Sentinel-6 MF validation and cross calibration activities

2023 Executive Summary

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1 Executive Summary

By succeeding to TOPEX/Poseidon, Jason-1, Jason-2 and Jason-3 on their primary ground track, Sentinel-6 MF has extended the high-precision ocean altimetry data record.

Sentinel-6 MF was launched on November 21st 2020. Its onboard altimeter (POS4) operates simultaneously in two acquisition modes in a so-called **interleaved mode**. These modes are:

- Low Resolution Mode, hereafter "LR", which is the historical mode used by previous altimeters in the Topex/Jason satellites.
- High Resolution Mode, hereafter "HR", a.k.a. Synthetic Aperture Radar (SAR) or Delay Doppler Altimetry (DDA), already used on Cryosat-2 and on the Sentinel-3 satellites.

HR data can be telemetered on ground either on RAW mode, i.e. with the full range window of the HR waveform, or in RMC mode, that transmits a truncated waveform thanks to on-board processing, to cut data volume in half. More information on the different telemetry configurations can be found in the L1 Product Generation Specification[1].
Sentinel-6 MF POS4 operates in LR plus HR-RMC mode globally since cycle 32 (2021/09/21). This configuration is called LRMC. Before 2021/09/21, several configurations have been tested via predefined mode masks, mainly in order to validate to HR-RMC performance versus HR-RAW.

During Sentinel-6 MF tandem phase with Jason-3 (2020/12/17 to 2022/04/07), both satellites were on the same ground-track (with only 30 seconds delay), which was a unique opportunity to precisely assess parameter discrepancies between both missions and detect geographically correlated biases, jumps or drifts. In order to calibrate both altimeters, POS4 was switched to its redundant side (POS4-B) on 2021/09/14. It remains in this configuration from this date onwards.
Thanks to this tandem phase, Sentinel-6 MF has been precisely calibrated leading to a seamless transition between Jason-3 and Sentinel-6 MF LR as reference mission in the DUACS system.

In July 2023, the **PB F08 full mission reprocessing for Sentinel-6 MF** was distributed for both LR and HR products. F08 LR products include a **new Numerical Retracking** (NR)for Ku-band in addition to MLE4 retracking. Numerical retracking allows accounting for the PTR shape evolution thanks to the use of in-flight PTRs. An anomaly on LR NR SWH was raised following the pre-operational validation of F08 data (AR 2620), and corrected in a patched version of PB F08 from 2023-10-05 sensing time. The anomaly will be retroactively corrected during the next reprocessing campaign.

During each cycle, missing measurements were monitored, spurious data were edited, and relevant parameters derived from instrumental measurements and geophysical corrections were analysed. Please note that analysis are done **over ocean** only, no assessment is done over hydrological targets.

[1] https://www.eumetsat.int/media/48261

1/ Data availability

Data availability over ocean is excellent for Sentinel-6 MF LR products, with 99.7 % of available data over the complete mission lifetime. It is only impacted by few events, occurring during Sentinel-6 MF commissioning phase, represented with grey lines on figure 1 and listed below.

Sentinel-6 MF HR requirements on data availability are met, with a slightly reduced percentage of available data compared to LR at 98.5 %. From cycle 4 to 31 (i.e. from 2021/02/05 to 2021/09/21, in red on the figure), different mode masks were activated on POS-4. Over these cycles, HR data were not always available globally. From cycle 32, the average percentage of available HR data is of 99.4 %, which is still lower than LR.

The following events impact data availability in both LR and HR products:

- POS4 restart on 2021/01/26
- POS4 restart on 2021/02/25
- POS4 restart on 2021/04/22
- Satellite switch off for satellite software patch from 2021/04/27 03:35 to 2021/04/28 17:07
- POS4 restart on 2021/08/26
- Switch from POS4-A to POS4-B on 2021/09/14.

No important event occurred over 2023.

