Assessment of individual and combined gravity field solutions from Swarm GPS data and mitigation of systematic errors

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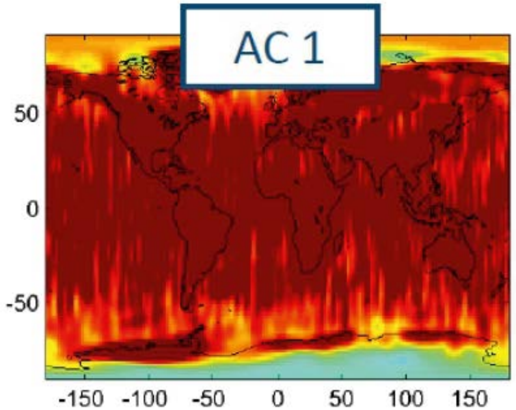
Availability of Swarm Gravity Field Solutions

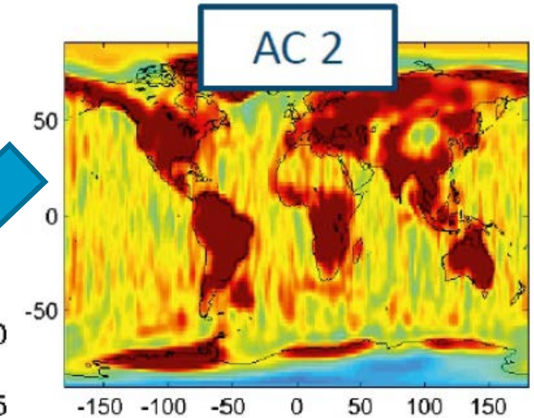
Analysis Center	Gravity Field Solutions	
Astronomical Institute, University of Bern AIUB	Celestial Mechanics Approach	– AIUB KIN Orbits
Astronomical Institute Czech Academy of Science ASU	Accceleration Approach	– AIUB KIN Orbits – IFG KIN Orbits – TU Delft KIN Orbits
Institute of Geodesy TU Graz IFG	Short-Arc Approach	– AIUB Orbits – IFG Orbits – TU Delft Orbits
Institute of Geodesy and Geoinformation University of Bonn IGG	Short-Arc Approach	– TU Delft Orbits

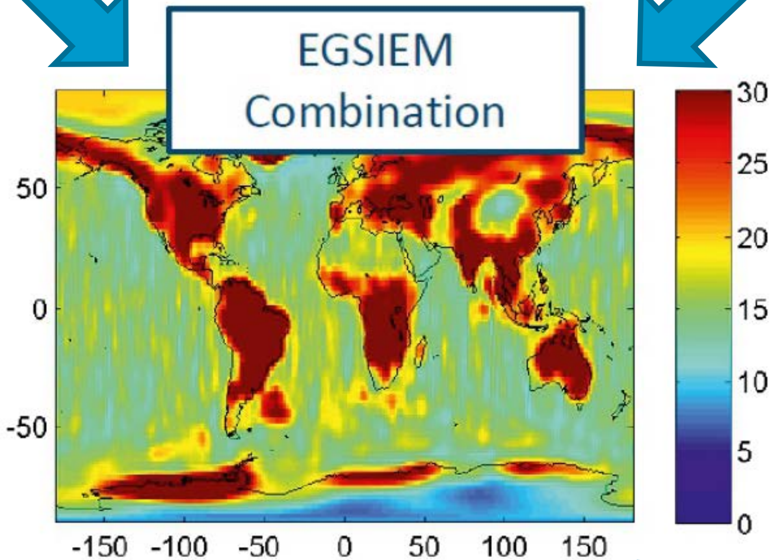
Analysis Centers (AC) are computing monthly Swarm Gravity Field Solutions using different approaches and different GPS-based kinematic orbit solutions. Gravity Field Solutions from additional AC are expected in the near future.

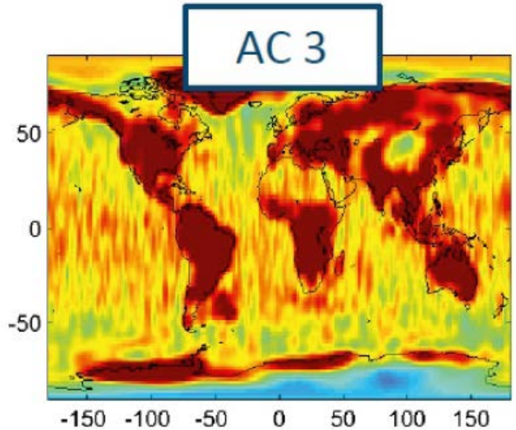
Improving Gravity Field Solutions by Combination

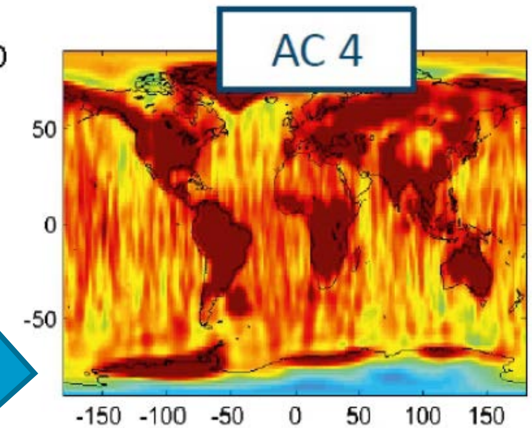
Combination Service of Time-variable Gravity Field Solutions (COST-G)





