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  - First draft of the paper (V1.0) ready in February.
  - Reviewed by co-authors in March.
  - Some feedback needed to better explain some parts of the paper.
  - Second draft (V2.0) prepared in April - delivered for the final meeting.
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Benefits of a second tandem flight phase between two successive satellite altimetry missions for assessing the instrumental stability

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Abstract.

The five successive reference missions, TOPEX/Poseidon, Jason-1, Jason-2, Jason-3, and more recently Sentinel-6 Michael Freilich, have ensured the continuity and long-term stability of the altimetry data record. Tandem flight phases have played a key role in verifying and ensuring the consistency of sea level measurements between successive altimetry reference missions. They enable us to measure the relative errors between the two altimeter missions. By averaging the short-term time correlated errors (< 10 days) over several months, the systematic instrumental errors can be assessed, allowing an accurate calibration of altimeter parameters. Thanks to a tandem phase, the global mean sea level offset between two successive altimeter satellites is estimated with an uncertainty of approximately $\pm$ 0.5 mm ([16-84]% confidence level). However, the detection of instrumental drift poses a challenge because of the short duration of the tandem phase. Therefore, this study aims to propose a novel validation method with a better ability to assess the stability of altimeter parameters in sea level estimates. It is based on the implementation of a second tandem flight phase between two successive satellites a few years after the initial one. Calculating sea level differences during the second tandem phase provides a new accurate evaluation of relative errors between the two successive altimeter missions . With a second tandem phase long enough, the short-term time correlated errors (< 10 days) will be averaged, allowing us to reevaluate systematic instrumental errors. The trend between the systematic errors made during the two tandem phases can be calculated to assess the stability of the altimeter parameters over the entire period that covers both tandem phases. In this paper, we present the approach developed to analyse the ability of this novel validation method to assess the altimeter parameter stability. On the global scale, we show that the 2-tandem-phase validation method allows us to assess the stability of the altimeter parameters with an uncertainty of approximately $\pm$ 0.15 mm yr^{-1} ([16-84]% confidence level). The uncertainty increases to $\pm$0.4-0.6 mm yr^{-1} at regional scales of 2000-4000 km ([16-84]% confidence level). We discussed the results with regard to the scenario foreseen for the second phase between Jason-3 and Sentinel-6 Michael Freilich planned for early 2025, 2 years and 9 months after the end of the first tandem phase. We conclude that conducting regular double tandem phases between successive altimetry missions would be a valuable approach to accurately evaluating the altimeter parameter stability in the future, both at global and regional spatial scales.

Overview

- TOPEX/Poseidon (TP), Jason-1, Jason-2, Jason-3, Sentinel-6 Michael Freilich have ensured the continuity and long-term stability of the altimetry data record.
- Main sources of uncertainties have been identified.
- Uncertainty in sea level trends over last 25 years ([5-95]% CL)
  - On the global scale: ± 0.3 mm yr−1
  - At regional scales: ± 0.8 to 1.3 mm yr−1

Source of uncertainties	Type of errors	Uncertainty (1σ)	Method / References
Altimeter noise / geophysical corrections	Correlated errors λ =2-months	$u_\sigma = 1.7$ mm over TP period $u_\sigma = 1.2$ mm over J1 period $u_\sigma = 1.1$ mm over J2 period $u_\sigma = 1.0$ mm over J3 period	This paper (Sect. 2.3)
Geophysical corrections / orbit	Correlated errors λ =1-year	$u_\sigma = 1.4$ mm over TP period $u_\sigma = 1.2$ mm over J1 period $u_\sigma = 1.1$ mm over J2 period $u_\sigma = 1.1$ mm over J3 period	This paper (Sect. 2.3)
Radiometer WTC	Correlated errors λ =5-years	$u_\sigma = 1.1$ mm over TP, J1, J2 periods $u_\sigma = 1.8$ mm over J3 period	Legeais et al. (2014) Thao et al. (2014) This paper (Sect. 2.3)
Orbits determination	Correlated errors λ =10-years	$u_\sigma = 1.12$ mm over TP period $u_\sigma = 0.5$ mm over Jasons period	Couhert et al. (2015); Rudenko et al. (2017)
Intermissions calibration offsets	Bias	$u_\Delta = 2\,mm$ for TP-A/B $u_\Delta = 0.3\,mm$ for TP/J1 $u_\Delta = 0.1\,mm$ for J1/J2 $u_\Delta = 0.2\,mm$ for J2/J3	This paper (sec. 2.2.1)
International Terrestrial Reference Frame (ITRF)	Drift	$u_\delta = 0.1\,mm/yr$ over 1993-present	Couhert et al. (2015)
Global Isostatic Adjustement (GIA)	Drift	$u_\delta = 0.05\,mm/yr$ over 1993-present	Spada (2017)
Topex-A/-B altimeter drift	Drift	$u_\delta = 0.7\,mm/yr$ over TP-A period $u_\delta = 0.1\,mm/yr$ over TP-B period	Ablain et al. (2017)

