Ocean Surface Topography Science Team Meeting (OSTST)

31 October – 4 Nov, 2022

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

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This presentation is based on a manuscript being prepared for journal submission by the listed authors. For people who are interested in the details of this research, please contact the lead author Boye Zhou via email at boye.zhou@utas.edu.au for more information.

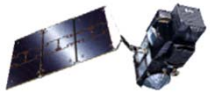
Ongoing buoy development in Bass Strait

TOPEX / Poseidon
Aug 1992

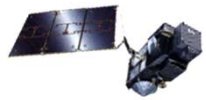
Jason-1
Dec 2001

OSTM/Jason-2
June 2008

Jason-3
Jan 2016

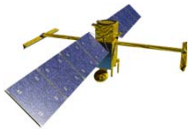


Sentinel-3A
Feb 2016



Sentinel-3B
Apr 2018

Sentinel-6 Michael Freilich
Nov 2020



SWOT
Dec 2022 (pending)

Recently upgraded UTas/IMOS Mk-VI GNSS/INS buoy at Bass Strait altimetry validation facility

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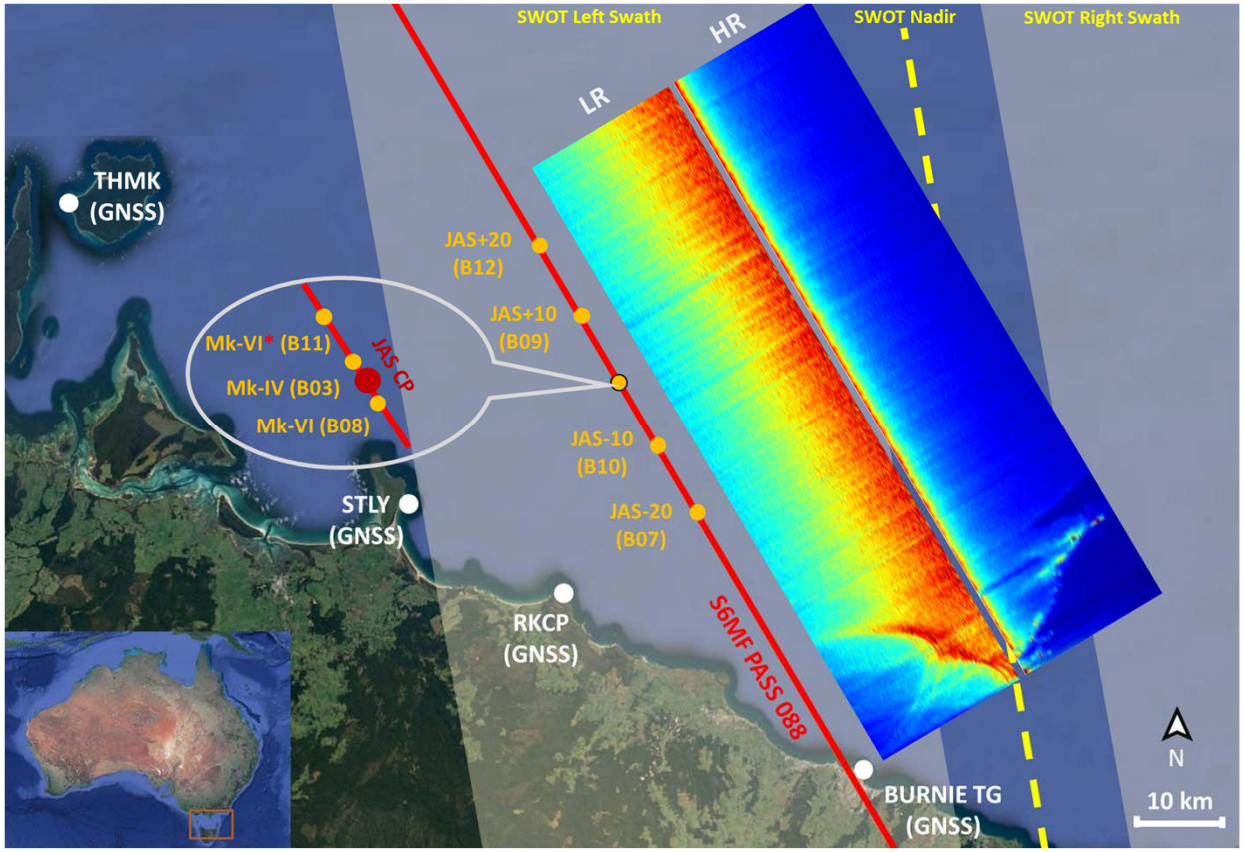
The Bass Strait facility presently contributes cycle-by-cycle estimates of absolute bias to the Ocean Surface Topography Science Team (OSTST) for the Jason-series missions and to the Sentinel-3 Validation Team (S3VT) for the Sentinel-3A and Sentinel-3B missions.

