Cal/Val: Results of past tandem missions

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Overview

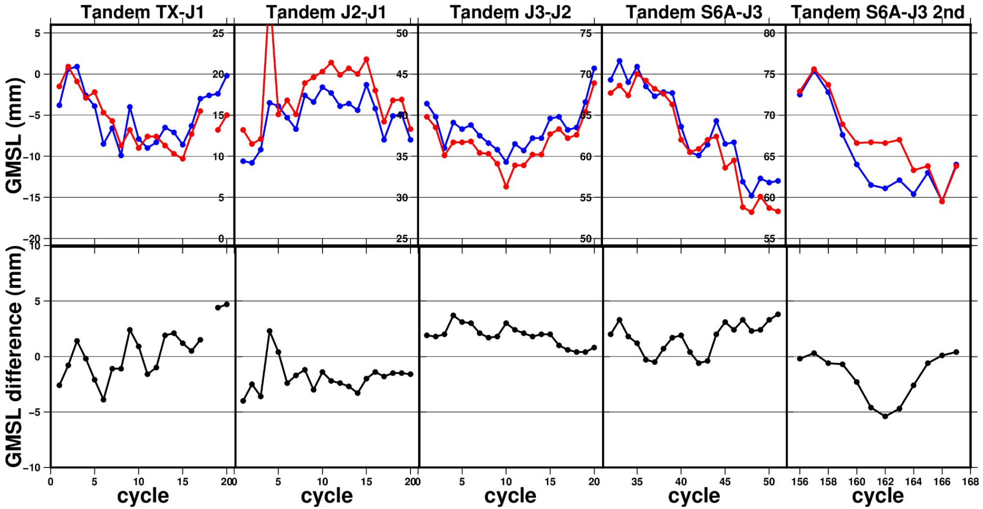
- ➔ Tandem flight phases have played a key role in verifying and ensuring the consistency of sea level measurements between successive reference missions.
- ➔ The tandem phases have been implemented after the launch of each new reference mission:
  - ◆ TP and Jason-1 (2002)
  - ◆ Jason-1 and Jason-2 (2008),
  - ◆ Jason-2 and Jason-3 (2016),
  - ◆ Jason-3 and S6-MF (2021–2022)
- ➔ A second tandem phase was implemented between Jason-3 and S6-MF (2025)
- ➔ During a tandem phase, the two successive reference missions follow each other on an identical ground track at intervals of around 1 minute.
- ➔ Upon completion of each tandem phase, the older reference mission is moved to an alternative orbit to enhance sea level observations.

Overview

- ➔ During a tandem phase, ocean and atmosphere **do not vary significantly** between measurements made by the two altimetry missions.
- ➔ Therefore, by comparing the sea level measurements from the two altimeters, the geophysical and atmospheric effects **cancel out**.
- ➔ We can therefore accurately determine **the relative errors** made by both altimetry missions, which are made up of several effects:
  - ◆ **instrumental** differences related to the altimeter characteristics and the processing of the altimeter measurements
  - ◆ Differences in the **precise orbit determination**
  - ◆ Differences in the **mean sea surface** in areas of strong geoid gradients
- ➔ **Systematic instrumental differences** are obtained after averaging the short-term time-correlated effects on the relative errors over a period of at least 100 days

