Altimeter validation results from the Bass Strait validation facility, Australia

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2. Integrated Marine Observing System
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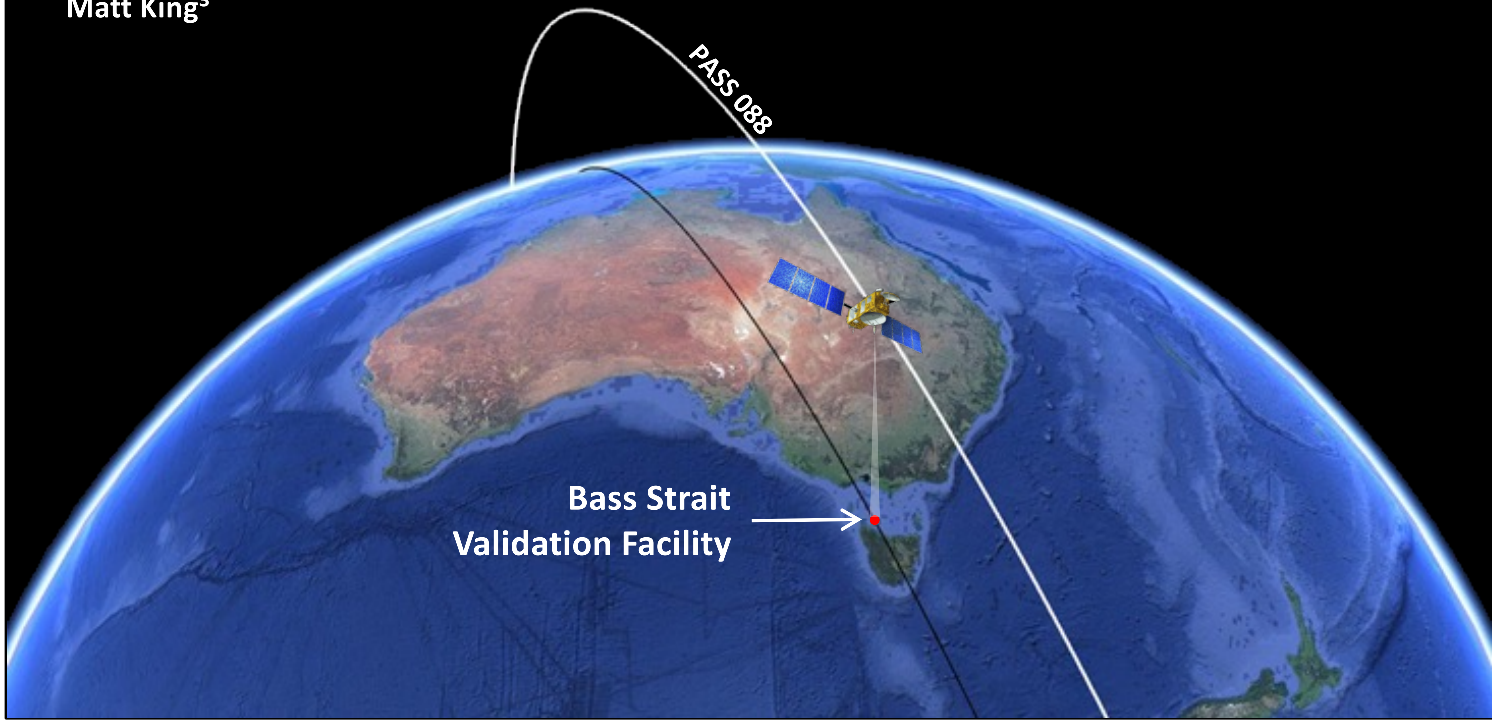

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15 YEARS of IMOS

IMOS Integrated Marine Observing System

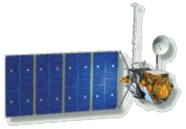
Ocean Surface Topography Science Team Meeting

31 Oct - 4 Nov 2022
Venice, Italy

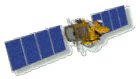
Acknowledgements:

- The work undertaken at the Bass Strait validation facility is a collaboration between the University of Tasmania (CI Watson: cwatson@utas.edu.au) and CSIRO (CI Legresy: Benoit.Legresy@csiro.au) – we acknowledge the effort by everyone in our team.
- We would like to acknowledge the ongoing support of the Australian Integrated Marine Observing System (IMOS). IMOS is enabled by the National Collaborative Research Infrastructure Strategy (NCRIS). It is operated by a consortium of institutions as an unincorporated joint venture, with the University of Tasmania as Lead Agent (www.imos.org.au)

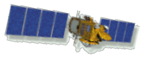
Bass Strait Validation Facility:



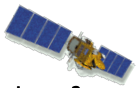
TOPEX / Poseidon
Aug 1992



Jason-1
Dec 2001

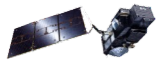


OSTM/Jason-2
June 2008



Jason-3
Jan 2016

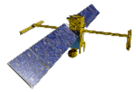
- Sustained and independent monitoring of altimeter absolute bias in Bass Strait, Australia, since the launch of TOPEX/Poseidon in late 1992.
- Part of the broad calibration and validation effort undertaken by the mission science team to ensure the ongoing high quality of the sea level climate data record.



Sentinel-3A
Feb 2016

Sentinel-3B
Apr 2018

Sentinel-6 / Michael Freilich
Nov 2020

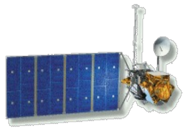


SWOT
Dec 2022 (pending)

Overarching Aim of the Bass Strait Validation Facility:

- To provide a valued contribution to the calibration and validation effort that underpins satellite altimetry.

Bass Strait Validation Facility: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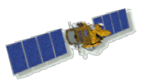
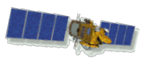
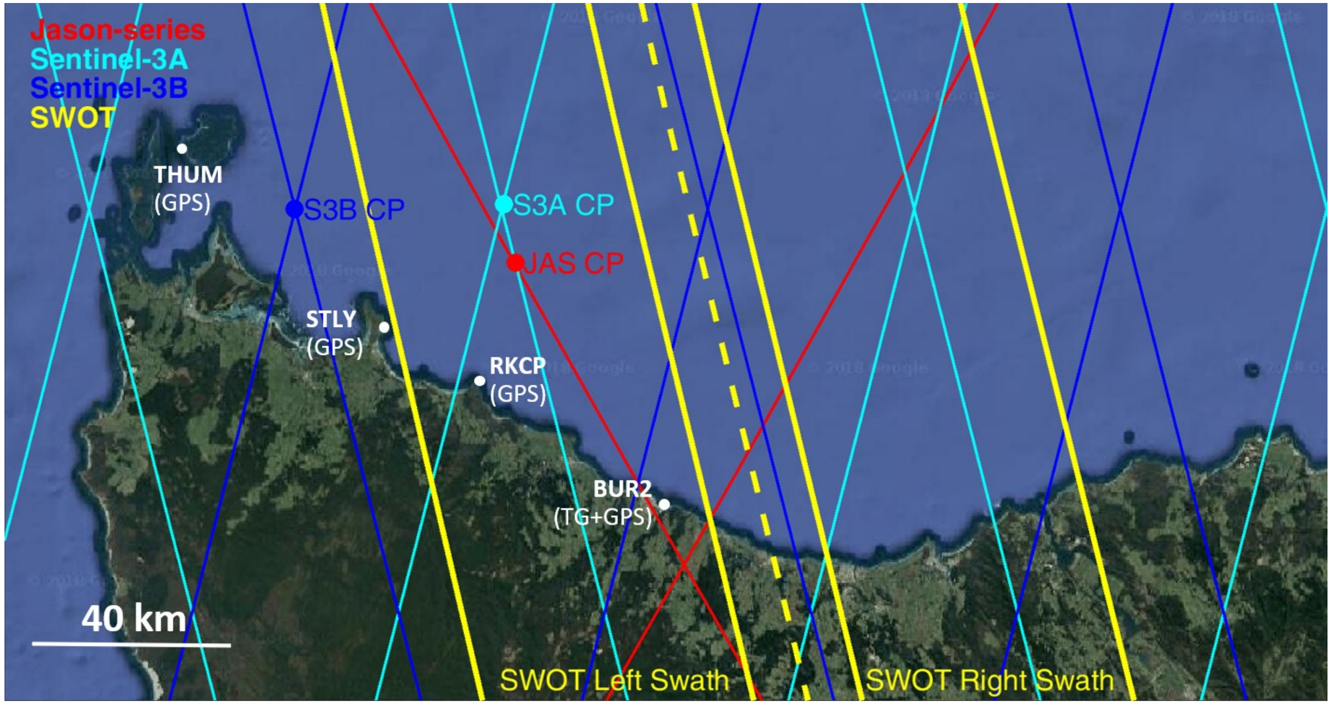
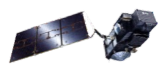
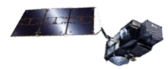

Jason-1
Dec 2001


OSTM/Jason-2
June 2008

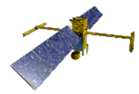

Jason-3
Jan 2016




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:

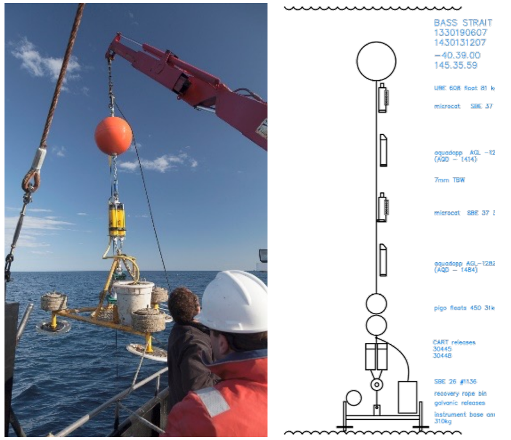
- Sustained in situ observation and validation of satellite altimetry at three key in situ comparison points (CPs): Jason-series / reference missions (JAS in red), Sentinel-3A (S3A in cyan) and Sentinel-3B (S3B in blue).
- Development of improved in situ instrumentation to enable validation of next generation 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.

