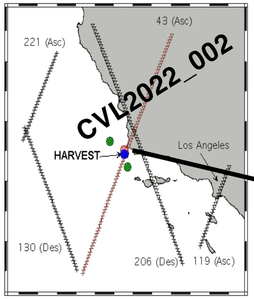
Absolute calibration results from Bass Strait, Corsica, and Harvest facilities



Harvest, United States:

T/P-Jason legacy

+ Extension for SARAL/AltiKa, Sentinel-3A&B

Preparation for SWOT

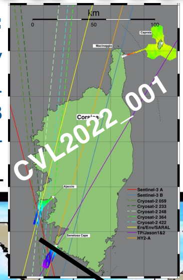
Bruce Haines (Jet Propulsion Laboratory, California Institute of Technology), **Shailen Desai** (Jet Propulsion Laboratory, California Institute of Technology), **Jean-Damien Desjonquères** (Jet Propulsion Laboratory, California Institute of Technology), **Bob Leben** (University of Colorado, Boulder), **Christian Meinig** (NOAA Pacific Marine Environmental Laboratory), **Scott Stalin** (NOAA Pacific Marine Environmental Laboratory), **Andy Wu** (Jet Propulsion Laboratory, California Institute of Technology)

Corsica, France:

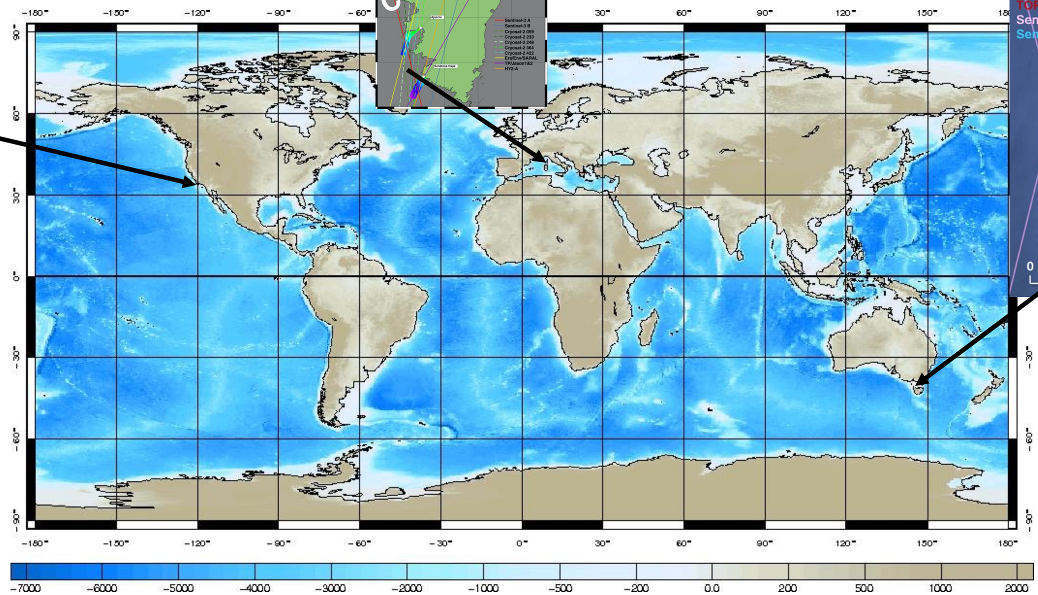
T/P-Jason legacy

+ ERS-Envisat, SARAL/AltiKa, CryoSat-2, HY-2A, Sentinel-3A&B

Preparation for SWOT



Pascal Bonnefond (Observatoire de Paris - SYRTE), **Olivier Laurain** (OCA/Géoazur), **Pierre Exertier** (GET), **Thierry Guinle** (CNES), **Pierre Féménias** (ESA/ESRIN)

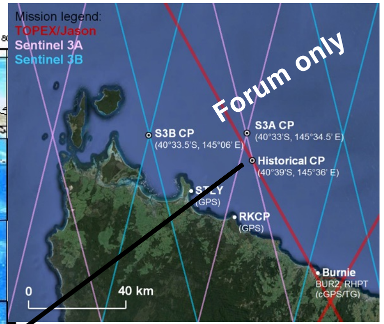


Bass Strait:

T/P-Jason legacy

+ Extension for Sentinel-3A&B

Preparation for SWOT



Benoit Legresy (CSIRO Climate Science Centre, Oceans and Atmosphere, Hobart, Australia. and Integrated Marine Observing System, Hobart, Australia.), **Christopher Watson** (School of Geography, Planning, and Spatial Sciences, University of Tasmania, Hobart, Australia. and Integrated Marine Observing System, Hobart, Australia.), **Jack Beardsley** (Integrated Marine Observing System, University of Tasmania, Hobart, Australia.), **Arthur Zhou** (School of Geography, Planning, and Spatial Sciences, University of Tasmania, Hobart, Australia.), **Matt King** (School of Geography, Planning, and Spatial Sciences, University of Tasmania, Hobart, Australia.)

Key points:

Common presentation gathering results from:

Posters:

CVL2022_001 - Jason-3 & Sentinel-6 MF calibration at the Corsica facilities Pascal Bonnefond et al.

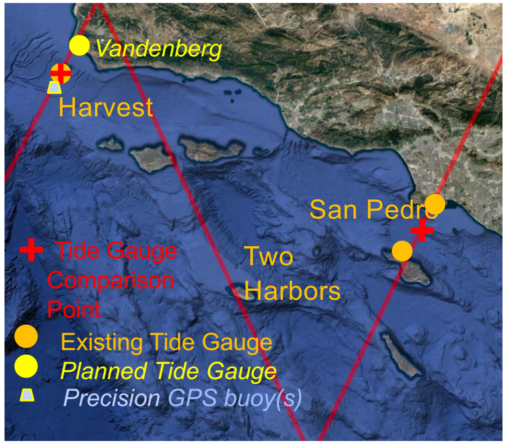
CVL2022_002 - The Harvest Experiment: Status and New Results from the Sentinel-6 Mission Bruce Haines et al.

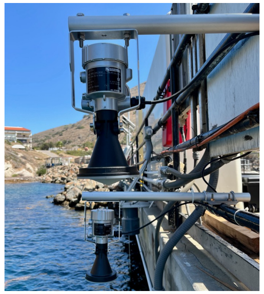
Forum only:

- Altimeter validation results from the Bass Strait validation facility, Australia Benoit Legresy et al.