First result: accurately link the GMSL time series together

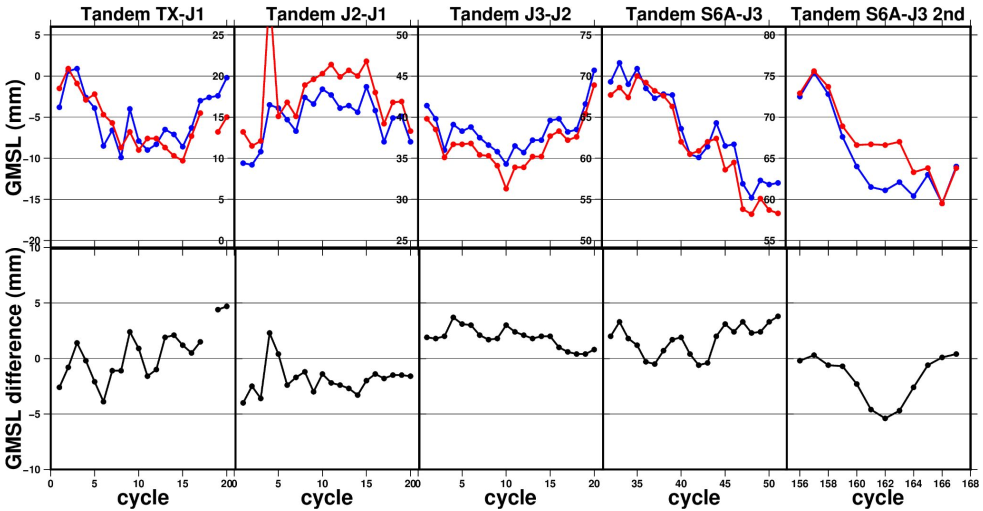
➔ **At global mean:** offset uncertainties are between **0.2 and 0.6 mm** (1-Sigma) during a tandem phase (Quet V., 2025)



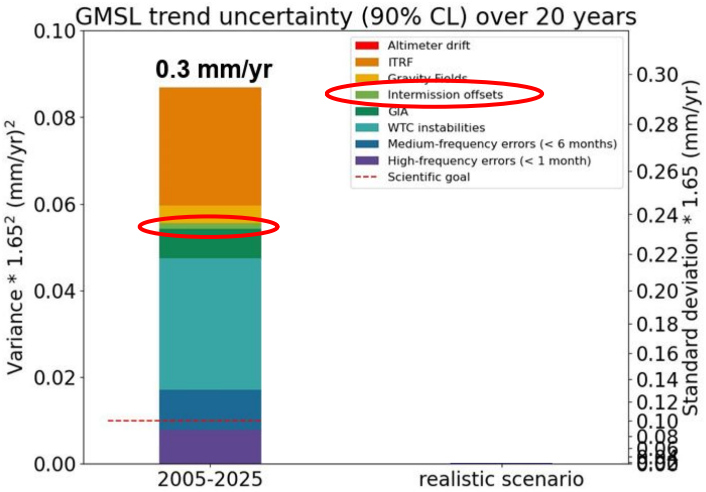
Global mean sea level and differences during tandem phases (RADS)

First result: accurately link the GMSL time series together

- ➔ **At global mean:** offset uncertainties are between **0.2 and 0.6 mm** (1-Sigma) during a tandem phase (Quet V., 2025)
- ➔ Contribution to GMSL trend uncertainties lower than **0.04 mm/yr** over 20 years (90% CL)



Global mean sea level and differences during tandem phases (RADS)

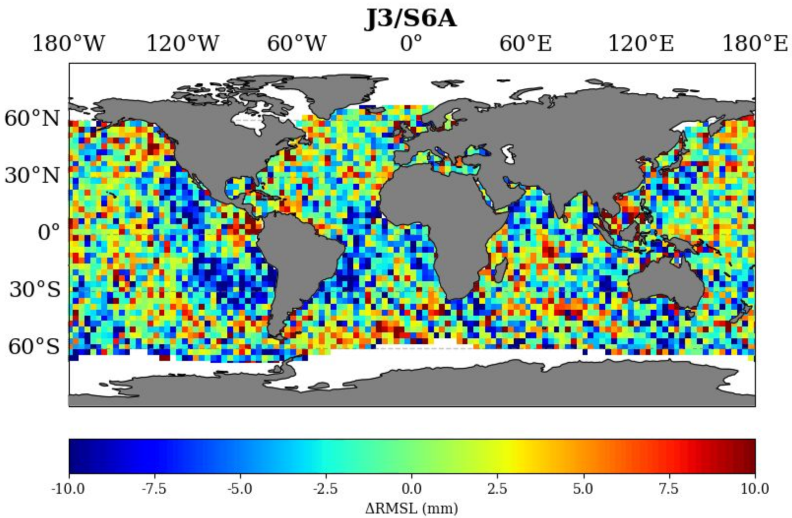


Uncertainty in global sea level **trends** over two 20-year periods (Jasons/S6-MF, and S6-NG)

