from one altimetry mission to another. We consider **data from the reference Jason-2 and Jason-3 missions,** each one of them with 3 years of data (i.e. 111 cycles, see section 3) on the same nominal orbit for a total of 6 years of data.
- This study focuses on the coastal zone whose exact definition varies widely from one type of altimetry application to the other. In this document, we define it as **the geographical area between the coastline and 200km offshore, at global scale** (Figure 1, top panel). which we call the global coastal zone hereinafter. Note that the choice of 200 km allows to include in this study the issue of data continuity between the coastal and the open ocean.
- As the coastal conditions are different from one region to the other, the performance of some algorithms may have a marked geographical dependency (e.g. the ocean tide correction). To take this variability into account, **the global analysis is completed by a regional analysis in 3 different areas** chosen because of their very different coastal and oceanographic contexts, and the availability of regional tidal corrections: **Mediterranean Sea, North East Atlantic and Eastern Australia** (Figure 1, middle and bottom panels).

The same diagnostics are computed for Jason-2 and Jason-3 data and for the four geographical domains illustrated in Figure 1 (global scale + three regions). For the global scale, North East Atlantic and Eastern Australia, all the data located within [0-200 km] from the land are used. For the Mediterranean Sea, we considered all data located within the sea, Black Sea excluded (the motivation of this choice was that the 200km isocontour only excludes a small patch between Turkey and Egypt, and a bigger patch midway between Libya, Italy and Greece).

