Reprocessing of GOCE Precise Science Orbits

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Introduction

- Gravity Field and Steady-State Ocean Circulation Explorer (GOCE) orbited Earth between March 2009 and November 2013 and conducted gradiometry measurements of Earth's gravity field.
- In the framework of the GOCE High-level Processing Facility (HPF), the Astronomical Institute of the University of Bern (AIUB) was responsible for the generation of the **GPS-based Precise Science Orbits (PSOs)** of the GOCE mission (Bock et al., 2014).
- Since the end of the GOCE mission the understanding of remaining artifacts, especially in gradiometer data, but also in GPS data, has improved a lot and the corresponding processors and processing strategies have been significantly advanced $\Longrightarrow$ ESA initiated **reprocessing of entire GOCE data**.
- AIUB is responsible for PSO reprocessing, using:
  - latest version of Bernese GNSS Software,
  - homogeneously reprocessed GPS products (reference frame: IGb08) from a reprocessing effort conducted at AIUB in the frame of the Horizon 2020 project European Gravity Service for Improved Emergency Management (EGSIEM, http://egsiem.eu),
  - refined data handling strategies to mitigate ionosphere-induced artifacts along the geomagnetic equator in GPS-only gravity field models derived from GOCE kinematic orbits.

GOCE PSO processing

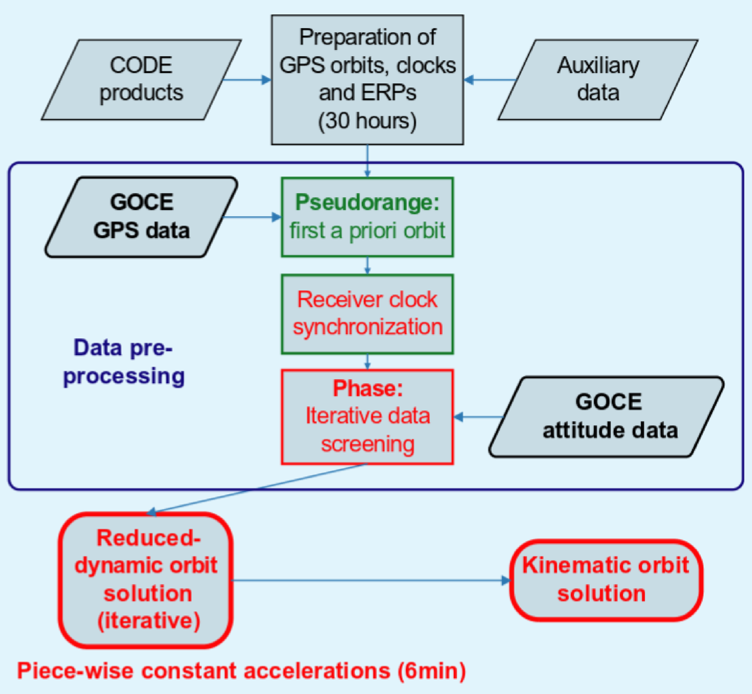

Figure 1: Flow diagram of GOCE PSO determination (from Bock et al., 2007). CODE: Center for Orbit Determination in Europe.

- GOCE PSOs are derived from tracking data of two 12-channel dual-frequency GPS receivers and the attitude information from star cameras. Only data of main GPS antenna is used, apart from days 003 and 006-041 of 2011, where only redundant receiver delivered data. Figure 1 shows the general data processing work flow, Tab. 1 summarizes the processing standards applied.
- The orbit arcs span 30 h each day (lasting from 21:00 of previous day to 03:00 of next day), avoiding orbit degradations at arc boundaries and allowing for 6 h orbit overlap computation as orbit quality indicator.

