



COPAS WP2.10 - Validation and performance report of task 2

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APPLICABLE DOCUMENTS

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1 Introduction

1.1 Document scope

This report addresses Task 2 of Work Package WP2.10 under the EUMETSAT COPAS Service Contract (Contract No. COPAS_4600002662). Its objective is to provide an assessment of the updated total SSB correction developed for SAR mode, aimed at resolving sea surface height (SSH) inconsistencies between Sentinel-3 SAR and PLRM data. These discrepancies are linked to differential effects caused by wave conditions and wind directionality [Raynal et al., 2019; Nencioli et al., 2023]. The computed models and performance assessment results are summarized in this document.

1.2 Background

EUMETSAT has defined a roadmap for improving the quality of Sentinel-3 marine altimetry data over the global ocean and has identified specific scientific studies to support the operational implementation of these planned evolutions.

Work Package WP2.10 was initiated in response to a recommendation made by the altimetry user community during the wrap-up altimetry session at the 8th S3VT meeting [EUMETSAT, 2023]:

“REC: Further investigate and correct geographical Sea Surface Height inconsistencies between PLRM and SAR due to directional wind and waves.”

To address this recommendation, the evolution of the Sea State Bias (SSB) model in SAR mode was proposed, aiming to correct both residual sea state and wind directional dependencies currently observed between SAR and PLRM Sea Surface Height (SSH) measurements. The approach was structured in two steps to produce an updated total SAR SSB correction.

- **Step 1** focused on developing a complementary SAR SSB correction term (hereafter referred to as Δ SSB), targeting SSH inconsistencies between SAR and PLRM data in Ku-band due to wind directionality. This work corresponds to Task 1 and was documented in Tran et al. [2024].
- **Step 2** involved computing the standard Ku-band SAR 2D SSB correction based on sea state conditions, ensuring consistency with the upcoming marine baseline collection (BC006) in terms of processing setup. Additionally, the Δ SSB term from Task 1 was updated to maintain homogeneity with this new 2D SSB solution. This work corresponds to Task 2 and the resulting total SAR SSB correction is defined as the sum of these two components which are presented in this report.

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

1.3 Dataset used

The Sentinel-3 products used in this study correspond to Level 2 Marine products from Baseline Collection 006 (specifically BC006.2), delivered by EUMETSAT to CLS in May 2025. The data are from the Sentinel-3A mission, covering cycles 59 to 86, which span a two-year period from mid-2020 to mid-2022.

This two-year period was selected during Task 1 due to its high stability and low variability, as no El Niño events were observed. It is worth noting that comparisons across different two-year periods showed no

significant changes in the geographical patterns related to wind direction, regardless of the presence or absence of El Niño events. Therefore, the application of the Δ SSB term is expected to provide consistent benefits across the entire S3A time series. Additionally, this correction was found to improve SAR data from Sentinel-3B as well.

The choice of a minimum two-year period for calibration is based on the relatively small magnitude of the signal to be modeled, typically only 1–2 cm in absolute value. Using more than one year of data helps reduce measurement noise. Longer time periods are particularly valuable for empirical model development, as they help mitigate interannual variations in wind and wave conditions, whereas one-year periods only capture seasonal variability.

A preliminary data assessment conducted during Task 1 revealed that the geographical patterns of (range + 2D SSB) differences between ascending and descending tracks were like those observed using range-only differences, as previously reported by Raynal et al. [2019] and Nencioli et al. [2023]. This finding is important because it confirms that the modeling strategy for correcting directional effects does not need to be revised if the 2D SSB versions are updated in the future, only the model parameters will need to be adjusted to maintain consistency.

Based on the results of Task 1, the work carried out in Task 2 focused on updating both the Ku-band SAR standard 2D SSB solution and the Δ SSB term, using data from the BC006.2 TDS provided by EUMETSAT.

2 SSB terms computation

The total SAR SSB correction in Ku-band consists of two components: the standard 2D SSB value and a small additional term, Δ SSB. Fine-tuned versions of both components have been computed and validated in this study for the Sentinel-3 missions, with the aim of accurately adjusting SAR-derived Sea Surface Height (SSH) estimates. Each component is presented in the following sections.

2.1 2D SSB model

The first component is an updated version of the standard 2D SSB model, developed as a function of both significant wave height (SWH) and wind speed (WS), using a non-parametric estimation technique based on kernel smoothing [Gaspar et al., 2002] applied to crossover SSH differences. This new version, like all models developed since 2018, incorporates the latest improvements in SSB modeling aimed at reducing centimeter-level offsets between different correction models, whether for the same altimetric mission or across different Ku-band missions [Tran et al., 2018; Tran et al., 2021].

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

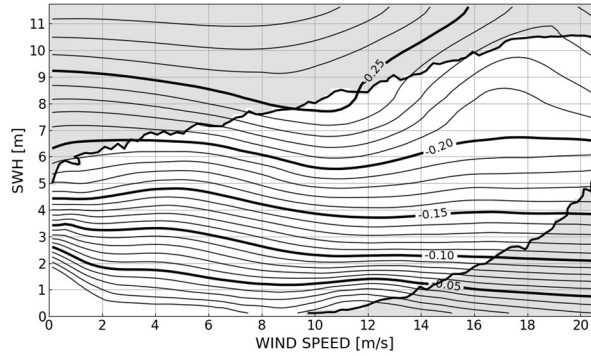


Figure 1: 2025 SAR 2D SSB model estimates (in meters), based on BC006.2 TDS data and computed using the modified non-parametric approach described in Tran et al. [2021].

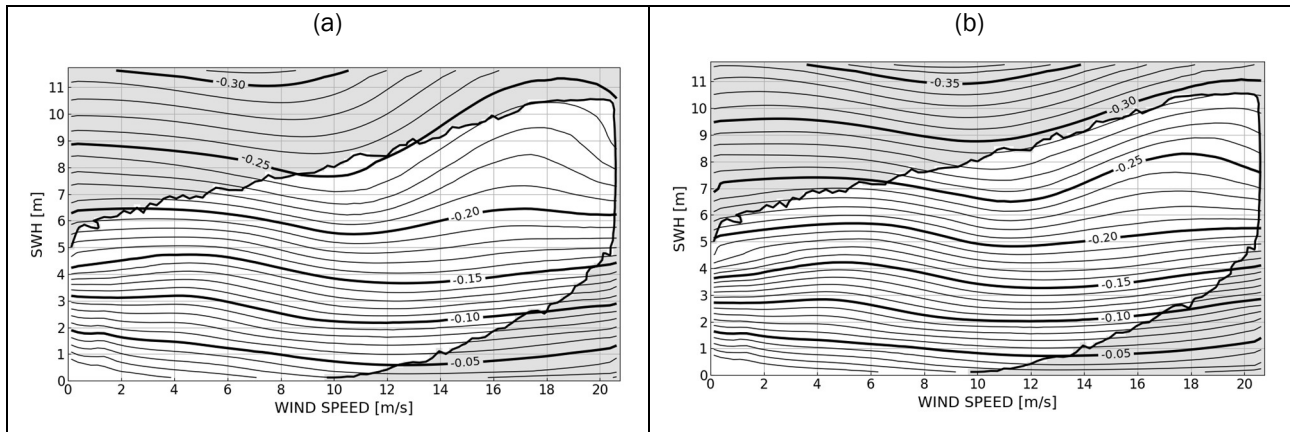


Figure 2: 2020 2D SSB model estimates (in meters), computed using the same approach as the new SAR model shown in Figure 1, for (a) S3A SAR and (b) PLRM data, respectively. The computation was carried out within the ESA S3 MPC project framework, using data from reprocessing version 004 (baseline 2.61, IPF 6.18).