As altimeters progressed from Low Resolution Mode (LRM) to Synthetic-Aperture Radar (SAR) and will enter a new era soon on the upcoming swath-based interferometric mission Surface Water Ocean Topography (SWOT), validation have become more and more stringent in its requirements, asking for more accurate and sustained SSH observations. To be prepared for such challenge, the UTas/IMOS altimetry validation buoy has achieved an upgrade from Mk-IV (old) to Mk-VI (new) design.

Formation of a buoy array in Bass Strait



***Mk-VI (B07-B12)** is the new generation GNSS/INS buoy, while Mk-IV (B03) is the old GNSS buoy at Bass Strait facility.

① **First trial buoy array** (1x old buoy + 6x new buoys) deployment in August 2021 in preparation for SWOT validation.

② 10-km spacing along Sentinel-6/Michael Freilich pass 088 at five locations, with a triplet buoy (1x old + 2x new) group at JAS CP.

③ The trial deployment is expected to help explore:

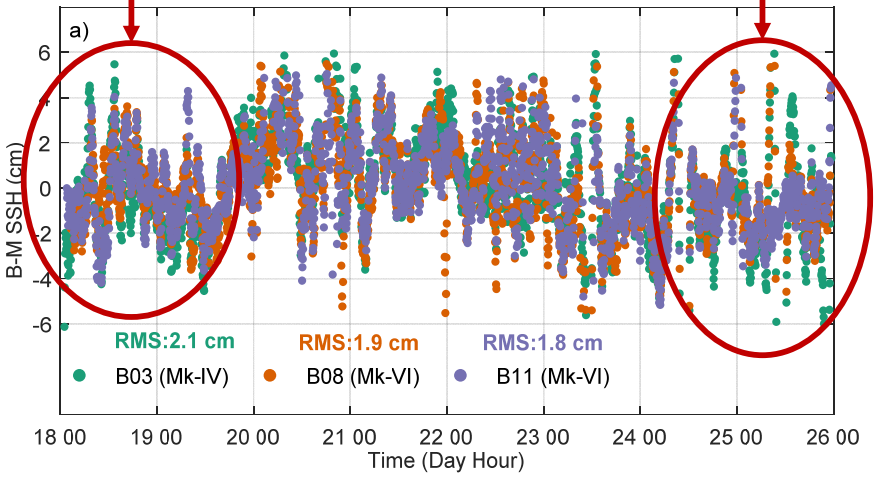
- old/new buoy transition (precision-wise)
- intra-swath ocean/atmosphere variability
- spatial scale of the buoy array errors
- quality of buoy/altimetry mission output

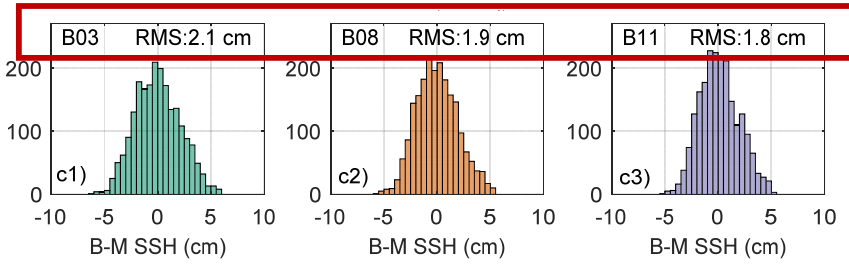
Along-track waveforms from both Low-Resolution (LR) and High-Resolution (HR) output by Sentinel-6 Michael Freilich (S6MF) are provided to show reasonable altimetry performance at the chosen deployed location.

Meanwhile, GNSS stations (see white text) are set up/upgraded along the coast on the islands of Tasmania for future research possibilities, e.g., weather system monitoring, GNSS reflectometry study etc.

Old/New buoy transition – overarching precision against mooring

① **Similar pattern** in the temporal domain from the triplet buoy group against the mooring with **some performance improvement**