Guerou et al., 2022

Overview

- Key role of tandem flight phases in verifying and ensuring the consistency of sea level measurements between successive reference missions.
  - TP and Jason-1 (2002), Jason-1 and Jason-2 (2008), Jason-2 and Jason-3 (2016), and Jason-3 and S6-MF (2021-2022).
- Direct estimate of the errors between 2 altimeter missions:
  - mainly short-term time-correlated errors (< 1-2 months): altimeter parameters, POD, MSS
  - geophysical and atmospheric errors are cancelled
  - long-term errors in POD are cancelled
- Averaging “random” errors allows us to assess systematic altimeter parameter errors.
- Accurate estimation of the GMSL offset: ± 0.5 mm yr−1 ([16-84]% CL)

Tandem phase	Offset uncertainty ([16-84]% CL) (mm)
TP-B/J1	0,6
J1/J2	0,3
J2/J3	0,4
J3/S6-MF	0,5

Guérou et al., 2023

Cadier et al., submitted

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Overview

- Because of the maximum duration of tandem phases (from 9 months to 1 year), the assessment of instrumental drift over time is quite difficult

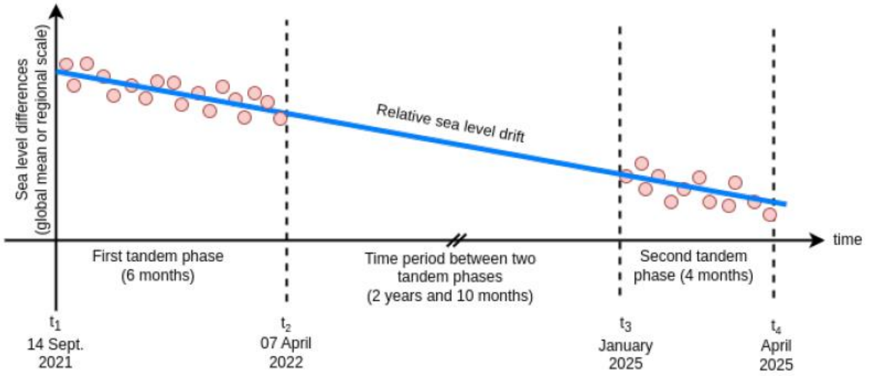
- Other validation methods exist on the global scale, based :
  - on cross-comparisons with altimeter missions together (e.g., crossover comparison, along-track comparison),
  - on comparisons with independent measurements (e.g., ocean model reanalysis, in situ data such as tide gauge measurements),
  - on the assessment of the sea level budget closure

- Instrumental drifts in the GMSL has been already detected:
  - TOPEX-A (1993-1999) with tide gauges: ~1.5 ± 1.0 mm yr^{-1} 5 (Watson, 2021)
  - S3A/S3B (2016-2021) with other altimeter missions : 1.2±0.6 mm yr^{-1} (Jugier, 2022) **=> now corrected**

- Uncertainty in the trend depends on the method (5-95]% CL) over a 10-year period):
  - tide gauges : ± 0.7 mm yr^{-1} (Ablain 2018; Watson, 2021)
  - along-track : ±0.3 m yr^{-1} on the global scale and ±1.2 mm $^{-1}$ at regional scales (Jugier, 2022).

Overview

- New validation method is proposed to assess the altimeter parameter stability
    - Based on the realisation of a second tandem phase a few years after the initial one
- Objective of the study is to demonstrate the ability of the 2-tandem-phase validation method to assess the altimeter parameter stability in sea level estimates.
    - at global and regional scales



Basic principle of the 2-tandem-phase validation method applied to the Jason-3 and S6-MF altimetry satellites.