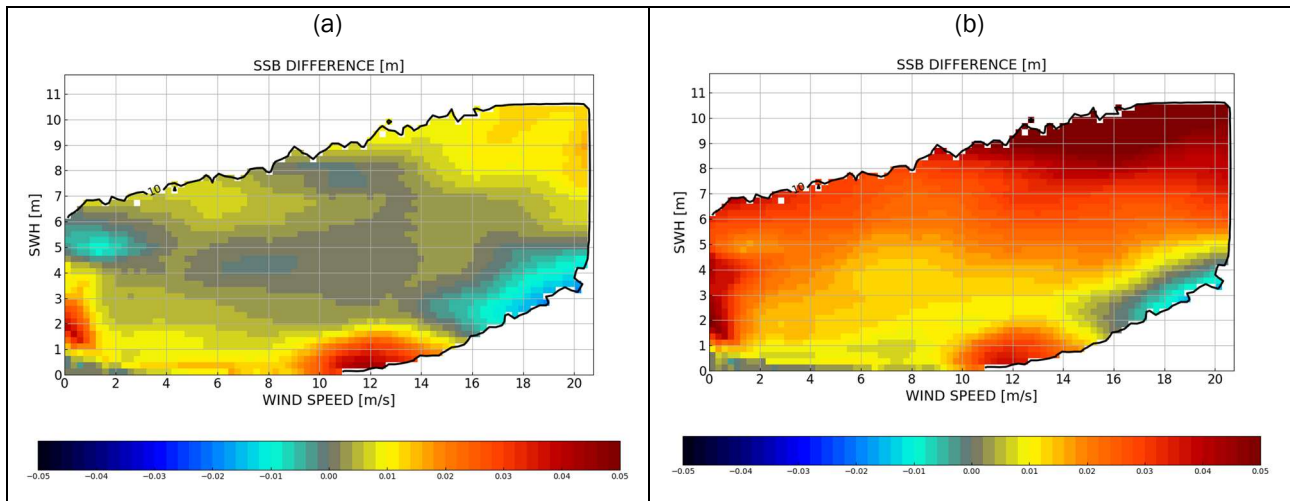


Figure 3: SSB differences (in meters) between the 2025 SAR model (Figure 1) and the 2020 models: (a) SAR (Figure 2a), and (b) PLRM (Figure 2b).

The new model is shown in **Figure 1**. As illustrated, within the populated data zone (highlighted with a white background), its behavior closely resembles that of the 2020 SAR model currently used to generate Marine Level-2 products in Baseline Collection 005 (BC005), shown in **Figure 2(a)**. Differences between the two models are generally within 1 cm across most of the 2D domain, as shown in **Figure 3(a)**. However, larger differences are observed when compared to PLRM SSB estimates, as shown in **Figure 3(b)**, reaching up to ~5 cm, with PLRM values typically higher than SAR values. The main

source of discrepancy between SAR and PLRM SSB values is a gradient that depends on SWH, while differences related to WS are of secondary importance.

2.2 Delta SSB model

In Task 1 [Tran, 2024], the SAR Δ SSB term was developed as an additional correction defined by:

$$\Delta\text{SSB} = \text{SAR}_{(\text{range} + 2\text{D SSB})} - \text{PLRM}_{(\text{range} + 2\text{D SSB})},$$

and depends on two variables: the projection of the wind vector onto the satellite track (referred to in the study as WS_PROJ_AT) and the SAR SWH.

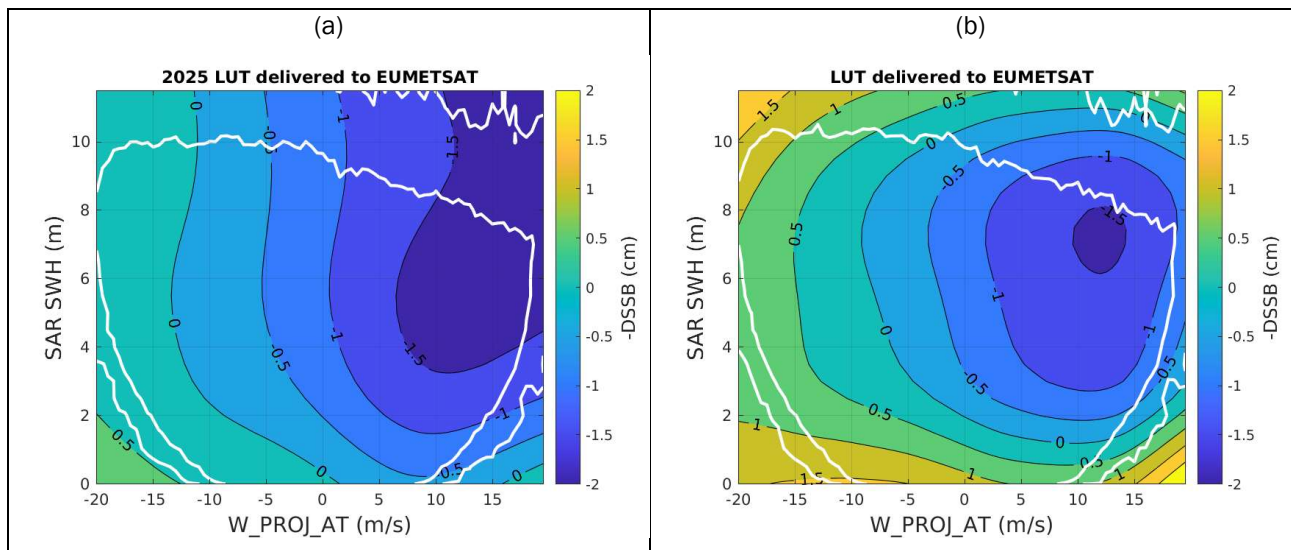


Figure 4: Two-dimensional plots of the LUTs delivered to EUMETSAT, showing $(-\Delta\text{SSB})$ values as a function of ECMWF wind projection along Sentinel-3A tracks and SAR significant wave height. The values are derived from spline-based models computed using the BC006.2 and BC005 datasets, respectively in panels (a) and (b).

