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Precise orbit determination for the GOCE satellite using GPS

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Abstract

Apart from the gradiometer as the core instrument, the first ESA Earth Explorer Core Mission GOCE (Gravity field and steady-state Ocean Circulation Explorer) will carry a 12-channel GPS receiver dedicated for precise orbit determination (POD) of the satellite. The EGG-C (European GOCE Gravity-Consortium), led by the Technical University in Munich, is building the GOCE HPF (High-level Processing Facility) dedicated to the Level 1b to Level 2 data processing. One of the tasks of this facility is the computation of the Precise Science Orbit (PSO) for GOCE. The PSO includes a reduced-dynamic and a kinematic orbit solution.

The baseline for the PSO is a zero-difference procedure using GPS satellite orbits, clocks, and Earth Rotation Parameters (ERPs) from CODE (Center for Orbit Determination in Europe), one of the IGS (International GNSS Service) Analysis Centers. The scheme for reduced-dynamic and kinematic orbit determination is based on experiences gained from CHAMP and GRACE POD and is realized in one processing flow. Particular emphasis is put on maximum consistency in the analysis of day boundary overlapping orbital arcs, as well as on the higher data sampling rate with respect to CHAMP and GRACE and on differences originating from different GPS antenna configurations.

We focus on the description of the procedure used for the two different orbit determinations and on the validation of the procedure using real data from the two GRACE satellites as well as simulated GOCE data.

Keywords: GOCE; Precise orbit determination; Zero-difference; GPS; CHAMP; GRACE

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1. Introduction

The GOCE (Gravity field and steady-state Ocean Circulation Explorer) satellite is the first ESA (European Space Agency) Earth Explorer Core Mission (Drinkwater et al., 2003) to be launched in December, 2007 from Plesetsk, Russia. The mission is dedicated to high-resolution gravity field extraction and carries, as the core instrument, a three-axis gradiometer. In addition, the measurements of the onboard GPS receiver allow for gravity field recovery of the low degree and order terms and for precise orbit determination (POD) of the satellite. The main focus of this paper is on the latter task.

ESA contracted the European GOCE Gravity-Consortium (EGG-C, see below) to implement the High-level Processing Facility (HPF) for the Level 1b to Level 2 data processing for the GOCE satellite and the computation of a highest quality static Earth gravity field and precise satellite orbits. DEOS (Department of Earth Observation and Space Systems, Delft University of Technology) and AIUB (Astronomical Institute of the University of Bern) together with IAPG (Institute of Astronomical and Physical Geodesy, Technical University of Munich) are – as part of EGG-C – responsible for the POD task, which is divided into the quicklook part (Rapid Science Orbit (RSO)) performed at DEOS and the Precise Science Orbit (PSO) (ESA, 2006) part performed at AIUB and IAPG.

The three groups have shown their capability to determine precise orbits of low Earth orbiting satellites equipped with GPS receivers like CHAMP (Reigber et al., 1998) or

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the two GRACE (Tapley and Reigber, 2001) satellites, e.g., Jäggi et al. (2006), Švehla et al. (2005), Van den IJssel and Visser (2003). The POD procedures for the GOCE satellite were developed when processing data gathered by these Low Earth Orbiters (LEOs). However, the procedures had to be revised and adapted for the new satellite mission. A detailed description of the procedure for the PSO is given in this paper.

A short description of the GOCE mission and the GOCE HPF is followed by a description of the POD procedures. The modifications for the 30-h processing and the impact of the special GOCE antenna characteristic are two issues, which are discussed in more detail.

