Altimeter validation results from the Bass Strait validation facility, Australia

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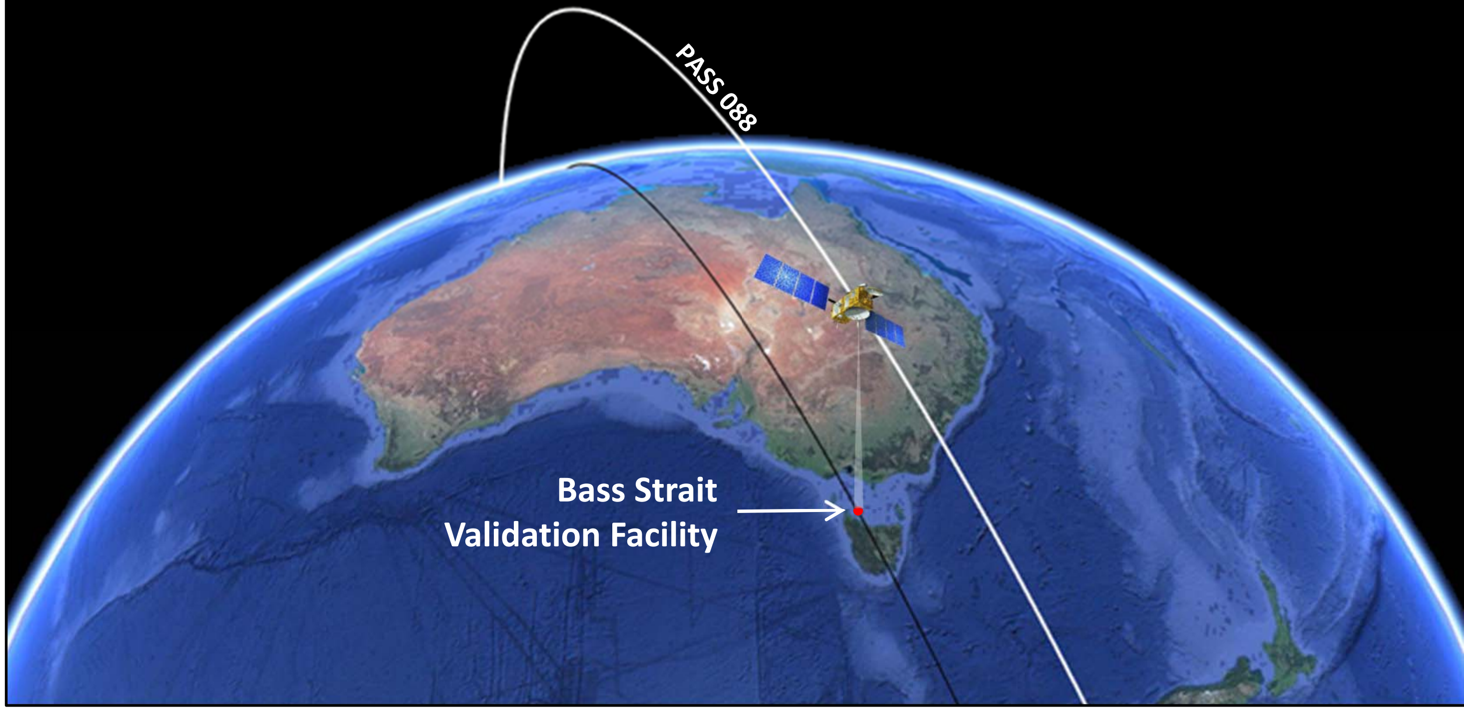
UNIVERSITY of TASMANIA AUSTRALIA

CSIRO

IMOS Integrated Marine Observing System



Ocean Surface Topography Science Team Meeting

October 19-23, 2020

Virtual Meeting

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.
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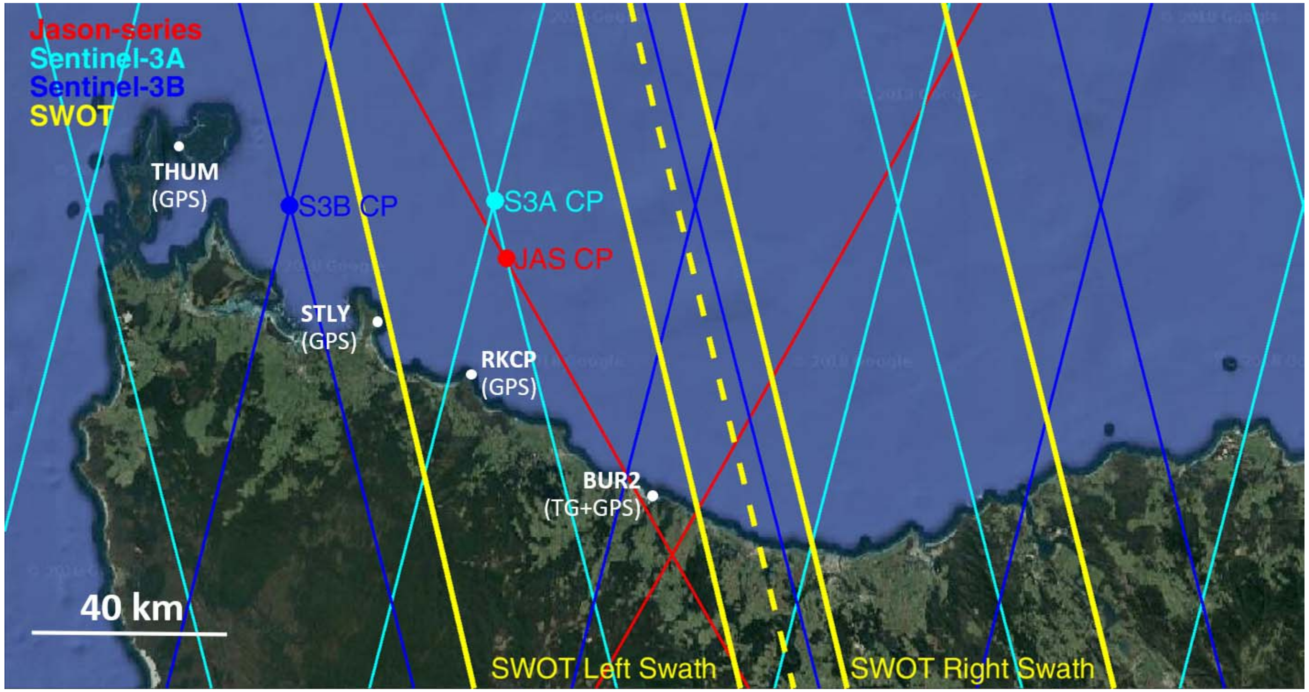
Bass Strait Validation Facility:

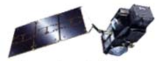
TOPEX / Poseidon
Aug 1992

Jason-1
Dec 2001

OSTM/Jason-2
June 2008

Jason-3
Jan 2016

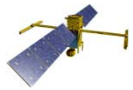




Sentinel-3A
Feb 2016

Sentinel-3B
Apr 2018

Sentinel-6 / Michael Freilich
Nov 2020 (planned)



SWOT
Feb 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 (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 capable of sustained deployment over SWOT validation phase.
- Our focus has been on improving our understanding of systematic errors in in situ measurements in order to keep pace with validation requirements of future missions.

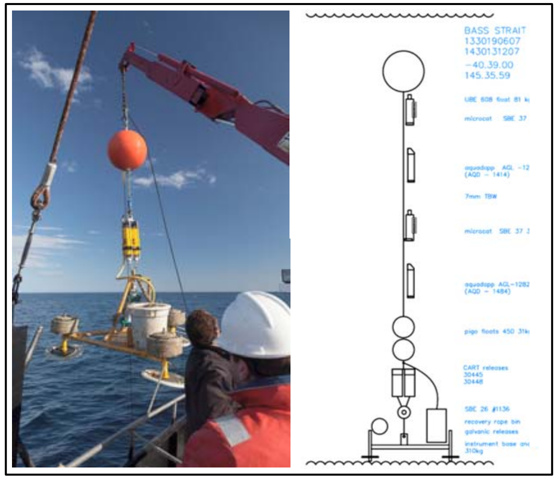
Geometric Approach:

GNSS/INS Equipped Buoys

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

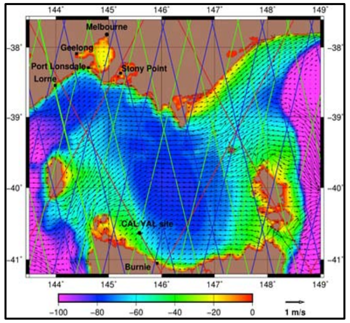
Tide Gauge / cGNSS

- “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 troposphere.



