Ocean Surface Topography Science Team Meeting (OSTST)

19-23 October, 2020

GNSS/INS-Equipped Buoys for Altimetry Validation: Lessons Learnt and New Directions from the Bass Strait Validation Facility

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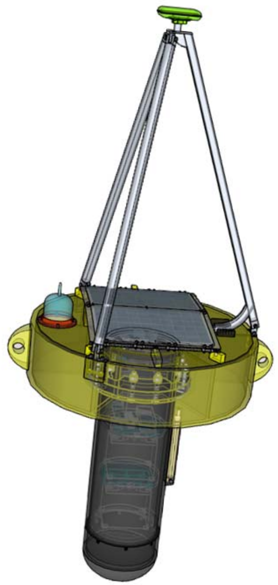

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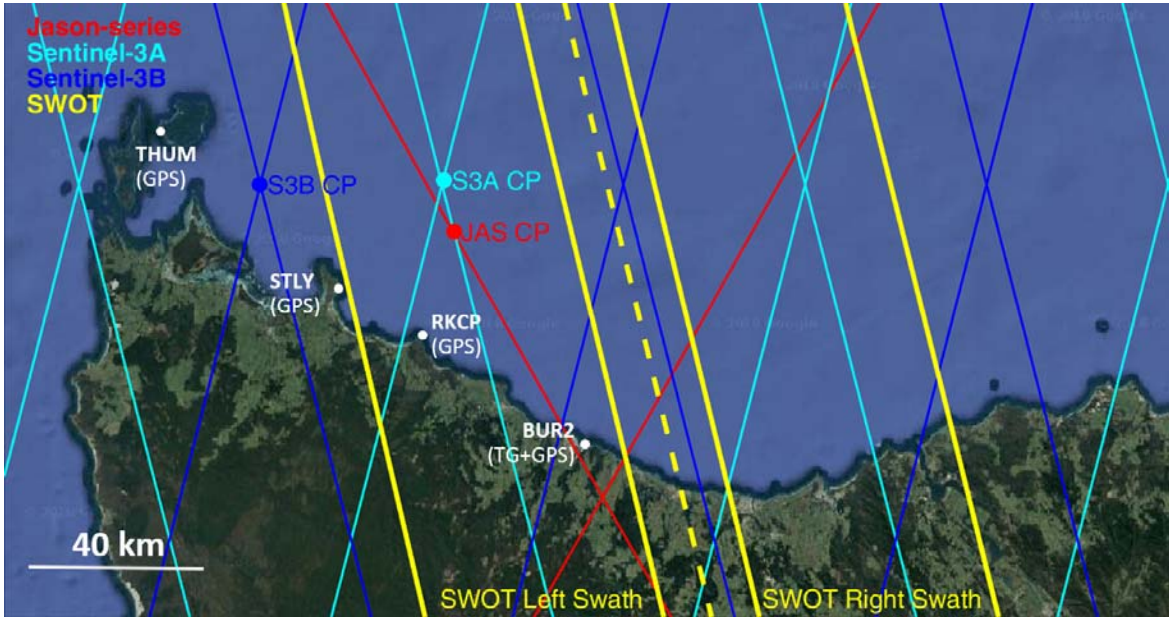
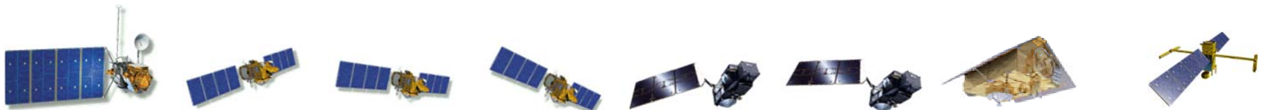
Paper Link: https://doi.org/10.3390/rs12183001

This presentation is based on a recently published paper in the Special Issue “Calibration and Validation of Satellite Altimetry“ of *Remote Sensing* by the listed authors. For people who are interested in the details of this research, please visit the link provided for more information.

Reference:
Zhou, Boye, et al. GNSS/INS-Equipped Buoys for Altimetry Validation: Lessons Learnt and New Directions from the Bass Strait Validation Facility. Remote Sensing 12.18 (2020): 3001. doi: 10.3390/rs12183001

Bass Strait Altimetry Validation Facility – Overview





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)

① A sustained contribution to satellite altimetry mission science teams for over 25 years spanning 6 missions and more to come.

② In situ instrumentation includes moored oceanographic instruments at various comparison points, accompanying with episodic **GPS buoy deployments** as crucial geometric validation method.

③ Validation requirements of future missions pose great challenges towards geometric method, hence call for improvements.

See Watson et al. presentation in the Cal/Val splinter in this meeting for more information

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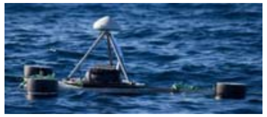
The facility presently contributes cycle-by-cycle estimates of absolute bias to the Ocean Surface Topography Science Team (OSTST) for the Jason-series missions and to the Sentinel-3 Validation Team (S3VT) for the Sentinel-3A and Sentinel-3B missions. As altimeters have progressed from Low Resolution Mode (LRM) to Synthetic-Aperture Radar (SAR) and will enter a new era with swath-based interferometric mission Surface Water Ocean Topography (SWOT), on-going development of GNSS buoy at Bass Strait has also taken up the challenge. The UTas/IMOS altimetry validation buoy is currently going through a major improvement to transit from a Mk-IV to Mk-V design in order to achieve sustained deployments. The focus is therefore on understanding systematic error contributions.

With abundant data resources at Bass Strait, we proposed this study:

Mk-IV GNSS Buoy



① What is the **overarching precision** of existing Mk-IV GNSS buoy?

1 Hz GNSS data from Mk-IV buoy at Jason comparison point (CP) – Buoy SSH*
Co-located 5-min sampling mooring data as reference “ground truth” – Mooring SSH

② What is the **systematic noise baseline** of existing Mk-IV GNSS buoy?

1 Hz GNSS data from two Mk-IV buoys deployed in proximity at Jason CP – Buoy δSSH*

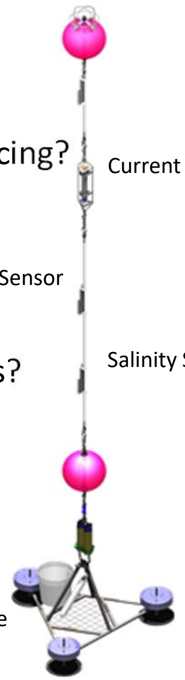
③ Can we develop an **empirical model for the buoyancy position** of the buoy as a function of external forcing?

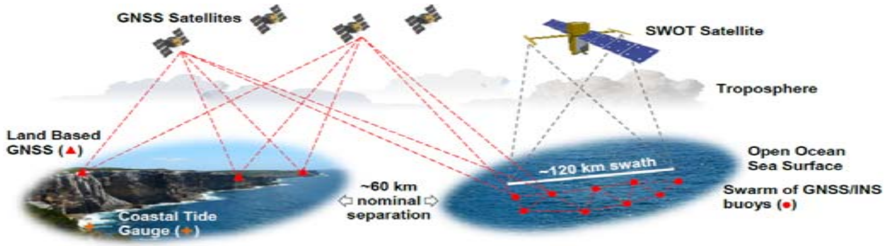
Buoy-minus-Mooring SSH residual
Co-located 20-min sampling current-meter data – Currents
Hourly hindcast operational atmospheric model ACCESS-R* – Surface wind stress

④ How will **observational models for the orientational variation** of the buoy platform affect SSH solutions?

2 Hz GNSS data + 100 Hz INS* data via modified GNSS/INS Mk-IV Buoy

In situ Mooring

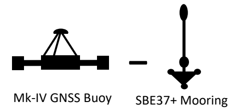




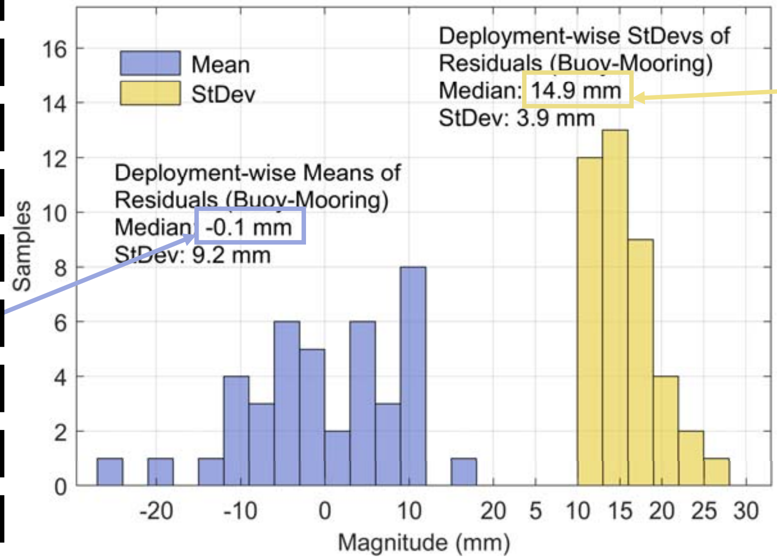
Acronym*

SSH: sea surface height
δSSH: differential sea surface height – important for benchmarking the systematic noise baseline within Mk-IV buoy system, and critical for understanding of the uncertainty in derived sea surface slope by surface buoys networks
ACCESS-R: Australian Community Climate and Earth-System Simulator – Regional Model (Aug. 2010 release)
INS: Inertial Navigation System

Overarching Precision – Statistics of Buoy-minus-Mooring residual

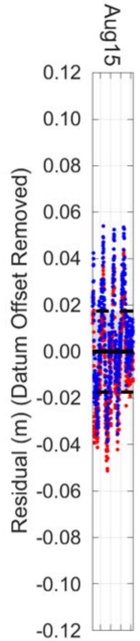
Res = 

① Co-located mooring used to benchmark the overarching precision of GNSS buoy shows consistency among in situ sea surface height measurements with deployment-wise means of the residual at **-0.1 mm** (blue bars)



A total of 27 deployments with 2015 hours of buoy data collected from the same comparison point. Each deployment is 48 hour in length. 25-min moving-average filter applied.
Both histograms shows reasonably well-shaped normal distribution.

