GPS-ONLY GRAVITY FIELD RECOVERY FROM GOCE

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ABSTRACT

The Gravity field and steady-state Ocean Circulation Explorer (GOCE), the first Earth Explorer Core Mission of the European Space Agency (ESA), is equipped with a 12-channel, dual-frequency Global Positioning System (GPS) receiver for precise orbit determination (POD), instrument time-tagging, and the determination of the long wavelength part of the Earth's gravity field. The very low orbital altitude of the GOCE satellite and the availability of dense 1 s GPS tracking data are unique and ideal characteristics to exploit the contribution of GPS high-low Satellite-to-Satellite Tracking (hl-SST) to gravity field recovery. We present a gravity field solution uniquely based on GOCE GPS hl-SST data covering a time period of about 1.7 years, and compare and combine it with a solution obtained from 8 years of GPS hl-SST data from the CHAllenging Minisatellite Payload (CHAMP) mission. Despite the much shorter time span covered by the GOCE data, the recovery of the Earth's gravity field may be significantly improved above degree 40 in the combined solution. Below degree 40 the quality of the spherical harmonic coefficients remains essentially unchanged with respect to the CHAMP-only solution.

Key words: GOCE; CHAMP; GPS; Kinematic positions; Gravity field recovery.

1. INTRODUCTION

Since the launch of the CHAllenging Minisatellite Payload mission (CHAMP, [16]) observations from the Global Positioning System (GPS) are not only used for precise orbit determination (POD), but have also been established as an important pillar for extracting the long wavelength part of the Earth's static gravity field [17]. Although current gravity missions such as the Gravity field and steady-state Ocean Circulation Explorer (GOCE, [3]) are equipped with other core instruments than GPS receivers, they still make use of the GPS high-low Satellite-to-Satellite Tracking (hl-SST) to support the determination of the low degree spherical harmonic (SH) coefficients of the Earth's gravity field. In the case of GOCE these coefficients are even exclusively determined from GPS data as the measurements of the core instrument, the three-axis gravity gradiometer, are band-limited [14]. The very low Earth orbit (LEO) of the GOCE satellite and the availability of dense 1 s GPS tracking data are perfectly suited to exploit the contribution of GPS hl-SST to gravity field recovery and to compare the GOCE results with those obtained from CHAMP, which marked the state-of-the-art of GPS-only gravity field recovery so far [15].

GOCE 1 s kinematic positions are computed at the Astronomical Institute of the University of Bern (AIUB) in the frame of the GOCE High-level Processing Facility (HPF, [7]) as part of the GOCE precise science orbit product (PSO, [1]). They are provided to the user community together with a band-limited part of the covariance matrix covering four off-diagonal blocks [4]. Based on this information a two-step procedure is applied to perform gravity field recovery according to [13], where first results based on shorter data spans were presented. In a first step the kinematic positions are weighted according to the covariance information and serve as pseudo-observations to set up normal equations on a daily basis for the unknown SH coefficients and for arc-specific orbit parameters in a generalized orbit determination problem. In a second step the arc-specific parameters are pre-eliminated and the reduced daily normal equations are accumulated into systems covering longer intervals. Eventually the accumulated systems are inverted in order to obtain the corrections of the SH coefficients with respect to the a priori gravity field parameters. The solutions presented in this article are based on EGM96 [8] serving as a priori model and are computed without applying any regularization.

2. IMPACT OF POSITION SAMPLING

In order to assess the impact of the position sampling on gravity field recovery, the original series of 1 sec GOCE kinematic positions is sampled to 5 and 30 sec for a test period starting on April 20 and ending on November 5, 2009. Figure 1 shows the square-roots of the degree difference variances of recoveries up to degree 90 with respect to ITG-GRACE03S [9] when either taking covariance information over four off-diagonal blocks into account ("04-sec cov") for the 1 sec GOCE kinematic positions, or when only considering the epoch-wise covariance information ("epoch cov") for the original 1 sec or