Geometric Approach:

- **Direct, geometric approach to in situ validation.**
- **Key in situ observations are made at offshore comparison points, hence there is no reliance on a geoid.**

GNSS/INS Equipped Buoys

- Deployed episodically at cross overs to determine absolute datum of in situ SSH time series.
- Extended to now include inertial sensors (INS) for orientation.



Moored Sensors

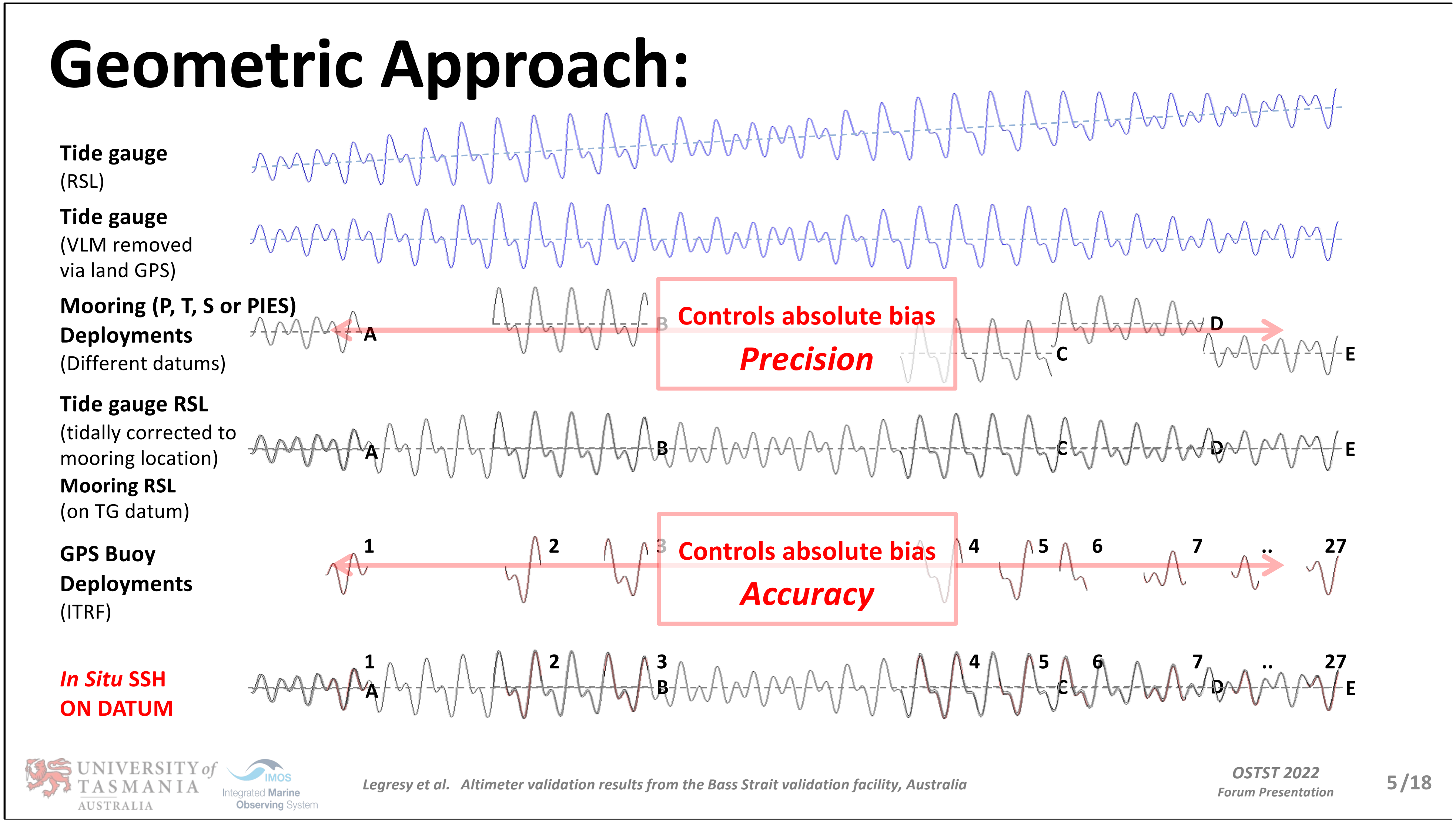
- Bottom pressure, temp and salinity to determine continuous SSH time series (datum defined by GNSS buoys).
- New current, waves, pressure inverted echo sounders (CWPIES) yield high and low frequency SSH as well as currents.

Tide Gauge / cGNSS

- "Climate quality" coastal tide gauge.
- Numerous inland GNSS to provide vertical land motion (VLM).
- Inland GNSS used in differential processing of buoys given favourable geometry.
- GNSS offer insight into spatial/temporal evolution of troposphere.

The Bass Strait Approach:

- Our approach is fully geometric involving direct comparison of situ SSH against altimeter SSH. Both are observed at the same physical location - the comparison point (CP).
- Moored oceanographic sensors at the comparison point are serviced on a 6-monthly repeating cycle. These yield the "mooring SSH" at 5-minute sampling.
- Episodic deployments of GNSS buoys are used to constrain the absolute datum of the mooring SSH.
- Sustained observations also exist from a coastal tide gauge which is part of the Australian Baseline Sea Level Monitoring Project (http://www.bom.gov.au/oceanography/projects/abslmp/abslmp.shtml).
- Inland GNSS stations assist in processing GNSS buoys as well as yield valuable information about vertical land motion and the troposphere.

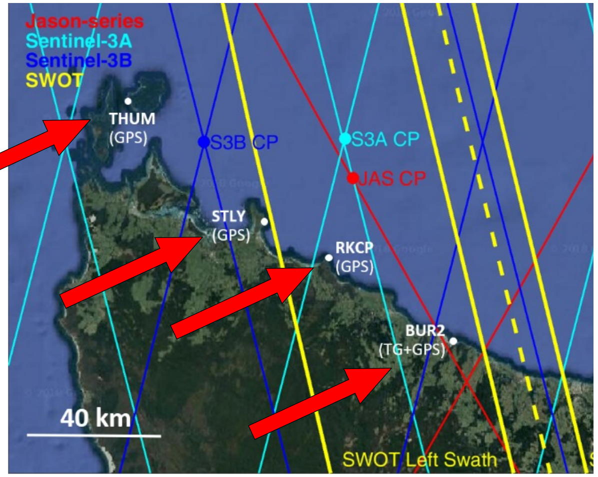


Key Points Behind Our Approach:

- Before considering the quality of altimeter data:
  - ➢ The uncertainty inherent to the **in situ mooring SSH** defines our **absolute bias** **precision**.
  - ➢ The uncertainty inherent to the **GNSS buoy SSH** defines our **absolute bias** **accuracy**.
- We recognise that in situ instrumentation must keep pace with advancing requirements of altimeter validation. Our focus has therefore been on developing new moored sensors (current, waves, pressure inverted echo sounder, CWPIES – see other presentation in this meeting by Legresy et al) and a new GNSS buoy array (see other presentation in this meeting by Zhou et al).

Bass Strait Datum

- Land based GNSS sites are critical to observe vertical land motion which influences relative sea level observations from the tide gauge and ocean moorings.



GNSS deployment at Rocky Cape (RKCP)

GNSS deployment at Stanley (STLY)

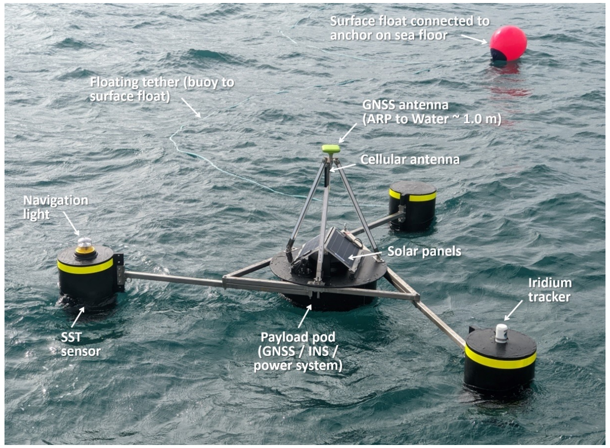
- GNSS sites are also used as reference stations in differential processing of GNSS buoys deployed at comparison points.
- Additionally, they offer insight into the evolution of the wet tropospheric delay.

