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

A. Jäggi[1], U. Meyer[1], L. Schreiter[1], V. Sterken[1], C. Dahle[2,1], D. Arnold[1],
J. Encarnação[3,4], P. Visser[3], E. Doornbos[3], J. van den IJssel[3], X. Mao[3],
E. Iorfida[3], A. Bezděk[5], J. Sebera[5], J. Klokočnik[5], T. Mayer-Gürr[6],
N. Zehentner[6], C.K. Shum[7], Y. Zhang[7], C. Lück[8], R. Rietbroek[8], J. Kusche[8]

[1]Astronomical Institute, University of Bern, Bern, Switzerland

[2]German Research Centre for Geosciences, Potsdam, Germany

[3]Faculty of Aerospace Engineering of the Delft University of Technology, Delft, The Netherlands

[4]Center for Space Research, University of Texas at Austin, Austin, Texas

[5]Astronomical Institute of the Czech Academy of Sciences, Prague, Czech Republic

[6]Institute of Geodesy of the Graz University of Technology, Graz, Austria

[7]School of Earth Science of the Ohio State University, Columbus, Ohio

[8]Institute of Geodesy and Geoinformation, University of Bonn, Bonn, Germany

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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

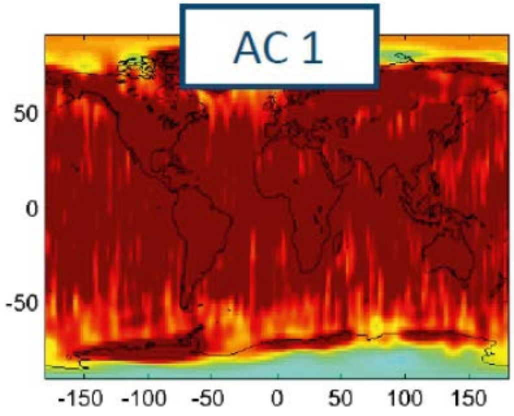
Analysis Centers (AC) are computing monthly Swarm Gravity Field Solutions using different approaches and different GPS-based kinematic orbit solutions. Gravity Field Solutions from additional AC are expected in the near future.

Improving Gravity Field Solutions by Combination

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

International
Association of
Geodesy
IAG
I G F S

AC 1



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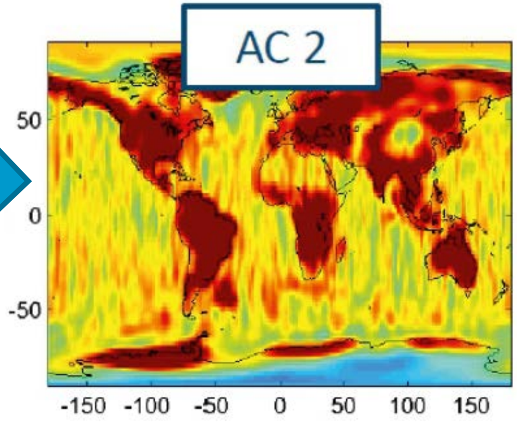
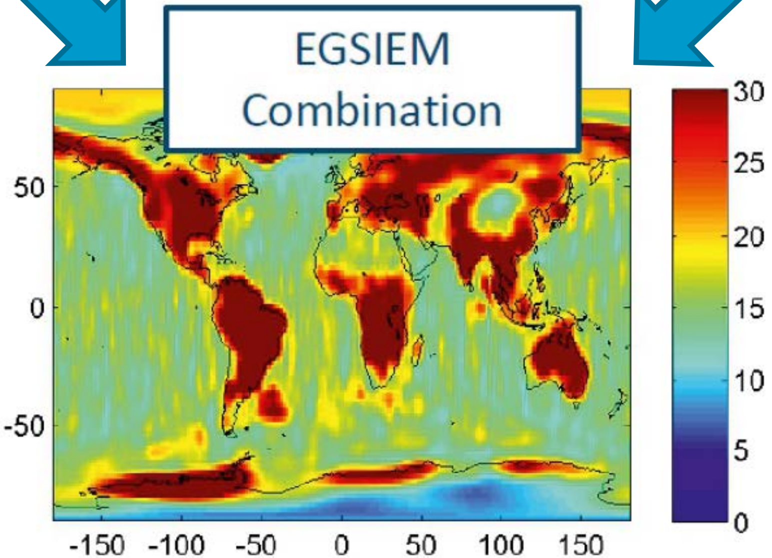