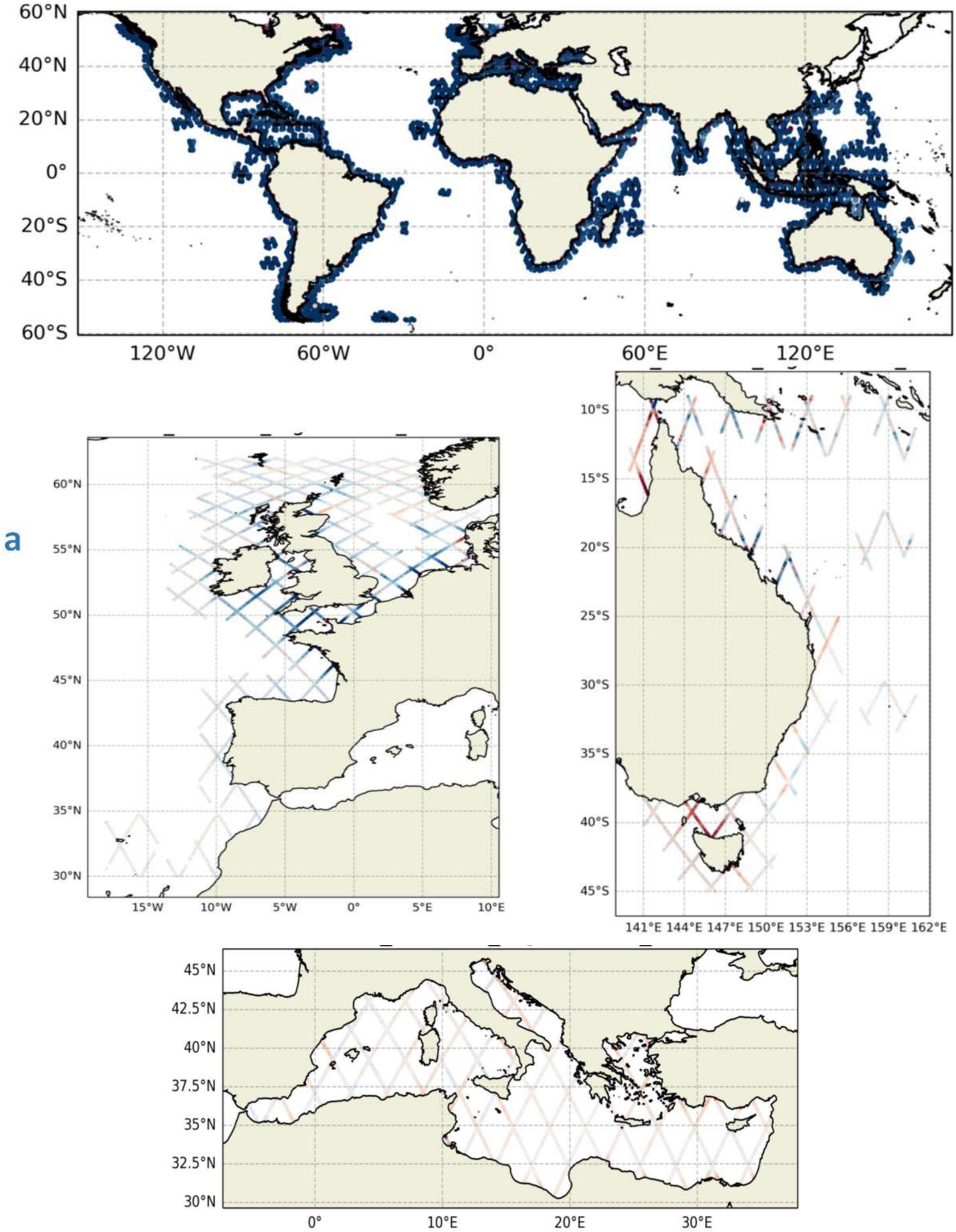


**Figure 1:** Geographical domains covered by the inter-comparison diagnostics: global (top), North East Atlantic (middle left), Eastern Australia (middle right) and Mediterranean Sea (bottom). All of them comprise the [0-200 km] coastal band except the Mediterranean Sea which is complete.

## 3. Input data

### 3.1 Altimetry data

The data period considered for each altimetry mission (constrained by the ALES retracker data availability - see below) is as follows:

- Jason-2: from cycle 193 (start: 27/09/2013) to cycle 303 (end: 02/12/2016)
- Jason-3: from cycle 1 (start: 17/02/2016) to cycle 111 (end: 22/02/2019)

We have initially planned to include all the sea level anomaly terms of Eq. 1 in the Round Robin but for the *Dry Tropospheric Correction* and the *Dynamic Atmospheric Correction*, only one solution was available. For the sake of simplicity, the *Solid earth tide height* and the *Geocentric pole tide height* were also discarded because considered non-critical for coastal sea level calculations.

For each sea level anomaly component finally included in the Round Robin (Table 1), **the algorithms to be evaluated were chosen because of their data availability for this study on a global scale and for the whole targeted time period (i.e. 2013-2019)**.
A few exceptions have been made for specific reasons:

- The ALES *altimeter range* and its *sea state bias correction* (ssb) datasets used, both derived with the ALES retracker, are those part of the the ESA CCI Coastal Sea Level product (https://www.nature.com/articles/s43247-022-00448-z). They are not global but cover a large part of the coastal ocean (except latitudes above 60°N, Japan, Alaska and the Okhotsk and Bering Sea zones on the north, and New Zealand, Antarctica and some small islands on the south, as shown in Figure 1 of the aforementioned article). Because the ALES retracker has been developed specifically for coastal altimetry, this study would not be complete without its inclusion. As a consequence, all the algorithms concerning the altimeter range and the ssb will be evaluated only where ALES data are available.
- The ocean tide correction from regional tidal model is, by definition, available only in its geographical area. For this project, regional tidal corrections were made available by CNES/Noveltis for the Mediterranean Sea, North East Atlantic and Eastern Australia regions. Including them in this study allows us to analyze the potential of regional tidal models for coastal altimetry. The evaluation of all the algorithms concerning the ocean tide correction will be done only in the regional analysis.
- Concerning the ocean tide correction, much more algorithms were available than the ones included in the present Round Robin study: DTU16 (Cheng and Andersen, 2010), EOT20 (Hart-Davis et al., 2021), FES2014b, FES2014, unstructured mesh version (Lyard et al., 2021), GOT4.10c (Ray et al., 1999), TPX09 (Egbert and Erofeeva, 2002) and the CNES regional models (NEA, Mediterranean Sea, Australia). A specific study was done by Noveltis at the beginning of this project to select only those tide corrections with the most interest for the coastal regions. In this Round Robin, it has been chosen to start from the result of this selection (Table 1). Results from the ocean tidal correction study done by Noveltis are available in a specific report (Section 6).
- Concerning the sea state bias (ssb), some of the new algorithms were available only for Jason-3 and not for Jason-2: MLE4 2D 20Hz, MLE4 3D 20Hz, Adaptive 3D 20Hz. Given that the ssb is identified as a critical issue in coastal altimetry, it was decided to include the analysis of the performances of these algorithms in this study. The