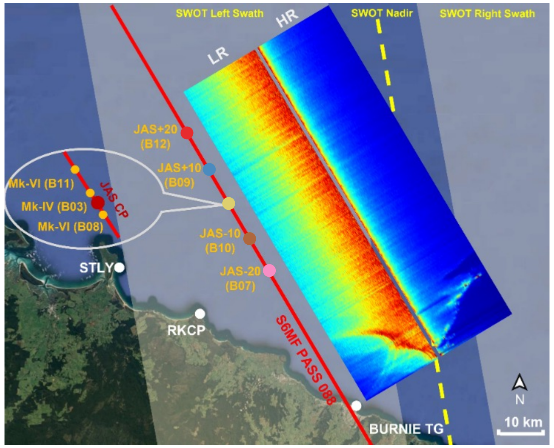
Key Points:

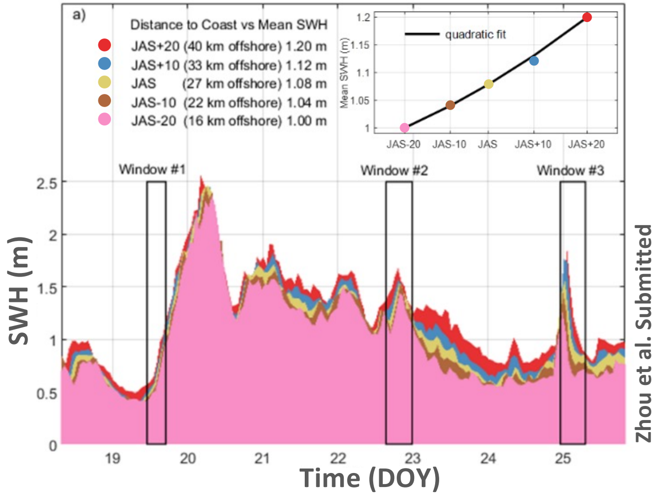
- The primary long running GNSS site at the Bass Strait facility is collocated with the tide gauge (site code: BUR2).
- Adjacent to BUR2 but away from the wharf complex is RHPT. Both sites suggest subsidence of ~-0.7 mm/yr which appears sufficiently linear over the GNSS record (see Riddell et al., 2020).
- We now have additional reference sites along the coast at Rocky Cape (RKCP), Stanley (STLY) and Three Hummock Island (THUM).
- These sites improve the geometry for differential processing of our GNSS buoys, as well as improve the estimation of the water vapour content of the troposphere – noting the standard west to east propagation of weather events in the area.
- Ref: Riddell, A., King, M.A., and Watson, C. (2020) Present-Day Vertical Land Motion of Australia From GPS Observations and Geophysical Models, *JGR*, DOI: 10.1029/2019JB018034.

In situ SSH: GNSS/INS Buoy Array

- GNSS buoys are critical for imposing the vertical datum on our precise SSH time series derived from offshore oceanographic moorings.
- We have expanded our GNSS buoy capability in the lead up to the launch of SWOT – this included the successful test deployment of a GNSS buoy array at 10 km spacing in Bass Strait. (Zhou et al, Submitted).



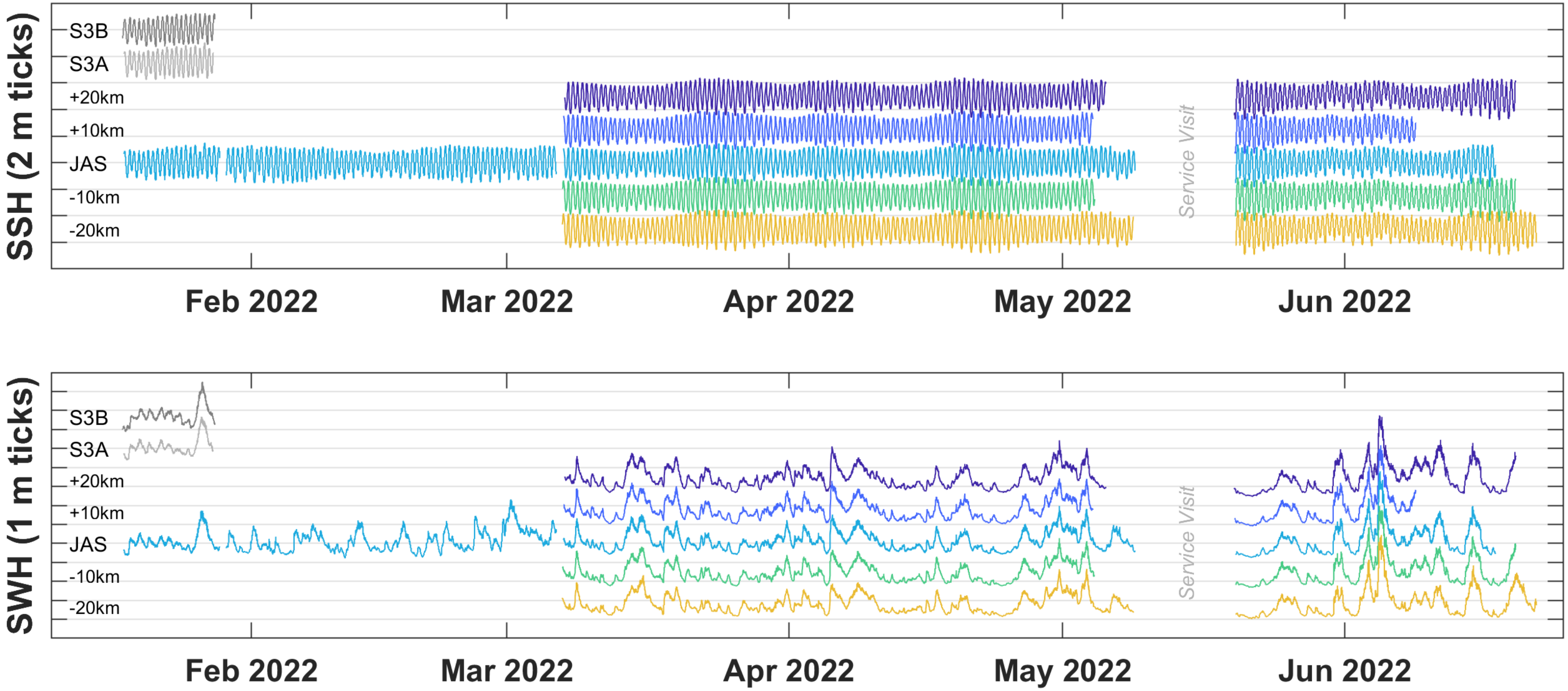




Key Points:

- Left panel: new GNSS/INS buoy used to define the datum of the Bass Strait SSH time series derived from offshore moored oceanographic instrumentation.
- Middle panel: location of the test deployment of the GNSS buoy array at 10 km spacing. Waveforms show an example of the Sentinel-6 LR (left) and HR (right) data along the red track.
- Right panel: temporal evolution of significant wave height over the buoy array for the duration of the test deployment. This work has been submitted for review by Zhou et al. See other presentation in this meeting by Zhou et al.
- See also other presentation in this meeting by Hay et al regarding GNSS processing in the Southern Ocean.
- Ref: Zhou, B. et al (2020) GNSS/INS-Equipped Buoys for Altimetry Validation: Lessons Learnt and New Directions from the Bass Strait Validation Facility. *Remote Sensing* DOI: 10.3390/rs12183001.