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.



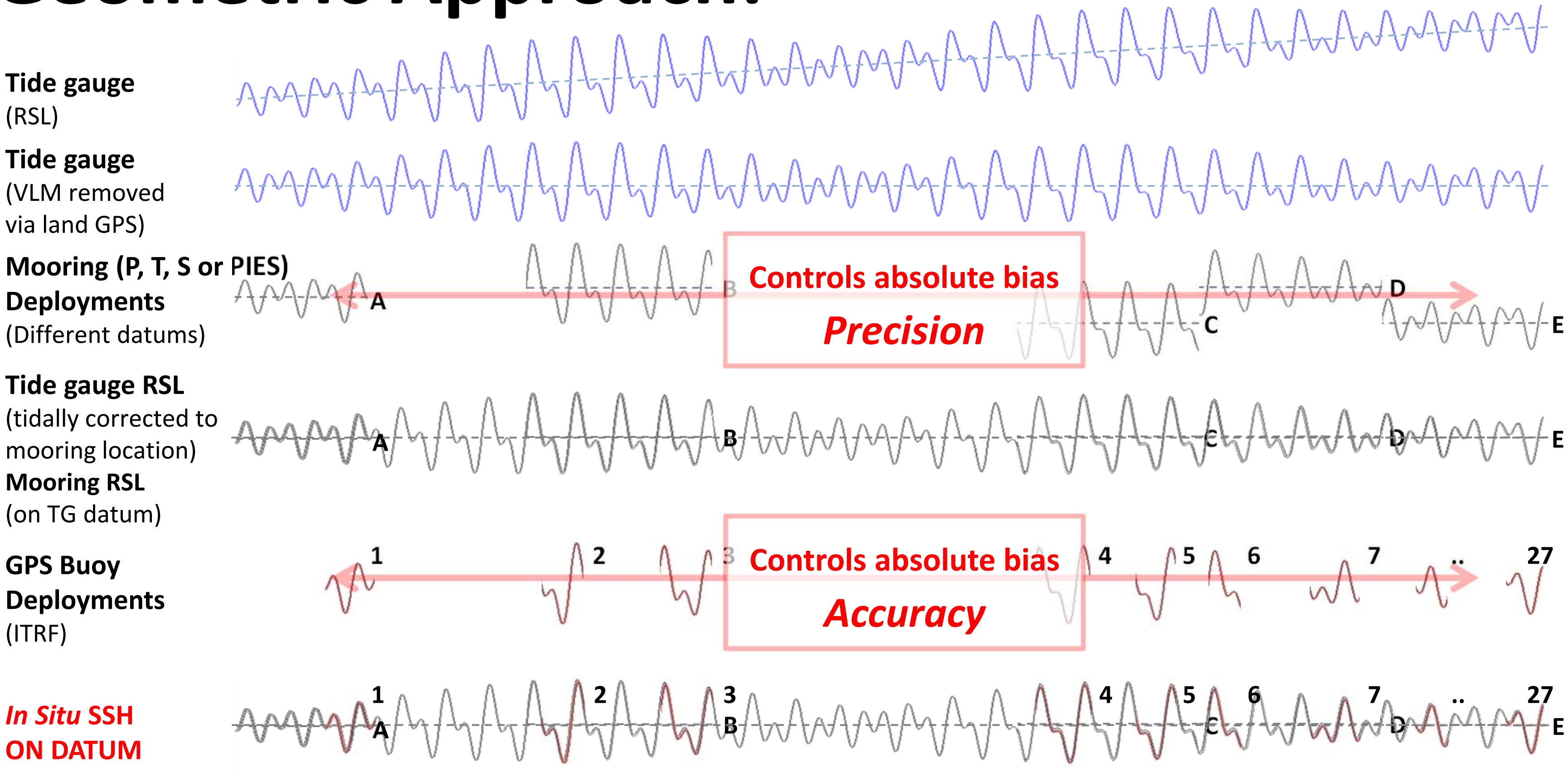
Modelling Activities

- Atmospheric pressure for mooring processing from ACCESS.
- High resolution ocean modelling to aid planning and interpretation of future SWOT validation.

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.

Geometric Approach:

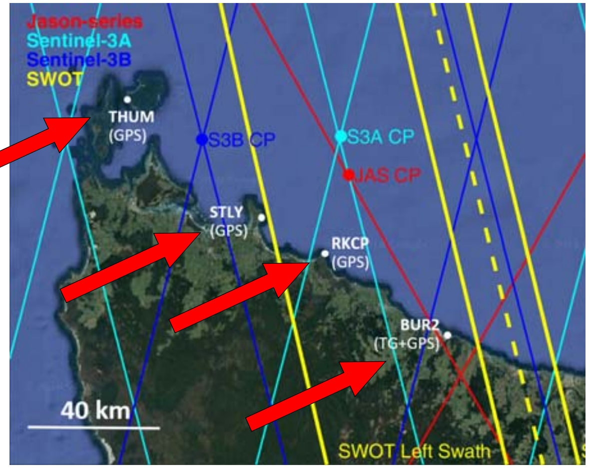


Key Points:

- 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) and understanding the systematic errors associated with the GNSS buoys (orientation, tether tension effects).

Bass Strait Datum

New GNSS deployment at Three Hummock Island (THUM)



- Land based GNSS sites are critical to observe vertical land motion which influences relative sea level observations from the tide gauge and mooring.
- Sites are also used as reference stations in differential processing of GNSS buoys deployed at comparison points.

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.
- In preparation for Sentinel-6 and SWOT, we have installed a permanent site on Three Hummock Island (THUM). Soon to deploy similar permanent sites at Stanley (STLY) and Rocky Cape (RKCP).
- These sites will 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.

Bass Strait Datum

- Our recently published work by Riddell et al. (2020) confirms subtle subsidence across SE Australia.
- Subsidence is not fully explained by GIA and surface mass transport models.
- For our Bass Strait validation work, we maintain VLM is sufficiently linear at -0.7 mm/yr.

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JGR Solid Earth

RESEARCH ARTICLE
10.1029/2019JB018034

Key Points:
- GPS-based vertical land motion at many individual sites across Australia is substantially different to GIA model predictions
- GPS velocities better reflect the solid Earth's long-term motion after spatiotemporal filtering and modeling of short-term geophysical effects
- Geodetic estimates of vertical motion of the Australian continent are yet to be fully explained by GIA and surface mass transport models

Supporting Information:
- Supporting Information S1

Present-Day Vertical Land Motion of Australia From GPS Observations and Geophysical Models

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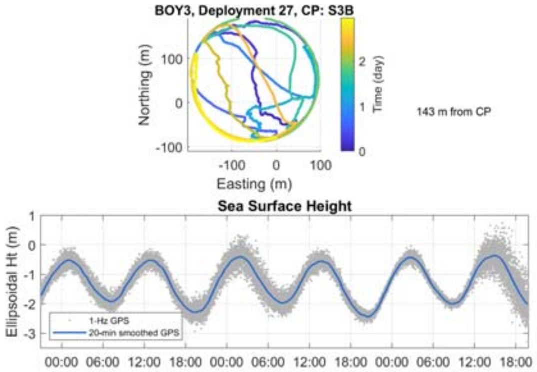
Abstract The secular rate of Australia's vertical surface deformation due to past ice-ocean loading changes is not consistent with present vertical velocities observed by a previously sparse network of Global Positioning System (GPS) sites. Current understanding of the Earth's rheology suggests that the expected vertical motion of the crust should be close to zero given that Australia is located in the far field of past ice sheet loading. Recent GPS measurements suggest that the vertical motion of the Australian continent at permanent sites is between 0 and −2 mm/year. Here we investigate if vertical deformation due to previous ice sheet loading can be recovered in the time series of Australian GPS sites through enlarging the number of sites compared to previous studies from ~20 to more than 100 and through the application of improved data filtering. We apply forward geophysical models of elastic surface displacement