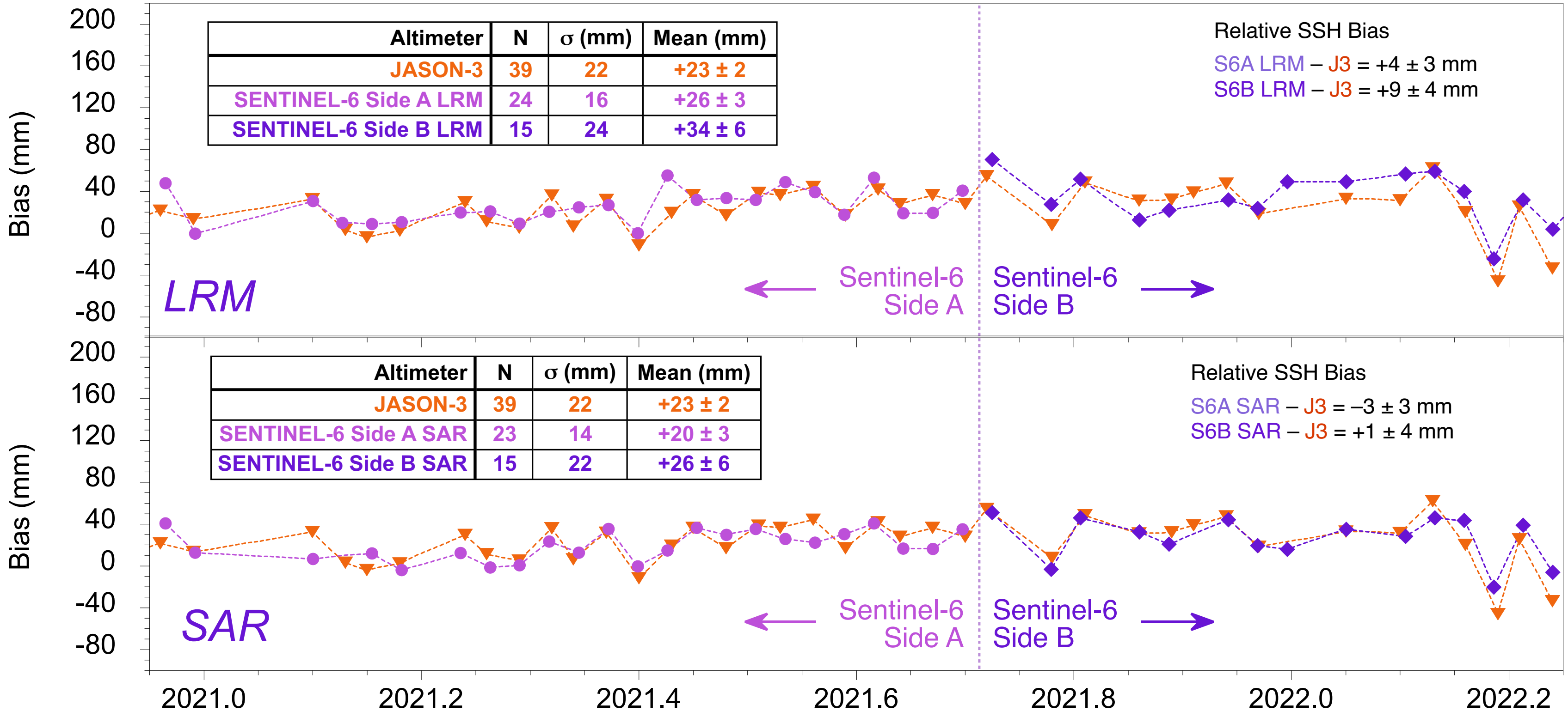
Platform Harvest: End of An Era

- **NASA Prime Verification Site for altimeter reference missions since 1992**
  - Supports continuous monitoring with redundant radar tide gauges and GPS.
  - Provides connection dating back to original TOPEX/Poseidon mission.
  - Exceptional verification record has been established for Sentinel-6.
- **Platform to be decommissioned**
  - Notice to vacate received summer 2022.
  - Platform to be placed on “cold standby” (TBD date): unmanned, except for inspection visits.
  - Plans for instrument removal awaiting approval.
  - Instruments continue to operate in interim.
- **Transition plan being followed**
  - New Harvest precise GPS buoy successfully deployed March 2022, following cadence of yearly swap outs.
  - Vandenberg tide gauge (recently approved) to be installed ASAP to enable overlap with Harvest.
  - Catalina buildout continues (transponder, new radar gauge in September 2022).





Harvest Absolute SSH Bias: Sentinel-6/Jason-3 Formation Flight



Key Points:

Here we focus on the Harvest calibration record during the Sentinel-6 verification phase, i.e. when the satellite was flying in formation with Jason-3 to promote direct comparison of the two satellite measurement systems.

The top panel uses the low-resolution mode (LRM, aka “pulse limited”) range from Sentinel-6, while the bottom panel uses range from the unfocused synthetic aperture radar (SAR) mode. The Jason-3 data (no SAR mode) provide the reference, and are the same in both cases.

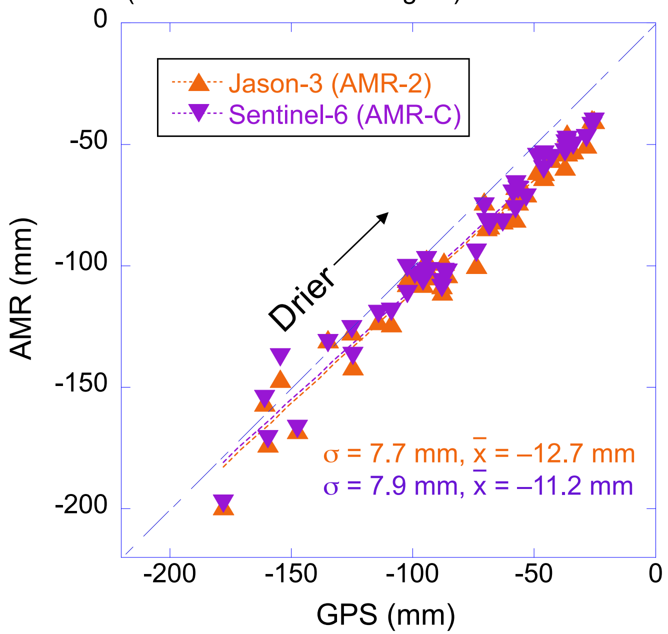
The absolute SSH bias estimates for all systems are slightly positive, ranging from 2–3 cm. While only the formal errors are provided in the figure, the total estimated error is closer to 1.5 cm, accounting primarily for uncertainty in the platform vertical.

The agreement between Sentinel-6 and Jason-3 is excellent, both in terms of relative bias (<1 cm) and point-to-point scatter (< 2 cm).

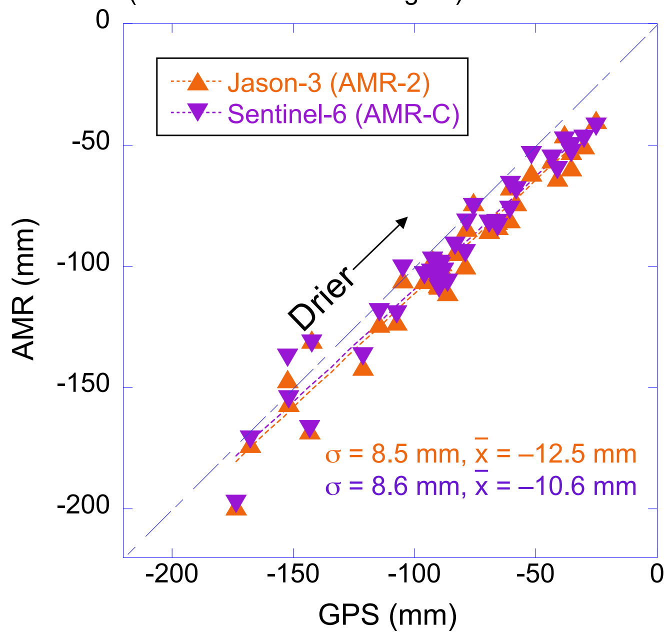
Wet Zenith Troposphere Calibration at Harvest

GPS vs. Radiometer During S6VT Verification Phase

Platform GPS vs. Radiometer
(N = 43 common overflights)



Buoy GPS vs. Radiometer
(N = 38 common overflights)



- AMR path delays wetter than GPS by ~1 cm.
- Comparisons hint at a scale error (differences larger for driest overflights).
- Excellent agreement between platform and buoy GPS (Mean = 0.2 mm, σ = 4 mm)

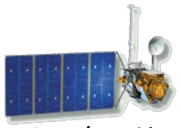
Key Points:

Precise GPS data collected at the Harvest site are used not only to determine the position of the platform, but also to estimate the zenith wet troposphere. This information is used in turn to monitor the performance of the Advanced Microwave Radiometers (AMR) on Jason-3 and Sentinel-6.