② Median of deployment-wise standard deviations at **~15 mm** (yellow bars) interpreted as the **overarching precision** of UTas/IMOS Mk-IV GNSS buoy



③ Deployments with standard deviation larger than 20 mm, such as in Aug. 2015 deployment, are believed to be affected by external forcing on the tether (wind, waves, currents). Time series of SSH presents dominant semi-diurnal signals.

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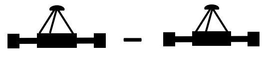
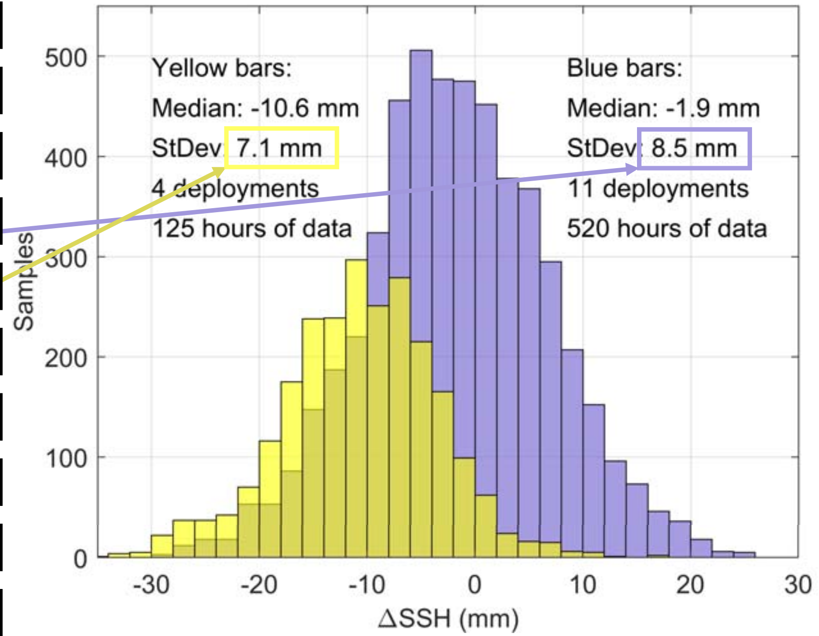
The systematic signals (e.g. presented in Aug. 2015) have an amplitude of up to 20 mm in semi-diurnal band. In the context of the cal/val requirements for the future SWOT mission, these biases, if left unattended, may limit potential contribution to ocean tidal modelling or SSH validation at frequencies in the tidal band.

Relative Precision – Statistics of Buoy-minus-Buoy residual (δSSH)

δSSH =  –

① Episodic dual-buoy deployments used to yield the systematic noise of the Mk-IV buoy system. The standard deviation of the residuals taken as the **noise floor** at **8.5 mm*** (**blue bars**).

*A sub-group of biased deployments (yellow bars) showing a standard deviation of **7.1 mm** is not considered within the relative precision assessment, yet is within the presumed noise level.



A total of 15 deployments with 645 hours of data where two buoys were deployed in close proximity, hereinafter referred as "dual-buoy deployment".

② **Key Points:**

Overarching precision: **15 mm**

Systematic noise floor: **8.5 mm**

③ **Q:** What causes the remaining "15 – 8.5" mm part of the residuals?

Possible sources:

External forcing on the tethered buoy

Orientation variation of the buoy platform

…

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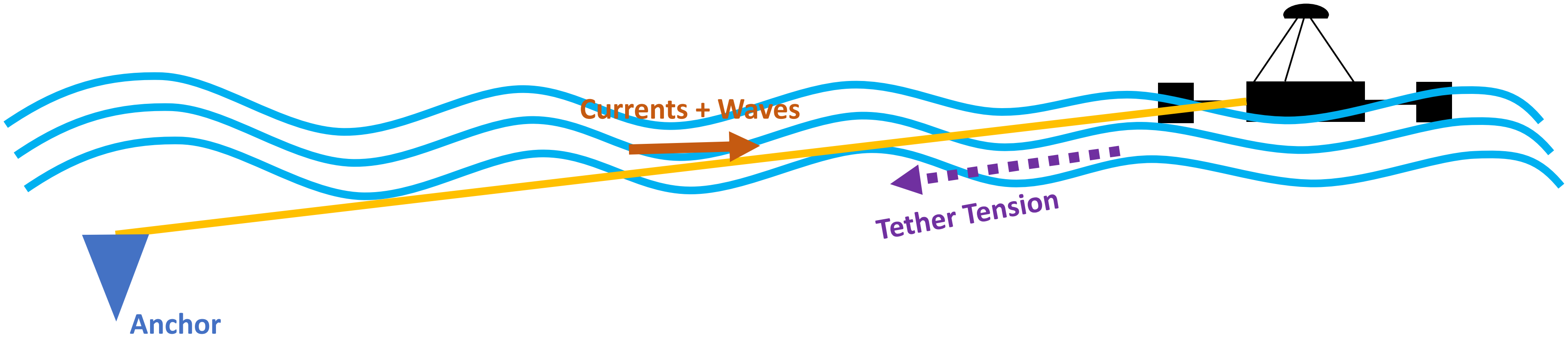
The underlying assumption for the acquired systematic noise floor is that most external factors affecting the precision will cancel out in the dual-buoy setup. However, since there is still a practical physical distance (30-40 metres) between two buoys, certain high frequency yet spatially decorrelated signals (e.g. wind waves, swells) should be filtered out before such an assessment. Hence, a 25-min moving mean filter is applied before differencing. Yet, whether the 25-min moving mean filter is the most appropriate is an open and important question.

Tether tension model – Buoy buoyancy position change as a function of external forcing



Standard Deployment Setup

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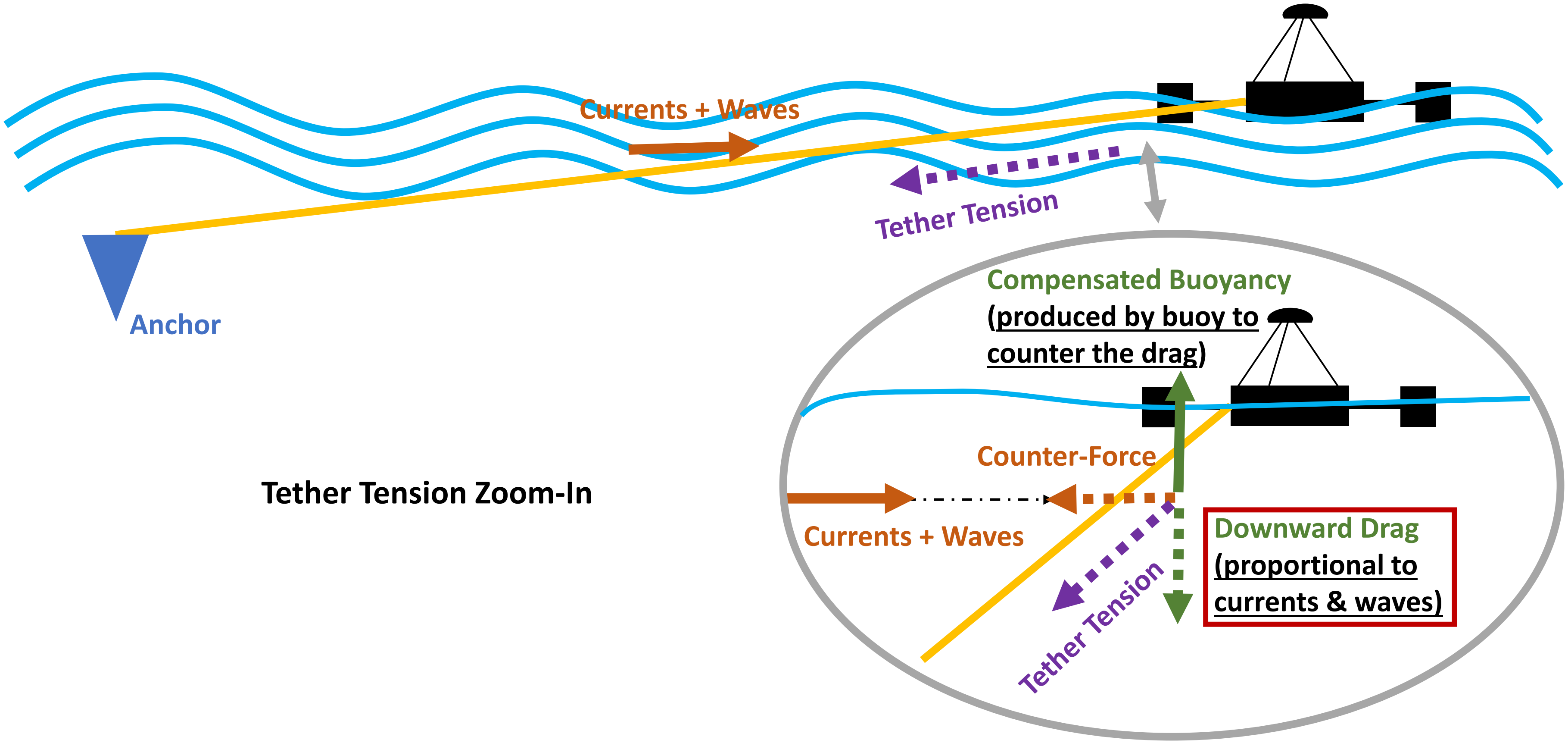
Tether tension model – Buoy buoyancy position change as a function of external forcing