2. The GOCE mission

The GOCE satellite will fly at the very low altitude of about 250 km in a sun-synchronous orbit with an inclination of 96.5° w.r.t. the Earth's equator. The payload of the spacecraft consists of the three-axis gradiometer, a 12-channel GPS receiver, and a Laser retro-reflector array, and star cameras and an ion propulsion assembly are part of the spacecraft system. The gradiometer and the GPS receiver are dedicated to gravity field recovery, where the GPS observations are mainly useful to recover the low degree and order terms of the geopotential. The star cameras are used for attitude control and the ion thruster, together with the accelerometers, for the realization of a drag-free flight of the satellite in along-track direction. The GPS receiver is connected to a helix antenna and provides dual-frequency GPS pseudorange and carrier phase measurements with a sampling rate of 1 Hz. The Laser retro-reflector array is used for SLR (Satellite Laser Ranging) measurements, which in this case serve mainly for an independent validation of the GPS POD.

3. The GOCE High-level Processing Facility

The GOCE High-level Processing Facility (HPF) is an ESA project performed by the EGG-C (European GOCE Gravity-Consortium). EGG-C is a group of the following ten European institutions (in alphabetical order of acronyms):

- Astronomical Institute of the University of Bern (AIUB), Switzerland.
- Centre d'Etudes Spatiales (CNES), Groupe de Recherche de Géodésie Spatiales (GRGS), Toulouse, France.
- Department of Earth Observation and Space Systems (DEOS), Delft University of Technology, The Netherlands.
- GeoForschungsZentrum (GFZ), Department 1 "Geodesy and Remote Sensing", Potsdam, Germany.
- Institute for Astronomical and Physical Geodesy (IAPG), Technical University of Munich, Germany, Principal Investigator of the project.
- Institute for Theoretical Geodesy (ITG), University of Bonn, Germany.
- Sezione Rilevamento, Politechnico di Milano (POLIMI), Italy.
- National Institute for Space Research (SRON), Utrecht, The Netherlands.
- Institute of Navigation and Satellite Geodesy, University of Technology (TUG), Graz, Austria.
- Department of Geophysics, University of Copenhagen (UCPH), Denmark.

It is the purpose of the GOCE HPF project to process the Level 1b data stemming from the GOCE satellite (gradiometer measurements, GPS data, and attitude data), and to produce the following Level 2 data:

- calibrated gravity field gradients,
- the Earth's static gravity field (accuracy: 1 mGal = 10^{-5} m/s^2 in terms of gravity anomalies, and 1–2 cm in terms of geoid heights with a resolution of 100 km), and
- precise orbits of the satellite (target accuracy: 1 cm, 1-dimensional).

Subsequently, we focus on the POD for the satellite, which is a central task of the HPF project. It consists of two parts, the Rapid Science Orbit (RSO) determination (Quicklook part) and a final analysis, the Precise Science Orbit (PSO) determination. DEOS is responsible for the generation of the RSO and AIUB for the generation of the PSO. The PSO itself is separated into two parts. Two kinds of orbit solutions are generated by AIUB, whereas the SLR-validation and the quality assessment are performed at IAPG.

4. Precise orbit determination procedures

4.1. Rapid Science Orbit

The RSO chain provides two types of orbits, one based on a reduced-dynamic (Bertiger et al., 1994) and the other on a kinematic orbit determination technique. The GPS ephemerides and clock parameters as well as the Earth Rotation Parameters (ERPs) are taken from quicklook ("rapid") solutions by the Center for Orbit Determination in Europe (CODE), one of the IGS (International GNSS service) (Dow et al., 2005) analysis centers, and kept fixed.

The reduced-dynamic orbit relies on triple differenced GPS dual-frequency carrier phase observations between GOCE, the GPS satellites and a nominal global network of 25 ground stations. By forming triple differences, one avoids to estimate clock parameters and carrier phase ambiguities. The methodology has been successfully applied for CHAMP POD (Van den IJssel and Visser, 2003). A large number of empirical accelerations is estimated by a Bayesian least-squares process. The nominal orbital arc length will be 30 h (each day) leading to 6-h overlaps between consecutive arcs. The center 24 h will be

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included into the RSO product. The core software program is the GEODYN package, kindly provided by the NASA Goddard Space Flight Center in Greenbelt, Maryland (Rowlands et al., 1995).

