Combination of Swarm gravity field models on normal equation level

ESA/DISC project “Multi-approach gravity field models from Swarm GPS data”

D. Arnold ¹  U. Meyer ¹  C. Dahle ²  A. Jäggi ¹  J. de Teixeira da Encarnação ³  Pieter Visser ⁴  and all other project partners

¹ Astronomical Institute, University of Bern, Switzerland, ² GFZ German Research Centre for Geosciences, Postsdam, Germany, ³ Center for Space Research, University of Texas at Austin, Austin, USA, ⁴ Faculty of Aerospace Engineering of the Delft University of Technology, Delft, The Netherlands

8th Swarm Data Quality Workshop
08-12 October 2018
ESA-ESRIN, Frascati, Italy
Outline

1. Multi-approach gravity field models from Swarm GPS data
2. Combination strategy
3. Combination at normal equation level
4. Conclusion
Multi-approach gravity field models from Swarm GPS data

- ESA/DISC-funded project (Sep 2017 - Dec 2018)
Multi-approach gravity field models from Swarm GPS data

- ESA/DISC-funded project (Sep 2017 - Dec 2018)
- Provide high-quality monthly gravity field models derived from Swarm kinematic orbits (computed by AIUB, IfG, TU Delft)
Multi-approach gravity field models from Swarm GPS data

- ESA/DISC-funded project (Sep 2017 - Dec 2018)
- Provide high-quality monthly gravity field models derived from Swarm kinematic orbits (computed by AIUB, IfG, TU Delft)
- Combine individual gravity solutions from different analysis centers (ACs):
  - AIUB: Celestial Mechanics Approach
  - ASU: Decorrelated Acceleration Approach
  - IfG: Short-Arc Approach
  - OSU: Improved Energy Balance Approach (not considered here)
Multi-approach gravity field models from Swarm GPS data

- ESA/DISC-funded project (Sep 2017 - Dec 2018)
- Provide high-quality monthly gravity field models derived from Swarm kinematic orbits (computed by AIUB, IfG, TU Delft)
- Combine individual gravity solutions from different analysis centers (ACs):
  - AIUB: Celestial Mechanics Approach
  - ASU: Decorrelated Acceleration Approach
  - IfG: Short-Arc Approach
  - OSU: Improved Energy Balance Approach (not considered here)
- Combination on solution level or on normal equation level
Multi-approach gravity field models from Swarm GPS data

- ESA/DISC-funded project (Sep 2017 - Dec 2018)
- Provide high-quality monthly gravity field models derived from Swarm kinematic orbits (computed by AIUB, IfG, TU Delft)
- Combine individual gravity solutions from different analysis centers (ACs):
  - AIUB: Celestial Mechanics Approach
  - ASU: Decorrelated Acceleration Approach
  - IfG: Short-Arc Approach
  - OSU: Improved Energy Balance Approach (not considered here)
- Combination on solution level or on normal equation level
Example application: Mass loss in Greenland

- GRACE-derived mass variations serve as reference
- All gravity fields truncated at degree 6 (max. resolution of SLR), no extra filter applied
- Swarm results: more noisy and larger signal amplitude (unknown reason)
Combination strategy
Same kinematic orbits, different ACs

- Combination is based on the assumption that all contributions contain the same signal but differ in noise.
Same kinematic orbits, different ACs

- Combination is based on the assumption that all contributions contain the same signal but differ in noise
- Biases introduced by the choice of kinematic orbits have to be avoided
Same kinematic orbits, different ACs

- Combination is based on the assumption that all contributions contain the same signal but differ in noise.
- Biases introduced by the choice of kinematic orbits have to be avoided.

Weights derived by variance component estimation (VCE) on solution level.

Anomaly: Difference to a GRACE-derived deterministic signal model.

- The combination (on solution level) based on AIUB kin. orbits shows advantages for the IfG processing strategy.
Same AC, different kinematic orbits

Example: ASU gravity fields based on different kinematic orbits

- Advantages for IfG orbits during periods of high solar activity, for AIUB orbits during periods of reduced solar activity or improved tracking
Same AC, different kinematic orbits

Example: ASU gravity fields based on different kinematic orbits

- Advantages for IfG orbits during periods of high solar activity, for AIUB orbits during periods of reduced solar activity or improved tracking
- TUD orbits suffer from artifacts due to ionospheric disturbances during times of high solar activity
Different ACs, different kinematic orbits

- Optimal in terms of biases would be a combination of all independent analysis centers and input kinematic orbits
Different ACs, different kinematic orbits

- Optimal in terms of biases would be a combination of all independent analysis centers and input kinematic orbits
- If certain orbits show pronounced problems, the AC processing these orbits will get lower weights (unattractive)
Combination at normal equation (NEQ) level
Relative weighting/scaling of NEQs (1)