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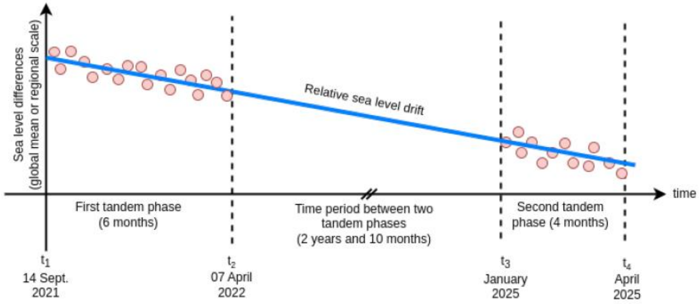
Method to estimate the uncertainty

1. calculation of an uncertainty budget of sea level differences during a tandem phase (time correlation and variance of errors)
2. Calculation of the variance covariance matrix during a tandem phase
3. Calculation of the uncertainty of the trend (blue line) :

$$\hat{\beta} = N(\beta, (X^t X)^{-1}(X^t \Sigma X)(X^t X)^{-1})$$

where X is the time vector and Sigma the error covariance matrix over the 2 tandem phases:

$$\Sigma = \left(\begin{array}{c|ccc} \Sigma_{tp\_1} & \begin{matrix} 0 & \dots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \dots & 0 \end{matrix} \\ \hline \begin{matrix} 0 & \dots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \dots & 0 \end{matrix} & \Sigma_{tp\_2} \end{array}\right)$$

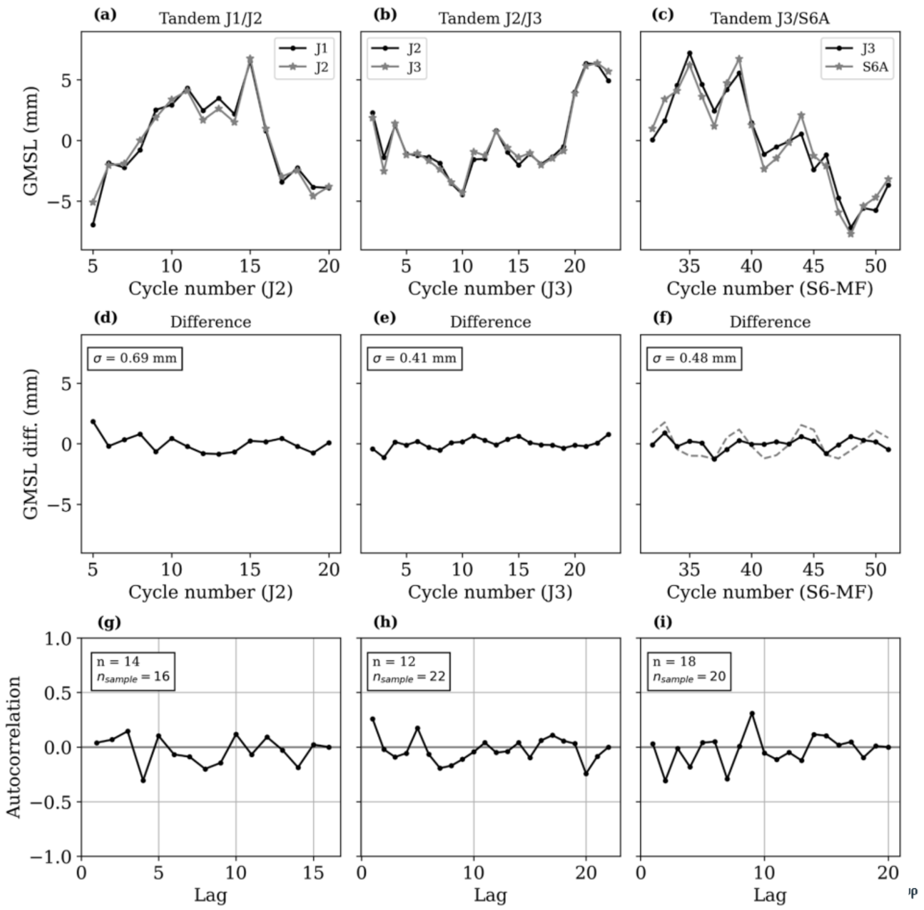


Uncertainty budget

- Sea level differences (=> relative errors) calculated over 3 tandem phases
- Calculation of the STD of differences
- Determination of time scale correlation

➔ On the global scale

➔ At the regional scales (from a few hundred to a few thousand of km)



Uncertainty budget

Table 1. Uncertainty budget of GMSL differences between two altimetry missions in tandem.

