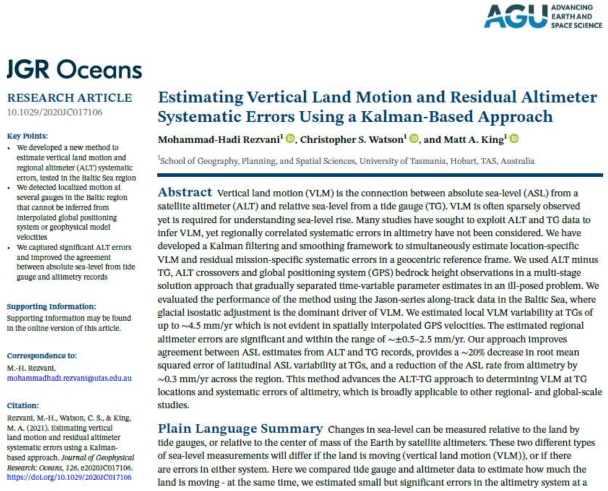
A Kalman-based approach to simultaneously estimate vertical land motion and altimeter-specific systematic errors using altimeter, tide gauge, and GPS measurements

Mohammad-Hadi Rezvani, Christopher S. Watson, Matt A. King

School of Geography, Planning, and Spatial Sciences,
University of Tasmania, Australia



JGR Oceans

RESEARCH ARTICLE
10.1029/2020JC017106

Key Points:
- We developed a new method to estimate vertical land motion and regional altimeter (ALT) systematic errors, tested in the Baltic Sea region
- We detected localized motion at several gauges in the Baltic region that cannot be inferred from interpolated global positioning system or geophysical model velocities
- We captured significant ALT errors and improved the agreement between absolute sea-level from tide gauge and altimetry records

Supporting Information:
Supporting Information may be found in the online version of this article.

Correspondence to:
M.-H. Rezvani,
mohammadhadi.rezvani@utas.edu.au

Citation:
Rezvani, M.-H., Watson, C. S., & King, M. A. (2021). Estimating vertical land motion and residual altimeter systematic errors using a Kalman-based approach. *Journal of Geophysical Research: Oceans*, *126*, e2020JC017106. https://doi.org/10.1029/2020JC017106

Estimating Vertical Land Motion and Residual Altimeter Systematic Errors Using a Kalman-Based Approach

Mohammad-Hadi Rezvani[1], Christopher S. Watson[1], and Matt A. King[1]

[1]School of Geography, Planning, and Spatial Sciences, University of Tasmania, Hobart, TAS, Australia

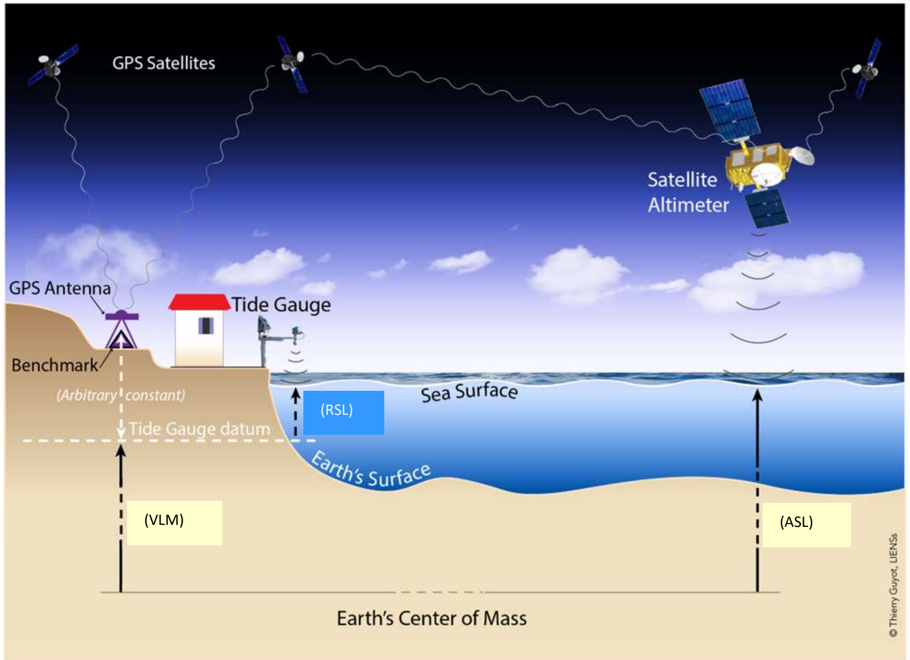
Abstract Vertical land motion (VLM) is the connection between absolute sea-level (ASL) from a satellite altimeter (ALT) and relative sea-level from a tide gauge (TG). VLM is often sparsely observed yet is required for understanding sea-level rise. Many studies have sought to exploit ALT and TG data to infer VLM, yet regionally correlated systematic errors in altimetry have not been considered. We have developed a Kalman filtering and smoothing framework to simultaneously estimate location-specific VLM and residual mission-specific systematic errors in a geocentric reference frame. We used ALT minus TG, ALT crossovers and global positioning system (GPS) bedrock height observations in a multi-stage solution approach that gradually separated time-variable parameter estimates in an ill-posed problem. We evaluated the performance of the method using the Jason-series along-track data in the Baltic Sea, where glacial isostatic adjustment is the dominant driver of VLM. We estimated local VLM variability at TGs of up to ~4.5 mm/yr which is not evident in spatially interpolated GPS velocities. The estimated regional altimeter errors are significant and within the range of ~±0.5–2.5 mm/yr. Our approach improves agreement between ASL estimates from ALT and TG records, provides a ~20% decrease in root mean squared error of latitudinal ASL variability at TGs, and a reduction of the ASL rate from altimetry by ~0.3 mm/yr across the region. This method advances the ALT-TG approach to determining VLM at TG locations and systematic errors of altimetry, which is broadly applicable to other regional- and global-scale studies.

Plain Language Summary Changes in sea-level can be measured relative to the land by tide gauges, or relative to the center of mass of the Earth by satellite altimeters. These two different types of sea-level measurements will differ if the land is moving (vertical land motion (VLM)), or if there are errors in either system. Here we compared tide gauge and altimeter data to estimate how much the land is moving - at the same time, we estimated small but significant errors in the altimetry system at a

Rezvani et al., 2021, JGR
https://doi.org/10.1029/2020JC017106

The Problem…

- Vertical Land Motion (VLM) is an important component when connecting absolute sea level (ASL, from altimetry) and relative sea level (RSL, from tide gauge).
- **How do we observe VLM at a tide gauge?**



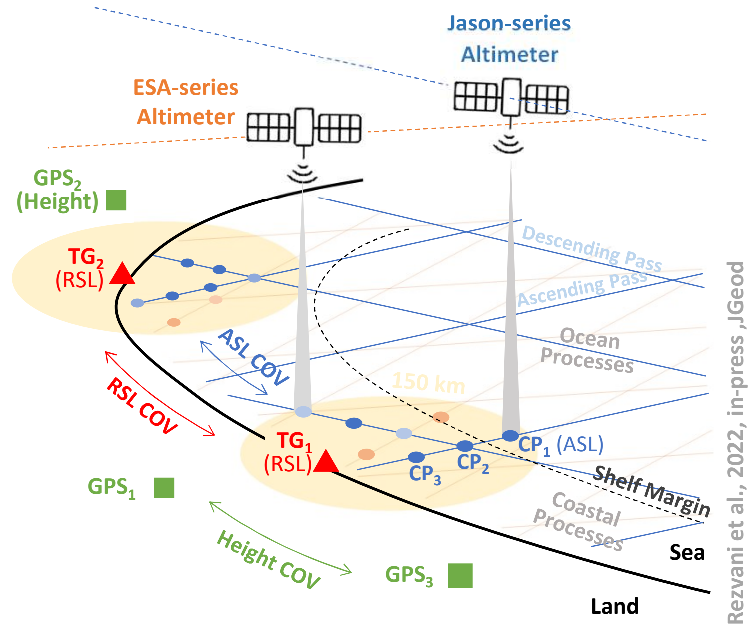
www.sonel.org

The Problem…

- We know that glacial isostatic adjustment (GIA) is only one component of VLM:
  - Modelled GIA VLM @ TGs is therefore only part of the picture….
- We know that GPS can provide estimates of VLM:
  - GPS @ TGs maybe too short / too sparse / high uncertainty etc…
  - GPS VLM interpolated to TGs maybe OK, maybe not OK (due to highly localised deformation)…
  - GPS VLM from a linear regression maybe OK, maybe not OK (due to time-dependant deformation)…
- Altimetry has been used to derive VLM @ TGs, but:
  - We know that systematic errors can affect performance (so-called bias drift)…
  - Studies estimating bias drift assume VLM@TGs is known (via GIA or GPS)…
  - Studies estimating VLM from altimetry assume bias drift is zero (or use global values)…
  - Studies estimating bias drift or VLM, apply a linear regression to derive the unknown quantities…
- **Here we attempt to estimate <u>both</u> linear and non-linear components of systematic errors & VLM. We test our engine on the Baltic sea, Australian, and South American & Antarctic Peninsula regions.**

Objectives…

- Can altimetry, TG, and inland GPS be used to simultaneously estimate improved vertical land motion at gauge locations, as well as any small geographically correlated biases in altimetry records?
- Can we make progress on understanding the limitations driven by differential oceanic signals between the altimeter and TG locations?
- Can we identify non-linear components in VLM or altimeter biases?



