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

A. Jäggi¹, U. Meyer¹, L. Schreiter¹, V. Sterken¹, C. Dahle^{2,1}, D. Arnold¹,
J. Encarnação^{3,4}, P. Visser³, E. Doornbos³, J. van den IJssel³, X. Mao³,
E. Iorfida³, A. Bezděk⁵, J. Sebera⁵, J. Klokočnik⁵, T. Mayer–Gürr⁶,
N. Zehentner⁶, C.K. Shum⁷, Y. Zhang⁷, C. Lück⁸, R. Rietbroek⁸, J. Kusche⁸

¹Astronomical Institute, University of Bern, Bern, Switzerland

²German Research Centre for Geosciences, Potsdam, Germany

³Faculty of Aerospace Engineering of the Delft University of Technology, Delft, The Netherlands
 ⁴Center for Space Research, University of Texas at Austin, Austin, Texas
 ⁵Astronomical Institute of the Czech Academy of Sciences, Prague, Czech Republic
 ⁶Institute of Geodesy of the Graz University of Technology, Graz, Austria
 ⁷School of Earth Science of the Ohio State University, Columbus, Ohio
 ⁸Institute 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



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Improving Gravity Field Solutions by Combination



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:

Iteration i > 0: $\hat{\mathbf{x}}_i = \frac{1}{\sum_k w_{k,i}} \sum_k w_{k,i} \mathbf{x}_k$

 $\hat{\mathbf{x}}_0 = \frac{1}{n} \sum_{k} \mathbf{x}_k$

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

with
$$w_{k,0} = \frac{1}{n} \quad \forall k, \ k = 1, ..., n$$

with
$$W_{k,i} = (1 - \frac{W_{k,i-1}}{\sum_{k} W_{k,i-1}}) / \text{RMS}(\mathbf{d}_{k,i-1})^2$$

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": $|dL_{gf}/dt| > 2 cm/s \rightarrow discard GPS$ observation (*L_{af}*: geometry–free linear combination)
- $|d^2L_{gf}/dt^2| > 0.025 \ cm/s^2$, $|\phi| < 50^\circ \rightarrow$ weight down obs. with $\sigma = 21$, as opposed to nominal $\sigma = 1$ (ϕ : geographical latitude)
- ROTI 1: Downweight data with σ = max(ROTI · 60,1)
 ROTI = Rate of
 ROTI 2: Downweight data with σ = exp(ROTI · 20)
 TEC Index

 $ROTI = \sqrt{\frac{\langle \Delta TEC^2 \rangle - \langle \Delta TEC \rangle^2}{\Delta t^2}}, \quad \Delta t = 1s, \, \langle x \rangle = \text{average of } x \text{ over 31 s}$ $TEC = \frac{L_{gf} f_1^2 f_2^2}{40.3m^3 s^{-2} (f_1^2 - f_2^2)} \cdot 10^{-16} \frac{TECU}{e/m^2}$

High Ionospheric Activity (2015/03)



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. ROTI 1



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



 d²L_{gf}/dt² criterion slightly better than dL_{gf}/dt criterion

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

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Intermediate Ionospheric Activity (2016/02)



Intermediate ionospheric activity, after tracking loop updates

 d²L_{gf}/dt² criterion slightly better than dL_{gf}/dt criterion

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

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Low Ionospheric Activity (2016/08)



Low ionospheric activity, after tracking loop updates

 d²L_{gf}/dt² 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

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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 ROTIbased weighting is not as efficient as the standard screening or the weighting based on d²L_{gf}/dt² criterion.
- ROTI-based weighting significantly reduces, however, the noise, also for time periods of low ionospheric activity.
- A combination of ROTI and d²L_{gf}/dt² based weighting seems promising to efficiently mitigate artifacts and reduce the noise.

Difference Degree Amplitudes



- dL_{gf}/dt slightly better for low degrees d²L_{qf}/dt² slightly better for higher degrees
- ROTI-based weighting is well suited to reduce the noise

AIUB



SLR Validation (Swarm-A, 2015/03)

Scenario	Reddynamic		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
$d^2 L_{gf}/dt^2$	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	Reddynamic		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
$d^2 L_{gf}/dt^2$	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	Reddynamic		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
$d^2 L_{gf}/dt^2$	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.