Resolving millimeter-level storm surge loading deformations using multi-GNSS data over the subdaily timescales

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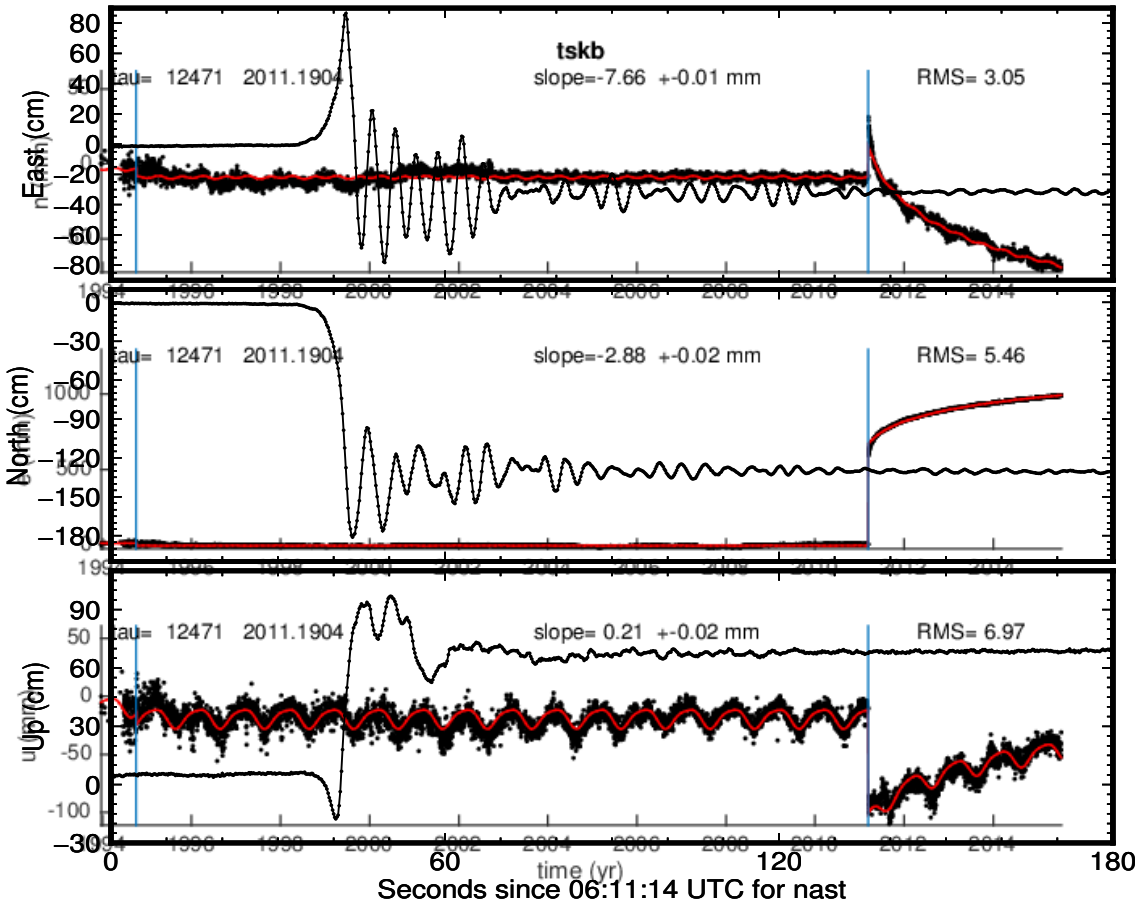
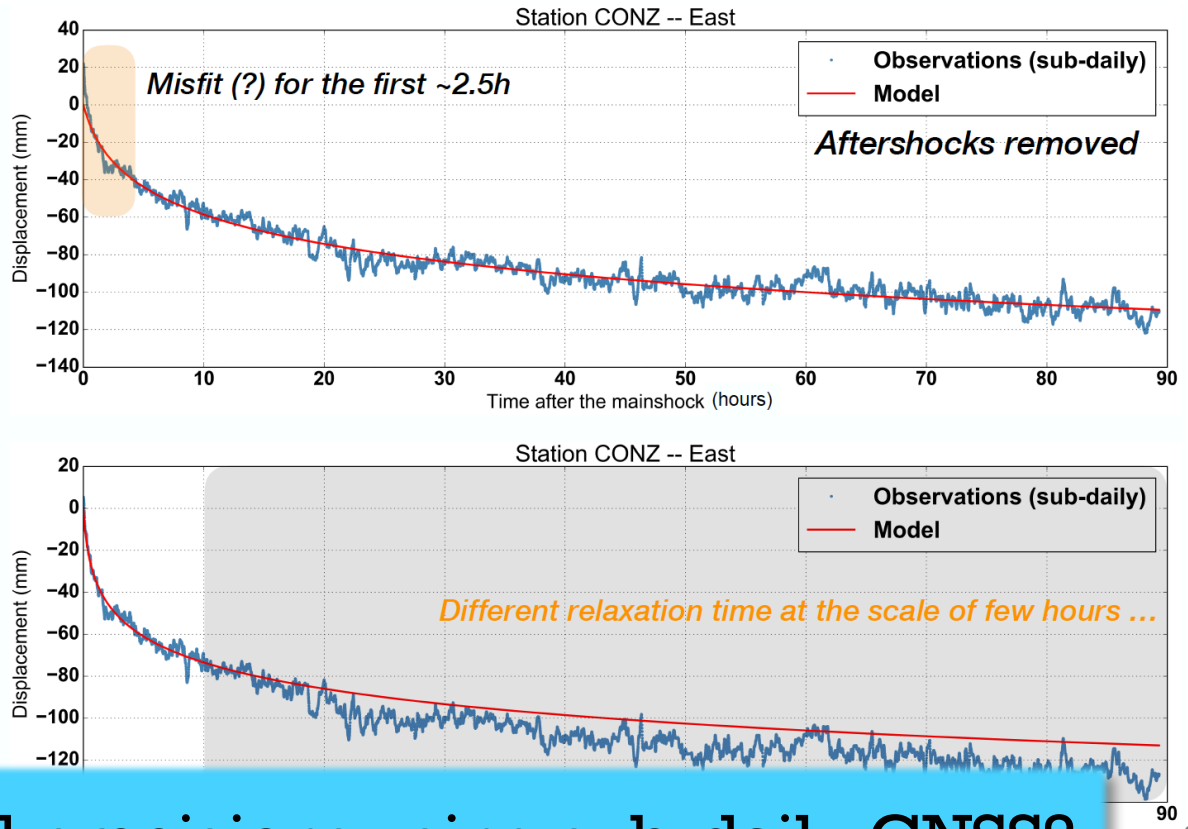
Daily GPS and high-rate GPS for crustal motions

- 24-hour solutions for tens of days, weeks or even years
  - Typical precision: 1-2 mm for east/north while 3-5 mm for up
  - Contribute to inter-seismic, post-seismic, ETS, creep events, etc.
- 1-10 Hz solutions for a few minutes
  - Typical precision: 2-3 cm for east/north while 5-10 cm for up
  - Contribute to co-seismic events (>M6), etc.