The kinematic orbit is computed from undifferenced GPS observations and is obtained by a point positioning technique connecting successive GPS carrier phase observations. The procedure is described in detail in Kroes (2006) and has been implemented in the GHOST software (Montenbruck et al., 2005). This software is developed under the auspices of the German Space Operations Centre in Oberpfaffenhofen, Germany. The kinematic orbits have a length of 24 h without overlaps between consecutive arcs; they are also included in the RSO product.

The latency for the RSO is one day and the target accuracy (3-dimensional) is 0.5 m.

4.2. Precise Science Orbit

The PSO consists of two orbits, a reduced-dynamic and a kinematic solution. Both solutions are produced in one processing flow, which implies that the pre-processing of the data is done only once and that the same data is used for the two solutions. The orbits are produced as 30-h arcs covering 3 h before and after the day considered. This orbital overlap allows for quality and consistency checks of adjacent orbits. The whole processing is performed with a tailored HPF version of the Bernese GPS Software (Dach et al., 2007). The latency for the generation of the two kinds of orbits for the PSO is one week and the required accuracy (1-dimensional) is 2 cm (target 1 cm).

The GPS satellite information (orbits, clock corrections, and ERPs) is taken from CODE, located at AIUB in Bern, Switzerland. The CODE final solution (middle day of a three-days solution) (Hugentobler et al., 2006) is used to generate a consistent set of GPS orbits, GPS clock corrections and ERPs. Since, the PSO determination procedures are based on a zero-difference processing approach precise high-rate GPS clock corrections are needed. In the following section, we briefly describe the generation of these high-rate GPS clock corrections.

4.2.1. High-rate GPS clock corrections

The sampling rate of the GOCE GPS measurements is 1 Hz. It will be the first time that this high-rate will be used for POD of a LEO satellite using a zero-difference approach. CHAMP and GRACE, e.g., both collect data with a sampling rate of 0.1 Hz, only. If accuracy requirements are more relaxed than for the GOCE PSO the official CODE GPS clock corrections, sampled at 30 s, are sufficient and may be linearly interpolated to the measurement epochs every 10 s or even 1 s. However, to meet the accuracy requirements of 2 cm for the resulting GOCE orbit positions such systematic error sources should be avoided as much as possible.

The RMS values of such interpolation errors are shown in Fig. 1. The values are plotted for one sample day (140 of year 2004) for each PRN and they are obtained from the differences between a reference set of 1 Hz GPS clock corrections and linearly interpolated 2-, 5-, 10-, and 30-s clock corrections. Four of these GPS clock correction sets (1-, 2-, 5-, 10-s) are generated by using the 1 Hz GPS tracking network of the IGS. This network consists of about 75 stations (status August 2006) and the data are available at the IGS global data center at CDDIS (Crustal Dynamics Data Information System), Greenbelt, USA. A densification of the official 30-s CODE final GPS clock corrections (Bock et al., 2004) to 1-, 2-, 5-, and 10-s, respectively, is done with these data. In order to be still consistent with the CODE final analysis, coordinates and troposphere zenith path delays of the high-rate stations are estimated using the CODE final orbits, clock corrections, and ERPs. The densification of the 30-s clock corrections is performed by an efficient algorithm using time-differenced phase measurements of the high-rate tracking stations. From these epoch-differences clock correction differences from epoch to epoch are estimated. These differences represent the relative change of the clock corrections. They are accumulated and fixed to the CODE's 30-s clock estimates. The result is a phase-consistent interpolation of the 30-s CODE clock estimates.