In situ SSH: GNSS/INS Buoy Array

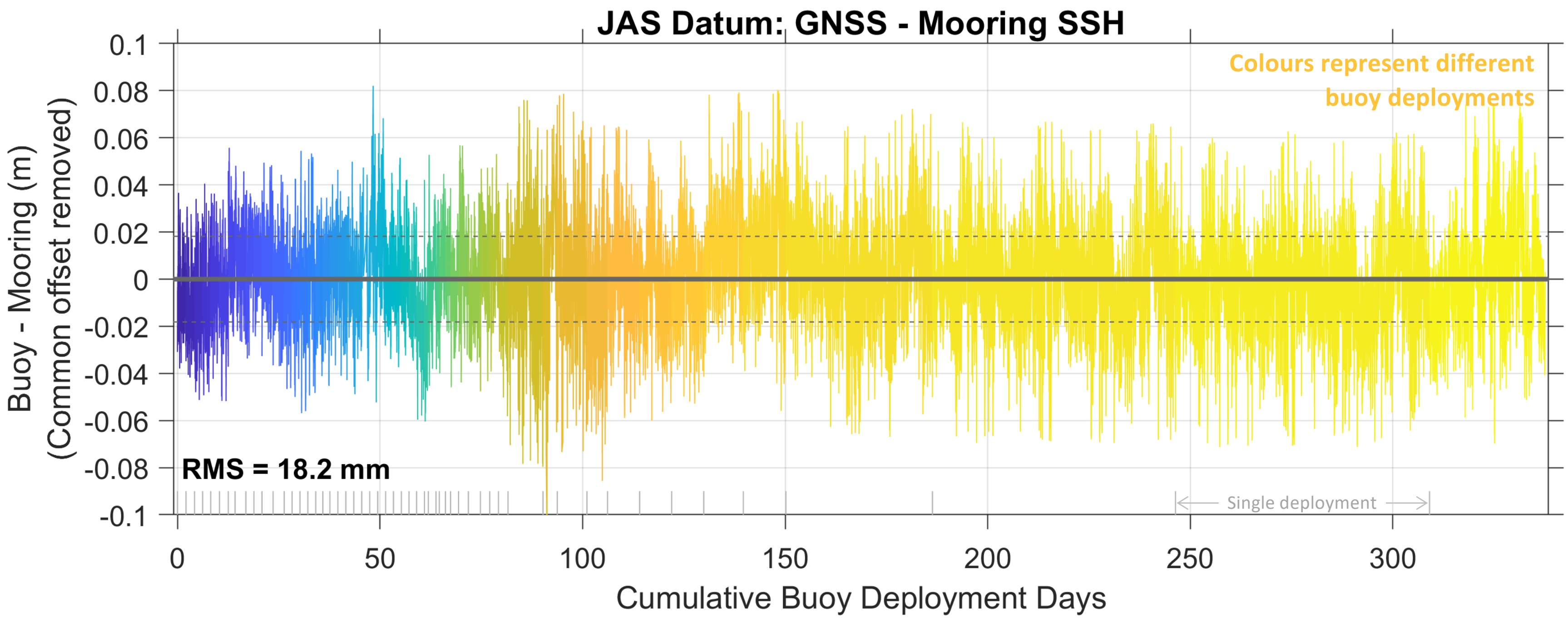


Key Points from our New Buoy Array:

- This plot shows a more recent example of an extended deployment from our new GNSS buoy array in Bass Strait. This extended capability has been developed in the lead up to the launch of the SWOT mission.
- Top panel: Smoothed SSH showing the tidal signal arbitrarily offset to highlight data from each comparison point. 0.5 Hz data has been processed and smoothed (to remove high frequency variability from waves) to form each of these time series.
- Bottom panel: Running SWH, arbitrarily offset. Typical SWH in this region of Bass Strait is ~1 m. Max SWH over this deployment was approaching 5 m.

Datum Determination (Buoy - JAS Mooring):

- Filtered GNSS buoy – mooring yields the mooring datum offset with noise contributions from both sensors.



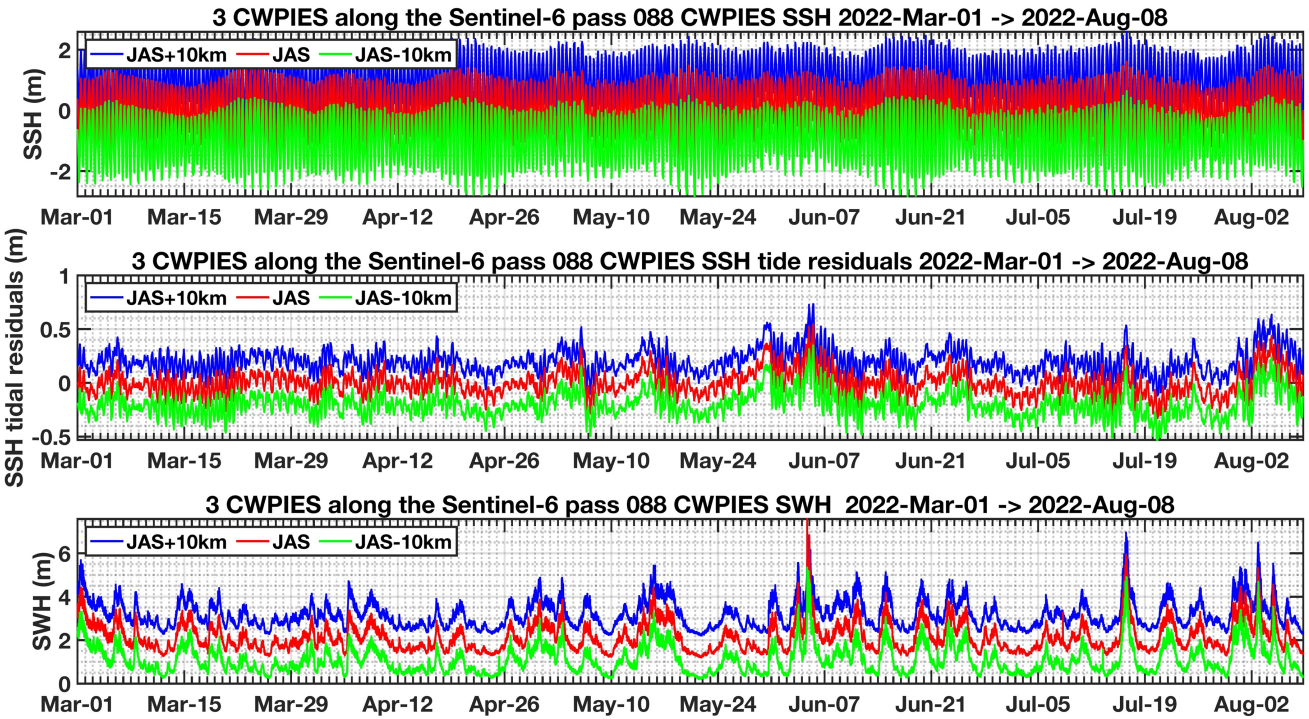
Key Points:

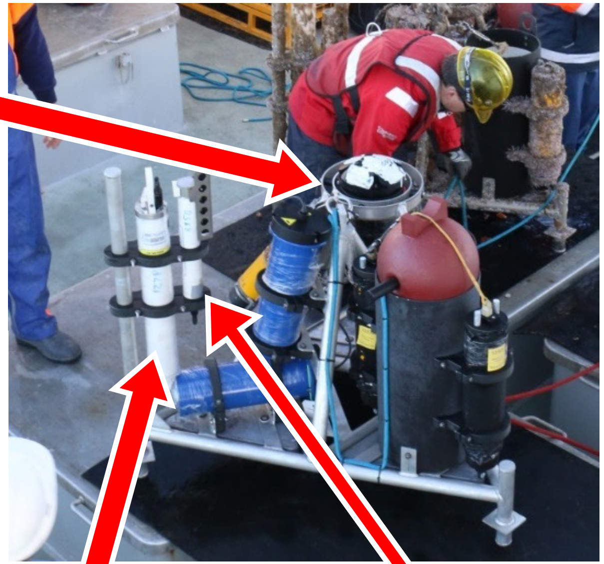
- The difference between mooring SSH and filtered buoy SSH yields the absolute datum of the mooring.
- Each buoy deployment here is shown in a different colour. Early deployments were typically of ~48 hours duration (as indicated by grey lines along x-axis). More recent deployments using the new GNSS buoys were much longer.
- The scatter here (~18 mm) gives an indication of the overarching precision with contributions from both GNSS buoys and mooring SSH. Each deployment is considered an independent sample with each deployment given equal weight in the overall solution of the datum.

In situ SSH:
Current, waves, pressure inverted echo sounder (CWPIES)

5 beam Acoustic Doppler Current Profiler

- Stabilised gimbal mount
- Centre beam is vertical and ranges to the surface @ 2 Hz
- All beams measure wave directional spectra in addition to the currents





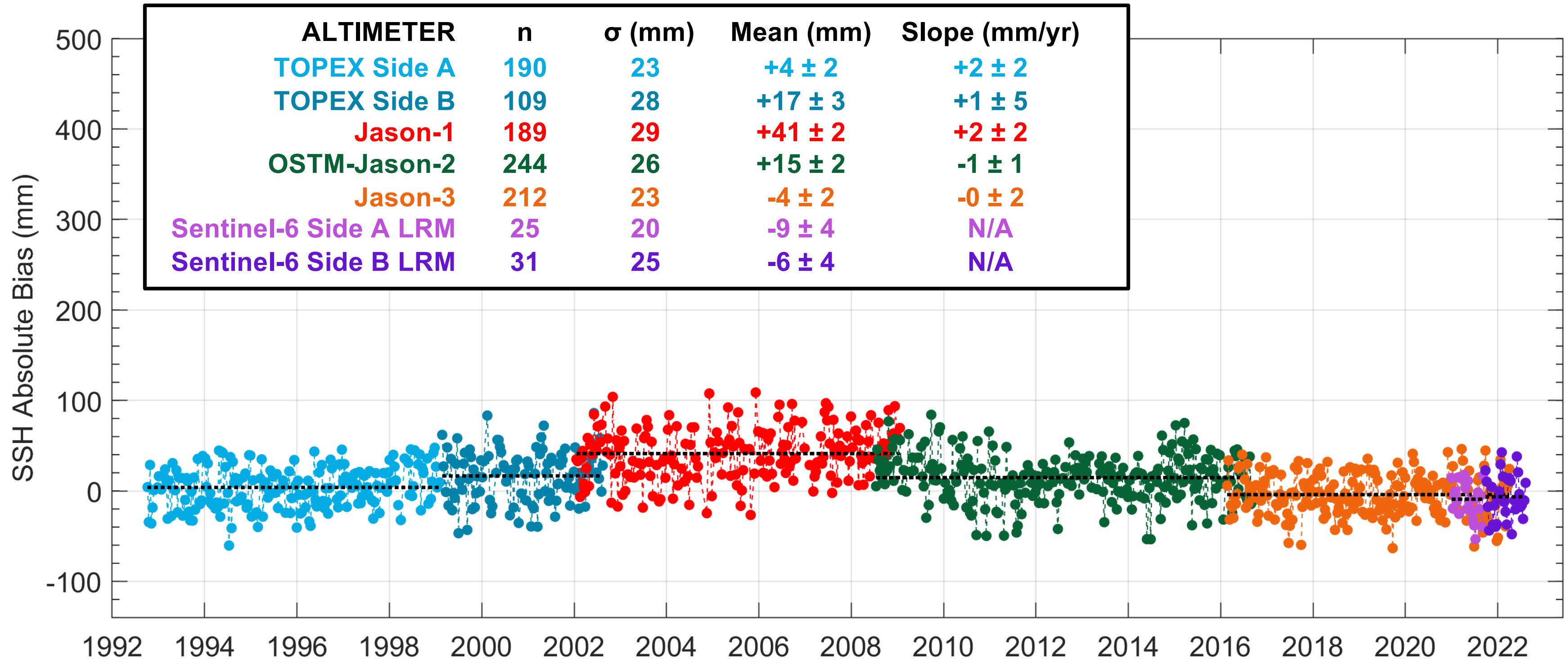
Bottom Pressure sensor

Temperature and Salinity sensor

Key Points:

Bass Strait
Absolute Bias Results

Absolute Bias at Bass Strait

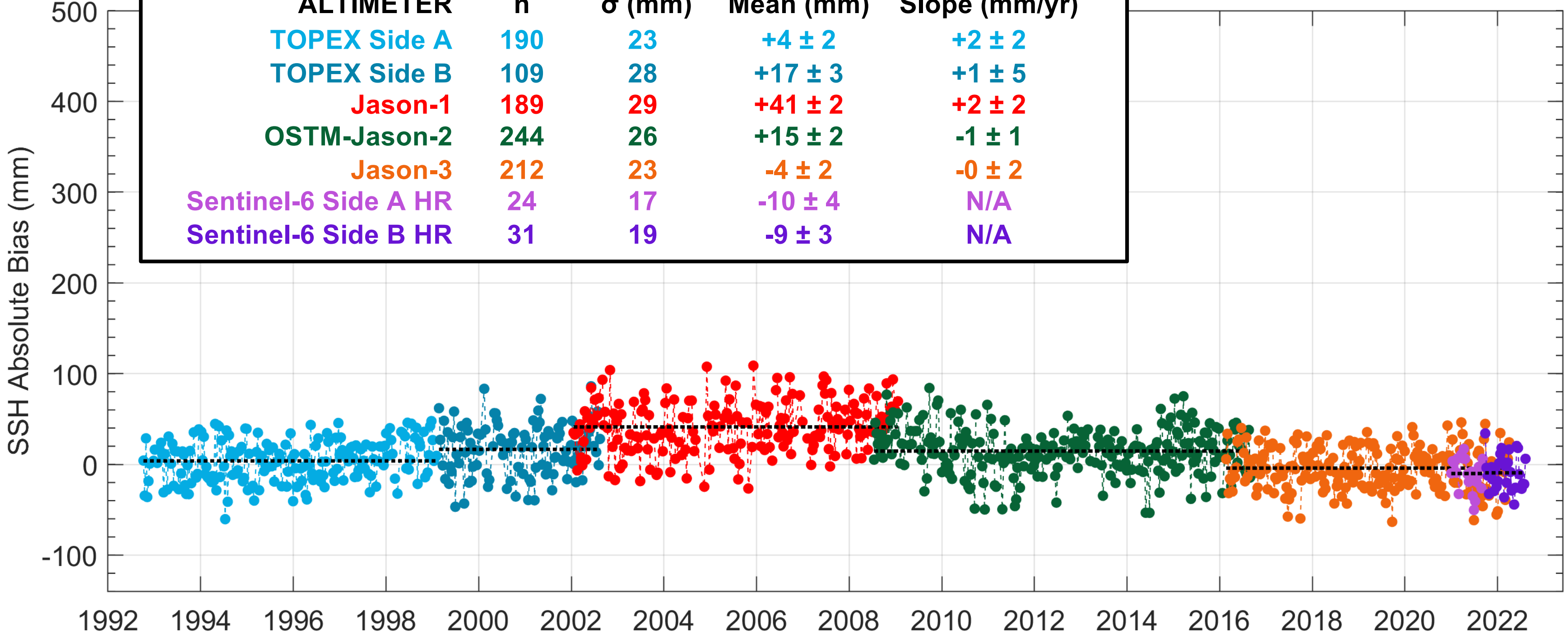


Key Points:

- The complete time series of altimeter absolute bias from Bass Strait shows biases that biases for TOPEX-A, TOPEX-B, Jason-2, Jason-3, Sentinel-6 Side A and Sentinel-6 Side B are indistinguishable from zero. Jason-1 remains significantly different from zero, yet comparable with results from Corsica and Gavdos.
- The quasi non-linear signal in OSTM/Jason-2 is spatially persistent (results not shown here from Storm Bay and other tide gauges in the region). Increased variability over TOPEX, Jason-1 and the early part of OSTM/Jason-2 reflects use of the tide gauge as the moored oceanographic instrumentation was not deployed for the majority of this time.
- The low variability reflects the high quality in situ observations and the mean SWH of just over 1 m in the region.

Absolute Bias at Bass Strait

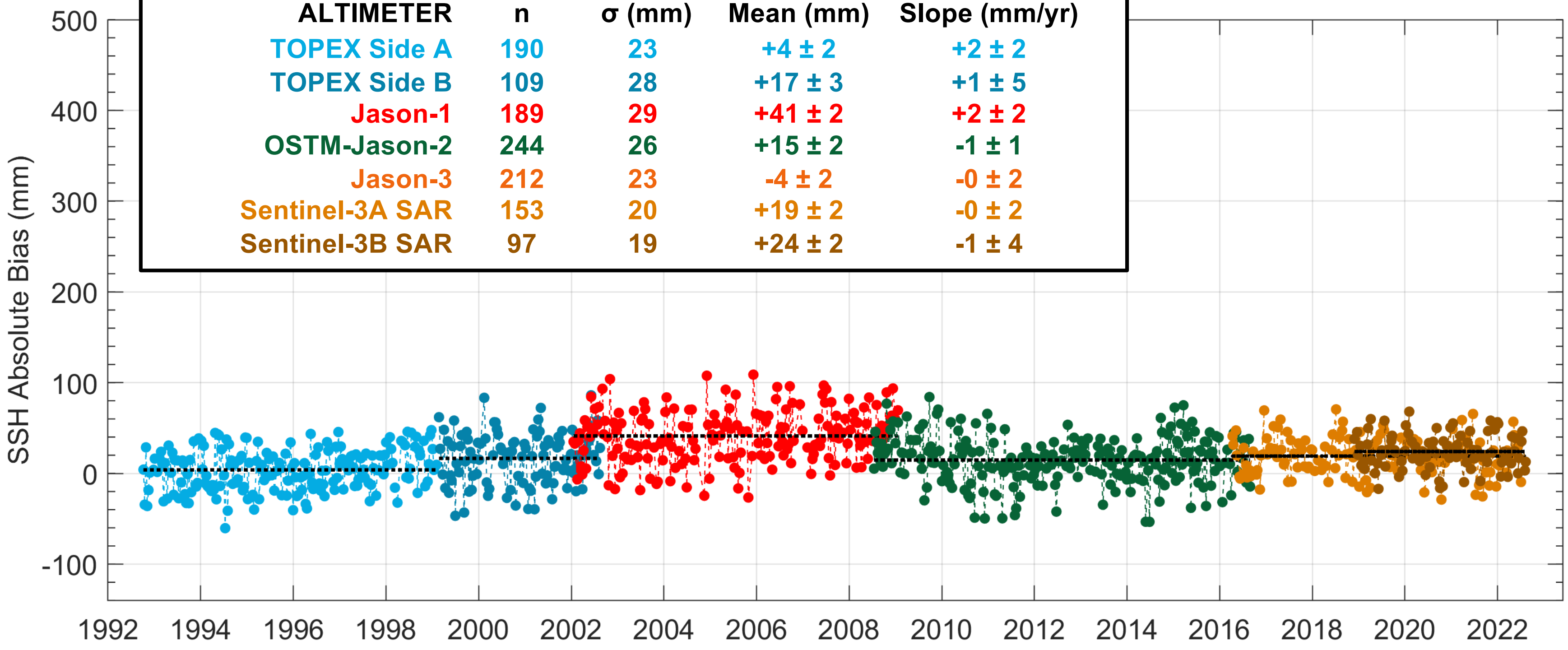
ALTIMETER	n	σ (mm)	Mean (mm)	Slope (mm/yr)
TOPEX Side A	190	23	+4 ± 2	+2 ± 2
TOPEX Side B	109	28	+17 ± 3	+1 ± 5
Jason-1	189	29	+41 ± 2	+2 ± 2
OSTM-Jason-2	244	26	+15 ± 2	-1 ± 1
Jason-3	212	23	-4 ± 2	-0 ± 2
Sentinel-6 Side A HR	24	17	-10 ± 4	N/A
Sentinel-6 Side B HR	31	19	-9 ± 3	N/A



Key Points:

- Negligible change when switching from low resolution mode to high resolution (SAR) mode on Sentinel-6.
- Results for Sentinel-6 Side A are indistinguishable from Sentinel-6 Side B (see later slide for more detail).
- Note all Sentinel-6 data here is Baseline 06.