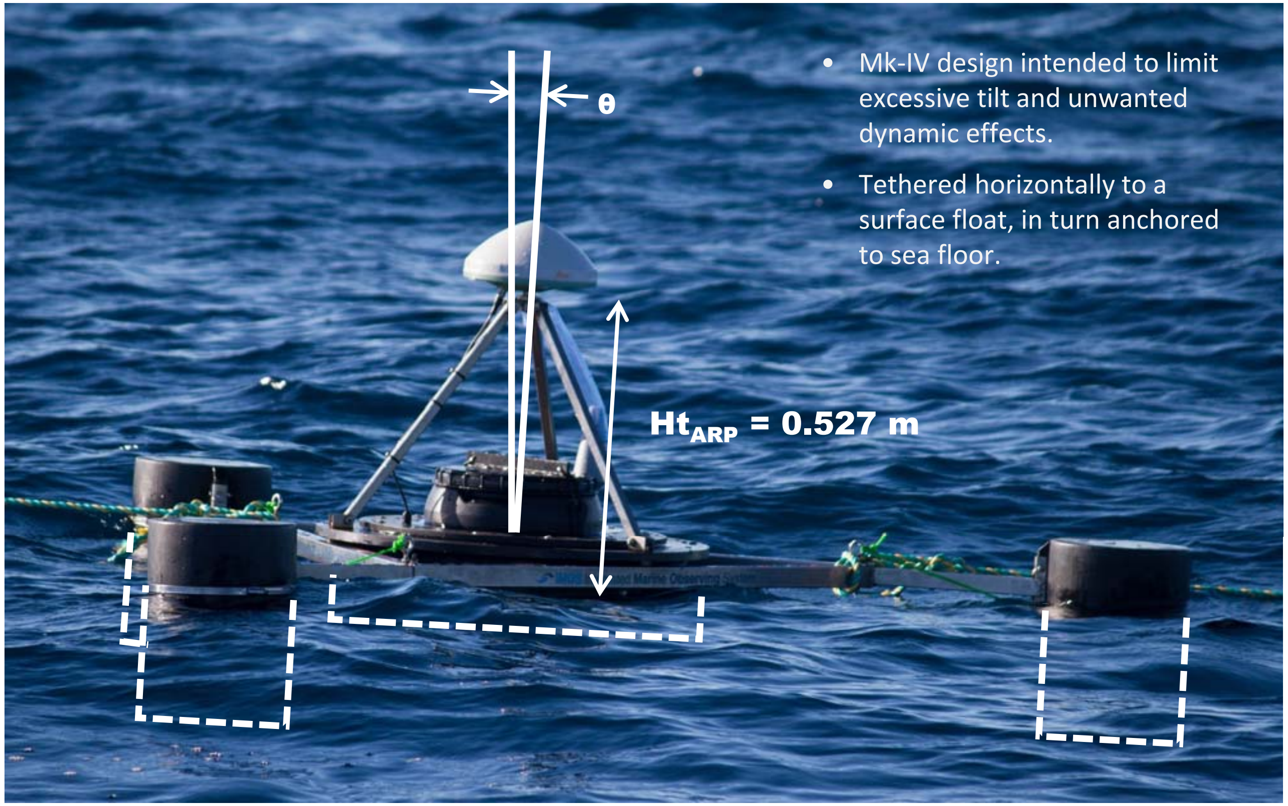
Key Points:
- Analysis of GNSS sites in the Australian region have long suggested subtle subsidence in SE Australia.
- Work reported by Riddell et al (2020) highlights the subsidence is only partially explained by GIA and surface mass transport models.
- Subsidence across Tasmania appears sufficiently linear over the GNSS record. We continue to adopt -0.7 mm/yr for the Burnie tide gauge.

- Reference: Riddell, A., King, M.A., and Watson, C. (2020) Present-Day Vertical Land Motion of Australia From GPS Observations and Geophysical Models, *Journal of Geophysical Research*, DOI: 10.1029/2019JB018034.

In situ SSH: GPS Buoys



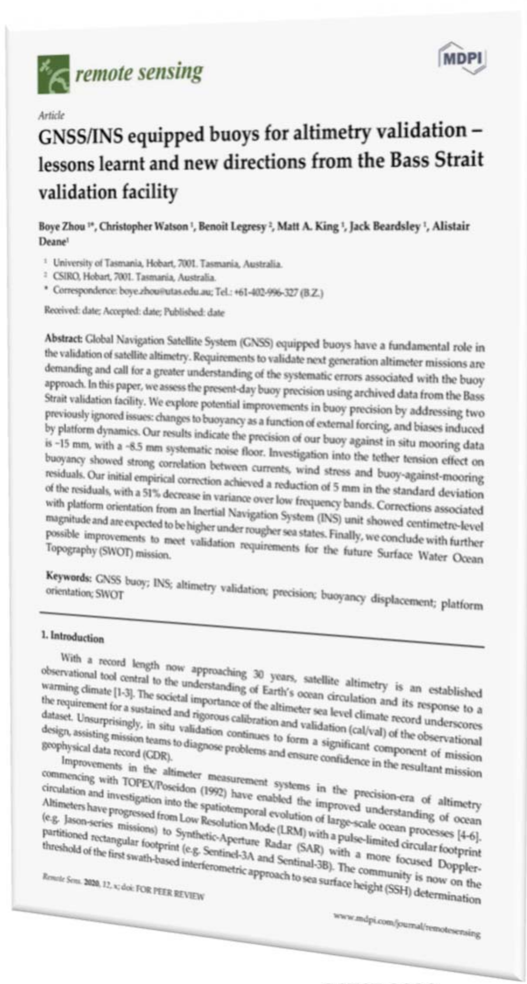
- GNSS buoys are critical for absolute datum determination.
- Our archive of deployments at Bass Strait provide opportunity to understand possible systematic effects and improve as we progress towards Sentinel-6 and SWOT.



Key Points:
- Top left panel shows horizontal buoy position over an example deployment at the S3B CP. Note the circular motion about the anchor as a function of time variable tidal currents and wind stress.
- Bottom left panel shows example 1-Hz SSH time series (grey dots) and 25-minute filtered SSH (blue line). Note the variable sea state over the deployment as indicated by the scatter of the 1-Hz data.
- The buoy photo is our Mk-IV buoy design. Note the horizontal tether on the left which is connected to a surface float which is then anchored to the ocean floor. This design is to minimise any tension induced changes in buoyancy position.

In situ SSH: GPS Buoys

- In preparation for Sentinel-6 and SWOT we have revisited the Bass Strait buoy deployments to ask:
  - ➢ What is the noise floor? (Std dev of ΔSSH between pairs of buoys deployed in close proximity **~8.5 mm**)
  - ➢ What is the overarching precision? (std dev against mooring SSH **~15 mm**)
  - ➢ What are the systematic errors and can we improve?
  - ➢ Recently published by Zhou et al. *Remote Sensing* (2020). See presentation at this OSTST by Zhou et al.
- Two key areas of improvement identified by Zhou et al.:
  - ➢ Impact of antenna orientation with robust treatment of inertial (INS) data (**one to several centimetres**)
  - ➢ Impact of tether tension (current and wind stress) on buoyancy position (**~5 mm reduction in std dev**)


remote sensing

MDPI

Article

GNSS/INS equipped buoys for altimetry validation – lessons learnt and new directions from the Bass Strait validation facility

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Abstract: Global Navigation Satellite System (GNSS) equipped buoys have a fundamental role in the validation of satellite altimetry. Requirements to validate next generation altimeter missions are demanding and call for a greater understanding of the systematic errors associated with the buoy approach. In this paper, we assess the present-day buoy precision using archived data from the Bass Strait validation facility. We explore potential improvements in buoy precision by addressing two previously ignored issues: changes to buoyancy as a function of external forcing, and biases induced by platform dynamics. Our results indicate the precision of our buoy against in situ mooring data is ~15 mm, with a ~8.5 mm systematic noise floor. Investigation into the tether tension effect on buoyancy showed strong correlation between currents, wind stress and buoy-against-mooring residuals. Our initial empirical correction achieved a reduction of 5 mm in the standard deviation of the residuals, with a 51% decrease in variance over low frequency bands. Corrections associated with platform orientation from an Inertial Navigation System (INS) unit showed centimetre-level magnitude and are expected to be higher under rougher sea states. Finally, we conclude with further possible improvements to meet validation requirements for the future Surface Water Ocean Topography (SWOT) mission.