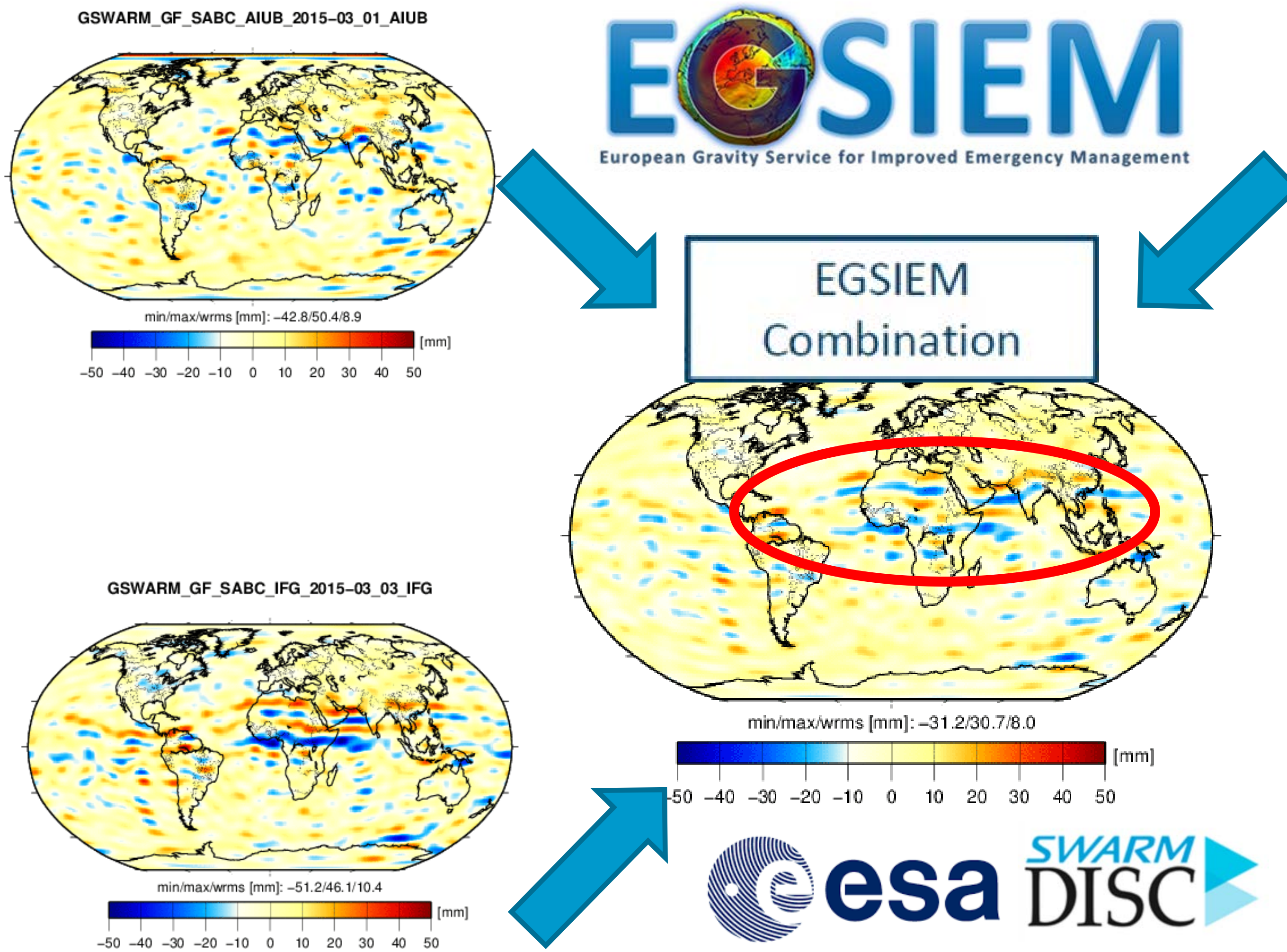






- Only one product for the user
- Reduced noise

Improving Gravity Field Solutions by Combination



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For Swarm

- not only the noise reduction is relevant (next 4 slides)
- in particular also the reduction of systematic errors (final slides)

Variance Component Estimation

The framework of Variance Component Estimation (VCE) is adopted to the individual gravity field solutions to compute combined solutions by a simple weighted average from *n* individual input solutions. The following explicit formulas result:

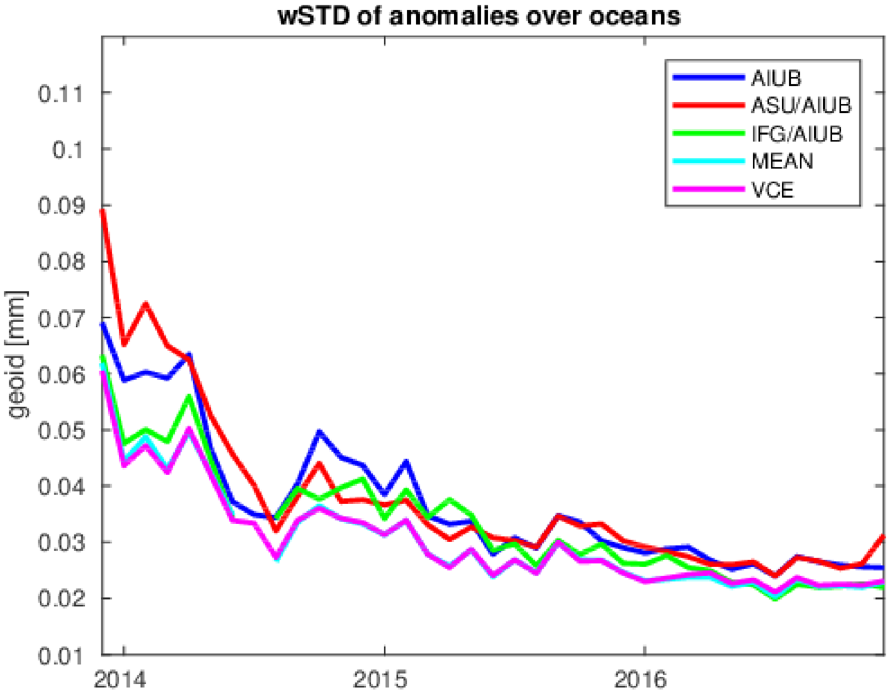
Iteration 0: $\hat{\mathbf{x}}_0 = \frac{1}{n}\sum_k \mathbf{x}_k$ with $w_{k,0} = \frac{1}{n} \quad \forall k, \; k = 1, \ldots, n$

