Investigating vertical land motion and altimetric systematic errors using a Kalman-based approach

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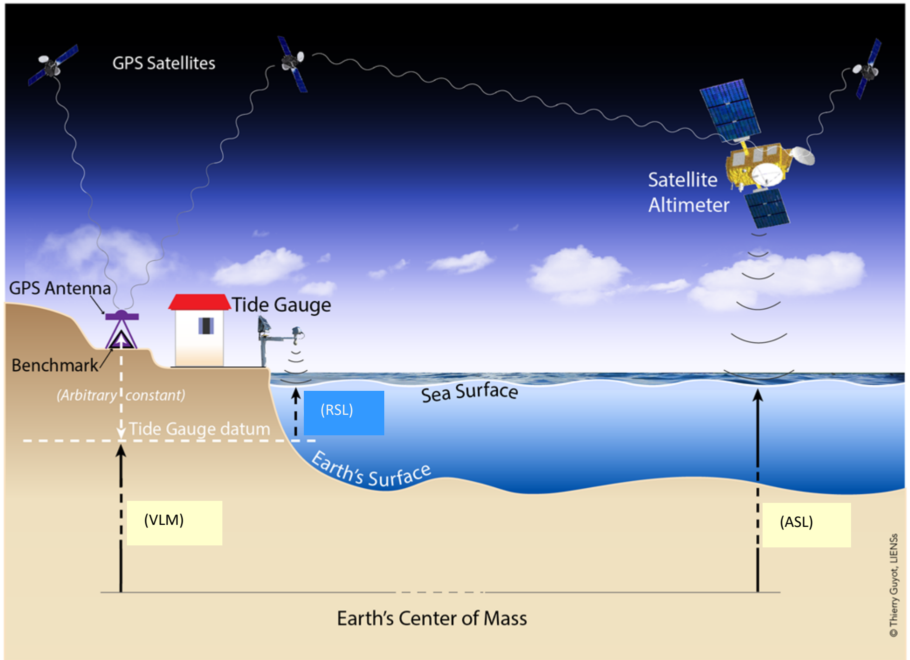
The Problem…

- Vertical Land Motion (VLM) is the vital connection between absolute sea level (ASL from altimetry) and relative sea level (RSL from tide gauges).
- **How do we observe VLM at a tide gauge?**



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The Problem…

- We know that glacial isostatic adjustment (GIA) is only one component of VLM:
  - ➢ GIA @ 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 localised motions)…
- Altimetry has been used to derive VLM @ TGs, but:
  - ➢ We know that systematic errors can affect performance (the 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).
- **Here we attempt to estimate both systematic errors & VLM. We test our engine on the Baltic sea region.**

Objectives…

Systematic errors in altimetry are usually evaluated using TG records on global scales, yet regionally correlated errors remain – for example, differences in orbit solutions alone show significant regional trends in some areas.

- **Can we make progress on estimating altimeter systematic errors at <u>regional</u> scales?**
- **Can we make progress on estimates of localised VLM at TGs that cannot be inferred from either GPS Kriging interpolations or GIA models?**
- **Can multi-mission altimetry, TG and inland GPS be used to simultaneously estimate improved vertical land motion at gauge locations, as well as geographically correlated biases in altimetry?**

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 (e.g. ITRF 2008, Altamimi et al. 2011).

- Our observations include the SSH difference (from altimeter minus TG, and tandem/dual altimeter crossovers), each from a distributed network of comparison points (CPs), and GPS height time series.

Method…

- Our state parameters includes:
  - Mission-specific bias drifts.
  - Location-specific VLM trends 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 proper 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 at the TG locations.
- **Solution 2:** Using these initial estimates of altimeter bias drift, we then loosen constraints on VLM at the TG locations – this approach enables investigation of geodetic sites with anomalous VLM.
- **Solution 3:** We then run an optimal solution using a priori estimates of bias drift and VLM from the former solutions, yet we constrain only those TGs exhibiting linear VLM.