RSL = relative sea level
ASL = absolute sea level (geocentric)
VLM = vertical land motion (geocentric)

Objectives…

Fundamental proposition:

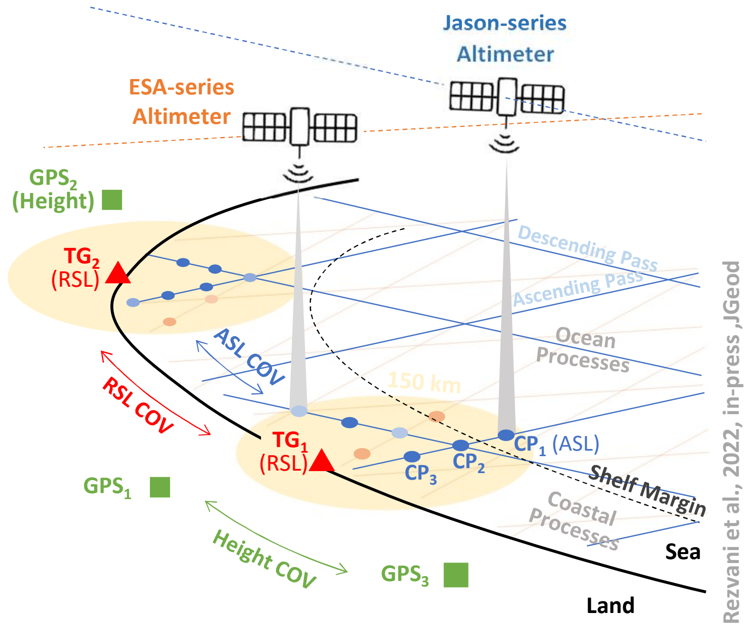
$$[\mathrm{VLM}]_{\mathrm{TG}_1} = [\mathrm{ASL}]_{\mathrm{TG}_1} - [\mathrm{RSL}]_{\mathrm{TG}_1}$$

where:

$$[\mathrm{ASL}]_{\mathrm{TG}_1} = [\mathrm{ASL}]_{\mathrm{CP}_1}^{\mathrm{ALT}_1} + [\mathrm{Bias}]_{\mathrm{CP}}^{\mathrm{ALT}_1} + [\mathrm{Residual}]_{\mathrm{CP}_1,\mathrm{TG}_1}^{\mathrm{ALT}_1}$$

Questions:

- Does altimetry have any non-zero and regionally coherent biases? (i.e. is $[\mathrm{Bias}]_{\mathrm{CP}}^{\mathrm{ALT}_1}$ significant?)
- Is the residual oceanic signal between the TG and ALT CP a limiting factor? (i.e. is $[\mathrm{Residual}]_{\mathrm{CP}_1,\mathrm{TG}_1}^{\mathrm{ALT}_1}$ a problem?)
- Is land motion at the nearest GPS site the same as at the TG? (i.e. is $[\mathrm{VLM}]_{\mathrm{GPS}_1} = [\mathrm{VLM}]_{\mathrm{TG}_1}$?)
- Can non-linear signals be resolved in $[\mathrm{Bias}]_{\mathrm{CP}}^{\mathrm{ALT}_1}$ and/or $[\mathrm{VLM}]_{\mathrm{TG}_1}$?



RSL = relative sea level
ASL = absolute sea level (geocentric)
VLM = vertical land motion (geocentric)

Method…

- We develop a space-time Kalman filtering and smoothing framework, with a discrete-time linear dynamic model.
- We parametrize mission-specific bias drift and location-specific land motion in the same reference frame.
- Our key observations include:
  - ➢ SSH differences from (multi-mission) altimeter minus TG, and tandem/dual altimeter crossovers over a distributed set of comparison points (CPs).
  - ➢ GPS height time series.
- Our dataset includes:
  - ➢ ASL series from the reference missions (TOPEX, Jason-1, OSTM/Jason-2 and Jason-3) and the non-reference missions (ERS-2, Envisat, SARAL/Altika and Sentinel-3A) from the RADS database (Scharroo et al., 2012).
  - ➢ Hourly RSL data from local TGs across 3 case study regions.
  - ➢ Daily ellipsoidal heights from inland GPS sites in the vicinity of the TGs from NGL database (Blewit et al., 2018).
  - ➢ GIA prediction rates from ICE6G_D model (used for comparison only).

Method…

- Our state parameters includes:
  - Linear components of mission-specific bias drifts.
  - Non-linear components of mission-specific bias drifts.
  - Linear components of location-specific VLM at TG and GPS sites.
  - Non-linear components of location-specific VLM at TG and GPS sites.
  - Intercepts of observational series.
  - Across track ASL slopes.
  - Temporally correlated measurement noise.

- Temporal constraints on parameter evolution (linear or non-linear in time) are controlled through tuning the a priori parameter uncertainty and process noise.

- Given the problem is inherently ill-posed, a multi-stage solution strategy is proposed.

Preliminary Analysis…

- GPS trends are derived from a maximum likelihood approach in Hector software (Bos et al. 2013), with consideration of an appropriate variance-covariance matrix for ‘white plus power-law’ stochastic noise model.

- A priori estimates of VLM at TG locations are estimated via Kriging interpolation of neighbouring GPS sites (within 150 km of each TG), using an appropriate scheme for weighting GPS velocity rates.

- Key components of the filter design include treatment of spatial correlations through analysis of semi-variances of observational residuals, as well as noise contents through AR1 modelling of the residuals.

Solution Strategy…

- **Solution 1:** We estimate initial regional altimeter bias drifts with tight constraints on interpolated VLM rates at the TG locations.
- **Solution 2:** Using these initial estimates of altimeter bias drift, we then loosen constraints on VLM trends at the TG locations – this approach enables investigation of geodetic sites with anomalous VLM.
- **Solution 3:** We then run an optimal solution to resolve potential time-variability in bias drift and VLM, with imposing tight constraints on VLM trends at any given TG from the former solution.

