

Vers une stabilité de l'ordre de 0,1 mm/an sur plusieurs décennies pour la mesure du niveau de la mer à l'aide de marégraphes associés à des instruments GNSS ?

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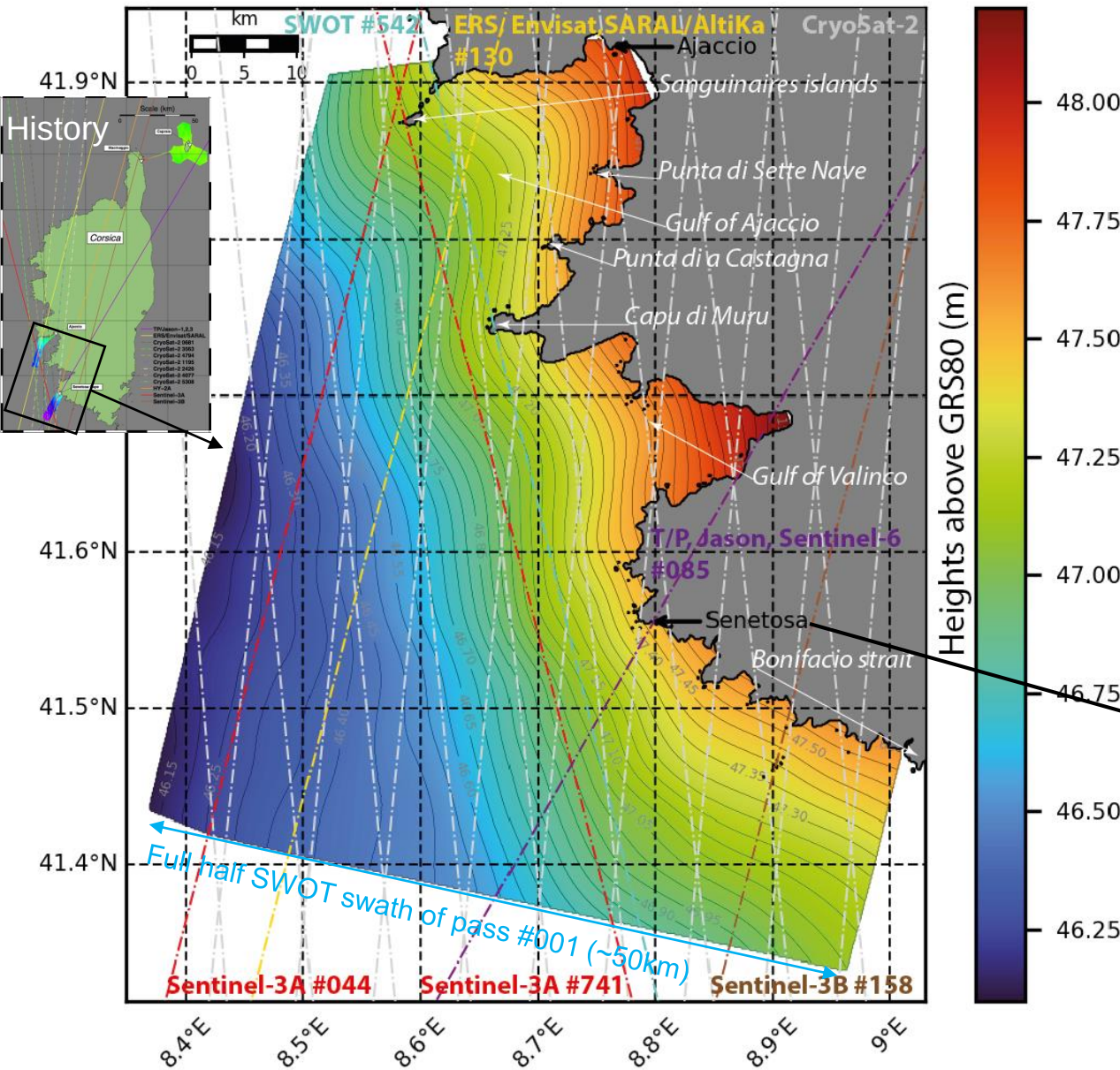
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For more details about the tide gauges and GNSS precision, scan the QR code or click on DOI link:

Bonnefond, P., Laurain, O., Exertier, P., Calzas, M., Drezen, C., Fichen, L., Guillot, A., Guinle, T., Picot, N. (2025). Towards 0.1mm/yr stability over decades for measuring sea level using tide gauges together with GNSS-based instruments? *Marine Geodesy* 49 (2): 258–287. <https://doi.org/10.1080/01490419.2025.2546920>

Corsica Multi-mission Calibration Site for altimetry long-term accurate monitoring

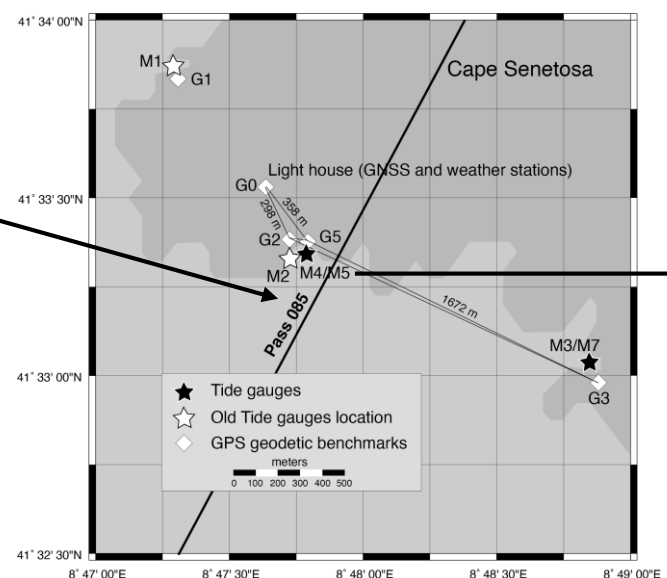


History:

- **Senetosa and Ajaccio calibration site** established for continuous monitoring of respectively since ~1998:
 - Sentinel-6 MF & Jason-3 (and formerly T/P and Jason-1&2)
 - SARAL/AltiKa (and formerly ERS, Envisat)
- **Open-ocean altimeter readings** connected to tide gauges via detailed local GNSS reference surfaces

“Recent” developments:

- **Widened GNSS reference surface** to cover a full half SWOT swath but also to perform monitoring of the nadir missions in a common geodetic reference frame (major surveys in 2021 & 2022) , see <https://doi.org/10.1080/01490419.2026.2731015>
- **Reference GNSS marker and receiver** duplicated since 2021 at Senetosa
- **New high-precision tide gauges** (since 2012) and weather stations at Senetosa (since 2015)

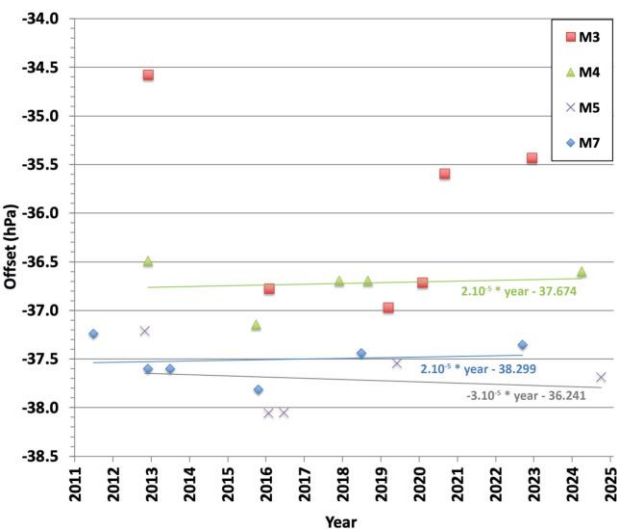


Part 1: Instrumental stability

Senetosa pressure tide gauges SSH stability monitored by:

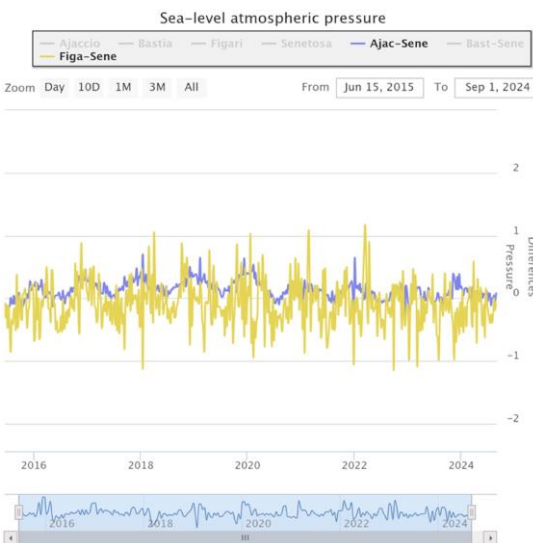
- A: Pressure sensors' calibrations (~every 2 years at SHOM)
- B: Atmospheric pressures used for compensation of tide gauge pressures
- C: Relative differences between the 4 tide gauges
- D: External control using GNSS-based measurements (GNSS-zodiac)

Derived potential drift: ~-0.1mm/yr



Variations of the calibration of the mean offset (~37hPa by construction) over the last 14 years for the Senetosa tide gauges.

A: Drift equivalent to 0.2–0.3mm/yr
Over the last 14 years but the calibration is applied and removes such potential drift



Atmospheric pressure differences in hPa between Ajaccio (Ajac) or Figari (Figa) and Senetosa (Sene) weather stations

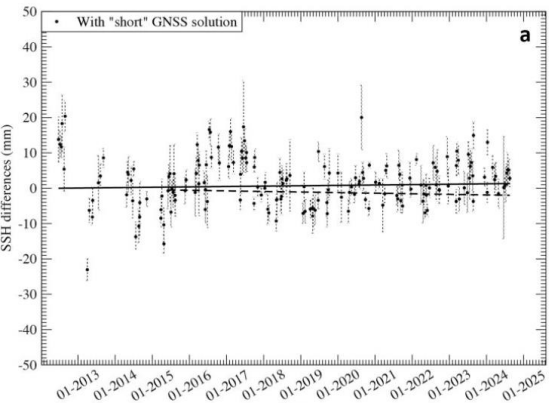
B: Drift due to the atmospheric pressure of ~-0.1mm/yr over the last 10 years

C: relative drift < -0.1mm/yr over last 10 years and mean SSH differences at a few mm level

Table 5. Statistics of the SSH differences between tide gauges themselves (Mi where i is the tide gauge number) at Senetosa, from 1 June 2015 to 30 August 2024.