Keywords: GNSS buoy; INS; altimetry validation; precision; buoyancy displacement; platform orientation; SWOT

1. Introduction

With a record length now approaching 30 years, satellite altimetry is an established observational tool central to the understanding of Earth's ocean circulation and its response to a warming climate [1-3]. The societal importance of the altimeter sea level climate record underscores the requirement for a sustained and rigorous calibration and validation (cal/val) of the observational dataset. Unsurprisingly, in situ validation continues to form a significant component of mission design, assisting mission teams to diagnose problems and ensure confidence in the resultant mission geophysical data record (GDR).

Improvements in the altimeter measurement systems in the precision-era of altimetry commencing with TOPEX/Poseidon (1992) have enabled the improved understanding of ocean circulation and investigation into the spatiotemporal evolution of large-scale ocean processes [4-6]. Altimeters have progressed from Low Resolution Mode (LRM) with a pulse-limited circular footprint (e.g. Jason-series missions) to Synthetic-Aperture Radar (SAR) with a more focused Doppler-partitioned rectangular footprint (e.g. Sentinel-3A and Sentinal-3B). The community is now on the threshold of the first swath-based interferometric approach to sea surface height (SSH) determination

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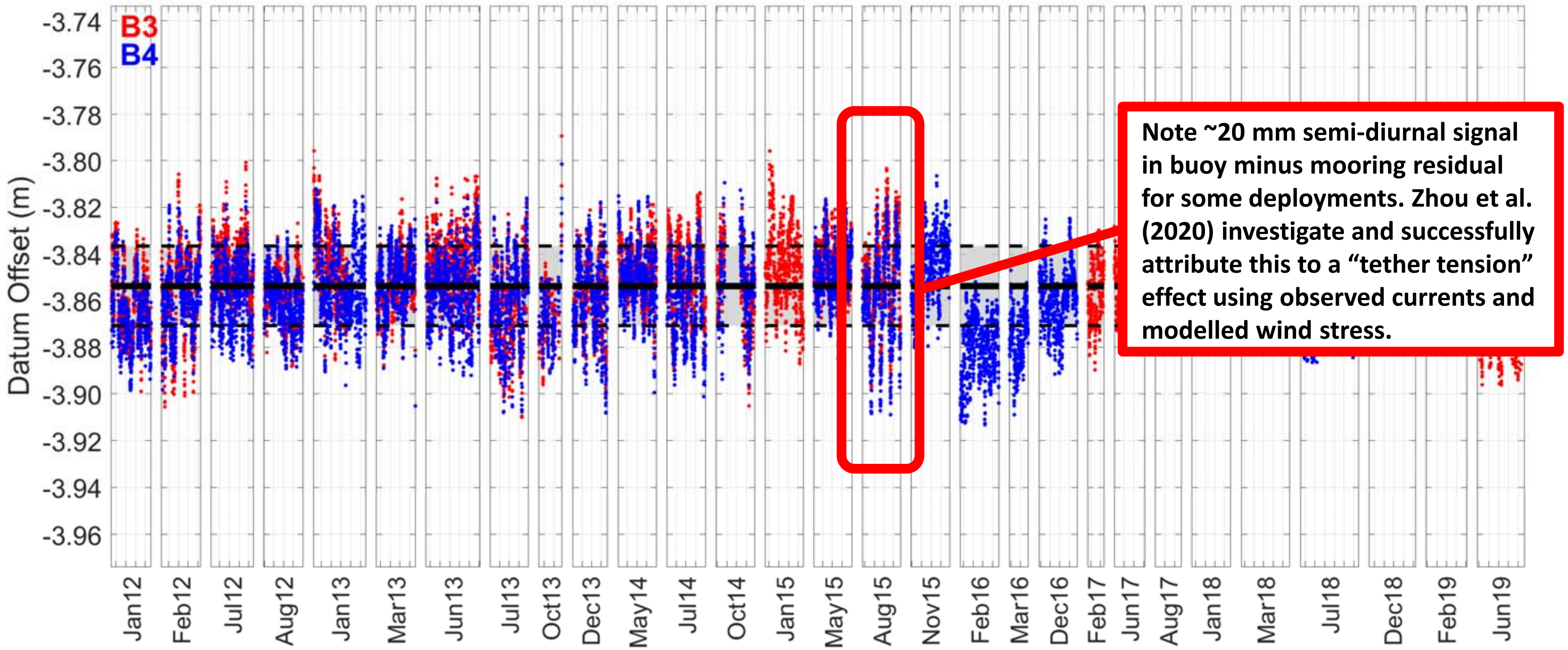
Key Points:

- The archive of buoy deployments at the Bass Strait facility enables a detailed investigation of buoy derived SSH using our Mk-IV design.
- Analysis of the ΔSSH between two buoys deployed with ~50 m gives a indication of the noise floor (~8.5 mm).
- Comparing SSH between the buoy and mooring gives an indication of the overarching precision (~15 mm).
- Further improvement requires understanding of systematic errors - Zhou et al. (2020) reports on the impact of coupling inertial (INS) data within the GNSS solutions, and an initial investigation into tether tension effects the mean buoyancy position. **See presentation by Zhou et al at this meeting**.

- Reference: Zhou, B., Watson, C., Legresy, B., King, M., Beardsley, J and Deane, A. (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

Datum Determination (Buoy - JAS Mooring):

- Filtered 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.
- The scatter here gives an indication of the overarching precision (~15 mm).
- The example deployment highlighted (Aug 2015) shows an anomalous semi-diurnal signal highlighted at previous OSTSTs which previously did not have an explanation. Work reported by Zhou et al. (2020) successfully attributes this to a buoyancy effect driven by changing tension on the tether.
- We empirically model this using observed currents and modelled wind stress (see Zhou et al). We are well situated to improve this empirical model for the next generation buoy design given we will have co-located deployments of GNSS buoys and CWPIES moorings.

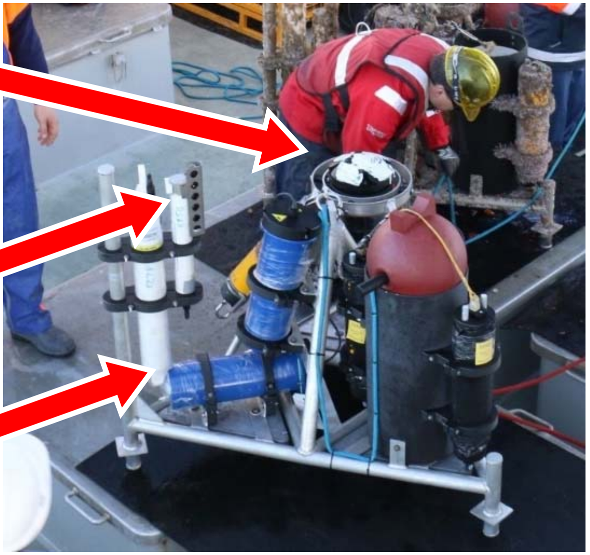
In situ SSH:
Current, waves, pressure inverted echo sounder (CWPIES)

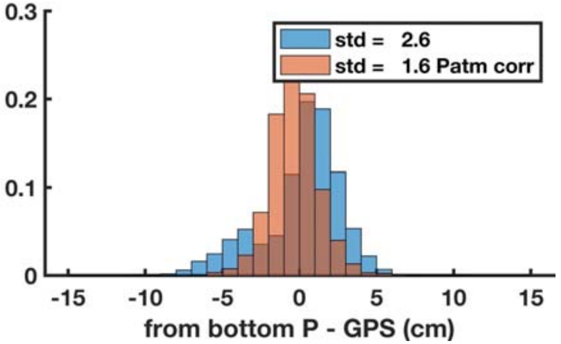
- We have now demonstrated the CWPIES as a valid alternative to our more traditional P / T / S mooring approach.
- CWPIES delivers other observables of interest… accurate SSH (at 2 Hz), wave field, currents, water column density and atmospheric pressure recovery without a surface expression.