Case Studies…

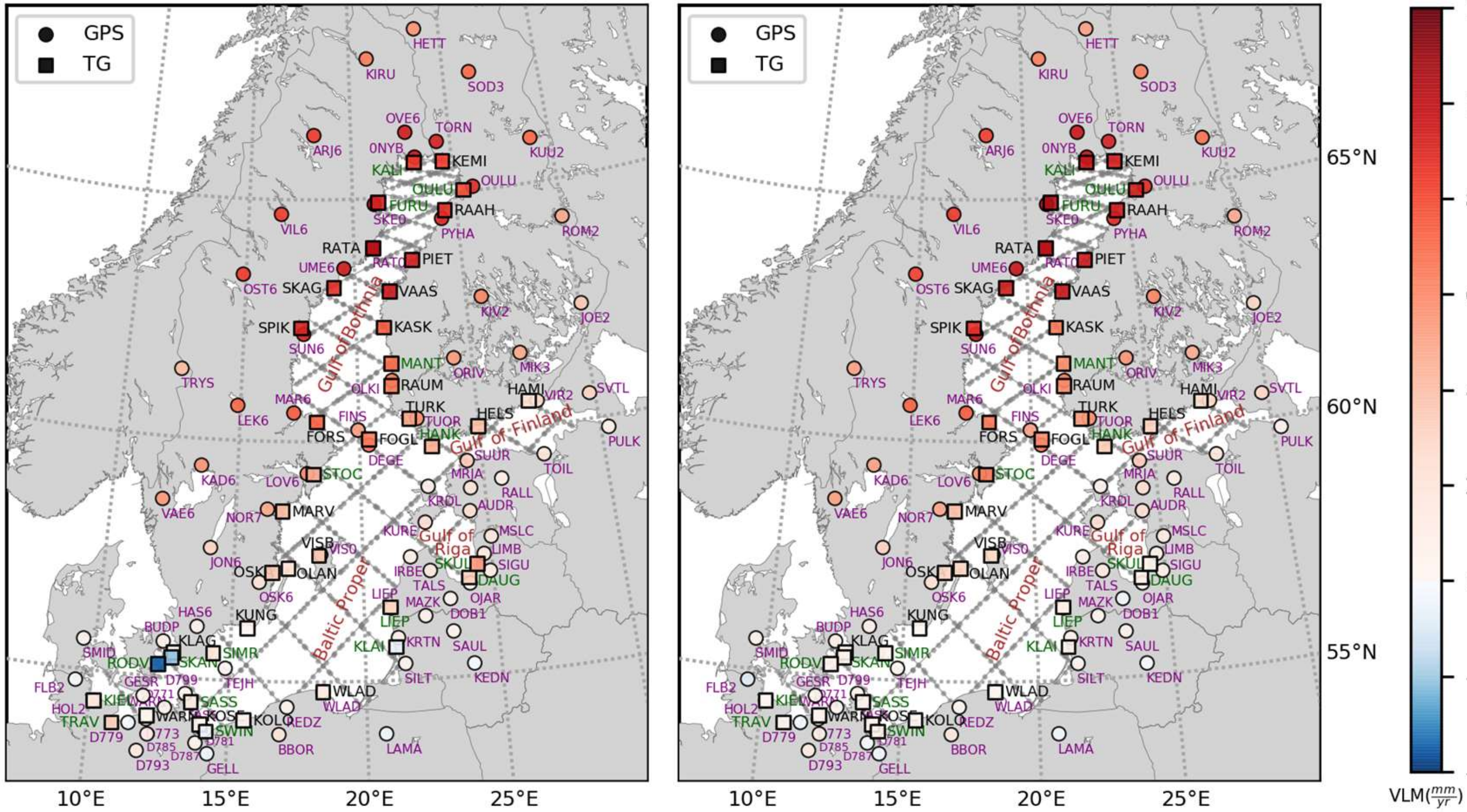
- First, we build the engine and test in the Baltic Sea, where:
  - A well-equipped array of GPS and TG stations exist.
  - GIA contributes heavily to VLM.
  - Published in Rezvani et al., 2021, JGR, https://doi.org/10.1029/2020JC017106
- Then we extend to investigate the performance of method in the Australia, where:
  - A well-equipped array of GPS and TG stations exist.
  - Non-GIA signals possibly contributes to continent-wide VLM.
  - Differential oceanographic signals between altimeter and TG measurement locations potentially bias the VLM estimates in narrow continental shelf regions.
  - In-press, Rezvani et al., 2022, Journal of Geodesy.
- Finally, we investigate the performance of method in the South America, where:
  - A sparse array of GPS and TG stations exist.
  - Time-variable signals, driven by either earthquakes or ice unloading, significantly contribute to local-scale VLM.

Baltic: Linear VLM Results (“Ours” vs Interpolated GPS)

- Good agreement between our VLM and Hector estimates at GPS sites (median of +0.04 mm/yr and WRMS of 0.18 mm/yr).
- At TGs, **we detect localised VLM at some TGs** (e.g., in the Gulf of Riga – green labels on figure), not inferred from interpolated GPS. Excluding these, the median difference is +0.11 mm/yr, with WRMS of 0.56 mm/yr.

Our linear VLM

GPS-Krig VLM at TG & Hector VLM at GPS

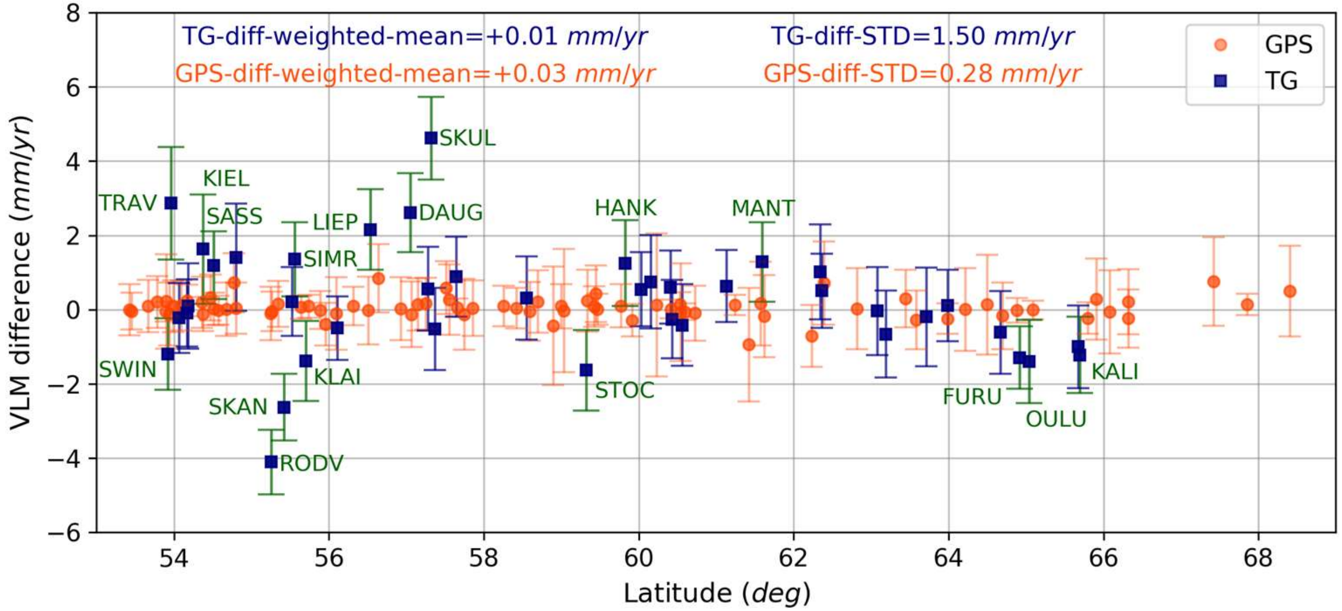


Baltic Sea

Baltic: Linear VLM Results (“Ours” minus Interpolated GPS)

- Differences at GPS sites (orange) show low variability.
- Differences to interpolated GPS at TG show increased variability and significant differences at some TGs (see green labels) suggesting real and localised VLM at these gauges.
- 17 TGs (green labels) have differences significant at the 1-sigma level. These differences range within ± ~4.5 mm/yr.

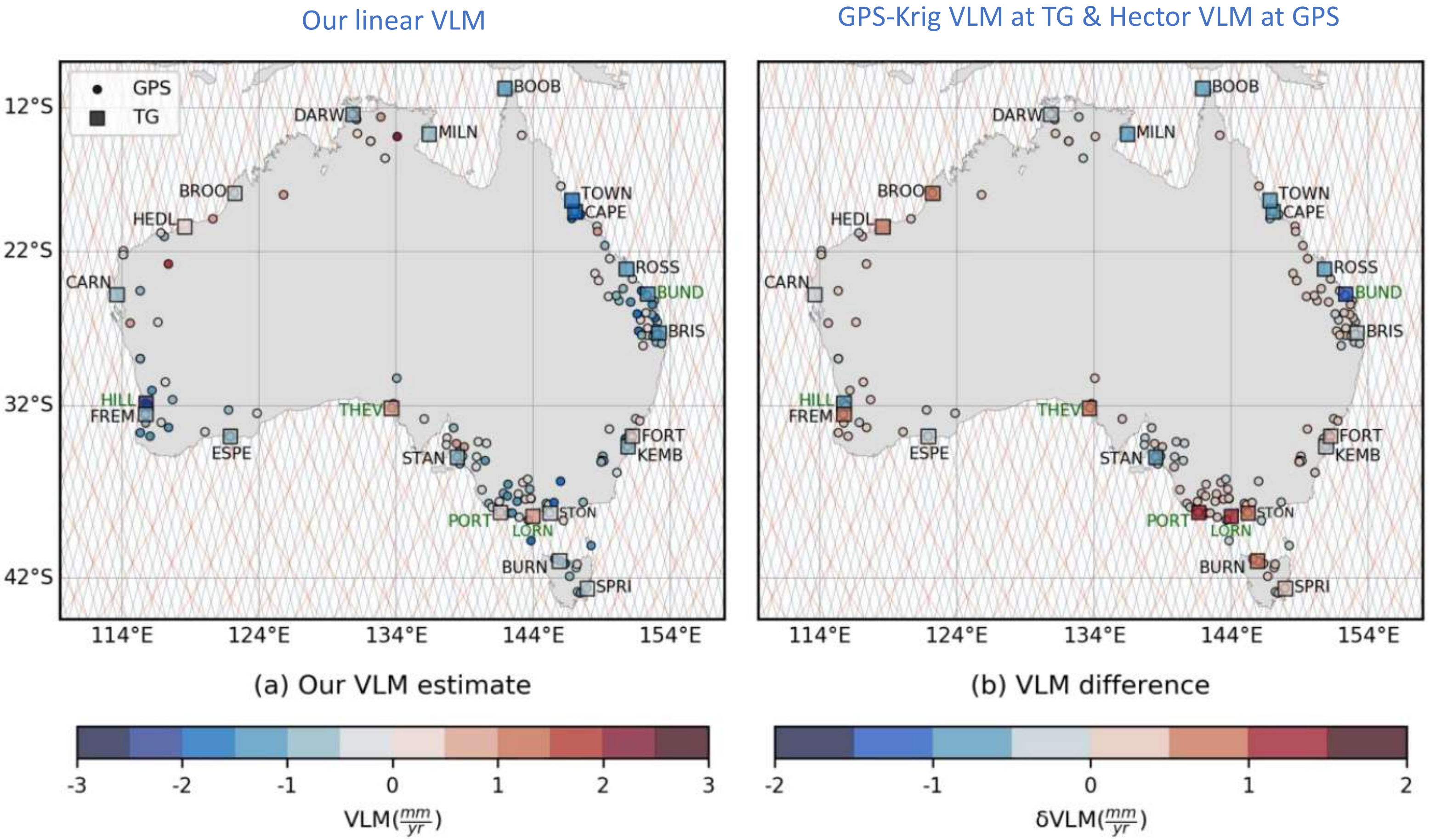
(Our linear VLM) minus (GPS-Krig VLM at TG & Hector VLM at GPS) in Baltic Sea