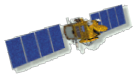
Depicted in the left panel is a scatter plot comparing GPS platform retrievals with those from the AMRs. The scatter of the instantaneous comparisons about the fit lines is better than 1 cm, which is considered state of the art. A slight bias (~1 cm) indicates that the AMR measures wetter than GPS, and there is also a hint of a scale error. Analysis of data from the Sentinel-6 High Resolution Microwave Radiometer (HRMR) data (provided in our poster) show similar patterns. The results testify to the high performance of both AMRs, but additional work is needed to fully understand the small, remaining systematic difference.

A precise GPS buoy has been moored near Harvest as a major element of the plan to compensate for the upcoming decommissioning of the platform. Though the process is more challenging due to the unpredictable motions of the buoy, these GPS data can also be used to estimate wet troposphere delay (right panel). The comparisons to AMR reinforce the results from the platform, and testify to the strength of the GPS data collected on the buoys.

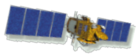
Bass Strait Validation Facility:



TOPEX / Poseidon
Aug 1992

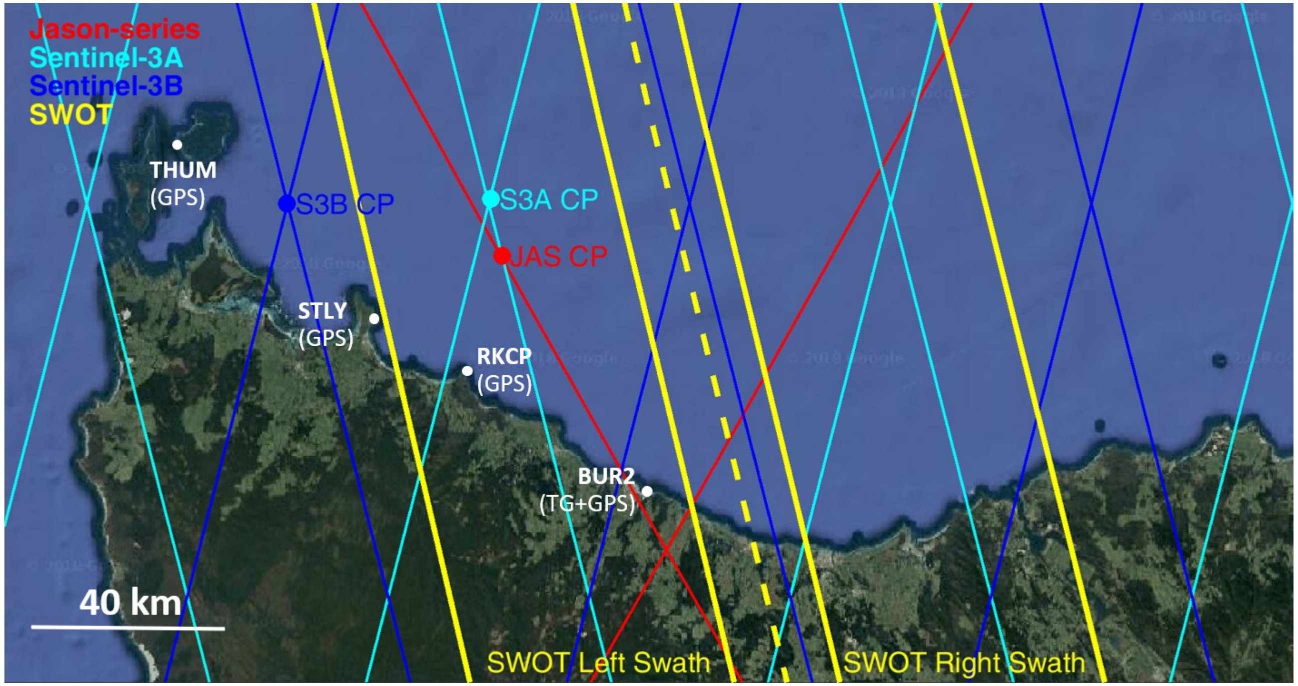


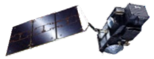
Jason-1
Dec 2001



OSTM/Jason-2
June 2008

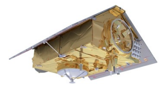
Jason-3
Jan 2016



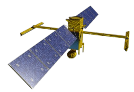


Sentinel-3A
Feb 2016

Sentinel-3B
Apr 2018



Sentinel-6 /
Michael Freilich
Nov 2020

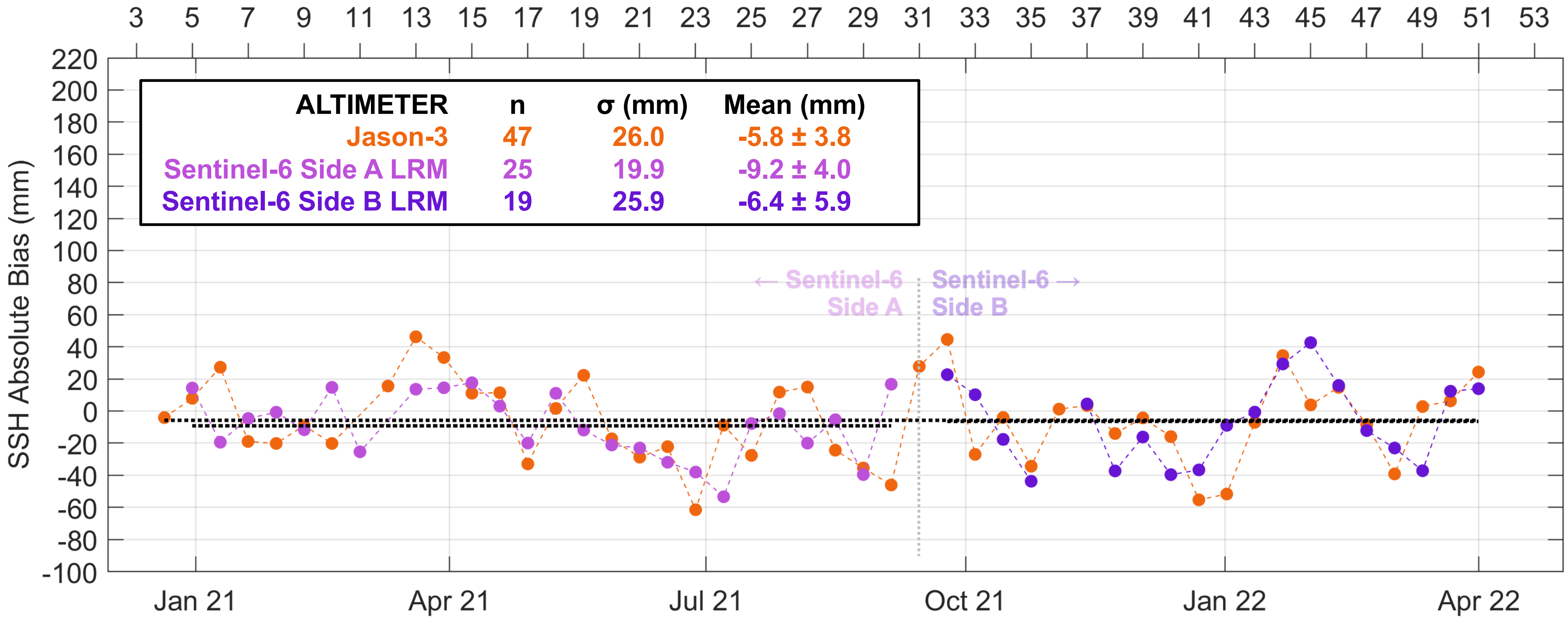


SWOT
Dec 2022 (planned)