GPS data	Undifferenced ionosphere-free carrier phase observations
Sampling	1 s (kin.), 10 s (red.-dyn.)
GPS antenna model	igs08.atx
Gravity field	GOCO05S (200 × 200)
Solid Earth tides	IERS2000
Pole tides	IERS2010
Ocean tides	EOT11A (50 × 50)
Non-gravitational forces	No explicit modeling
Empirical parameters	Constant and 6-minutes piecewise constant accelerations (constrained) in radial, along-track, cross-track

Table 1: Processing standards used for PSO reprocessing

For the PSO reprocessing the following major steps were required:

1. Preparation of GPS products (orbits and 5 s clock corrections) in 30 h batches
2. Computation of new Phase Center Variation (PCV) maps for GOCE GPS antennas
3. Establishment of data handling strategies to mitigate ionosphere-induced artifacts along the geomagnetic equator in GPS kinematic orbits (see below).

30 h GPS products

- 30 h PSO arcs require GPS products in 30 h batches.
- The EGSIEM GPS products were computed in 24 h batches, the clock corrections did not contain midnight epoch of subsequent day (last epoch each day: 23:59:55 GPST).
- While 24 h GPS orbit positions can readily be concatenated to longer batches, the creation of 30 h clock corrections from 24 h batches is more tricky (due to orbit and clock offsets at day boundaries).
- Procedures for proper clock concatenation developed in the frame of HPF (Bock et al., 2007), but they require midnight epoch of subsequent day.
- GPS clocks are noisy and do not allow for straightforward extrapolation without degradation, not even over 5 s from 23:59:55 to 00:00:00.
- The midnight epochs had to be computed from a proper clock densification from 30 s to 5 s sampling, using GPS data of ground stations (same stations as used for creation of EGSIEM clock products).

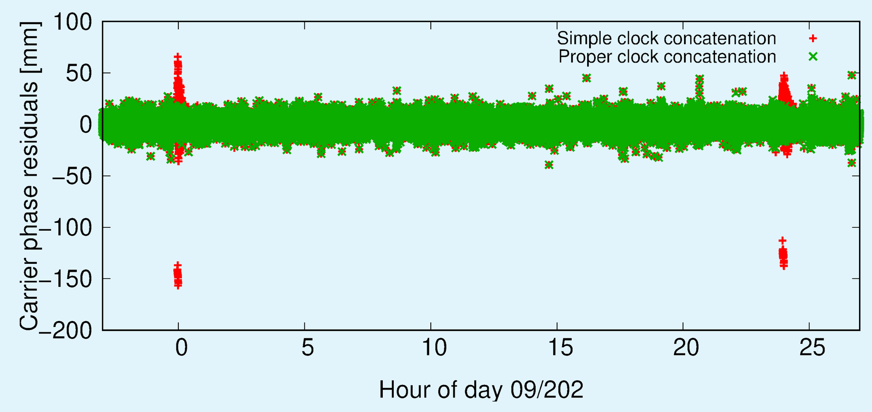

Figure 2: Ionosphere-free carrier phase residuals of a reduced-dynamic GOCE POD for day 09/202 (21 July 2009) when using 30 h GPS clock corrections from a simple concatenation (red) and the finally adopted proper concatenation (green). Simple clock concatenation leads to obvious degradations at the day boundaries.

PCV maps

- GPS PCV patterns used for operational GOCE PSOs had constant values for zenith angles 14-17°. Extended in the meantime $\rightarrow$ generation of new GOCE PCV map required (consistency with igs08.atx).
- GOCE PCV maps created by iterative stacking of carrier phase residuals of a reduced-dynamic POD of an extended time span (10 iterations, main antenna: 249 days from 12 April - 31 December 2009, redundant antenna: 172 days from 26 March 2010 - 20 October 2013).