Australia: Linear VLM Results ("Ours" vs Interpolated GPS)

- Good agreement between our VLM and Hector estimates at GPS sites (median of +0.06 mm/yr and WRMS of 0.12 mm/yr).

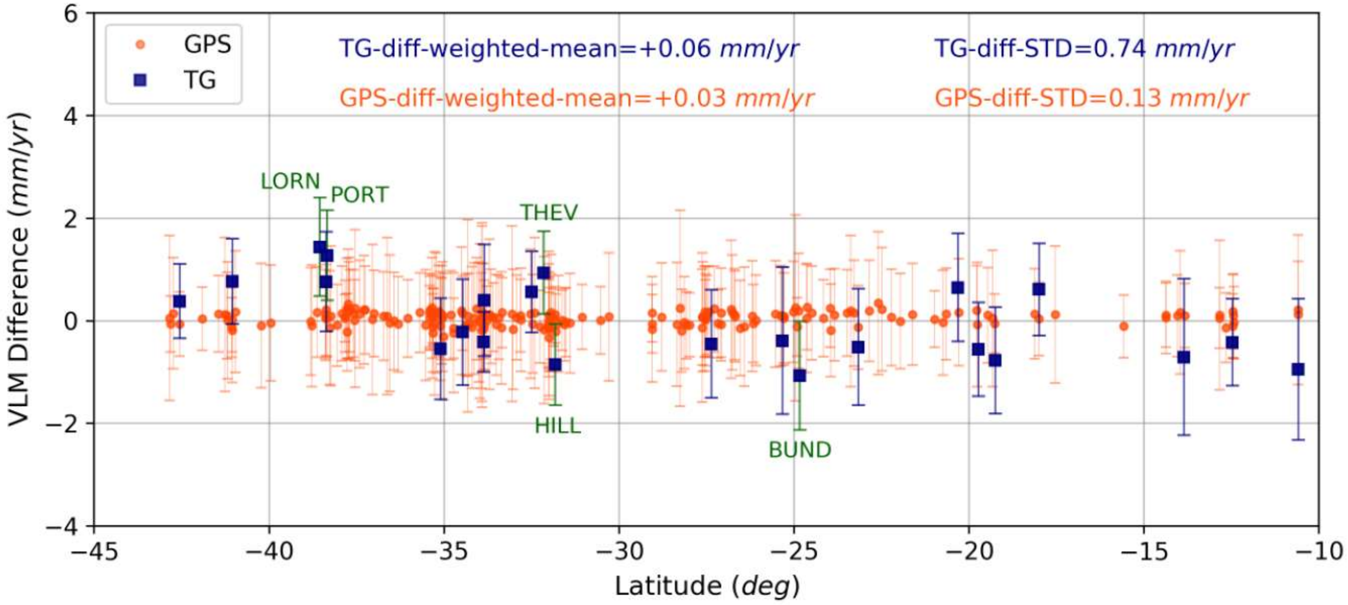
- At TGs, **we detect localised VLM at some TGs** (e.g., in the Fremantle basin– green labels on figure), not inferred from interpolated GPS. Excluding these, the median difference is +0.19 mm/yr, with WRMS of 0.58 mm/yr.



Australia: Linear VLM Results ("Ours" minus Interpolated GPS)

- Differences at GPS sites (orange) show low variability, similarly.
- Differences to interpolated GPS at TG show increased variability and significant differences at some TGs (see green labels) suggesting real and localised VLM at these gauges.
- 5 TGs (green labels) have differences significant at the 1-sigma level. These differences range within ± ~1.5 mm/yr.

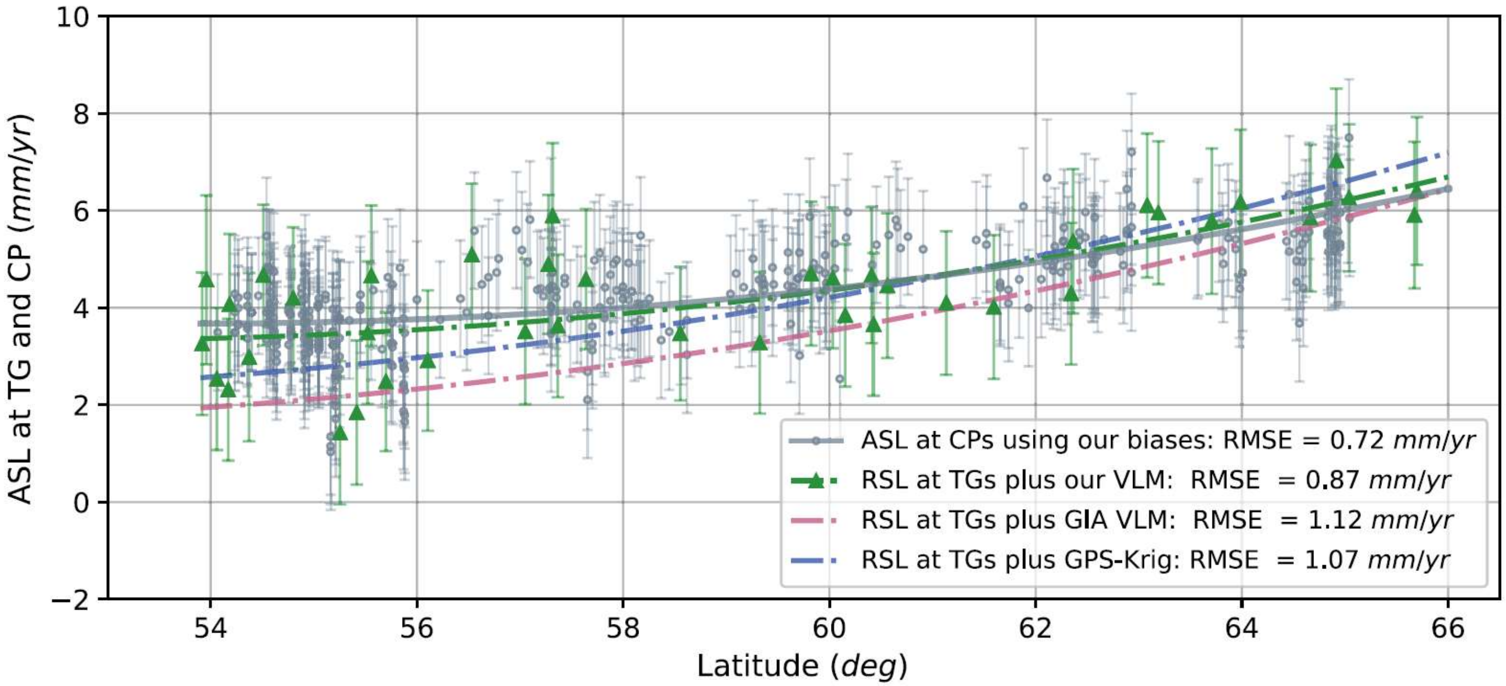
(Our linear VLM) minus (GPS-Krig VLM at TG & Hector VLM at GPS) in Australia



Baltic: ASL at TGs versus at Altimeter Comparison Points

- We see a good agreement between ASL estimates at TGs and at CPs (with our mission specific bias drifts applied).
- Our approach shows a ~20% decrease (in terms of STD) in ASL variability over the catchment.
- Suggests we are capturing mission-specific errors and TG-specific VLM.