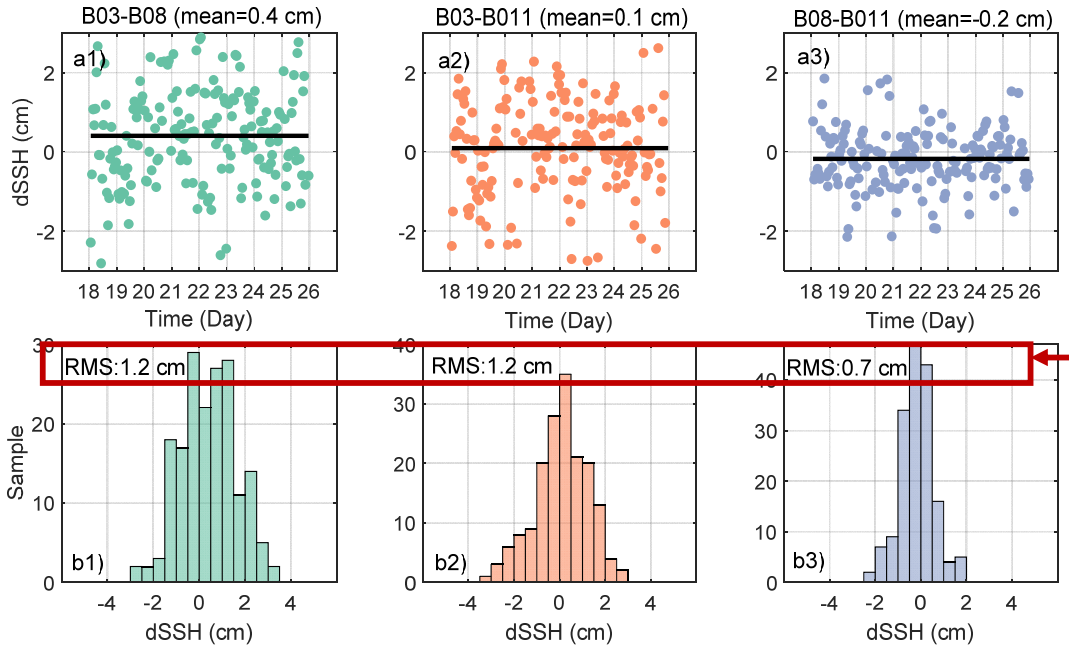


Residual of SSH solutions from Mk-IV, Mk-VIs minus in situ mooring solutions over the trial deployment (~193 hours)

② **Slightly reduced RMS** against the mooring for the new buoys (B8 & B11) – warrant for extended deployment to validate possible improvement.

From the old Mk-IV to the new Mk-VI buoy design, the main changes in the features are: instalment of solar panels to achieve sustained deployment duration (previously 48 hours vs. present several months) in preparation for SWOT fast-sampling phase; elevated antenna height (from ~0.6 m to ~1.0 m) with larger floats for avoidance of GNSS outage in high sea states; addition of inertial unit to quantify impact of orientation variations on SSH solutions.

Old/New buoy transition – relative precision within the triplet group



Differential SSH solutions (~193 hours) among the buoy group, providing information of the systematic noise within the buoy system.

① The standard deviation of the differential SSH (dSSH) taken as the noise baseline. The magnitude (**7-12 mm**) remains generally at the same level of **~8.5 mm** as per previous investigation[1] using twin buoy setup.

② Extended data record is needed for further assessment of possible noise baseline changes in the new buoy system:

σ(Old – Old) = 8.5 mm (from Ref. [1])

σ(Old – New) = 12 mm

σ(New – New) = 7.0 mm

③ **Key Points**:

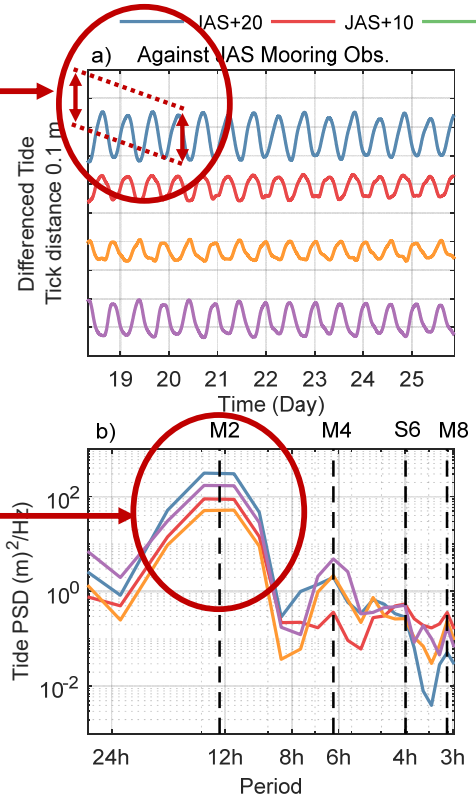
Buoy precision shows insignificant changes during design transition (overarching precision: **15 mm** with noise baseline: **8.5 mm**)

Ref [1]: Zhou B, Watson C, Legresy B, King MA, Beardsley J, Deane A. GNSS/INS-equipped buoys for altimetry validation: Lessons learnt and new directions from the Bass Strait validation facility. Remote Sensing. 2020 Sep 15;12(18):3001. https://doi.org/10.3390/rs12183001

Tidal differences – intra-swath variability

① When differenced against the central JAS comparison point, up **0.15 m** tidal height difference over 20 km.

② Major differences in **M2 tidal band** along the buoy array as further away from the coast.