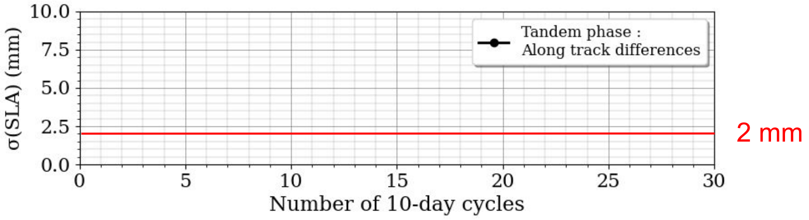
Ablain M., LPS Vienna , 2025 & **Lalau N.** , Eumetsat Conf, 2025
How to improve the Sea Level Rise Stability Uncertainty budget for S6NG

Second result: accurately detect regional MSL differences

➔ **At regional scales (a few hundred km):** systematic regional mean sea level differences until 2 mm (at 1-sigma) can be detected



Evolution of the standard deviation of the regional MSL differences according to the period length

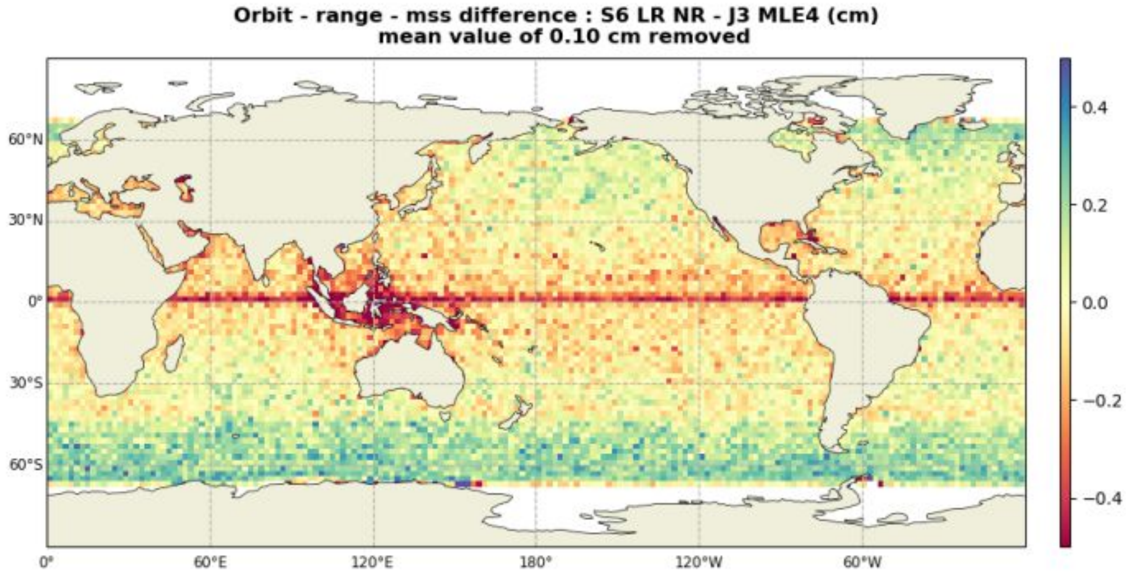


Lalau et al. 2025, outcomes from the ESA-supported ASELSU project (www.aselsu.org)

Second result: accurately detect regional MSL differences

➔ Systematic MSL differences were detected **between Jason-3 and S6-MF in the equatorial band** which were first detected when comparing TOPEX and Jason-2 20 years prior (in 2002)

➔ Investigations have shown that these systematic differences in MSL were due to an **artefact in Jason's ground segments**.



