COPAS WP2.10 - Final Report

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COPAS Statement of Work, 4600002662 WP#2_10 Sentinel-3_SeaStateBiasSea_State_Bias

COPAS Technical Proposal, CLS-ENV-PC-21-0397

COPAS Managerial Proposal, CLS-ENV-PC-21-0397

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1 COPAS WP2.10 final report

1.1 Document scope

This is the final report of the Work Package WP2.10 for the EUMETSAT COPAS Service Contract (contract number COPAS_4600002662). The work package tackles the issue of the sea surface height (SSH) inconsistencies between Sentinel-3 SAR and PLRM linked to the directionality of the wind [Raynal et al. 2019; Nencioli et al. 2023] as task #1 and the one linked to the state of the waves as task #2.

1.2 Context

EUMETSAT has defined the evolutions roadmap to improve the Sentinel-3 marine altimetry data quality in the global ocean and has identified specific scientific studies to be performed in support to the operational implementation of the identified roadmap's evolutions.

This work-package WP2.10 has been initiated as response to the recommendation expressed by the altimetry user community at the 8th S3VT meeting during the wrap-up altimetry session [EUMETSAT, 2023]:

> "*REC: Further investigate and correct geographical Sea Surface Height inconsistencies between PLRM and SAR due to directional wind and waves*"

The recommendation was foreseen to be implemented by evolving the sea state bias (SSB) model in SAR mode for correcting both the residual sea state and wind directional dependencies currently observed between SAR and PLRM sea surface heights (SSH). The choice was to tackle this issue in two steps to form an updated SAR SSB correction. The first step aims to compute a complementary SAR SSB correction term (called hereafter Delta SSB) that will focus on the Sentinel-3 SSH inconsistencies between SAR and PLRM data due to the directional effect related to wind. The second step will consist in recomputing the standard 2D SSB correction driven by the sea-state conditions to be homogeneous with the next marine baseline collection (i.e. BC006) in terms of processing setups. The upcoming SAR SSB will thus be defined as the sum of these two components.

If successful, the outcome of this work-package is expected to be implemented, as part of the marine baseline collection BC006, in the SRAL Level-2 Processor deployed in the EUMETSAT Sentinel-3 Ground Segment Payload Data Processing (PDP).

Following this design setup, the WP consists of two tasks, one mandatory and one optional:

- Task 1: SAR mode Delta SSB in Ku Band (mandatory)
- Task 2: SAR mode 2D SSB in Ku Band (optional)

The first task was considered mandatory and started at the KO meeting, whereas the second task was considered optional since it has a dependency with a critical input not available at the KO meeting date. The activation of the optional task by EUMETSAT was decided at the end of 2024.

1.3 Accomplished tasks

Task 1 of WP2.10 was completed by CLS in 2024. The initial activities concerned first the selection of two data periods, one for performing the calibration of the empirical models and the other for their validation and performance assessments. The different worries raised at the kick-off meeting concerned the impact of El Nino events on the directional effect analyzed in the present study but also the consistency between S3A and S3B data.

The comparisons made from different 2-year periods indicated that there are no significant changes in the observed geographical patterns due to wind direction between periods with occurrences of El Nino events or not. Therefore, homogeneous benefits can be expected of the application of the Delta SSB term for all the S3A time series. Another found result is that there are no significant differences between S3A and S3B data concerning the directional effect. Therefore, it was confirmed that S3B data can be used for validation/performance purposes. Data from S3A cycles 59 to 86 corresponding to a 2-year period covering mid-2020 to mid-2022 will be used for the model calibration while data from S3B cycles 40 to 53 (i.e. 1-year period from mid-2020 to mid-2021) will be used for the validation and performance evaluations. This choice of a minimum 2-year period for the calibration is related to the fact that the signal to model is small only up to 1-2 cm in absolute value and having more data than 1 year helps to beat down more the measurement noise. Longer time periods are always an asset for such empirical development to limit the inter-annual variations in wind and wave conditions while 1-year periods allow only to consider the seasonal variations.