Key Objectives of the Bass Strait Validation Facility:

- Sustained in situ observation and validation of satellite altimetry at three key in situ comparison points (CPs): Jason-series / reference missions (JAS in red), Sentinel-3A (S3A in cyan) and Sentinel-3B (S3B in blue).
- Development of improved in situ instrumentation to enable validation of next generation advanced altimeters (Sentinel-6 and SWOT). In particular:
  - ➢ Development of a current, waves, pressure inverted echo sounder (CWPIES) enabling precise observation of currents, waves and SSH.
  - ➢ Development of a new GNSS/INS buoy array capable of sustained deployment over SWOT validation phase.

Absolute Bias at Bass Strait – J3/S6 FFP

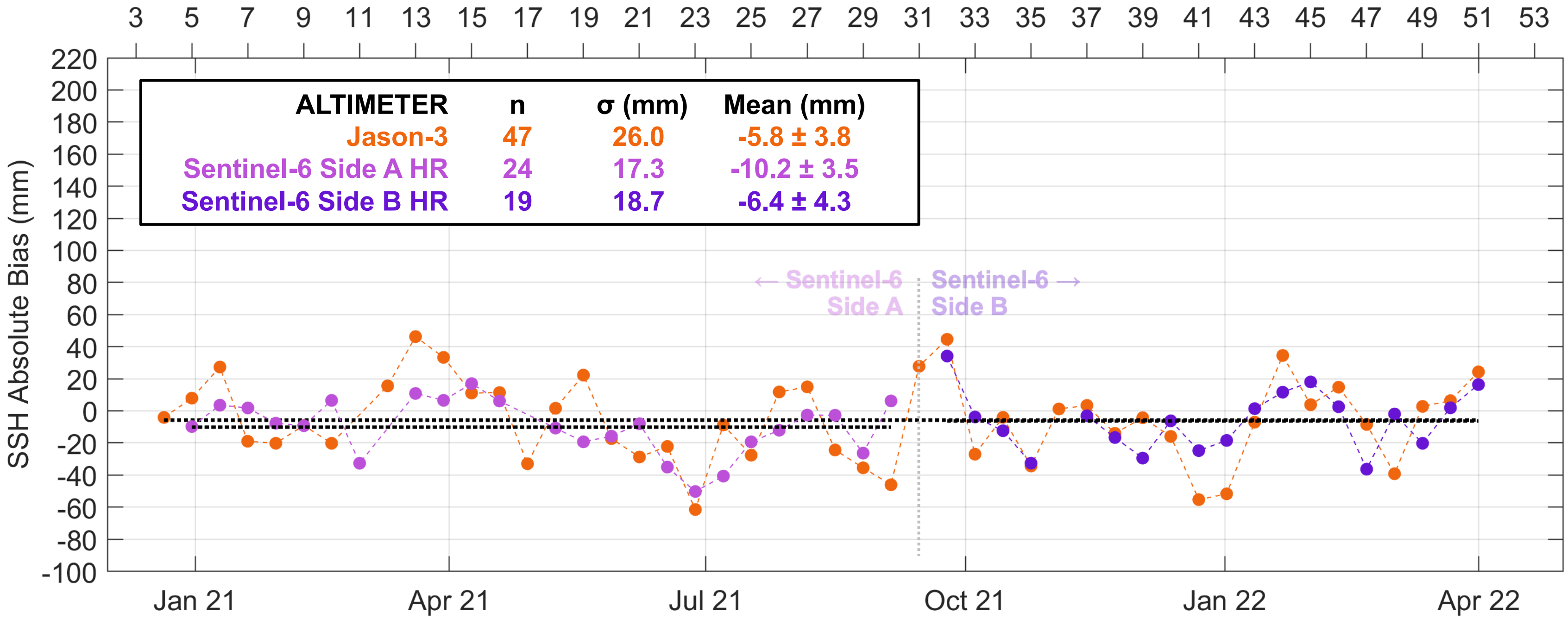


Relative bias: S6A LRM – J3 = -3.4 ± 4.6 mm
S6B LRM – J3 = +0.5 ± 5.1 mm

Key Points:

- Over the formation flight phases, Jason-3, Sentinel-6 Side A and Sentinel-6 Side B biases show negligible differences.
- Relative bias from common cycles indistinguishable from zero.
- No clear changes of behaviour in the switch from Side A to Side B for Sentinel-6.

Absolute Bias at Bass Strait – J3/S6 FFP



Relative bias: **S6A HR – J3 = -2.2 ± 4.7 mm**
S6B HR – J3 = +0.6 ± 4.4 mm

UNIVERSITY of TASMANIA AUSTRALIA

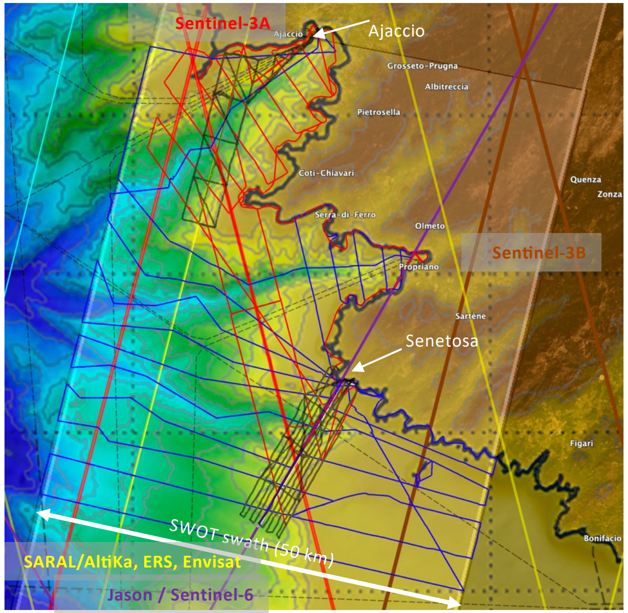
IMOS Integrated Marine Observing System

Legresy et al. Altimeter validation results from the Bass Strait validation facility, Australia

Key Points:

- Variability for Sentinel-6 biases using HR mode data have sub-2 cm variability. Note this includes contributions from the altimeter and in situ data.
- Again, relative bias from common cycles indistinguishable from zero.