evaluation of all the algorithms concerning the ssb correction will be done only for Jason-3 (at both global and regional scales).

**The SLA components and algorithms finally selected in this Round Robin are listed in Table 1. They represent a total of 21 algorithms inter-compared**, at both global and regional scale, with a large number of diagnostics (see sections 4 and 5). Note that there are several versions of the same algorithm. This information is also provided in Table 1.

| Components used in the calculation of altimetric SLA | List of algorithms analysed |
|---|---|
| **Altimeter Range** | **3 solutions:**<br>• Retracker MLE4 – GDR version<br>• Retracker Adaptive (*Tourain et al., 2021*) – GDR version GDR<br>• Retracker ALES (*Passaro et al., 2014*) – version ESA CCI Coastal Sea level product |
| **Ionospheric correction** | **2 solutions:**<br>• Dual-frequency, filtered* – GDR version<br>• GIM (*Ijima et al., 1999*)* – GDR version |
| **Wet tropo correction** | **3 solutions:**<br>• Radiometer* – GDR version<br>• 3D ECMWF model* – GDR version<br>• GPD+* (*Fernandes et al, 2015*) – from AVISO+ 2022 |
| **Ocean tide correction** | **4 solutions:**<br>• EOT20 (*Hart-Davis et al., 2021*)<br>• FES2014b – GDR version<br>• FES2014, unstructured mesh version (*Lyard et al., 2021*), provided by Noveltis<br>• CNES regional models (NEA, Mediterranean Sea, Australia) , provided by Noveltis |
| **Sea State Bias (SSB) correction** | **6 solutions:**<br>• MLE4 2D 1Hz* - GDR version<br>• MLE4 2D 20Hz (*Tran et al., 2019*), provided by CNES<br>• MLE4 3D 20Hz, provided by CNES<br>• Adaptive 2D 20Hz (*Thibaut et al., 2021*), provided by CNES<br>• Adaptive 3D 20Hz, provided by CNES<br>• ALES 20Hz (*Passaro et al., 2018*) – version ESA CCI Coastal Sea level product |
| **Mean Sea Surface Height (MSSH)** | **3 solutions:**<br>• CNES_CLS15* (Pujol et al, 2016) – GDR version<br>• SIO* (Sandwell et al, 2017)<br>• CNES_CLS22* (Schaeffer et al., 2022) – provided by CNES |

**Table 1 :** Components of the altimetric SLA included in the Round Robin exercise (column 1), with the list of algorithms tested for each one (column 2). The algorithms currently used in operational sea level products and that are considered as the reference algorithm for each component are underlined. GDR version means GDR-F for Jason-3 and GDR-D for Jason-2.

**Important remark:** the fields in Table 1 that are marked with an asterisk were calculated at 1Hz only and have been linearly interpolated to 20Hz for the purposes of this study (all diagnostics have been computed using 20Hz data). The others were calculated directly at 20Hz.

The basic principle of the inter-comparison diagnostics is to compare all algorithms selected in this study with the reference ones. **The reference algorithms are defined as the state of the art of the SLA data (variable called ssha) available in the GDR product distributed at the beginning of the study** (GDR-F version for Jason-3, GDR-D for Jason-2). They are underlined in Table 1.