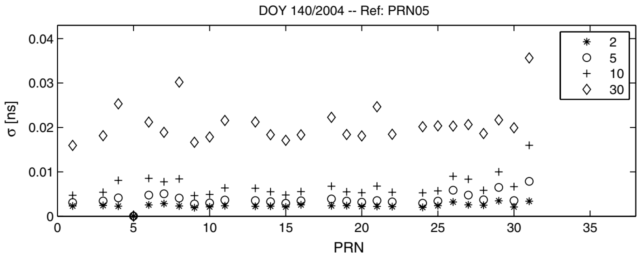

Fig. 1. Satellite-specific RMS errors (ns) of differences between 1 s clock corrections and interpolated clock corrections with different sampling rates (2, 5, 10, 30 s). Reference clock: PRN05.

Fig. 1 shows that the systematic error introduced by interpolating 30-s GPS clock corrections to 1 Hz is larger than the phase measurement noise of the ionosphere-free linear combination ($3 \cdot \sigma_{L1} = 3.1$ mm corresponds to 0.01 ns).

A degradation of the GOCE orbit results due to the errors introduced by the interpolation of 30-s GPS clock corrections to 1 Hz are avoided with the generation of high-rate GPS clock corrections with a higher sampling rate within the framework of the GOCE HPF project.

The selection of the higher sampling rate is a trade off between accuracy requirements and data amount and processing time issues. The question is, whether computed 1 Hz GPS clock corrections are really necessary, or whether a lower rate between 1 and 30 s, e.g., 5 or 10 s, is sufficient to meet the accuracy requirements, when interpolating the clock corrections to the measurement epochs of 1 s. A reduced sampling rate would lead to a reduced amount of data and to shorter processing times for computation of the high-rate GPS clock corrections.

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In order to answer the question we look again at Fig. 1. Due to the selection of PRN05 as a linear behaving reference clock for the determination of the GPS clock corrections, the RMS values are as small for all four interpolated clock correction sets. All other RMS values for the interpolation of 2- and 5-s clock corrections are also below 0.01 ns. This is below the phase measurement noise and, therefore, a sampling rate of 2 or even 5 s for the high-rate GPS clock corrections seems to be sufficient for GOCE data processing.

In addition, we studied the impact of the clock interpolation on the resulting kinematic positions of a LEO. For this purpose we simulated error-free GPS 1-s observations for the two GRACE satellites using 1 Hz GPS clock corrections and then performed a kinematic point positioning using the four different clock correction sets (2-, 5-, 10-, and 30-s) linearly interpolated to 1 Hz. The interpolation errors then propagate into the resulting GRACE satellite positions.

The GRACE orbits used for the simulation of the data are taken as reference. Fig. 2 shows the RMS errors of the coordinate differences for GRACE A w.r.t. the reference orbit obtained with different interpolated GPS clock corrections for seven days of error-free simulations. It can be seen that the values are below or at the 1-mm level for the clock correction sets with 2- and 5-s sampling rate. Since an interpolation error at the 1-mm level is acceptable for the accuracy requirements of the GOCE orbit solutions, it was decided to densify the official 30-s CODE final clock corrections to 5 s using sampled 1 Hz IGS tracking data and the CODE final GPS orbits and ERPs.

4.2.2. POD procedure

Fig. 3 shows a simplified flow diagram of the entire PSO determination procedure. It is based on a zero-difference approach, which is why no ground station data is needed for processing the GOCE GPS data.