Type of comparison (distance)	Mean (mm)	σ (mm)	Drift (mm/yr)	Number of values
M4-M3 (~1.7 km)	+5.3	7.9	+0.17 ± 0.02	242282
M5-M3 (~1.7 km)	+6.9	8.3	+0.05 ± 0.01	292166
M3-M7 (~0.3 m)	-1.8	6.2	-0.11 ± 0.01	266058
M4-M5 (~0.3 m)	-2.4	4.3	-0.16 ± 0.01	354880
M4-M7 (~1.7 km)	+2.3	8.7	-0.04 ± 0.02	323352
M5-M7 (~1.7 km)	+4.5	8.6	-0.13 ± 0.02	345364
Average	+3.1	7.3	-0.04 ± 0.01	304017

The distances between the instruments are indicated in brackets.



SSH differences between GNSS-zodiac and tide gauges from 6 July 2012 to 30 August 2024.

D: Drift of ~-0.1mm/yr over last 12 years and mean SSH differences at a few mm level



Part 2: Vertical Land Motion (VLM)

Methodology:

- Coordinates' time series have been produced by SPOTGINS (<https://ac-gnss.pagelab.univ-lr.fr/spotgins/>)
- Analysis of GNSS time series for 4 stations in the South of Corsica with more than 10 years of data

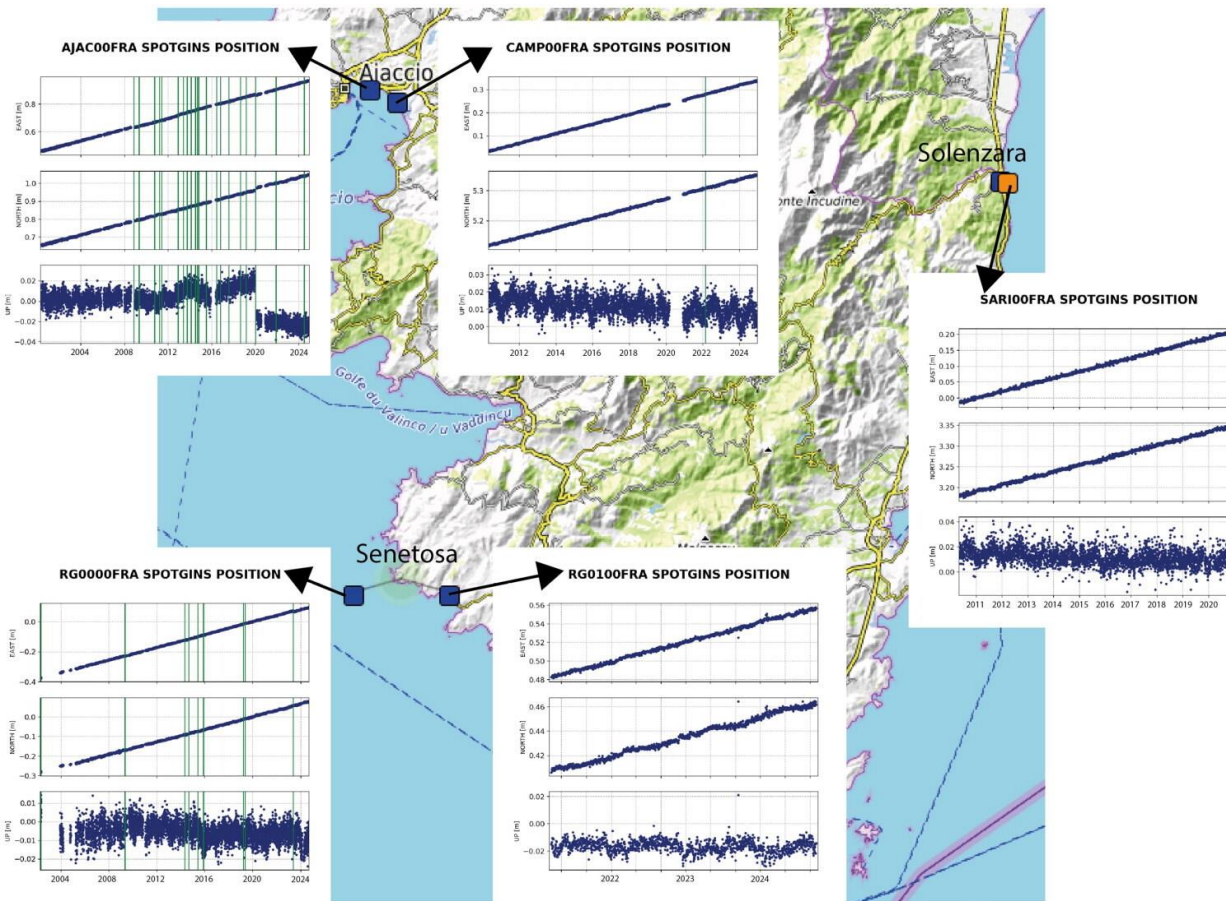


Table 2. Vertical velocities of GNSS sites in the South of Corsica issued from SPOTGINS time series (<https://ac-gnss.pagelab.univ-lr.fr/spotgins/>) and estimated with a more sophisticated model before linear least squares weighted by the standard deviation of each daily point using SARI tool (Santamaría-Gómez 2019) from (<https://en.poletterresolide.fr/geodesy-plotter-en/>).