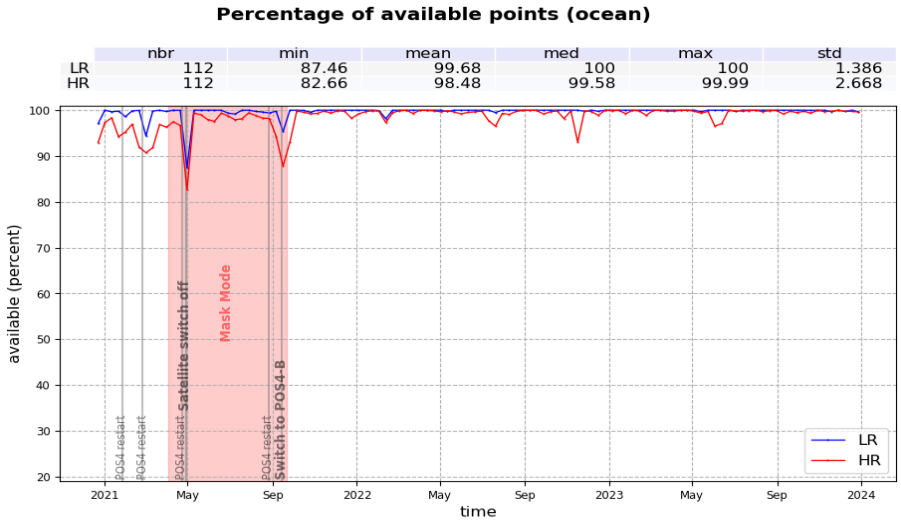

Figure 1: Percentage of available data over ocean for NTC Sentinel-6 MF LR (blue) and HR (red) per cycle.

2/ Sea Level Anomalies

Sentinel-6 MF and Jason-3 SSHA follow identical seasonal cycles and variations (cf figure 2), with mean value of 4.9 cm for Sentinel-6 MF LR MLE4, 4.2 cm for Sentinel-6 MF LR NR, 3.8 cm for Sentinel-6 MF HR and 3.6 cm for Jason-3. Excluding the Caspian Sea, Sentinel-6 MF SSHA cyclic standard deviation is similar between all datasets. The spike in HR on April 28th, 2021, visible on both mean and standard deviation, is caused by a higher number of missing passes on that day.

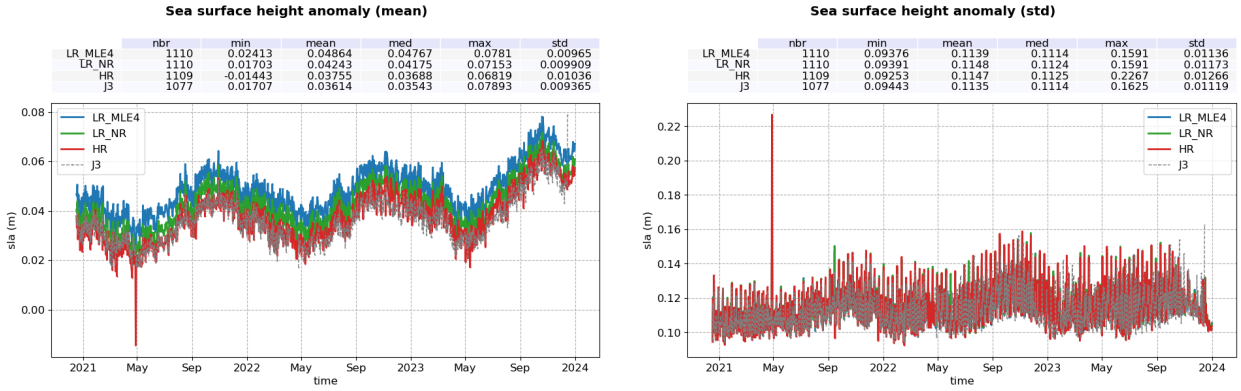

Figure 2: Mean (left) and standard deviation (right) SSHA by day for LR MLE4 (red), LR NR (green), HR (blue) and Jason-3 (black).