Corsica Multi-mission Calibration Site



June 2021 and May 2022 surveys. Black lines for surveys of Ajaccio (2005) and Senetosa (1999) reference surfaces (bathymetry in background)

Evolution of the Corsica facilities:

- **Extension/unification of the reference surfaces**
  - Junction of the historical Senetosa and Ajaccio references surfaces following the Sentinel-3A ground track (**measurements in June 2021, 378 nautical miles**)
  - Extend and densify the reference surface in preparation of SWOT (**measurements in May 2022, 508 nautical miles**)
- **Preliminary results**
  - Measurements using **CalNaGeo and Cyclopée**: preliminary results show a **very good consistency** (few mm in average / 20 mm standard deviation)

Key Points:

•**Senetosa CNES calibration site** established in 1998: Supports continuous monitoring of Jason-3 (and formerly T/P and Jason-1&2). Equipped with 4 pressure tide gauges leveled to the permanent GPS receiver

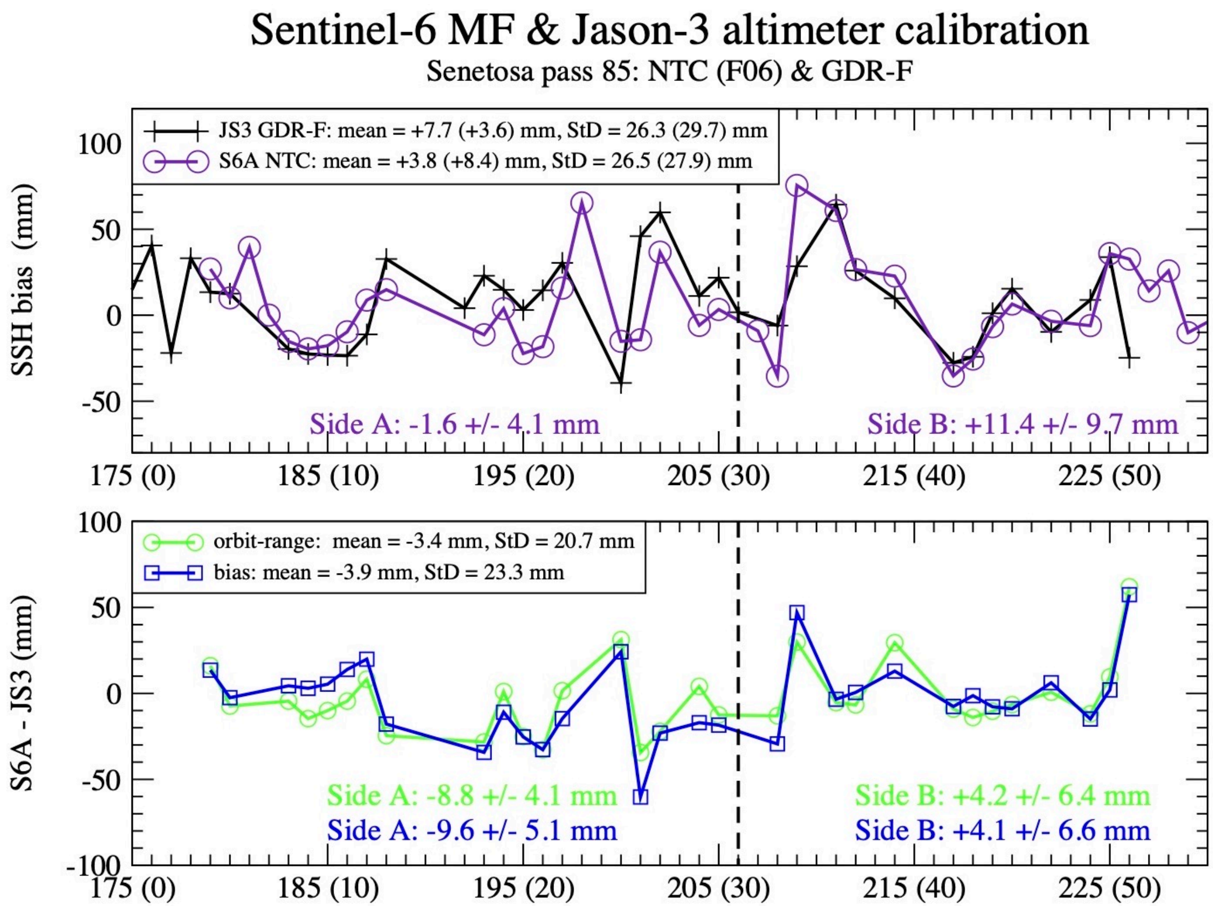
•**Ajaccio configuration** established in 2000**:** Supports continuous monitoring of SARAL/AltiKa (and formerly ERS, Envisat). Fiducial point near Ajaccio equipped with GPS/SLR(FTLRS)/DORIS. Equipped with a radar tide gauge (SHOM) leveled to the permanent GPS receiver

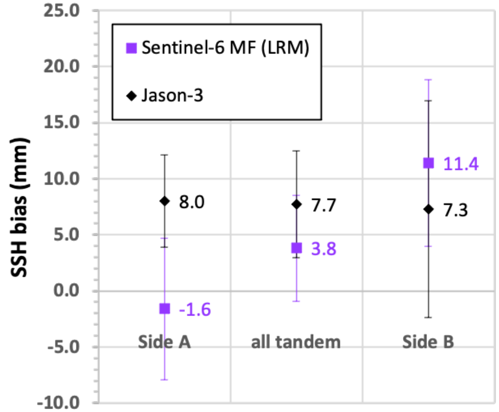
•**Corsica multi-mission calibration site: existing facilities also used for CryoSat-2, HY-2A and Sentinel-3A&B**

•**Open-ocean altimeter readings** connected to tide gauges via detailed **local geoid model.** Derived from intensive GPS-catamaran surveys along ground track (in 1999 for Senetosa). Extension to Ajaccio (2005) and Capraia (2004). Open-ocean verification locations for GNSS-based SSH measurement systems deployments. **Recent connection of the Ajaccio and Senetosa local geoids along the Sentinel-3A track**

All recent results and history of the Corsica calibration site are available in this paper: Bonnefond, P., Exertier, P., Laurain, O., Guinle, T., Féménias, P. (2019) Corsica: A 20-Yr Multi-Mission Absolute Altimeter Calibration Site, Advances in Space Research, Special Issue « 25 Years of Progress in Radar Altimetry », doi : https://doi.org/10.1016/j.asr.2019.09.049

Sentinel-6 MF (NTC, LRM) – Jason-3 (GDR-F, LRM) (>10 km from the coast)