Source of uncertainty		**Time correlation of errors**	**Uncertainties (1-σ)**
short-term time-correlated errors due to altimeter processing, precise orbit determination, etc.		short-term time-correlated errors $\lambda < 1$ month	$U_\sigma = 0.7$ mm for Jason-1/Jason-2 $U_\sigma = 0.4$ mm for Jason-2/Jason-3 $U_\sigma = 0.5$ mm for Jason-3/S6-MF[1]
		short-term time-correlated errors 1 month $< \lambda <$ 1 year	$U_\sigma = 0$: no uncertainty identified
Stability of the wet tropospheric correction (WTC)		long-term time-correlated errors $\lambda < 5$ years	$U_\sigma = 0$: model WTC are used to cancel WTC errors in GMSL differences
Precise orbit determination stability	International Terrestrial Reference System (ITRF)	Linear time-correlated errors	$U_\delta = 0$: errors are cancelled between two missions in tandem
	Gravity fields	long-term time-correlated errors $\lambda < 10$ years	$U_\sigma = 0$: errors are cancelled between two missions in tandem
GIA correction		Linear time-correlated errors	$U_\delta = 0$: errors are cancelled between two missions in tandem

[1] The uncertainty budget in this study is constructed by taking the $U\sigma$ for Jason-3/S6-MF

Uncertainty budget

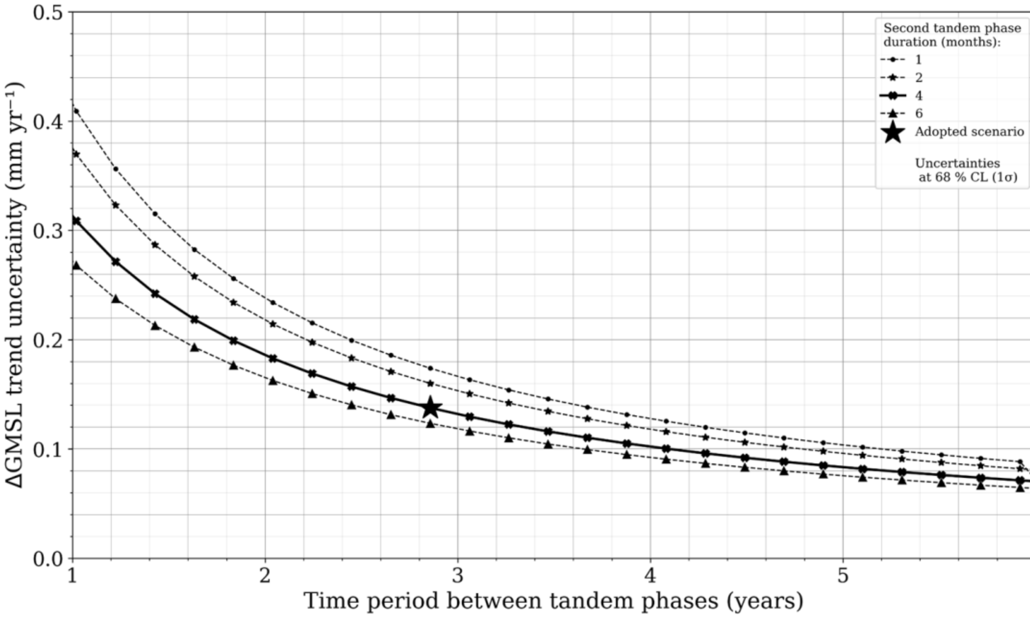
Table 2. Uncertainty budget of regional sea level differences between two altimetry missions in tandem. Values are provided for $9° \times 9°$ box sizes within a [16-84]% confidence level.

Source of uncertainty	Time correlation of errors	Uncertainty (1-σ)
Short time-correlated errors due to altimeter processing, precise orbit determination, oceanic variability, etc ..	short-term time-correlated errors λ <1 month	$U_\sigma \in [1.8, 4.8]$[1] mm Location dependent
Stability of the wet tropospheric correction (WTC)	long-term time-correlated errors λ <5 years	$U_\sigma = 0$: model WTC are used to cancel WTC errors in sea level differences
Precise orbit determination stability	Linear time-correlated errors	$U_\delta = 0$
Altimeter parameter stability	Linear time-correlated errors	$U_\delta = 0$
GIA correction	Linear time-correlated errors	$U_\delta = 0$

[1] The uncertainty budget in this study is constructed by taking the median value : $U_\sigma = 2.3$ mm for $\lambda < 1$ month.

