GPS-only gravity field recovery with GOCE, CHAMP, and GRACE

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Abstract

Gravity missions such as the Gravity field and steady-state Ocean Circulation Explorer (GOCE) are equipped with onboard Global Positioning System (GPS) receivers for precise orbit determination (POD), instrument time-tagging, and the extraction 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 ideal characteristics to exploit the contribution of GPS high-low Satellite-to-Satellite Tracking (hl-SST) to gravity field determination. We present gravity field solutions based on about 8 months of GOCE GPS hl-SST data from 2009 and compare the results with those obtained from the CHAllenging Minisatellite Payload (CHAMP) and Gravity Recovery And Climate Experiment (GRACE) missions. The very low orbital altitude of GOCE significantly improves gravity field recovery from GPS hl-SST data above degree 20, but not for the degrees below 20, where the quality of the spherical harmonic coefficients remains essentially unchanged. Despite the limited time span of GOCE data used, the gravity field of the Earth can be resolved up to about degree 115 using GPS data only. Empirically determined phase center variations (PCVs) of the GOCE onboard GPS helix antenna are, however, mandatory to achieve this performance.

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1. Introduction

In the last decade observations from the Global Positioning System (GPS) have been established as an important pillar for gravity missions. Since the launch of the CHAllenging Minisatellite Payload mission (CHAMP, Reigber et al., 1998) GPS sensors are not only used as a key tracking system for precise orbit determination (POD) but also for extracting the long wavelength part of the Earth’s static gravity field (Reigber et al., 2003). Although current gravity missions such as the Gravity Recovery And Climate Experiment (GRACE, Tapley et al., 2004) and the Gravity field and steady-state Ocean Circulation Explorer (GOCE, Drinkwater et al., 2006) are equipped with other core instruments, 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 (Pail et al., 2006).

GOCE was launched on 17 March, 2009 into a sun-synchronous, dusk-dawn orbit with an initial mean altitude of 287.91 km (mean distance from the geocenter minus the equatorial Earth radius). After a descent phase of about half a year the first measurement and operational phase (MOP-1) has started on 29 September, 2009 at a mean altitude of 259.56 km, which corresponds to a repeat cycle of 979 revolutions in 61 days. The very low Earth orbit (LEO) of the GOCE satellite is 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 and GRACE, which have been providing GPS hl-SST data for more than 8 years.

Section 2 shortly reviews the methods of kinematic orbit determination and subsequent gravity field determination.
underlying this article. Section 3 compares gravity field solutions obtained from GOCE, CHAMP, and GRACE, and discusses the impact of a high data sampling rate and the limitation due to the polar gap in the case of the sun-synchronous GOCE orbit. Section 4 has the focus on the phase center modeling of the GOCE GPS antenna and compares the results with the experience gained from the analysis of GRACE data. Section 5 compares the results with those obtained in the frame of the GOCE High-level Processing Facility (HPF, Koop et al., 2006).

2. Method used for GPS-only gravity field recovery

A three-step procedure is applied to gravity field recovery from GOCE, CHAMP, and GRACE GPS data according to the Celestial Mechanics Approach (Beutler et al., 2010). In a first step GPS observations are processed to derive kinematic LEO positions at the measurement epochs together with the associated covariance information (see Section 2.1). In a second step the kinematic LEO 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 gravity field coefficients in a generalized orbit determination problem (see Section 2.2). In a third step the daily normal equations may be modified and are accumulated into monthly, annual, and multiannual systems (see Section 2.3).

2.1. Step I: kinematic orbit determination

The geometric strength and the high density of GPS observations allows for a purely geometrical approach to determine kinematic LEO positions at the observation epochs by precise point positioning (Svehla and Rothacher, 2004). The kinematic positions are determined in a standard least-squares adjustment process of GPS observations together with all other relevant parameters without using any information on LEO dynamics. A band-limited part of the full covariance matrix of kinematic positions may be efficiently derived in the course of kinematic orbit determination.

The high-rate satellite clock corrections (Bock et al., 2009) and the final GPS orbits from the Center for Orbit Determination in Europe (CODE, Dach et al., 2009) are used together with attitude data from the star trackers to process the undifferenced Level 1b GPS carrier phase tracking data of the CHAMP, GRACE, and GOCE mission for kinematic orbit determination.