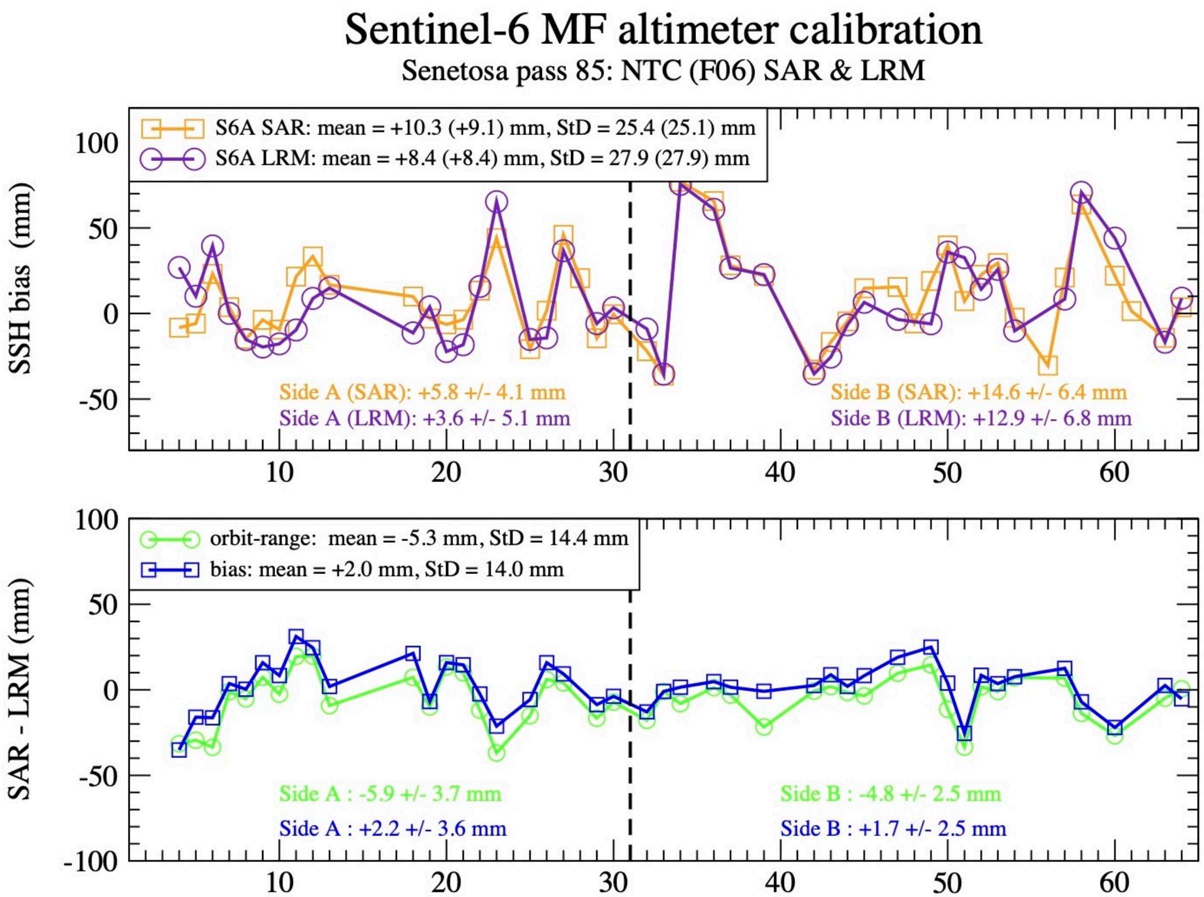
- While Jason-3 SSH bias is stable over Side A and Side B periods (8.0/7.3mm), on Sentinel-6 MF the switch between **Side A and Side B exhibits a 13mm difference** (-1.6/11.4mm) during FFP. **Side B range is shorter than Side A**.
- Side B being now operational, the SSH bias with Jason-3 is close to zero (+4.1mm).
- No significant correction differences between Jason-3 (GDR-F) and Sentinel-6 MF (NTC, F06).

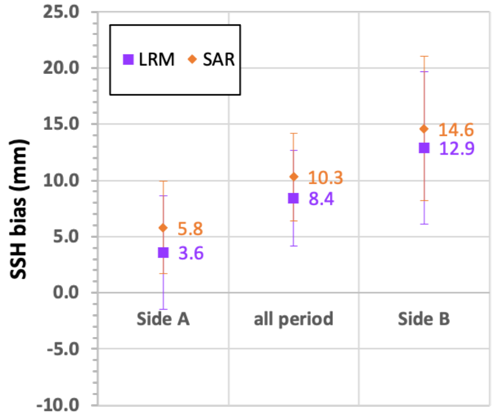
Key Points:

While Jason-3 SSH bias is stable over Side A and Side B periods (8.0/7.3mm), on Sentinel-6 MF the switch between Side A and Side B exhibits a 13mm difference (-1.6/11.4mm).
Side B range is shorter than Side A by 13mm.
Side B being now operational, the SSH bias with Jason-3 is close to zero (+4.1mm).

No significant correction differences between Jason-3 (GDR-F) and Sentinel-6 MF (NTC, F06).
Even SWH and wind speed are in very good agreement (-3cm/+0.1m/s). Compared to Jason-3, Sentinel-6 MF Sigma0 is lower by 1.32dB with no significant difference between Side A and Side B (-1.37/-1.27dB)

Sentinel-6 MF (NTC, SAR) – Sentinel-6 MF (NTC, LRM) (>10 km from the coast)