Case Study…

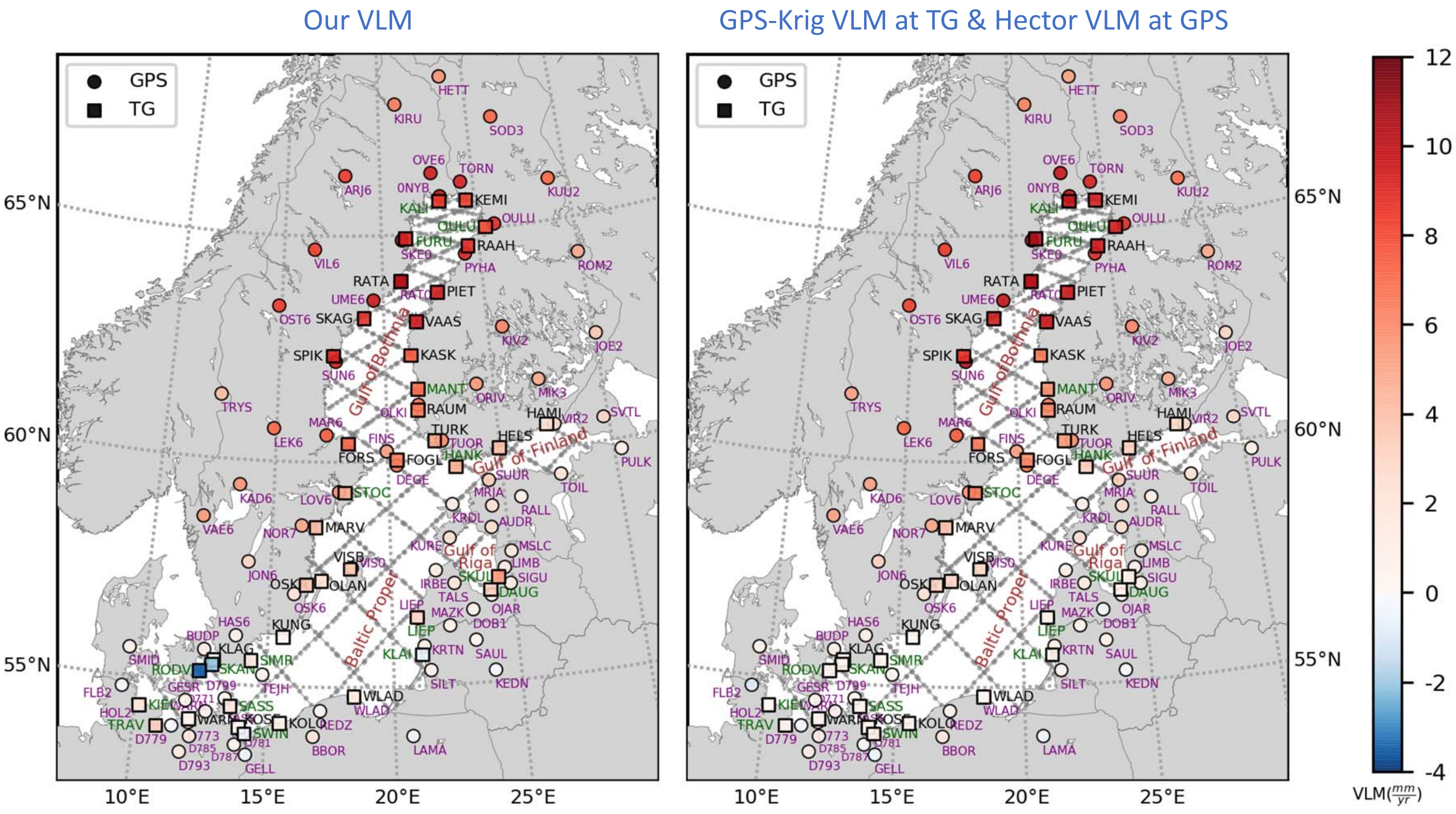
- We investigate the performance of method in the Baltic Sea, where:
  - An array of GPS and TG stations exist.
  - GIA contributes heavily to VLM.

- Our dataset includes:
  - 10-day ASL series from the reference missions (TOPEX, Jason-1, OSTM/Jason-2 and Jason-3) from the RADS database (Scharroo et al., 2012).
  - Hourly RSL data from 41 TGs.
  - Daily ellipsoidal heights from 80 inland GPS sites nearby TGs from NGL Nevada database (Blewit et al., 2018).
  - GIA prediction rates from ICE6G-D model (used for comparison only).