EUMETSAT imposed the constraint to use only information derived from ECMWF model outputs, which are already available in the EUMETSAT Marine Level 2 products. Consequently, WS_PROJ_AT values are computed from the ECMWF wind vector using the mathematical definition provided in Section 2.2.4 of Tran [2024].

To comply with the convention adopted for SAR total SSB computation:

$$\text{SAR total SSB} = \text{standard SSB} + \Delta\text{SSB},$$

the 2D LUT delivered to EUMETSAT was generated to contain values of $-\Delta\text{SSB}$. Two versions of this LUT are shown in **Figure 4**. Panel (a) presents the updated version based on the BC006.2 TDS while panel (b) reproduces Figure 4 from Tran [2024], where the LUT was computed using the BC005 dataset. By construction, **Figure 4** exhibits behavior opposite to that shown in **Figure 5**, which illustrates the ΔSSB behavior derived from a bin-averaging approach in panels (a) and (c) while panels (c) and (c) display the corresponding spline-based models. The differences between the 2025 and 2024 versions are light, typically at the millimeter scale.

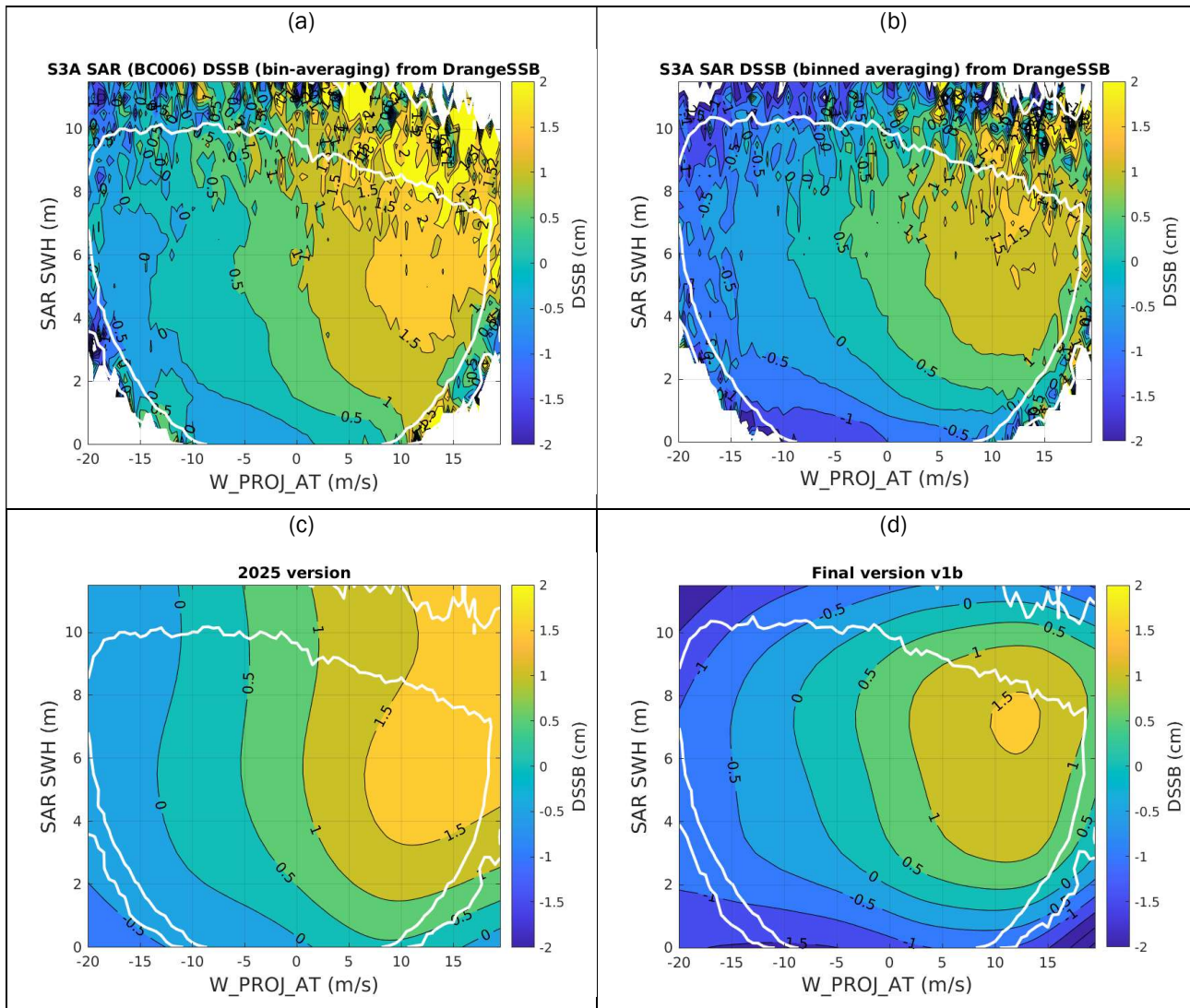


Figure 5: Two-dimensional plots showing the behavior of Δ SSB values as a function of ECMWF wind projection along Sentinel-3A tracks and SAR significant wave height, derived from a bin-averaging approach and computed using the BC006.2 and BC005 datasets, respectively in panels (a) and (b). Panels (c) and (d) display the corresponding spline-based models.

3 Algorithm validation

Various diagnostics were performed to quantify the differences between the new estimates of the 2D SSB, Δ SSB, and total SSB corrections, and those provided in the BC006.2 TDS. These results are grouped in this section dedicated to validation assessment.

Figure 6 presents three scatter plots, each comparing one of these correction components. The x-axis represents the TDS values, while the y-axis shows the corresponding new estimates. The color of each scatter point reflects data density, ranging from sparse (dark blue) to dense (dark red) regions. A diagonal reference line is also included to indicate the ideal case where the new and TDS values are in perfect agreement.

Based on the two-year dataset, the differences in 2D SSB values are confirmed to be small, ranging from -3 cm to +1 cm, with most values falling between -0.9 cm and +0.3 cm. The linear fit is close to the reference line, with a slope of 1.04.

For the Δ SSB component, differences can reach -3 cm, but the most populated interval lies between -1.1 cm and -0.1 cm. The linear fit has a slope of 0.75, indicating relatively large differences between the LUTs developed in Tasks 1 and 2.

Total SSB values are primarily driven by the 2D SSB estimates. Differences between the new and TDS values range from -4 cm to $+3$ cm, with most data between -0.4 cm and $+0.3$ cm. The linear fit is nearly perfect, with a slope of 1.01. This is expected, as the Δ SSB term was specifically developed to align SAR SSH data with PLRM SSH data, while the SAR 2D SSB model is computed independently of PLRM one. As a result, if SAR 2D SSB estimates diverge from PLRM values, the Δ SSB term compensates to reduce these discrepancies to a certain extent.