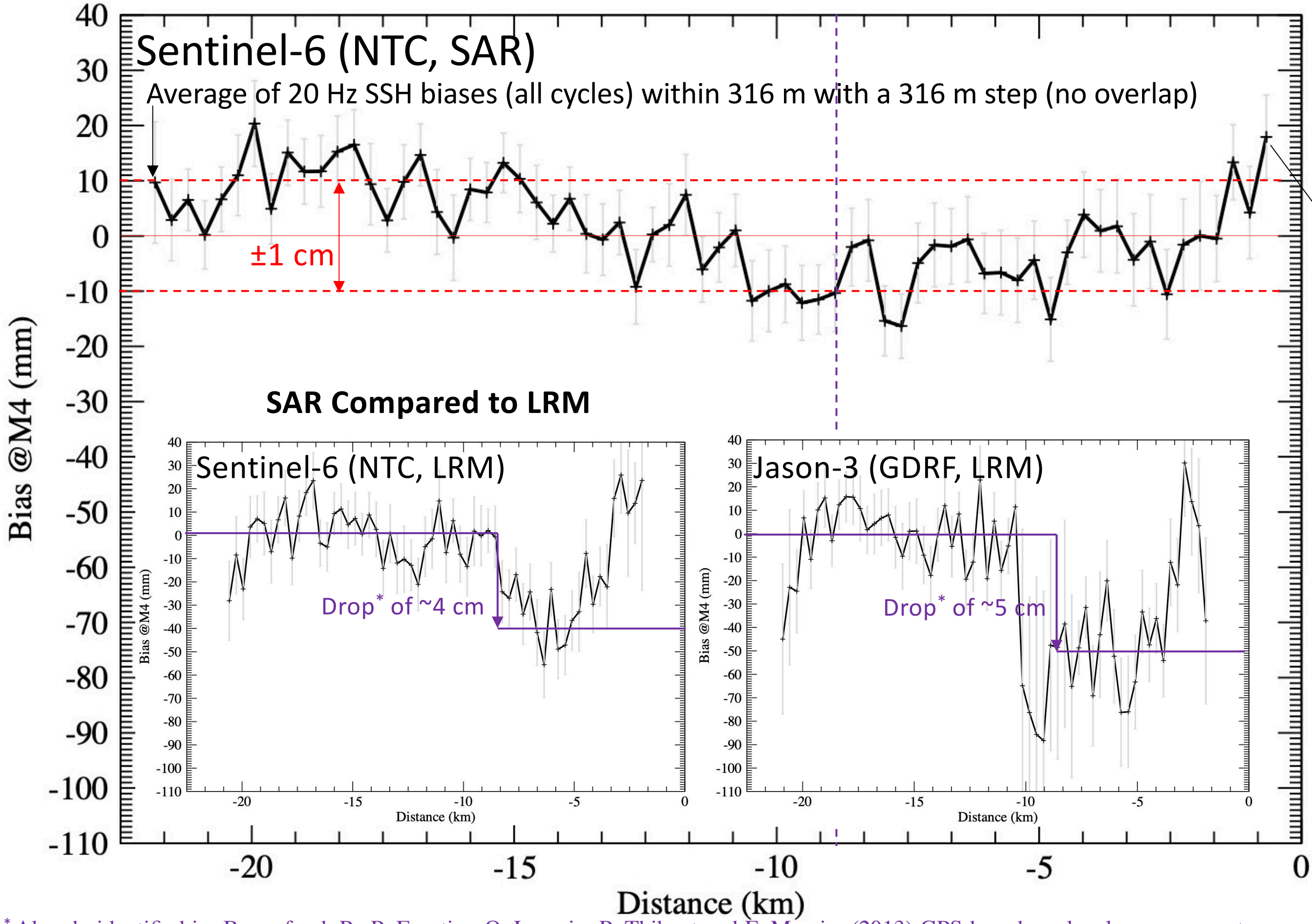


- Range **differences** (orbit-range) between **LR and HR are small and stable** between Side A and Side B (-5.9/-4.8mm), LR range being shorter than HR.
- **SSH biases are even smaller and more stable** (+2.2/+1.7mm) but **mainly due to a compensation by SSB correction** (differences for SWH (+15cm) and wind speed (+0.24m/s) between LR and HR).

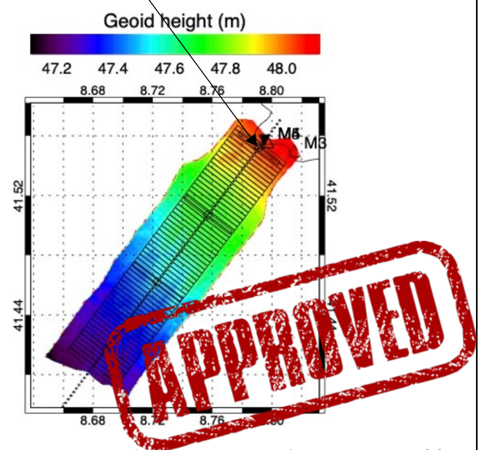
Key Points:

Range differences (orbit-range) between LR and HR are small and stable between Side A and Side B (-5.9/-4.8mm), LR range being shorter than HR. SSH biases are even smaller and more stable (+2.2/+1.7mm) but mainly due to a compensation by SSB correction (differences for SWH (+15cm) and wind speed (+0.24m/s) between LR and HR).

Sentinel-6 MF (NTC, SAR) close look up to the coast (all cycles)



- **Most of the averaged of 20Hz SSH biases in boxes of 316 m are within ±1 cm (standard deviation of 8.6 mm)**
- **Standard deviation of SAR 20Hz data is improved by ~2: 28 mm compared to 60 mm with LRM (65 mm for Jason-3)**
- **The drop in LRM due to land contamination for distance below ~8-10 km disappears in SAR (comparable drop in LRM for Sentinel-6 MF and Jason-3)**



* Already identified in: Bonnefond, P., P. Exertier, O. Laurain, P. Thibaut and F. Mercier (2013) GPS-based sea level measurements to help the characterization of land contamination in coastal areas, Advances in Space Research, 10.1016/j.asr.2012.07.007

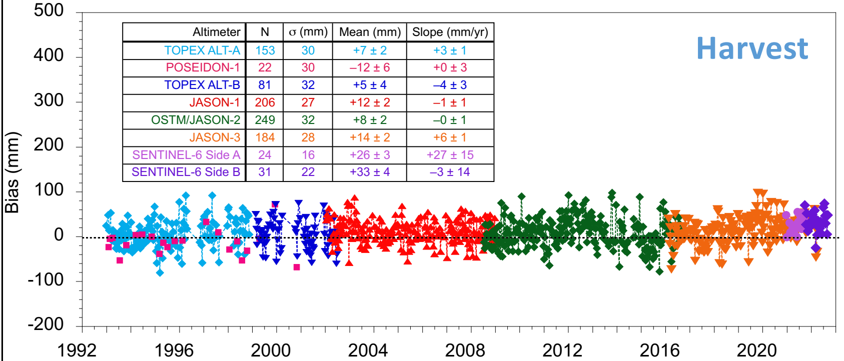
OSTST meeting, Venice, October 31 – November 4 2022 11

Key Points:

Valid (and accurate) measurements up to the coast (few hundred meters) allowing close comparison with tide gauges.
On the whole set of cycles, the standard deviation of SAR 20Hz data is improved by ~2: 28 mm compared to 60 mm with LRM (65 mm for Jason-3).

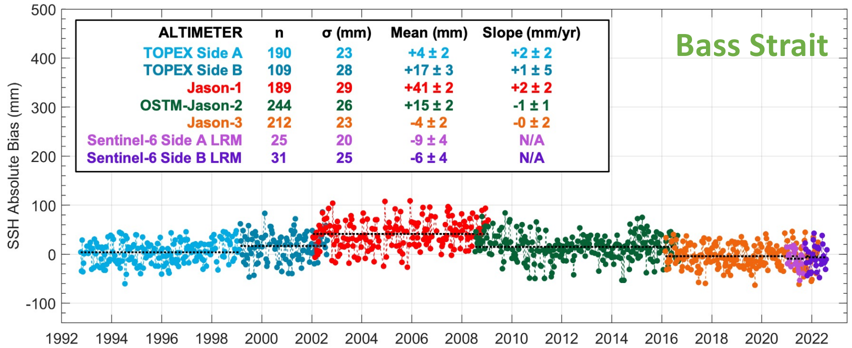
Most of the averaged of 20Hz SSH biases in boxes of 316 m are within ±1 cm (standard deviation of 8.6 mm).
The drop in LRM due to land contamination for distance below ~8-10 km disappears in SAR.
Comparable drop in LRM for Sentinel-6 MF and Jason-3 (even if smaller for Sentinel-6 MF).

Harvest, Bass Strait and Corsica Long-Term SSH Calibration Record

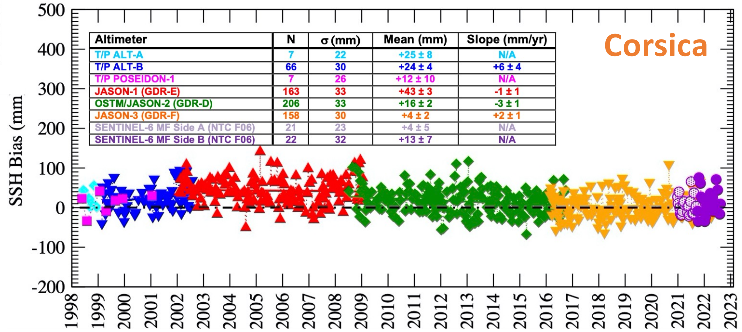


Altimeter	N	σ (mm)	Mean (mm)	Slope (mm/yr)
TOPEX ALT-A	153	30	+7 ± 2	+3 ± 1
POSEIDON-1	22	30	–12 ± 6	+0 ± 3
TOPEX ALT-B	81	32	+5 ± 4	–4 ± 3
JASON-1	206	27	+12 ± 2	–1 ± 1
OSTM/JASON-2	249	32	+8 ± 2	–0 ± 1
JASON-3	184	28	+14 ± 2	+6 ± 1
SENTINEL-6 Side A	24	16	+26 ± 3	+27 ± 15
SENTINEL-6 Side B	31	22	+33 ± 4	–3 ± 14

- Most of our bias estimates overlap, hence insignificant differences.
- Bias repeatability is now quite incredible across our three sites.
- Decrease of the standard deviation shows evolution in altimeters but also highlights we are doing well from an in situ perspective.