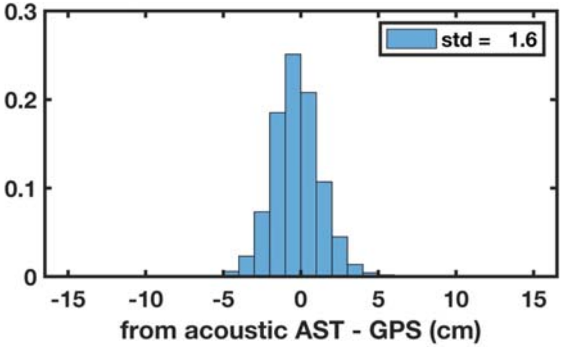
5 beam Acoustic Doppler Current Profiler
- Stabilised gimbal mount
- Centre beam is vertical and ranges to the surface @ 2 Hz

Temperature and Conductivity sensor

Bottom Pressure sensor



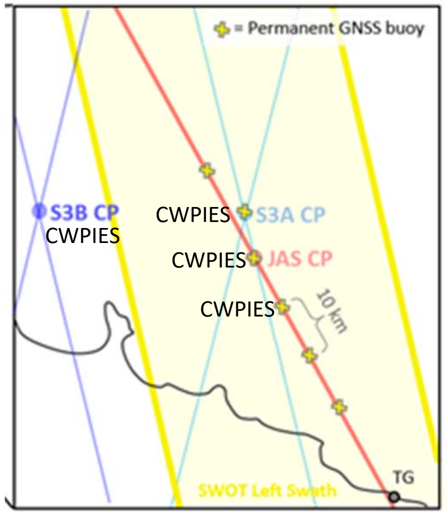




Key Points:
- A key challenge to overcome with the CWPIES was to ensure vertical pointing of the 5-beam acoustic sensor using a gimbal mount.
- The CWPIES approach is less sensitive to drift compared to bottom pressure sensors – they also deliver SSH across high and low frequency bands, as well as current and atmospheric pressure. This combination makes them highly suitable for Sentinel-6 and SWOT validation, complementary to GNSS buoys.
- Analysis of simultaneous GNSS buoy and CWPIES deployments is presently underway in preparation for along track Sentinel-6 deployments – this has been impacted by COVID related delays with Mk-V buoy construction and deployment.

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

- CWPIES less sensitive to drift compared to bottom pressure.
- Comparable low frequency SSH to GPS and bottom pressure corrected for dynamic height and atmospheric pressure.
- High frequency wave and current data – aids in determination of tether tension model for GNSS buoy.



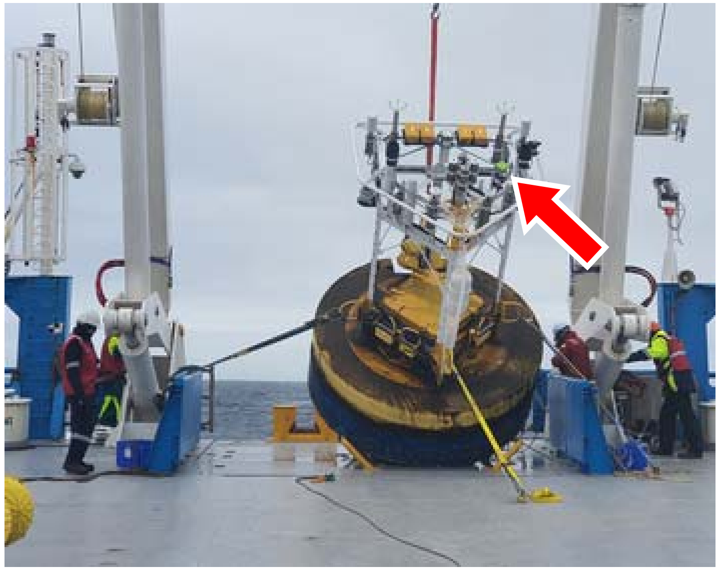
- Mk-V GNSS/INS buoy shown above deployed over CWPIES – currently under analysis.
- Next deployment aims to deploy 3 CWPIES along the Sentinel-6 track adjacent to the JAS comparison point (Dec 2020 – Mar 2021).

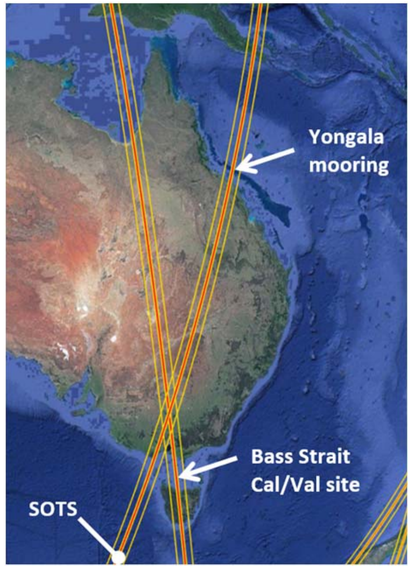
Key Points:

- Along track deployment of multiple CWPIES will offer insight into short-spatial scale variations in currents, sea state, water density, SSH, and atmospheric pressure.
- The first deployment of Mk-V prototype buoys (pictured) over CWPIES is under analysis.
- We hope to use our experience over the Sentinel-6 validation phase to further inform SWOT validation over the fast-sampling period in the same location (yellow shaded area in right hand figure).

Other Developments

- First year-long test deployment of GNSS on the SOTS mooring in Southern Ocean was recently retrieved and redeployed.
- SOTS is a secondary target in our validation plan for the fast-sampling phase of the SWOT mission.
- Highly dynamic region of the southern ocean (Hs ~4 m, max ~13 m)





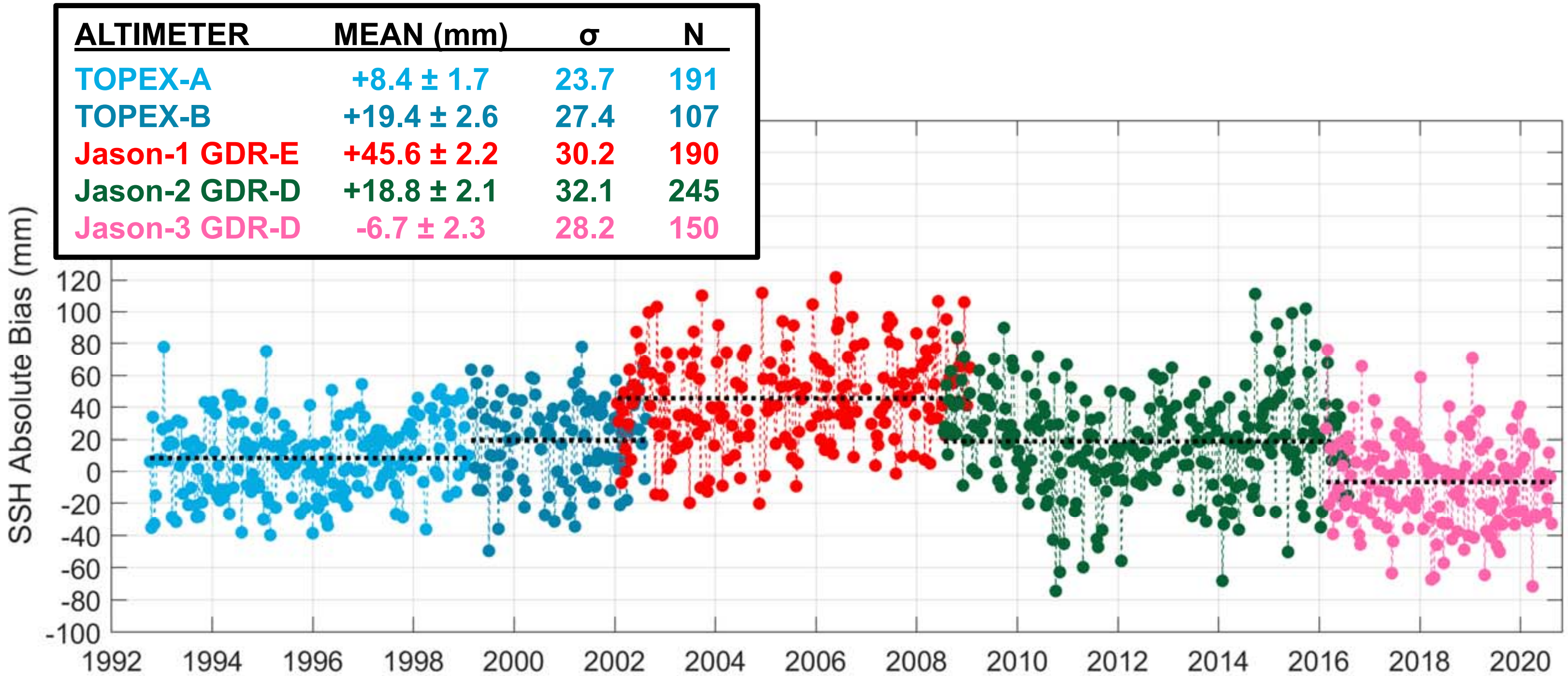
Key Points:

- Secondary point-wise targets in preparation for SWOT include the Southern Ocean SOTS mooring and the reference site at Yongala.
- In both cases, GNSS has been added to existing surface platforms.
- The first test deployment was located on a Jason-series / Sentinel-3a cross over. Challenging opportunity to explore GNSS derived SSH in a dynamic setting.