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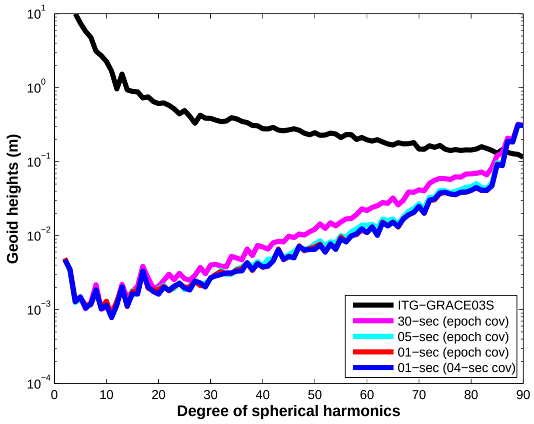

Figure 1. Square-roots of degree difference variances of gravity field recoveries from GOCE kinematic positions with respect to ITG-GRACE03S using different sampling intervals (April 20, 2009 – November 5, 2009).

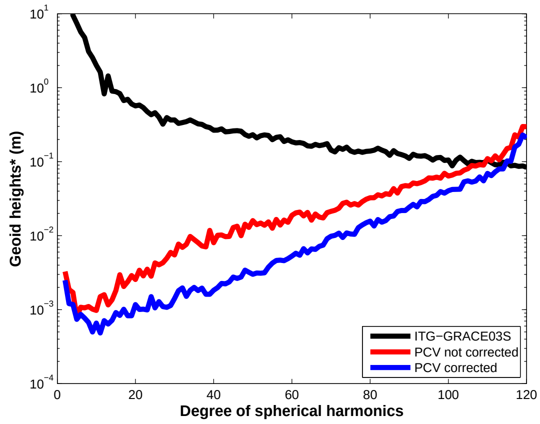

Figure 2. Square-roots of degree difference variances of gravity field recoveries from GOCE kinematic positions with respect to ITG-GRACE03S (: zonal and near-zonal terms excluded), computed either with or without antenna PCVs corrected (April 20, 2009 – December 31, 2009).*

the sampled 5 and 30 sec GOCE kinematic positions. The quality of the recovered gravity field is significantly improved for the higher degrees when processing kinematic positions with 5 instead of 30 sec sampling, but no improvement at all is achieved for degrees below 20 when increasing the position sampling, which is an indication for the presence of unmodeled systematic errors. Figure 1 shows that the recovered gravity field is only marginally improved when the position sampling is further increased to 1 sec, which may be partly caused by the linearly interpolated 5 sec GPS clock corrections used for the determination of the kinematic PSO positions. Figure 1 also shows that even the most correct solution, taking covariances over four off-diagonal blocks into account, is not able to further improve gravity field recovery from GOCE hl-SST data.

3. IMPACT OF ANTENNA PHASE CENTER VARIATIONS

Empirical phase center variations (PCVs) of the GOCE helix main antenna have been found to significantly impact the quality of the GOCE POD results [2]. Figure 2 shows the square-roots of the degree difference variances (zonal and near-zonal terms excluded due to the polar gap degradation according to [19]) of recoveries up to degree 120 from two different sets of about 8 months of GOCE 1 sec kinematic positions, computed either by neglecting PCVs in the kinematic orbit determination ("PCV not corrected") or by empirically correcting for them ("PCV corrected"). Figure 2 confirms that antenna PCV modeling is not only important for GOCE POD, but also for the subsequent recovery of the Earth's gravity field from kinematic positions which are particularly sensitive to antenna PCV mismodelings. Figure 2 shows that the SH coefficients are significantly improved up to the highest degrees when empirical PCVs are properly taken into account, which is related to rather complicated small-scale structures of the PCVs of the GOCE helix main antenna.

4. GOCE SST-ONLY SOLUTION

GOCE 1 sec kinematic positions from about 1.7 years have been processed (April 20, 2009 to December 31, 2010) to assess the current state of the performance of GOCE SST-only solutions. Figure 3 shows the square-roots of the degree difference variances of the recovery up to degree 120 with respect to ITG-GRACE2010 [10]. Zonal and near-zonal terms are again excluded in the comparison due to the polar gap degradation which is inherent to any unconstrained GOCE-only solution. The comparison of the GOCE SST-only gravity field model with the model AIUB-CHAMP03S based on eight years of CHAMP GPS data [15] shown in Fig. 3 indicates that the GOCE solution is still inferior at the lower degrees, which has to be attributed to the much smaller time span covered by the GOCE data (1.7 vs. 8 years). At the higher degrees, however, the GOCE SST-only solution is significantly better due to the much lower orbital altitude of the GOCE satellite. The potential of GOCE GPS hl-SST gravity field recovery is impressively demonstrated by the significantly smaller slope of the differences shown in Fig. 3 with a crossing point at about degree 50 with the CHAMP solution. The omission errors of the GOCE SST-only solution beyond degree 115 are significant and indicate a sensitivity beyond the maximum degree of 120, even if the solution is currently just based on about 1.7 years of data.