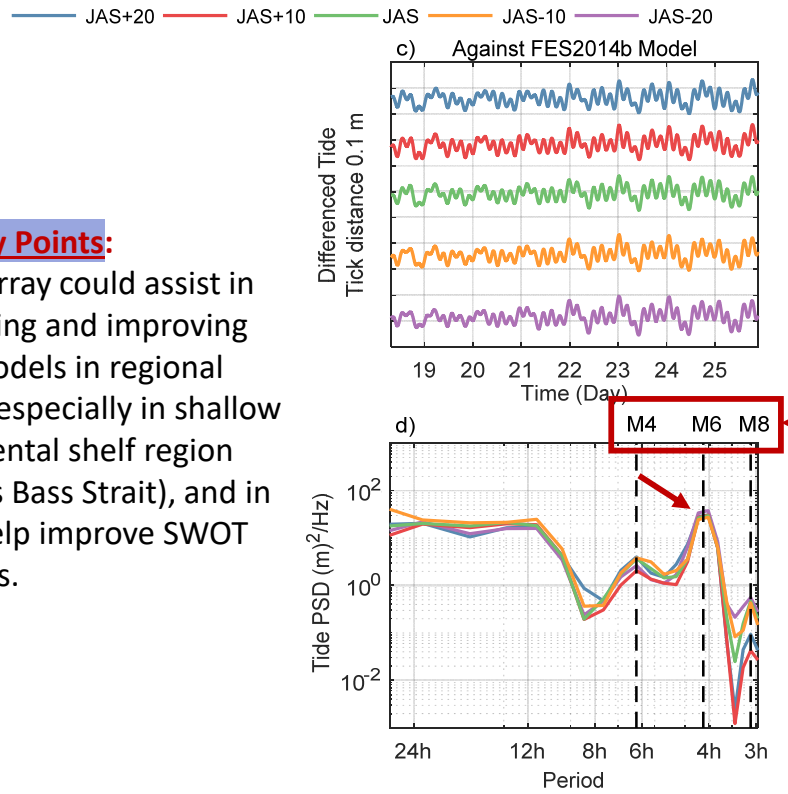
Difference of the observed tide along the buoy array with respect to the reference tidal height series* at Jason CP.

③ **Key Points**:
As well known, improved tidal modelling will be required to correctly interpret SWOT observations.

*Reference tide at Jason comparison point (CP) is derived based on the tidal analysis of decade-long SSH record from the in situ mooring using Utide Matlab toolbox[2].

Ref [2]: Codiga, D.L., 2011. Unified tidal analysis and prediction using the UTide Matlab functions.

Tidal differences – FES2014b tide model comparison



① Shallow-water constituents stands out when referenced against FES2014b – **M6** amplitude difference at **2 cm**.

② **Key Points**:

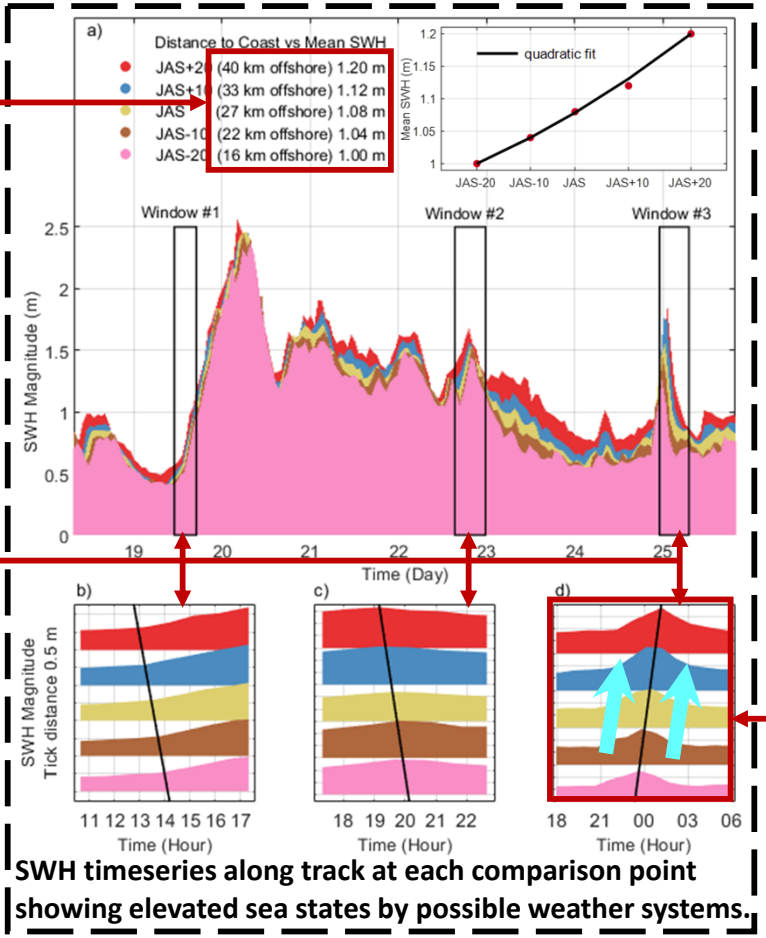
Buoy array could assist in validating and improving tide models in regional areas (especially in shallow continental shelf region such as Bass Strait), and in turn help improve SWOT outputs.

Tide series from the FES2014b model is removed from the observed tide at each comparison point.

Sea state within the swath – frontal system propagation

① Increased significant wave height (SWH) due to lack of shielding from the land and more exposure to the weather.