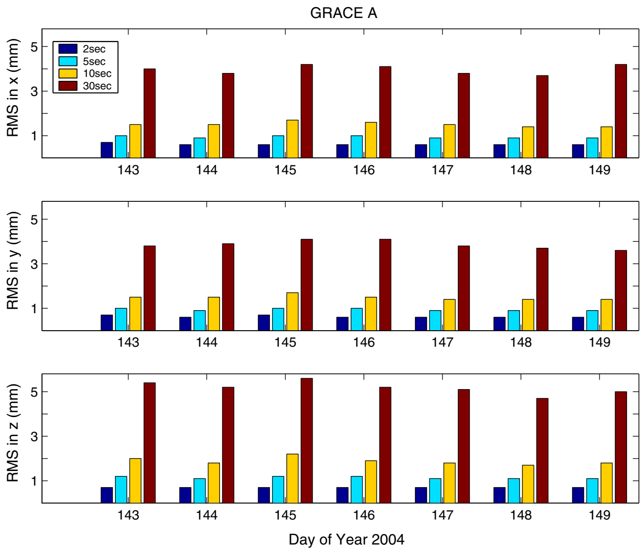

Fig. 2. RMS values (mm) of coordinates for GRACE A using different interpolated GPS clock corrections (from left to right 2-, 5-, 10-, and 30-s clock correction sets).

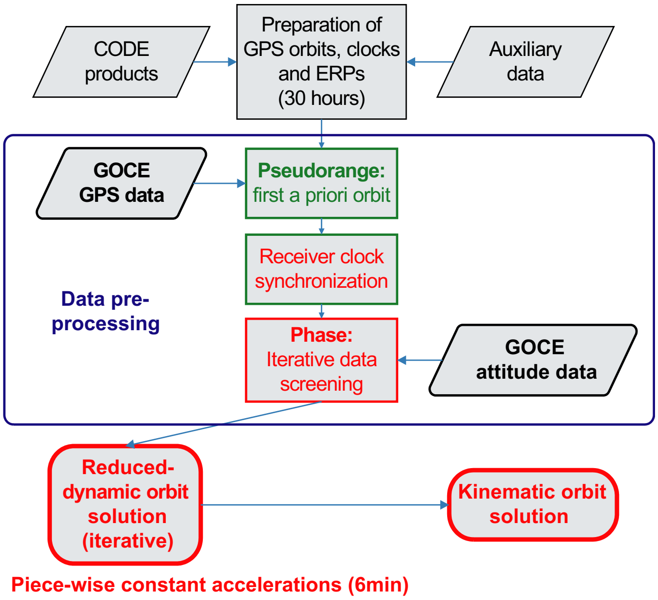

Fig. 3. Flow diagram of PSO determination procedure.

In the first part the GPS orbits, clock corrections, and ERPs are prepared for the 30-h arc processing. This part is described in more detail in Section 5.

The second part includes the pre-processing of the GOCE GPS observations. It is the most time-consuming part of the whole procedure. The first step consists of the generation of an a priori orbit based on pseudorange measurements. A single point positioning is carried out every 30 s. An orbit integration program generates an a priori orbit based on these positions by estimating the following orbit parameters:

- six osculating elements at the initial epoch and
- nine empirical parameters that include in each of the three directions radial, along-track, and cross-track a constant and a once-per revolution periodic acceleration (Colombo, 1989).

This orbit is used for a receiver clock synchronization to GPS time for all measurement epochs (1 Hz). As the a priori orbit has not yet the quality required for a reliable pre-processing of the phase measurements, it is improved iteratively. The GOCE attitude data is now used for the first time in the processing scheme. In a loop the following steps are performed three times always using the orbit from the previous step as new a priori orbit:

- screening of the 1 Hz phase measurements
- orbit improvement based on the screened phase measurements (sampled to 30 s), estimation of
  - six osculating elements at the initial epoch,
  - nine empirical parameters in the radial, along-track, and cross-track directions,

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– every 15 min a stochastic pulse in radial, along-track, and cross-track directions.

In most cases the third and last iteration step is not necessary because the phase measurements are screened exactly with the same result as after the second iteration. The resulting orbit is already a quite good representation of the true GOCE trajectory, however, not yet meeting the accuracy requirements. It is now used as a priori orbit for the final reduced-dynamic GOCE orbit determination. This solution is performed with carrier phase observations sampled to 10 s, again iteratively, using the results of the first iteration as new a priori information for the second iteration. The orbit is parametrized as follows:

- six osculating elements,
- three constant empirical accelerations in radial, along-track, and cross-track directions, and
- every 6 min a piece-wise constant acceleration in radial, along-track, and cross-track direction.