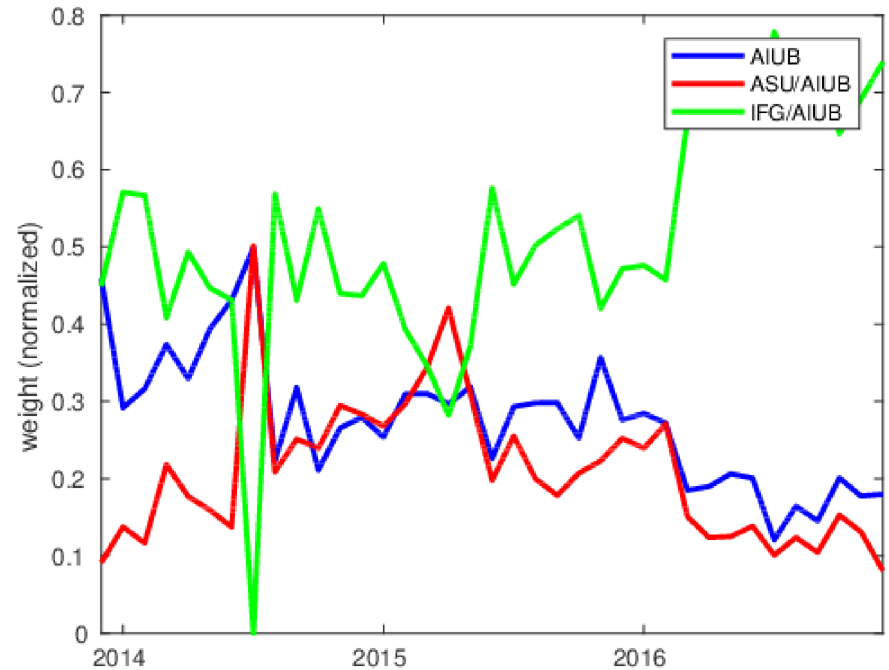
Iteration $i > 0$: $\hat{\mathbf{x}}_i = \frac{1}{\sum_k w_{k,i}} \sum_k w_{k,i}\mathbf{x}_k$ with $w_{k,i} = (1 - \frac{w_{k,i-1}}{\sum_k w_{k,i-1}}) / \mathrm{RMS}(\mathbf{d}_{k,i-1})^2$,

$\mathbf{d}_{k,i-1} = \mathbf{x}_k - \hat{\mathbf{x}}_{i-1}$ Differences to the combined solution $\hat{\mathbf{x}}_{i-1}$ from the previous iteration

Note that iteration 0 is equivalent to a simple average, iteration 1 is equivalent to the simple weighted average. Further iterations are required until the procedure converges.