Motivation: improving sub-daily GNSS precisions

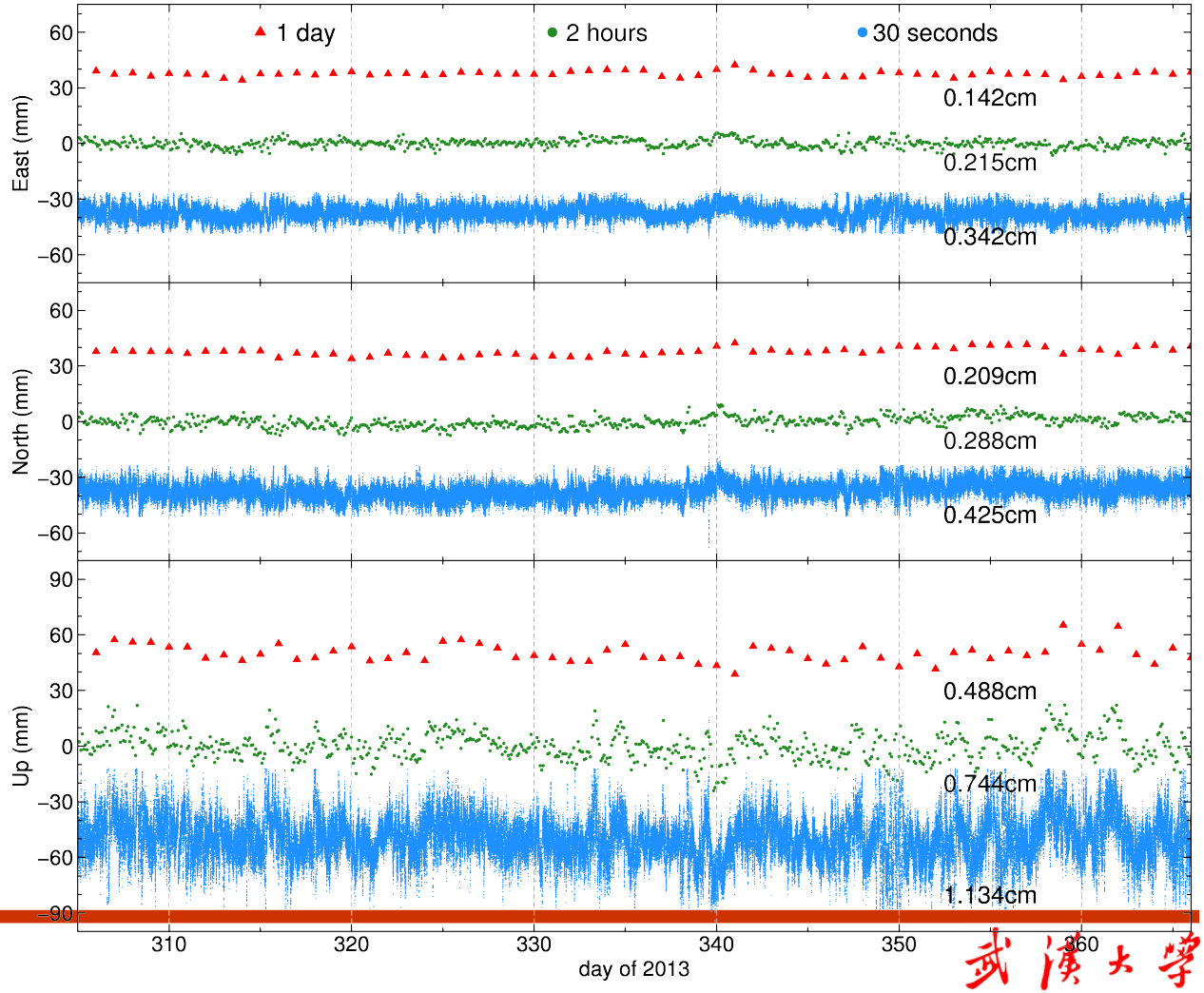
- "Slow" transient events
  - Very early post-seismic, pre-eruption volcanic unrest, etc.
  - Daily GPS: no sufficient resolution
  - hr-GPS: not precise enough
- Sub-daily GPS/GNSS
  - Resolve positions every tens of min. or few hours
  - No need for high-rate data or epoch-wise solutions



Can we achieve mm-level precisions using sub-daily GNSS?

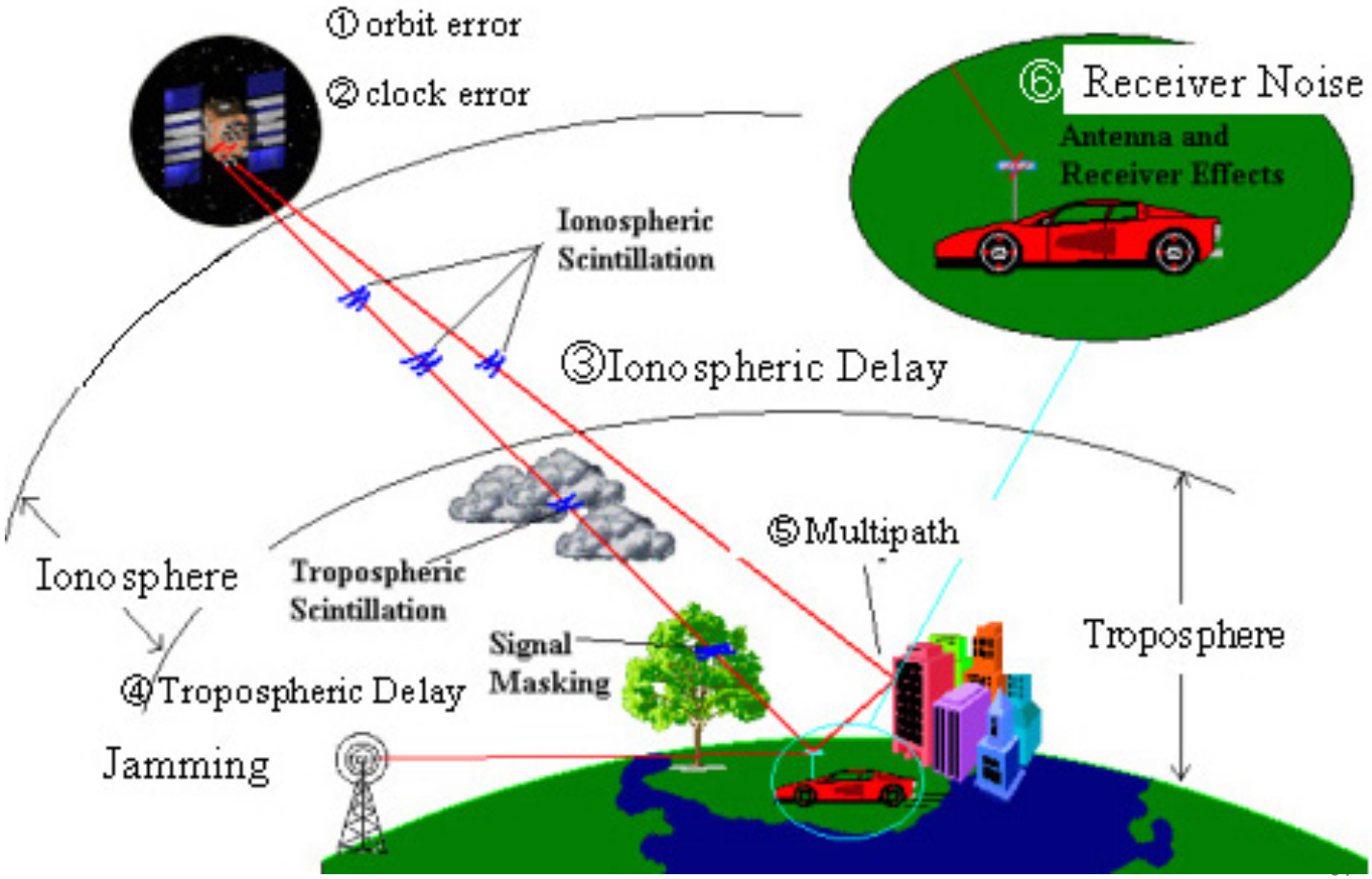
Comparison among 24-h, epoch-wise and sub-daily GNSS

- Noisier in case of shorter estimate intervals
- Longer-period errors remain even after we increase the estimation intervals
- Make sub-daily GNSS comparable to daily GNSS?