Bass Strait
Absolute Bias Results

Absolute Bias at Bass Strait (vs TG)

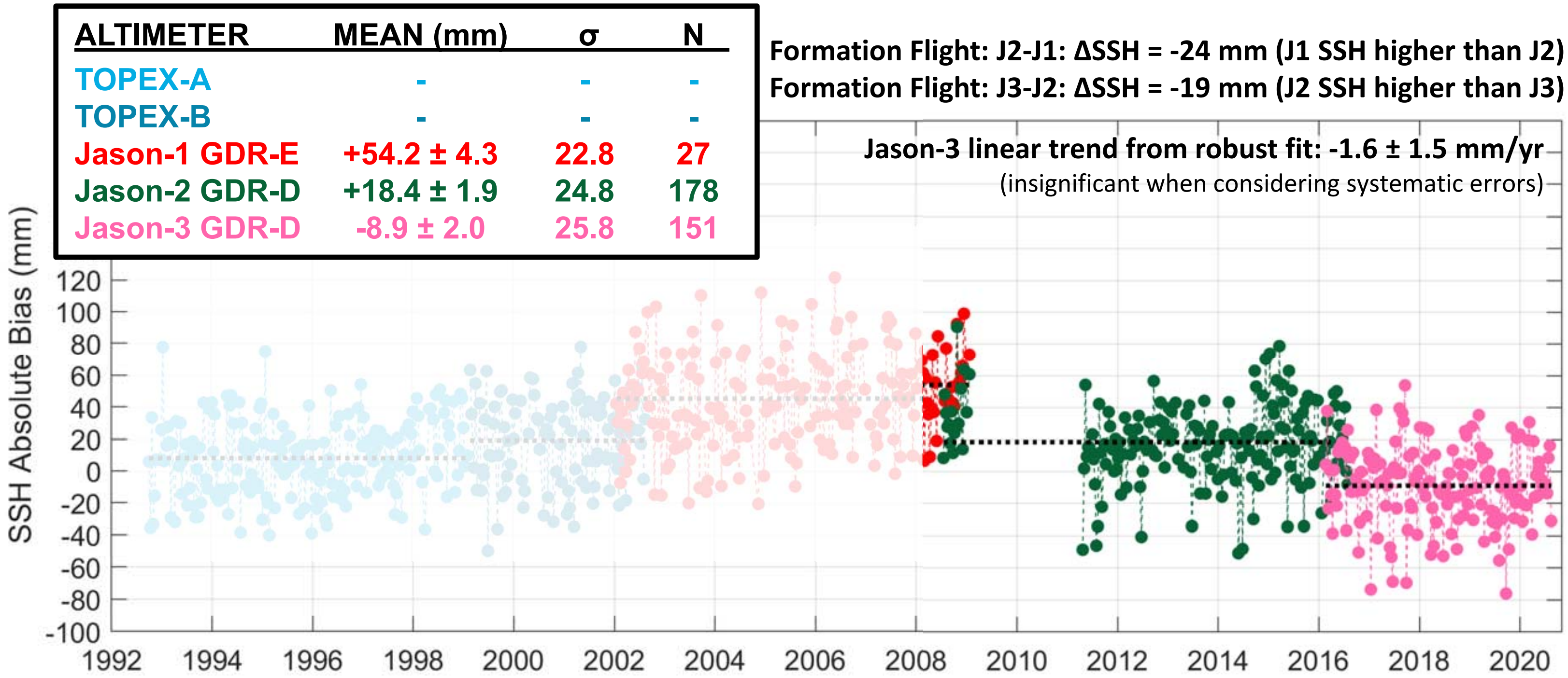
(expect higher variability than against mooring).



Key Points:

- The complete time series of altimeter absolute bias from Bass Strait shows biases that are likely indistinguishable from zero for TOPEX-A, TOPEX-B, Jason-2 and Jason-3.
- Jason-1 remains significantly different from zero, yet comparable with results from Corsica and Gavdos.
- Non-linear signal in Jason-2 is spatially persistent (results not shown here from Storm Bay and other tide gauges in the region).

Absolute Bias at Bass Strait (vs Mooring)

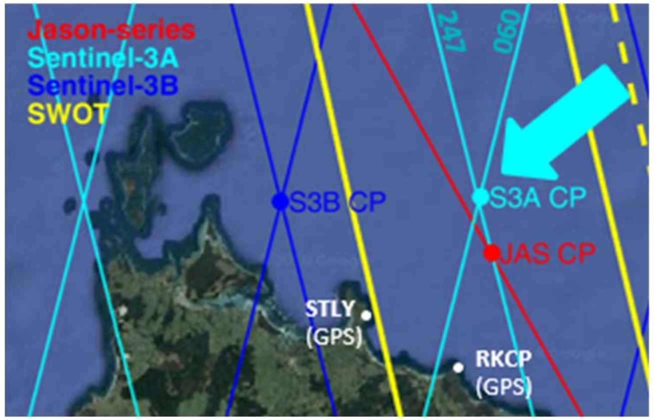


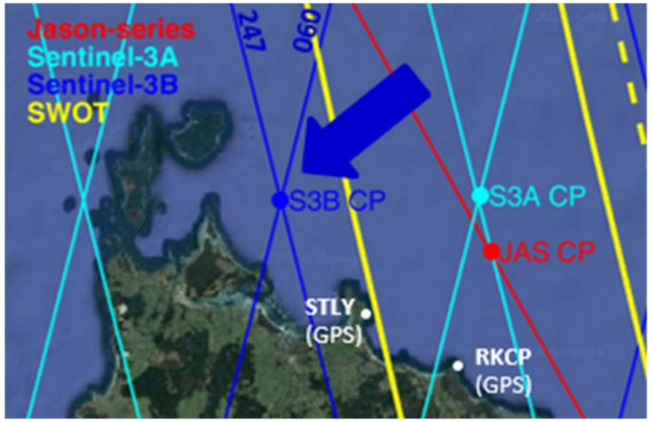
Key Points:

- When computing absolute bias from the co-located mooring SSH (available over J1/J2 tandem phase and post ~2011), we see reduced variability now at the level of ~25 mm.
- Linear trend for Jason-3 computed using a robust fit shows a slight negative trend but this is unlikely to be significant given contribution of systematic errors.

Sentinel-3A and Sentinel-3B

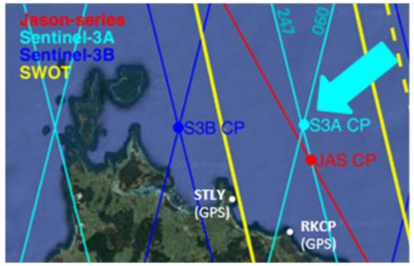
- Both S3A and S3B comparison points are located at cross over locations.
- S3A comparison point (**S3A**) is ~9 km north of our Jason-series comparison point (**JAS**).
- S3B comparison point (**S3B**) is ~44 km west (~28 m depth c.f. ~52 m depth, location of CWPIES deployment).