Definition of the reference SLA for Jason-2:

***SLA = Altitude of satellite* (GDR-D) – *Altimeter range* (MLE4, GDR-D) – *Ionospheric correction* (Dual-frequency, filtered, GDR-D) – *Dry tropospheric correction* (GDR-D, field "model_dry_tropo_cor_zero_altitude") – *Wet tropospheric correction* (radiometer, GDR-D) – *Sea state bias correction* (MLE4 1Hz, GDR-D) – *Solid earth tide height* (GDR-D) – *Geocentric ocean tide* (FES2014b, GDR-D) – *Geocentric pole tide height* (GDR-D) – - *Dynamic atmospheric correction* (GDR-D) – *mean sea surface* height (CNES_CLS15, GDR-D) (Eq.2)**

Definition of the reference SLA for Jason-3:

***SLA = Altitude of satellite* (GDR-F) – *Altimeter range* (MLE4, GDR-F) – *Ionospheric correction* (Dual-frequency, filtered, GDR-F) – *Dry tropospheric correction* (GDR-F field "model_dry_tropo_cor_zero_altitude") – *Wet tropospheric correction* (radiometer, GDR-F) – *Sea state bias correction* (MLE4 1Hz, GDR-F) – *Solid earth tide height* (GDR-F) – *Geocentric ocean tide* (FES2014b, GDR-F) – *Geocentric pole tide height* (GDR-F) – - *Dynamic atmospheric correction* (GDR-F) – *mean sea surface* height (CNES_CLS15, GDR-F) (Eq.3)**

### 3.2 External data

External data used as a reference in the altimetry algorithm analysis consist in tide gauge sea level observations from different networks, covering Jason-2 and Jason-3 periods.

The tide gauge data sources are:

- Mediterranean Sea: CMEMS (Europe), DATASHOM (France), MAREOGRAFICO (Rete Mareografica Nazionale from Italy);
- North East Atlantic: BODC, DATASHOM, UHSLC;
- Australia: UHSLC, BOM (BATHY CNES project database).

Several selection criteria are used (all of them must apply):

- Time period: data available from 2013 to 2019.
- General location: tide gauge station < 50 km from a Jason track.
- Coastal location: tide gauge station should not be located too deep inside estuaries and bays (to account for coastal conditions, not estuarial).
- Data rate: hourly sea level data is required for this study.

- Data quality: tide gauge stations with too many gaps in the time series are removed

In the North East Atlantic, 13 stations meet all the selection criteria. They are 12 and 8 in the Mediterranean Sea and in the Eastern Australia region, respectively (see Figure 2).