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.



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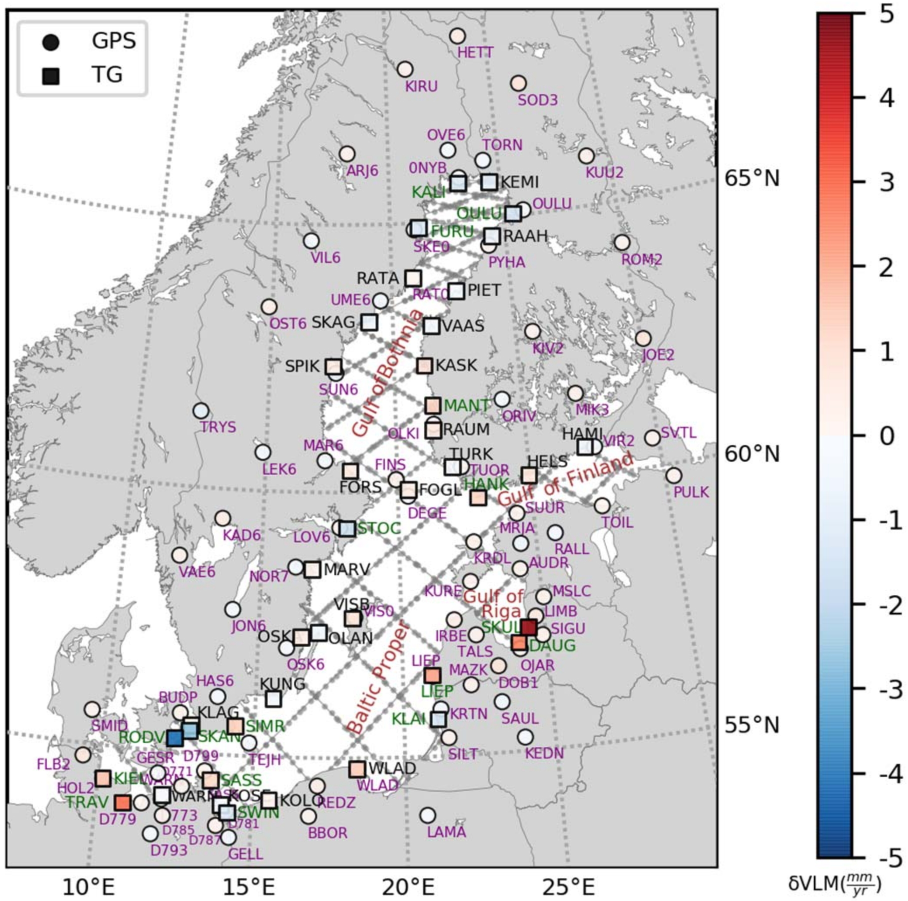
VLM Results (“Ours” minus Interpolated GPS)…