Tether Tension Zoom-In

Source of buoyancy displacement

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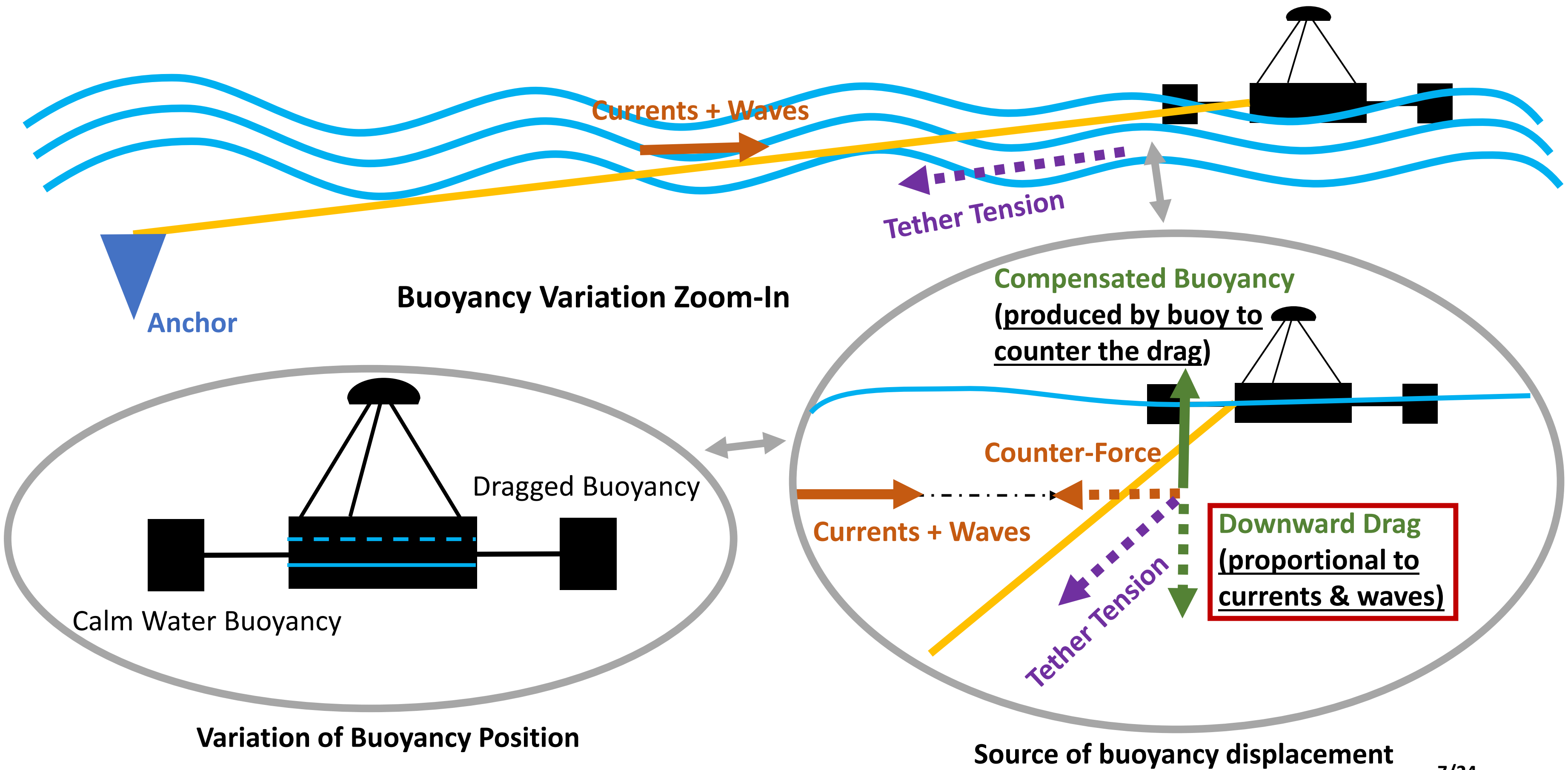
Tether tension model – Buoy buoyancy position change as a function of external forcing



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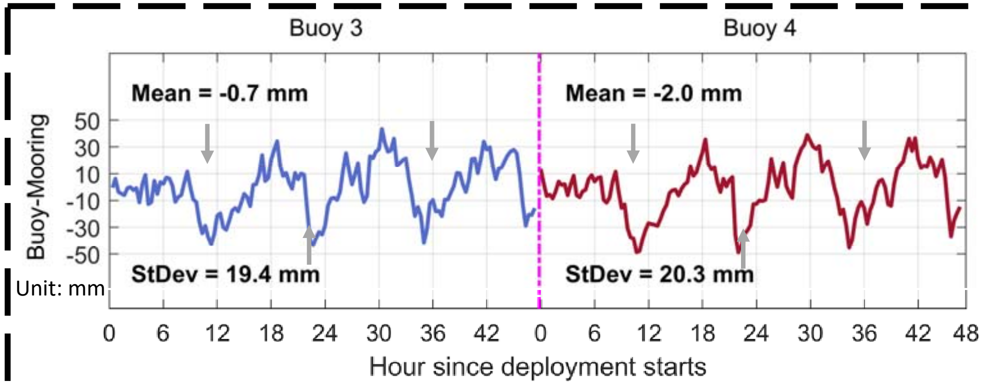
Tether tension model – Finding correlation between residuals and external forcing

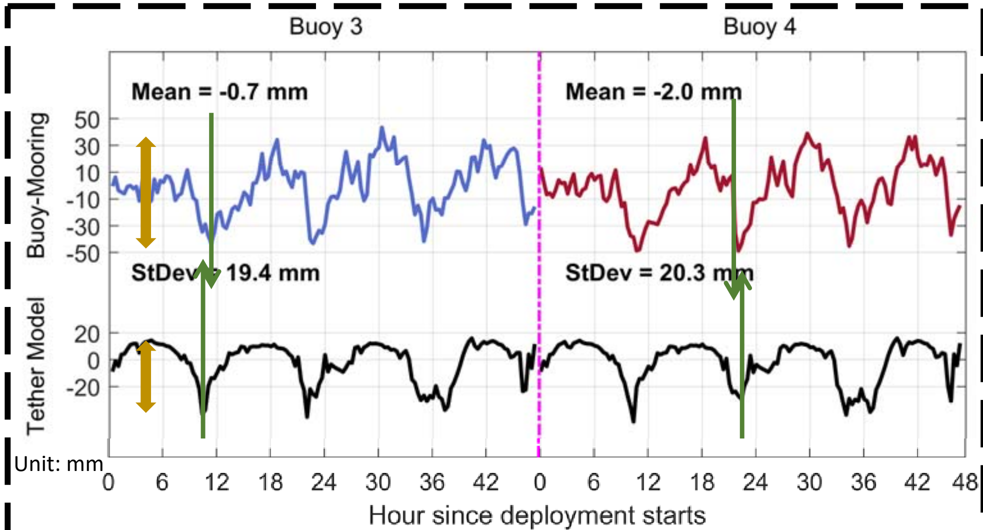
Recall: "In some of the deployments, we have dominant **12-hour signals** in the buoy-minus-mooring residuals"



Aug. 2015 buoy deployment used as case study for tether model

Tether tension model – Finding correlation between residuals and external forcing

① Based on our model that uses modelled wind stress and observed currents, we were able to generate quasi-semi-diurnal signals matching the peaks of the residual with **75% in range** and **~20-min variation in temporal response** – within the resolution of the hourly input.



Aug. 2015 buoy deployment used as case study for tether model

⓪ We used ACCESS regional wind stress (hourly) and in situ current-meter measurements (20-min) as input to generate the modelled tether tension time series

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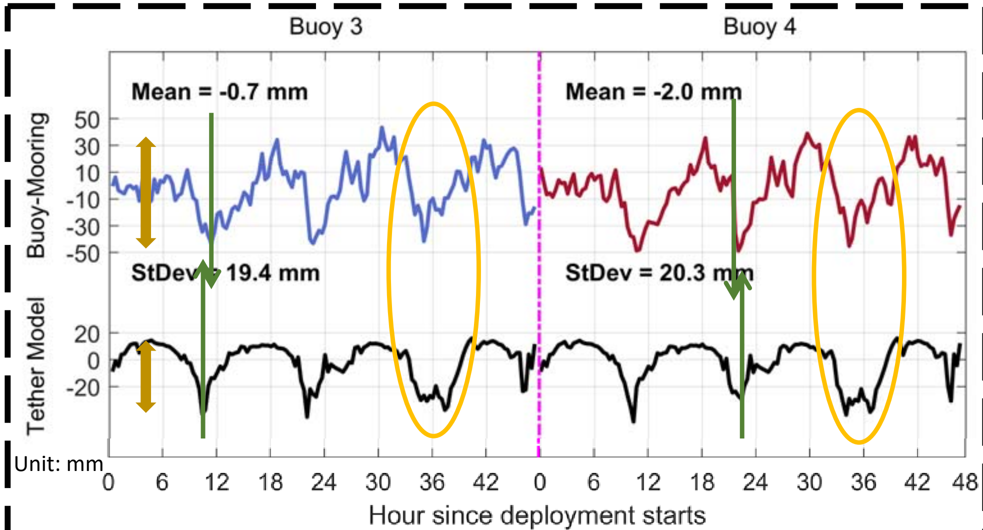
② Some **higher frequency variability** is also reproduced through modelling (e.g. between 30–42 hours)



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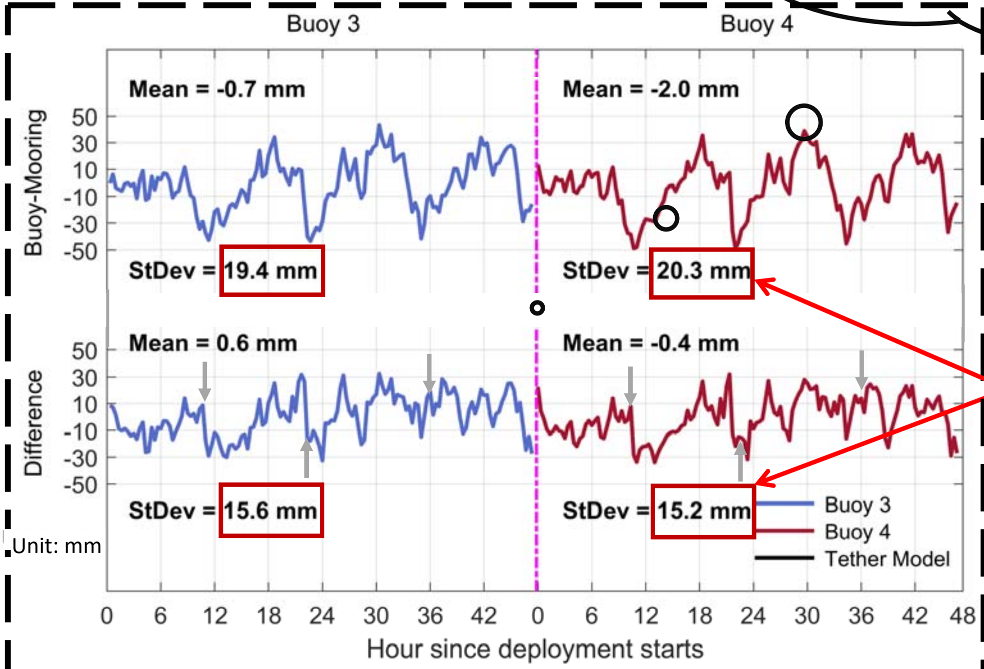