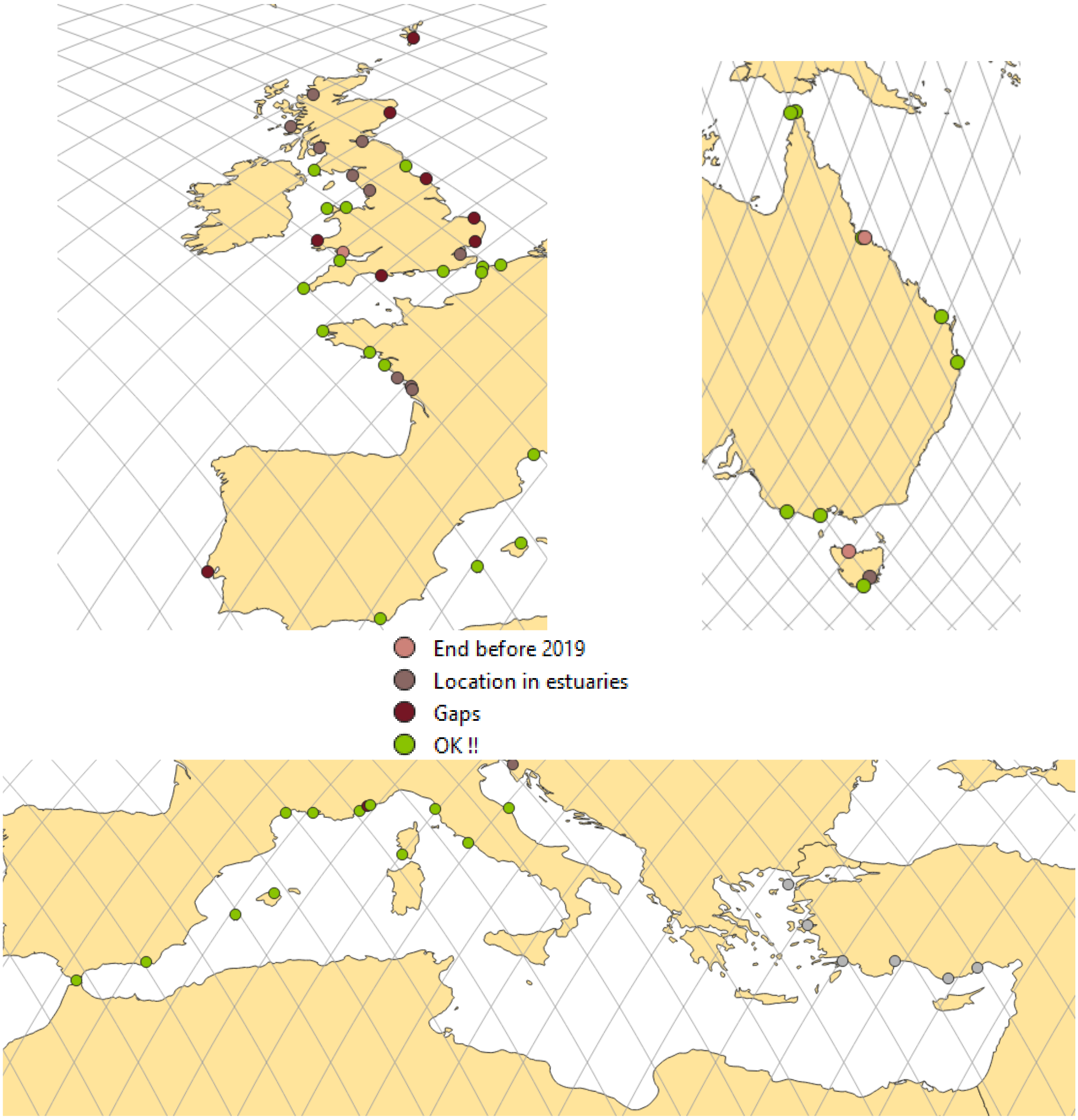


**Figure 2:** Jason tracks (black lines) and tide gauge stations (circles) in the North East Atlantic (top left), Eastern Australia (top right) and Mediterranean Sea (bottom. For each of them, the tide gauge data used in this Round Robin exercise are indicated in green.

## 4. Type of diagnostics

The inter-comparison diagnostics can be classified according to three complementary objectives.

**Inter-comparison between the different algorithms for each SLA component**

Objective: for each algorithm, measure the internal consistency compared to the reference solution and its relative performance in terms of SLA data availability and SLA variance reduction.
Types: Histograms, mean, standard deviation (STD), % of data available.
Geographical domains:
Global, North East Atlantic, Eastern Australia and Mediterranean Sea.

**External data comparison using in-situ measurements:**

Objective: use independent tide gauge data to assess the impact of each algorithm on the SLA calculation accuracy.
Types: Statistics (correlation, STD, Root Mean Square of the Difference or RMSD), SLA data availability at local scale.
Geographical domains: North East Atlantic, Eastern Australia and Mediterranean Sea.

**Inter-comparison between 2 altimetry missions:**

Objective: for each algorithm, when possible, measure the consistency of all the results between different altimetry missions.
Types: All the diagnostics listed above done for both Jason-2 and Jason-3 (with some exceptions when an algorithm is not available for one mission, see section 3).
Geographical domains: global coastal zone, North East Atlantic, Eastern Australia and Mediterranean Sea.