The NR - MLE4 SSHA differences monitoring on figure 3 shows an about 1.5mm jump at side B switch, resulting from range and ionosphere correction behaviours. The corresponding map highlights a significant SWH correlation, with about -1.5 cm decrease between 0.5 and 8m-SWH. This behaviour is expected and is part of the improvement brought by the numerical retracker. Indeed, contrary to MLE4, numerical retracker outputs are not corrected by instrumental LUTs, which are applied as function of SWH values. Numerical retracker retrievals are then less sensitive to any approximation in the LUT estimation.

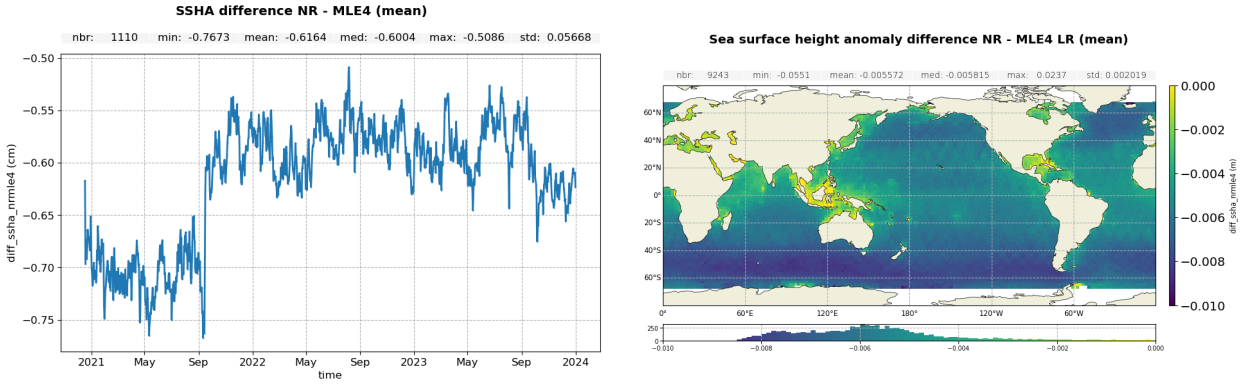

Figure 3: Left : Time monitoring per day of Sentinel-6 MF NR - MLE4 SSHA in meters, without the Caspian Sea. Right : gridded map computed over 2023.

3/ Performance at crossover points

Looking at SSH difference at mono-mission crossovers, mean values are well centred around 0 for LR MLE4, LR NR and HR data (figure 4 left panel). A small 120-day signal similar to Jason-3 is visible with amplitude below 1.5 cm. This signal disappear with the use of JPL orbits instead of CNES POE-F (cf Cadier et al. 2024, under review [**?**]). Further investigations are required to fully understand this behavior.
Concerning SSH error at mono-mission crossovers ($STD\ /\ \sqrt{2}$), Sentinel-6 MF shows very good and stable performance with an error of 3.3 cm for Sentinel-6 MF LR MLE4, LR NR and Jason-3 (figure 4 right panel). The error for Sentinel-6 MF HR SSH is slightly lower (3.2 cm).