Combination: use of the same orbits

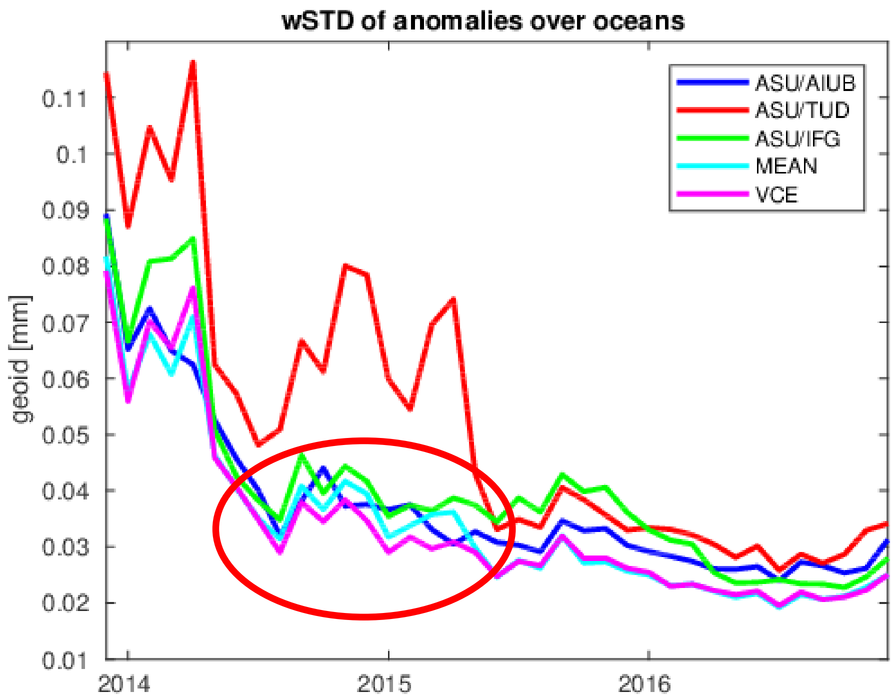


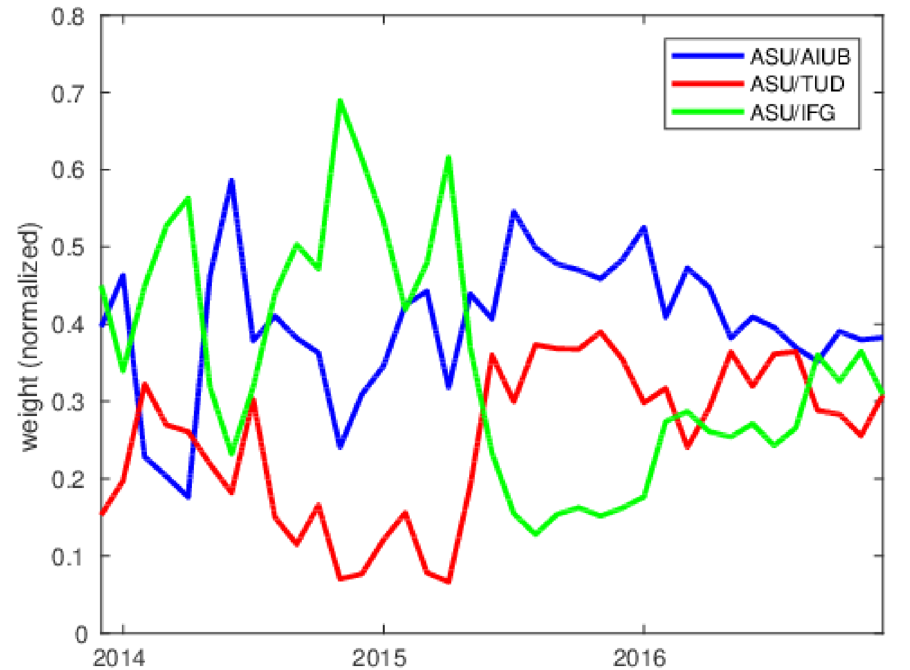


Test case: all solutions based on AIUB orbits:

- Combined solutions show lower noise than individual solutions
- Almost no difference between simple average and weighted average
- Weights suggest best performance of IfG approach

Combination: use of the same approach

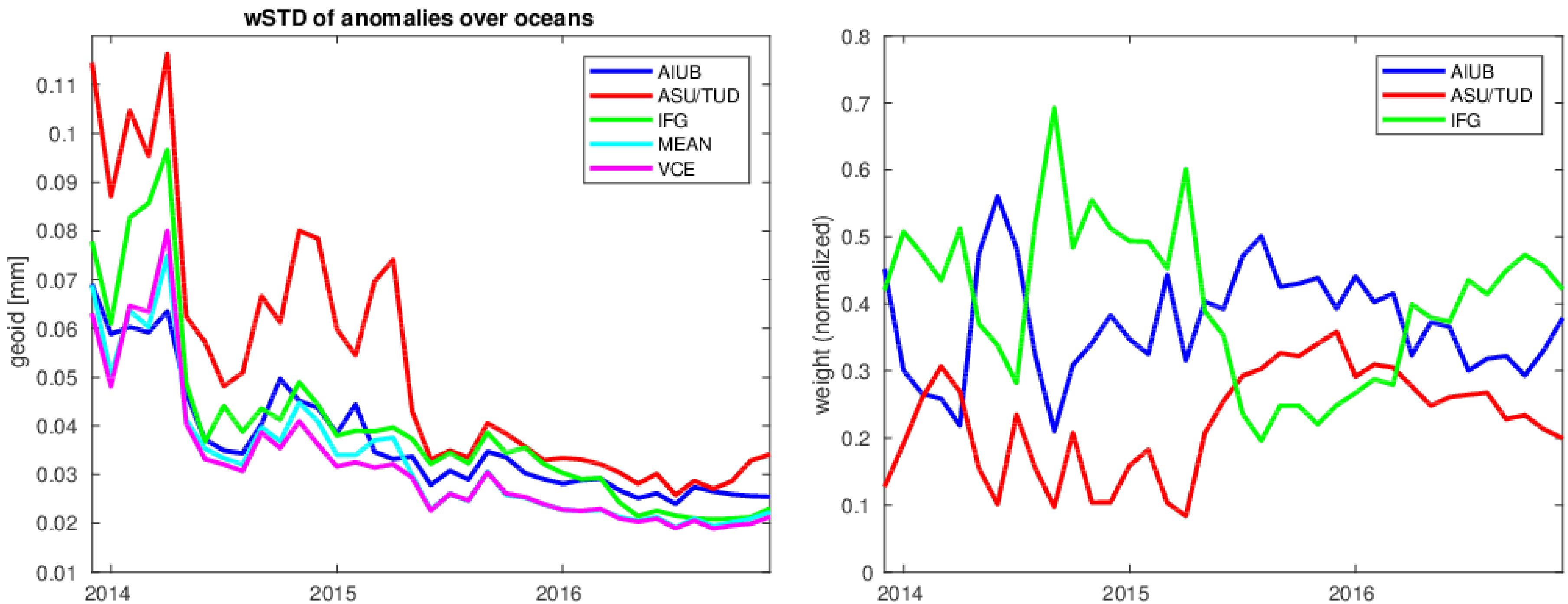




Test case: all solutions based on ASU approach:

- Orbit quality highly impacts the quality of the gravity field solutions
- Weighted average may compensate this to a certain extent
- Weights generally suggest best performance of AIUB orbits

Combination: all input is independent



All solutions completely independent:

- Situation is a mixture of previous slides
- Combination generally performs best
- Weights suggest best performances of IfG and AIUB solutions

More information in the talk by Encarnação et al.:
Signal contents of combined monthly gravity field models derived from Swarm GPS data, Fri 13 Apr, 09:45 – 10:00, Room D1