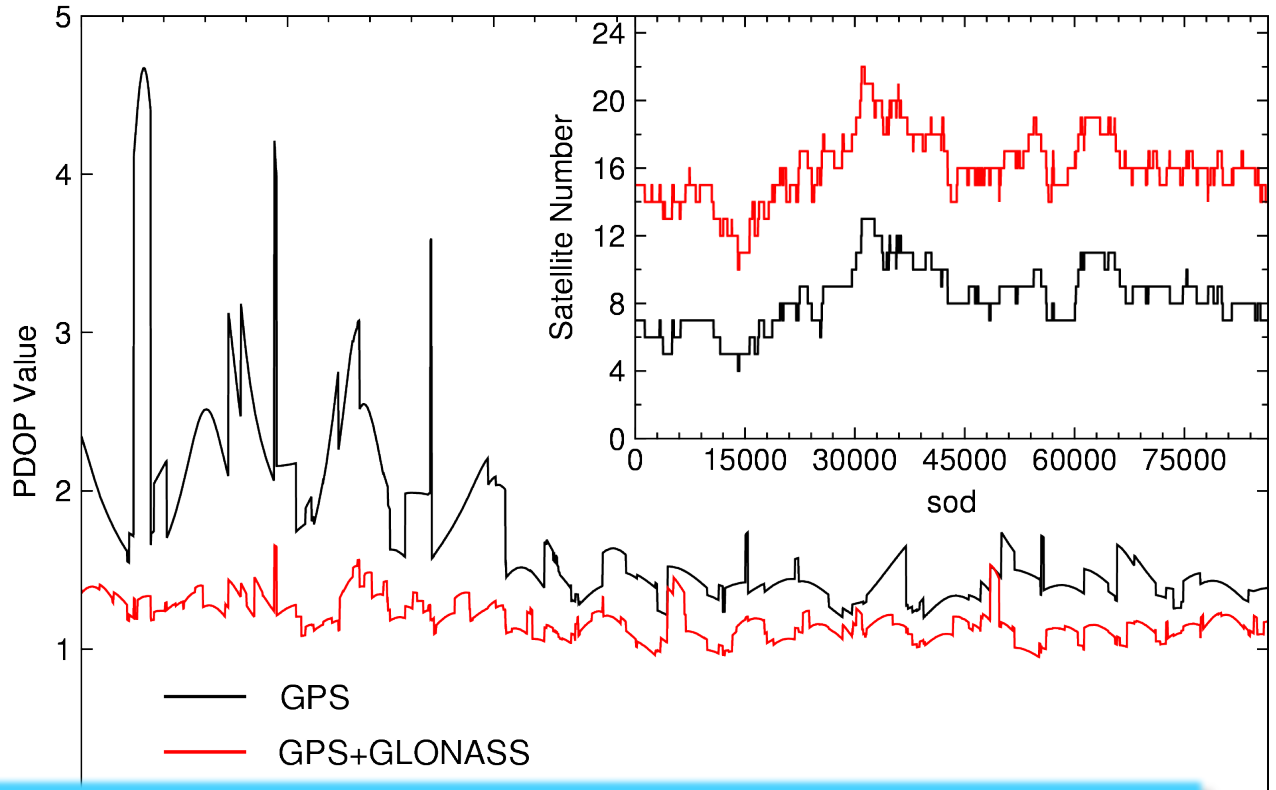
Errors to be mitigated for sub-daily GNSS

- Orbit, multipath, atmosphere errors are dominant for long periods
- Mitigation strategy
  - Multi-GNSS integration
  - Orbital repeat time (ORT) filtering
  - Resolve ambiguities & troposphere delays using 24-hour data
  - Higher-order ionosphere modeling



Data: GPS+GLONASS

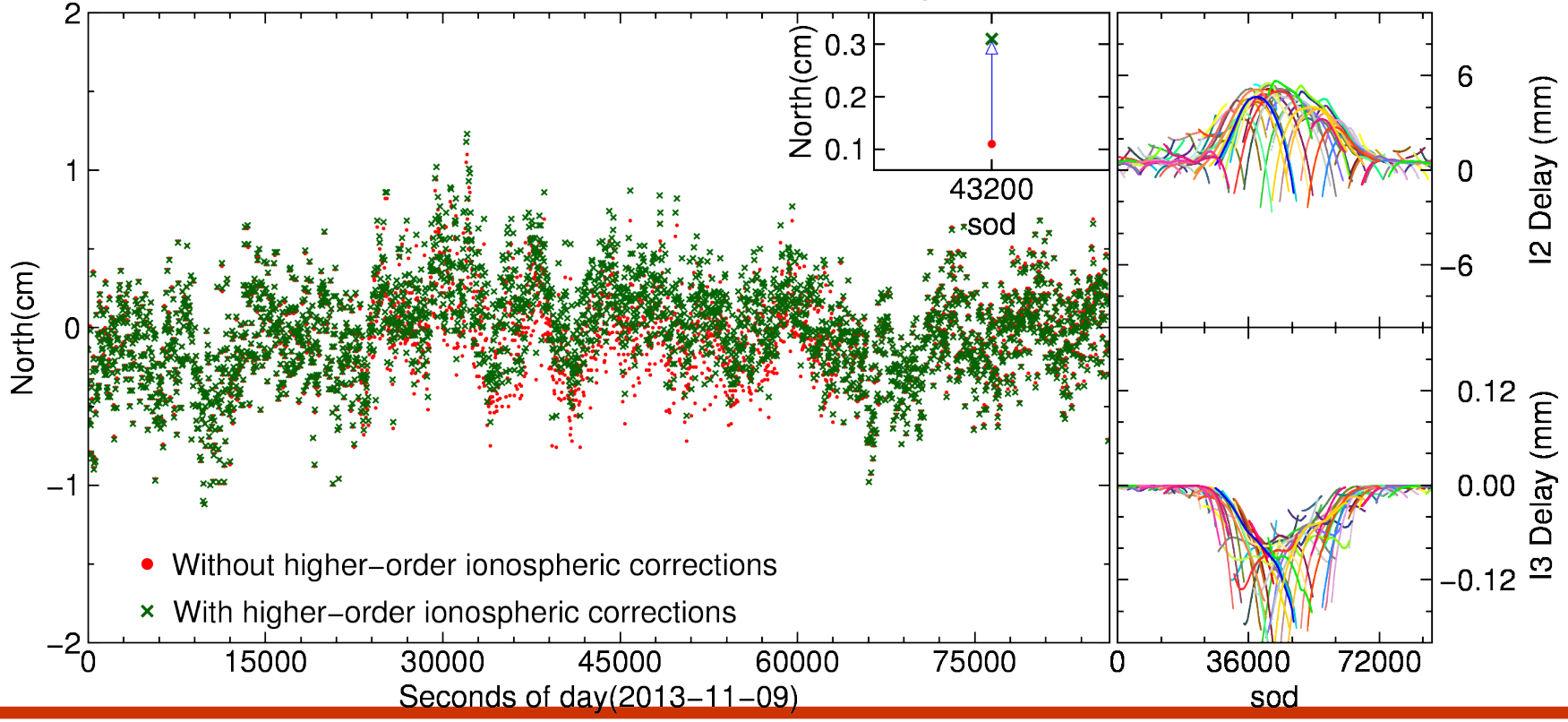
- 61days: Nov. 1–Dec. 31, 2013
- 33 GPS/GLONASS stations
- 30-s sampling rate
- Precise point positioning
- Zero-diff. ambiguity fixing
  - GPS
  - GLONASS
- Re-estimate satellite clocks