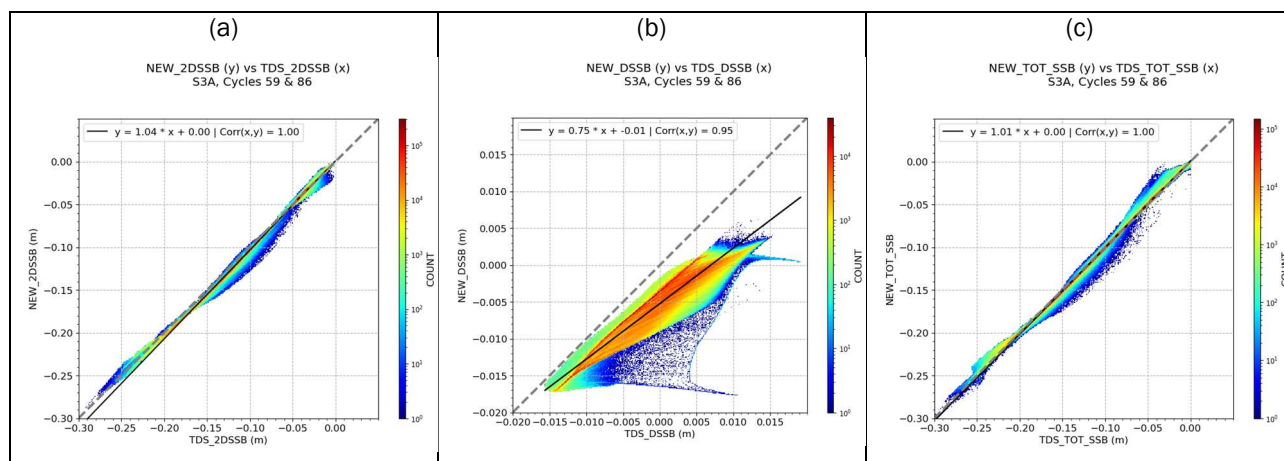


Figure 6: Scatter plots comparing updated SSB values with reference values from the BC006.2 TDS, for: (a) 2D SSB, (b) Δ SSB, and (c) total SSB correction.

Figure 7 presents histograms for the new SAR total SSB, the TDS total SSB, and the PLRM SSB. All three distributions are very similar, with only slight global biases observed between them:

- a bias of -0.05 cm between the new and TDS SAR total SSB versions,
- a bias of $+0.85$ cm between the new SAR total SSB and the PLRM SSB,
- and a bias of $+0.90$ cm between the TDS SAR total SSB and the PLRM SSB.

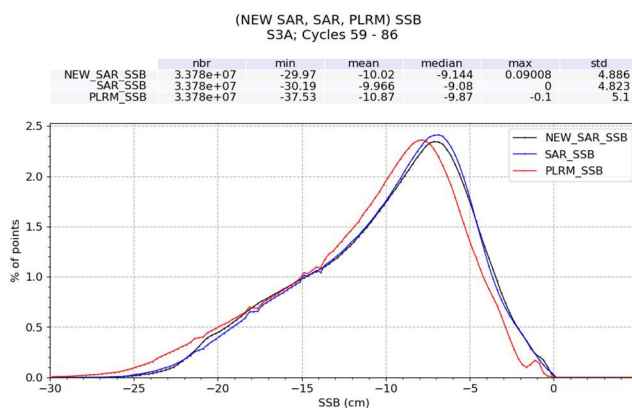


Figure 7: Histograms for the new SAR total SSB, the SAR total SSB and PLRM 2D SSB values. The two latter come from the BC006.2 TDS.

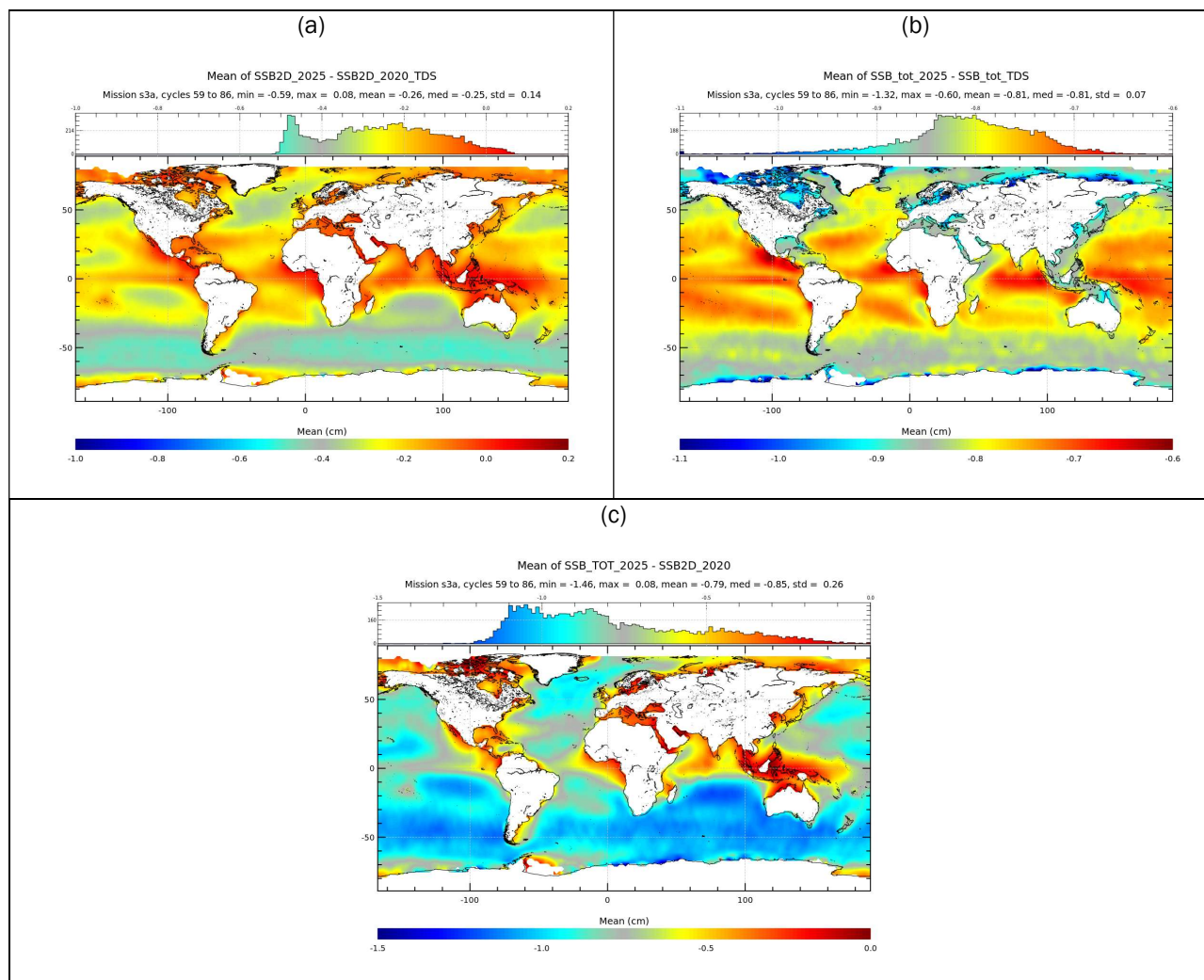


Figure 8: Mean SSB difference maps from the two-year TDS comparing (a) the 2025 and 2020 versions of the 2D SSB, (b) the 2025 and BC006.2 TDS versions of the total SSB corrections, and (c) the 2025 total SSB and the 2020 2D SSB corrections.