Absolute Bias at Bass Strait



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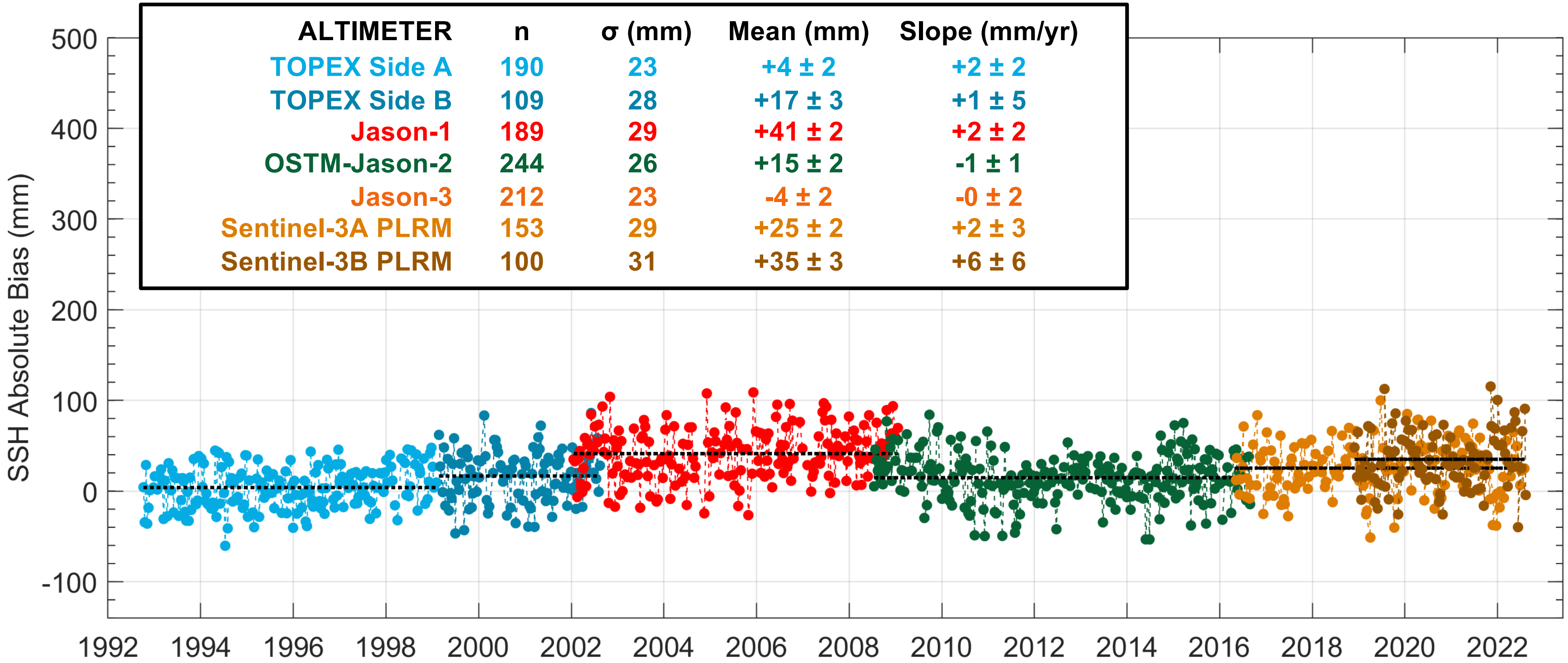
Jason-3	212	23	-4 ± 2	-0 ± 2
Sentinel-3A SAR	153	20	+19 ± 2	-0 ± 2
Sentinel-3B SAR	97	19	+24 ± 2	-1 ± 4

Key Points:

- Sentinel-3A and 3B are validated using infrastructure deployed at crossover locations nearby to the reference mission comparison point.
- Sentinel-3A/B biases for SAR mode data are at the 2 cm level. Variability is comparable to Sentinel-6 HR data.
- See spare slides for further detail regarding Sentinel-3A and B.

Absolute Bias at Bass Strait



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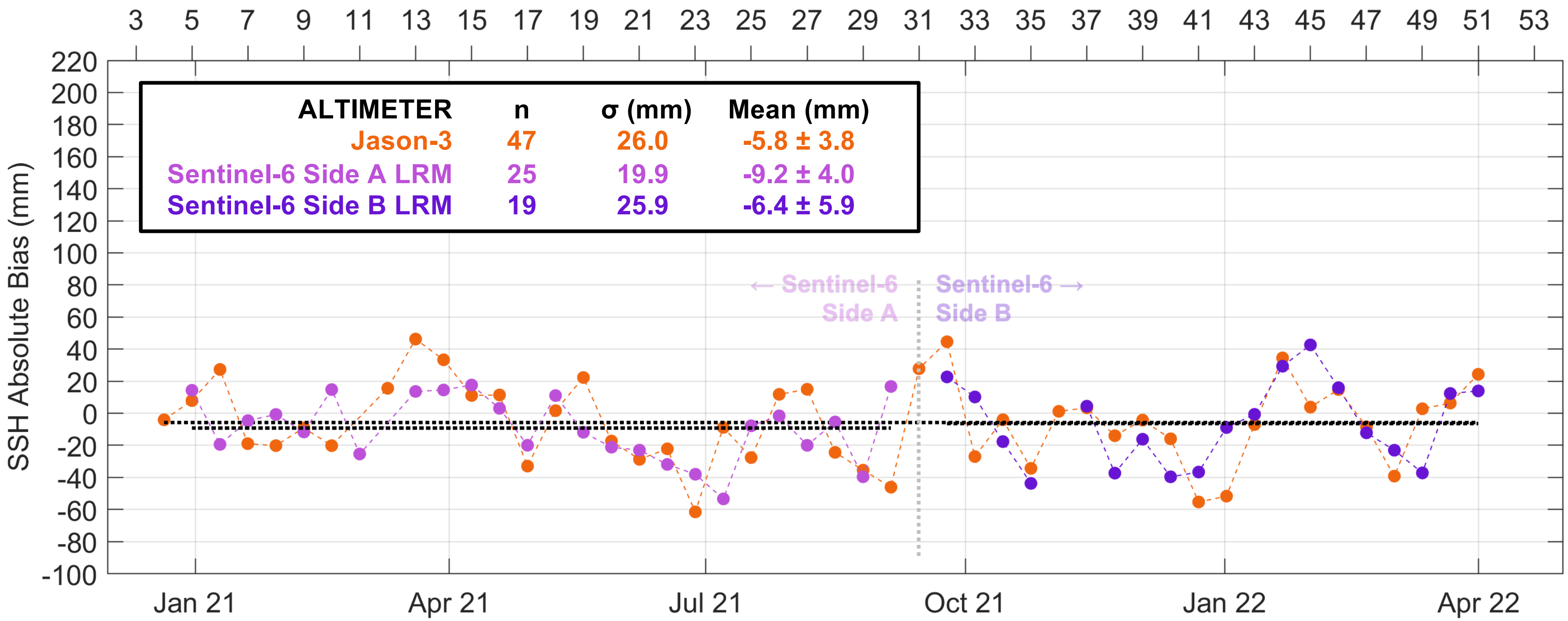
OSTM-Jason-2	244	26	+15 ± 2	-1 ± 1
Jason-3	212	23	-4 ± 2	-0 ± 2
Sentinel-3A PLRM	153	29	+25 ± 2	+2 ± 3
Sentinel-3B PLRM	100	31	+35 ± 3	+6 ± 6

Key Points:

- Sentinel-3A/B biases for PLRM mode data are almost 1 cm higher. As expected, variability also increases.