Another preliminary data assessment showed similar geographical patterns from (range+2D SSB) differences between ascending and descending tracks than from solely the range differences as reported by Raynal et al. [2019] then by Nencioli et al. [2023]. This result is important since it means that the modeling strategy defined for correcting the directional effect will not need to be modified if the 2D SSB versions are updated afterwards. Only the model parameters will need to be adapted for homogeneity.

Finally, the last part of these initial activities concerned the determination of the most appropriate regression variable to use in the Delta SSB modeling. It was found that it is the projection of the wind vector on the satellite track (noted in the study w_proj_at) that displayed similar geographic distribution with the patterns reported. Note that EUMETSAT imposed the constraint to use only information coming from the ECMWF model that is already available in the EUMETSAT marine L2 products. Therefore, the w_proj_at variables are derived from the ECMWF wind vector. Since information about the satellite flying direction with respect to the north is also needed, CLS built two LUTs (one for the ascending passes and the other for the descending passes) that provide the satellite azimuth angle as a function of latitude. If w_proj_at is the main driver to describe the wind directional effect, it has also been shown that the altimeter-derived significant wave height (SWH) needs also to be considered to more completely describe such geophysical behavior. After discussion with EUMETSAT, it was decided to use SAR SWH for this modeling.

The second phase of the task was dedicated to the development of the Delta SSB model in the form of a two-dimensional LUT based on (ECMWF w_proj_at, SAR SWH). CLS used the Feng et al [2010]'s approach (i.e. a spline-based non-parametric estimation) to derive the 2D LUT. Furthermore, a sensitivity analysis was performed to assess the dependency of the LUT on different combinations of shifts in the input distributions. Finally, a validation and performance assessment has been performed from S3B data to quantify the improvement brought by this Delta SSB term in enhancing the S3 SAR SSH precision. Results are reported in the associated document (CLS-ENV-RP-24-0683) delivered also to EUMETSAT.

Task 2 of WP2.10 was completed by CLS in 2025. The activities carried out focused on updating both the standard Ku-band SAR 2D SSB correction, based on sea state conditions, and the ΔSSB term developed in Task 1 to ensure consistency with the new 2D SSB solution. The resulting total SAR SSB correction, obtained by summing these two components, is detailed in the Task 2 report (CLS-ENV-RP-25-0199).

The Sentinel-3 data used in this study come from Baseline Collection 006 (specifically BC006.2) TDS, delivered by EUMETSAT to CLS in May 2025. These data originate from the Sentinel-3A mission and cover cycles 59 to 86, spanning a two-year period from mid-2020 to mid-2022.

The key innovation in Task 2, compared to Task 1, lies in the computation of the SAR 2D SSB correction using data from this TDS. This component represents an updated version of the standard empirical 2D SSB model, developed as a function of both significant wave height (SWH) and wind speed (WS). It was constructed using a non-parametric estimation technique based on kernel smoothing [Gaspar et al., 2002], applied to crossover SSH differences. Like all models developed since 2018, this version integrates the latest advancements in SSB modeling aimed at minimizing centimeter-level discrepancies between correction models, whether within the same altimetric mission or across different Ku-band missions [Tran et al., 2018; Tran et al., 2021].

In this study, SWH refers to the corrected SAR version with the NOAA LUT applied. Wind speed is derived using Abdalla's algorithm [Abdalla, 2007; Abdalla, 2012], based solely on SAR sigma0, as agreed during the Task 2 kick-off meeting.

Finally, a validation and performance assessment was conducted using S3A BC006.2 TDS data to quantify the improvements brought by the new total SSB correction in enhancing S3 SAR SSH precision. These results support the use of the new total SSB LUTs in the next marine baseline collection within the EUMETSAT Sentinel-3 Ground Segment Payload Data Processing (PDP) system. Full details are provided in the associated report (CLS-ENV-RP-25-0199), also delivered to EUMETSAT.