Figure 4 shows geoid height differences computed up to degree and order 100 (including zonal and near-zonal coefficients) of the GOCE SST-only solution with respect to ITG-GRACE2010, whereas regions with lati-

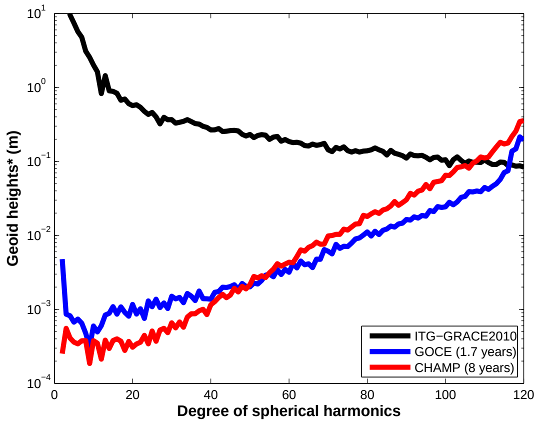

Figure 3. Square-roots of degree difference variances of the GOCE SST-only solution and the CHAMP SST-only solution with respect to ITG-GRACE2010 (: zonal and*

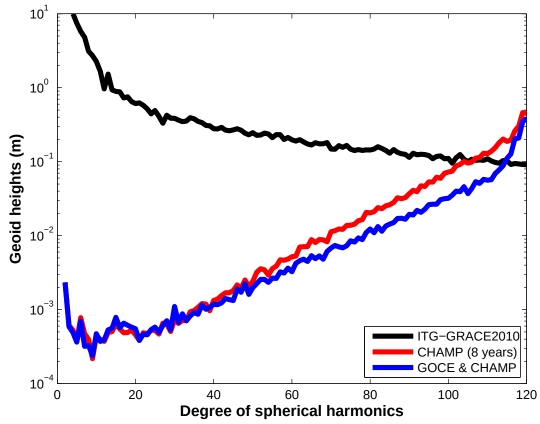

Figure 6. Square-roots of degree difference variances of the combined GOCE & CHAMP SST-only solution with respect to ITG-GRACE2010 (zonal and near-zonal terms

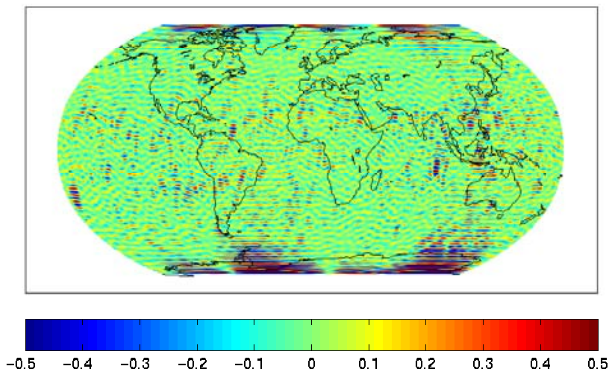

Figure 4. Geoid height differences (m) up to degree and order 100 of the GOCE SST-only solution with respect to ITG-GRACE2010 (polar gap regions excluded).

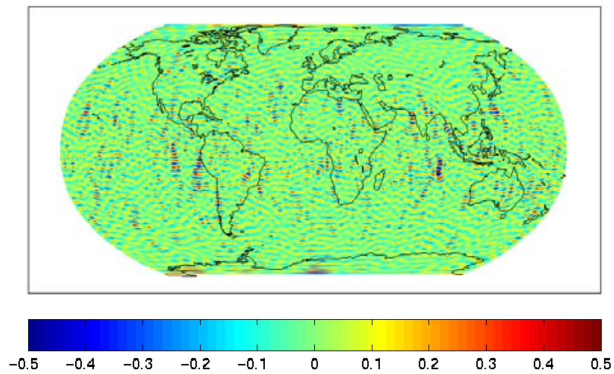

Figure 7. Geoid height differences (m) up to degree and order 100 of the GOCE & CHAMP SST-only solution with respect to ITG-GRACE2010 (polar gap regions excluded).