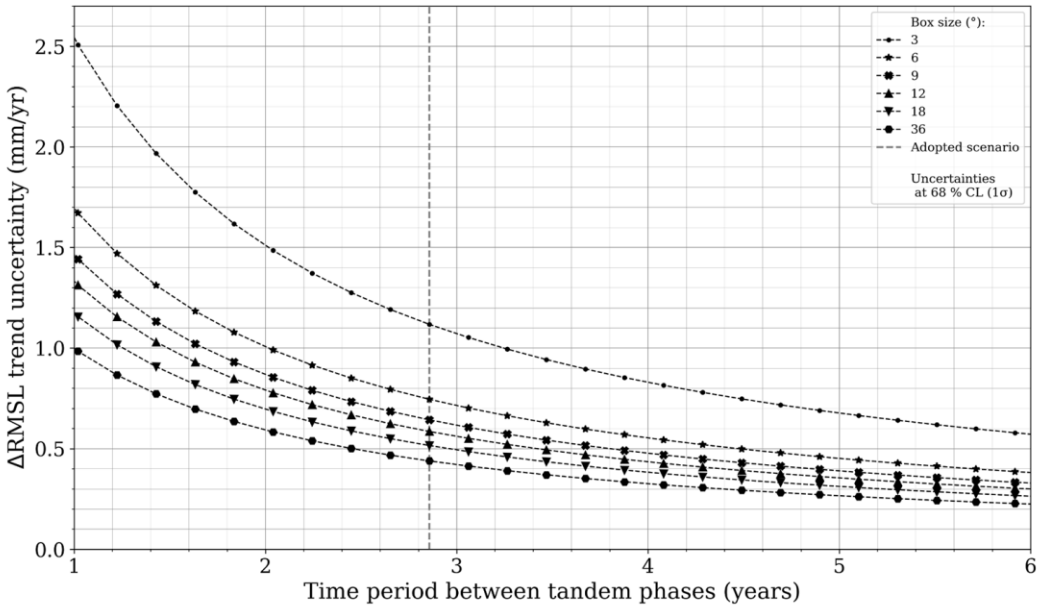
Uncertainty calculation on the global scale

- Evolution of the uncertainty of the trend in GMSL differences as a function of the time elapsed between the two tandem phase.
- The duration of first phase has been set to 6 months (duration S6MF side B / J3)
- The star shows the scenario adopted for the second tandem phase between S6-MF and Jason-3



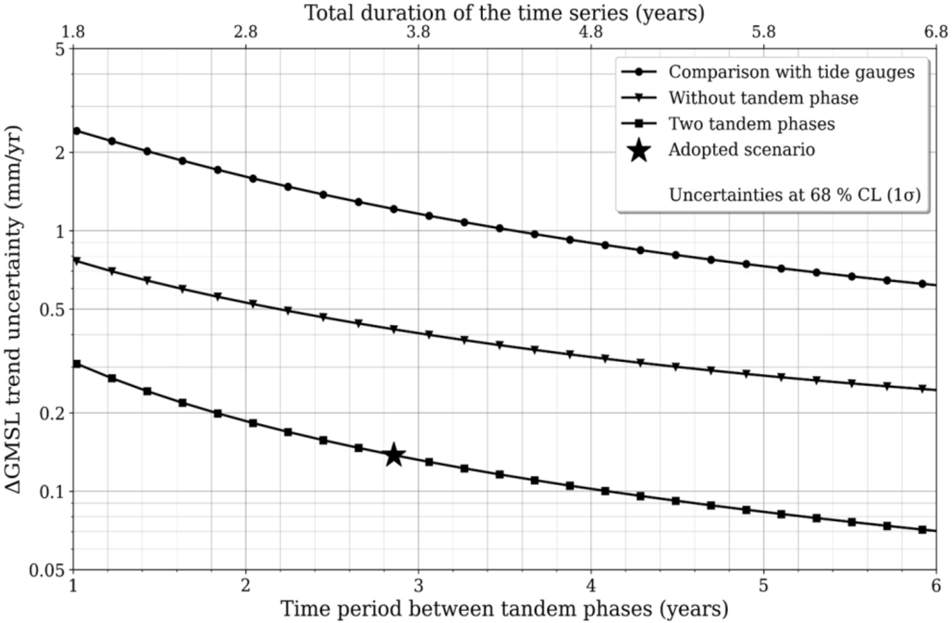
Uncertainty calculation at regional scales