Mitigation of Systematic Errors: test cases

- Original GPS data
- „Standard screening“: $|dL_{gf}/dt| > 2\ cm/s$ ➔ discard GPS observation (L_{gf}: geometry–free linear combination)
- $|d^2L_{gf}/dt^2| > 0.025\ cm/s^2$, $|\phi| < 50°$ ➔ weight down obs. with $\sigma = 21$, as opposed to nominal $\sigma = 1$ (ϕ: geographical latitude)
- ROTI 1: Downweight data with $\sigma = \max(ROTI \cdot 60{,}1)$
- ROTI 2: Downweight data with $\sigma = \exp(ROTI \cdot 20)$

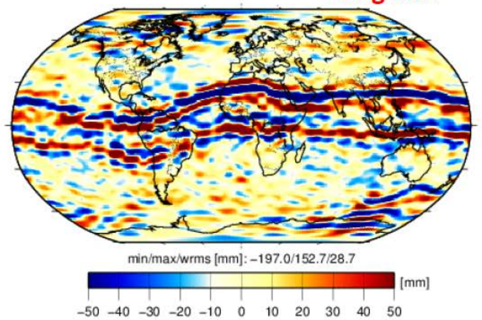
ROTI = Rate of TEC Index

$$ROTI = \sqrt{\frac{\langle \Delta TEC^2\rangle - \langle \Delta TEC\rangle^2}{\Delta t^2}},\quad \Delta t = 1s,\ \langle x\rangle = \text{average of } x \text{ over 31 s}$$

$$TEC = \frac{L_{gf} f_1^2 f_2^2}{40.3 m^3 s^{-2}\left(f_1^2 - f_2^2\right)} \cdot 10^{-16} \frac{TECU}{e/m^2}$$

High Ionospheric Activity (2015/03)

Original

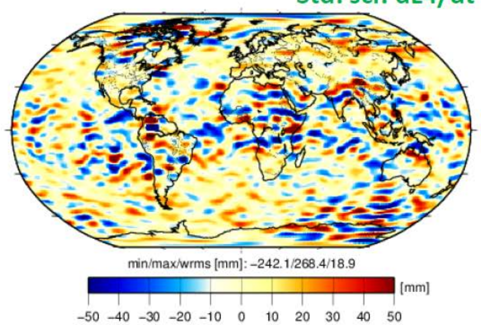


wRMS ocean [mm]:

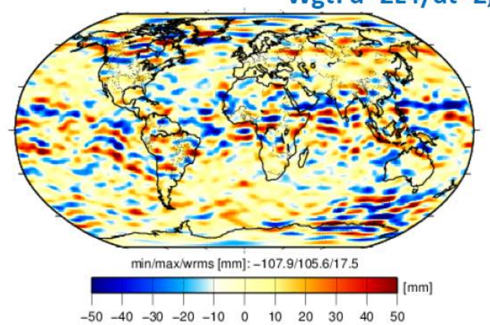
au: 31.5
av: 18.6 aw: 17.7
ax: 19.5 ay: 19.2

High ionospheric activity, prior to tracking loop updates

Std. scr. dL4/dt

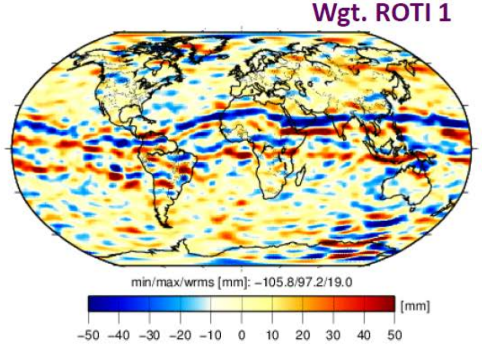


Wgt. d^2L4/dt^2, eq.

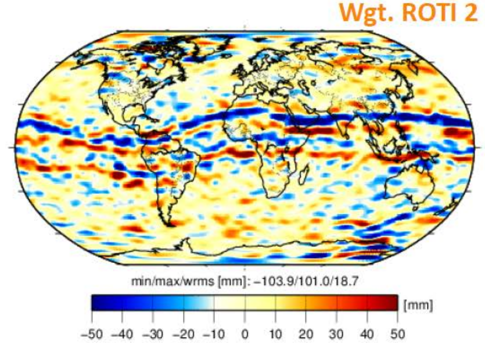


- d^2L_{gf}/dt^2 criterion slightly better than dL_{gf}/dt criterion

Wgt. ROTI 1

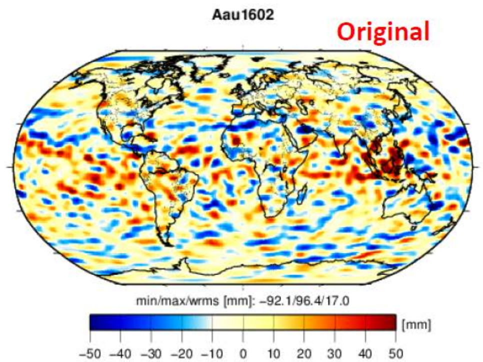


Wgt. ROTI 2



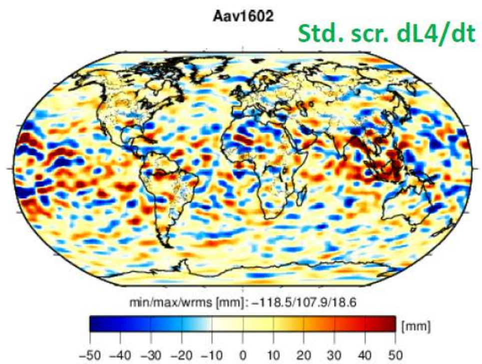
- ROTI-based weighting not as efficient to remove arte-facts along geomagnetic equator