② Clear evidence of changing sea states across the spatial-temporal domain – research potential of the buoy array application in the **monitoring of weather system movement.**

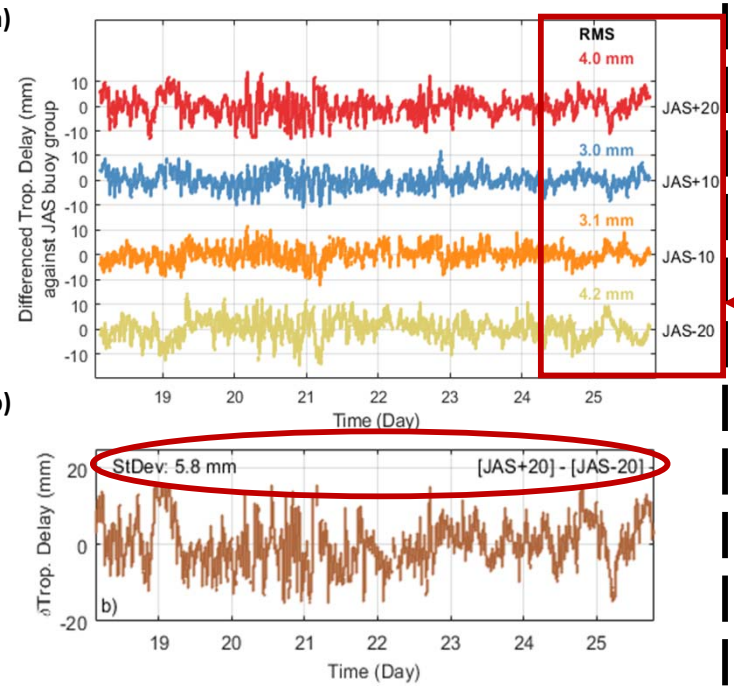


SWH timeseries along track at each comparison point showing elevated sea states by possible weather systems.

③ Possible case of a southerly frontal system observed in the 3rd window – evident also on a later slide (tropospheric delay time series, Page 10)

Tropospheric delay with the swath – intra-swath variability

② Variability of the tropospheric delay over a distance of **40 km** along the buoy array is at **5.8 mm** over the weather window of the trial deployment in Bass Strait**.**



a) difference of the tropospheric delay* along track with respect to the reference timeseries at Jason CP;
b) difference of the tropospheric delay between JAS+20 and JAS-20 CP over 40 km

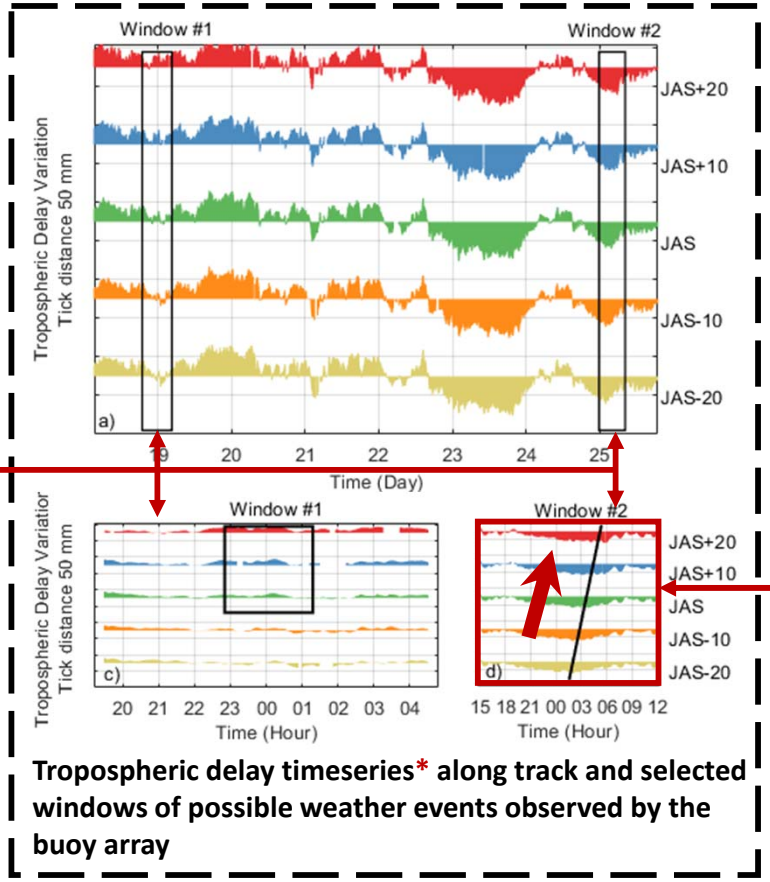
① Increased RMS of the differenced series observed as the location gets away from the Jason CP – providing some information of the **variabilities expected in the SWOT swath-based observations** due to tropospheric delay alone.

③ **Key Points:**
Important to understand the **variability of the troposphere** and handle it properly in SWOT swath-based output as **only one radiometer is used to observe across the swath**.

*Tropospheric delay series for the buoys are extracted from GipsyX solutions provided by Dr. Christopher Watson.