- Same analyses on regional scales with different spatial scales.
- The second tandem phase has been set to 4 months.
- The dashed vertical line shows the scenario adopted for the second tandem phase between S66MF and Jason-3



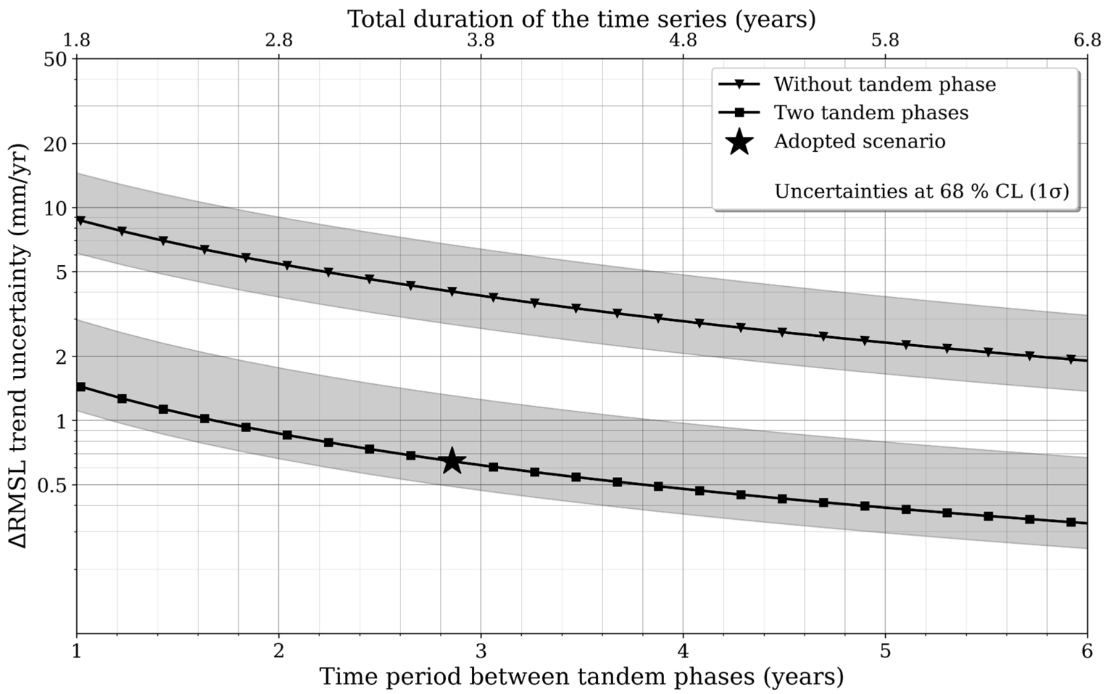
Comparison with other validation methods (global scale)

- Comparison of the uncertainty with 2 other validation methods:
    - comparison with tide gauges ;
    - inter-mission comparison without tandem
- Uncertainties calculated with the same approach based on uncertainty budget of sea level differences
- Duration of the second tandem phase has been set to 4 months.
- The star shows the scenario adopted for the second tandem phase between S6-MF and Jason-3



Comparison with other validation methods (regional scales)

- Comparison with the along-track method outside a tandem phase
- Cell size of 9°x9° corresponding to 1000 km spatial
- The envelope represents the spatial distribution of uncertainties between the 16th and 84th percentile (i.e., 1-σ) values.



Conclusions

- The 2-tandem-phase validation method will allow us to assess the altimeter parameter stability with unprecedented low uncertainties ([16-84]% CL):
    - less than ± 0.1 mm yr^{-1} at global scale for time periods between the two tandem phases of 4 years and beyond
    - less than ± 0.5 mm yr^{-1} in a CL for spatial scales of about 1000 km
    - 3 to 8 times better than with the other validation methods
- The method will be applied for the first time between S6-MF and Jason-3 after the realisation of the second tandem phase early in 2025.
- The method is only applicable over the period encompassing the 2 tandem phase and does not allow the assessment of the altimeter parameter stability outside this period
- To take a larger benefit of this novel validation method, this involves regularly implementing double tandem phases between two successive altimetry missions in the future.