Global maps of mean SSB differences are shown in **Figure 8**. Panel (a) compares the 2025 and 2020 versions of the 2D SSB correction. Panel (b) compares the 2025 version of the total SSB correction with the one provided in the BC006.2 TDS. The geographical patterns in the two maps are not entirely similar, highlighting the significant impact of Δ SSB differences. This is expected, as the magnitude of the Δ SSB differences is comparable to that of the 2D SSB differences. Panel (c) compares the 2025 total SSB with the 2020 2D SSB used in BC005 products to correct SAR SSH.

The last results in this section focus on the impact of the Δ SSB correction on the BC005 and BC006.2 datasets, corresponding respectively to Tasks 1 and 2. The objective is to verify that the anomalous patterns associated with Δ SSB are similarly observed, and effectively reduced, in both studies. This is clearly evident when comparing the maps in **Figures 9 and 10**.

The geographical patterns in panels (a) and (b) of **Figure 9** are nearly identical, indicating that the change in the SAR pair (*range* + 2D SSB) versus the PLRM data does not significantly affect these maps. Applying the Δ SSB correction, tailored to each dataset, significantly and consistently reduces the wind directional effect on SAR data. As a result, the geographical SSH inconsistencies between SAR and PLRM data are mitigated in both datasets as shown in **Figure 10**.

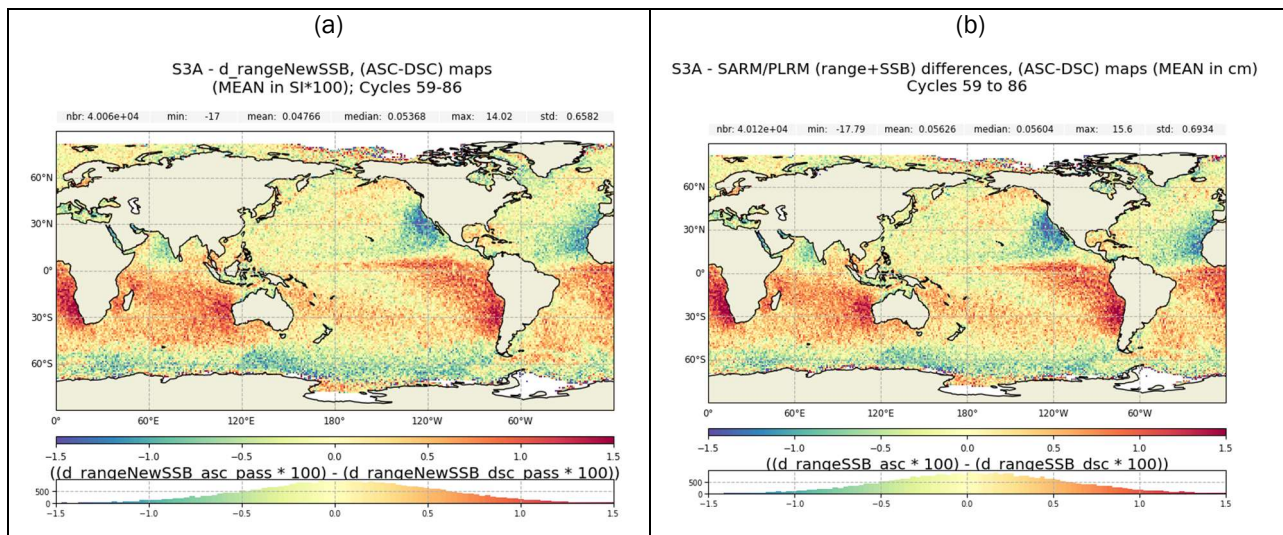


Figure 9: Differences of (ascending minus descending) binned maps of mean differences between SAR (range + 2D SSB) and PLRM (range + 2D SSB) values using data from: (a) the BC006.2 TDS with the 2025 version of the 2D SSB, and (b) the BC005 dataset with the 2020 version of the 2D SSB.

Note that after applying the Δ SSB correction, a residual inconsistency between SAR and PLRM data remains, primarily in the high southern latitudes. This feature was already highlighted in the results of Task 1. A more in-depth analysis is recommended to better understand this residual pattern and its root cause. A potential correlation with the orbital height rate was suggested during discussions between CLS and EUMETSAT at the time (see Figure 8 in Tran [2024]).