Cadier et al., 2025, Assessment of Sentinel-6MF low resolution numerical retracker over ocean: Continuity on reference orbit and improvements. https://doi.org/10.1016/j.asr.2024.11.045

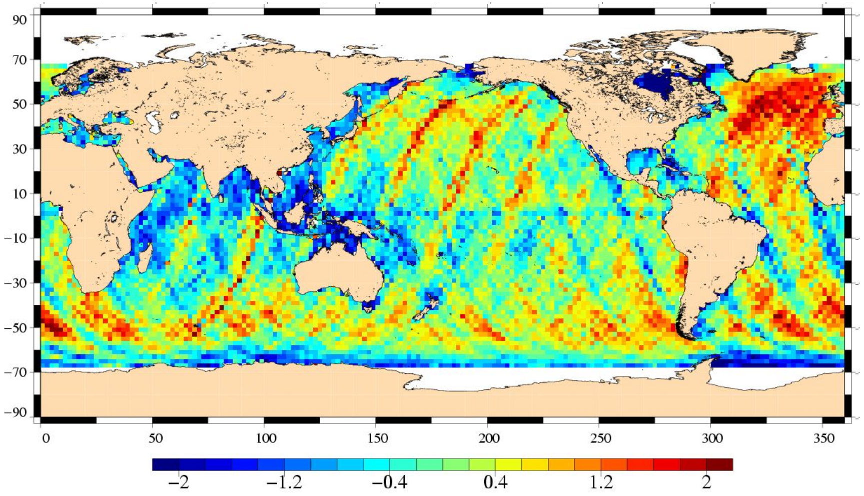
Third result: measure the improvements of instrumental processing and POD solutions

➔ Tandem phases were used as a **reference period** to measure/quantify **improvements** in altimeter instrumental processing and POD solutions (e.g. TOPEX/Jason-1) in order to reduce regional systematic differences in MSL.

Use of new orbits (GRACE)

+ new retracking (LSE & MLE4)

+ new SSB



TOPEX-Jason-1 SSH (cm) [Cycles JA1 1-21]
(without SSB correction)

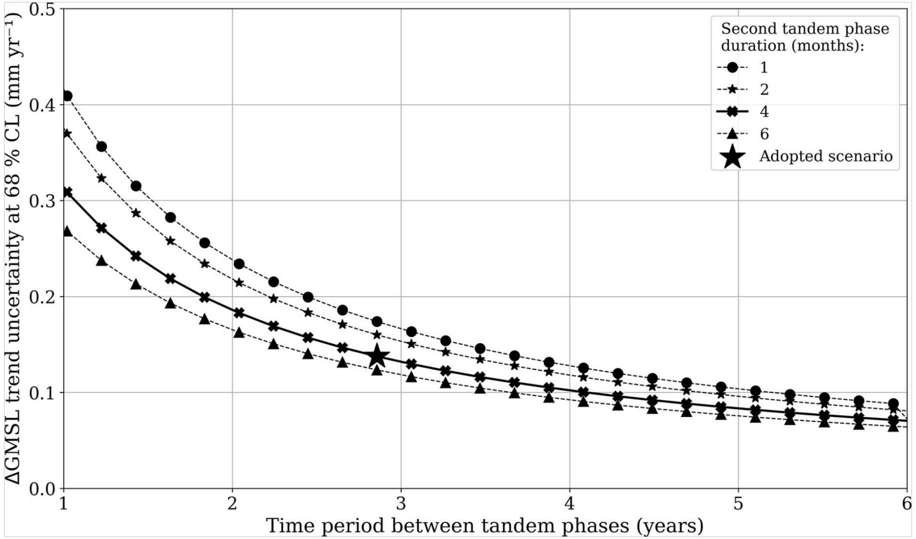
Ablain et al., 2012,
"Reciprocal benefits of multi-mission satellite altimetry comparisons"

Fourth result: benefit of a second tandem phase

➔ **New cross-validation method** based on the realization of a s**econd tandem phase** between two successive reference missions a few years after the initial phase : applied to Jason-3 and Sentinel 6-MF (Jan 2025- April 2025)

➔ Able to assess the instrumental stability of Jason-3 and S6-MF with with an uncertainty of:

- **0.14 mm yr^{-1}** (1-sigma) at global mean
- **0.65 mm yr^{-1}** (1-sigma) for spatial scales of about 1000 km



M. Ablain et al., 2025, Benefits of a second tandem flight phase between two successive satellite altimetry missions for assessing instrumental stability, Ocean Sci., 21, 343–358, https://doi.org/10.5194/os-21-343-2025, 2025.