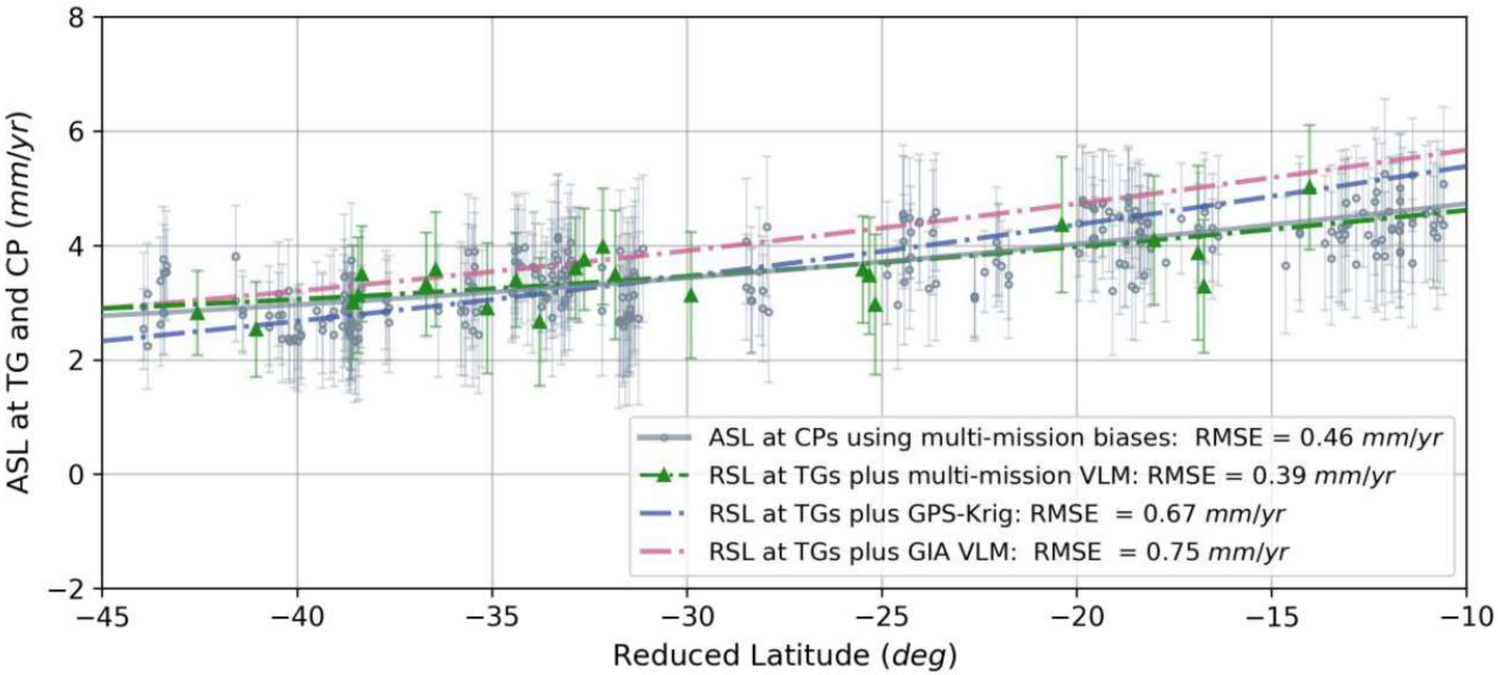
ASL at altimetry CPs vs. ASL at TGs, from Our, GPS-Kriging and GIA VLM in Baltic Sea



Australia: ASL at TGs versus at Altimeter Comparison Points

- Similarly, we see a good agreement between ASL estimates at TGs and at CPs (with our mission specific bias drifts applied).
- Our approach shows a ~40% decrease (in terms of STD) in ASL variability around the continent compared to when using GPS-Krig VLM.

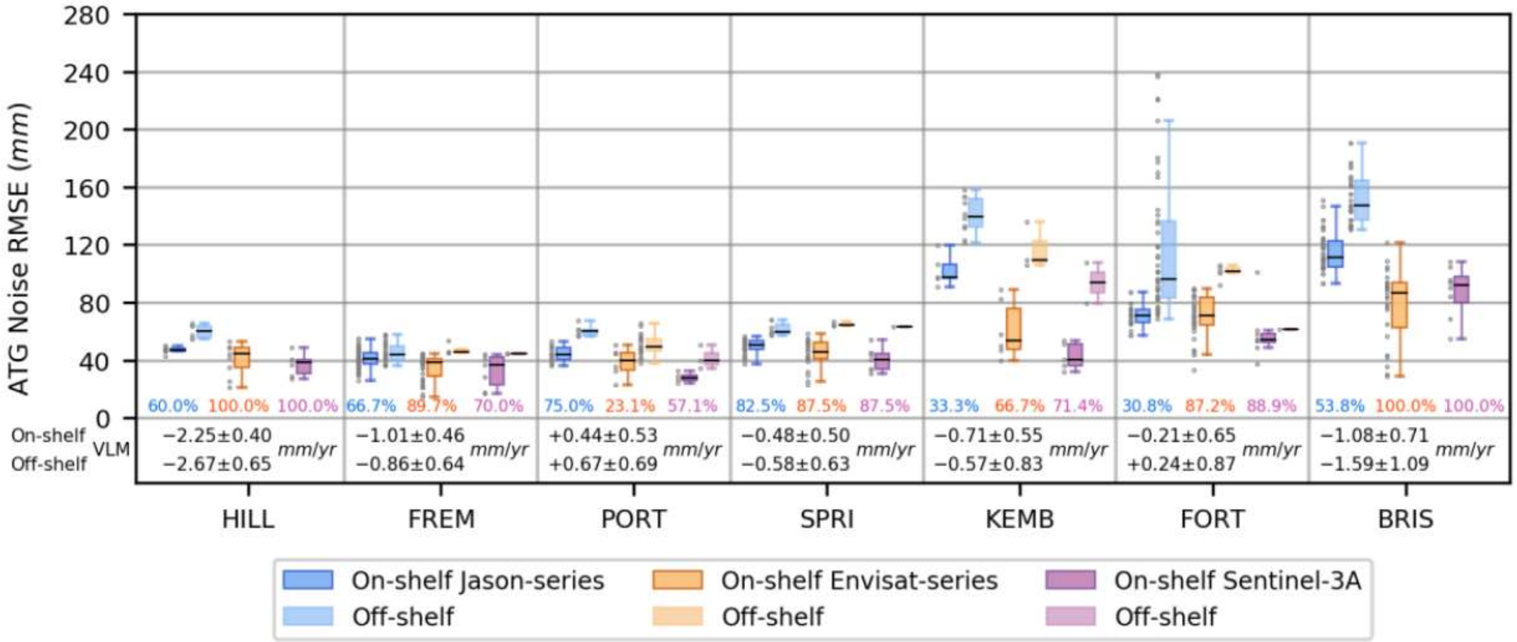
ASL at altimetry CPs vs. ASL at TGs, from Our, GPS-Kriging and GIA VLM in Australia



Impact of Differential Oceanographic Signals on Linear VLM Results

- We compute the estimates of VLM at TGs located in the narrow continental shelf using on-shelf and off-shelf CPs).
- Our approach suggests a significant difference of up to ~0.5 mm/yr between on-shelf and off-shelf VLMs estimated at TGs adjacent to East Australian Current (EAC).
- As expected, we found a significant increase in ALT-TG noise for TGs adjacent to the EAC.