EGSIEM
Combination



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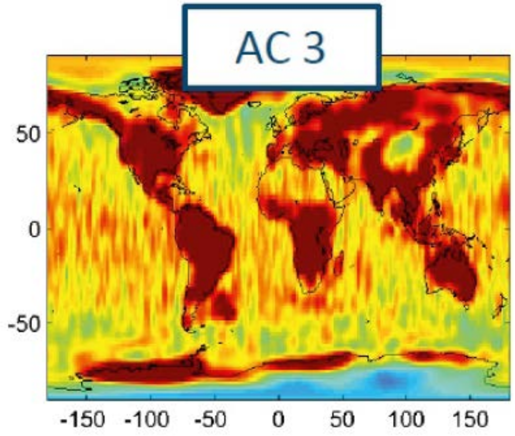
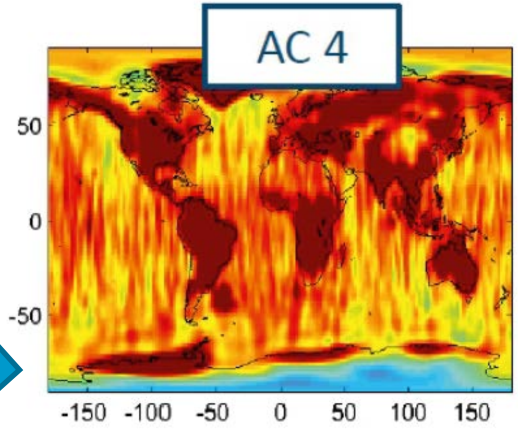


AC 4



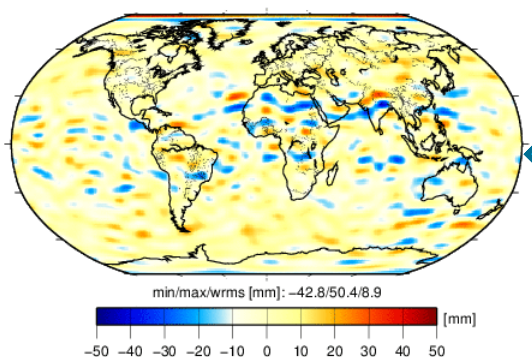
- Only one product for the user
- Reduced noise

Improving Gravity Field Solutions by Combination

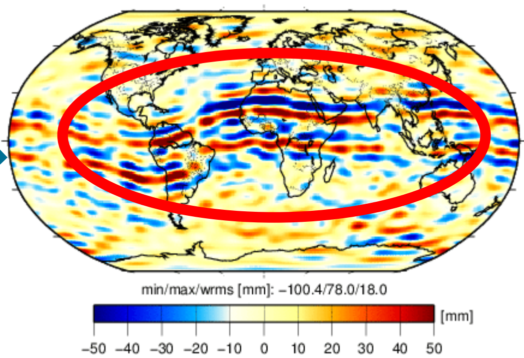
EGSIEM

European Gravity Service for Improved Emergency Management

GSWARM_GF_SABC_AIUB_2015-03_01_AIUB


min/max/wrms [mm]: −42.8/50.4/8.9

GSWARM_GF_SABC_ASU_2015-03_01_TUD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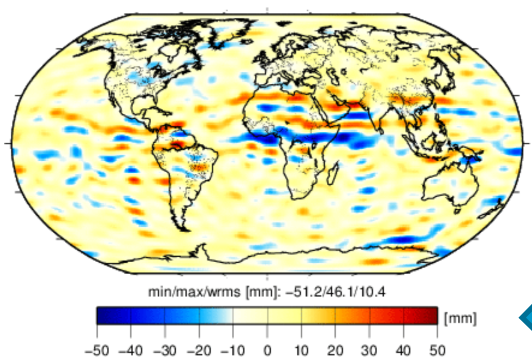
GSWARM_GF_SABC_IFG_2015-03_03_IFG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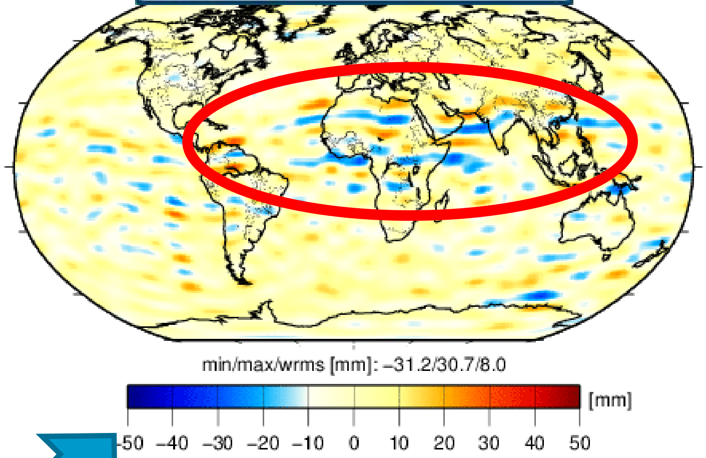
EGSIEM
Combination