Site name	Vertical velocity and uncertainty (mm/yr)	Series length (yr)	Series range (yr start – yr end)
RG00	$+0.24 \pm 0.03$ [0.23]* ($+0.11 \pm 0.03$ [0.34]*)	20.7488 (12.17)	2003.9356–2024.6844 (2012.5–2024.67)
AJAC	-0.13 ± 0.02 mm/yr [0.19]* (-0.63 ± 0.07 [0.37]*)	24.6065 (12.17)	2000.3402–2024.9467 (2012.5–2024.67)
CAMP	-0.56 ± 0.02 mm/yr [0.28]* (-0.50 ± 0.04 [0.34]*)	14.5810 (12.17)	2010.3657–2024.9467 (2012.5–2024.67)
SARI	-0.78 ± 0.03 mm/yr [0.38]* (-0.67 ± 0.04 [0.48]*)	10.3597 (8.2186)	2010.3657–2020.7254 (2012.5–2020.7254)
Average	-0.31 ± 0.03 mm/yr [0.27]* (-0.42 ± 0.05 [0.38]*)		

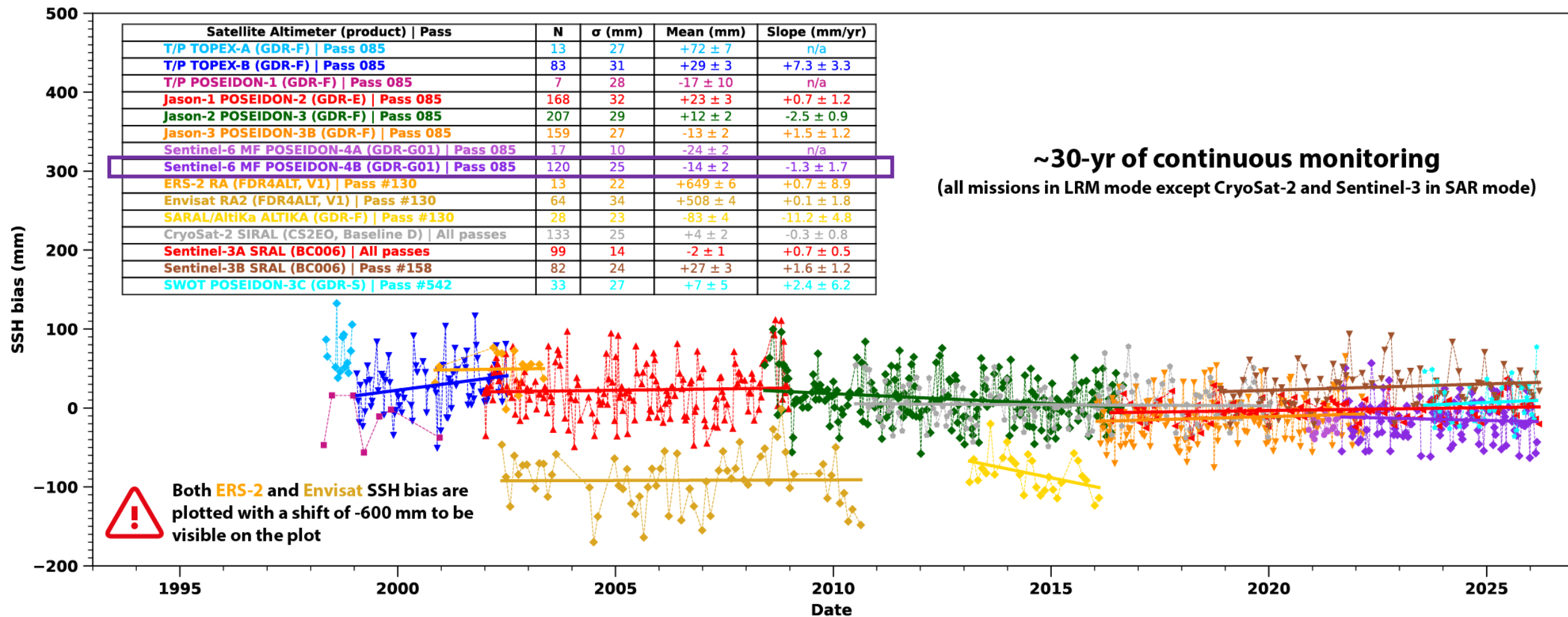
The aforementioned model is characterized by a more sophisticated design, incorporating a sinusoidal fit in conjunction with offsets (see Table 3). Values in brackets correspond to the time period studied in section ‘comparisons of the measurement systems (tide gauges and GNSS-zodiac)’ (6 July 2012 to 30 August 2024).