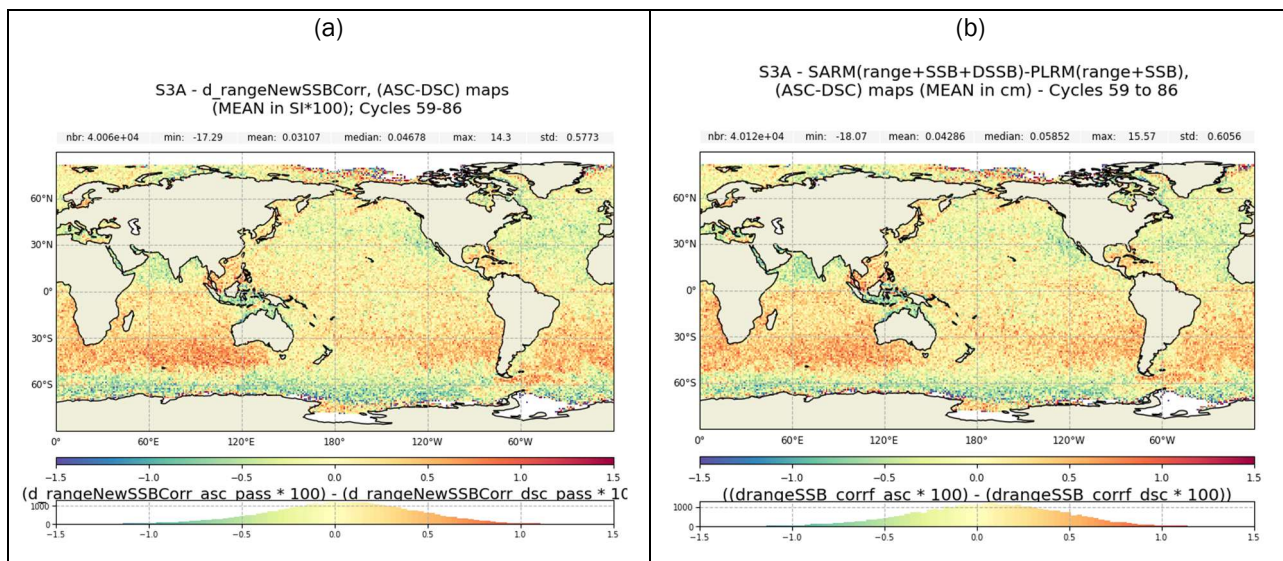


Figure 10: Same as Figure 9, except that total SSB corrections are applied to SAR data. Panel (a) corresponds to the combination of 2D SSB v2025 and Δ SSB v2025, while panel (b) uses 2D SSB v2020 and Δ SSB v2024.

4 Performance assessment

Diagnostics related to the performance assessment of the new SSB versions are grouped in this section. The standard approach in altimetry for evaluating new models against reference benchmarks was applied, using the recognized metric for SSB model comparison: the calculation of total variance

reduction in the derived Sea Surface Height (SSH) after applying the respective SSB corrections. The results are summarized below.

This variance reduction metric was evaluated over two distinct datasets built from the BC006.2 TDS: the SSH crossover dataset, and the Sea Level Anomaly (SLA) dataset, which represents the time-variable component of SSH and is defined relative to a gridded Mean Sea Surface (MSS) model that includes both geoid and mean ocean circulation.

Depending on the focus of the diagnostic, the reference models used are either: the 2020 SAR 2D SSB version, or the SAR total SSB version used in the generation of the TDS, which combines the 2020 2D SSB with the 2024 Δ SSB correction.

4.1 Crossovers dataset

SSH crossover differences refer to the discrepancies in SSH measurements between ascending and descending satellite passes at their intersection points. These differences are systematically analyzed to assess data quality and, consequently, SSH precision. To minimize the influence of ocean variability at each crossover location, only crossover points with time lags shorter than 10 days within a single cycle are selected. A reduction in this diagnostic indicates improved internal consistency of sea level measurements between ascending and descending passes within the 10-day window and thus reflects a more accurate SSH estimate.

The SSH variance reduction diagnostics shown in **Figures 11 to 13** illustrate the improvements brought by the new SSB corrections, either as 2D SSB or total SSB, in enhancing the precision of Sentinel-3A SAR SLA data. In this context, negative values (in cm^2) indicate an improvement in correction performance. The new 2D SSB solution yields an average variance reduction of approximately -0.09 cm^2 compared to the reference model. The new total SSB correction shows a smaller reduction of about -0.03 cm^2 .

These reductions are relatively small but still significant, as expected, given the similarity in behavior between the two 2D SSB versions, and the even closer alignment between the two total SSB solutions in terms of global patterns. The comparison presented in **Figure 13** between the application of the 2025 total SSB correction and the 2020 2D SSB correction shows an average variance reduction of approximately -0.6 cm^2 .

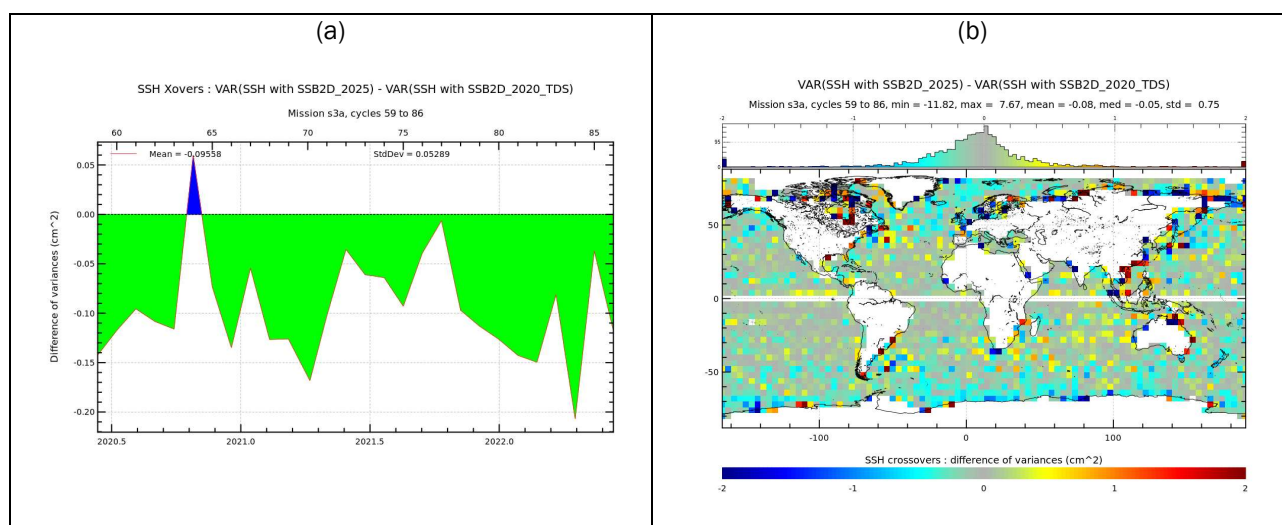


Figure 11: Differences in SAR SLA variance at crossovers (in cm^2) for S3A, resulting from the use of either the 2025 or 2020 2D SSB model in SLA computation: (a) presented as a time series of cyclic statistical indicators, and (b) as a spatial map averaged over a two-year period.