Tropospheric delay with the swath – frontal system propagation

① Clear evidence of varying tropospheric delays across the spatial-temporal domain (similar to the SWH series), highlighting again the research potential of the buoy array application in the **monitoring of weather system movement.**

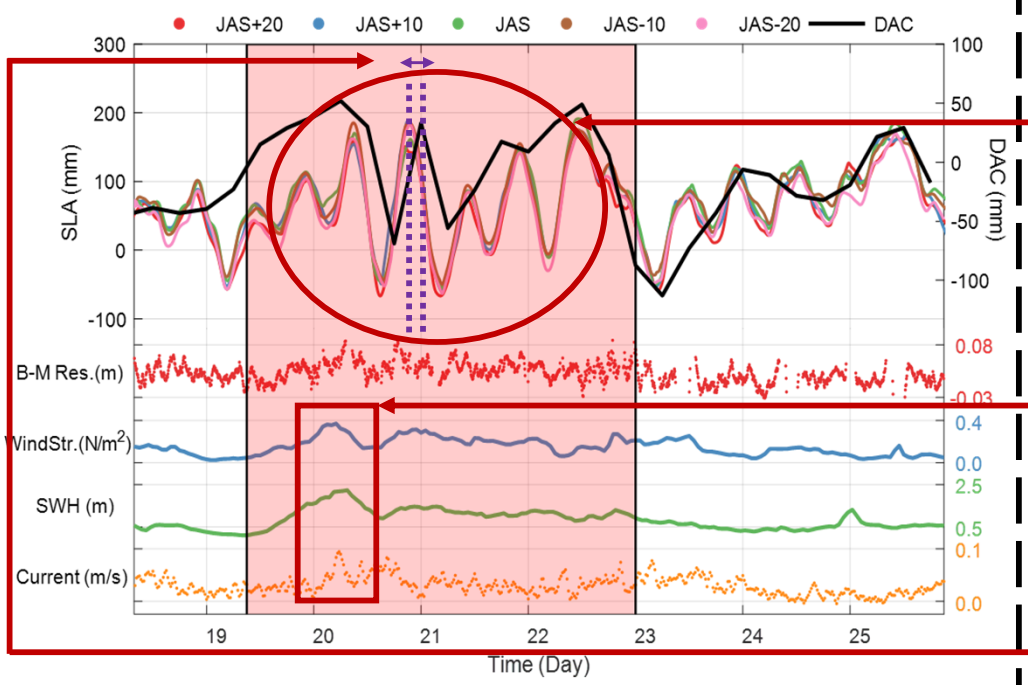


Tropospheric delay timeseries* along track and selected windows of possible weather events observed by the buoy array

② Possible case of a southerly frontal system observed in the 2nd window – evident also on a previous slide (SWH time series, Page 8).

*All five timeseries in the figure are differenced against a common mean value of all tropospheric series from the buoys.

Sea level anomaly along track – tidal resonance in Bass Strait



Sea level anomaly (SLA) timeseries across five deployed locations along with modelled Dynamic Atmospheric Correction (DAC), wind stress from ACCESS numerical weather model, current from in situ current-meter, buoy derived SWH and differenced series of buoy-minus-mooring SSH solutions.

① SLA series* showed strong **semi-diurnal signals** in all the buoys captured in the trial deployment.

② Excited M2 component induced by **strong surface wind** is likely the cause – occurrence of tidal resonance in Bass Strait has been investigated by others previously[3].

③ DAC models (e.g., by CNES/CNRS-Legos/CLS) are used in altimetry outputs. However, an **obvious phase shift** is evident when compared with in situ observations – low temporal resolution of the DAC model (6-hourly).

④ **Key Points:**
As known, enhancements to DAC resolution will be required to correctly interpret SWOT data – **techniques such as the buoy array could help!**

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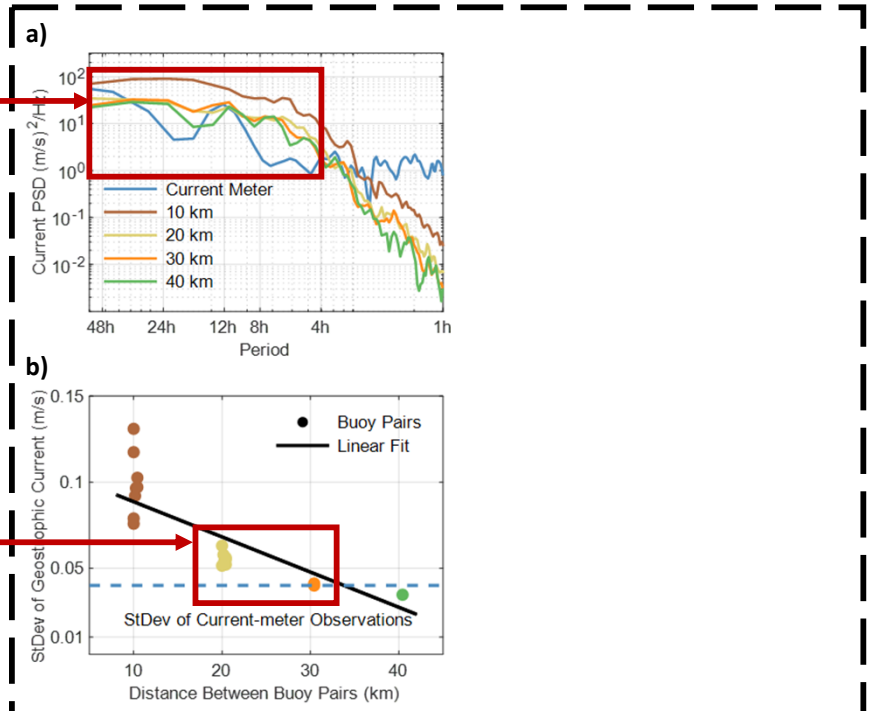
*SLA series shown in the figure has been corrected by tidal analysis results using UTide but not corrected for the DAC.