The more GNSS satellites, the better geometry and precisions

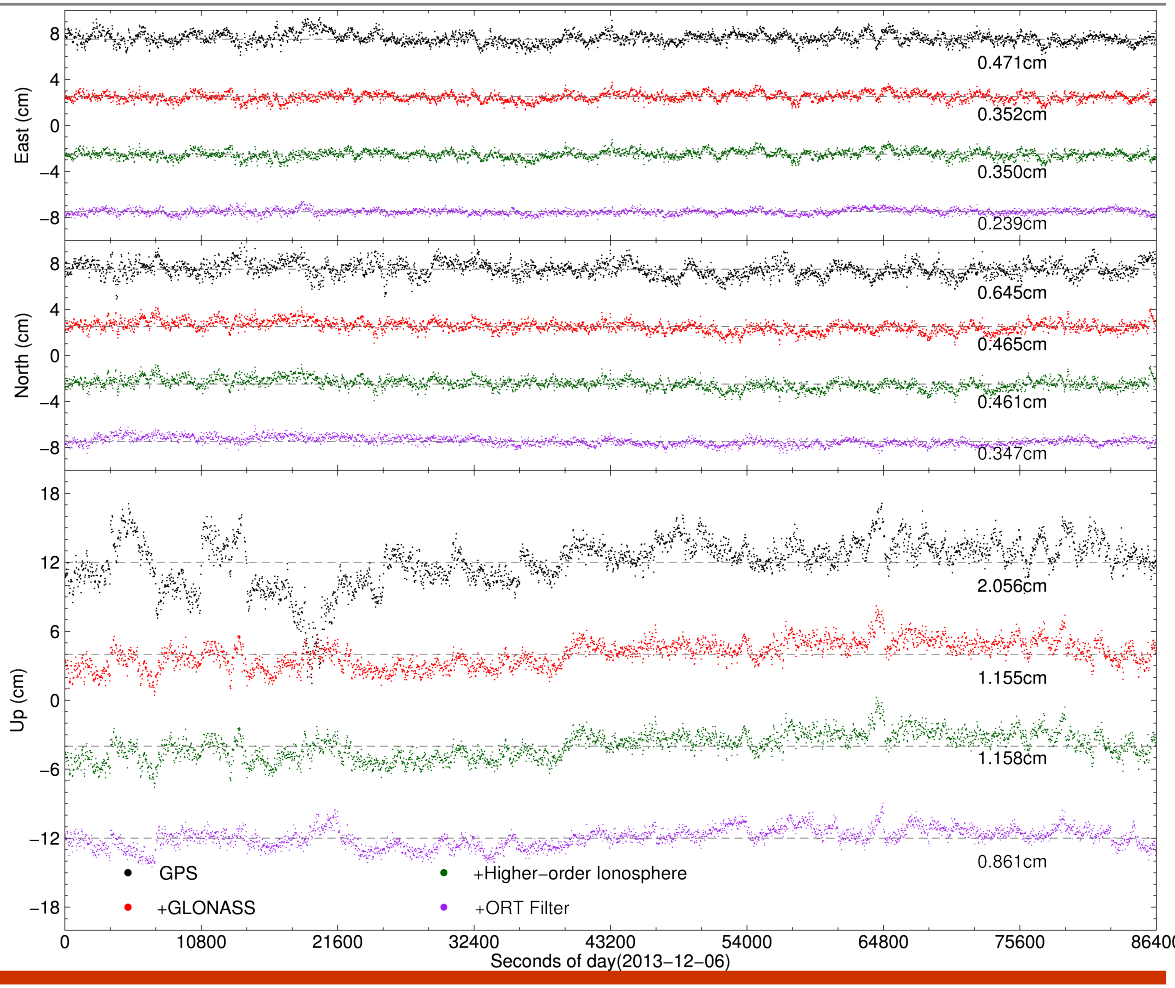
Corrections: higher-order ionosphere delays

- I2 delays can reach 6 mm and I3 can reach 0.2 mm
- Epoch-wise variation in the north is most significant



How do these affect displacements: hr-GNSS demonstration

- Improving precision by
  - integrating GLONASS
  - correcting for higher-order ionosphere delays
  - applying ORT filtering
- Finally, improved from (0.47, 0.65, 2.06) cm to (0.24, 0.35, 0.86) cm for epoch-wise displacements