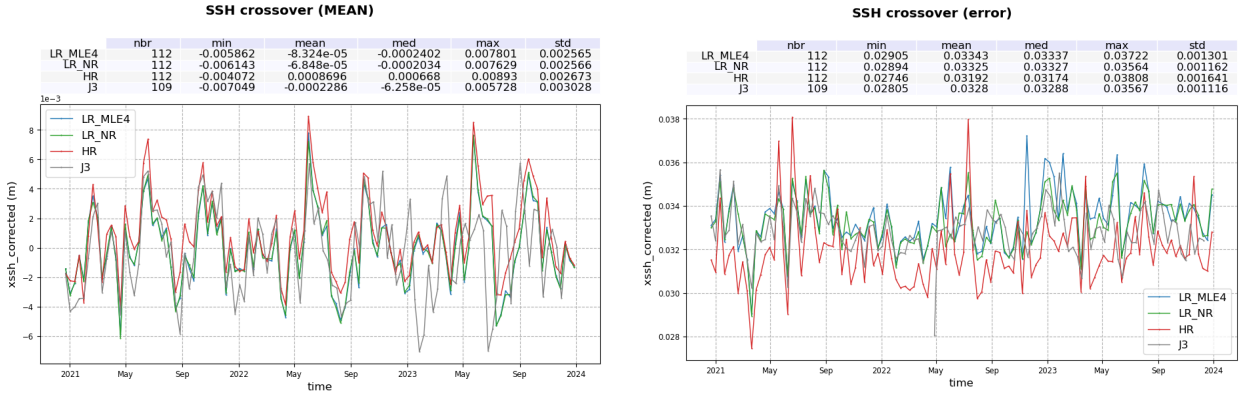

Figure 4: Monitoring of SSH difference at mono-mission crossover for Sentinel-6 MF LR MLE4 (blue), LR NR (green), Sentinel-6 MF HR (red) and Jason-3 (black), mean (left) and error (right) per cycle. Only data with |latitude| < 50 °, bathymetry < -1000 m and low oceanic variability were selected.

The mean SSH differences at Sentinel-6 MF/Jason-3 crossovers is following the same variations for LR MLE4, LR NR and HR, with means of -1.7 cm, -1.1 cm and 0.1 cm respectively (figure 5 top panel). On all curves, a jump of about -3 mm is visible at the end of April 2021, concomitant with a Sentinel-6 MF restart on April 27-28th, 2021. Then, on both S6-MF LR NR/J3 and S6-MF HR/J3 datasets, a downward drift is visible until approximately the end of the tandem phase in April 2022. These drifts might be caused by the evolution of the Jason-3 PTR shape in the first case, that would not be compensated by a similar effect in Sentinel-6 MF LR NR due to the use of the in-flight PTR, and by the range walk effect impacting HR data in the second case.

No significant regional pattern can be seen in the Sentinel-6 MF LR/Jason-3 SSH crossovers differences for both MLE4 and NR (figure 5 bottom panels). The map of Sentinel-6 MF HR/Jason-3 SSH differences at crossover highlights the absence of skewness parameter in the HR processing, leading to correlation to sea state conditions in the comparison to Jason-3.

