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Using Swarm for gravity field determination – an overview after 3+ years in orbit

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Introduction

Besides its primary objective, observing the Earth's magnetic field and the ionosphere, the Swarm Mission can also be regarded as a gravity field mission. Its payload, in particular GPS receivers and star trackers, allows to estimate the long-wavelength part of the Earth's gravity field and its variations in time by means of high-low satellite-to-satellite tracking (hl-SST). This capability has gained even more relevance since the dedicated gravity field mission GRACE will soon reach the end of its nominal mission and the successor GRACE-FO will not be launched before December 2017. Thinking of ways to bridge the gap between GRACE and GRACE-FO in a best possible manner, the Swarm satellites will play an essential role.

First results from different groups have indicated that Swarm-derived gravity field solutions are generally of comparable quality w.r.t. corresponding hl-SST solutions derived from GRACE. However, there were also systematic deficiencies identified that are related to ionospheric disturbances affecting the GPS observations[1]. Most prominently, Swarm gravity fields were degraded by two spurious bands north and south of the Earth's geomagnetic equator. Updated tracking loop settings of the Swarm GPS receivers have helped to significantly mitigate these effects and improve the quality of the gravity field solutions[2].

Swarm Processing at AIUB

Orbit and gravity field determination

- At the Astronomical Institute of the University of Bern (AIUB), kinematic Swarm orbits are routinely processed and gravity field solutions are derived thereof using the Celestial Mechanics Approach (CMA)[3]. For more details about the processing see the poster "Combined Swarm/Sentinel Gravity Fields" by D. Arnold et al. (4th Swarm Science Meeting, PaperID 97).
- Currently, the AIUB Swarm monthly gravity field time series consists of 37 solutions covering the period December 2013 till December 2016 and is able to monitor large mass variations such as in Amazon basin at spatial scales of ~1500 km (Fig. 1).

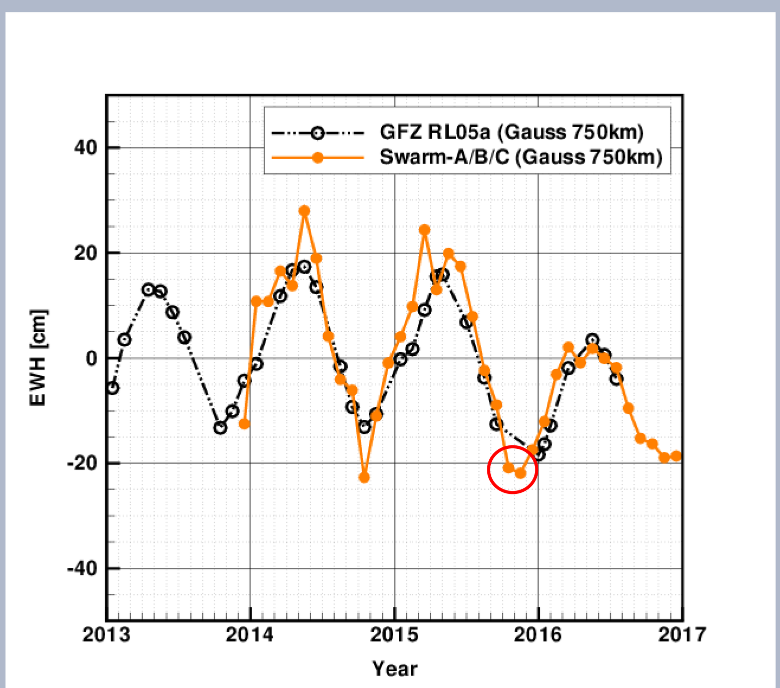

Fig. 1: Basin average time series for the Amazon basin in terms of EWH [cm] from the AIUB combined Swarm-A/B/C solutions and the GFZ RL05a GRACE solutions (Gaussian smoothing with 750km radius is applied and C_{20} is replaced for both time series). Note that some months are missing in the GRACE time series, e.g. Oct & Nov 2015.

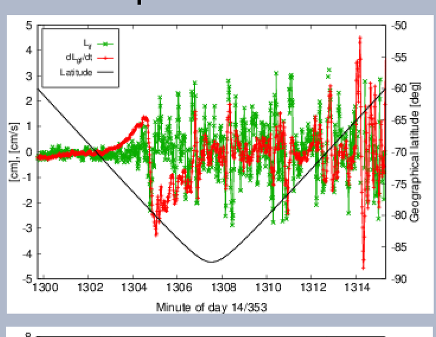

Fig. 2: dL_{gf}/dt (red), L_{if} carrier phase residuals of kinematic POD (green) and geographical latitude (black) for Swarm-A passing the south pole on day 2014/353 (Dec 19th, 2014).