*Square bracket corresponds to uncertainty including noise analysis (white and flicker)

Even close to the uncertainty (0.27mm/yr), the averaged Vertical Land Motion suggests a subsidence of the South of Corsica at the level of -0.31mm/yr

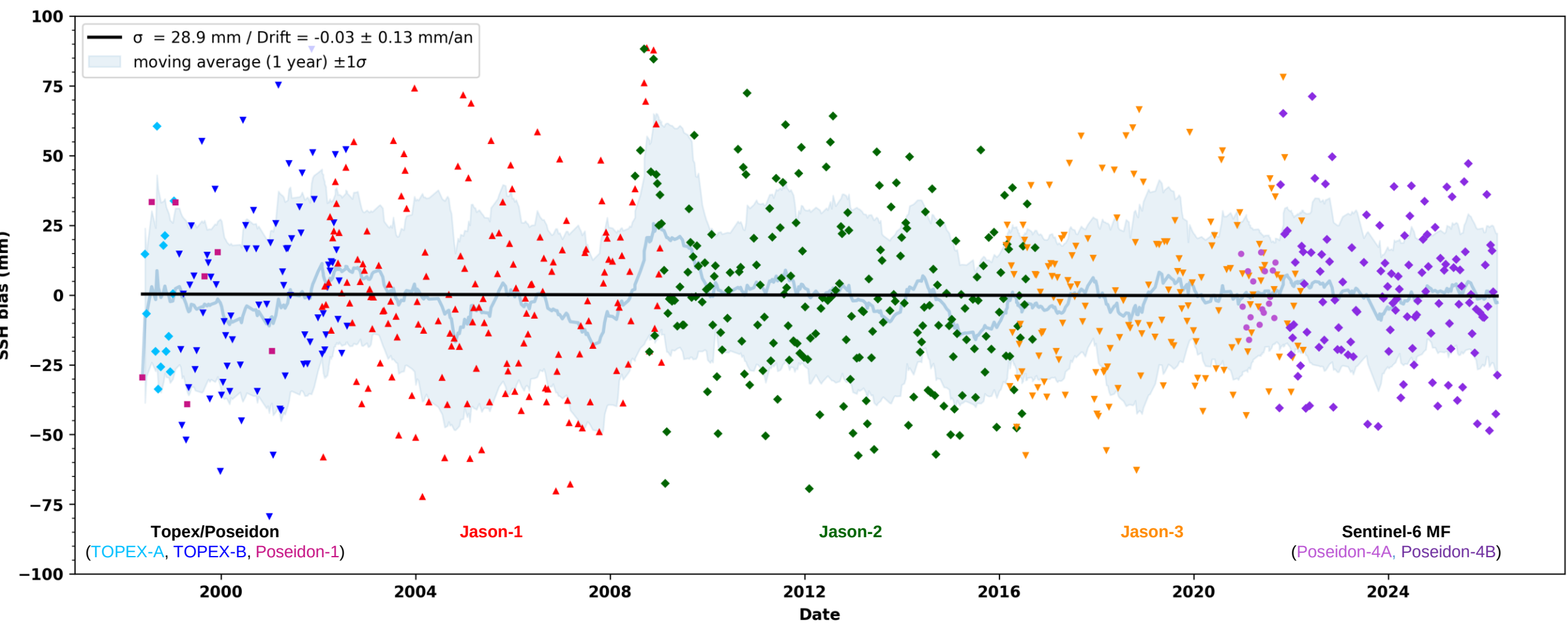
In consequence, the SSH biases from altimeter calibration increase by +0.31mm/yr (applied for results presented in the following slides).

A review of ~30 years of nadir altimetry



Recent missions (e.g. Sentinel-6 MF) exhibit a remarkable small absolute SSH bias with a derived slope statistically not significant.

Reference missions' UNBIASED time series



After removing the respective absolute SSH biases (no individual trend removed) for each reference mission:
Over ~30-yr the time series shows a **negligible drift** with a **high stability of ~0.1 mm/yr**

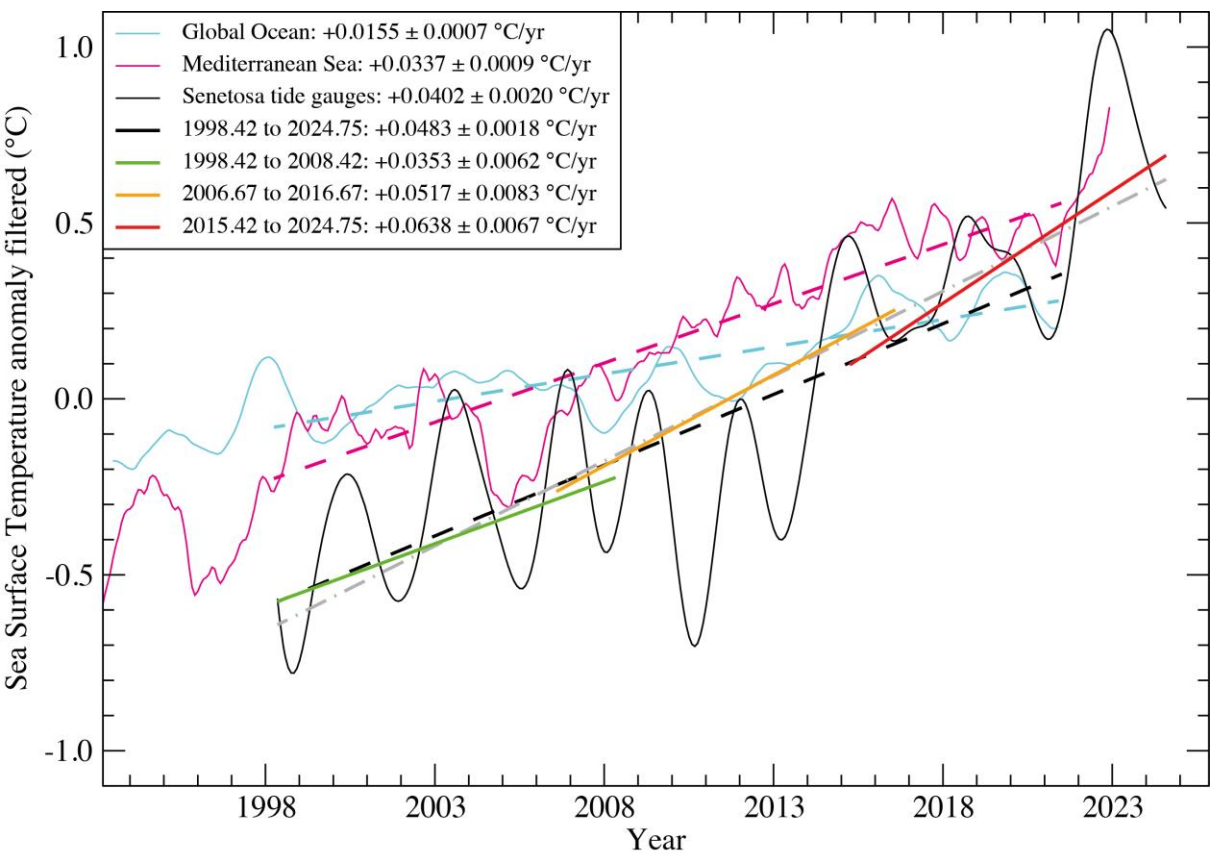
The blue line and its envelop shows the evolution of the standard deviation, illustrating the increase of stability for recent missions