To go further

1) To update the uncertainty budget of the second tandem phase between S6 and Jason-3.
2) To assess the S6-MF sea level uncertainty budget, where currently no long-term time correlated errors (> 1 year) are defined (e.g. Are there any sea state effects ?).
3) Extend the approach to assess the stability of the wet troposphere correction derived from the MWR.
4) To generalise the approach by regularly repeating a double tandem phase and to analyse the benefits on the stability of the altimeter parameters.
5) To investigate the benefits of a derived approach based on the implementation of a 3 tandem phase between three satellites, such as the 3 tandem phase planned between S3A, S3B and S3C.

Appendix-A

Uncertainties of the trend in regional mean sea level differences of the 2-tandem-phase validation method for a 9° x 9° cell size
and for a 2-year and 9 month time spent between the two Jason-3 and S6-MF tandem phases.

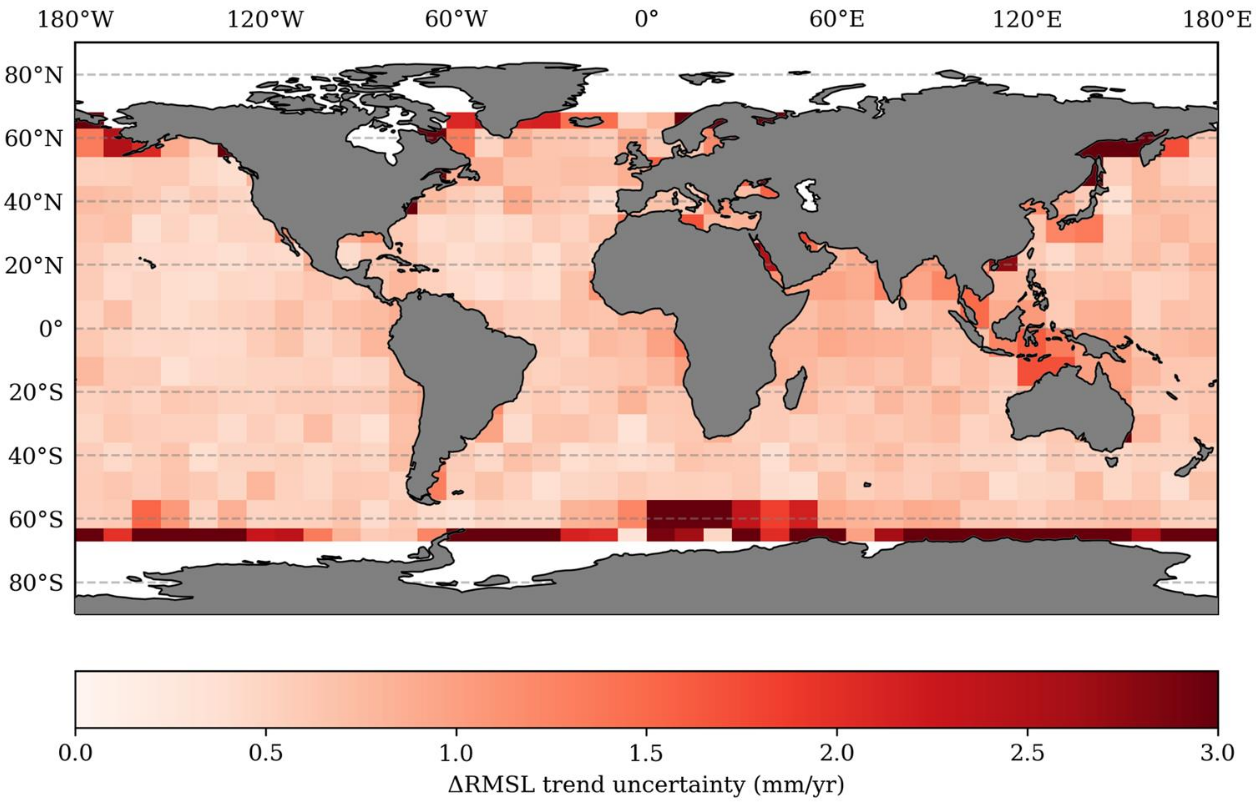


Table A1. Uncertainty budget of GMSL differences between altimeter measurements and tide gauges data from GLOSS/CLIVAR network (from Ablain et al. (2018)).