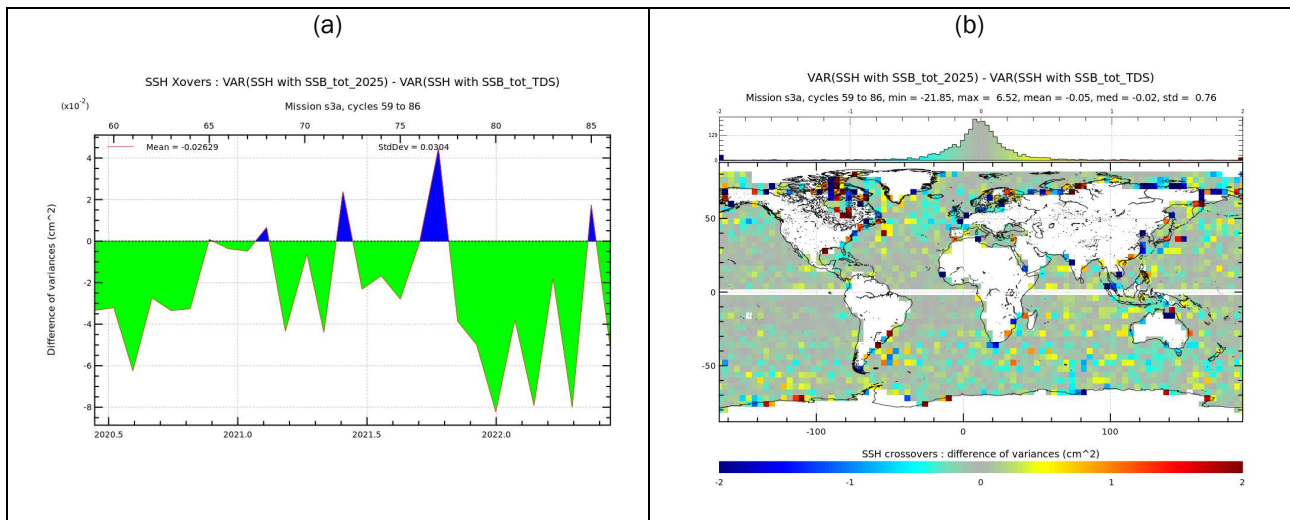


Figure 12: Same as Figure 11, except that total SSB corrections are applied: the 2025 version (2D SSB + Δ SSB), against the total SSB corrections (2020 2D SSB + 2024 Δ SSB) from the BC006.2 TDS.

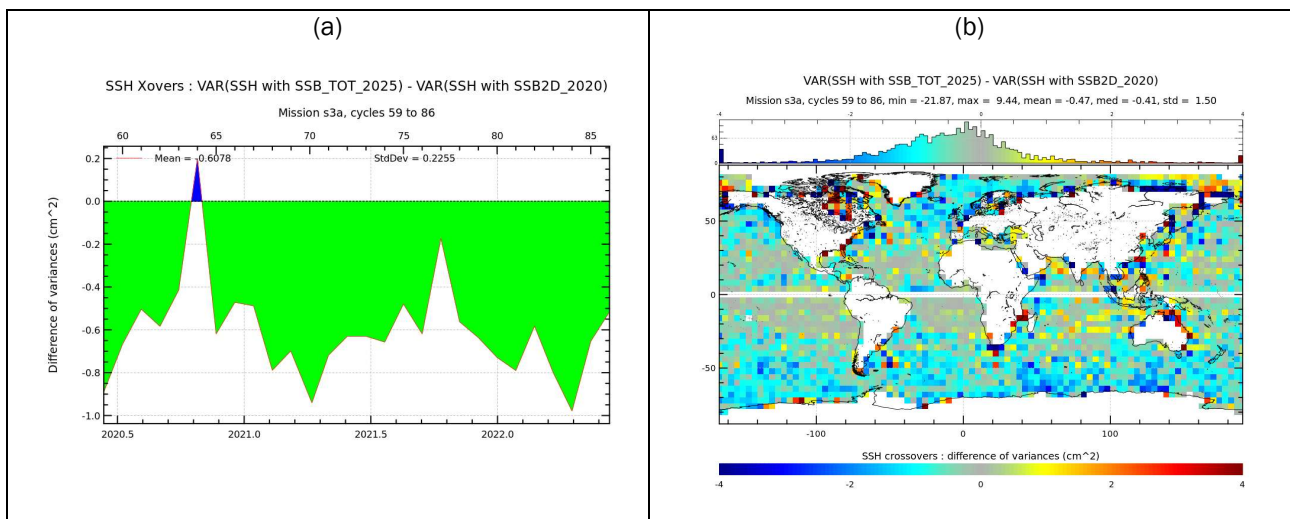


Figure 13: Same as Figure 11, except that the SSB corrections applied are the 2025 total SSB against the 2020 2D SSB from the BC006.2 TDS.

4.2 SLA dataset

The variance reduction diagnostics derived from the SLA dataset are presented in **Figures 14 to 16**. The new 2D SSB solution achieves an average variance reduction of approximately -0.3 cm^2 compared to the 2020 reference model. In contrast, the new total SSB correction versus the TDS total SSB one does not show any improvement for this dataset, with a variance reduction value of only 0.005 cm^2 (see **Figure 15**). This lack of improvement is attributed to the strategy used to construct the SAR total SSB, which involved aligning it with PLRM data. **Figure 16** presents a comparison between the application of the 2025 total SSB corrections and the 2020 2D SSB correction, showing an average variance reduction of approximately -0.7 cm^2 .

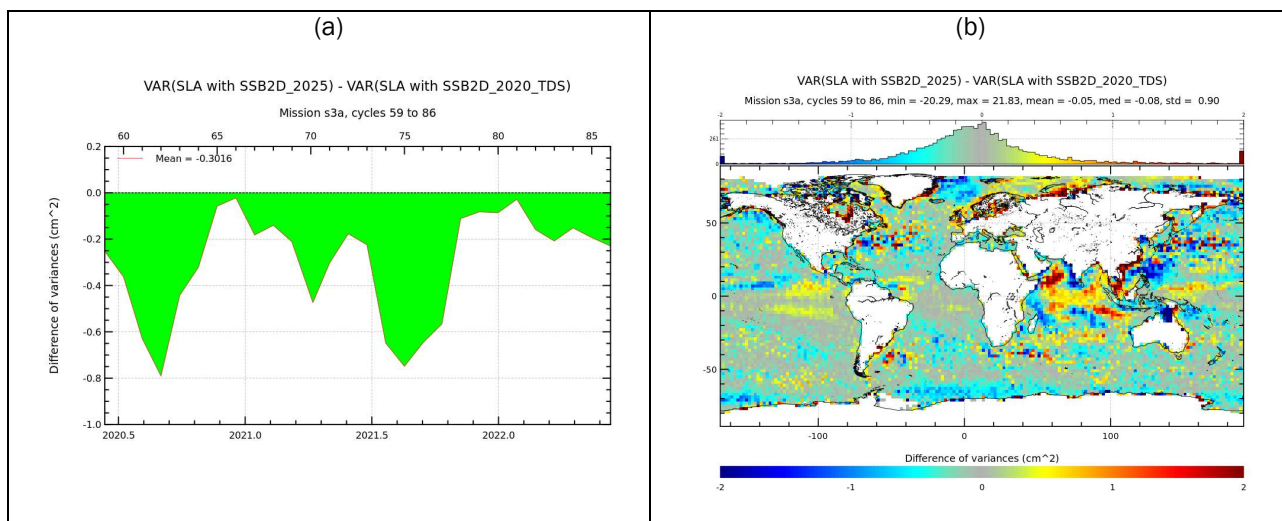


Figure 14: SAR SLA variance differences (in cm^2) from the global dataset for the S3A mission, computed using either the 2025 or the 2020 version of the 2D SSB model in the SLA calculation: (a) shown as a cyclic statistical indicator over time, and (b) as a spatial map over the two-year period.