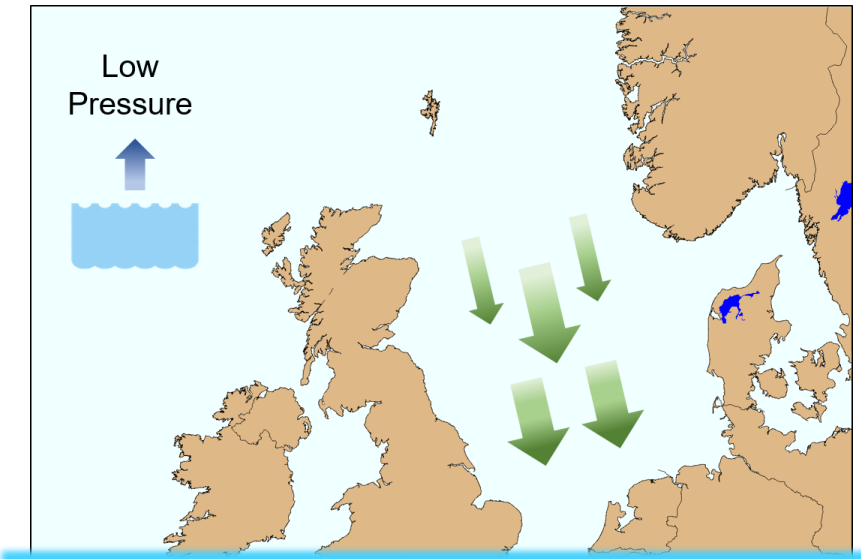


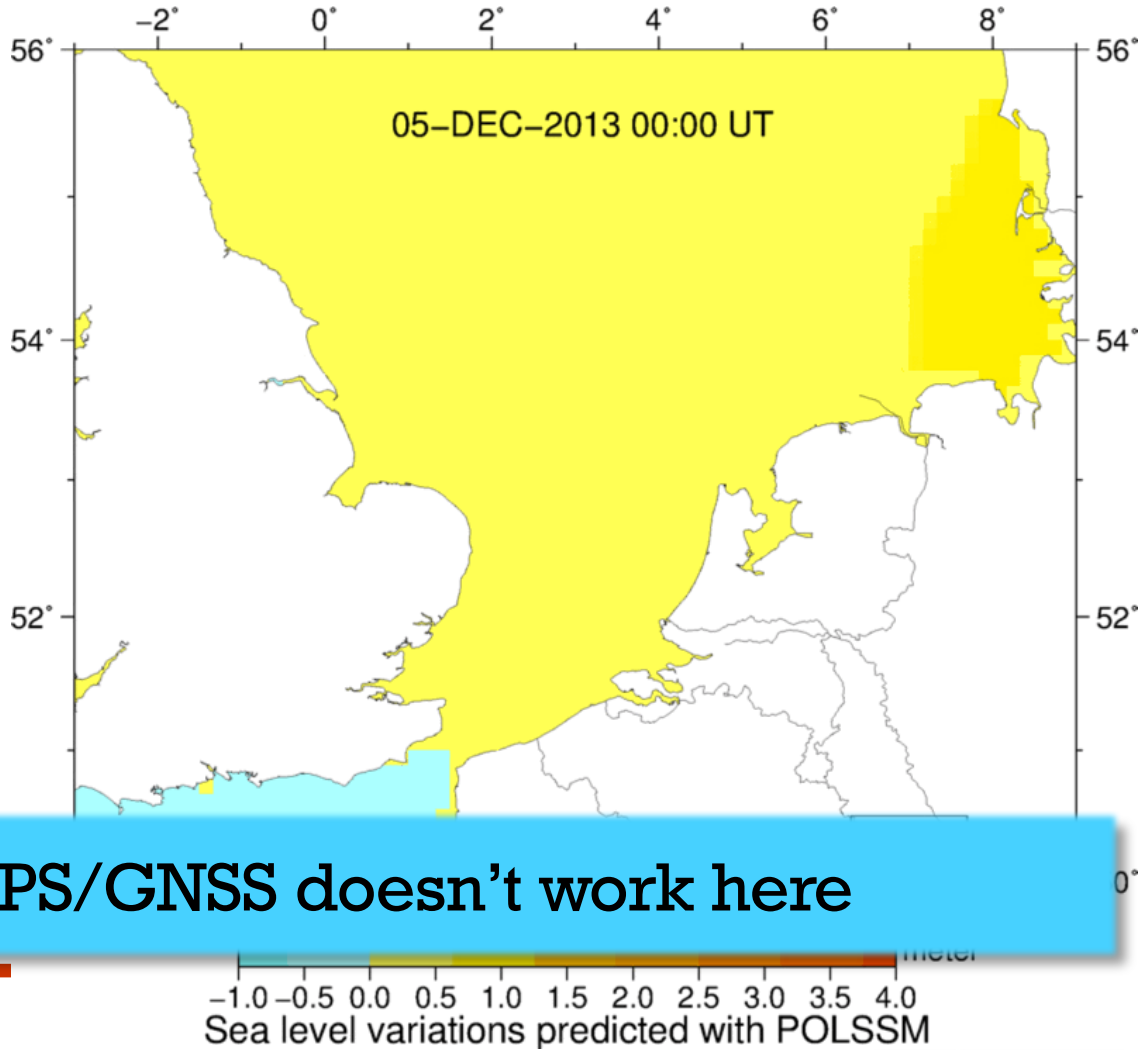
Then, overall statistics for 2-hourly solutions

ID	Solution types	Mean Difference RMS (mm)			Mean Improvement Rate (Compared with the former one)	
		E	N	U	Horizontal	Vertical
1	GPS	2.46	3.25	8.19	-	-
2	+GLONASS	2.41	2.95	6.88	6.5%	16%
3	+Higher-order ionosphere corrections	2.39	2.89	6.86	1.5%	0.1%
4	+ORT filter	2.26	2.71	6.19	5.5%	10%

Case study: the Dec. 5, 2013 storm surge event

- The evolution of sea levels over 48 hours (Dec. 5-6, 2013)
- Sea level anomaly of up to 4 m