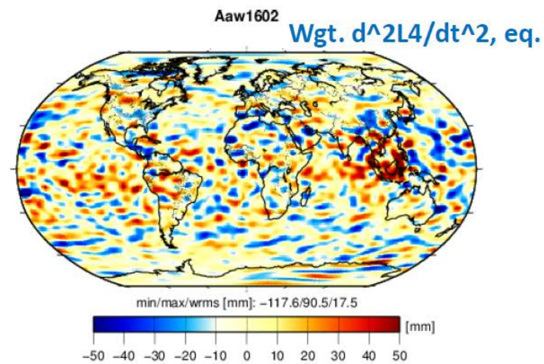
Intermediate Ionospheric Activity (2016/02)



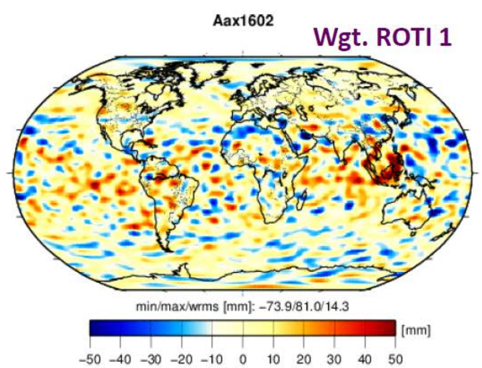
wRMS ocean [mm]:	
au: 17.4	
av: 18.0	aw: 17.9
ax: 14.6	ay: 14.6

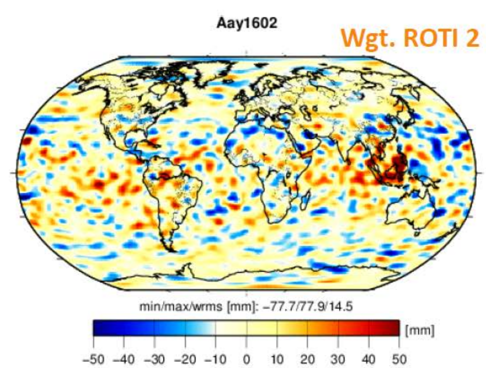
Intermediate ionospheric activity, after tracking loop updates





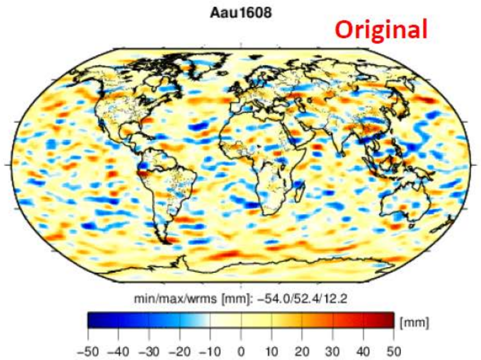
- d^2L_{gf}/dt^2 criterion slightly better than dL_{gf}/dt criterion





- ROTI-based weighting is advantageous to reduce the noise for periods of lower ionospheric activity

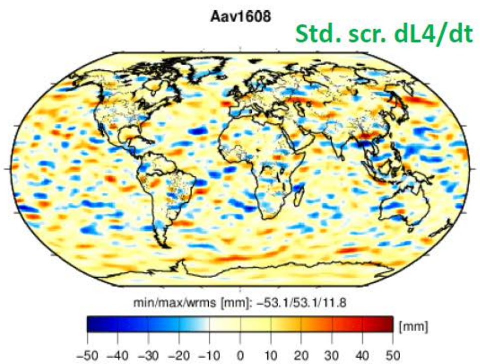
Low Ionospheric Activity (2016/08)