There are then different types of diagnostics that are based on the same input data, derived from the altimetry measurements or from tide gauge data listed in Section 3:

- Along-track sea level components: values of the altimetric corrections (used in the SLA calculation), the mean sea surface or the altimetric range along the ground track of the satellite at 20 Hz.
- Along-track SLA: SLA along the ground track of the satellite at 20 Hz and for valid measurements.
- Tide gauge: tide gauge sea level data from different network in the North East Atlantic, Eastern Australia and Mediterranean Sea, and selected according the criteria listed in section 3.2.

In order to obtain precise temporal (and then statistical) analyses, all the along-track sea level components and along-track SLA are binned along the theoretical ground track of the satellite at 20Hz: in this way, the sampling of the theoretical ground track is the same for each cycle of the Jason missions.

## 5. Description of Diagnostics

Here we describe the inter-comparison diagnostics of this Round Robin exercise, all available in a dedicated area (see section 6). It will allow each user of this study to understand the role and objective of each diagnosis, and therefore to bring their own expertise to choose the best algorithms for their coastal application.

**General approach:**
The study has been organised by SLA terms. For each one of them, the different algorithms are first inter-compared in terms of data availability (spatial pattern of the data availability, data availability as a function of distance to the coast) and general statistics (mean, standard deviation, histograms of values). In a second time, the impact of the different algorithms tested for this component on the SLA calculation is analysed. Therefore, only term (algorithm) of the SLA definition (Eq 1) changes at a time. All the other SLA components are those of the reference algorithms (Eq 2). The inter-comparison between the different algorithms is then redone in terms of data availability and general statistics, but also in terms of comparison to the tide gauge measurements in the three regions (statistics and local altimetry data availability to analyse the corresponding statistics).

**Editing applied:**

- For each SLA component: no editing, all values used.
- On SLA: values outside the window [-3m ; 3m] flagged everywhere except in the Mediterranean sea where the window [-1m ; 1m] is applied.

**Selection of altimetry data for the tide gauge comparison:**

Selection is based solely on the distance between observations. For each tide gauge station, the nearest altimetry track is selected. The SLA altimetry data along this track that are used in the comparison must be located at a distance to the coast less than 20 km and at a distance to the tide gauge station less than 40 km.

**Diagnostics for each SLA component (at global scale and for the three regions):**

- Spatial analysis: Map of the number of data available on the 111 cycles analysed for the algorithm and altimetry mission considered
- Spatial analysis Map of the difference in the number of data available between 2 algorithms, on the 111 cycles analysed for the altimetry mission considered.
- Spatial analysis: Map of the standard deviation of values on the 111 cycles analysed for the algorithm and altimetry mission considered.
- Spatial analysis: Map of the difference in standard deviation of values between 2 algorithms, on the 111 cycles analysed for the altimetry mission considered.
- Spatial analysis: Map of the temporal average of values on the 111 cycles analysed for the algorithm and altimetry mission considered.
- Spatial analysis: Map of the difference in the temporal average of values between 2 algorithms, on the 111 cycles analysed for the altimetry mission considered.
- General analysis: Histogram of value for the algorithm and altimetry mission considered
- General analysis: Histogram of the standard deviation of values for the algorithm and altimetry mission considered
- Along-track analysis: number of data available as a function of distance to the coast on the 111 cycles analysed for the algorithm and altimetry mission considered (+ zoom on the [0-20 km] coastal band).

- Along-track analysis: standard deviation of values as a function of distance to the coast on the 111 cycles analysed for the algorithm and altimetry mission considered (+ zoom on the [0-20 km] coastal band).