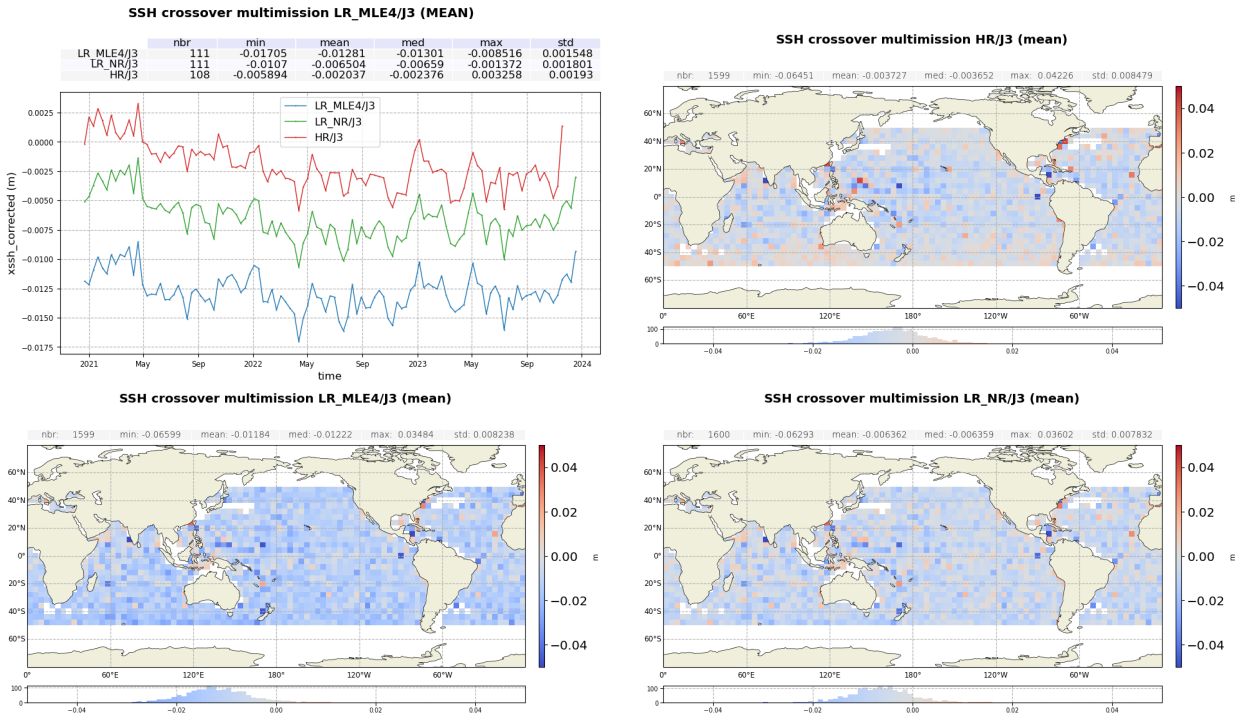

Figure 5: Cyclic monitoring of Sentinel-6 MF - Jason-3 SSH crossover differences mean (top left) and maps over year 2023 for HR (top right), LR MLE4 (bottom left) and LR NR (bottom right). Only data with |latitude| < 50 °, bathymetry < -1000 m and low oceanic variability were selected.

4/ Contribution to Global Mean Sea Level

Since April 2022 (Sentinel-6 MF cycle 52), Sentinel-6 MF is the reference altimetry mission to estimate the Global Mean Sea Level (GMSL), replacing Jason-3. Regional and global biases between missions have to be precisely estimated in order to ensure the quality of the reference GMSL series as seen on Figure 6. For more clarifications, see the dedicated section on AVISO+ website[2].

Sentinel-6 MF GMSL are impacted by two known effects:

- the evolution of the PTR shape in the range direction. It impacts range and SWH estimates both in LR MLE4 and HR SAMOSA. Numerical retracker allows accounting for the PTR shape evolution thanks to the use of in-flight PTRs. HR NR is implemented in the PB F09 deployed in February 2024.
- the evolution of the PTR shape in the azimuth direction, impacting the range variations within a burst, in HR only. It is corrected thanks to the range walk correction, that is available in PB F09.

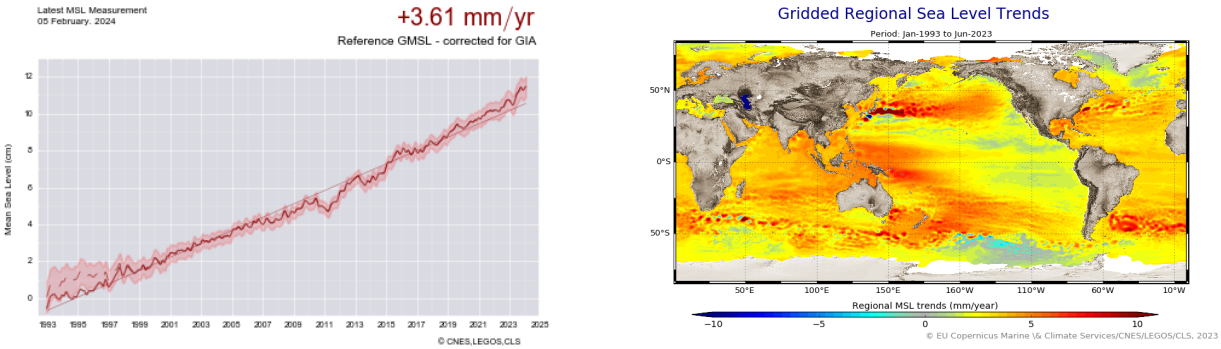

Figure 6: Global (left) and regional (right) MSL trends from 1993 onwards.

[2] https://www.aviso.altimetry.fr/en/data/products/ocean-indicators-products/mean-sea-level.html