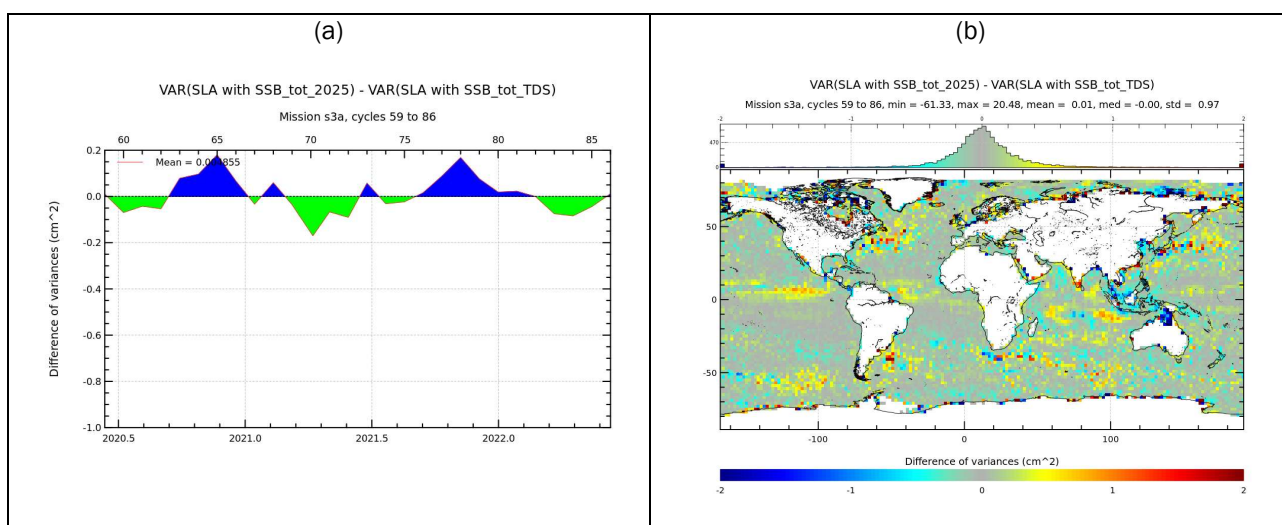


Figure 15: Same as Figure 13, but with total SSB corrections applied: the 2025 version (2D SSB + ΔSSB), against the total SSB corrections (2020 2D SSB + 2024 ΔSSB) from the BC006.2 TDS.

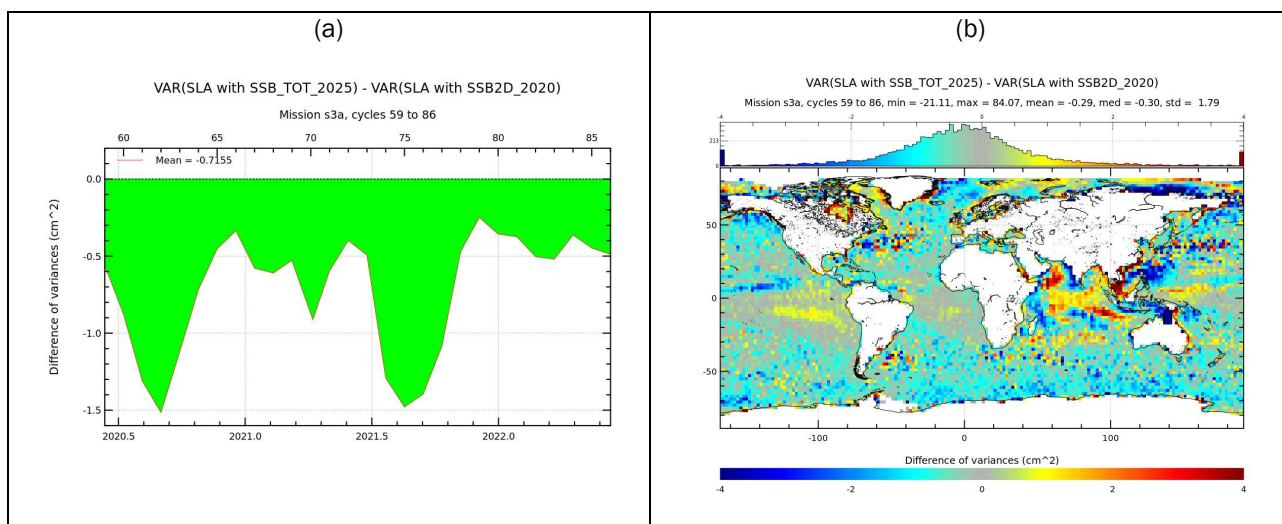


Figure 16: Same as Figure 13, except that the SSB corrections applied are the 2025 total SSB against the 2020 2D SSB from the BC006.2 TDS.

Finally, the last diagnostic concerns the comparison of the 1-Hz SLA spectra. As shown in **Figure 17**, using either the new total SSB version or the estimates provided in the TDS does not significantly alter the spectrum. This outcome was expected, given that the two estimates are very similar and the SSB correction is relatively minor compared to other corrections involved in SLA computation.

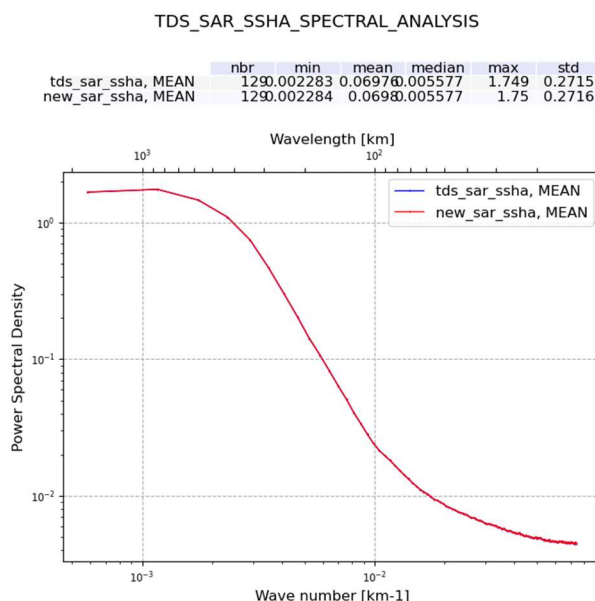


Figure 17: Comparison of 1-Hz SLA spectra for Sentinel-3A SAR mode data, using either the updated total SSB correction (2D SSB + Δ SSB, version 2025) or the total SSB estimates provided in the TDS.

5 Conclusion and recommendations

The validation and performance analyses conducted in Task 2 of WP2.10 focused on updating the two SAR SSB components, 2D SSB and Δ SSB, that together form the total SSB correction. The results revealed 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 Δ SSB 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 Δ SSB 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 Δ SSB 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.

All requirements established in the Work Package Description (WPD) have been fulfilled.