Mean Sea Level Rise observed at Senetosa by the local tide gauges

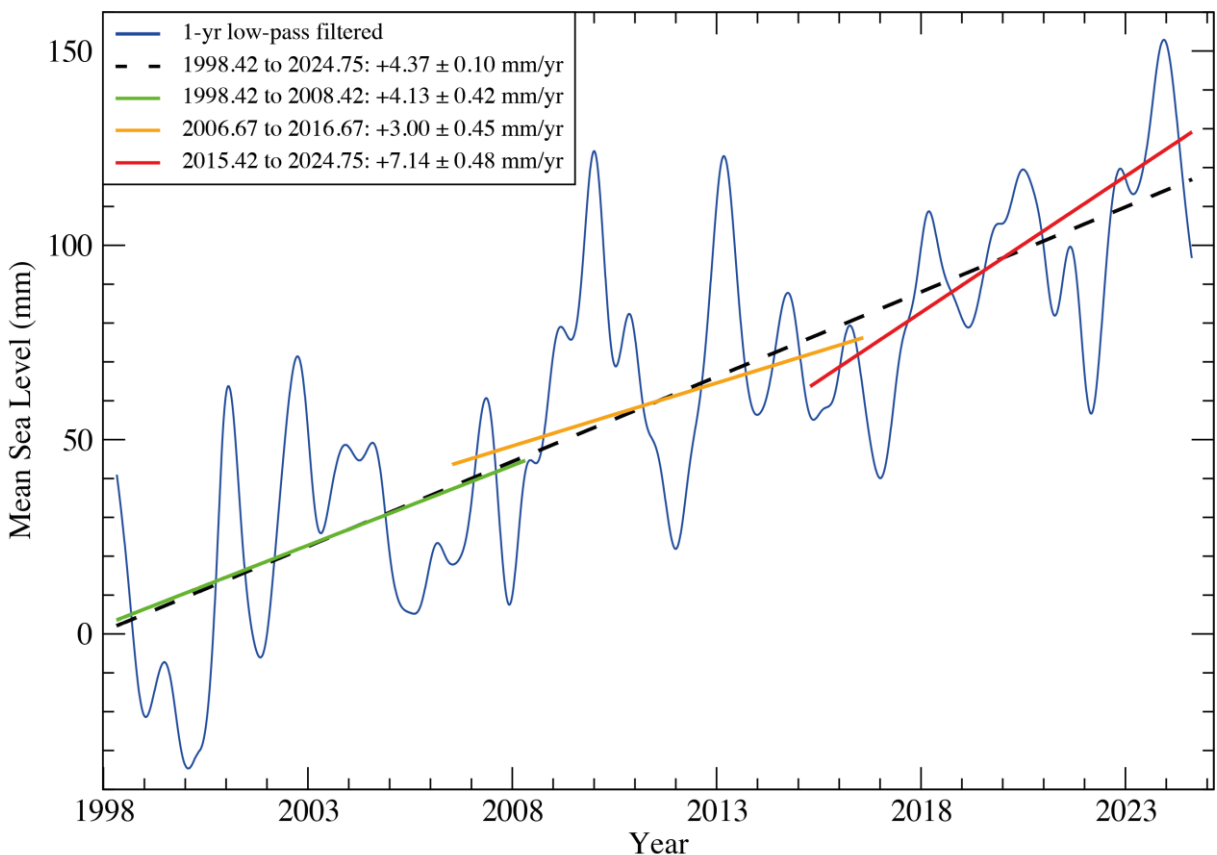
Key issues and findings:

- Over ~26 years of continuous monitoring the Mean Sea Level Rise is 4.37 mm/yr with an uncertainty of 0.10 mm/yr,
- This study also shows an increase in rate of the Mean Sea Level Rise recorded over the last 10 years (7.14 mm/yr) compared to the first 10 years (4.37 mm/yr),
- This is mostly attributable to the increase in rate of the sea temperature over the whole time period and especially during the last 2 years,
- We also have estimated an acceleration of about +0.18 mm/yr² and +0.23 mm/yr² from respectively Senetosa and Ajaccio tide gauges.