- Different ACs use different normalizations for NEQ generation → NEQs first need to be scaled to balance the general level of impact on the monthly combination (pair-wise comparison of solutions)
- Only apply one scaling factor per time series to keep relative accuracy information between months
Weights derived from VCE (on solution level):

- Weights are biased, since kinematic orbits are used unevenly (2×IfG, 1×AIUB) $\rightarrow$ AIUB solution systematically differs from other solutions and gets downweighted
- Not applied for final combined solutions
Validation: noise over ocean areas

- Combination on solution level: VCE is not optimal (orbit bias) and is out-performed by the arithmetic mean.
Validation: noise over ocean areas

- Combination on solution level: VCE is not optimal (orbit bias) and is out-performed by the arithmetic mean
- The arithmetic mean at NEQ level closely resembles the arithmetic mean at solution level
**Validation: noise over ocean areas**

- Combination on solution level: VCE is not optimal (orbit bias) and is out-performed by the arithmetic mean.
- The arithmetic mean at NEQ level closely resembles the arithmetic mean at solution level.
- Applying VCE-based weights at NEQ-level (NEQf) closely reproduces the combination by VCE at solution level.
- Introduction of monthly empirical scaling factors (NEQe) will not result in significant improvement.
Spectral analysis of anomalies

- At high degrees the two combined solutions are very comparable.
• At high degrees the two combined solutions are very comparable
• At low degrees the combination on NEQ level is driven by the AIUB solution, which has unrealistically small formal errors at low degrees
• At high degrees the two combined solutions are very comparable.
• At low degrees the combination on NEQ level is driven by the AIUB solution, which has unrealistically small formal errors at low degrees.
• AIUB solution has problems at low degrees during times of high ionospheric activities → degradation of combination on NEQ level (less severe during periods of low ionospheric activity).
• At high degrees the two combined solutions are very comparable
• At low degrees the combination on NEQ level is driven by the AIUB solution, which has unrealistically small formal errors at low degrees
• AIUB solution has problems at low degrees during times of high ionospheric activities → degradation of combination on NEQ level (less severe during periods of low ionospheric activity)
• At high degrees the two combined solutions are very comparable
• At low degrees the combination on NEQ level is driven by the AIUB solution, which has unrealistically small formal errors at low degrees
• AIUB solution has problems at low degrees during times of high ionospheric activities → degradation of combination on NEQ level (less severe during periods of low ionospheric activity)
• Swarm kinematic orbits from different processing centers show different performances, depending on ionospheric activity
• An unbiased combination of Swarm-derived gravity fields from different ACs requires a homogeneous use of kinematic orbits, otherwise VCE will downweight solutions which are derived from underrepresented kinematic orbits
• At low degrees combination on NEQ level is dominated by AIUB solution due to its (too) low formal errors. This is problematic during high ionospheric activity, where the AIUB solutions are degraded in the lower degrees

→ Tests with revised strategies to mitigate ionosphere-induced artifacts in AIUB orbits on-going (however, seems to improve mainly higher degrees)
Thank you
Swarm gravity field processing at AIUB
Daily RMS of orbit fit reflects ionospheric disturbances due to solar activity:
So does the monthly RMS of gravity field model adjustment:

![Graph showing monthly RMS of gravity field model adjustment from 2014 to 2018. The graph includes lines for SWARM C, SWARM A, and SWARM B, with peaks and troughs indicating variations in RMS values.]
Contribution analysis

Contribution of individual Swarm satellites to monthly gravity field solutions:

- SWARM A: 06/2018
- SWARM B: 06/2018
- SWARM C: 06/2018
Quality checks of individual contributions (1)

- Combination by Variance Component Estimation (VCE) on solution level (convergence after 3-4 iterations)
- Noise is evaluated independently by variability over ocean areas
- Low weights together with low noise indicate damaged signal
Quality checks of individual contributions (2)

- OSU time series biased towards static GRACE a priori model due to use of satellite velocities taken from dynamic orbits
• OSU time series biased towards static GRACE a priori model due to use of satellite velocities taken from dynamic orbits
• With decreasing noise in 2015 and 2016 the regularization of OSU gravity fields is less obvious, but correlation analysis with GRACE solutions still reveals attenuated signal content
• OSU time series biased towards static GRACE a priori model due to use of satellite velocities taken from dynamic orbits
• With decreasing noise in 2015 and 2016 the regularization of OSU gravity fields is less obvious, but correlation analysis with GRACE solutions still reveals attenuated signal content
Same AC, different kinematic orbits

Example: IfG gravity fields based on different kinematic orbits

- Combination of IfG gravity fields based on different kinematic orbits confirms the findings of the ASU combination