GRACE 30 s kinematic positions were computed at the Astronomical Institute of the University of Bern (AIUB) for various studies on LEO POD (e.g., Jäggi et al., 2009b) and for gravity field recovery with inter-satellite K-band data (Jäggi et al., in press), whereas CHAMP 10 s kinematic positions were used to exploit GPS-based gravity field recovery (Prange et al., 2010). GOCE 1 s kinematic positions are computed at AIUB in the frame of the GOCE HPF as part of the GOCE precise science orbit product (Bock et al., 2007). They are provided to the user community together with a band-limited part of the covariance matrix covering four off-diagonal blocks (EGG-C, 2008).

Kinematic positions are particularly sensitive to a correct modeling of the antenna phase center location as no constraints are imposed by dynamic models on the epoch-wise estimated positions. Special care has to be taken to empirically correct for phase center variations (PCVs) of the LEO GPS antennas in order not to deteriorate the kinematic positions and the subsequent gravity field recovery (Jäggi et al., 2009b). If not stated differently, empirical PCVs are used for kinematic orbit determination in this article.

2.2. Step II: generalized orbit determination

The equation of motion of a LEO satellite including all perturbations reads in the inertial frame as

$$\ddot{r} = -\frac{\mathbf{GM}}{r^3} + \mathbf{f}(t, r, \dot{r}, q_1, \ldots, q_d),$$  

where $\mathbf{GM}$ denotes the gravity parameter of the Earth, $r$ and $\dot{r}$ represent the satellite position and velocity, and $\mathbf{f}_1$ denotes the perturbing acceleration. The initial conditions $r(t_0) = r(a, e, i, \Omega, \omega, T_0; t_0)$ and $\dot{r}(t_0)$ are defined by six Keplerian osculating elements, e.g., $a, e, i, \Omega, \omega, T_0$. The parameters $q_1, \ldots, q_d$ in Eq. (1) denote $d$ additional parameters considered as unknowns, e.g., arc-specific orbit parameters and general parameters such as gravity field coefficients.

In a first step a priori orbits for gravity field determination are computed on a daily basis. Based on a selected a priori force model (defined by an a priori gravity field model, ocean tide model, etc.) the kinematic positions, weighted according to the covariance information from Section 2.1, are fitted by numerically integrating the equation of motion (1) and by adjusting arc-specific orbit parameters. Efficient numerical integration techniques are applied to solve the variational equations (Beutler, 2005) in order to obtain the required partial derivatives. As accelerometer data need not necessarily be taken into account to derive GPS-only gravity field solutions of high quality (Prange et al., 2009), arc-specific empirical parameters are set up in addition to the six Keplerian osculating elements. Constant and once-per-revolution empirical accelerations acting over the entire daily arcs are set up in the radial, along-track, and cross-track directions to compensate for the main part of the unmodeled non-gravitational perturbations. In analogy to Jäggi et al. (2009a), remaining deficiencies are captured by setting up low-degree polynomials (degree 3) for the along-track accelerations and, in particular, by estimating additional pseudo-stochastic pulses (instantaneous velocity changes) at predefined epochs for the radial, along-track, and cross-track directions. Pseudo-stochastic pulses do not affect the LEO trajectory in-between the pulse epochs and are thus well suited for gravity field recovery. A
rather short spacing of 6 min is used between subsequent pulse epochs for satellites at very low altitudes such as GOCE, whereas 15 min are used for the GRACE satellites flying at a much higher orbital altitude. The parameterization allows to start gravity field recovery from EGM96 (Lemoine et al., 1997) serving as a priori gravity field model without the need for iterations.

Based on the computed a priori orbits \(r_0(t)\) gravity field recovery from kinematic positions is set up as a generalized orbit improvement problem (Beutler et al., 2010). The actual orbits \(r(t)\) are expressed as truncated Taylor series with respect to the unknown parameters \(p_i\) (arc-specific orbit parameters and the unknown SH coefficients) about the a priori orbits, which are represented by the a priori parameter values \(p_{0i}\):

\[
r(t) = r_0(t) + \sum_{i=1}^{n} \frac{\partial r_0(t)}{\partial p_i} \cdot \Delta p_i,
\]

where \(\Delta p_i = p_i - p_{0i}\) denote the \(n = 6 + d\) corrections considered as unknown for each daily arc. The partial derivatives with respect to all parameters allow it to set up the daily normal equations based on kinematic positions for all parameters according to standard least-squares adjustment.

2.3. Step III: normal equation handling

Arc-specific parameters are pre-eliminated before the daily normal equations are accumulated into normal equation systems covering longer time spans, e.g., several months or years. The accumulated normal equation system is eventually inverted in order to obtain the corrections of the SH coefficients with respect to the a priori gravity field coefficients and the associated full covariance information. No regularizations are applied to compute the gravity field solutions presented in this article.