**Diagnostics for each SLA solution (at both global and for the three regions):**

- Spatial analysis: Map of the difference in the number of SLA data available between 2 algorithms, on the 111 cycles analysed for the altimetry mission considered.
- Spatial analysis: Map of the difference in standard deviation of SLA values between 2 algorithms, on the 111 cycles analysed for the altimetry mission considered
- Spatial analysis: Map of the difference in the temporal average of SLA values between 2 algorithms, on the 111 cycles analysed for the altimetry mission considered.
- Along-track analysis: number of SLA data available as a function of distance to the coast on the 111 cycles analysed for the algorithm and altimetry mission considered (+ zoom on the [0-20 km] coastal band).
- Along-track analysis: standard deviation of SLA values as a function of distance to the coast on the 111 cycles analysed for the algorithm and altimetry mission considered (+ zoom on the [0-20 km] coastal band).
- Along-track analysis: temporal mean of SLA values as a function of distance to the coast on the 111 cycles analysed for the algorithm and altimetry mission considered (+ zoom on the [0-20 km] coastal band).

**Diagnostics for each SLA solution and for each tide gauge station (for the three regions only):**

- Spatial analysis: Map of the correlation values between SLA tide gauge and SLA altimetry data in the vicinity of the tide gauge for the algorithm and altimetry mission considered.
- Spatial analysis: Map of the RMSD values between SLA tide gauge and SLA altimetry data in the vicinity of the tide gauge for the algorithm and altimetry mission considered.
- Spatial analysis: Map of the RMS values of SLA altimetry data in the vicinity of the tide gauge for the algorithm and altimetry mission considered.
- Spatial analysis: Map of the % of SLA altimetry values (over 111 cycles) in the vicinity of the tide gauge for the algorithm and altimetry mission considered.
- Along-track analysis: % of SLA altimetry data available as a function of distance to the coast on the 111 cycles analysed for the algorithm and altimetry mission considered.
- Along-track analysis: STD of SLA altimetry values as a function of distance to the coast on the 111 cycles analysed for the algorithm and altimetry mission considered.
- Along-track analysis: correlation values between altimetry and tide gauge SLA as a function of distance to the coast on the 111 cycles analysed for the algorithm and altimetry mission considered.
- General statistics: Taylor diagrams
- Mean statistics in terms of valid altimetry SLA data, correlation, STD and RMSD in the selected coastal area.
- Local analysis: SLA Time series of the most correlated SLA altimetry point and of the tide gauge station.
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## 6. Organisation of the diagnostics:

We have evaluated 21 algorithms at global scale and for the three regions for both Jason-2 and Jason-3 missions (when possible). Finally, the total number of inter-comparison diagnostics reach several hundred. They are all available by following the links provided in Table 2.

All the diagnostics linked to the evaluation of the same SLA component are classified per altimetry mission: they are grouped in a report. An evaluation report has been made for the global coastal zone and for each of the three regions. Table 2 describes the organisation for each evaluation report and provides the ftp access links.

There is an additional report concerning the evaluation of a more complete set of tidal models than the one considered in Table 1:
https://www.aviso.altimetry.fr/fileadmin/documents/data/products/alticap/REPORTS/TIDE/Tide_allsolutions.pdf

| Components used in the calculation of altimetric SLA Altimetry mission | | Zone | | | |
|---|---|---|---|---|---|
| | | Global | North East Atlantic | Mediterranean Sea | eastern Australia |
| Altimeter Range | Jason-2 | Please refer to the list of reports: https://www.aviso.altimetry.fr/en/data/products/sea-surface-height-products/global/altimetry-innovative-coastal-approach-product-alticap/roundrobin-reports.html | | | |
| | Jason-3 | | | | |
| Ionospheric correction | Jason-2 | | | | |
| | Jason-3 | | | | |
| Wet tropo correction | Jason-2 | | | | |
| | Jason-3 | | | | |
| Ocean tide correction | Jason-2 | | | | |
| | Jason-3 | | | | |
| Sea State Bias (SSB) correction | Jason-3 | | | | |
| Mean Sea Surface Height (MSSH) | Jason-2 | | | | |
| | Jason-3 | | | | |

**Table 2 :** Organisation of the evaluation reports and access links.

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