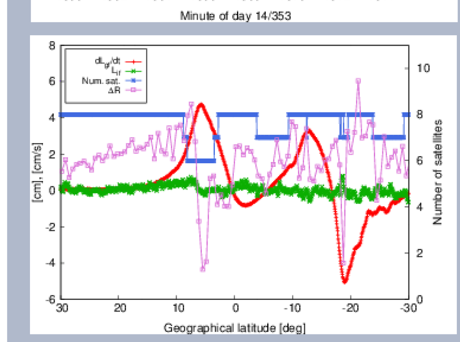

Fig. 3: dL_{gf}/dt (red), L_{if} carrier phase residuals of kinematic POD (green), number of GPS satellites used for kinematic positioning (blue) and difference in radial direction between reduced-dynamic and kinematic orbit (magenta) for Swarm-A passing the equator on day 2014/305 (Nov 1st, 2014) west of South America.

Impact of ionospheric disturbances on GPS observations

- Daily RMS values of GPS carrier phase residuals of the kinematic POD are clearly correlated with the Total Electron Content (TEC) in the ionosphere and thus vary between 4 and 8 mm.
- The carrier phase residuals are also geographically correlated, i.e. they are significantly larger over the geomagnetic poles and around the geomagnetic equator. In particular the problems around the geomagnetic equator are propagated into Swarm gravity field solutions when these kinematic orbit positions are used as pseudo-observations[1]. Again, the magnitude of these systematic errors varies depending on the ionospheric activity.
- By analyzing the first time derivative of the geometry-free linear combination (dL_{gf}/dt), it is shown that different mechanisms act in polar and equatorial regions[2]: At high latitudes, mainly high-frequency scintillation-like features occur resulting in larger carrier phase residuals (Fig. 2). Equatorial crossings are rather characterized by large, but deterministic changes of dL_{gf}/dt which are not reflected by larger residuals, but cause systematic biases in the kinematic orbit positions (Fig. 3).

GPS data screening

- As a first, data-driven attempt to mitigate these ionosphere-induced problems, a GPS data screening on observation level is applied at AIUB by simply omitting any observation where dL_{gf}/dt exceeds a threshold of 2 cm/s[1].
- Results based on this screened data show less pronounced systematic artefacts around the geomagnetic equator (Fig. 5, left), but some systematic errors can still remain in the gravity solutions and the effectiveness of the data screening depends on the ionospheric activity.
- Further drawbacks of this method are: screened orbits perform slightly worse in SLR orbit validation and the very low degrees of the gravity solutions, which are on the other hand the ones of most interest, can be degraded as well.