min/max/wrms [mm]: −31.2/30.7/8.0

For Swarm

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

esa SWARM DISC

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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:

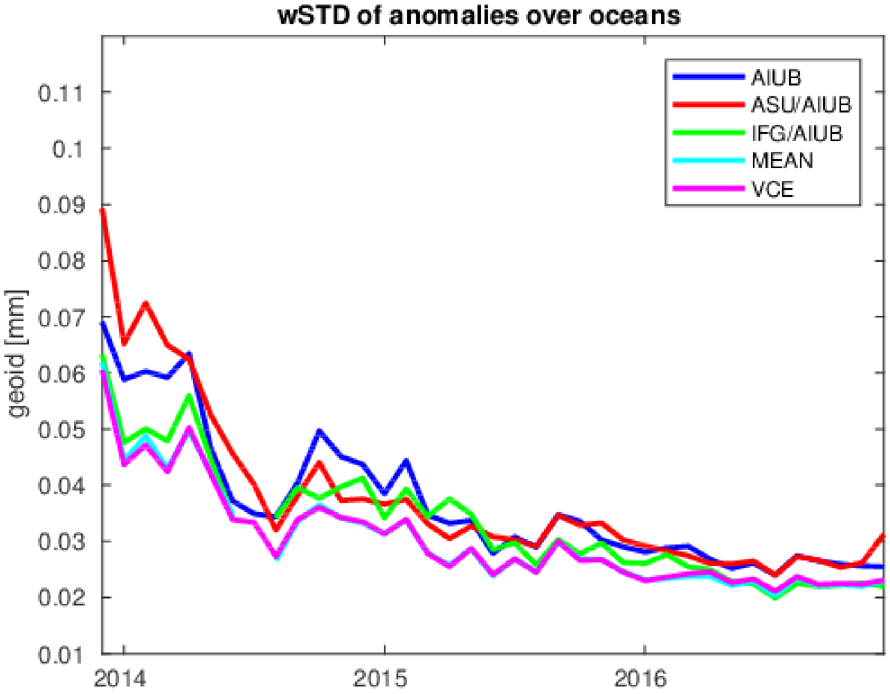
Iteration 0: $$\hat{\mathbf{x}}_0 = \frac{1}{n}\sum_k \mathbf{x}_k$$ with $$w_{k,0} = \frac{1}{n} \quad \forall k, \;\; k = 1,\ldots,n$$

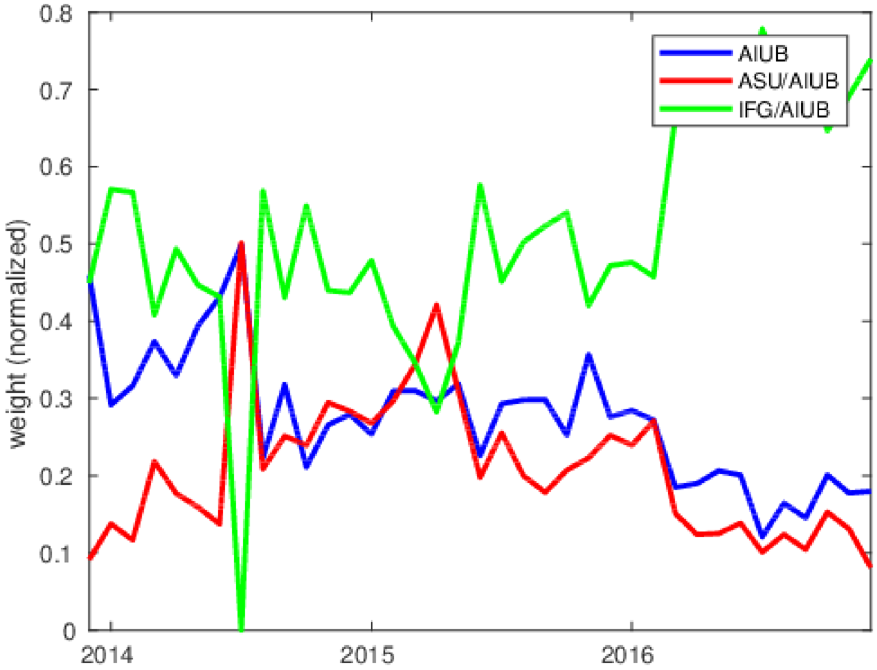
Iteration $i > 0$: $$\hat{\mathbf{x}}_i = \frac{1}{\sum_k w_{k,i}} \sum_k w_{k,i}\mathbf{x}_k$$ with $$w_{k,i} = \Big(1 - \frac{w_{k,i-1}}{\sum_k w_{k,i-1}}\Big) / \mathrm{RMS}(\mathbf{d}_{k,i-1})^2;$$