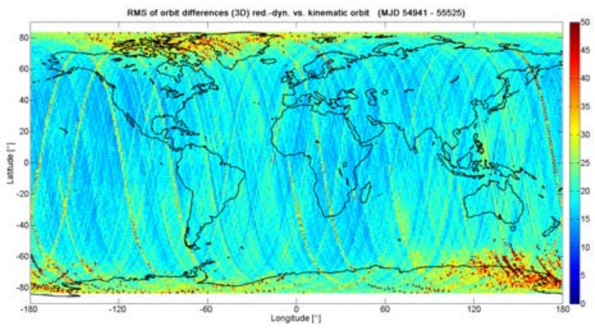

Figure 5. RMS of orbit differences (mm) between the kinematic and the reduced-dynamic GOCE PSO products per $1^\circ \times 1^\circ$ geographical bins. Pronounced larger differences are visible over the geomagnetic poles, indicating that the quality of the kinematic PSO product is degraded over these regions. Correlations with unexpected L2 losses in the vicinity of the geomagnetic poles are currently under investigation.

tudes $|\phi| > 83^\circ$ are excluded in the comparison due to the sun-synchronous GOCE orbit. Apart from the regions in the vicinity of the geomagnetic poles, Fig. 4 shows a rather homogeneous pattern of differences with an overall RMS of 14.3 cm. The homogeneous pattern is caused by the only weakly estimated high degree zonal coefficients, whereas the degradation over the geomagnetic poles is caused by an additional degradation of the kinematic orbits in these regions as shown in Fig. 5.

Figure 5 shows the differences between the kinematic and the reduced-dynamic positions of the PSO product per $1^\circ \times 1^\circ$ geographical bins and reveals pronounced differences in the vicinity of the geomagnetic poles, especially in the southern hemisphere. The root-cause of the larger differences is still a topic of further research, but might be related to unexpected losses of GPS carrier phase observations on the second carrier frequency (L2 losses) in the vicinity of the geomagnetic poles [11].

5. COMBINED GOCE & CHAMP SST-ONLY SOLUTION

The GOCE SST-only solution presented in Sect. 4 has been combined on the normal equation level with the AIUB-CHAMP03S solution based on eight years of CHAMP GPS data. Figure 6 shows the square-roots of the degree difference variances of the recovery up to degree 120 with respect to ITG-GRACE2010 for the combined GOCE & CHAMP model and for the AIUB-CHAMP03S model. As opposed to Fig. 3 the zonal and near-zonal terms are included in the comparison shown in Fig. 6, because the combined GOCE & CHAMP solution does not suffer from any degradation of the zonal and near-zonal coefficients due to the less pronounced polar gap in the CHAMP ground track coverage.

Figure 7 shows geoid height differences computed up to degree and order 100 of the combined GOCE & CHAMP solution with respect to ITG-GRACE2010, whereas regions with latitudes $|\phi| > 83°$ are again excluded in the comparison for a direct comparison with Fig. 4. As opposed to Fig. 4 a very homogeneous pattern of differences is seen in Fig. 7 with an overall RMS of 10.1 cm and without any indication for a degradation over the geomagnetic poles (RMS of 10.2 cm with the polar regions included).

6. VALIDATION OF THE LOW DEGREE SH COEFFICIENTS

LAGEOS orbits are mainly sensitive to the coefficients of the Earth's gravity field up to about degree 20. Weekly solutions for the LAGEOS satellite orbits have been estimated from Satellite Laser Ranging (SLR) data together with Earth rotation parameters, station coordinates, and range biases according to [18]. Figure 8 shows the RMS of the weekly solutions obtained from SLR data covering the year 2009 when using the gravity field models EIGEN-GL04C [5], ITG-GRACE2010, and the combined GOCE & CHAMP solution from Sect. 5 for the dynamic LAGEOS orbit determination up to degree 50, respectively. The overall RMS of 7.40 mm, 7.60 mm, and 7.39 mm indicate that the low degree SH coefficients of the combined GOCE & CHAMP SST-only solution are fully competitive and even slightly better than those from the GRACE-based models EIGEN-GL04C and ITG-GRACE2010.