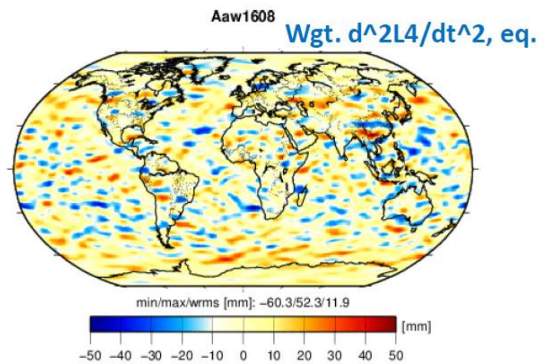


wRMS ocean [mm]:	
au: 12.7	
av: 12.0	aw: 12.3
ax: 9.8	ay: 9.9

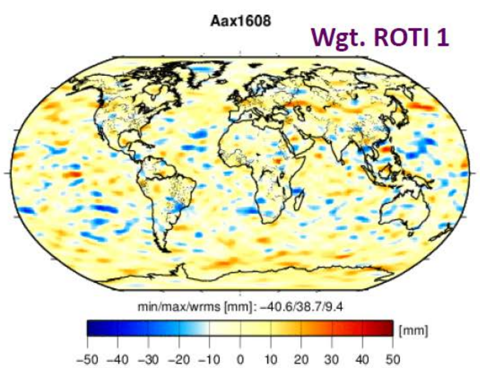
Low ionospheric activity,

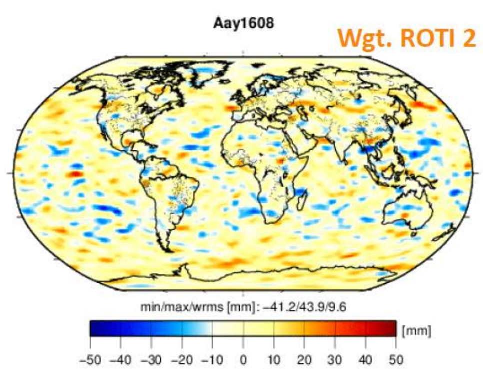
after tracking loop updates





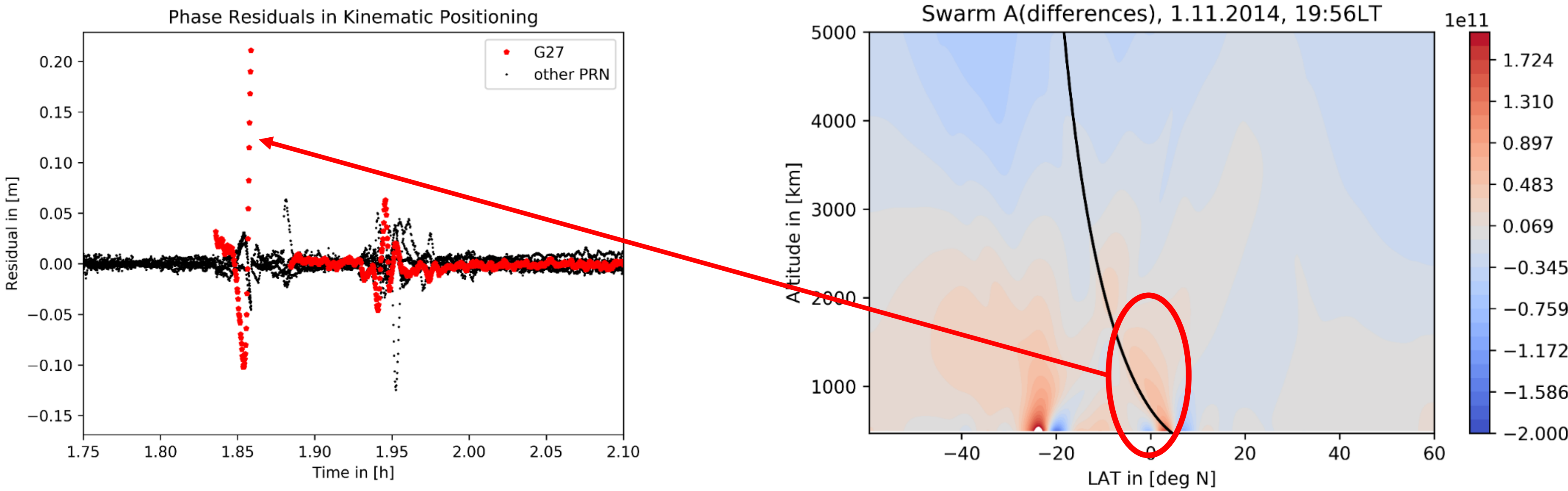
- d^2L_{gf}/dt^2 criterion is here slightly worse than dL_{gf}/dt criterion





- ROTI-based weighting is very helpful to reduce the noise for periods of low ionospheric activity

Impact on Ionosphere/Plasmasphere Reconstruction



Original GPS Data | Weighted GPS Data

- Swarm GPS data issues are significant for reconstruction of upper ionosphere
- Difference pattern may be related to data that were problematic for POD

More Information on the poster X4.262 by Schreiter et al.:

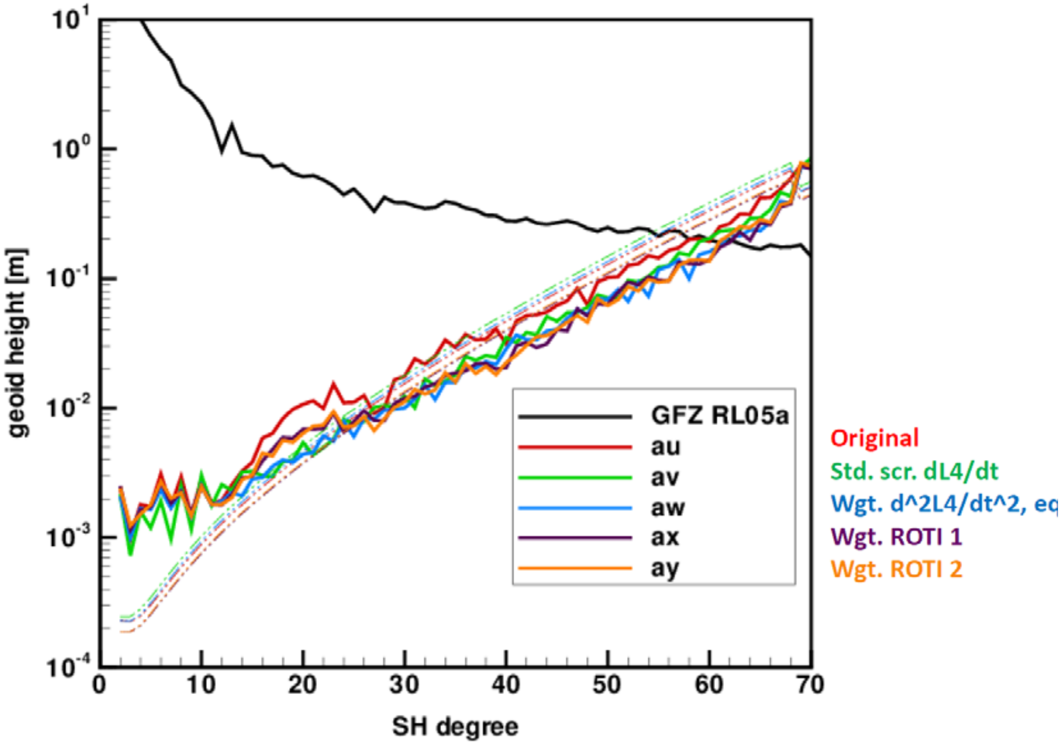
Imaging the topside ionosphere and the plasmasphere using Swarm GPS observations, Mon 09 Apr, 17:30 – 19:00, Hall X4