Aug. 2015 buoy deployment used as case study for tether model

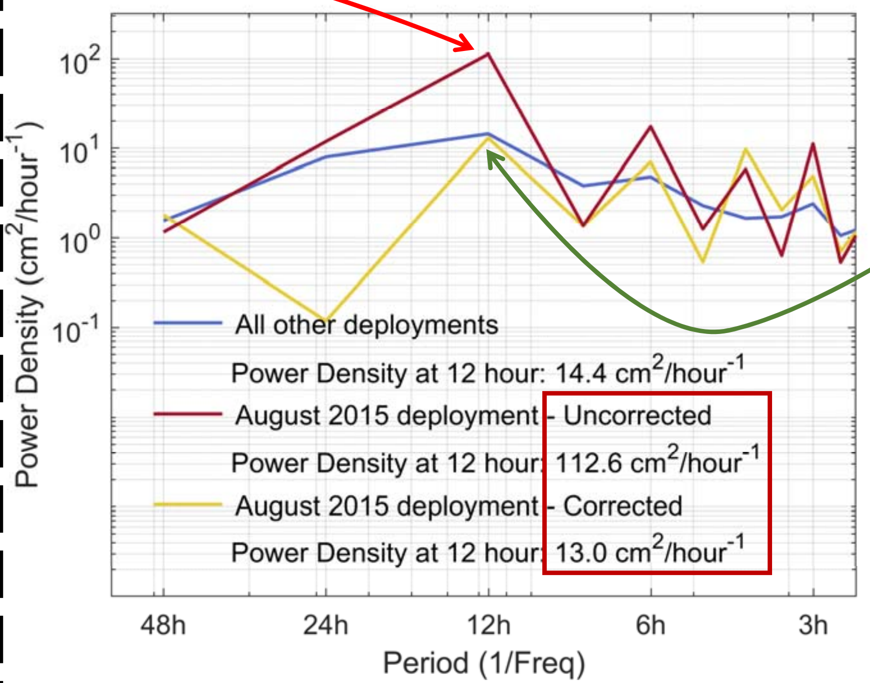
③ Upon removal of the modelled tether tension effect, a **~5 mm reduction** in standard deviation can be observed with obvious **attenuation** of low frequency signals (**semi-diurnal**) and also the mean of the residual brought further to zero.

From the limited dataset we can assemble using current-meter data and hindcast modelled wind stress, these initial results from an empirical model showed a variance reduction of ~40% (i.e. 5 mm equivalent). However, because of the limited temporal and spatial resolution of the input, our model is still sensitive in parameterization and can not be globally applied to all deployments.

Tether tension model – What it looks like in the frequency domain?

① An apparent **anomaly** for Aug. 2015 **at 12-hour** band can be observed with larger than a magnitude energy level

③ Energy reduction also seen at other low frequency bands, with an **overall 50% reduction** in **variance** statistically speaking.



A total of 27 deployments used to generate the power spectrums; frequency range selectively shown to focus on the low frequency bands.

② After applying empirical tether model, **power density** at 12-hour band is **reduced** to the same level as in all other deployments.

④ **Key Points:**

Reasonable **correlation** between waves/currents and buoy-minus-mooring residuals

Further work needed for a more advanced tether model backed up with **high resolution** input

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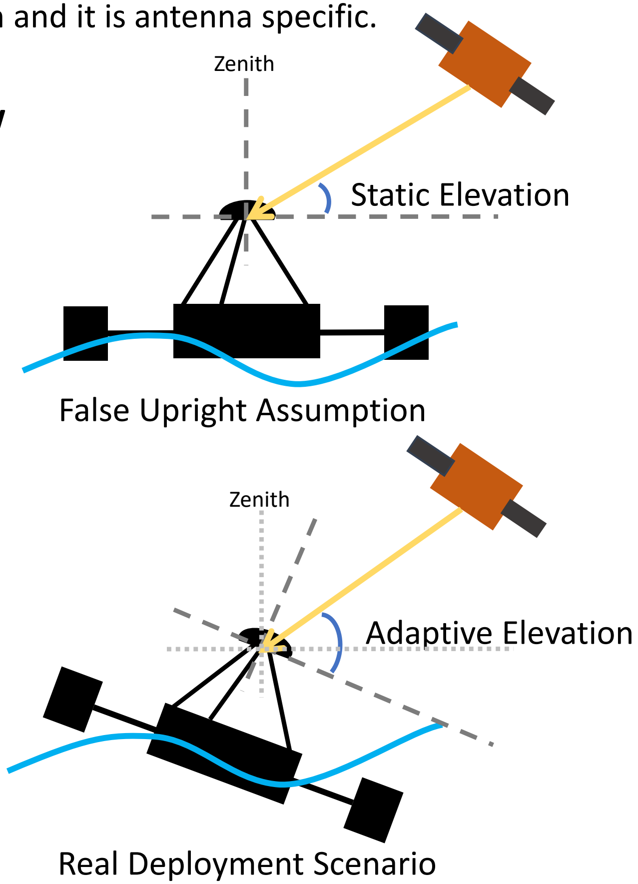
In the context of SWOT validation at the Bass Strait facility, improved understanding of the tether tension modelling will be possible given the planned co-location of new GNSS/INS Mk-V buoys with 5-beam ADCP instruments operating as a shallow water current, waves and pressure inverted echo sounder (CWPIES).

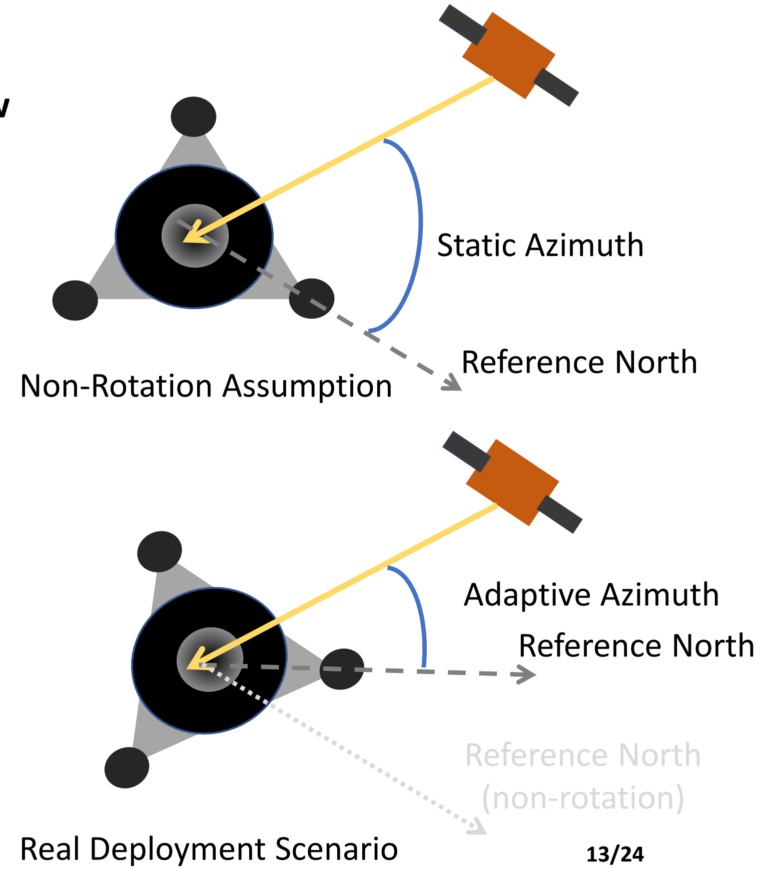
Orientation Variation – Visualizing the impact on GNSS positioning in marine domain

Phase Centre Variation (PCV): this associates with the variation of entry points of GNSS signals from different elevation and azimuth and it is antenna specific.