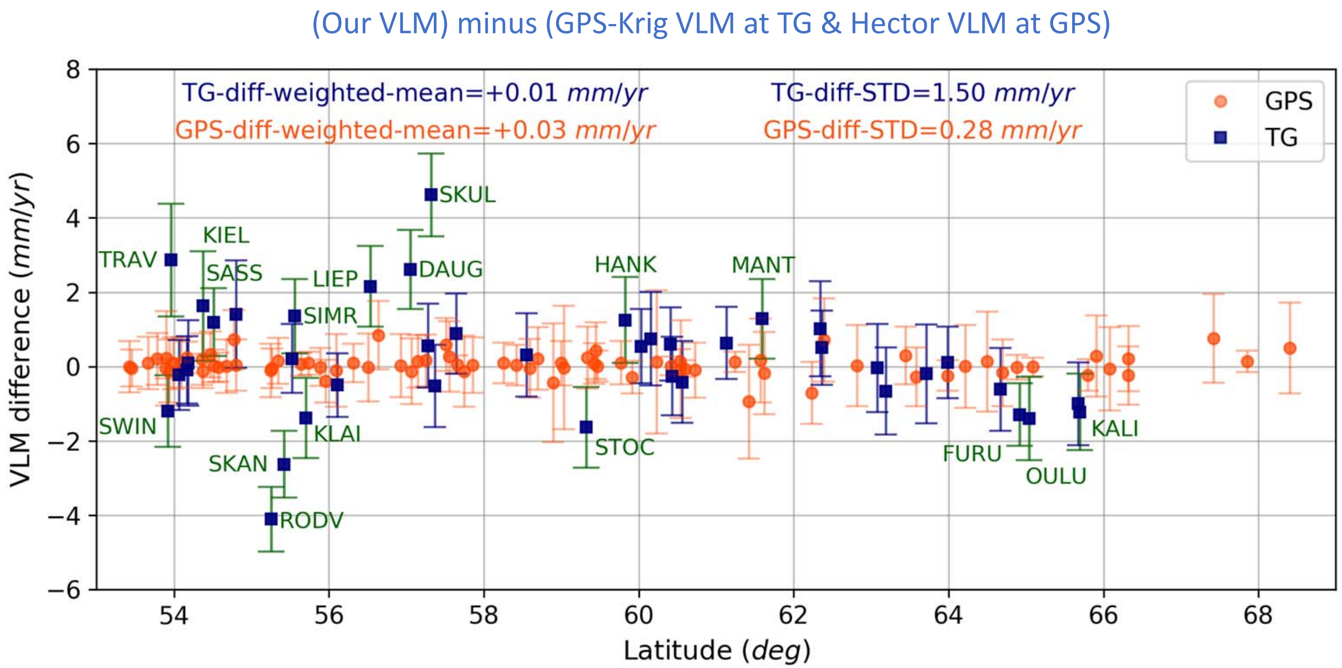
- The difference map shows negligible differences between our VLM and Hector at GPS sites (as expected).
- Significant differences between our VLM and GPS-Krig VLMs at TGs are evident in various locations.
- We perceive localised VLM at some TGs (in middle of Baltic Sea towards the Gulf of Finland, the Gulf of Riga, Baltic Proper and Danish Straits), which cannot be reflected in either GPS-Krig or GIA VLM estimates.

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



VLM Results ("Ours" minus Interpolated GPS)…

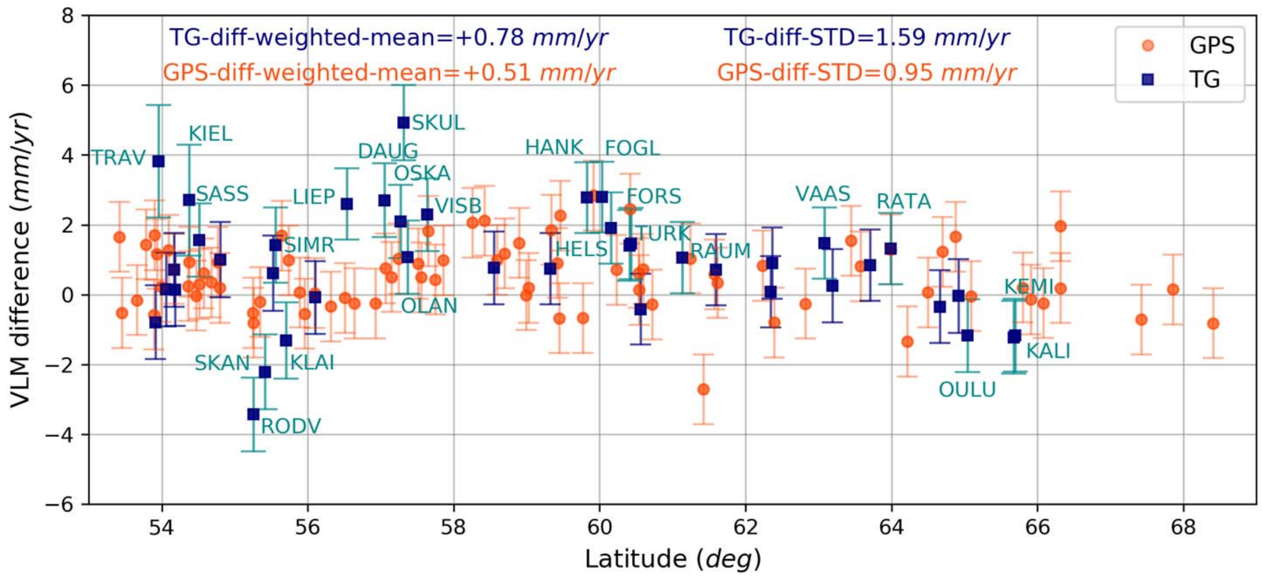
- Differences at GPS sites (orange) show low variability.
- Differences to interpolated GPS at TG show increased variability and significant differences at some TGs (see green labels) suggesting real and localised VLM at these gauges.
- 17 TGs (green labels) have differences significant at the 1-sigma level. These differences range from −4.10 to +4.62 mm/yr.