Summary

- ➔ Tandem phases allowed the precise calibration of two altimeters with the detection of **systematic instrumental and POD differences** of a few millimeters to a few centimeters at different spatial scales from a few hundred kilometers to the global scale.
  - ◆ At global mean, tandem phases allowed to accurately link GMSL time series together with an uncertainty between **0.2 and 0.6 mm** (1-sigma)
  - ◆ At regional scale (a few hundred km) tandem phases allowed to detect systematic regional MSL differences **up to 2 mm** (at 1-sigma)
- ➔ Tandem phases were also used as a **reference period** to measure improvements in altimeter instrumental processing and POD solutions (e.g. TOPEX/Jason-1) in order to reduce regional systematic differences **(errors)** in MSL.
- ➔ The realization of a **second tandem phase** between Jason-3 and S6-MF will allow us to accurately assess the instrumental stability of both satellites

Cal/Val: Results from Dedicated Calibration Sites - Bass Strait, Corsica, Gavdos and Harvest

Pascal Bonnefond, Christopher Watson, Bruce J Haines, Stelios Mertikas

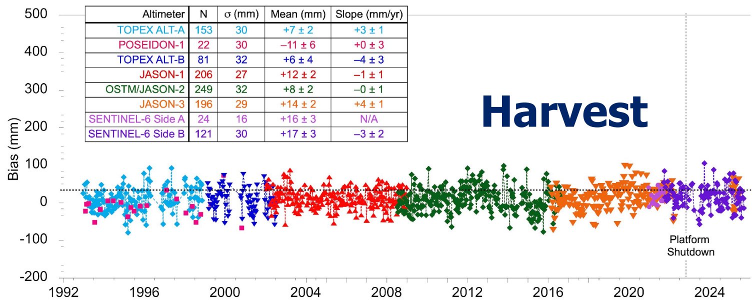
16 November 2025

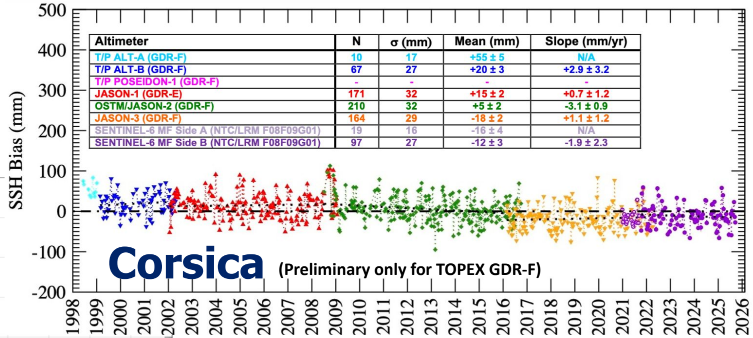
Current Results from Dedicated Calibration Sites

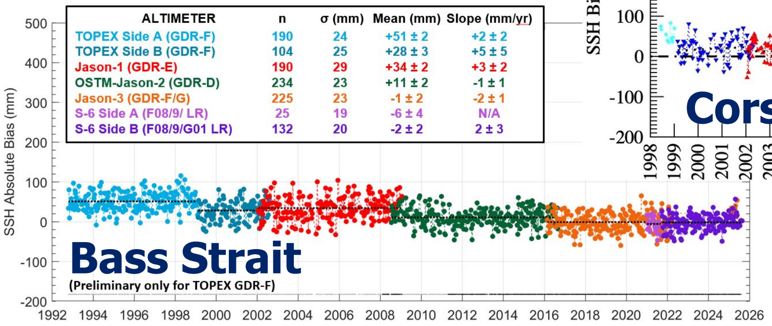
All missions/sites time series from Absolute SSH Bias Estimates

(Bonnefond et al., [Corsica], Haines et al. [Harvest], Watson et al. [Bass Strait])

Historical cal/val sites continue to support in-situ cal/val of reference missions from diverse locations, approaches, and in-situ instruments. Results show centimeter-level consistency for all missions