Side View



Top View



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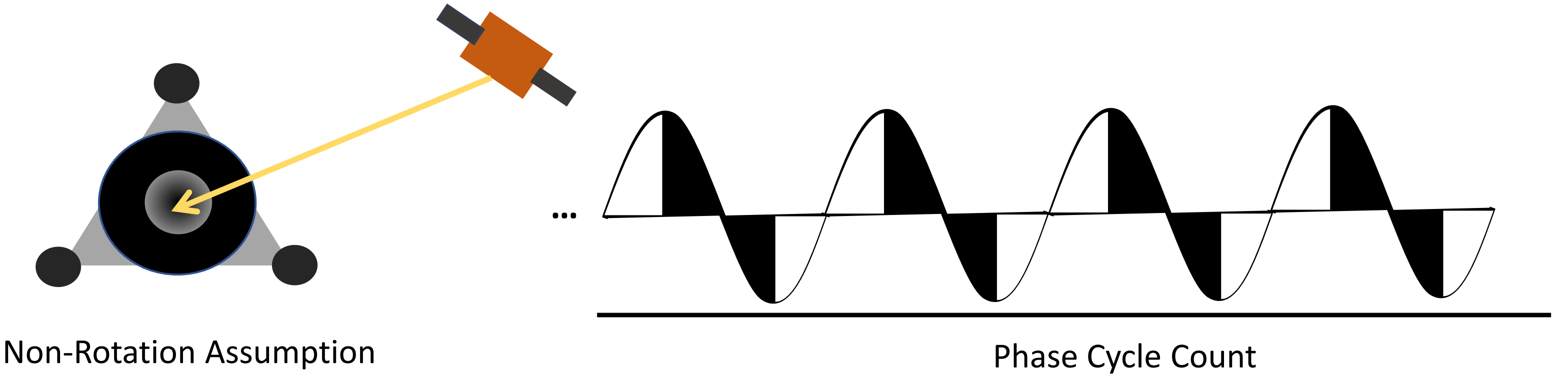
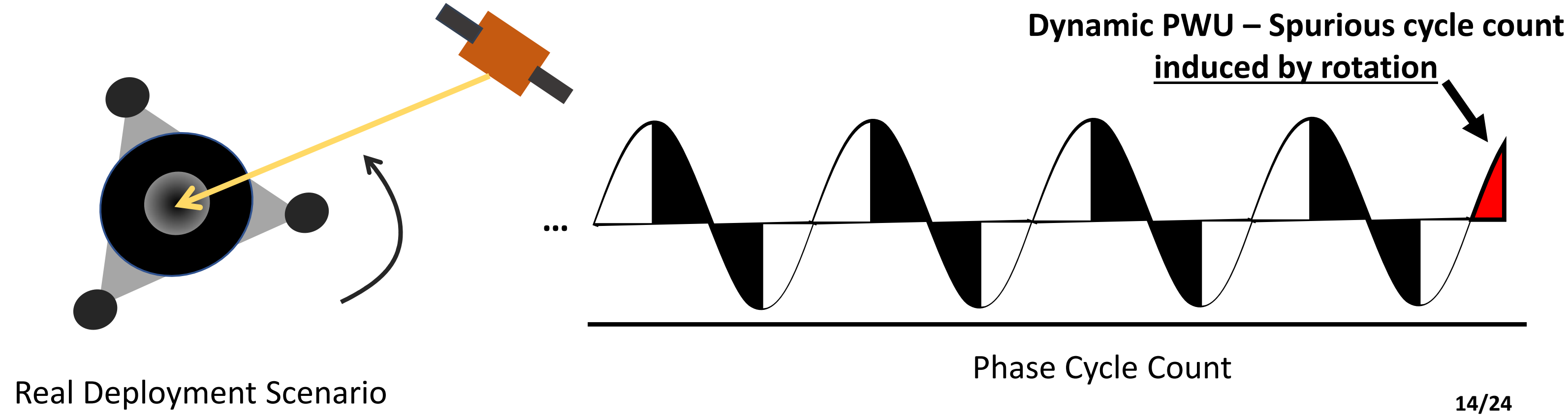
Orientation Variation – Visualizing the impact on GNSS positioning in marine domain

Phase Wrap-Up (PWU): this associates with a fraction of mis-counted phase cycles induced by the relative rotation between the satellite and the receiver due to the electromagnetic nature of circularly polarized GNSS signals.

Top View





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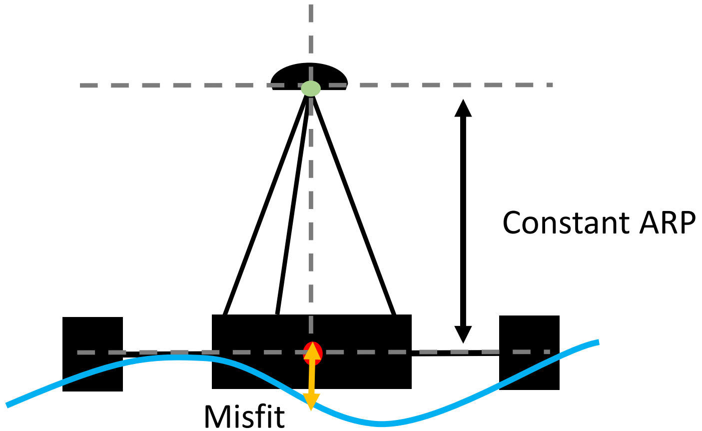
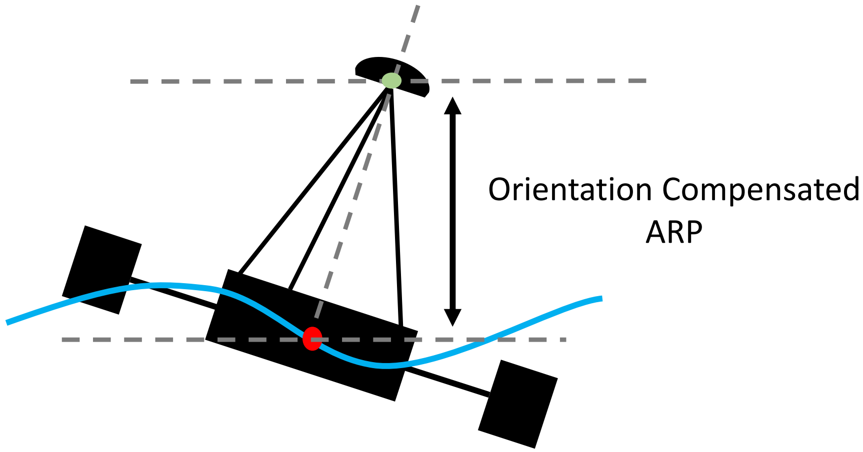
Orientation Variation – Visualizing the impact on GNSS positioning in marine domain

Antenna Reference Point (ARP): this is an offset calibrated by the antenna provider and later measured by the surveyor to reduce the vertical height from the antenna to the point of interest.

Side View



False Upright Assumption



Real Deployment Scenario

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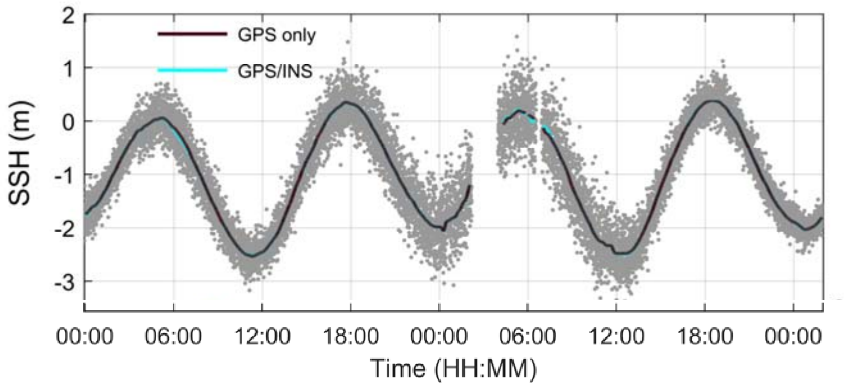
Orientation Variation – Addition of an INS* unit on the Mk-IV buoy

⓪ Adaptive PCV, dynamic PWU and orientation compensated ARP have been applied to the GPS/INS solution at observational level with source code modified in MIT TRACK* positioning software.



Grey dots in the top panel show sub-samples from raw 2 Hz GPS/INS solutions as an indicator of varying sea states

① GPS/INS solutions show **less than 1 cm difference** from GPS only solutions in **calm sea state** – largely indistinguishable cyan and black lines

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Given the low speed scenarios in our buoy deployments and our INS unit being consumer grade, the integration implemented in this study can be interpreted as a loosely coupled GNSS/INS case, although all orientation corrections are applied at GNSS observational level.

Reference:

TRACK, MIT. "GPS differential phase kinematic positioning program." (2011).

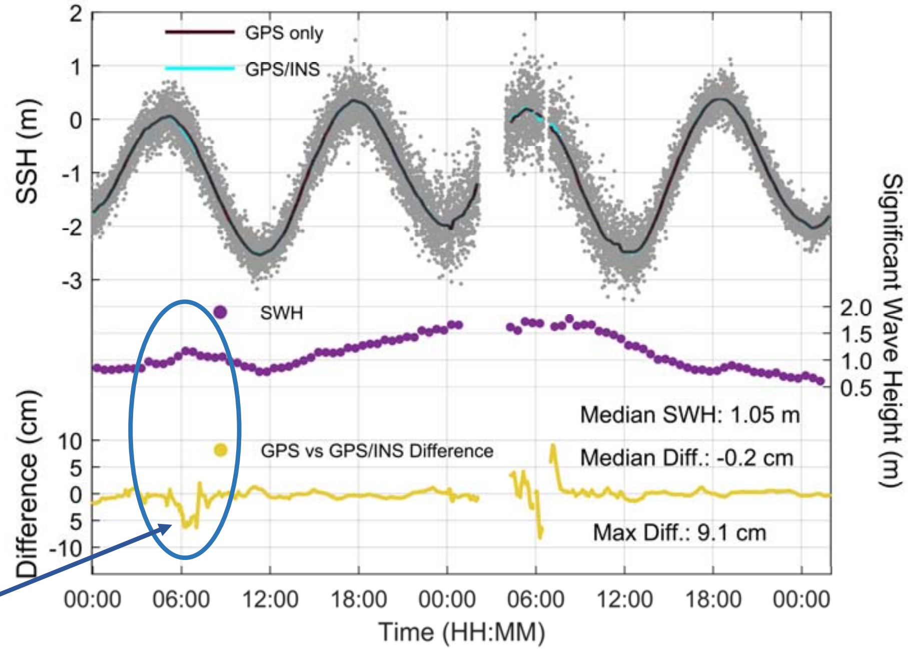
*Acronyms

INS: Inertial Navigation System

Orientation Variation – Addition of an INS unit on the Mk-IV buoy

⓪ Adaptive PCV, dynamic PWU and orientation compensated ARP have been applied to the GPS/INS solution at observational level with source code modified in MIT TRACK positioning software.

② As **sea state rises**, variations can be as large as **~5 cm** – evident **around first 6:00 mark**



Grey dots in the top panel show sub-samples from raw 2 Hz GPS/INS solutions as an indicator of varying sea states;
Mid panel shows 30-min windowed significant wave heights also associated with sea states.