Conclusion

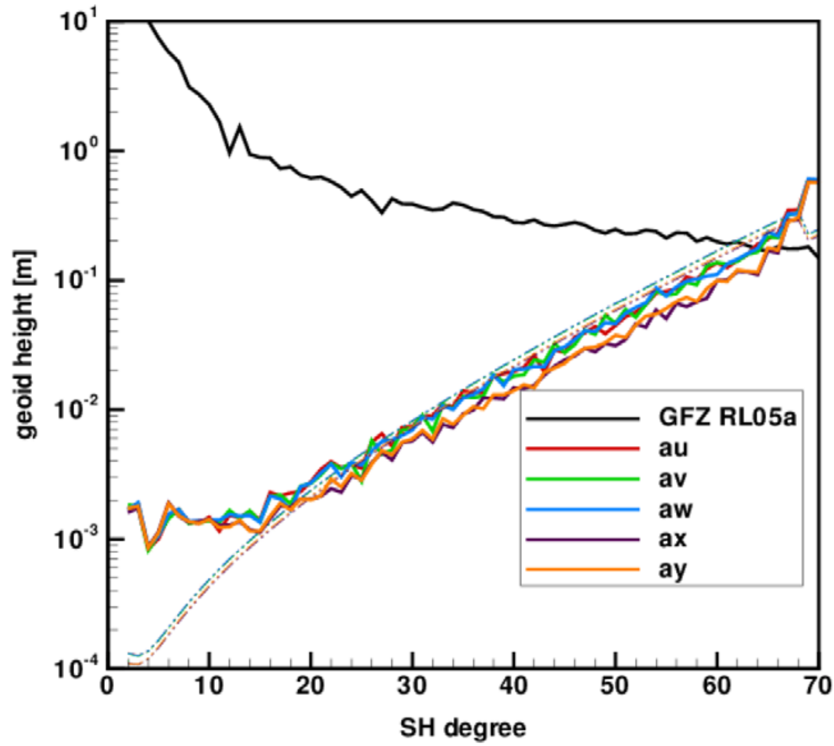
- Several analysis centers are computing Swarm monthly gravity field solutions on a regular basis.
- Combining independent gravity field solutions reduces the noise of the individual solutions.
- Systematic errors along the geomagnetic equator are affecting the Swarm solutions, especially during periods of high ionospheric activity and before the tracking loop updates.
- To remove artifacts around geomagnetic equator the ROTI-based weighting is not as efficient as the standard screening or the weighting based on d^2L_{gf}/dt^2 criterion.
- ROTI-based weighting significantly reduces, however, the noise, also for time periods of low ionospheric activity.
- A combination of ROTI and d^2L_{gf}/dt^2 based weighting seems promising to efficiently mitigate artifacts and reduce the noise.

Difference Degree Amplitudes

High ionospheric activity (2015/03)



Low ionospheric activity (2016/08)



- dL_{gf}/dt slightly better for low degrees
  d^2L_{gf}/dt^2 slightly better for higher degrees
- ROTI–based weighting is well suited to reduce the noise

Combination of ROTI–based weighting with dL_{gf}/dt or d^2L_{gf}/dt^2 criterion might be optimal.

SLR Validation (Swarm-A, 2015/03)

Scenario	Red.–dynamic		Kinematic	
	Mean (mm)	Std. dev. (mm)	Mean (mm)	Std. dev. (mm)
Original	4.6	27.3	2.4	31.1
Std. screening	3.7	26.9	0.7	31.4
d^2L_{gf}/dt^2	4.6	27.3	1.9	32.5
ROTI 1	4.9	26.5	1.0	28.8
ROTI 2	5.0	25.8	0.9	28.7

SLR observations of Graz, Greenbelt, Haleakala, Hartebeesthoek, Herstmonceux, Matera, Mount Stromlo, Potsdam, Wettzell (SOSW), Wettzell (WLRS), Yarragadee, and Zimmerwald, 20cm outlier threshold, 10°elevation cutoff.

SLR Validation (Swarm-A, 2016/02)

Scenario	Red.–dynamic		Kinematic	
	Mean (mm)	Std. dev. (mm)	Mean (mm)	Std. dev. (mm)
Original	8.4	12.1	6.4	16.5
Std. screening	8.1	13.1	6.3	22.9
d^2L_{gf}/dt^2	8.4	12.1	6.1	16.0
ROTI 1	8.5	12.5	5.7	15.4
ROTI 2	8.5	12.6	5.9	15.5

SLR observations of Graz, Greenbelt, Haleakala, Hartebeesthoek, Herstmonceux, Matera, Mount Stromlo, Potsdam, Wettzell (SOSW), Wettzell (WLRS), Yarragadee, and Zimmerwald, 20cm outlier threshold, 10°elevation cutoff.

SLR Validation (Swarm-A, 2016/08)

Scenario	Red.–dynamic		Kinematic	
	Mean (mm)	Std. dev. (mm)	Mean (mm)	Std. dev. (mm)
Original	4.9	14.2	3.9	16.6
Std. screening	5.0	14.3	3.9	16.7
d^2L_{gf}/dt^2	4.9	14.2	3.9	16.8
ROTI 1	4.7	14.7	3.8	17.0
ROTI 2	4.7	14.7	3.8	16.9

SLR observations of Graz, Greenbelt, Haleakala, Hartebeesthoek, Herstmonceux, Matera, Mount Stromlo, Potsdam, Wettzell (SOSW), Wettzell (WLRS), Yarragadee, and Zimmerwald, 20cm outlier threshold, 10°elevation cutoff.