Our linear VLMs computed from on-shelf and off-shelf CPs around Australia

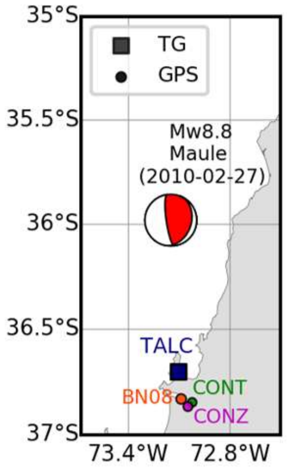


South America: Non-Linear VLM Results Driven by Earthquake ("Ours" vs nearby GPS)…

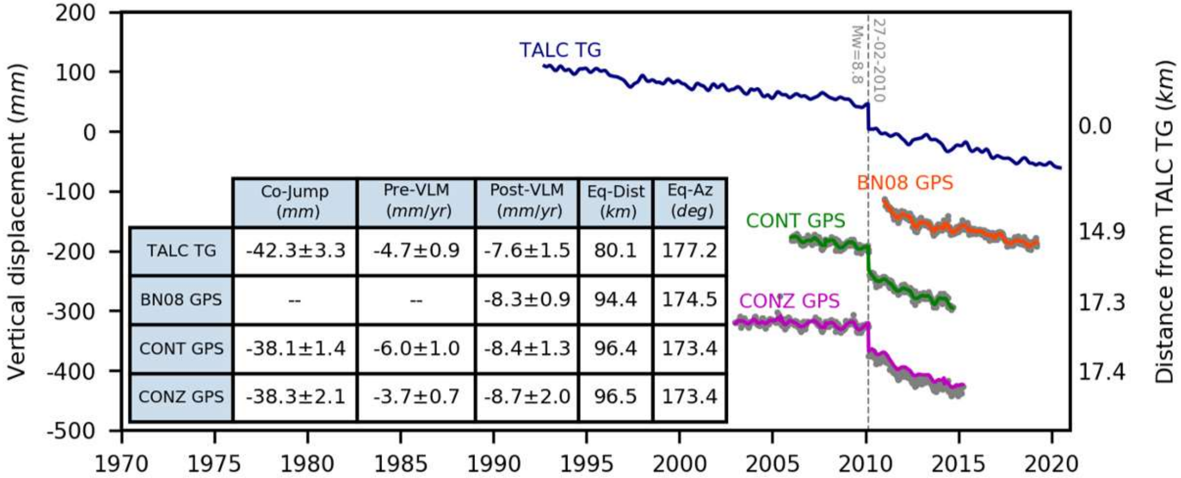
- Good agreement between our non-linear VLM estimates at TG and GPS sites.

- At TG, **we detect co-seismic jumps and change in pre- and post-seismic velocities** (TALC TG – blue curve on figure), comparable with the nearby GPS sites (at BN08, CONT and CONZ locations).

- Note the spatially coherent variability nature of the co-seismic jumps and velocity changes.



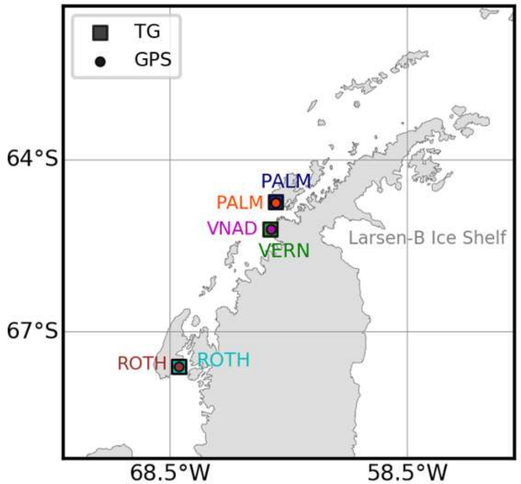
Our non-linear VLM in South America



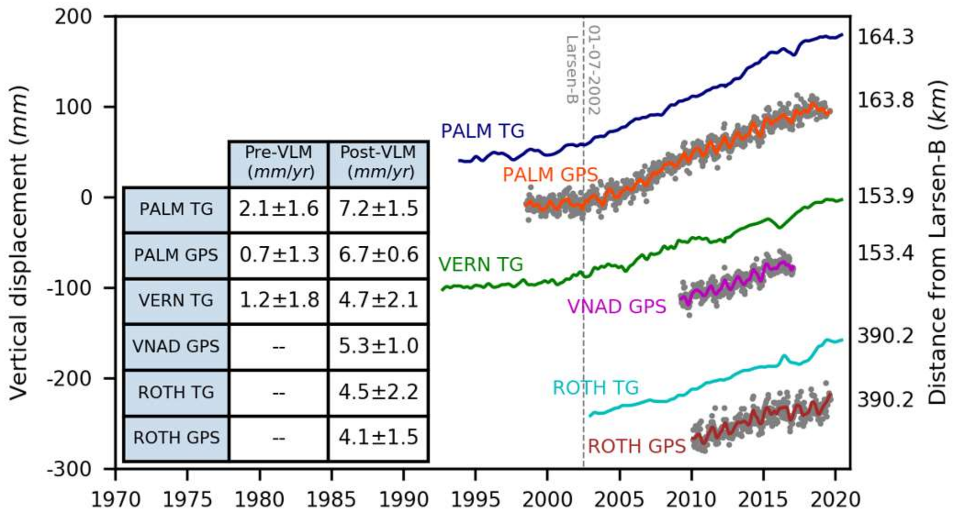
	Co-Jump (mm)	Pre-VLM (mm/yr)	Post-VLM (mm/yr)	Eq-Dist (km)	Eq-Az (deg)
TALC TG	-42.3±3.3	-4.7±0.9	-7.6±1.5	80.1	177.2
BN08 GPS	--	--	-8.3±0.9	94.4	174.5
CONT GPS	-38.1±1.4	-6.0±1.0	-8.4±1.3	96.4	173.4
CONZ GPS	-38.3±2.1	-3.7±0.7	-8.7±2.0	96.5	173.4

Antarctic Peninsula: Non-Linear VLM Results Driven by Ice-Unloading ("Ours" vs nearby GPS)…

- Similarly, good agreement between our non-linear VLM estimates at TG and GPS sites.
- **We detect the solid –Earth response to Larsen-B ice loss in 2002** (notably in PALM TG and PALM GPS – blue and orange curves on figure), in good agreement with other geodetic sites. Further to the south, this effect is reduced as expected at ROTH station.