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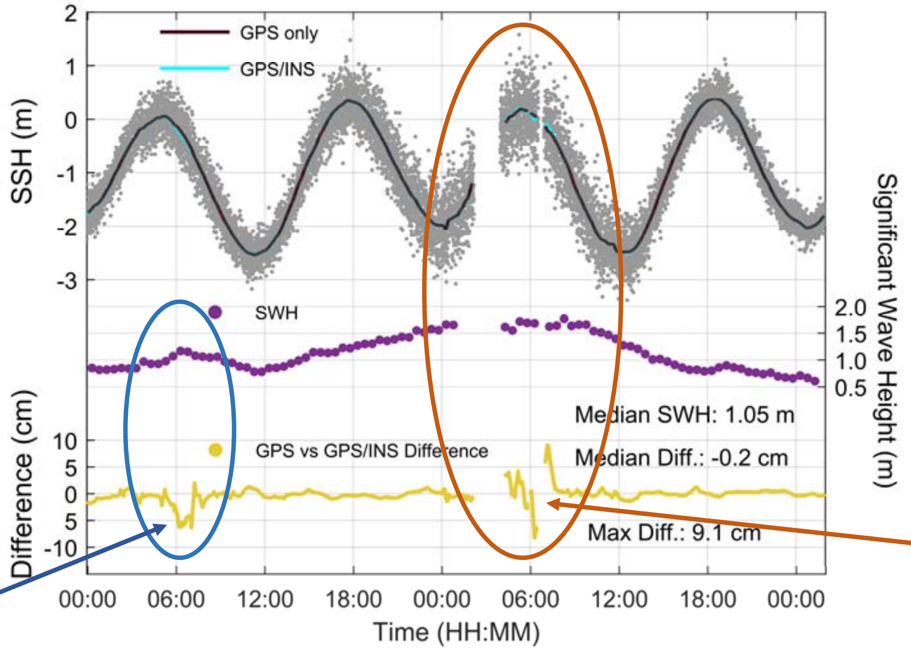

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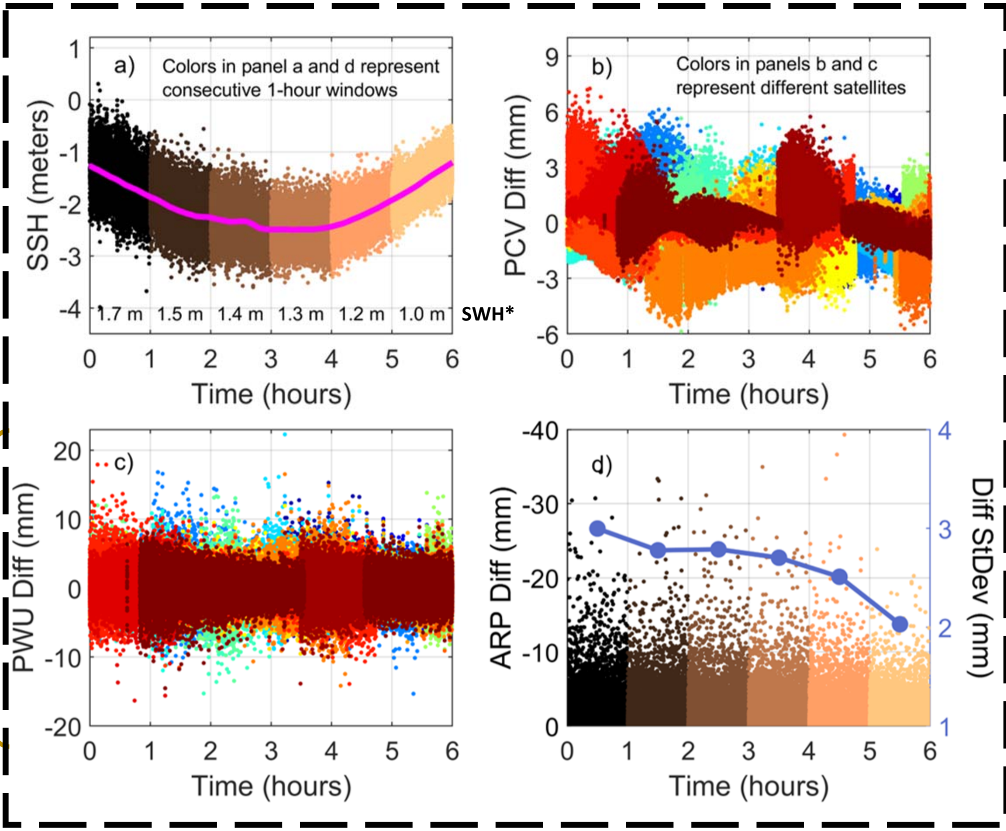
① GPS/INS solutions show **less than 1 cm difference** from GPS only solutions in **calm sea state** – largely indistinguishable cyan and black lines

③ As sea state becomes **rough**, loss-of-lock between GNSS buoy and satellites happens and even **larger variation** between GPS and GPS/INS solution can be seen – partially due to unsettling sea states, partially due to re-sync between GPS and INS module within the buoy system.

Orientation Variation – Observational model introduced in TRACK

① Six-hour segment of GPS/INS SSH solutions selected to show the role of INS unit in addressing orientation variation of the buoy platform



② **Adaptive PCV** showed a **9 mm** range of path-length correction. With pitch/roll as the dominant contributing factor, it narrows as the sea states settles.

③ **Dynamic PWU** showed a **20 mm** range of path-length correction. With yaw as the dominant contributing factor, it is relatively consistent in magnitudes across the segment.

④ **Orientation compensated ARP** shows a predominantly **<10 mm** offset for SSH measured by Mk-IV buoy – expected to be **larger for higher** antenna height design (i.e. the new Mk-V buoy)

*Scatter of the orientation compensated ARP **rises/drops** along with the **sea state**.

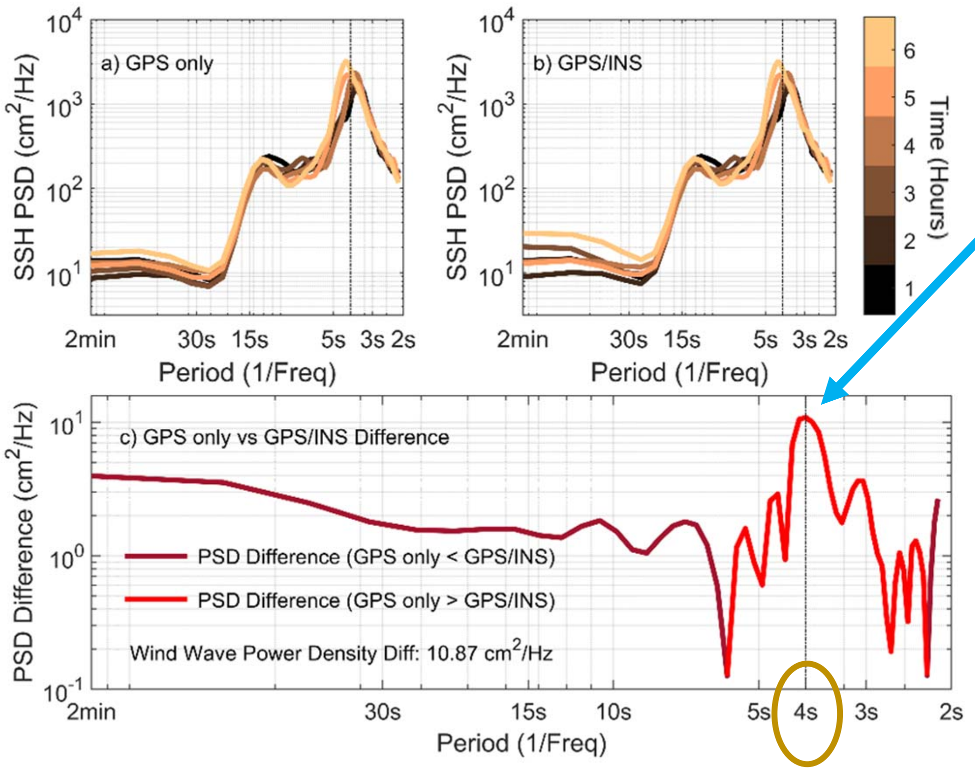
Magnitude of these three effects in the study are based on a modified Mk-IV buoy with the addition of an INS unit. There effects are expected to have bigger impacts in Mk-V buoys given an extended antenna height and a prolonged deployment span by design.

*Acronyms

SWH: Significant Wave Height - an indicator of sea states, normally the larger SWH is, the rougher the sea state is.

Orientation Variation – Inspection of the GPS/INS SSH solutions in the frequency domain

① More obvious difference can be seen when differencing power densities at corresponding high frequency bands.



Spectrums used to highlight the signals addressed by the INS unit in high frequency bands where wind wave and swells reside

② An **over-estimation** of the magnitude of wind waves is at **~11 cm^2/Hz** for GPS only solutions by failing to address the biases induced by orientation variation of the buoy platform

③ **Key Points:**

Impacts become **obvious** in **rougher sea states** and **larger buoy platforms**

Biases induced can reach up to **several centimetres** in SSH solutions and thus have to be addressed

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While the addition of INS unit can assist our understanding of the energy evolution between swell and wind waves better, we also note that the use of GNSS-equipped buoys to characterize the true high frequency sea state is dependent on the hydrodynamic properties of the buoy. Also, in this study, we were not able to formally quantify the orientation induced biases given either a lack of INS instrument in historical deployment or contemporary mooring data not yet serviced. Hence, we require further deployments with new Mk-V buoy design along with co-located mooring data to fully understand the performance of GNSS/INS equipped buoy.

Implication for existing/future missions – Mapping precisions onto wavenumber spectrum

① We projected the point-based standard deviations in this study onto the wavenumber spectrum.