3. GPS-only gravity field recovery from GOCE, CHAMP, and GRACE

Relying on the methods described in Section 2, gravity field determination was performed using GPS hl-SST data from the GOCE, CHAMP, and GRACE satellites. Starting April 20, 2009, GOCE 1 s GPS data were used until the end of the year 2009 to compute gravity field solutions using different processing options (details are provided in the following sections). The GOCE GPS-only solutions based on 1 s kinematic positions are compared with results obtained from 30 s GRACE B GPS data covering 1 year (Jäggi et al., 2009b) and from 10 s CHAMP GPS data covering 8 years (Prange, 2010).

Fig. 1 shows the square-roots of the degree difference variances of gravity field recoveries from GRACE B, GOCE, and CHAMP kinematic positions.

3.1. Data sampling

The 10 s sampling of the CHAMP and GRACE Level 1b GPS data allows to compute kinematic positions every 10 s at maximum, or, depending on the availability of high-rate GPS satellite clock corrections, only every 30 s. The 1 s sampling of the GOCE Level 1b GPS data allows it for the first time to compute kinematic positions at a 1 s spacing for a gravity mission. For this purpose high-rate GPS clock corrections are computed in the frame of the GOCE HPF with a sampling of 5 s, which are linearly interpolated to 1 s for the GOCE kinematic orbit determination without significant loss of orbit accuracy (Bock et al., 2009). Apart from the correlations induced by the clock interpolation, and the correlations caused by the carrier phase ambiguities, kinematic positions are fully independent. Every single position contains additional gravity
field information and is, in principle, expected to improve gravity field recovery (Jäggi et al., 2008).

In order to study the impact of the position sampling on gravity field recovery, the original series of 1 s GOCE kinematic positions is sampled to 5 and 30 s for a test period starting on April 20 and ending on November 5, 2009. Fig. 2 shows the square-roots of the degree difference variances of recoveries up to degree 90 when either taking covariance information over four off-diagonal blocks into account (“04-sec cov”) for the 1 s GOCE kinematic positions, or when only considering the epoch-wise covariance information (“epoch cov”) for the original 1 s or the sampled 5 and 30 s 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 s sampling, but no improvement at all is achieved for degrees below 20 when increasing the position sampling. This either means that ITG-GRACE03S “sees” something different for the low degrees, or that the GOCE hl-SST solutions are limited by systematic errors showing up at low degrees first. Similar observations were already reported for GRACE hl-SST solutions (Jäggi et al., 2009a). Fig. 2 shows that the recovered gravity field is only marginally improved when the position sampling is further increased to 1 s, which may be partly caused by the 5 s clock corrections used for the kinematic orbit determination. Fig. 2 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.

3.2. Maximum resolution and polar gap

The low orbital altitude of GOCE allows to solve for SH coefficients up to degrees higher than 90. Fig. 3 (left) shows the square-roots of the degree difference variances of corresponding recoveries up to degree 110 and 120, respectively. A degradation of the unconstrained gravity field solution due to the GOCE orbit characteristics is, however, starting to become more pronounced when increasing the maximum degree. Due to the sun-synchronous orbit the pattern of the ground-tracks does not cover the entire Earth, but leaves caps around the poles of about 6.5° without data coverage. Due to this polar gap the zonal and near-zonal terms are only weakly determined (Sneeuw and van Gelderen, 1997). Fig. 4 shows the coefficient differences to ITG-GRACE03S up to degree 120 and confirms that the degradation is indeed caused by the zonal and near-zonal coefficients, implying that the degree difference variances shown in Fig. 3 (left) are dominated by few weakly determined SH coefficients. Degree difference medians or degree difference variances with zonal and near-zonal terms excluded, e.g., according to the rule of thumb given by van Gelderen and Koop (1997) (right).
Gelderen and Koop (1997), are thus more convenient when analyzing GOCE solutions obtained without regularizations. Fig. 3 (right) shows that the reduced degree difference variances do not show any degradation when increasing the maximum degree from 110 to 120. They even suggest that a slightly larger maximum degree could have been chosen.