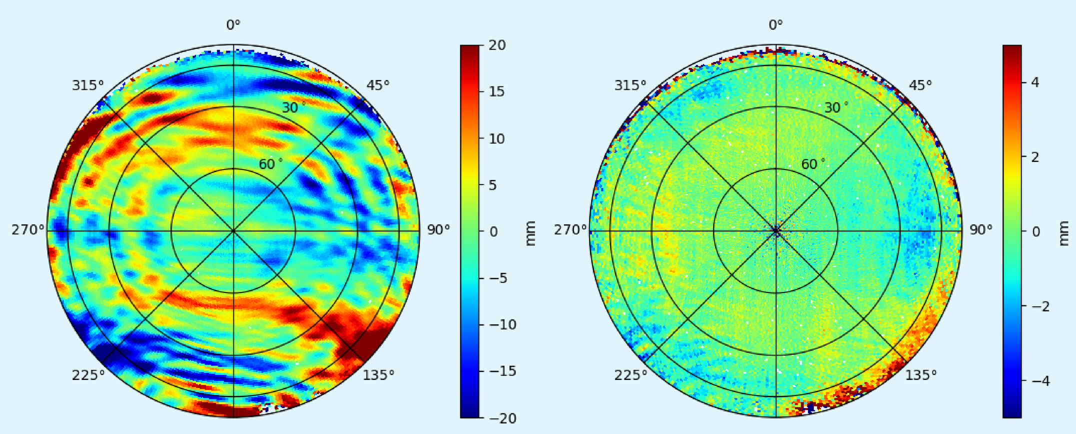

Figure 3: New PCV map of main GOCE GPS antenna (left) and differences w.r.t. PCV map used for generation of operational PSOs (right).

Ionosphere-induced artifacts

- Operational PSOs showed systematic degradations along geomagnetic equator, which became stronger with larger ionospheric activity and which show up in GPS-only GOCE gravity fields derived from kinematic orbit positions as pronounced bands (Jäggi et al., 2015):

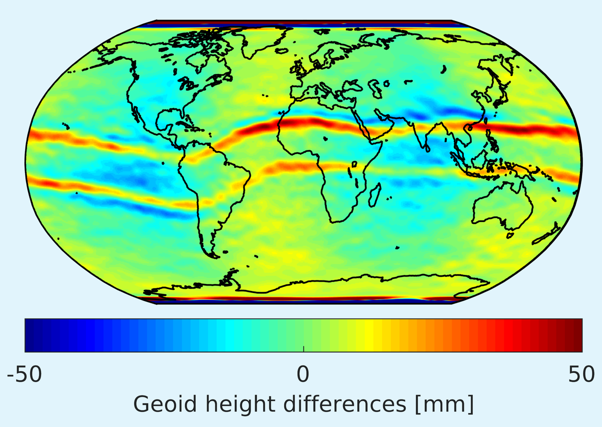

Figure 4: Geoid height differences (w.r.t. ITSG-Grace2016) of a degree-120 GPS-only gravity field solution for November 2009-July 2012, using the operationally generated kinematic PSOs (300 km Gauss filtered).

- Was understood to be caused by GPS receiver problems at high ionospheric dynamics (similar problems for Swarm).
- During GOCE operational PSO generation the following mitigation strategy was developed: For each GPS observation,
  1. compute geometry-free linear combination $L_{gf} = L_1 - L_2$ of carrier phase measurements L_1 and L_2 on both GPS frequencies f_1 and f_2,
  2. discard observation if $|dL_{gf}/dt| > 5$ cm/s.
- Allowed to strongly reduce the artifacts in the GOCE GPS-only gravity field solutions, but significantly degraded PSO quality (in terms of SLR residuals or overlaps) $\longrightarrow$ **was not applied for the generation of the operational PSO products**.
- Further tests performed to assess impact of other mitigation strategies, based on **higher time derivatives of L_{gf}** and the **Rate of TEC (Total Electron Content) Index (ROTI)**,

$$ROTI = \sqrt{\frac{\langle \Delta TEC^2\rangle - \langle \Delta TEC\rangle^2}{\Delta t^2}}$$

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

which is a measure for scintillation (averaging over 30 s).