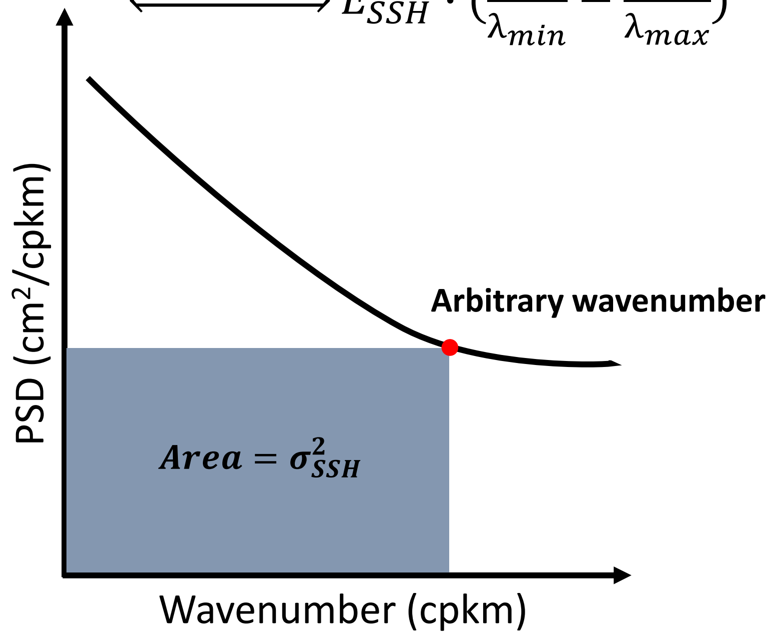
② **The assumption considers GNSS acquired positions contains only white noise** in the context of oceanic process studies, which is only safe to do for the purpose of assessing buoy precision from the perspective of a geometric validation method.

③ As a result, **the area in the wavenumber spectrum represents the variance** (i.e. standard deviation squared) of a certain signal.

④ **The power density does not correspond to any wavenumber**

$$\sigma_{SSH}^2 \xLeftrightarrow{\text{spatial domain}} \int_{1/\lambda_{max}}^{1/\lambda_{min}} E_{SSH}(f)df\ , f = 1/\lambda$$

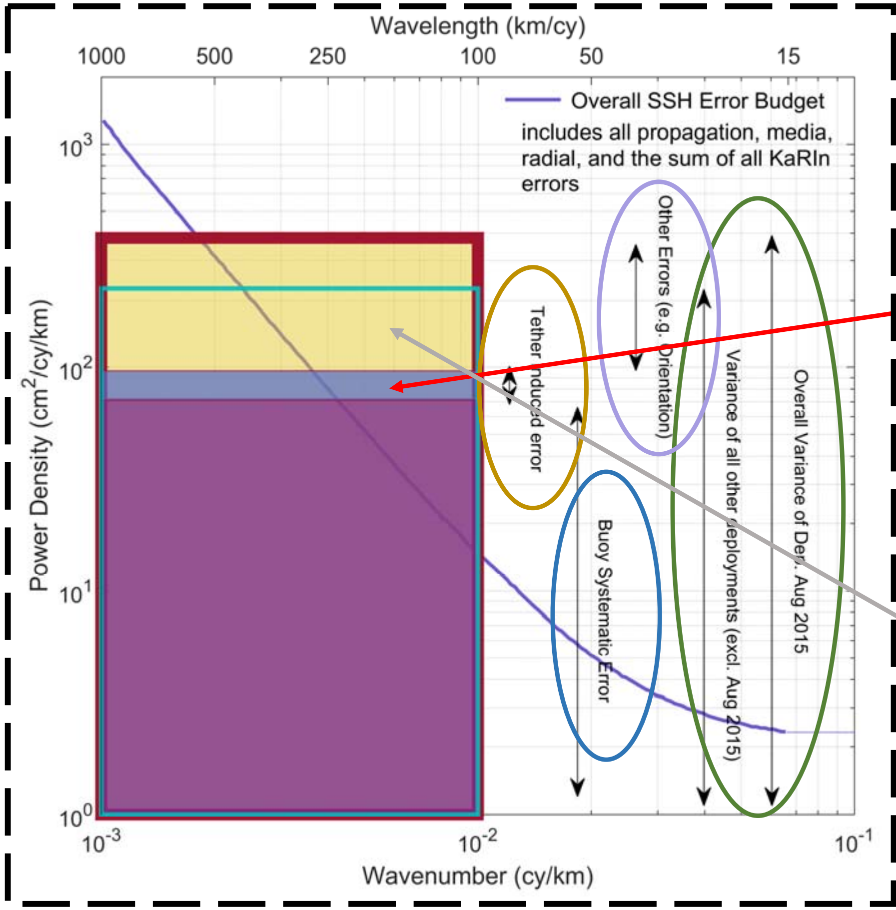
$$\xLeftrightarrow{\text{White Noise}} E_{SSH} \cdot \left(\frac{1}{\lambda_{min}} - \frac{1}{\lambda_{max}}\right)$$



Implication for existing/future missions – Will buoy catch up with the requirements?

① Our analysis presented a mooring referenced precision assessment for the UTas/IMOS Mk-IV buoy, with the **overarching precision** at **15 mm**, including a **8.5 mm** **systematic error** baseline.

② Investigation into **two previously ignored error sources** was initiated: the **external forcing** on the tethered buoy and the **orientation variation** of the platform.



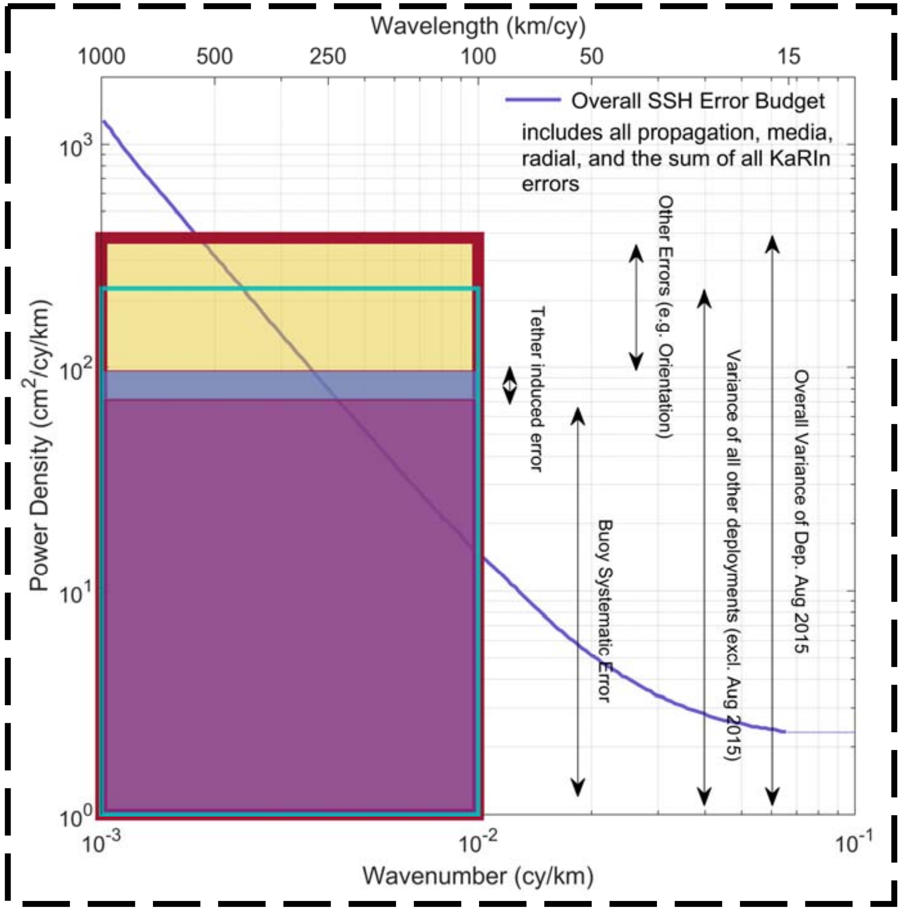
③ Case study of our **empirical tether model** shows a promising energy reduction in low frequency bands associated with a **5 mm** standard deviation **reduction** in the buoy-minus-mooring residual.

④ GNSS/INS integration to address the platform dynamics shows potential centimetre biases will be induced , especially in **rough sea states.**

We mapped standard deviations in this study against the wavelength of 100 km simply for comparative purposes.

In order to validate missions for the aimed ocean process scale, any method should have a noise level below the error budget curve. This poses a challenge to further address and reduce potential error sources (i.e. the areas) in SSH solutions by GNSS buoys.

Implication for existing/future missions – Will buoy catch up with the requirements?



Key Points:

We need to understand the **systematic error structure** associated with the buoy approach better.

Further effort needed to **address/quantify some of the error sources identified in this study** to prepare for future altimetry validation activity

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Ocean Surface Topography Science Team Meeting (OSTST)

19-23 October, 2020

Paper Link to Zhou et al. [2020] in *Remote Sensing*: https://doi.org/10.3390/rs12183001

Recap:

Statistics from archived data at Bass Strait:

① UTas/IMOS Mk-IV Buoy has an **overarching precision of 15 mm with a 8.5 mm systematic noise baseline;**

Further enhancement & recent development:

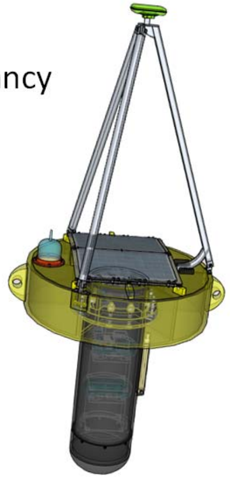
② Initial tether tension investigation found reasonable correlation between variation of the buoyancy position and currents/waves**, improved RMS* of the buoy-minus-mooring residual by 25%;**

③ INS integration removed **centimetre biases in SSH solutions;**

Future trajectory of buoy development at Bass Strait:

④ Improvements possible using **high resolution input for the tether tension model;**