VLM Results ("Ours" minus GIA)…

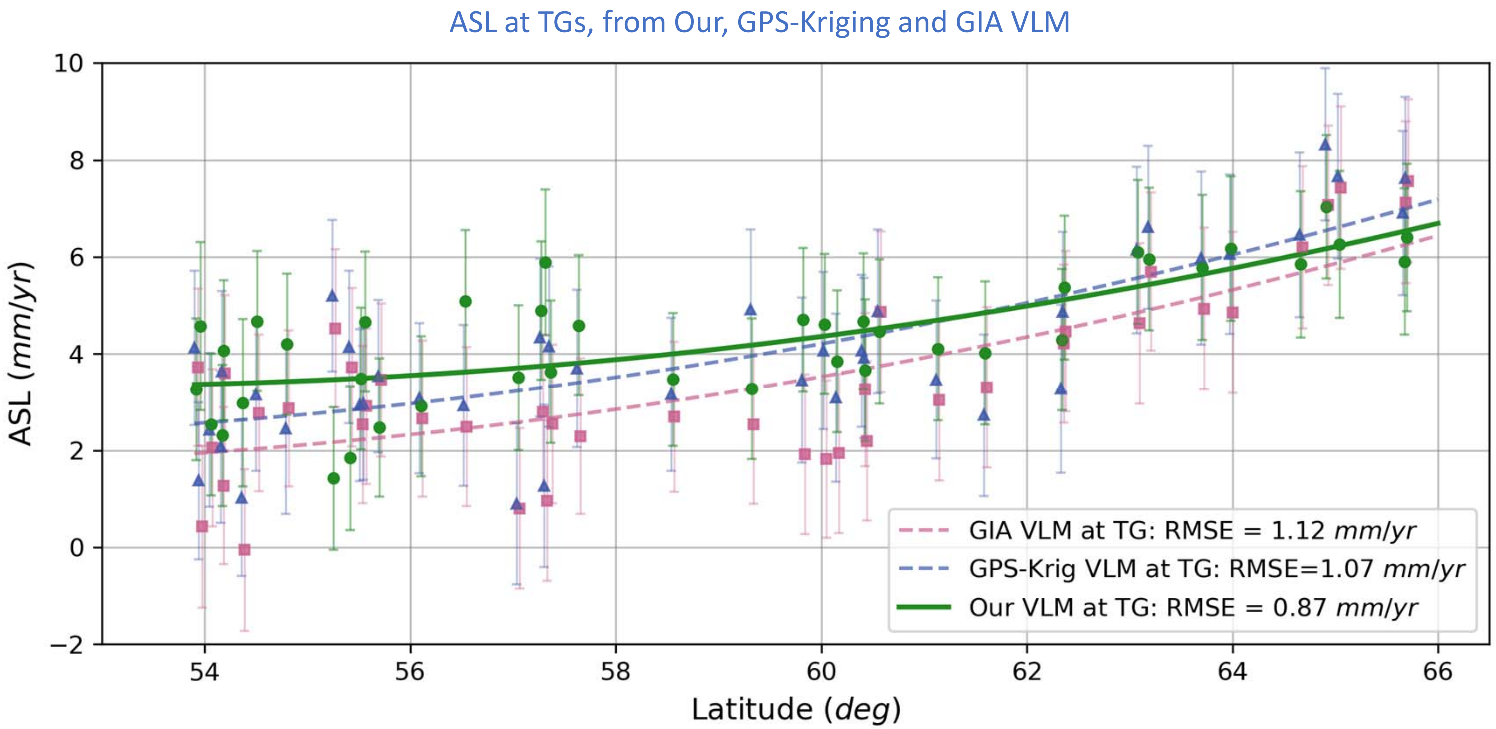
- Comparison with GIA shows a small positive bias of ICE6G-D GIA with respect to our VLM values.
- Non-GIA patterns of motion emerging in the southern region.
- Significant differences (1-sigma) at TGs shown with cyan labels. Challenging to assess uncertainty given formal errors.