Sea Temperature (°C)



Sea Level (mm)



Conclusions

- In situ SSH stability (tide gauges):
 - 😊 **No significant instrumental drift confirmed by internal and external control ($<0.1\text{mm/yr}$)**
 - 😞 **Vertical Land Motion suggests a subsidence of the South of Corsica at the level of -0.31mm/yr but the uncertainty remains relatively high (0.27mm/yr)**
- Full SSH bias reprocessing for TOPEX/Poseidon, Jason-1,2,3 and Sentinel-6 MF with the new reference surface and latest products' reprocessing:
 - Latest reprocessing (GDR-F) **improves the inter-mission consistency** and reduce the individual mission's standard deviations
 - Applying the **Vertical Land Motion (-0.31mm/yr)** also improves the inter-mission consistency (reduces the standard deviation of the SSH biases time series by $\sim 3\text{mm}$)
- **Mean Sea Level Rise in Corsica**
 - Over ~ 26 years, **Mean Sea Level Rise is $4.37 \pm 0.10 \text{ mm/yr}$**
 - An **increase in rate of the Mean Sea Level Rise** recorded over the last 10 years compared to the first 10 years, **mostly attributable to the increase in rate of the sea temperature**



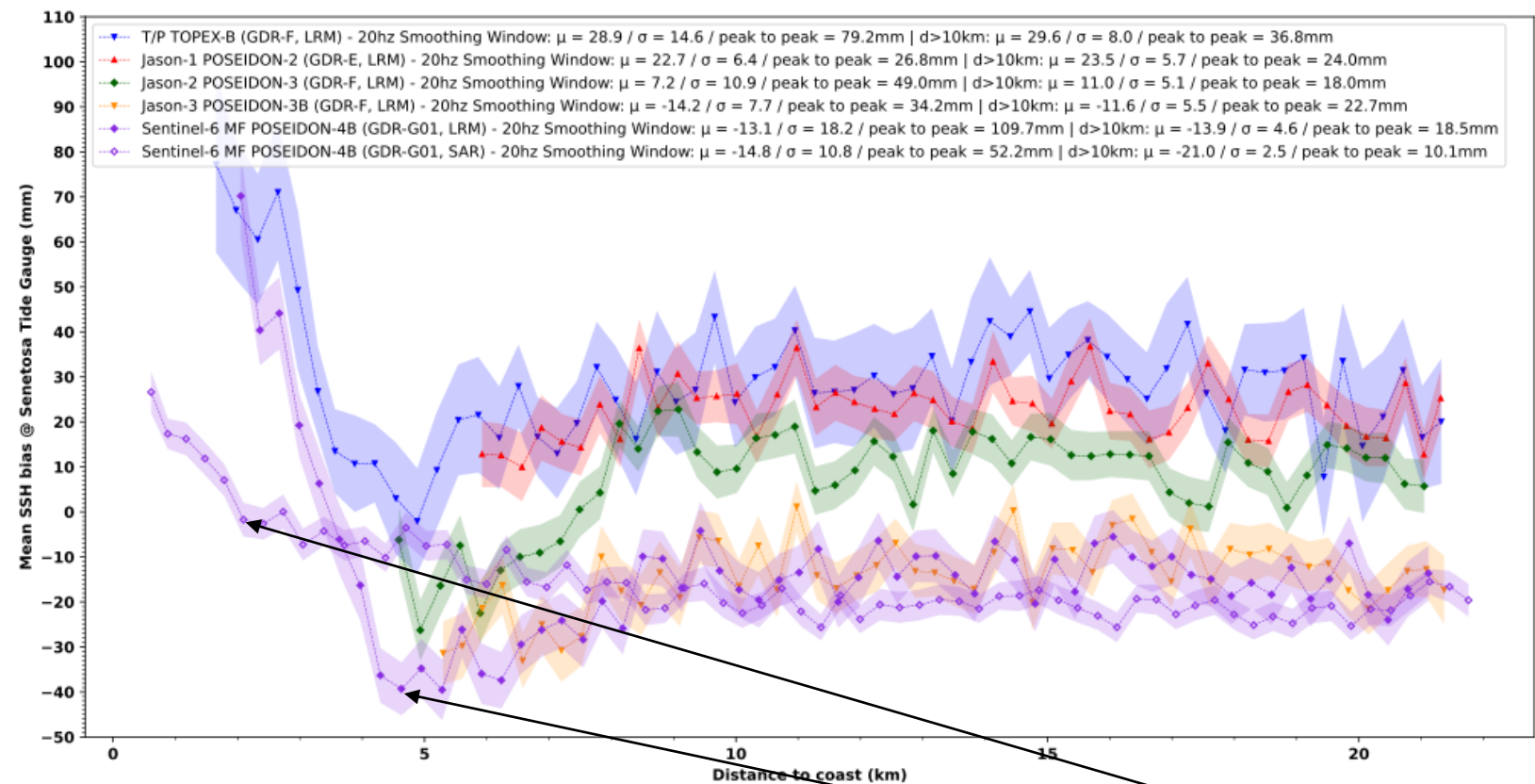
To download **individual Senetosa tide gauges** time series on **Aviso+**, scan the QR code or click on DOI link:
<https://doi.org/10.24400/527896/a01-2025.003>