⑤ Vital to include **orientation information for future Cal/Val activity.**



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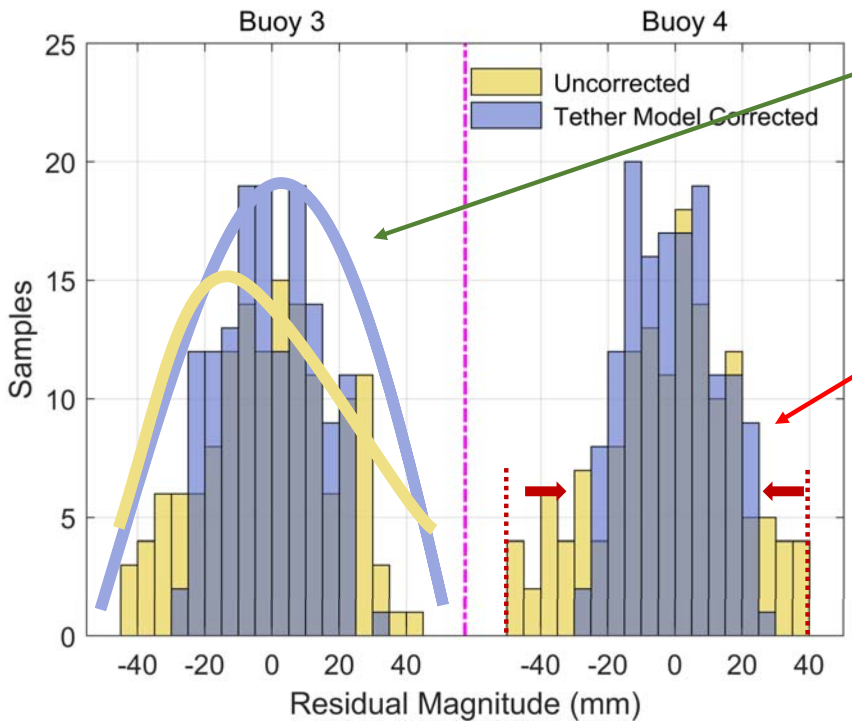
*Acronyms
RMS: Root Mean Square

Spares:



Distribution of the buoy-minus-mooring residual before and after tether model correction

- A **reduced** asymmetry can be seen after applying the tether model – the tilting induced by the tether towards the anchor point is addressed to some extent
- The **narrowed** width of the histogram can be seen as the reduced range in the residual – semi-diurnal signals have been attenuated to some extent

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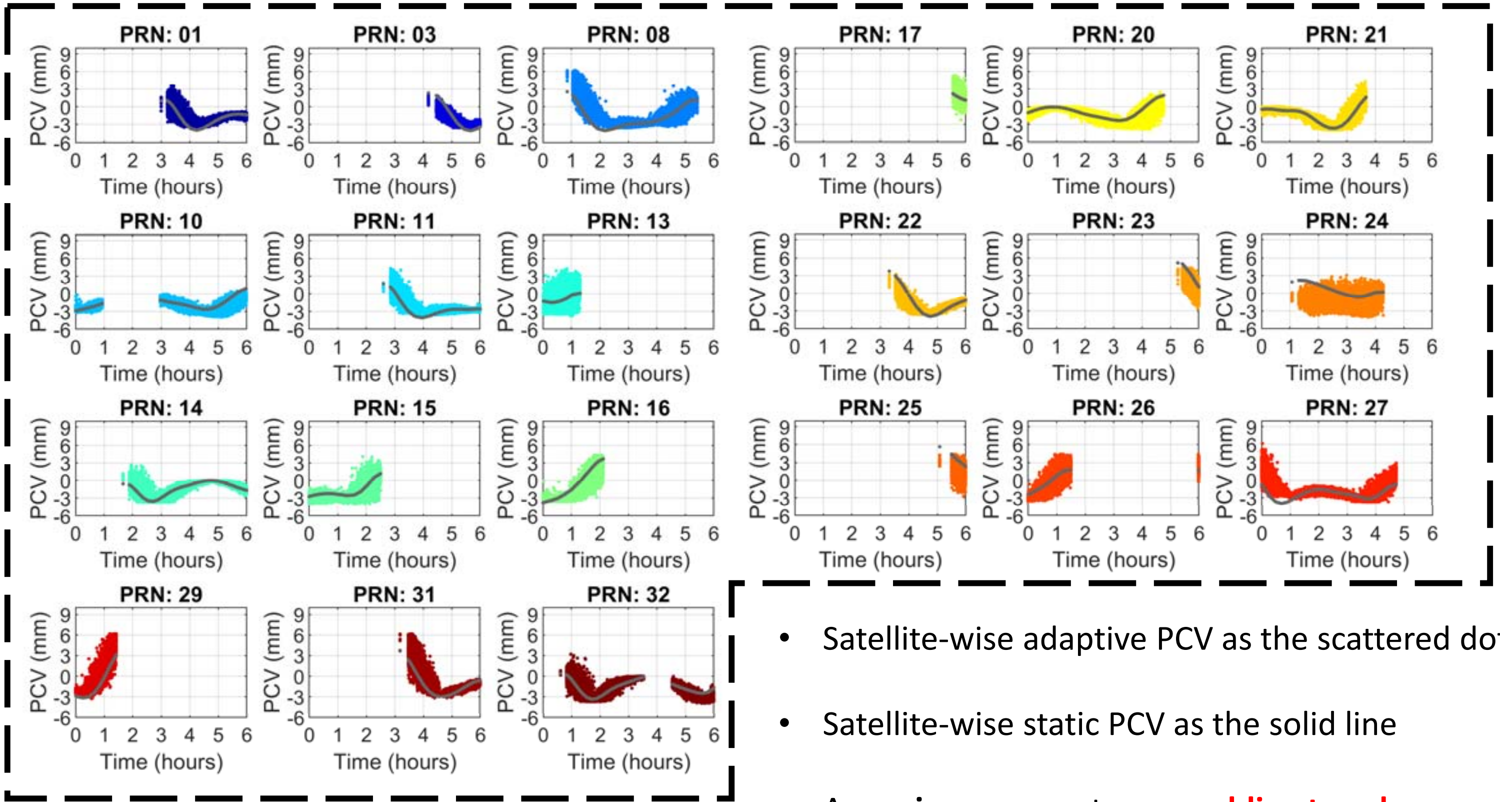
Spares:



- Satellite-wise adaptive PCV as the scattered dots
- Satellite-wise static PCV as the solid line
- A **varying range** yet a **resembling trend**

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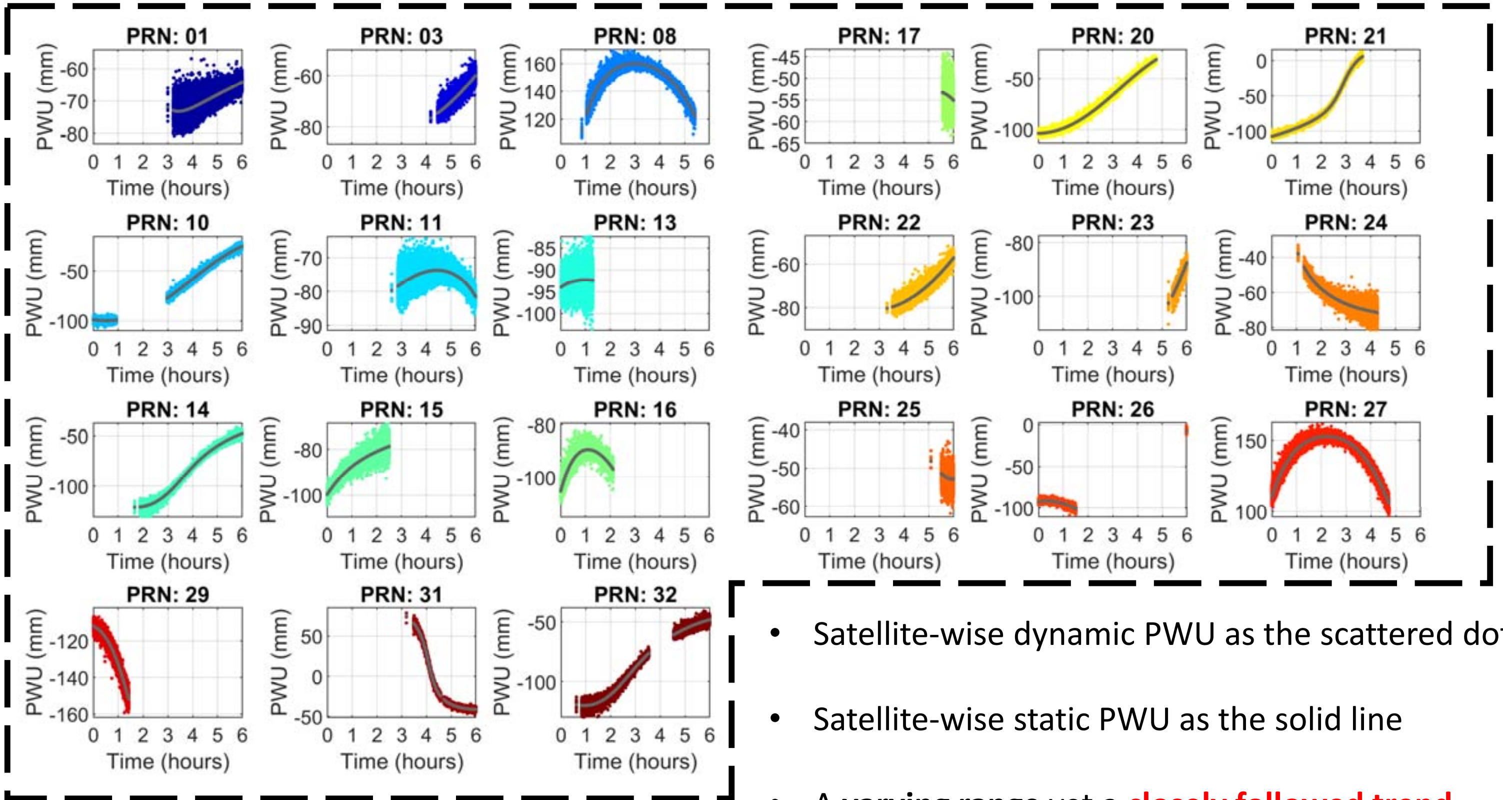
Compared with static PCV in conventional GNSS processing, adaptive PCV addresses the false assumption of a zenith point antenna.

Spares:



- Satellite-wise dynamic PWU as the scattered dots
- Satellite-wise static PWU as the solid line
- A **varying range** yet a **closely followed trend**

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Static PWU is not usually considered in double-differencing solutions up to medium-length baselines since it is normally cancelled out. However, for a rotating rover station pairing with a non-rotational ground station, it can no longer be cancelled and has to be considered when forming double-differencing pairs, which is the dynamic PWU addressed in this study.