(Our VLM) minus (GIA VLM)



Impact of VLM on ASL at Tide Gauges

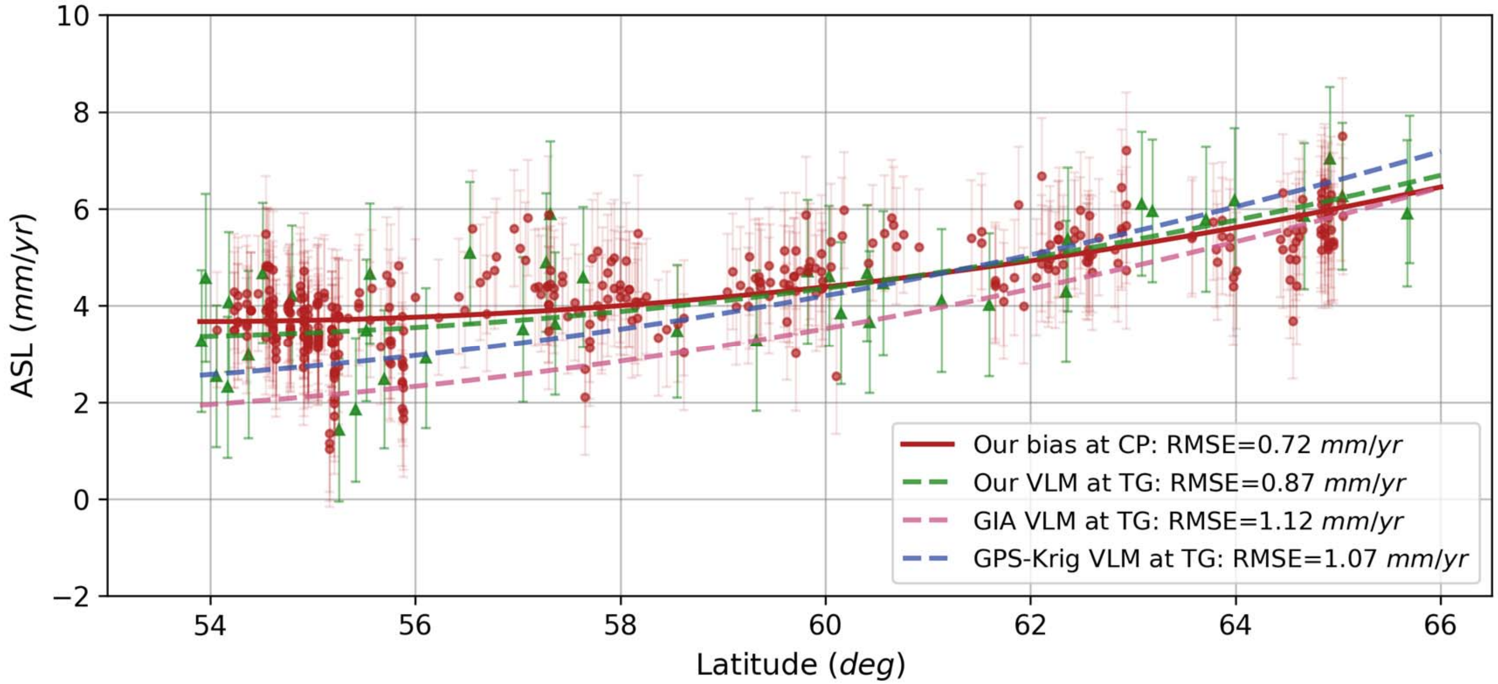
- ASL trend is known to vary with latitude in the Baltic (e.g. Madsen et al. 2019).
- Here we estimate ASL from TGs over the altimeter era using different VLM (GIA, interpolated GPS and from our solution).
- Note the scatter of ASL trends about a simple quadratic polynomial with latitude is a minimum for our VLM solution. Implies we are capturing local land motion in our solution.