ALTIMETER	n	σ (mm)	Mean (mm)	Slope (mm/yr)
TOPEX Side A	190	23	+4 ± 2	+2 ± 2
TOPEX Side B	109	28	+17 ± 3	+1 ± 5
Jason-1	189	29	+41 ± 2	+2 ± 2
OSTM-Jason-2	244	26	+15 ± 2	-1 ± 1
Jason-3	212	23	-4 ± 2	-0 ± 2
Sentinel-6 Side A LRM	25	20	-9 ± 4	N/A
Sentinel-6 Side B LRM	31	25	-6 ± 4	N/A



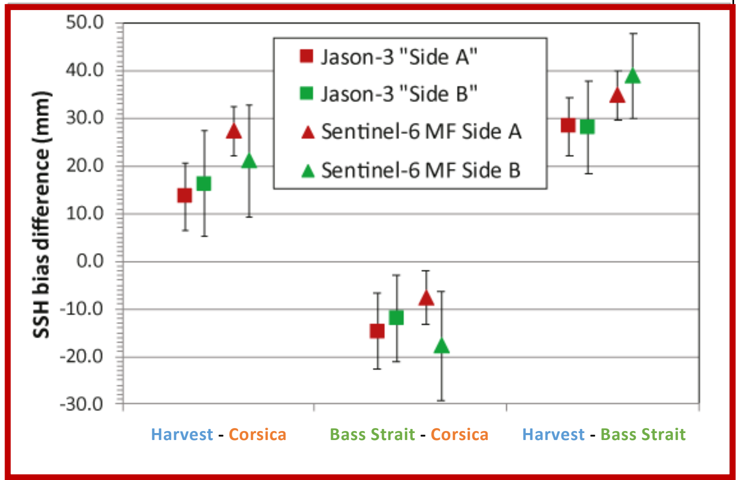
Altimeter	N	σ (mm)	Mean (mm)	Slope (mm/yr)
T/P ALT-A	7	22	+25 ± 8	N/A
T/P ALT-B	66	30	+24 ± 4	+6 ± 4
T/P POSEIDON-1	7	26	+12 ± 10	N/A
JASON-1 (GDR-E)	163	33	+43 ± 3	-1 ± 1
OSTM/JASON-2 (GDR-D)	206	33	+16 ± 2	-3 ± 1
JASON-3 (GDR-F)	158	30	+4 ± 2	+2 ± 1
SENTINEL-6 MF Side A (NTC F06)	21	23	+4 ± 5	N/A
SENTINEL-6 MF Side B (NTC F06)	22	32	+13 ± 7	N/A

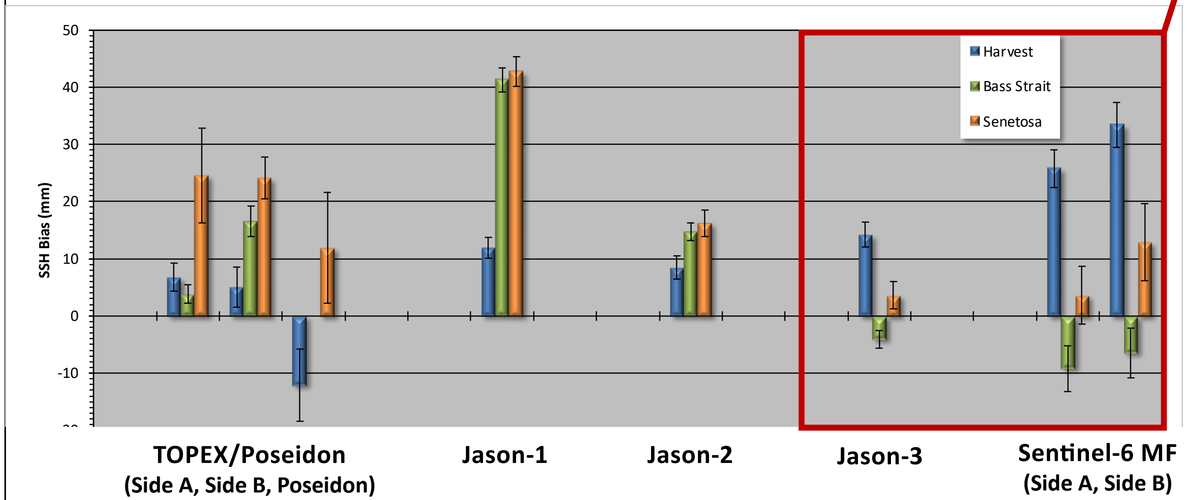
Key points:
- A very good consistency between sites
- An improvement of the standard deviation illustrating both altimeter evolution (especially with SAR) and accurate in situ instruments

Comparisons of absolute SSH biases from Harvest, Bass Strait and Corsica

A long history covering all the Reference Altimetry Missions for 30yr:

- Independent absolute biases from diverse locations, approaches and in situ instruments (type of tide gauges, GNSS buoys, moorings, transponder, …).
- Discrepancies BETWEEN SITES is typically at the cm level (insignificant). However:
  - Unexplained significant differences remain for Jason-1.
  - No clear site-specific systematic effect is present.
- A homogeneous standard (e.g. orbit, corrections etc) for all missions may offer further insight.





During Formation Flight:

- **Very small intermission SSH biases** (<10mm)
- **High level SSH Bias repeatability** across our three sites. **SAR range also improves the repeatability** (down to ~20mm) and provides accurate data up to the coast (few hundred meters)
- **Side B range shorter than A** by few millimeters (H: 8mm / BS: 3mm / C: 13mm)
- Larger unexplained differences with Harvest (see CVL2022_002 for details)

Key points:

- Very small intermission bias between Jason-3 and Sentinel-6
- SAR range improves the repeatability (cycle by cycle) (not shown here, see backup slides and other presentations)
- Sentinel-6 MF Side B altimeter range is shorter than Side A by few mm

Questions or Comments?

For further details, please see other presentations (on site or in Forums):

This presentation:

Absolute calibration results from Bass Strait, Corsica, and Harvest facilities
Pascal Bonnefond, Bruce Haines, Benoit Legresy and Christopher Watson

Posters:

CVL2022_001 - Jason-3 & Sentinel-6 MF calibration at the Corsica facilities
Pascal Bonnefond et al.

CVL2022_002 - The Harvest Experiment: Status and New Results from the Sentinel-6 Mission
Bruce Haines et al.

Forum only:

- Altimeter validation results from the Bass Strait validation facility, Australia
  Benoit Legresy et al.
- CWPIES, a shallow water current, waves and pressure inverted echo sounder for higher resolution satellite altimetry calibration and validation.
  Benoit Legresy et al.
- Along track analysis of a GNSS/INS buoy array in the context of Sentinel-6 and future SWOT altimetry validation at the Bass Strait facility
  Boye Zhou et al.
- Preliminary results from GNSS processing at the Southern Ocean SOFS site in preparation for SWOT validation
  Andrea Hay et al.
- A Kalman-based approach to simultaneously estimate vertical land motion and altimeter-specific systematic errors using altimeter, tide gauge, and GPS measurements
  Mohammad-Hadi Rezvani et al.

Key points:
Enjoy the meeting and forum!