$$\mathbf{d}_{k,i-1} = \mathbf{x}_k - \hat{\mathbf{x}}_{i-1}$$ 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

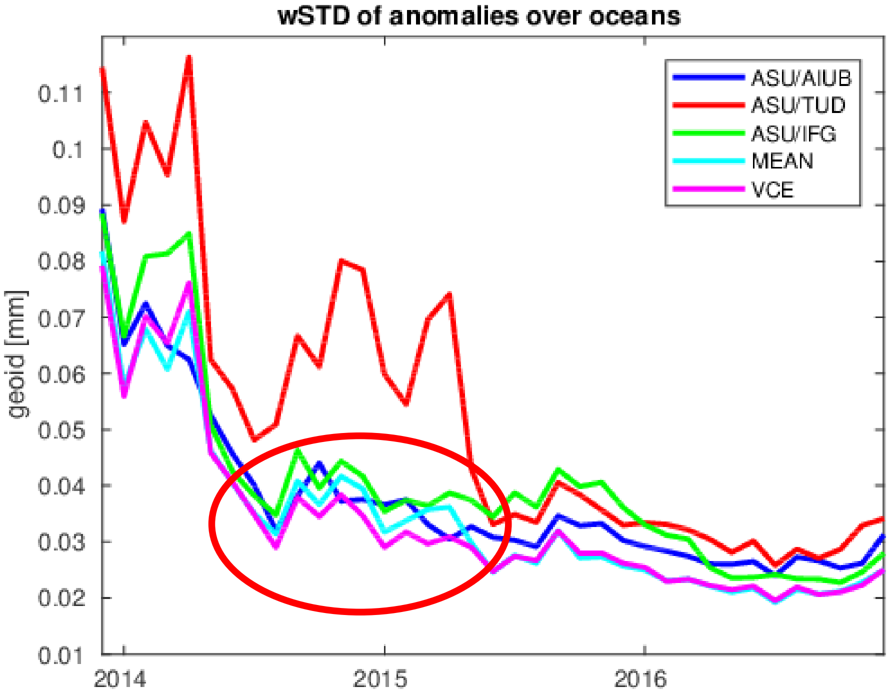




Test case: all solutions based on AIUB orbits:

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

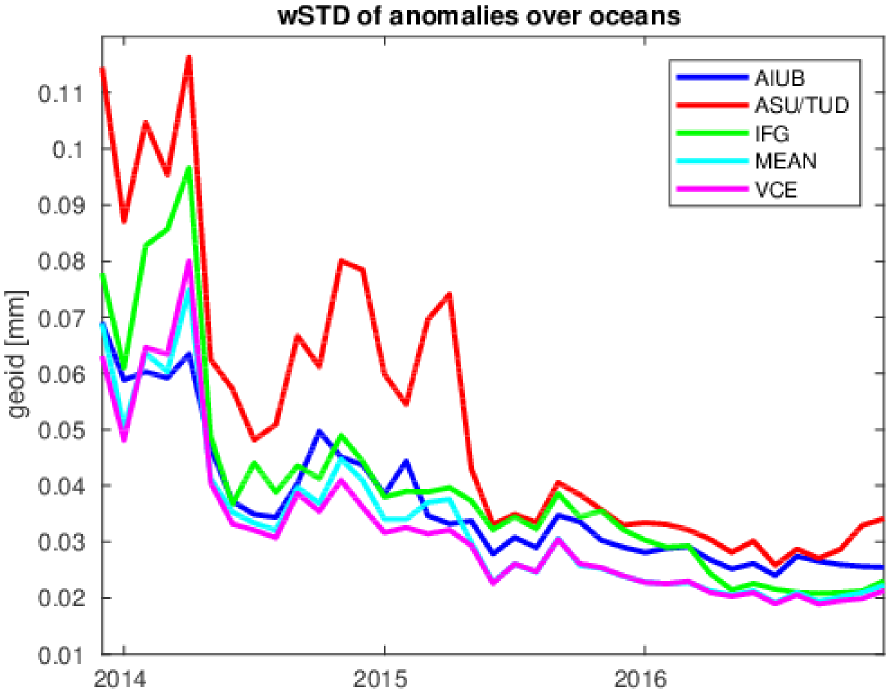
Combination: use of the same approach



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 $\sigma = \exp(ROTI \cdot 20)$

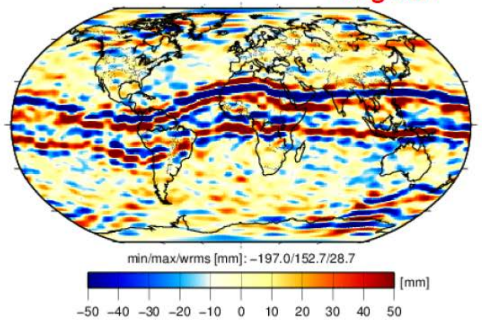
ROTI = Rate of TEC Index

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

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

High Ionospheric Activity (2015/03)

Original



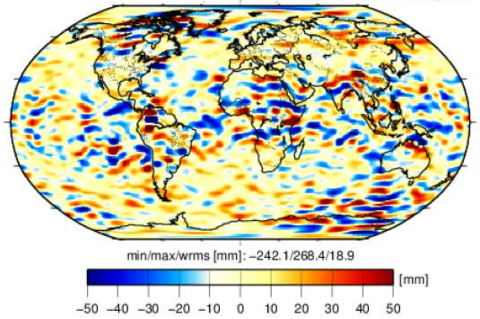
wRMS ocean [mm]:

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

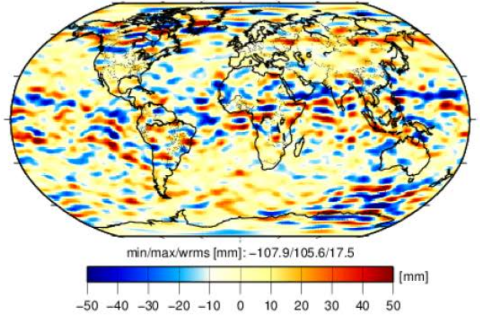
High ionospheric activity,

prior to tracking loop updates

Std. scr. dL4/dt

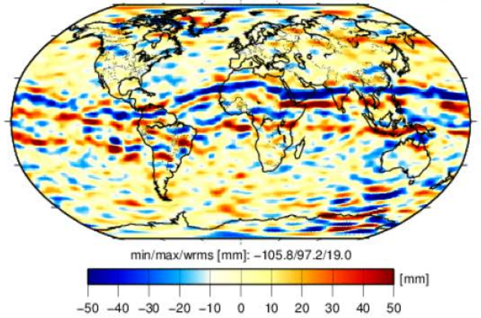


Wgt. d^2L4/dt^2, eq.

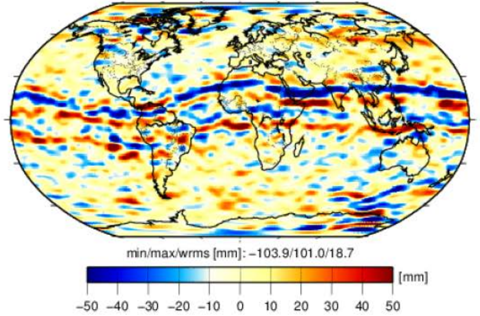


- d^2L_{gf}/dt^2 criterion slightly better than dL_{gf}/dt criterion

Wgt. ROTI 1



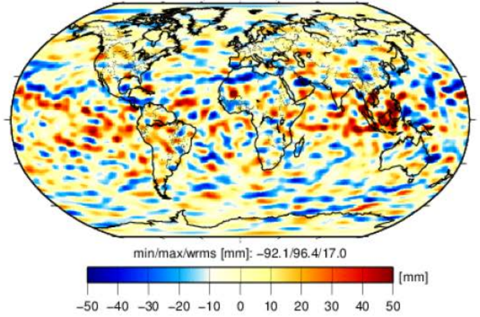
Wgt. ROTI 2



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

Intermediate Ionospheric Activity (2016/02)