To download **the synthetic (average) Senetosa sea level** time series on **REFMAR**, scan the QR code or click on DOI link:
<https://dx.doi.org/10.17183/REFMAR#792>

Backup slides

Land contamination in altimetry measurements

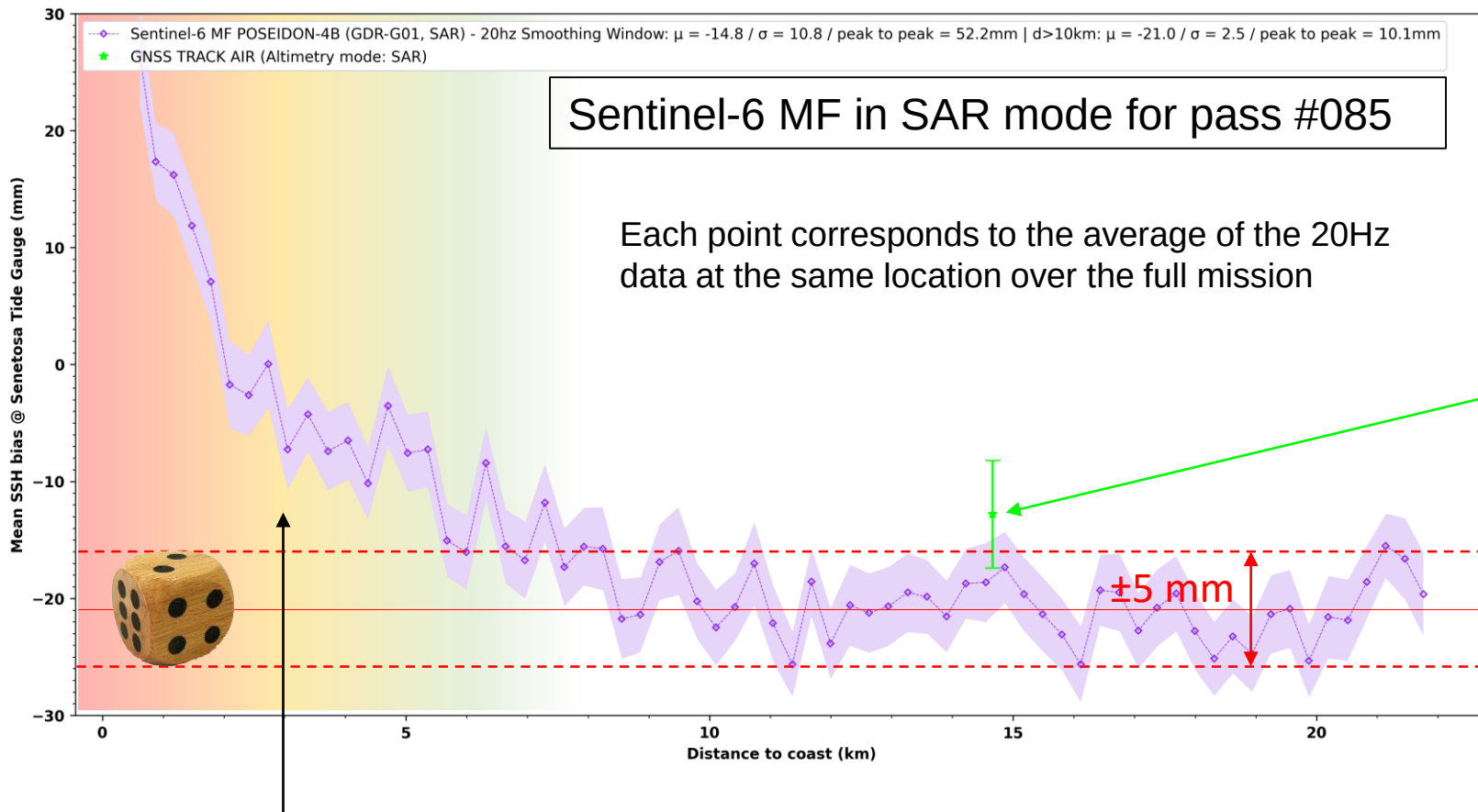


The behavior is quite similar for all the satellites in LRM: a SSH drop of few cm between 8 and 5 km, followed by a more important rise (several cm) in SSH over the last 5 km.

This land contamination in LRM avoids using data in this area to derive a SSH bias coherent with open ocean conditions.

Thanks to Sentinel-6 with the 2 modes in interleaved (see diamonds, LRM=filled/SAR=empty):
Dispersion into uncontaminated areas (>10 km) is also considerably reduced in SAR (2.5mm) compared to LRM (4.6mm).

Close look up to the coast thanks to SAR



- **Most of the averaged of 20Hz SSH biases** in boxes of 316 m are **within $\pm 5\text{mm}$** (standard deviation of 2.5mm)
- **Standard error** (see error bars) of SAR individual 20Hz data is **improved by ~2**: ~5mm compared to ~10mm with LRM
- **GNSS-based sea level** measurements (GNSS-zodiac) show a **consistent SSH bias (only ~5mm difference)** compared to the one derived from tide gauges

A clear reduction of the coastal contamination with SAR mode (compare to LRM) for which a more regular pattern is observed, starting at 8 km, but significantly increasing by more than 2 cm over the last 3 km.