1.4 Conclusions and way forward

The analysis performed in Tasks 1 and 2 evidenced that:

- The new 2D SSB is similar to the 2020 version used in the BC005 processing chain, with differences mostly ranging between –0.9 cm and +0.3 cm. It provides a slight improvement in S3A SSH precision compared to the reference solution.
- The application of the new ΔSSB significantly reduces the wind directional effect on SAR BC006.2 data, as expected from Task 1 results, thereby improving the geographical consistency of SSH between SAR and PLRM data in the BC006.2 TDS.
- The new total SSB correction closely resembles the version used to generate the BC006.2 dataset due to the strategy adopted for determining the ΔSSB component. Specifically, the constraint to align SAR SSH values with PLRM SSH values introduces a form of interdependence between the 2D SSB and the associated ΔSSB values. The resulting pair forming the total SSB correction shows a slight improvement in S3A SSH precision, as indicated by performance diagnostics based on the crossover dataset.
- Based on these findings, CLS recommends implementing the new correction to benefit from the modest improvement in S3 SSH precision and to ensure consistency in the production of the next marine product baseline.
- The results also confirm the presence of another inconsistency between SAR and PLRM data, primarily observed in the southern high latitudes. Further investigation is recommended to understand this new feature and its underlying cause. A potential correlation with orbital height rate has been suggested in Task 1.
- The Task 1 developed approach effectively mitigates the wind directional effect on SAR SSH, enhancing consistency between SAR and PLRM data. Since this effect is also observed in Sentinel-6 SAR data, CLS recommends applying a similar correction to improve the Sentinel-6 dataset.

This study highlights the importance of evolving SSB corrections for delay/Doppler altimeters, moving beyond the standard 2D SSB to more complex models incorporating at least three parameters. In the present case, the three-dimensional version is based on (S3 SWH, S3 WS, ECMWF W_PROJ_AT), while another version reported in Tran [2021] uses the triplet (S3 SWH, S3 WS, ERA-5 mean wave period). These findings identify two additional metocean variables from models, W_PROJ_AT and mean wave period, as beneficial for improving the representation of SSB behavior. Amarouche et al. [2023] also identified along-track Stokes drift velocity as a significant SAR SSB descriptor. More recently, a proposal was made to replace mean wave period with vertical velocity, although no results have been reported yet. In total, at least a set of five promising descriptors of SAR SSB have been identified, which could be used to develop a more comprehensive correction.

Another recommended direction is to develop the SAR SSB model independently from PLRM/LRM data (i.e., range and SSB), to avoid propagating inconsistencies that may arise from imperfections in either dataset.

1.5 Deliverables

In addition to the present COPAS WP2.10 final report, two complementary documents, CLS-ENV-RP-24-0683 and CLS-ENV-RP-25-0199, have also been delivered to EUMETSAT. These reports contain the full validation and performance assessment results for Tasks 1 and 2, respectively. The first report also includes a section detailing the operational implementation of the Delta SSB correction, as well as a section addressing Task 1 requirements through the completion of the compliance matrix.

By the end of 2024, three datasets were delivered to EUMETSAT for Task 1, all in ASCII format. EUMETSAT agreed to handle the conversion to NetCDF format on their side:

- Two separate 1-dimensional LUTs for computing the satellite azimuth angle as a function of latitude, one for ascending passes and one for descending passes (LUT_sat_direction_s3a_asc.txt and LUT_sat_direction_s3a_dsc.txt).
- A single 2-dimensional LUT for computing the SAR Delta SSB term as a function of both the projection of the ECMWF wind vector onto the satellite track and SAR SWH (LUT_SAR_delta_ssb_ecmwfws_sarswh_final2024.dat).

In 2025, two additional datasets were delivered to EUMETSAT for Task 2, also in ASCII format, with EUMETSAT again responsible for the NetCDF conversion:

- A 2-dimensional LUT for computing the SAR 2D SSB term as a function of SAR SWH and wind speed derived from Abdalla's algorithm (ssb2d_Ku_SAR_s3a_2025.dat).
- A 2-dimensional LUT for computing the SAR Delta SSB term as a function of the projection of the ECMWF wind vector onto the satellite track and SAR SWH (LUT_SAR_delta_ssb_ecmwfws_sarswh_final2025.dat).