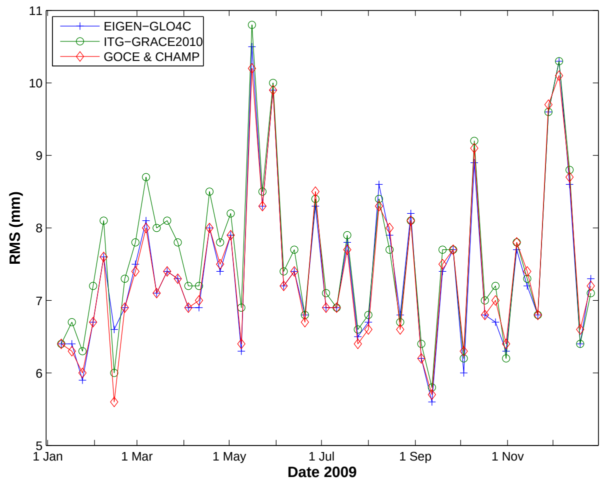

Figure 8. RMS of weekly orbital fits to the two LAGEOS satellites using SLR data and different gravity field models for dynamic orbit determination.

7. VALIDATION OF THE HIGH DEGREE SH COEFFICIENTS

T. Gruber from the Institut für Astronomische und Physikalische Geodäsie of the Technische Universität München compared the geoid heights derived from EIGEN-5S, ITG-GRACE03S, ITG-GRACE2010, AIUB-CHAMP03S, the GOCE SST-only solution, and the combined GOCE & CHAMP solution with geoid heights derived from different sets of levelling data using the method described in [6]. Table 1 shows the RMS values of the differences around the mean values between the filtered geoid heights from levelling and geoid heights from the different models up to degree 60. In analogy to Sect. 6 the results confirm that the SST-only solutions are very close to the GRACE-based models and of high quality, provided that they are not validated up to higher degrees. Even the validation with the high quality data set over Germany reveals almost no differences between the SST models and the GRACE-based models.

8. CONCLUSIONS

A GOCE SST-only model based on about 1.7 years of 1-sec kinematic positions of the GOCE PSO product has been computed. The model is of high quality thanks to the availability of a dense sampling of the kinematic positions (5-sec sampling should be used at least), the empirical correction of the antenna phase center variations of the GOCE helix main antenna for generating the GOCE PSO product, and the very low orbital altitude of the GOCE satellite. Weaknesses of the GOCE SST-only solution are the zonal and near-zonal coefficients due to the polar gap caused by the sun-synchronous orbit and the degradation over the geomagnetic poles due to possible correlations with unexpected L2 carrier phase losses. A combined solution based on the GOCE SST-only solution and a solution based on eight years of CHAMP data has been computed. The resulting model is significantly improved above degree 40 with respect to the CHAMP-only solution due to the much lower orbital altitude of the GOCE satellite. The combined solution is neither degraded over the polar regions, nor in the zonal and near-zonal SH coefficients. The external validation with SLR and terrestrial data confirms a very high quality of the recovered low degree SH coefficients close to those of

Table 1. RMS of differences (cm) between different levelling data sets and geoid heights from gravity field models up to degree 60 (1-sigma outlier criterion applied).

	EIGEN 5S	ITG GRACE03S	ITG GRACE2010	AIUB CHAMP03S	GOCE SST-only	GOCE & CHAMP
Australia (GPS)	13.2	13.2	13.2	13.3	13.2	13.1
Germany (EUVN)	1.7	1.6	1.8	2.0	1.9	1.8
Germany (GPS)	2.0	2.0	1.9	2.1	2.1	2.0
Canada (GPS)	8.4	8.5	8.7	8.7	8.0	8.6
EUREF (GPS)	8.9	8.9	9.1	9.0	8.9	9.0
Japan (GPS)	5.9	5.9	5.9	5.8	6.1	5.8

GRACE-based models.

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