- Downweighting instead of omitting GPS data turned out more beneficial (avoid setting up new carrier phase ambiguity parameters). Finally chosen strategy (ϕ: geographic latitude of GOCE):
  1. If $|d^2L_{gf}/dt^2| > 0.04$ cm/s^2 and $|\phi| < 50°$, set $\sigma_d = 5$, otherwise $\sigma_d = 1$
  2. Set $\sigma_r = 6 \cdot \mathrm{ROTI}$
  3. Use $\sigma = \max(\sigma_d, \sigma_r)$ for downweighting GPS observation.

Orbit results

Figure 5 shows the carrier phase residuals for the reduced-dynamic POD, the differences between reduced-dynamic and kinematic PSOs, and the orbit overlaps for the entire GOCE mission, for both the operationally generated and reprocessed PSOs. These orbit quality measures show clear time-dependent variations due to different ionospheric activities.

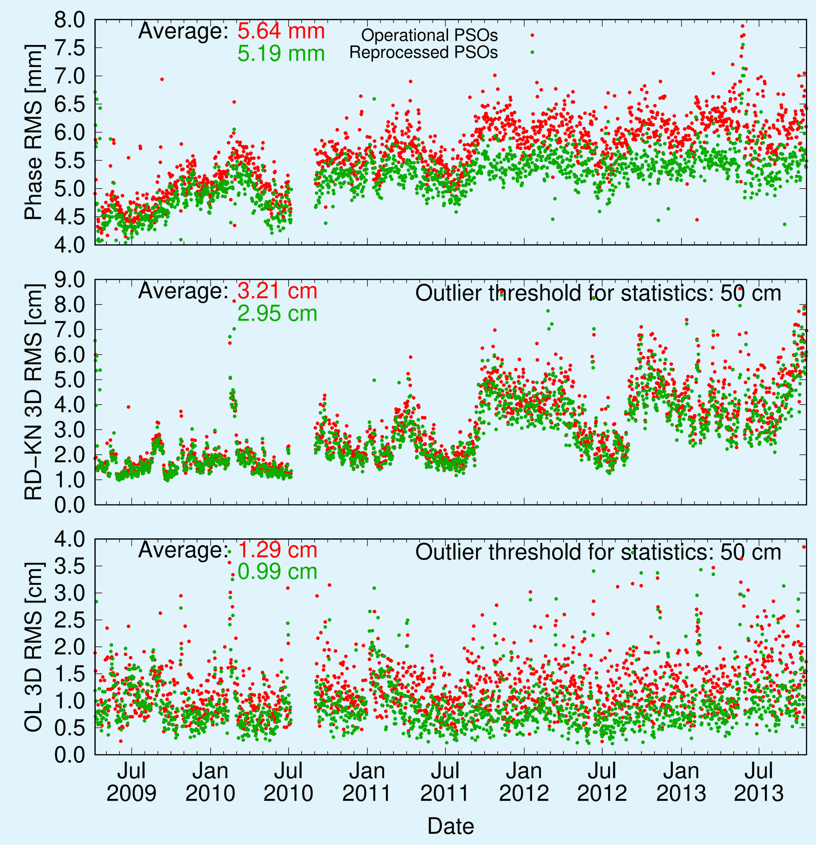

Figure 5: Top: Daily RMS values of ionosphere-free carrier phase residuals of reduced-dynamic POD. Middle: Daily RMS values of 3D differences between reduced-dynamic and kinematic PSOs. Bottom: Daily RMS values of 3D overlaps (i.e., differences between subsequent orbit arcs from 21:00 to 03:00) for the reduced-dynamic PSOs. The numbers in the plots show the average RMS values over the entire time span.

Table 2 shows the Satellite Laser Ranging (SLR) residual statistics for the reduced-dynamic and kinematic PSOs. SLR normal points from 17 laser stations were used for the validation, outliers larger than 20 cm were rejected, a few passes were manually removed. Station coordinates were introduced according to SLRF2008, no parameters were adjusted.