Our non-linear VLM in Antarctic Peninsula

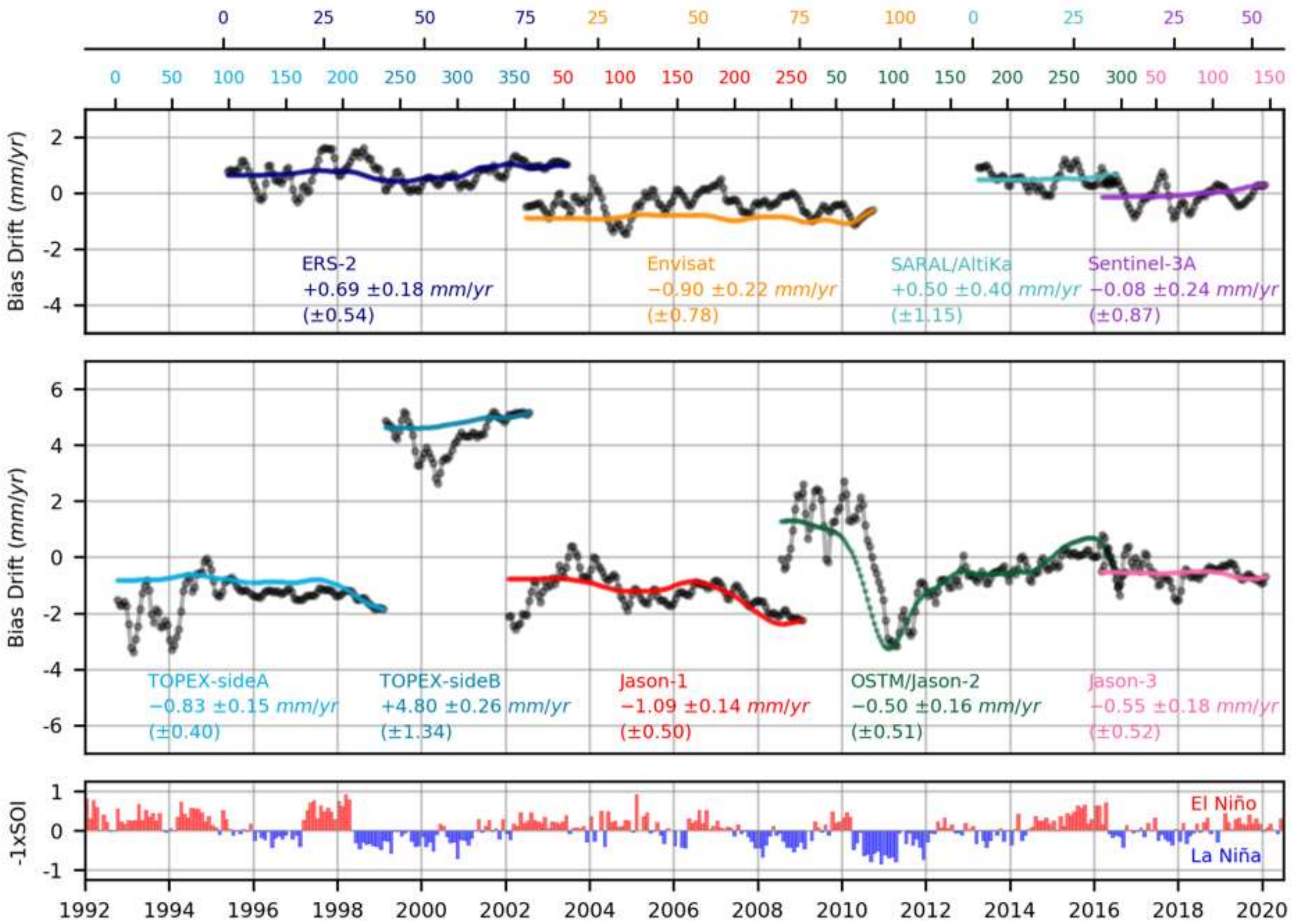


	Pre-VLM (mm/yr)	Post-VLM (mm/yr)
PALM TG	2.1±1.6	7.2±1.5
PALM GPS	0.7±1.3	6.7±0.6
VERN TG	1.2±1.8	4.7±2.1
VNAD GPS	--	5.3±1.0
ROTH TG	--	4.5±2.2
ROTH GPS	--	4.1±1.5

Time-Variable Systematic Errors in Mission-Specific Altimetry…

- Relatively loose process noise enables substantial evolution in time of this mission-specific parameter in the forward solution.
- The return smoothing pass loosely constrains the variables to derive time-variable estimates.
- Forward and backward estimates show convergence after ~2.5 years.
- Substantial time-variability for OSTM/Jason-2 highlights potential effects driven by 2010-2012 La Niña phenomenon (this signal is not influenced by the end of the Envisat mission).

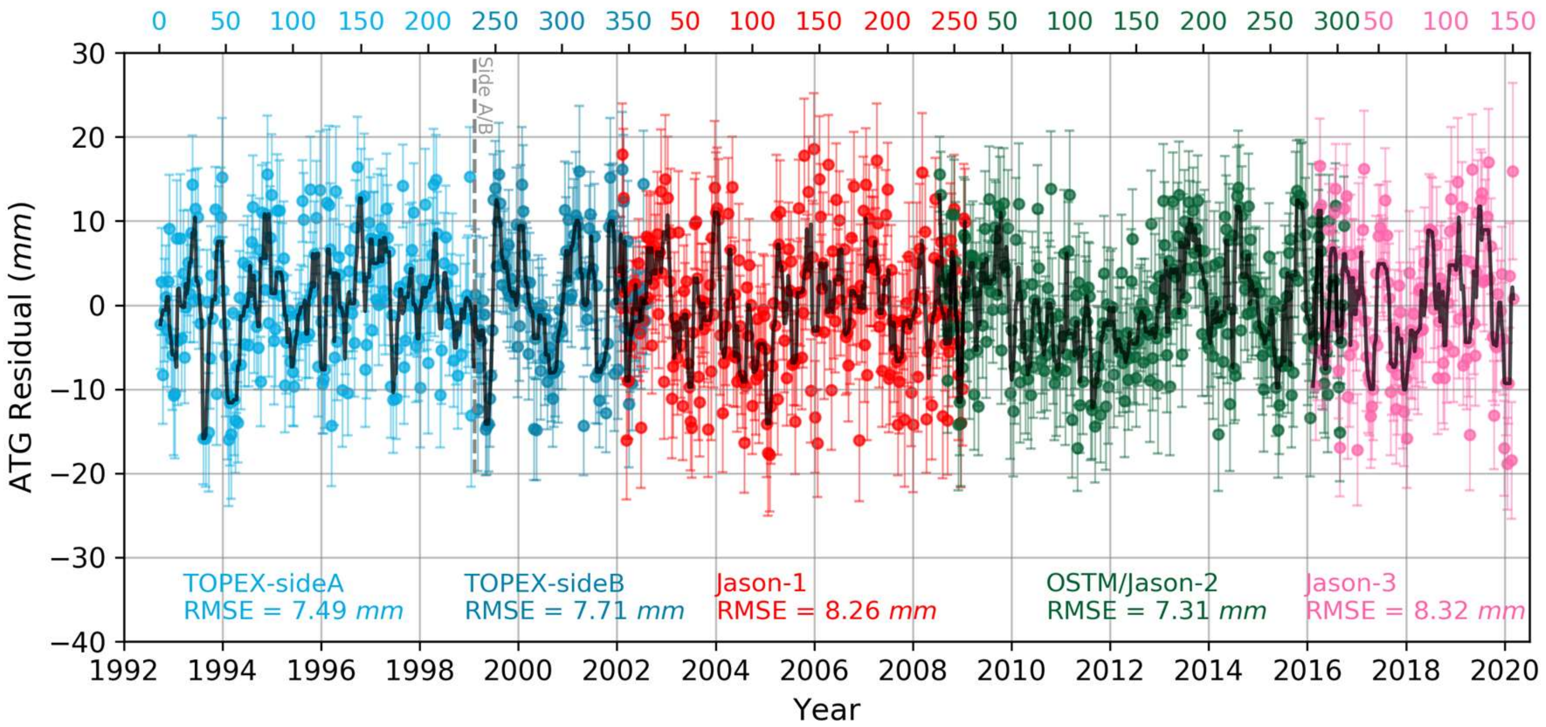
Potential systematic errors in the reference and non-reference mission altimetry in Australia



Baltic: ALT-TG Residuals, Treated Bias Drifts as Linear …

- Stacked residuals offer a useful insight. Higher variability than global results as expected.
- The assumption that altimeter bias drift behaves linearly with time is undoubtedly optimistic.
- Non-linear behaviour in Jason-2 in particular is interesting – this is also observed at the Bass Strait validation facility.

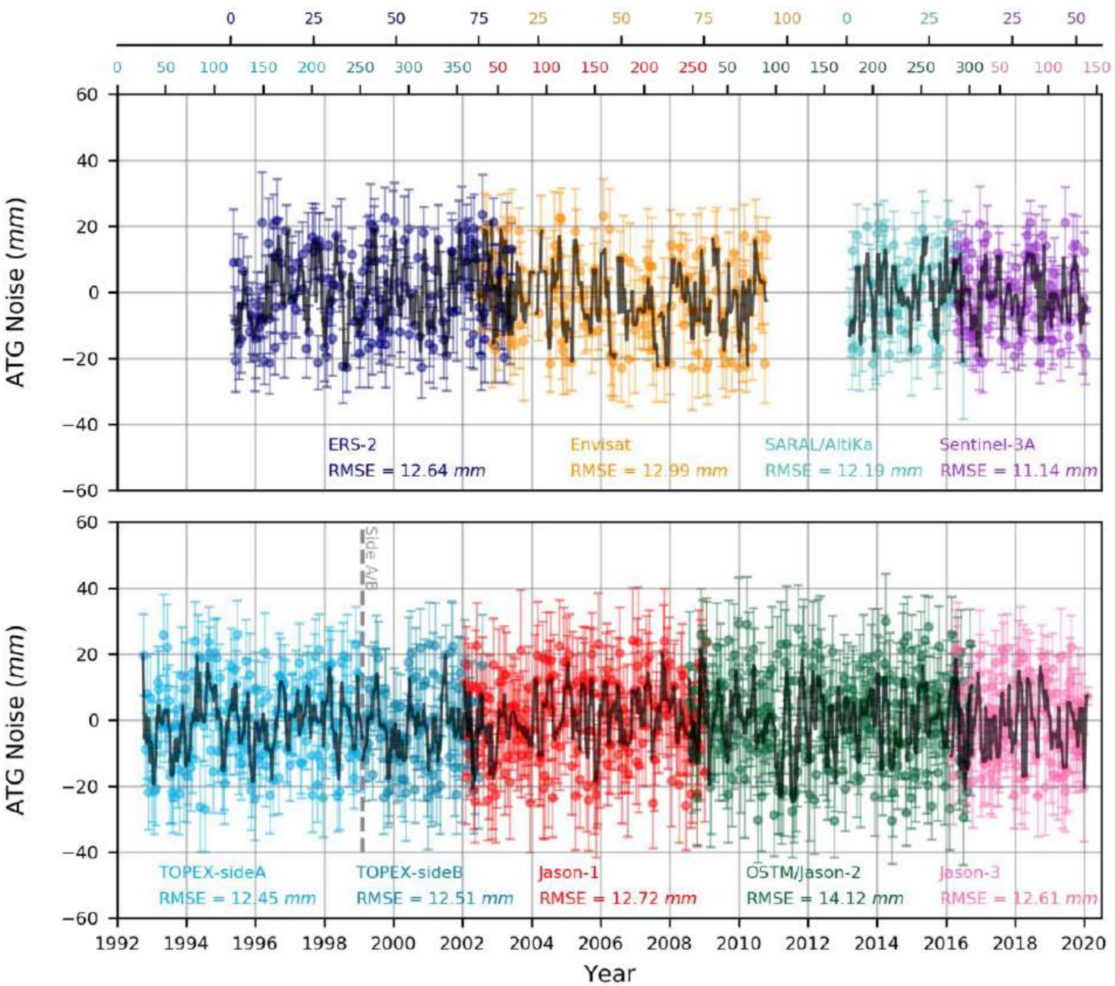
Cycle-by-cycle weighted average of ATG residuals in Baltic Sea