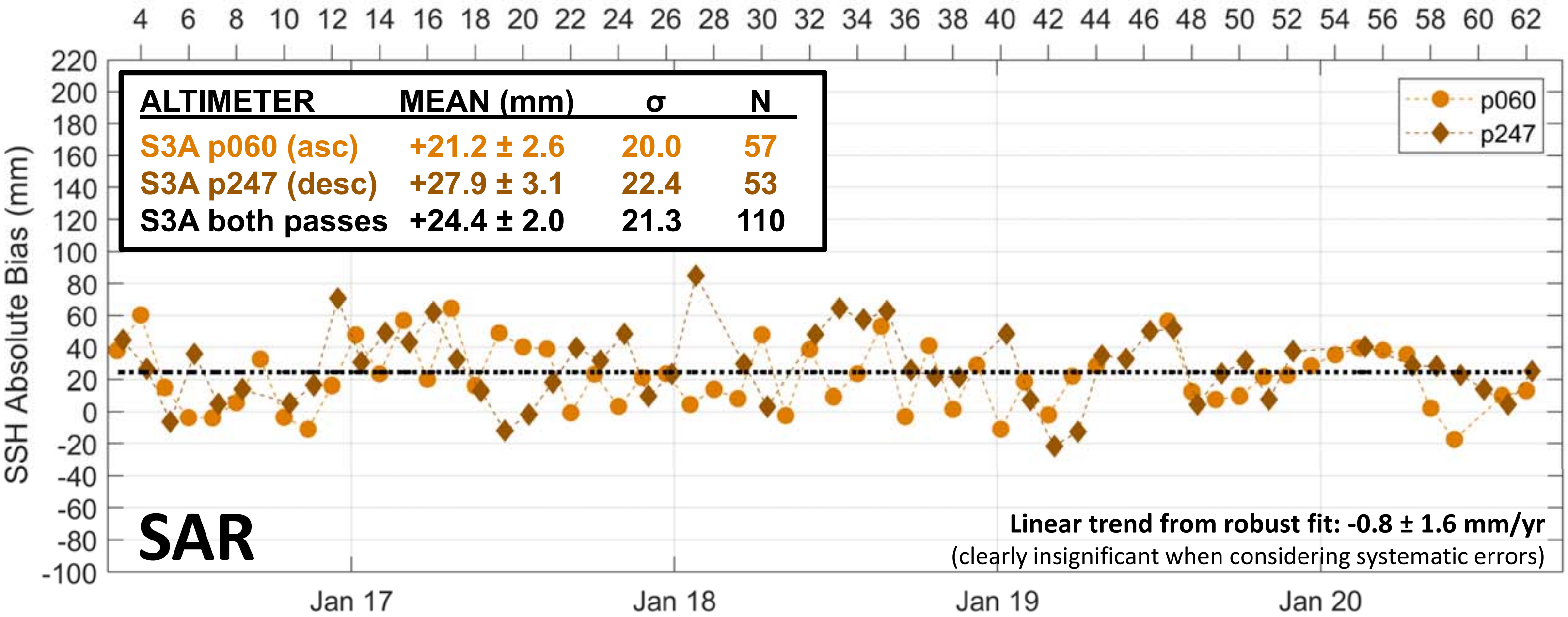


Key Points:
- Following slides show our S3A and S3B absolute bias estimates, each from cross over locations shown above.

Sentinel-3A Absolute Bias (SAR)



- S3A, Non time critical data, Baseline 4 via RADS, cycles 3-62.
- Baseline 4 bias is 5 mm higher than Baseline 3 (over cycles 3-48).
- Bias variability (stdev ~21 mm) is approaching the in situ noise.

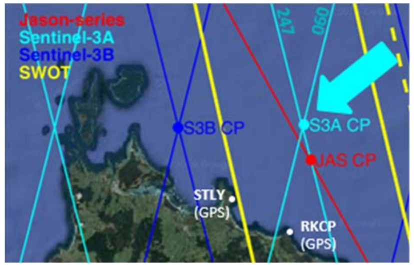


ALTIMETER	MEAN (mm)	σ	N
S3A p060 (asc)	+21.2 ± 2.6	20.0	57
S3A p247 (desc)	+27.9 ± 3.1	22.4	53
S3A both passes	+24.4 ± 2.0	21.3	110

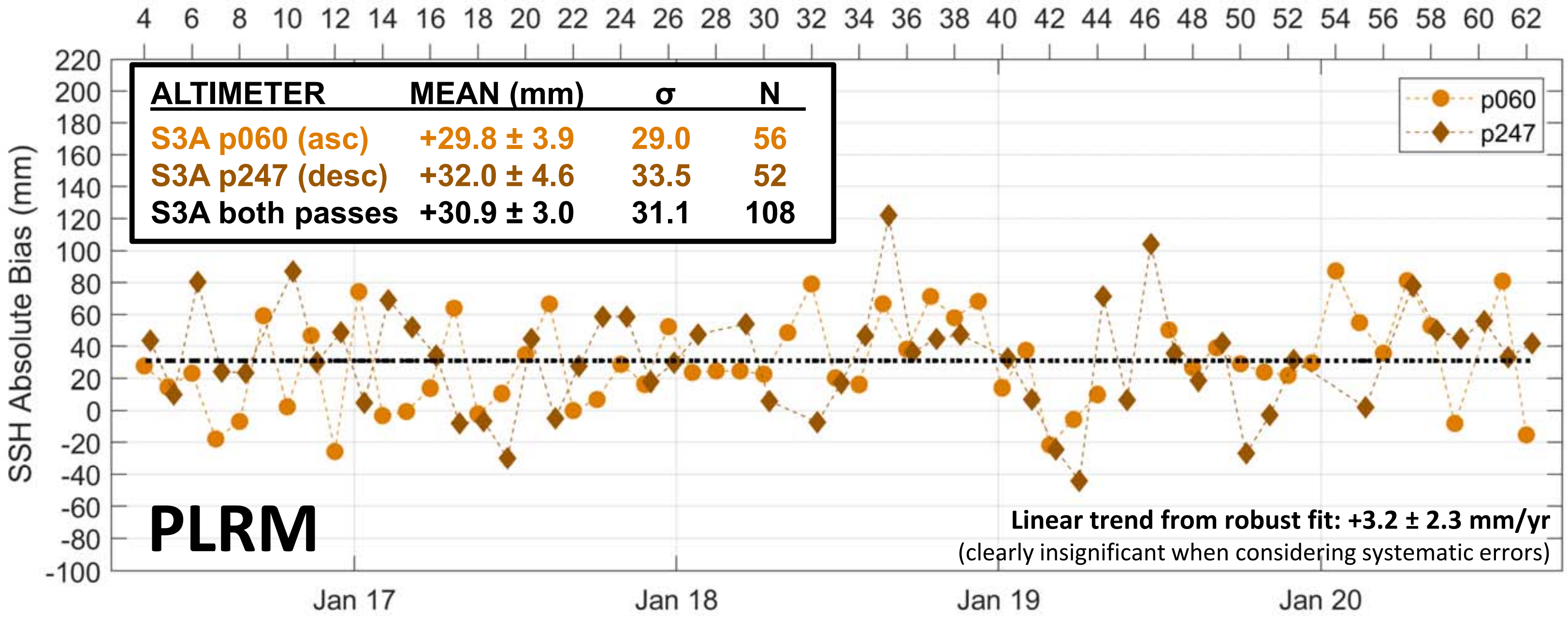
Key Points:

- S3A SAR bias emerging as significantly different from zero at ~24 mm (slight increase when shifting from Baseline 3 to 4 processing). Subtle negative trend is unlikely significant.
- Variability is very low and approaching the in situ noise. This provides motivation for our work to further develop our GNSS/INS and CWPIES in situ instrumentation.
- Note we expect to recompute our datum solutions for S3A and S3B using new buoy deployments prior to the 2020 S3VT meeting in December.

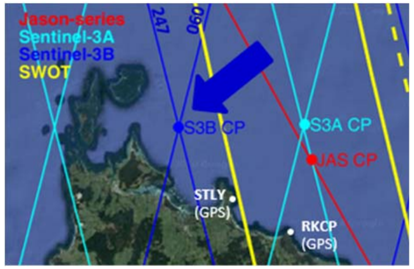
Sentinel-3A Absolute Bias (PLRM)