Source of uncertainty	Time correlation of errors	Uncertainty (1-σ)
Short time-correlated due to tide gauge and altimeter measurement errors, but also due to the collocation of both datasets.	short-term time-correlated errors $\lambda < 6$ months	$U_\sigma = 4.0$ mm for T/P $U_\sigma = 3.5$ mm for Jason-1 $U_\sigma = 2.3$ mm for Jason-2/Jason-3[1]
	short-term time-correlated errors 6 months $< \lambda < 1$ year	$U_\sigma = 1.0$ mm for T/P $U_\sigma = 0.7$ mm for Jason-1 $U_\sigma = 0.5$ mm for Jason-2/Jason-3[1]
Large time correlated errors due to tide gauge networks (e.g. averaging method to take into spatial distribution), long-term stability of tide gauge time serie	long-term time-correlated errors $\lambda < 3$ years	$U_\delta = 0.1 * \sqrt{2}$ mm yr^{-1}
	long-term time-correlated errors $\lambda < 10$ years	$U_\sigma = 1.0$ mm
Linear time-correlated over all the altimetry period due to the VLM errors of the tide-gauge network.	Linear time-correlated errors	$U_\delta = 0.2$ mm yr^{-1}

[1] The uncertainty budget in this study is constructed by taking the U_σ for Jason-2/Jason-3

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Appendix-C

Table B1. Uncertainty budget of the GMSL differences between two altimetry missions not in tandem (from Jugier et al., 2022).

Source of uncertainty		Time correlation of errors	Uncertainties (1-σ)
short-term time-correlated errors due to altimeter processing, precise orbit determination, etc.		short-term time-correlated errors $\lambda < 2$ months	$U_\sigma \in [0.6, 0.8]$[1] mm Depending on altimeter missions
		short-term time-correlated errors 2 months $< \lambda < 1$ year	$U_\sigma \in [0.5, 0.7]$[1] mm Depending on altimeter missions
Stability of the wet tropospheric correction (WTC)		long-term time-correlated errors $\lambda < 5$ years	$U_\sigma = 0$: model WTC are used to cancel WTC errors in GMSL differences
Precise orbit determination stability	International Terrestrial Reference System (ITRF)	Linear time-correlated errors	$U_\delta = 0.1 * \sqrt{2}$ mm yr^{-1}
	Gravity fields	long-term time-correlated errors $\lambda < 10$ years	$U_\sigma = 0.5 * \sqrt{2}$ mm yr^{-1}
GIA correction		Linear time-correlated errors	$U_\delta = 0$

[1] The uncertainty budget in this study is constructed by taking the mean value of the range : $U_\sigma = 0.7$ mm for $\lambda < 2$ months and $U_\sigma = 0.6$ mm for 2 months $< \lambda <$ 1 year.

Appendix-D

Table C1. Uncertainty budget of the MSL differences between two altimetry missions not in tandem (from Jugier et al., 2022). Values are provided for $9° \times 9°$ box sizes within a 16th-percentile and 84th-percentile interval.

Source of uncertainty	Time correlation of errors	Uncertainties (1-σ)
short-term time-correlated errors due to altimeter processing, precise orbit determination, etc.	short-term time-correlated errors $\lambda < 2$ months	$U_\sigma \in [0.6, 0.8]$[1] mm Depending on altimeter missions
	short-term time-correlated errors 2 months $< \lambda < 1$ year	$U_\sigma \in [0.5, 0.7]$[1] mm Depending on altimeter missions
Stability of the wet tropospheric correction (WTC)	long-term time-correlated errors $\lambda < 5$ years	$U_\sigma = 0$: model WTC are used to cancel WTC errors in GMSL differences
Precise orbit determination stability	Linear time-correlated errors	$U_\delta = 0.33 * \sqrt{2}$ mm yr^{-1}
Gravity fields	long-term time-correlated errors $\lambda < 10$ years	$U_\sigma = 0.5 * \sqrt{2}$ mm yr^{-1}
GIA correction	Linear time-correlated errors	$U_\delta = 0$

[1] The uncertainty budget in this study is constructed by taking the median value : $U_\sigma = 9.4$ mm for $\lambda < 2$ months and $U_\sigma = 4.9$ mm for 2 months $< \lambda < 1$ year.