Ref [3]: Wijeratne EM, Pattiaratchi CB, Eliot M, Haigh ID. Tidal characteristics in Bass Strait, south-east Australia. Estuarine, Coastal and Shelf Science. 2012 Dec 1;114:156-65.

Spatial scale of the buoy array errors – inferred/observed geostrophic current

① Similar level of energy to the current-meter in the low frequency bands [48h-4h] for buoy pairs of 20/30/40 km.

② Scatter of the standard deviations for the same buoy-pair separation group reduced and its magnitude decreased closely to the same level as the current-meter observations at **20-km** mark.

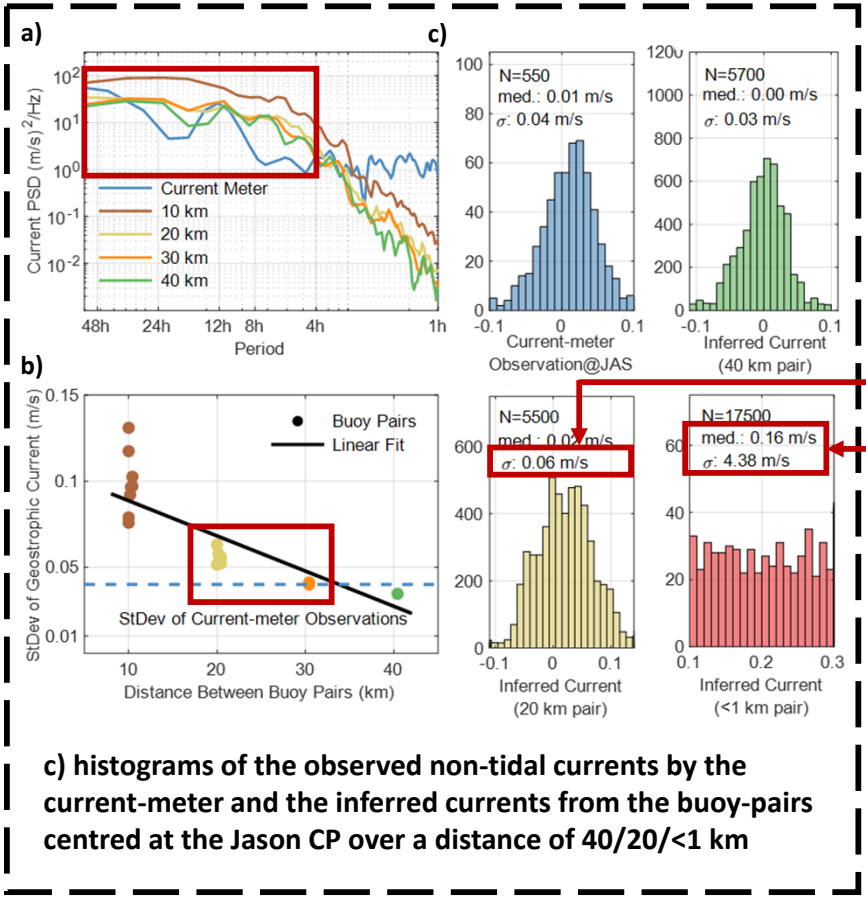


a) spectral analysis results of the non-tidal currents from buoy pairs against the current-meter;
b) standard deviation of the inferred current series as a function of buoy pair separation distance.

Understanding the spatial scale of the errors in the buoy array is crucial in future SWOT validation activities. Under the assumption of geostrophic balance in the deployed area in Bass Strait, we compared observed currents* by the in situ current-meter and the inferred currents by the buoy-pairs randomly formed from the array.

*Non-tidal currents are used/shown in the figure to investigate the spatial scale of the buoy errors in favour of its high signal-noise ratio (SNR) feature –interested signals are errors in both sources rather than the current for this case, while tidal currents are used to estimate an azimuth bias in the current-meter observations also in favour of its high SNR – interested signals are the actual tidal current for this.

Spatial scale of the buoy array errors – geostrophic current at Jason CP



c) histograms of the observed non-tidal currents by the current-meter and the inferred currents from the buoy-pairs centred at the Jason CP over a distance of 40/20/<1 km

① Comparable statistics starting from 20-km separation by the buoy pair.

② Currents from <1 km buoy pair suffered from low SNR where systematic errors within the buoys are more significant than the geostrophic current signal in Bass Strait over short distance (<1 km).