Since, we are processing undifferenced carrier phase observations, the phase ambiguities and the epoch-wise receiver clock corrections have to be estimated. In order to limit the dimension of the normal equation matrix, the receiver clock correction parameters are pre-eliminated after every measurement epoch. The reduced-dynamic orbit for the GOCE satellite obtained in this way, is delivered to the Central Processing Facility of the HPF as an SP3c-file (Hilla, 2002), containing Earth-fixed positions and velocities at a 10-s sampling.

The same carrier phase observation data are used to produce the kinematic orbit solution as for the reduced-dynamic orbit solution, except that the sampling is increased from 10 to 1 s. Although, the reduced-dynamic orbit solution is used as a priori information for the kinematic solution, no dynamic model information enters the kinematic solution. In addition to the phase ambiguities and the receiver clock corrections, epoch-wise unconstrained kinematic coordinates are estimated. The final kinematic orbit solution is delivered as SP3c-file containing Earth-fixed positions for each observation epoch.

In order to support the usage of the orbit solutions in the inertial reference frame, a rotation matrix between the Earth-fixed and the inertial reference frame is computed for each epoch of the kinematic orbit and added to the final PSO product. Finally the statistics of the residuals for the two orbit solutions are generated, a comparison with the RSO solutions is performed, and an internal quality report is issued. The SLR-validation and the preparation of the official quality report is performed afterwards at IAPG. All time series are cut to the center 24 h for the final PSO product. This final PSO product has a latency of four weeks.

4.3. GRACE results

The described PSO procedure was developed using the experiences gained with the generation of precise orbits for CHAMP (Jäggi et al., 2006) and for the two GRACE satellites (Jäggi et al., 2007). The GRACE data set of about 60 days (242–298/2003) was used to validate the PSO procedure developed for GOCE. The only difference to the future GOCE processing is the data sampling rate, which in the case of GRACE is only 0.1 Hz.

Figs. 4 and 5 show the results of this GRACE data processing performed for days 242–298 of year 2003. The results of the validation for the reduced-dynamic orbits