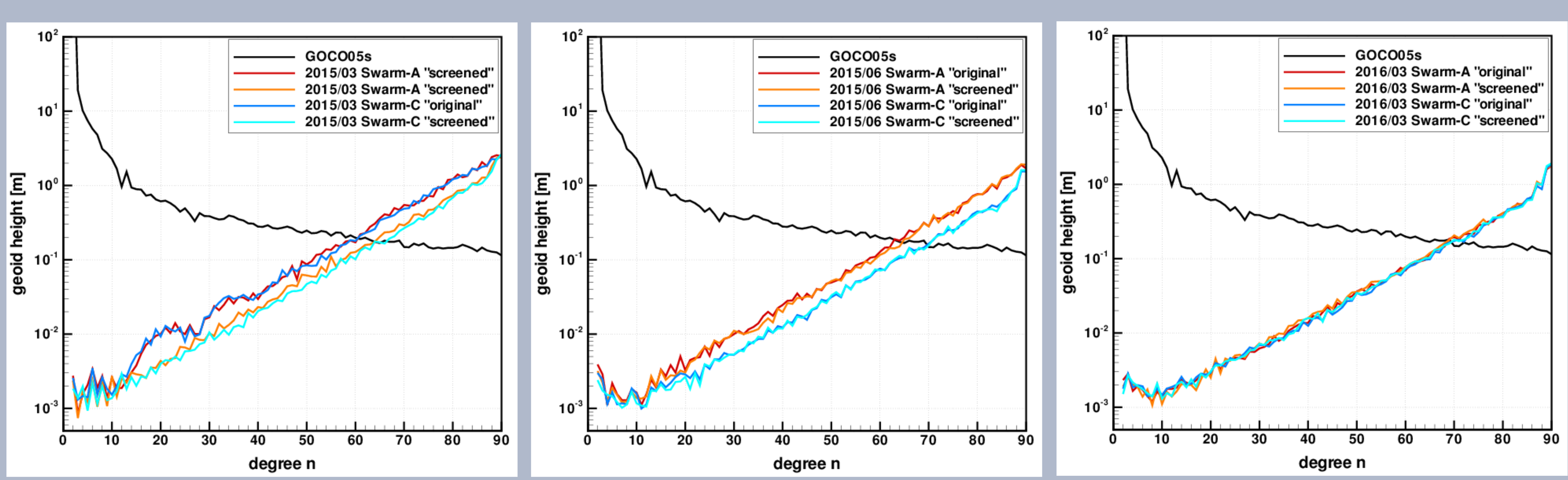

Fig. 4: Degree amplitudes w.r.t. GOCO05s of Swarm-A and -C individual monthly gravity field solutions based on original and screened GPS data for March 2015 (left), June 2015 (middle) and March 2016 (right).

Impact of updated tracking loop settings

- In order to improve the robustness of GPS tracking against ionospheric scintillation, the Swarm GPS receivers' tracking loop bandwidths have been stepwise widened.
- These updates started in May 2015 and have not been done simultaneously on all three satellites. Consequently, there are certain periods where the co-orbiting Swarm-A and -C satellites have different tracking loop settings and thus, comparing their individual gravity field results allows for an assessment of the impact of the tracking loop updates on gravity field recovery[2].
- In June 2015, the bandwidth for L_2 on Swarm-A was still set to its initial value of 0.25 Hz whereas on Swarm-C it has been updated to 0.5 Hz. In addition, the ionospheric activity in this month was high enough to significantly affect orbit and gravity field results. Looking at Figs. 4 and 5, it becomes obvious that this first tracking loop update from 0.25 Hz to 0.5 Hz helps to substantially improve Swarm gravity field solutions and its effect even exceeds the effect of the GPS data screening. It has to be noted that these improvements are not related to missing GPS observations around the geomagnetic equator.
- Further tracking loop updates to bandwidths of 0.75 Hz (Swarm-A and –C) and 1 Hz (so far on Swarm-C only) did not show any additional improvements, but since the times they were implemented, the ionospheric activity has been relatively low and a possible impact on Swarm precise science orbits and gravity field solutions needs to be investigated as soon as a long enough period with higher ionospheric activity is available.

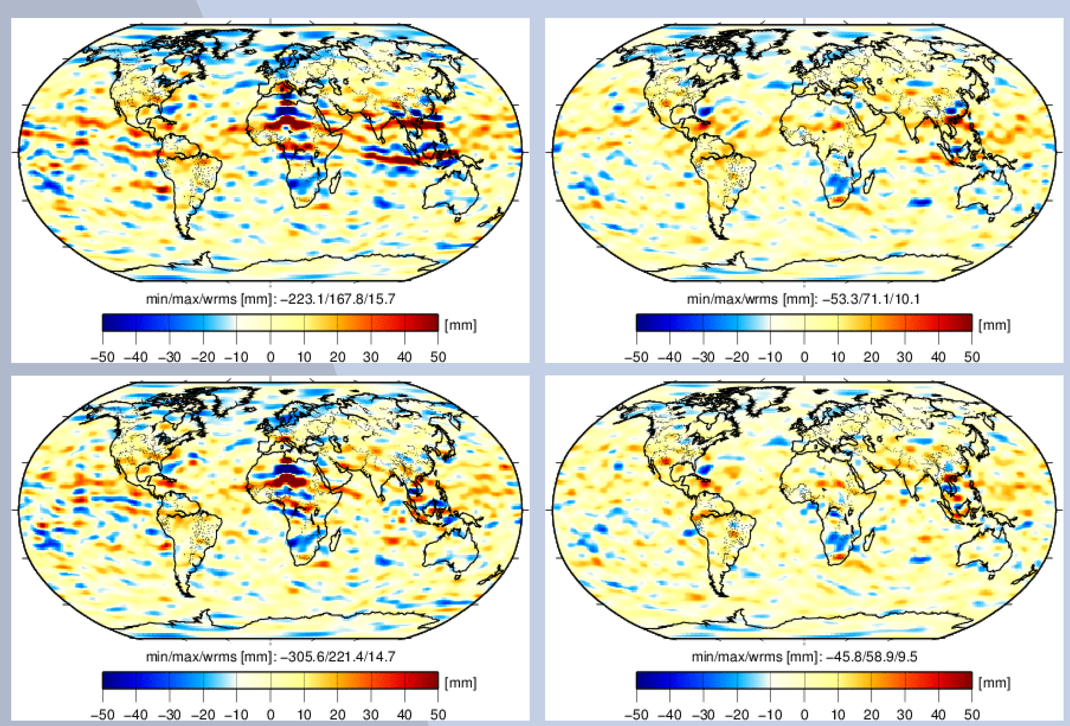

Fig. 5: Geoid height variations w.r.t. GOCO05s of Swarm-A (left) and Swarm-C (right) individual monthly gravity field solutions for June 2015 based on original (top) and screened (bottom) kinematic orbits. Gaussian smoothing with 400km radius is applied.