The degradation of the zonal and near-zonal coefficients due to the polar gap is inherent to unconstrained GOCE solutions, but immediately disappears if the normal equations from GOCE GPS hl-SST are combined with the normal equations from GRACE GPS hl-SST. Fig. 5 shows the square-roots of the degree difference variances of a recovery up to degree 120 obtained from 30 s GRACE B GPS data covering the year 2009 and its combination with GOCE. Thanks to the almost polar GRACE orbit no degradation of zonal and near-zonal coefficients is seen in the degree difference variances of the combined solution, apart from degrees 2 and 3 which are dominated by the GOCE solution. Further investigations are needed to better understand the not yet optimal recovery of these degrees, which is partly caused by the rather short spacing of the pseudostochastic pulses.

4. Impact of PCVs

Due to different antenna types used onboard different gravity missions (chokering antennas onboard CHAMP and GRACE, helix antennas onboard GOCE) and additional error sources encountered in the spacecraft environment, e.g., different near-field multipath, the impact of systematic errors on kinematic orbit determination and subsequent gravity field recovery is not the same for the different gravity missions. Focusing on gravity field recovery, the empirical PCV modeling for the LEO GPS receiver antennas is subsequently compared for the GRACE and GOCE gravity missions.

4.1. GRACE

Empirical PCVs were generated in an iterative procedure from reduced-dynamic carrier phase residuals from 362 days of GRACE A and GRACE B GPS data collected by the onboard chokering antennas in the year 2007 (Jäggi et al., 2009b). Fig. 6 shows the correction maps with a resolution of 1° × 1° in an antenna-fixed coordinate system. Note that the azimuth of 0° points into the direction of flight for both satellites and that an elevation cut-off angle of 5° was used. The patterns show a patchy structure of systematic carrier phase variations with amplitudes of typically ±1 cm. They are similar for both GRACE antennas, except for the bottom part of Fig. 6 (left) which is affected by receiver internal cross-talk due to the active occultation antenna onboard GRACE A. For details we refer to (Jäggi et al., 2009b).

Fig. 7 shows the square-roots of the degree difference variances of annual recoveries up to degree 120 from GRACE A and GRACE B GPS data collected by the onboard chokering antennas in the year 2007 (Jäggi et al., 2009b). Fig. 6 shows the correction maps with a resolution of 1° × 1° in an antenna-fixed coordinate system. Note that the azimuth of 0° points into the direction of flight for both satellites and that an elevation cut-off angle of 5° was used. The patterns show a patchy structure of systematic carrier phase variations with amplitudes of typically ±1 cm. They are similar for both GRACE antennas, except for the bottom part of Fig. 6 (left) which is affected by receiver internal cross-talk due to the active occultation antenna onboard GRACE A. For details we refer to (Jäggi et al., 2009b).

Fig. 7 shows the square-roots of the degree difference variances of annual recoveries up to degree 120 from GRACE A and GRACE B GPS data collected by the onboard chokering antennas in the year 2007 (Jäggi et al., 2009b). Fig. 6 shows the correction maps with a resolution of 1° × 1° in an antenna-fixed coordinate system. Note that the azimuth of 0° points into the direction of flight for both satellites and that an elevation cut-off angle of 5° was used. The patterns show a patchy structure of systematic carrier phase variations with amplitudes of typically ±1 cm. They are similar for both GRACE antennas, except for the bottom part of Fig. 6 (left) which is affected by receiver internal cross-talk due to the active occultation antenna onboard GRACE A. For details we refer to (Jäggi et al., 2009b).

4.2. GOCE

Empirical PCVs were generated in analogy to Section 4.1 from 154 days of GOCE GPS data collected by the
onboard main helix antenna in the year 2009 (Bock et al., submitted for publication). Fig. 8 shows the correction map with a resolution of 1° × 1° in an antenna-fixed coordinate system. Note that the azimuth of 0° points into the direction of flight and that an elevation cut-off angle of 0° was applied. The pattern shows a completely different and more complicated structure as that of GRACE with significantly larger amplitudes of up to ±3 cm. For details we refer to (Bock et al., submitted for publication).

Fig. 9 shows the square-roots of the degree difference variances (zonal and near-zonal terms excluded in analogy to Section 3.2) of recoveries up to degree 120 from about 8 months of GOCE 1 s kinematic positions when either neglecting PCVs for the kinematic orbit determination (“PCV not corrected”), or when empirically correcting for them (“PCV corrected (RD)”). Also for GOCE a significant improvement of the recovered SH coefficients can be recognized when PCVs are corrected for. The improvement is even more pronounced than for GRACE due to the larger amplitudes of the systematic variations shown in Fig. 8. Note, as well, that the SH coefficients are significantly improved up to the highest degree due to the considerably smaller structures in the PCVs of the GOCE helix antenna than in the GRACE chokering antennas.