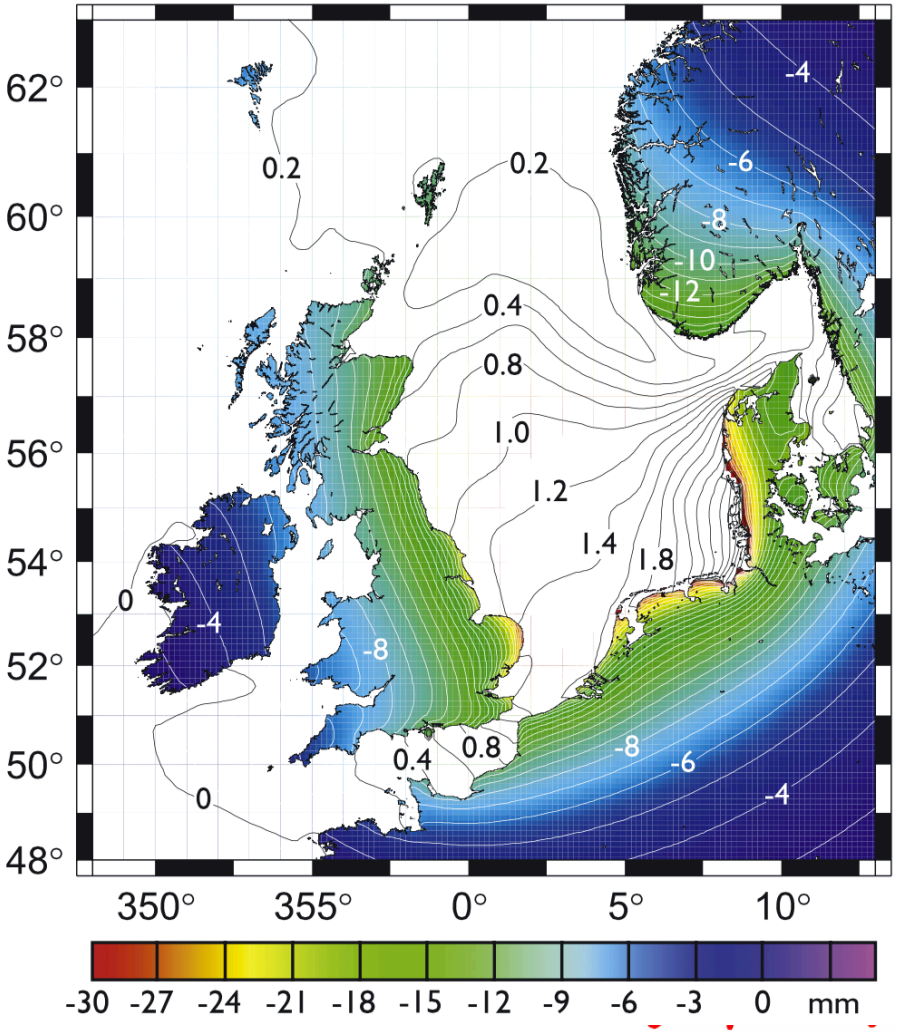




Daily or high-rate GPS/GNSS doesn't work here

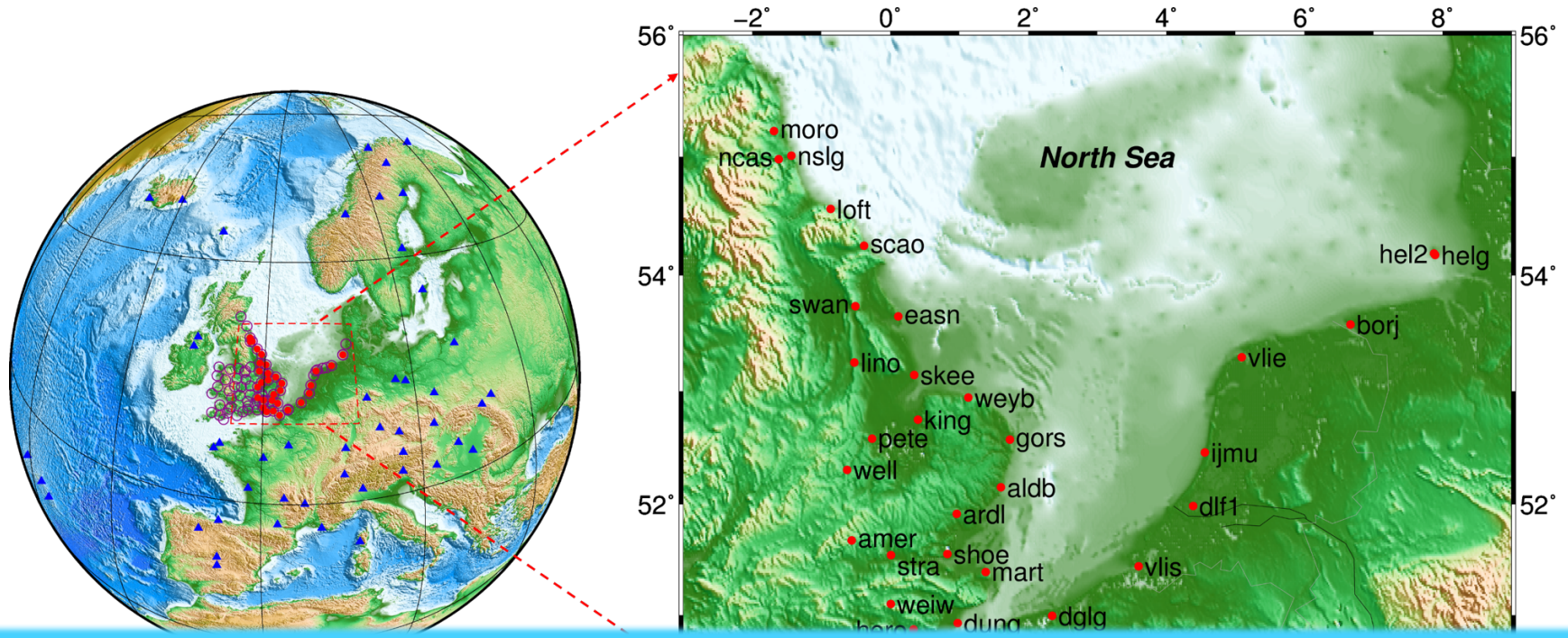
Predicted loading displacements: POLSSM

- Proudman Oceanographic Laboratory Storm Surge Model (POLSSM)
  - Fratepietro et al. (2006)
  - Non-tidal hourly sea levels for the NW European continental shelf
  - 12 km grid across the North Sea
  - Predicted sea level error: ~10 cm
  - Convolving the predicted sea levels with the Green's functions in the CE frame (Farrell 1972)
  - Predicted loading displacement error: nominally sub-mm level



Case study: the Dec. 5, 2013 storm surge event

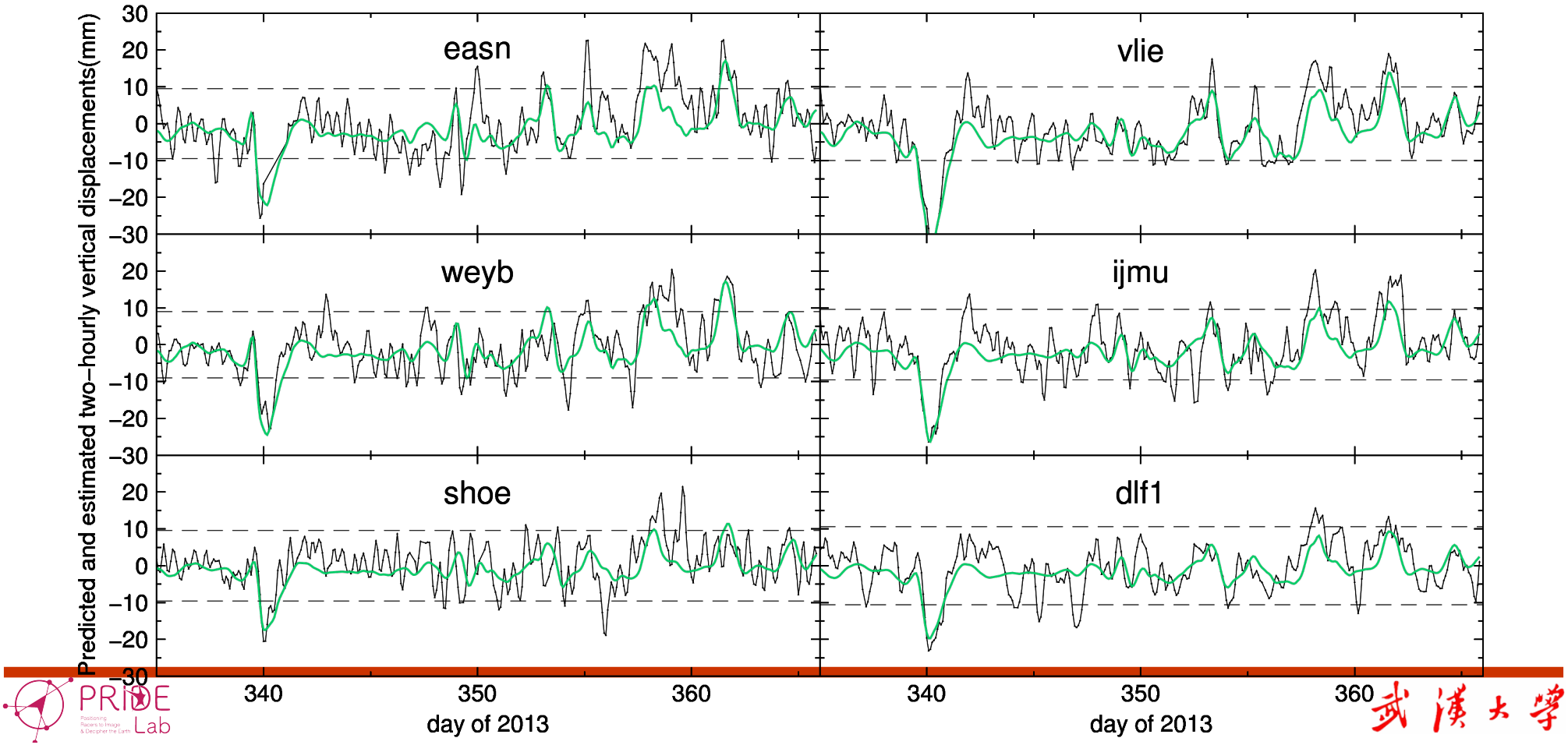
- Sea level changes of up to a few meters over several hours