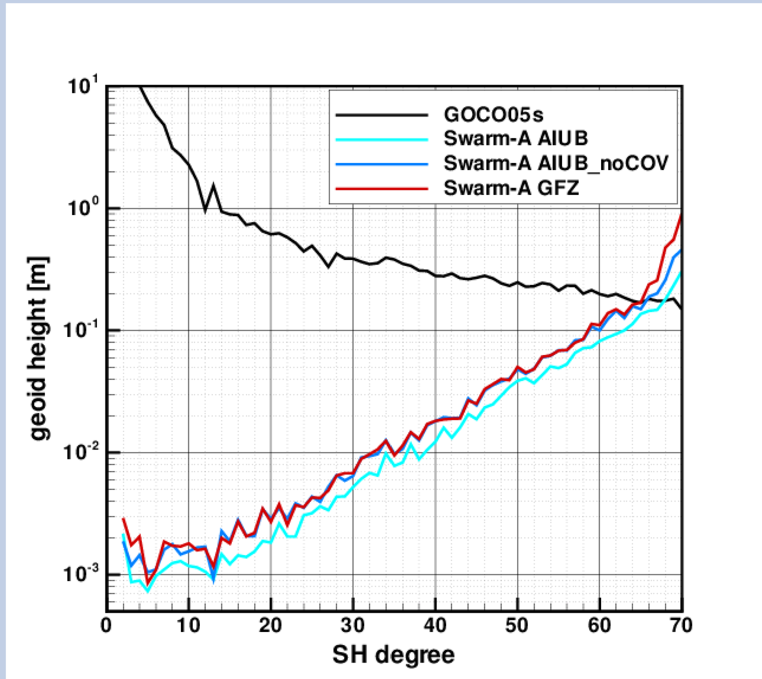

Fig. 6: Degree amplitudes w.r.t. GOCO05s of Swarm-A monthly solutions for July 2016 from AIUB and GFZ. Kinematic orbits from AIUB are used as pseudo-observations for all solutions. Unlike usual, no epoch-wise covariance information is used in the AIUB_noCov solution to allow for a fair comparison with the GFZ solution.

Swarm Processing at GFZ

Orbit determination

- At GFZ, dynamic Swarm-A/B/C orbits for the month July 2016 have been generated in a similar setup as applied for CHAMP and GRACE Rapid Science Orbits[4].
- Daily RMS values of GPS carrier phase residuals are between 6 and 7 mm which is close to the official Swarm Level2 reduced-dynamic orbit product generated at TU Delft reporting 5 mm in periods with similar ionospheric activity as in July 2016[5].
- So far, no attitude information is used and 30s GPS clocks are used (5s clocks are used at TU Delft as well as AIUB) yielding room for further improvements.

Gravity field determination

- Usually, hl-SST gravity field recovery at GFZ would be based on GPS phase and code observations, i.e. directly after orbit determination normal equations including the solve-for gravity field parameters would be set up. However, for reasons that have to be further investigated, resulting Swarm gravity fields turned out to be significantly worse than expected.
- If kinematic orbits from AIUB are used as pseudo-observations instead, the GFZ Swarm solution is comparable to the one from AIUB (Fig. 6).

Summary & Outlook

Monthly Swarm hl-SST gravity fields are routinely processed at AIUB and shall be also routinely processed at GFZ in the near future. Their quality is good enough to detect large-scale mass variations. Particularly during the first approx. 1.5 years of the Swarm mission, kinematic orbit positions and subsequently the gravity fields are systematically degraded over the geomagnetic poles and along the geomagnetic equator. The tracking loop updates helped to improve the quality of the GPS data making additional data screening less critical or even obsolete. However, this might change again under the condition of very high ionospheric activity. Therefore, an optimized screening threshold taking both ionospheric activity and tracking loop settings into account seems to be necessary in order to obtain the best possible Swarm gravity fields.

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