Aau1602 **Original**

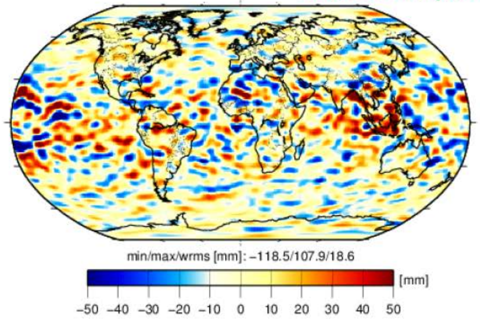


wRMS ocean [mm]:

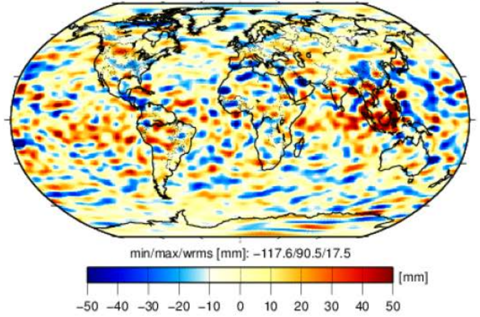
au: 17.4
av: 18.0
aw: 17.9
ax: 14.6
ay: 14.6

Intermediate ionospheric activity, after tracking loop updates

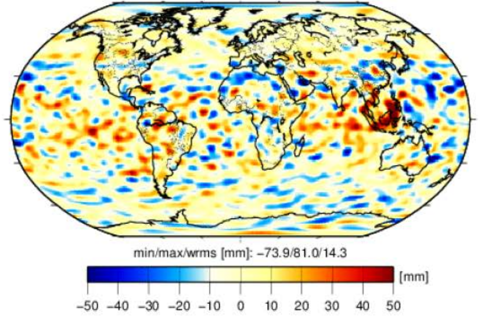
Aav1602 **Std. scr. dL4/dt**



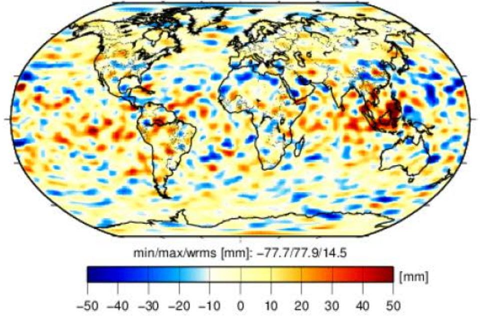
Aaw1602 **Wgt. d^2L4/dt^2, eq.**



Aax1602 **Wgt. ROTI 1**



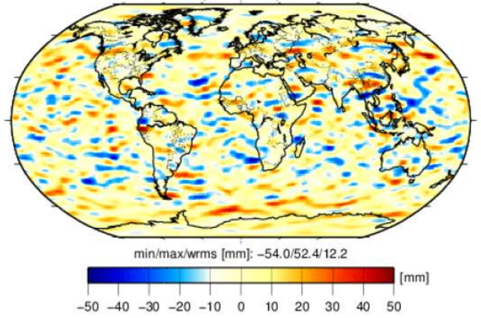
Aay1602 **Wgt. ROTI 2**



- 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)

Aau1608 **Original**



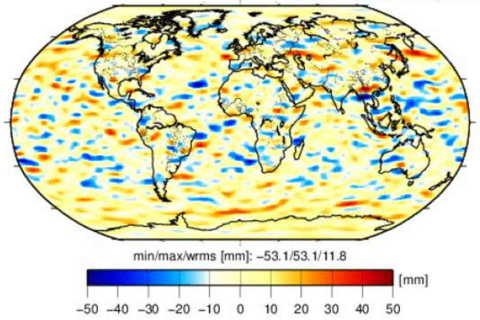
wRMS ocean [mm]:

au: 12.7
av: 12.0 aw: 12.3
ax: 9.8 ay: 9.9

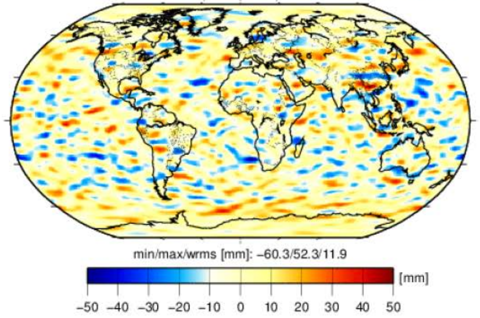
Low ionospheric activity,

after tracking loop updates

Aav1608 **Std. scr. dL4/dt**

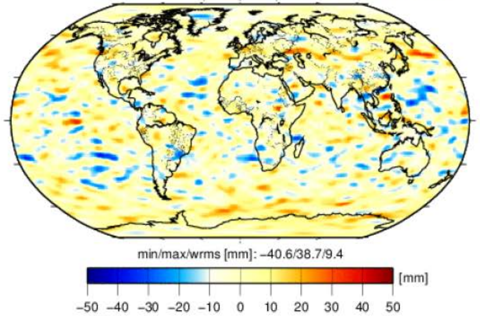


Aaw1608 **Wgt. d^2L4/dt^2, eq.**

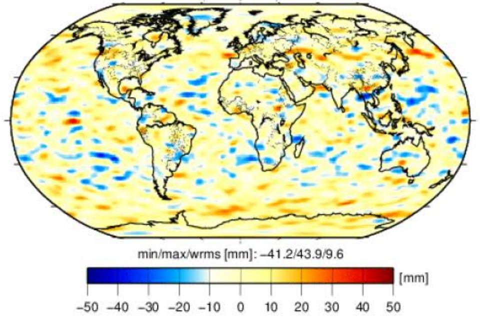


- d^2L_{gf}/dt^2 criterion is here slightly worse than dL_{gf}/dt criterion

Aax1608 **Wgt. ROTI 1**

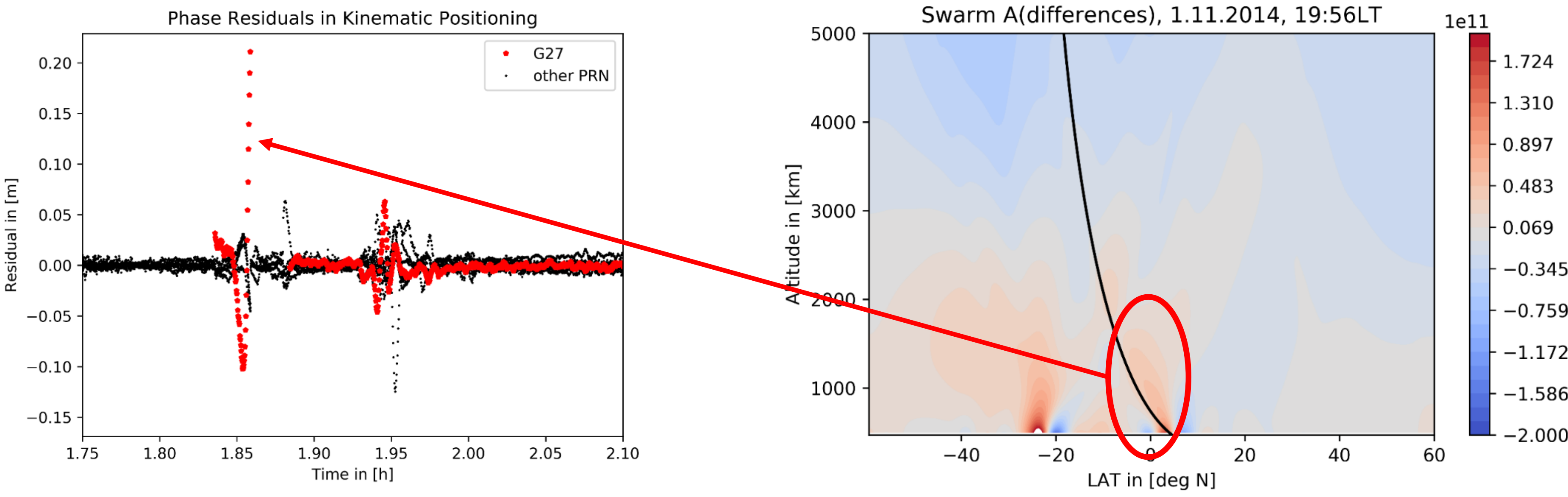


Aay1608 **Wgt. ROTI 2**



- 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.:

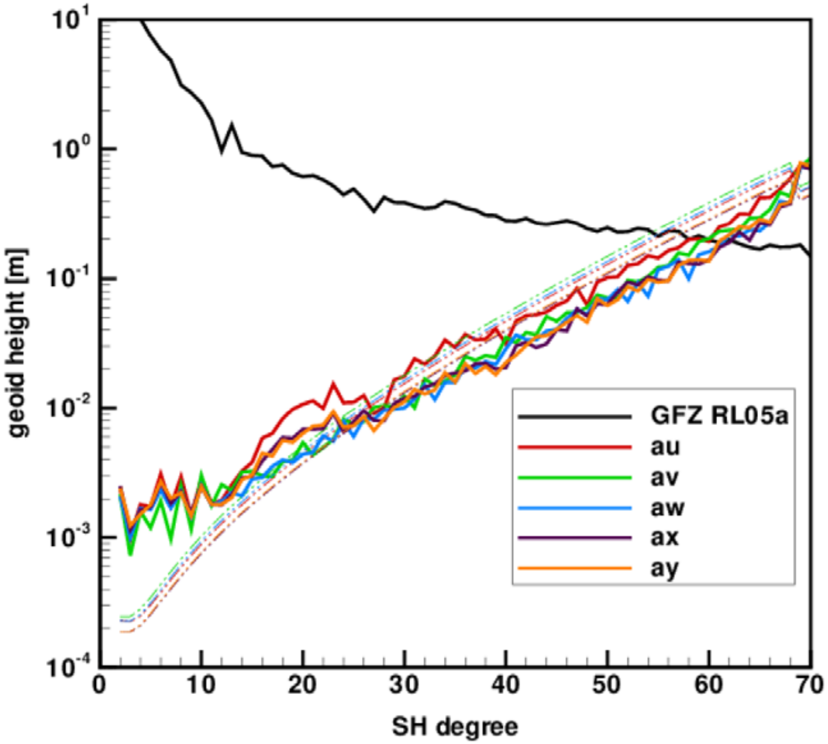
Imaging the topside ionosphere and the plasmasphere using Swarm GPS observations, Mon 09 Apr, 17:30 – 19:00, Hall X4

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.

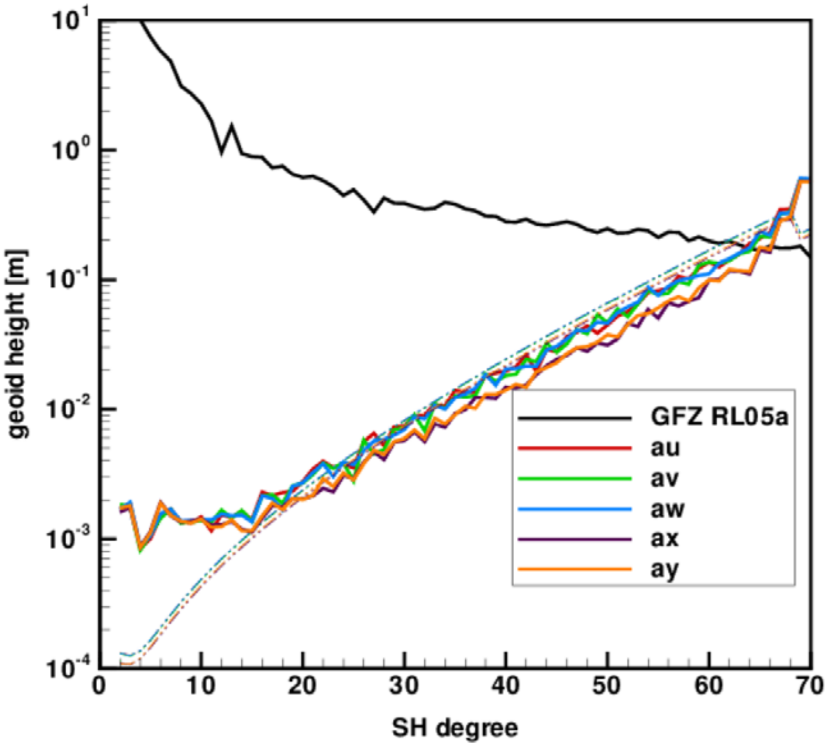
Difference Degree Amplitudes

High ionospheric activity (2015/03)



Original
Std. scr. dL4/dt
Wgt. d^2L4/dt^2, eq
Wgt. ROTI 1
Wgt. ROTI 2

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.