Australia: ALT-TG Residuals, Treated Bias Drifts as Non-Linear …

- Similarly, higher variability than global results as expected.
- As the time-variability in altimeter bias drift was captured in the state vector, these stacked residuals are linearised as expected.
- This points towards our approach capturing a common mode residual non linear signal in each altimeter mission.

Cycle-by-cycle weighted average of ATG residuals in Australia

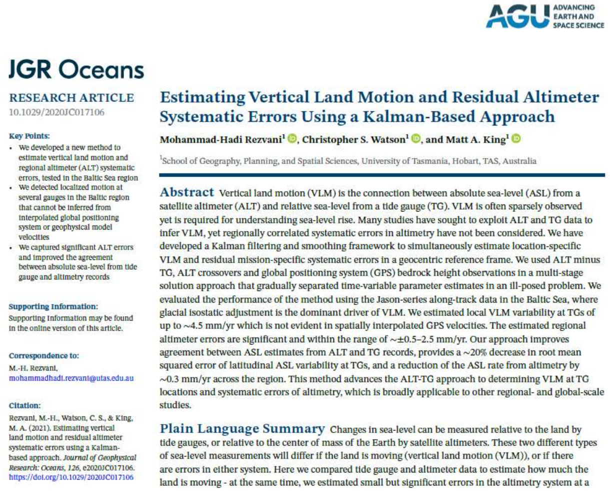


Conclusions and Outlook…

- Numerical results suggest that the method can effectively estimate the linear and non-linear components of VLM at TGs using altimeter-TG data.
- Simultaneous estimation of small but significant mission-specific biases in altimetry, and their potential non-linearity helps to improve our solutions.
- Differential oceanic signals between the TG and ALT locations remain an issue. Multi-mission solutions assist here given improved ground track spacing and proximity to tide gauges.
- Appropriate tuning of the filter is critical and depends on our assumptions and characteristics of the study region.
- Next steps include inclusion of Sentinel-3B and expansion to global solutions.
- Paper in Australia has been accepted for publication in Journal of Geodesy, and the work spanning South America is being revised ready for submission for publication.

Questions?
Please add your question to the forum or send via email.

Mohammad-Hadi Rezvani, mohammadhadi.rezvani@utas.edu.au
Christopher S. Watson, Matt A. King
School of Geography, Planning, and Spatial Sciences,
University of Tasmania, Australia



JGR Oceans

RESEARCH ARTICLE
10.1029/2020JC017106

Key Points:
- We developed a new method to estimate vertical land motion and regional altimeter (ALT) systematic errors, tested in the Baltic Sea region
- We detected localized motion at several gauges in the Baltic region that cannot be inferred from interpolated global positioning system or geophysical model velocities
- We captured significant ALT errors and improved the agreement between absolute sea-level from tide gauge and altimetry records

Supporting Information:
Supporting Information may be found in the online version of this article.

Correspondence to:
M.-H. Rezvani,
mohammadhadi.rezvani@utas.edu.au

Citation:
Rezvani, M.-H., Watson, C. S., & King, M. A. (2021). Estimating vertical land motion and residual altimeter systematic errors using a Kalman-based approach. *Journal of Geophysical Research: Oceans, 126*, e2020JC017106. https://doi.org/10.1029/2020JC017106

Estimating Vertical Land Motion and Residual Altimeter Systematic Errors Using a Kalman-Based Approach

Mohammad-Hadi Rezvani[1], Christopher S. Watson[1], and Matt A. King[1]

[1]School of Geography, Planning, and Spatial Sciences, University of Tasmania, Hobart, TAS, Australia

Abstract Vertical land motion (VLM) is the connection between absolute sea-level (ASL) from a satellite altimeter (ALT) and relative sea-level from a tide gauge (TG). VLM is often sparsely observed yet is required for understanding sea-level rise. Many studies have sought to exploit ALT and TG data to infer VLM, yet regionally correlated systematic errors in altimetry have not been considered. We have developed a Kalman filtering and smoothing framework to simultaneously estimate location-specific VLM and residual mission-specific systematic errors in a geocentric reference frame. We used ALT minus TG, ALT crossovers and global positioning system (GPS) bedrock height observations in a multi-stage solution approach that gradually separated time-variable parameter estimates in an ill-posed problem. We evaluated the performance of the method using the Jason-series along-track data in the Baltic Sea, where glacial isostatic adjustment is the dominant driver of VLM. We estimated local VLM variability at TGs of up to ~4.5 mm/yr which is not evident in spatially interpolated GPS velocities. The estimated regional altimeter errors are significant and within the range of ~±0.5–2.5 mm/yr. Our approach improves agreement between ASL estimates from ALT and TG records, provides a ~20% decrease in root mean squared error of latitudinal ASL variability at TGs, and a reduction of the ASL rate from altimetry by ~0.3 mm/yr across the region. This method advances the ALT-TG approach to determining VLM at TG locations and systematic errors of altimetry, which is broadly applicable to other regional- and global-scale studies.

Plain Language Summary Changes in sea-level can be measured relative to the land by tide gauges, or relative to the center of mass of the Earth by satellite altimeters. These two different types of sea-level measurements will differ if the land is moving (vertical land motion (VLM)), or if there are errors in either system. Here we compared tide gauge and altimeter data to estimate how much the land is moving - at the same time, we estimated small but significant errors in the altimetry system at a

Rezvani et al., 2021, JGR
https://doi.org/10.1029/2020JC017106

References …

Altamimi, Z., Collilieux, X., Métivier, L. (2011) ITRF2008: an improved solution of the international terrestrial reference frame. Journal of Geodesy, 85, 457–473. https://doi.org/10.1007/s00190-011-0444-4.

Blewitt, G., Hammond, W. C., Kreemer, C. (2018) Harnessing the GPS data explosion for interdisciplinary science, Eos, 99, https://doi.org/10.1029/2018EO104623.

Bos, M. S., Williams, S. D. P., Araújo, I. B., Bastos, L. (2013) The effect of temporal correlated noise on the sea level rate and acceleration uncertainty, Geophys. J. Int., 196, 1423–1430, https://doi.org/10.1093/gji/ggt481.

Madsen, K.S., Høyer, J.L., Suursaar, Ü., She, J., Knudsen, P. (2019) Sea Level Trends and Variability of the Baltic Sea From 2D Statistical Reconstruction and Altimetry. Front. Earth Sci. 7:243. https://doi.org/ 10.3389/feart.2019.00243.

Scharroo, R., Leuliette, E. W., Lillibridge, J. L., Byrne, D., Naeije, M. C., Mitchum, G. T. (2012) RADS: Consistent multimission products, in: Proceedings of Symposium on 20 Years of Progress in Radar Altimetry, Vol. 20, 59–60.

Acknowledgements …

- This research was supported under the Australian Research Council's Special Research Initiative for Antarctic Gateway Partnership (Project ID SR140300001).
- Aspects of this work were also supported by the Australian Research Council Discovery Project DP150100615.
- This work has benefitted from the Bass Strait altimeter validation facility which is supported by Australia’s Integrated Marine Observing System (IMOS) – IMOS is enabled by the National Collaborative Research Infrastructure Strategy (NCRIS).
- Access to the RADS altimeter database, local tide gauge databases, and NGL GPS series are highly appreciated.
- The UTas HPC facilities have been employed for computations.