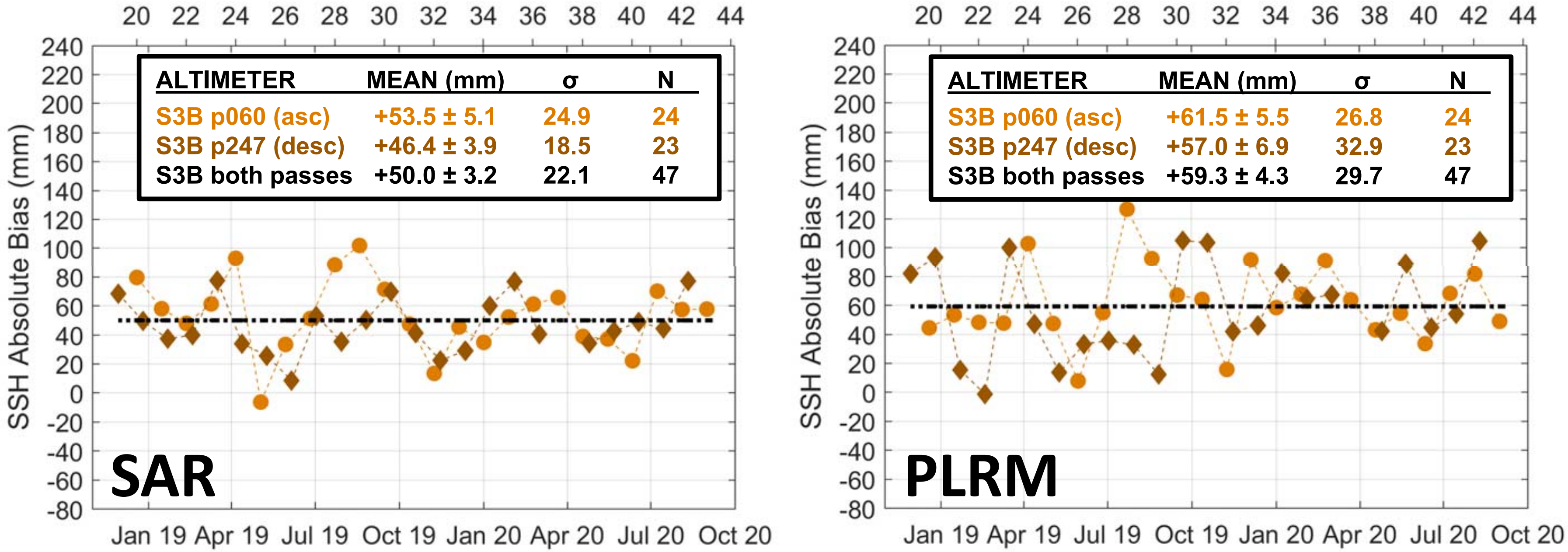
- S3A PLRM bias is ~7 mm higher than SAR bias (mean: 31 v 24 mm).
- S3A PLRM bias is more variable than SAR bias (stdev: 31 v 21 mm).



Sentinel-3B Absolute Bias



- S3B SAR bias is ~26 mm higher than S3A SAR bias.
- Baseline 4 bias is 16 mm higher than Baseline 3 (over cycles 19-28).
- Similarly to S3A, the S3B PLRM bias is ~9 mm higher than SAR (mean: 59 v 50 mm).
- Similarly to S3A, the S3B PLRM bias is more variable than SAR (stdev: 30 v 22 mm).



Key Points:

- S3B SAR bias is now ~26 mm higher than S3A (larger increase of 16 mm when shifting from Baseline 3 to 4 processing).
- Similar variability to S3A.
- Our S3B datum has higher uncertainty given fewer buoy deployments. We are in the process of recomputing this datum using new buoy and mooring deployments prior to the 2020 S3VT meeting in December.

Conclusions from Bass Strait

- Very low variability in Jason-3, S3A and S3B bias estimates underscores the importance of improved understanding of systematic effects in in situ SSH. Promising developments at Bass Strait (GNSS buoys / CWPIES) in the context of future missions.
- **Jason-1** (GDR-E) remains significantly different from zero which is not yet understood.
- **Jason-3** (GDR-D) bias insignificantly different from zero (-9 mm).
- S3A SAR bias (Baseline 4) is +24 mm (stdev 21 mm). Bias and variability increases with PLRM.
- S3B SAR bias (Baseline 4) ~26 mm higher than S3A. Very similar increase to bias and variability when using PLRM.
- Non-averaging errors likely limit absolute bias uncertainty to ±10-15 mm.

Mission	Cycles	Absolute Bias	Std Dev
TOPEX-A	1 -> 235	+8 mm	24 mm (TG*)
TOPEX-B	236 -> 365	+19 mm	27 mm (TG*)
Jason-1 GDR-E	1 -> 259	+47 mm	30 mm (TG*)
Jason-2 GDR-D	1 -> 298	+19 mm **+18 mm**	32 mm (TG) **25 mm (Mooring)**
Jason-3 GDR-D	1 -> 166	-6.7 mm **-8.9 mm**	28 mm (TG) **26 mm (Mooring)**
S3A **SAR** S3A PLRM	3 -> 62 3 -> 62	**+24 mm** +31 mm	**21 mm (Mooring#)** 31 mm (Mooring#)
S3B SAR **S3B** PLRM	19 -> 43 19 -> 43	**+50 mm** +59 mm	**22 mm (Mooring#)** 30 mm (Mooring#)

* Solutions adopt VLM of -0.7 mm/yr at the tide gauge
# Pending update to mooring datum prior to S3VT 2020

Key Points:

- Variability in bias estimates now approaching the in situ noise (e.g. 21 mm for S3A). Advancing altimetry calls for advances in the in situ instrumentation – hence our progress with GNSS/INS buoys and CWPIES in preparation for Sentinel-6 and SWOT.
- Our S3B datum has higher uncertainty given fewer buoy deployments. We are in the process of recomputing this datum using new buoy and mooring deployments prior to the 2020 S3VT meeting in December.

Questions or Comments?

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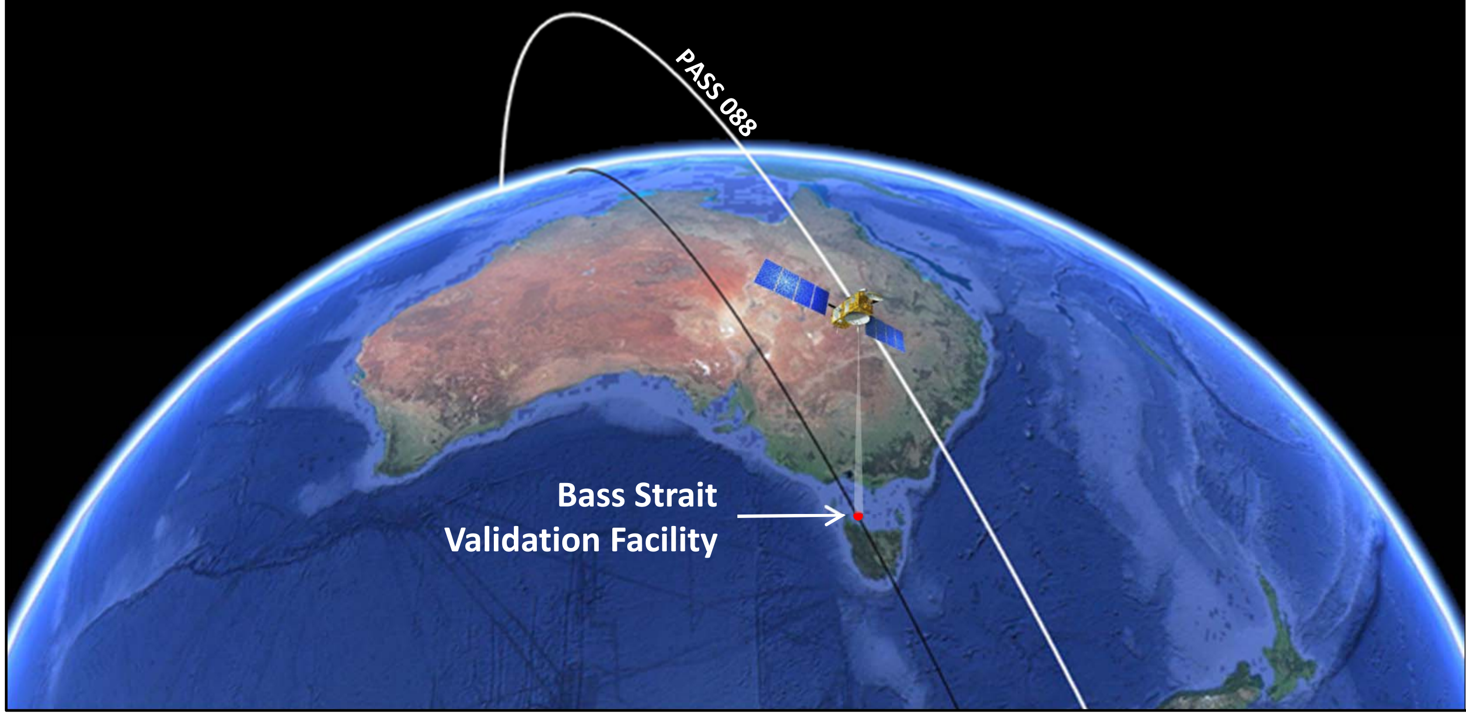

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