Absolute Bias at Bass Strait – J3/S6 FFP

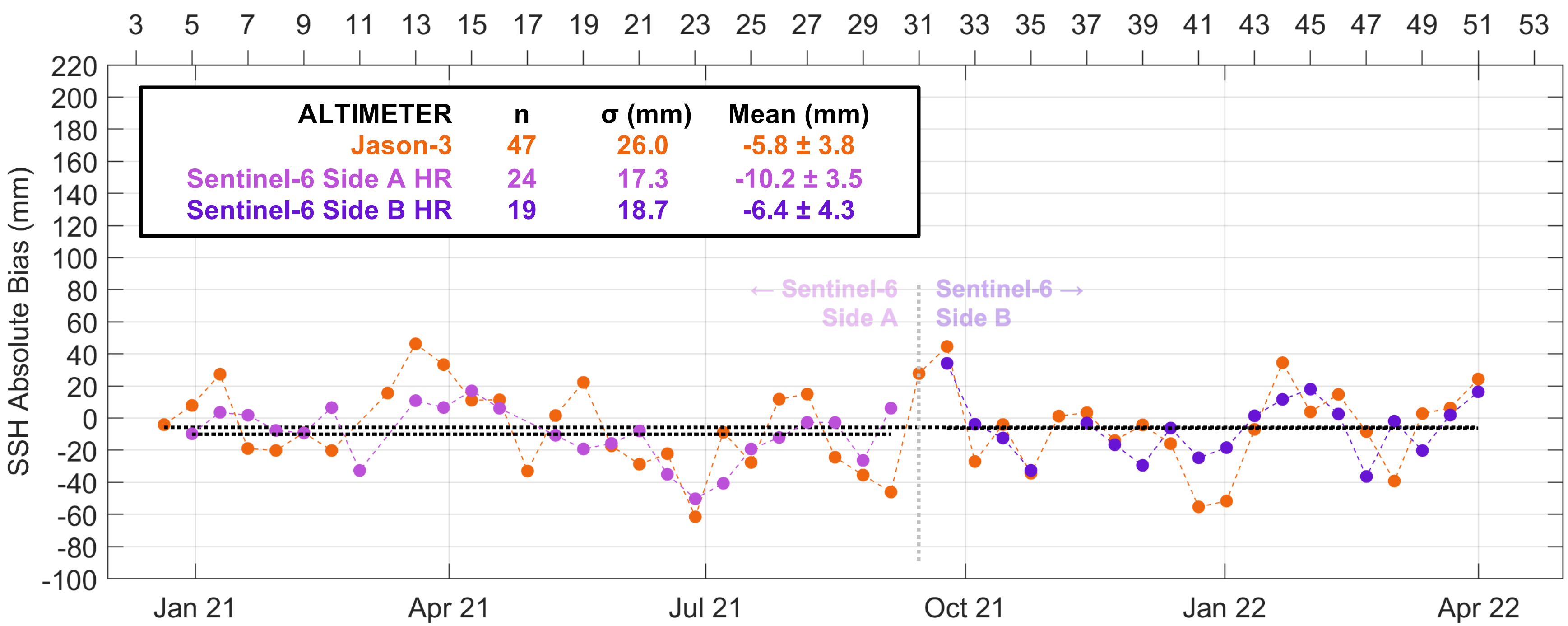


Relative bias: **S6A LRM – J3 = -3.4 ± 4.6 mm**
S6B LRM – J3 = +0.5 ± 5.1 mm

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

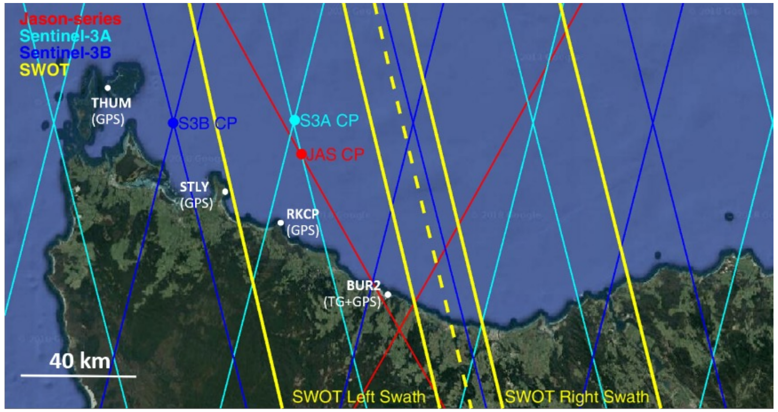


Relative bias: S6A HR – J3 = -2.2 ± 4.7 mm
S6B HR – J3 = +0.6 ± 4.4 mm

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.

Conclusions from Bass Strait



- Very low variability in bias estimates at Bass Strait highlights the evolution of altimetry and the high quality in situ data in use at the facility.
- Promising developments at Bass Strait (GNSS buoys / CWPIES) in the context of validation future missions at this site.
- Jason-1 (GDR-E) is the only mission with a bias significantly different from zero which is not yet understood.
- HR (SAR) data from Sentinel-3A/B and Sentinel-6 yields biases with variability lower than 2 cm.
- All trends are indistinguishable from zero.
- Non-averaging errors likely limit absolute bias uncertainty to ±10 mm.

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Sentinel-6 Side A LRM	25	20	-9 ± 4	N/A
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Sentinel-6 Side B LRM	31	25	-6 ± 4	N/A
Sentinel-6 Side B HR	31	19	-9 ± 3	N/A

Questions or Comments?

Please ask via the forum or email.

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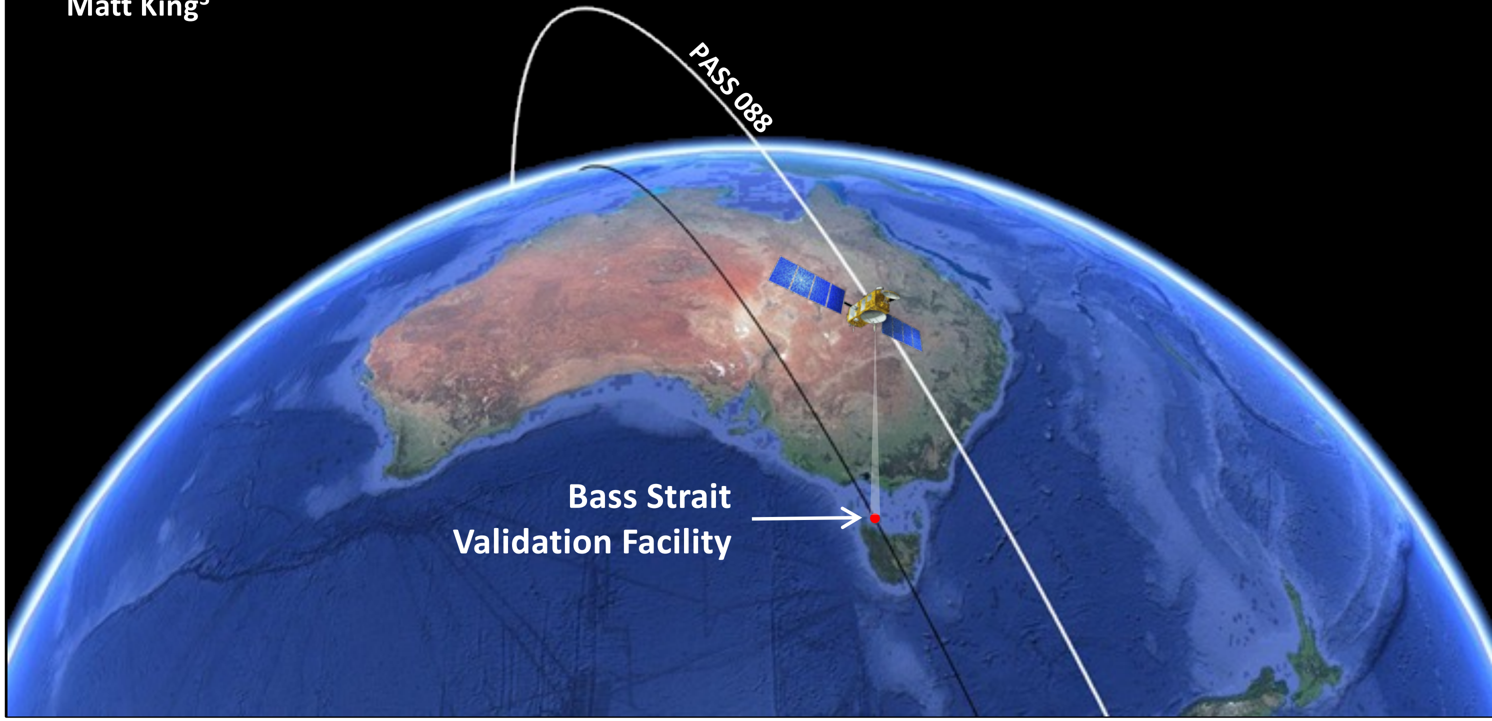

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Ocean Surface Topography Science Team Meeting

31 Oct - 4 Nov 2022
Venice, Italy

Acknowledgements:

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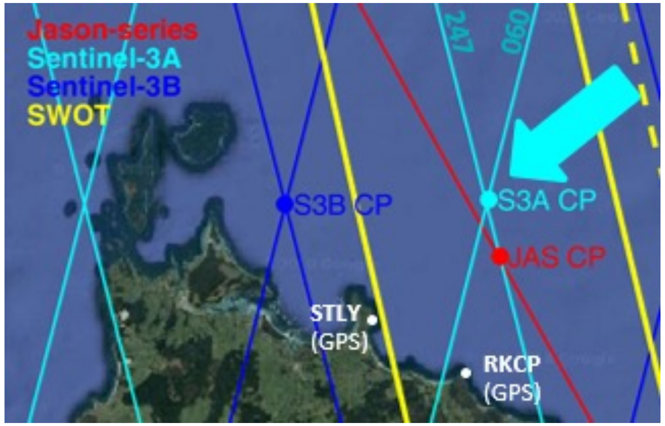
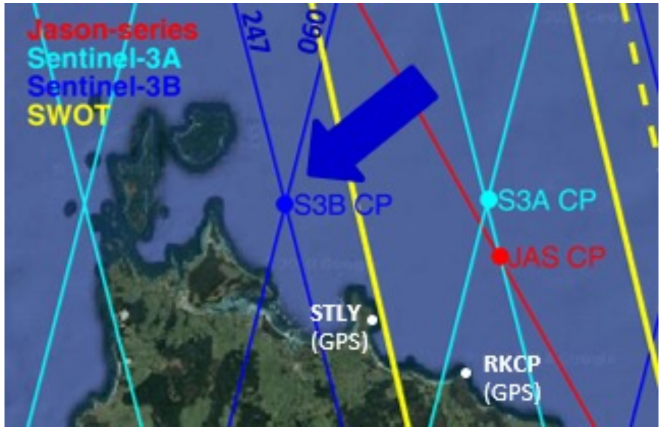
Spares

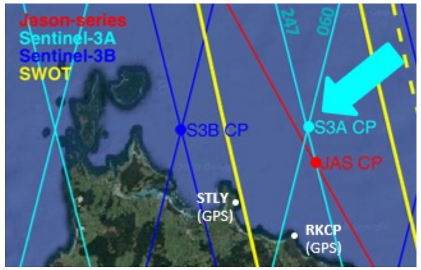
Sentinel-3A and Sentinel-3B

- Both S3A and S3B comparison points are located at cross over locations.
- S3A comparison point (**S3A**) is ~9 km north of our Jason-series comparison point (**JAS**).
- S3B comparison point (**S3B**) is ~44 km west (~28 m depth c.f. ~52 m depth).