	Operational		Reprocessed	
Year	red.-dyn.	kin.	red.-dyn.	kin.
2009	$+0.1 \pm 17.3$	-0.8 ± 18.2	$+2.3 \pm 17.6$	$+1.9 \pm 19.1$
2010	$+2.5 \pm 15.3$	$+3.0 \pm 17.9$	$+5.3 \pm 15.9$	$+5.0 \pm 18.0$
2011	$+2.4 \pm 15.2$	$+3.0 \pm 23.3$	$+3.9 \pm 15.2$	$+5.0 \pm 22.1$
2012	$+4.8 \pm 18.4$	$+7.1 \pm 26.6$	$+5.6 \pm 18.2$	$+7.8 \pm 24.6$
2013	$+0.4 \pm 24.9$	$+3.4 \pm 30.7$	$+1.4 \pm 23.0$	$+4.2 \pm 27.1$

Table 2: SLR residual statistics (mean and standard deviation in mm).

GPS-only gravity field results

The reprocessed kinematic GOCE orbit positions and their epoch-wise covariance information allow to significantly reduce the pronounced bands along the geomagnetic equator in derived gravity field solutions. In fact, the downweighting strategy introduced earlier was found by numerous tests with different strategies, where orbit and gravity field quality served as benchmark.

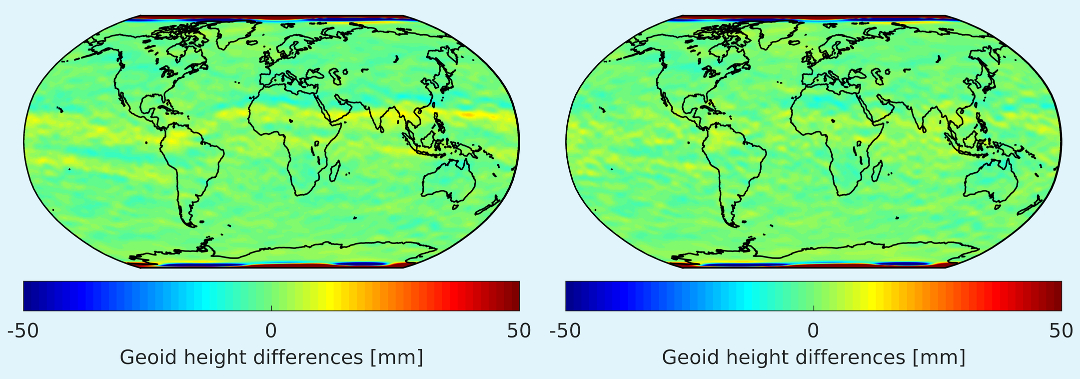

Figure 6: Geoid height differences (w.r.t. ITSG-Grace2016) of degree-120 GPS-only gravity field solutions for November 2009-July 2012, using the reprocessed kinematic PSOs (300 km Gauss filtered). Left: Only outliers in kinematic positions removed (comparable to Fig. 4). Right: Additional screening of kinematic positions with large variance. In contrast to the solution shown in Fig. 4, these solutions were computed using the common mode accelerometer data, improving the lowest degrees.

Summary and conclusion

- AIUB has reprocessed the reduced-dynamic and kinematic GOCE PSOs in the frame of an ESA-initiated reprocessing campaign of the entire GOCE data.
- The latest version of the Bernese GNSS Software and the GPS products of the EGSIEM reprocessing campaign were used. In addition, a more advanced GPS data downweighting strategy was developed and used to mitigate ionosphere-induced artifacts in kinematic orbits.
- The data downweighting proved to not degrade the absolute orbit quality and to be capable of removing the artifact in derived GPS-only gravity field models along the geomagnetic equator to a large extent.

References

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