③ **Key Points**:

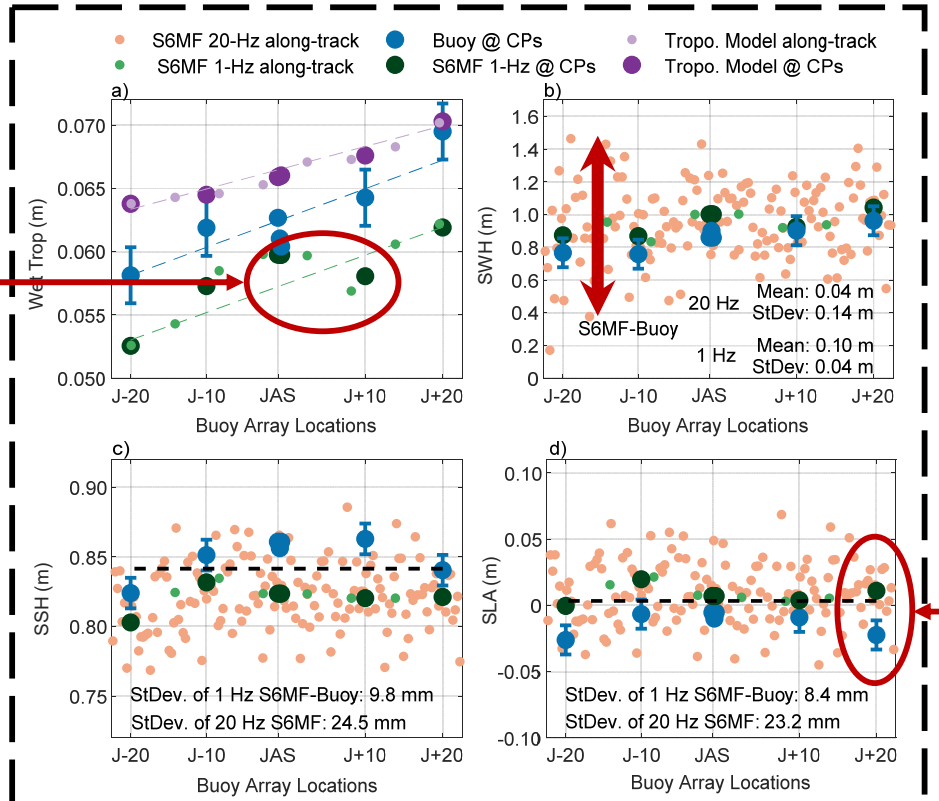
20-km spacing of the buoy array may be **more suitable** for future SWOT validation activities **in Bass Strait**.

For a more direct comparison with the current-meter, we further investigated the buoy pairs centred at the Jason CP – only one 40-km pair and one 20-km pair is available.

Three <1 km buoy pairs (B03-B08, B03-B11, B08-B11) are included in the investigation to get a sense of the current SNR with respect to the systematic errors of the buoy platform.

Comparison of buoy and altimetry output – buoy vs Sentinel-6 Michael Freilich

① S6MF radiometer observations showed large variations – **possible land contamination at JAS and J+10** due to proximity to the coast (stretch of an headland) with respect to the radiometer footprint.



Buoy derived quantities vs. S6MF F06 outputs, a) tropospheric zenith wet delay (ZWD); b) SWH; c) SSH; d) SLA

② **SWH by the buoy is highly comparable with the 1-Hz altimetry output.** However, the 20-Hz series from the S6MF is more scattered but remains within the mission performance requirements.

③ SSH from the buoy array is generally consistent with S6MF 1-Hz output.

④ In the SLA series, **some discrepancy became evident at J+20** – possibly due to issues such as double differencing limitation in the buoy approach, highlighting the **advantage of precise point positioning (PPP) as further away from the coast**.

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In all four panels, the triple buoy group provide some information about the uncertainty of the corresponding quantities derived via buoy approach – the scatter of the triplet solutions at JAS comparison point indicates the accuracy of the buoy approach for the estimation of the wet tropospheric delay, and observation of the SWH, SSH and SLA.

In general, based on the comparison between buoy and altimetry results, performance of both is reasonable. Some possible land contamination issue was identified for the radiometer onboard S6MF near the coast (around JAS and JAS+10), while solutions from buoys (JAS+10, JAS+20) further away from the land based reference station warrants enhancements in the double-differencing processing method used in this analysis.

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Summary:

① Old/New buoy transition:

- Performance of the UTas/IMOS Mk-VI Buoy remains unchanged temporarily with overarching precision of **15 mm** with a **8.5 mm** systematic noise baseline – any potential improvement needs longer deployment to validate (**in progress**).

② Buoy functionality – intra-swath ocean/atmosphere variability:

- **GNSS buoy array allows in situ observation of the spatial and temporal evolution of tide, SWH, troposphere** – all required to correctly interpret SWOT data..

③ Spatial scale of the buoy array errors:

- **20-km** spacing array is reasonable in Bass Strait for SWOT validation activities**.**

④ Quality of buoy/altimetry mission output:

- Outputs from both are generally **consistent with each other**;
- **Longer deployment is needed** for further performance assessment.

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