ASL at Tide Gauges 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.

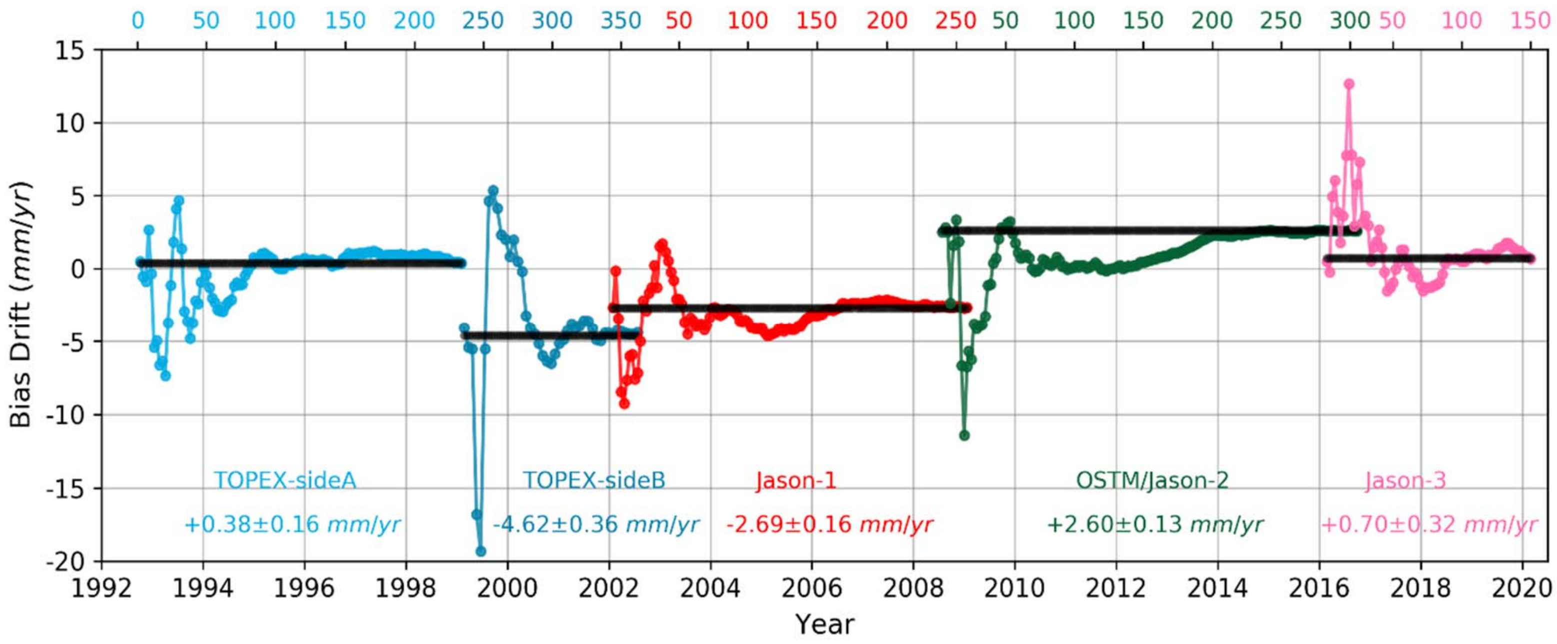
ASL at altimetry CPs vs. ASL at TGs, from Our, GPS-Kriging and GIA VLM



Mission-specific Systematic Errors in Altimetry…

- Relatively tight process noise enables subtle evolution in time of this mission-specific parameter in the forward solution.
- The return smoothing pass effectively constrains the variables to derive time-fixed estimates.
- Forward and backward estimates show convergence after ~2.5 years.
- Long convergence time for OSTM/Jason-2 highlights potential increased variability.