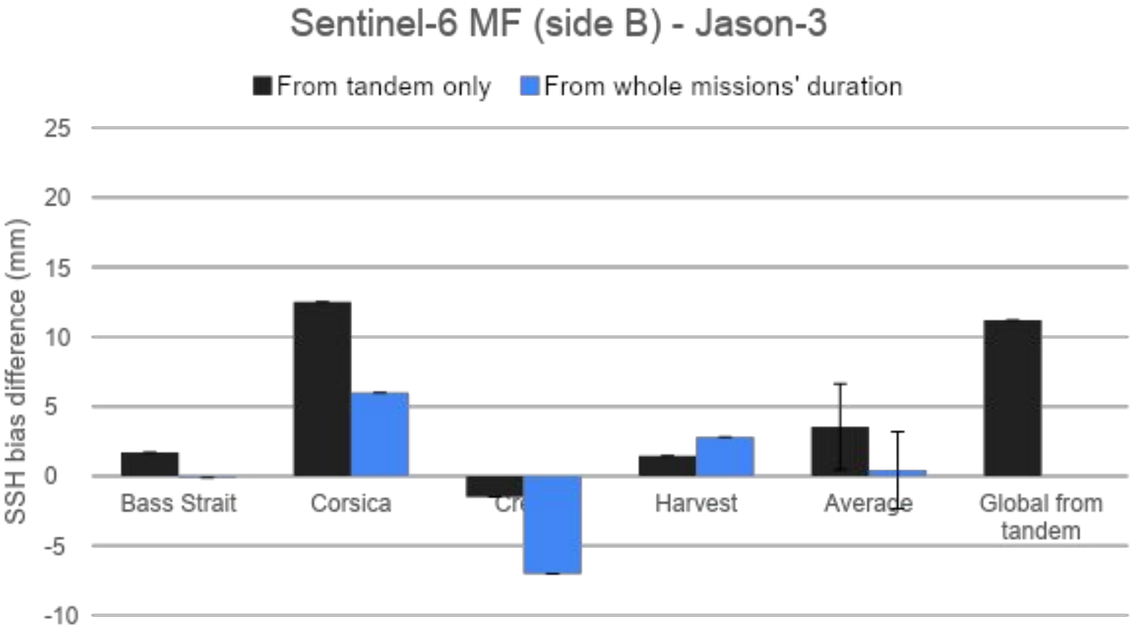


Needs to be consolidated when all missions' products will be reprocessed with the same standards (GDR-G)

Current Results from Dedicated Calibration Sites (con’t)

Intermission bias from Absolute SSH Bias Estimates difference

(Bonnefond et al., [Corsica], Haines et al. [Harvest], Mertikas et al. [Gavdos], Watson et al. [Bass Strait])



- **Consistent results from all sites at the few mm level during the tandem phase with an average of +3.5mm close to global determination (+11.2mm)**
- **Over the whole missions’ duration The relative SSH bias is changed by ~3mm**

Needs to be consolidated when Jason-3 and Sentinel-6 MF products will be reprocessed and delivered with the same standards (GDR-G)

Current Results from Dedicated Calibration Sites (con't)

Key messages to take from the absolute sites

- In situ absolute cal/val sites still provide the only truly independent 'whole-of-system' evidence base to confirm altimeter measurement precision and accuracy, under the specific oceanographic conditions of the site.

- We expect some variation site to site, this is borne out in other more comprehensive validation approaches that are relative in nature (e.g. along track collinear differences during tandem missions).

- Striving to assess bias stability at a single site is perhaps a step too far (there still feels to be too much evidence of non-gaussian noise on either side of the equation for this).

- Subtle differences in absolute bias results at any site, between missions / sides / processing versions does provide insights on the expression of changes as a function of specific site conditions.

- Meaningful comparisons are best made using homogeneous altimeter data products (also true for global studies)

- An important point is also the time needed to achieve a new set of reliable absolute calibration sites (FRM compliant) in case of an orbit change (Sentinel-6NG): this could take many years (e.g. vertical land motion assessment) and cost a significant amount.