PCVs derived from reduced-dynamic carrier phase residuals might be affected by the gravity field model used for the reduced-dynamic orbit determination and indirectly bias the performed gravity field recovery. Truly independent PCVs were thus generated in an iterative procedure from carrier phase residuals of the kinematic GOCE orbit determination using the same amount of 154 days of GPS data. Although it is not possible to generate exactly the same PCV correction map using the kinematic residuals,
the impact on gravity field recovery is essentially the same for both series of GOCE 1 s kinematic positions, as shown in Fig. 9 (“PCV corrected (KIN)”).

5. Comparison with HPF solutions

Gravity field recovery in the frame of the GOCE HPF is mainly based on the measurements of the three-axis gravity gradiometer, but also on the positions obtained from the precise science orbit product. Due to the limited measurement bandwidth of the gradiometer, the low degree SH coefficients are even exclusively determined from the GPS-based GOCE orbit positions up to about degrees 20–30 (Pail et al., 2006). In order to assess the quality of the results presented in this article, the solutions are compared with GPS-only solutions used in the frame of the GOCE HPF for gravity field recovery. As only the GPS hl-SST contribution underlying the time-wise solution (Pail et al., in press) is based on the kinematic positions of the precise science orbit product, and thus independent from the GRACE gravity field model used for orbit determination (EGG-C, 2010), the comparison is currently restricted to the GPS hl-SST solution computed at the Institute of Navigation and Satellite Geodesy (INAS) of the Graz University of Technology.

Fig. 10 shows the square-roots of the degree difference variances of the recoveries computed at INAS and AIUB with respect to ITG-GRACE03S. The solutions to be compared are based on the same set of 1 s kinematic positions covering a period of two months (November and December), whereas the final AIUB solution obtained from 8 months of data is included for comparison as well. Fig. 10 shows that the AIUB two-months solution is better than the GPS hl-SST contribution computed at INAS, apart from degree 2 which is not yet of a good quality as already mentioned in Section 3.2. For most degrees the AIUB solution is, however, about a factor of $\sqrt{3}$ better, which is related to the energy-balance approach used at INAS. The comparison with the final solution based on 8 months of data also shows that a significant quality improvement is expected when using longer series of GOCE data, even if they are from the descent phase of the satellite.

6. Conclusions

Gravity field recovery from about 8 months of GOCE GPS hl-SST data was performed and compared to gravity field results obtained from 8 years of CHAMP and 1 year of GRACE GPS hl-SST data. Although the low orbital altitude of GOCE was hardly beneficial for improving the recovery of the very low degrees, a significantly improved recovery resulted for the high degrees. Based on the limited time span of about 8 months of GOCE GPS data, the Earth’s gravity field could be resolved up to about degree 115, apart from the zonal and near-zonal SH coefficients, which are degraded due to the polar gap. Compared to CHAMP and GRACE, GOCE GPS hl-SST gravity field solutions yield smallest slopes in degree difference variance plots with respect to superior GRACE K-band-based gravity field solutions. Although the results from 8 years of CHAMP data are still superior, GOCE is expected to give better GPS-based results than CHAMP at higher degrees when more data become available.

The 1 s sampling of the GOCE Level 1b GPS data allows it for the first time to compute kinematic positions of a gravity mission every second and to use this dense sampling of positions for gravity field determination. Gravity field solutions based on the full 1 s position sampling are, however, only marginally better than solutions based on a reduced 5 s position sampling, which may be related to the linear interpolation of the GPS satellite clock corrections from 5 to 1 s. For the recovery of the SH coefficients below degree 20 it was even found to be sufficient to
use a position sampling of 30 s. The presence of systematic errors, which show up at low degrees first, might explain such a behavior.

PCVs of the GOCE helix antennas are considerably larger than PCVs of the GRACE choking antennas. Consequently, their impact on gravity field estimation is more pronounced than for GRACE and has to be carefully modeled. PCVs determined iteratively from reduced-dynamic or kinematic carrier phase residuals were found to be slightly different, but no significant differences were found in the resulting gravity field solutions. Their use is indispensable to achieve the best results using GOCE GPS hL-SST for gravity field recovery.

The comparison with GPS-only solutions used in the frame of the GOCE HPF confirms that the Celestial Mechanics Approach is well suited to exploit the contribution of GOCE GPS hL-SST to gravity field determination.

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