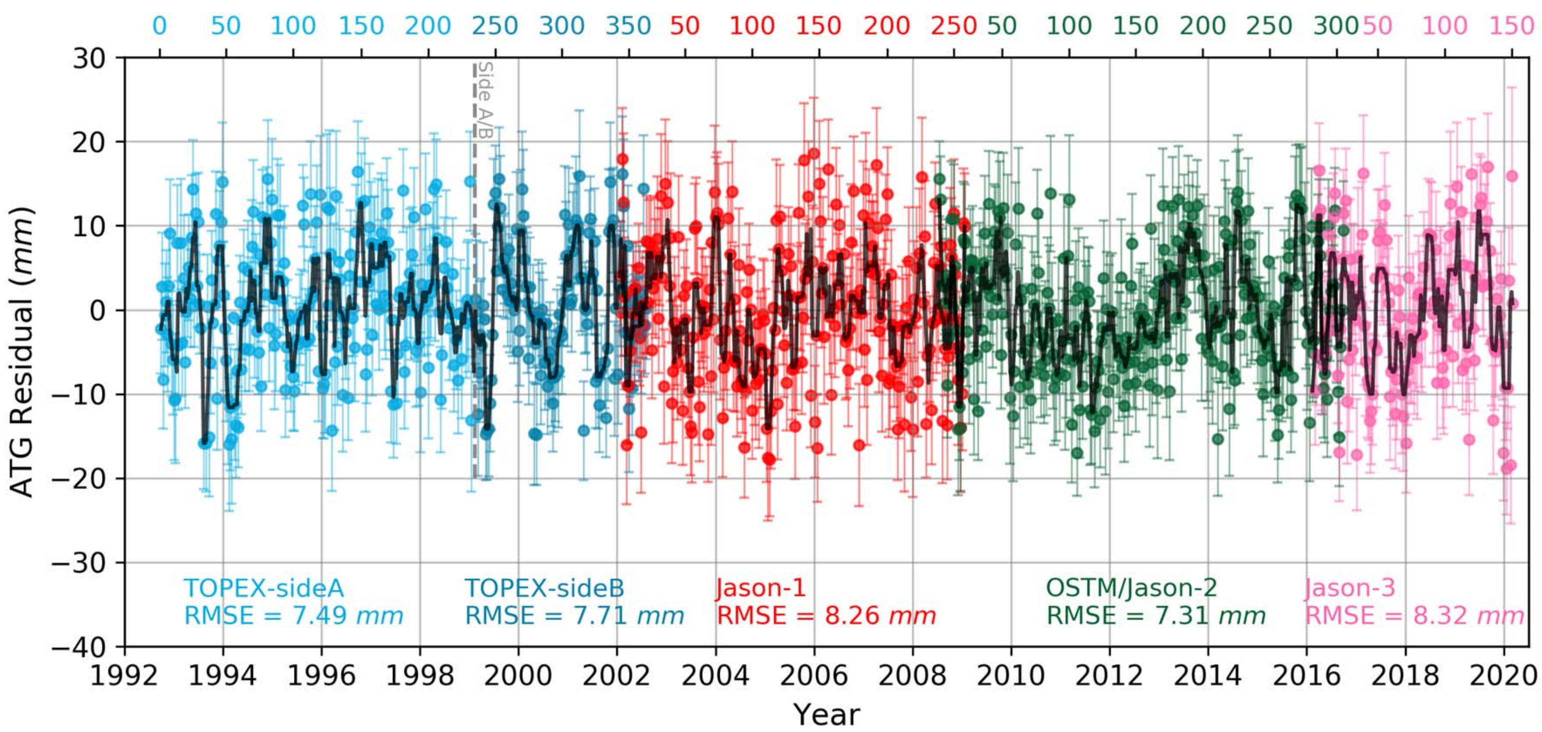
Potential systematic errors in the reference mission altimetry



ALT-TG Residuals…

- 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 may point to regional orbit differences.

Cycle-by-cycle weighted average of ATG residuals



Conclusions and Outlook…

- Numerical results suggest that the method can effectively estimate improved VLM at TGs using altimeter data.
- Simultaneous estimation of small but significant mission-specific biases in altimetry helps to improve our solutions.
- The method offers a flexible framework that considers proper treatment of measurement noise and spatio-temporal correlation.
- Appropriate tuning of the filter is critical and depends on our assumptions and characteristics of the study region.
- Next steps include inclusion of non-reference missions (e.g. ERS/Envisat, Sentinel-3A/B) and expansion to global solutions.
- Paper in preparation for submission.

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Acknowledgements …

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