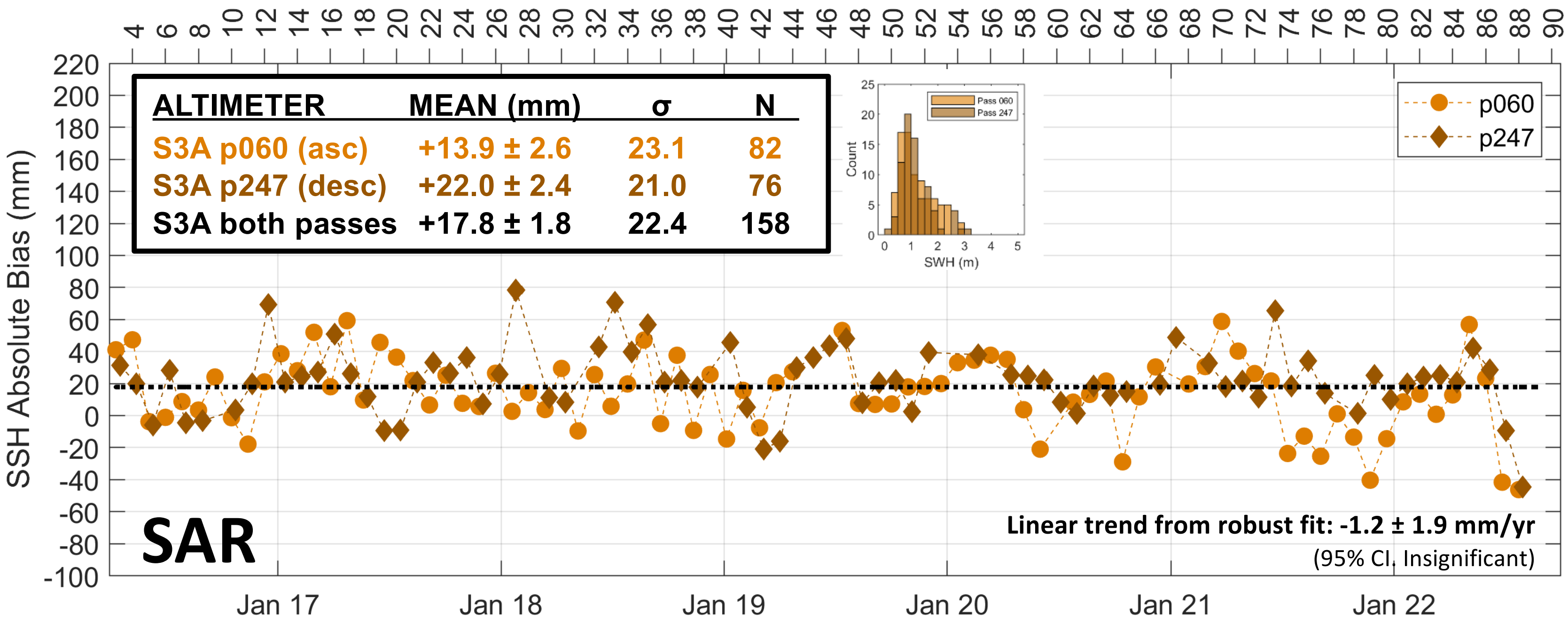




Sentinel-3A Absolute Bias (SAR)



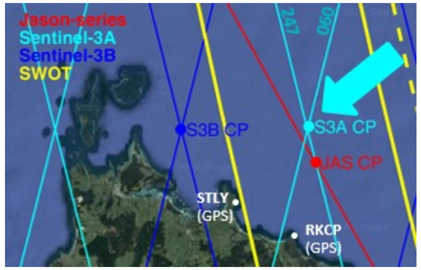
- S3A, Non time critical data, Baseline 4 and 5 via RADS, cycles 3-89.
- Bias at the 2 cm level (18 mm).
- Bias variability (stdev ~22 mm) is approaching the in situ noise.

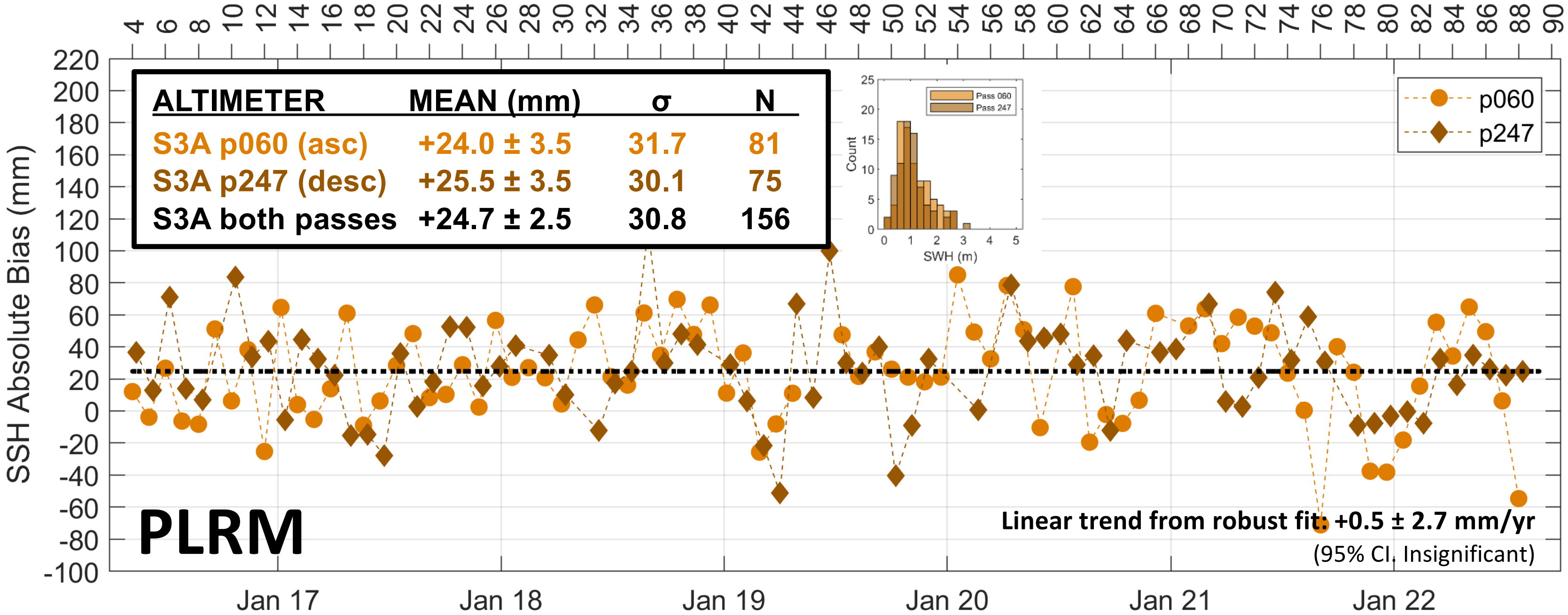


←PB04 | PB05→
(from c87)

Sentinel-3A Absolute Bias (PLRM)

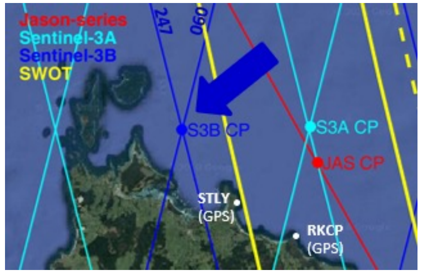
- S3A PLRM bias is ~7 mm higher than SAR bias (mean: 25 v 18 mm).
- S3A PLRM bias is more variable than SAR bias (stdev: 31 v 22 mm).





←PB04 | PB05→
(from c87)

Sentinel-3B Absolute Bias (SAR)



- S3B SAR bias is ~6 mm higher than S3A SAR bias (mean: 24 v 18 mm).
- Similarly to S3A, the S3B PLRM bias is ~12 mm higher than SAR (mean: 36 v 24 mm).
- Similarly to S3A, the S3B PLRM bias is more variable than SAR (stdev: 31 v 20 mm).