Let's try sub-daily (2-hourly) GNSS instead

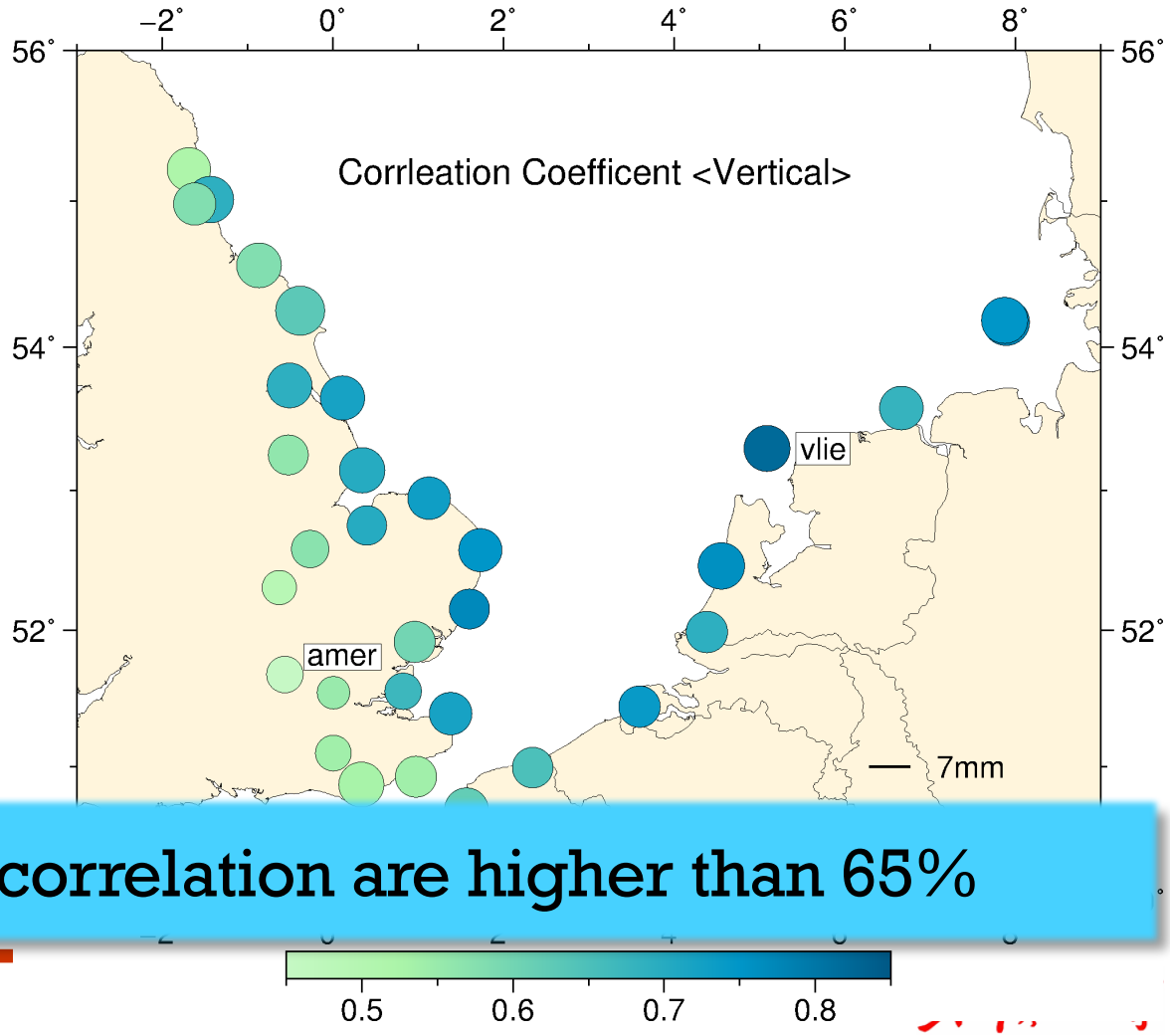
Vertical displacements

- Vertical displacement time series at 6 stations spanning 30 days in Dec.



Vertical displacements

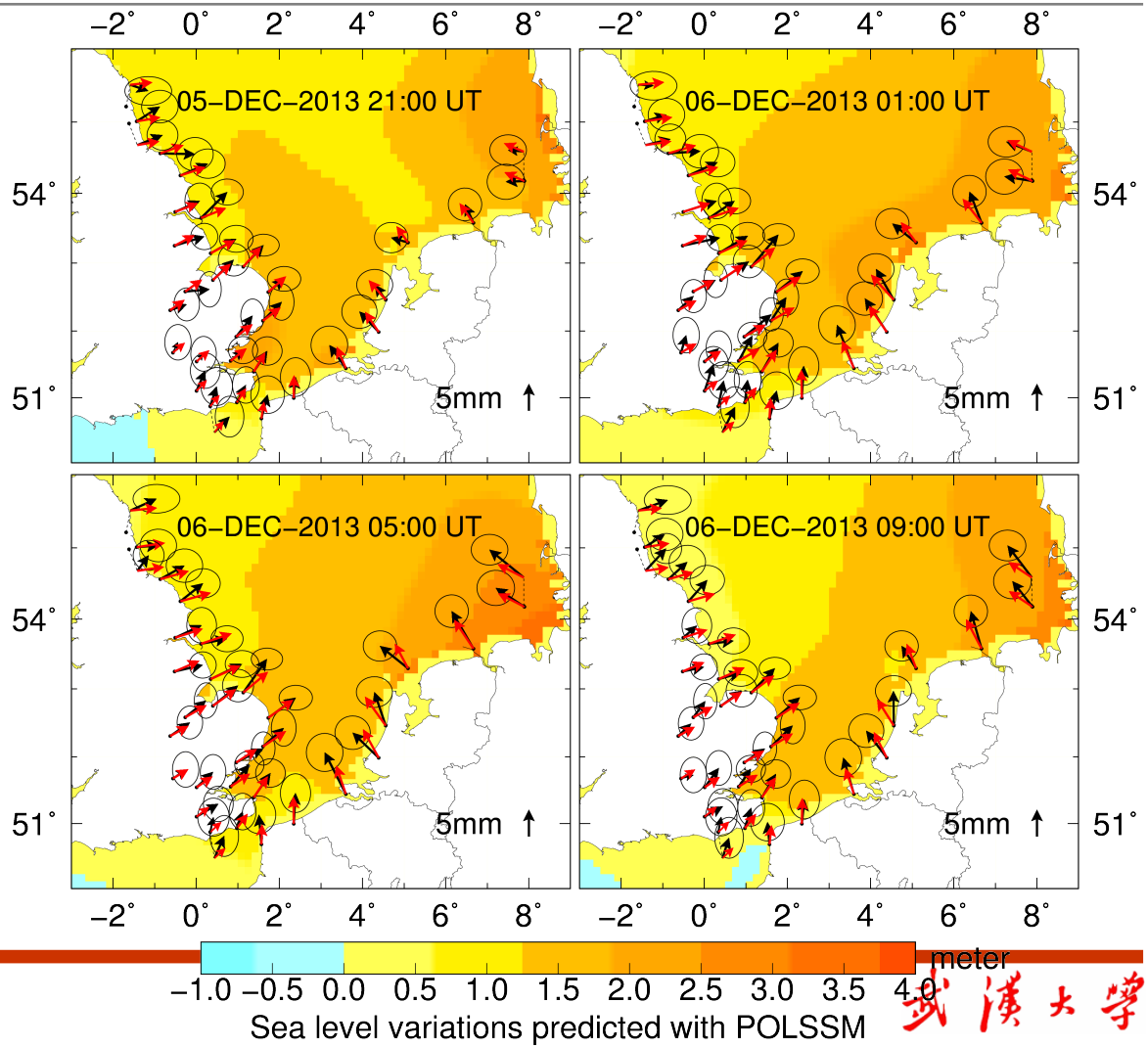
- Correlation coefficients between estimated and predicted displacements
- Higher correlations at coastal stations



The average vertical correlation are higher than 65%

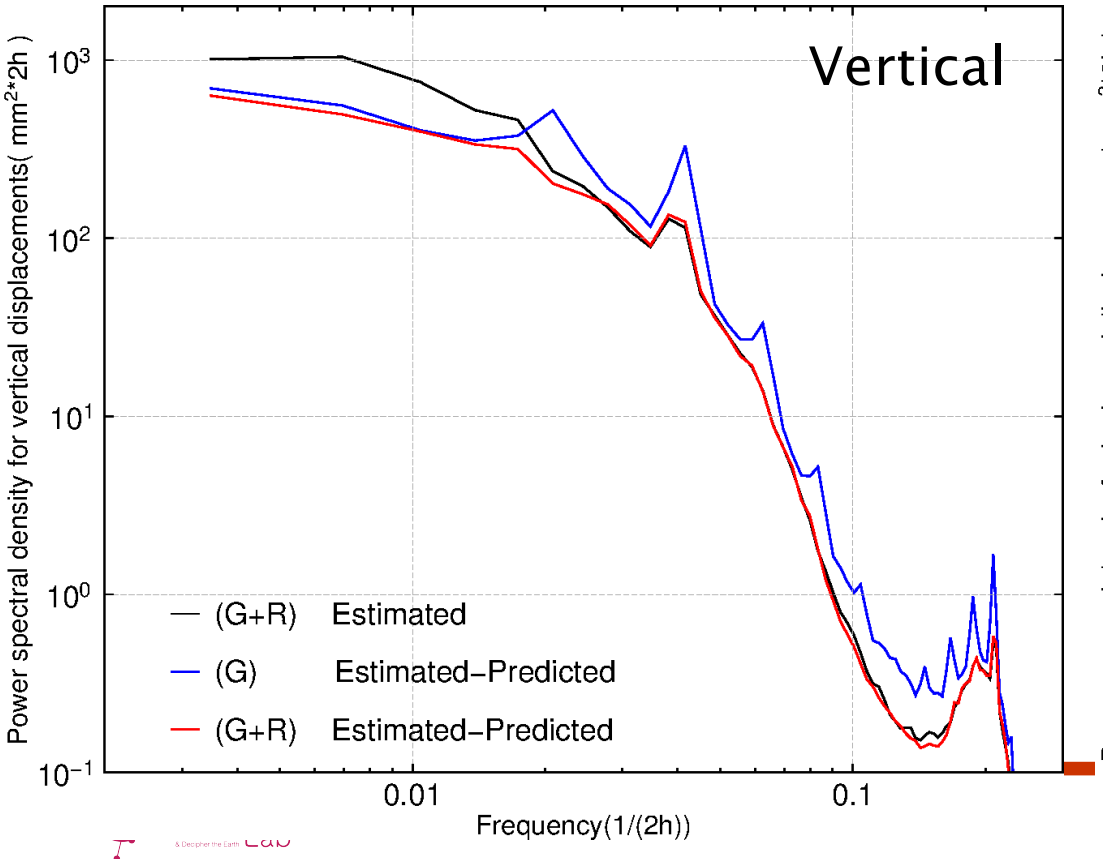
Horizontal displacements

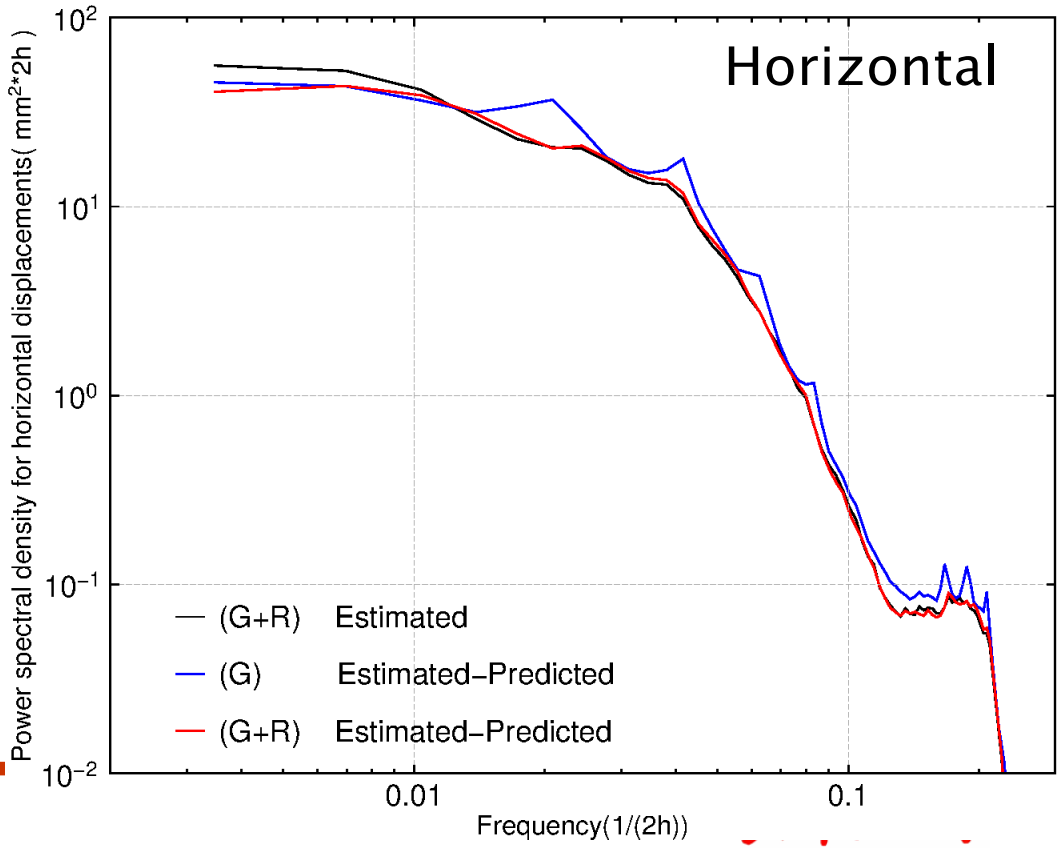
- Horizontal displacements at 21:00, 1:00, 5:00 and 9:00 from Dec 5-6, 2013
- The estimated and predicted displacements correlated well in both phase and amplitude



What about frequency domain?

- Multi-GNSS ORT filtering for higher precision over a broad frequency band
- 2-h time series most correlated with POLSSM predictions over >4 d periods





Conclusions and suggestions

- Improving the precision of subdaily GNSS
  - Multi-GNSS: 6.5% (horizontal) and 16% (vertical)
  - Higher-order ionospheric correction: 1.5% (horizontal)
  - The ORT filter: 5.5% (horizontal) and 10% (vertical)
- Sub-daily GNSS can capture mm-level loading deformations
  - The RMS of the 2-h time series are 2.4 mm (East), 2.9 mm (North) and 7.4 mm (Up)
- More GNSS can be included
- What's the major barrier to further improving sub-daily GNSS?
  - Atmosphere? Orbit?

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Thank you

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