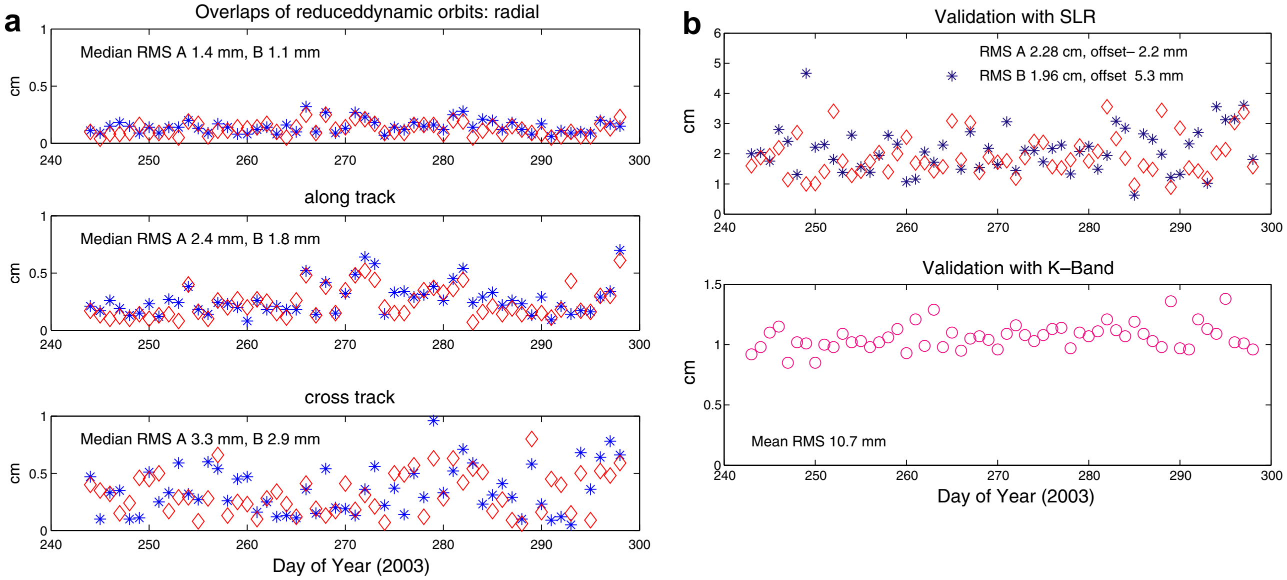

Fig. 4. Validation of reduced-dynamic orbit solutions for GRACE A (*) and B (◇), days 242 to 298/2003. (a) RMS errors (cm) for 4 h-overlaps of reduced-dynamic orbits. (b) Top: RMS errors (cm) of validation with SLR. Bottom: RMS errors (cm) of the validation with the K-band link between the two GRACE satellites.

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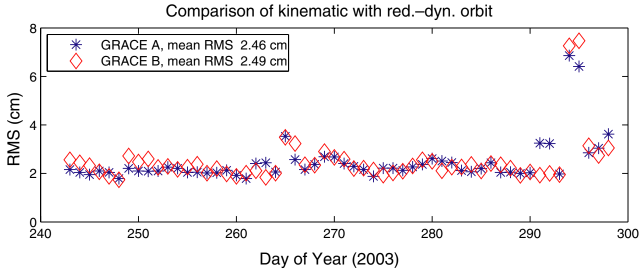

Fig. 5. RMS (cm) per coordinate from comparison of kinematic with reduced-dynamic orbit solutions for GRACE A and B, days 242–298/2003.

of the two GRACE satellites are summarized in Fig. 4. The quality of the overlaps (Fig. 4a) and the validation with SLR (Fig. 4b, top) and with the K-band link (Fig. 4b, bottom) show that the quality of the reduced-dynamic GRACE orbits is of the order of a few centimeters.

The kinematic solutions are then compared to the reduced-dynamic orbits. The RMS errors per coordinate of the orbit differences can be found in Fig. 5. Except for two days, the RMS errors are below 4 cm, which shows the good consistency of the kinematic and the reduced-dynamic orbit solutions. The SLR-validation of kinematic solutions requires a reduced-dynamic orbit solution to interpolate the kinematic positions to the epochs of the SLR observations. The overall SLR RMS errors are 3.08–2.88 cm for GRACE A and B, respectively. This indicates that the reduced-dynamic orbits are of slightly better quality than the kinematic orbits.

The results let us conclude that the developed POD procedure is suitable for the GOCE PSO determination and that the PSO requirement of 2 cm accuracy per coordinate for the GOCE orbits will be met.

5. Orbit overlap analysis using daily 30-h arcs

In order to get the best possible consistency with the used GPS satellite products and to obtain the best possible consistent orbit solution we had to implement some dedicated procedures for the 30-h overlap processing.

The CODE GPS products are generated in a fixed 24-h processing scheme. This inevitably leads to small inconsistencies at the day boundaries for the orbits and the clock corrections. Fig. 6 shows for an arbitrarily selected day boundary between days 131–132 of year 2006 the radial orbit and clock offsets of all GPS satellites. The clock offsets are about one order of magnitude larger than the radial orbit offsets, because of the limited precision of the pseudorange measurements. The pseudorange measurements, precise to about three decimeters, define the absolute level for the GPS clocks. Since, we need only phase measurements from GOCE for POD we may add an arbitrary constant to satellite clock values without degrading the quality of the clocks, provided that the differences between two satellite clocks from one epoch to the next stays constant. The constant offset common to all epochs can be fully absorbed by the phase ambiguity.

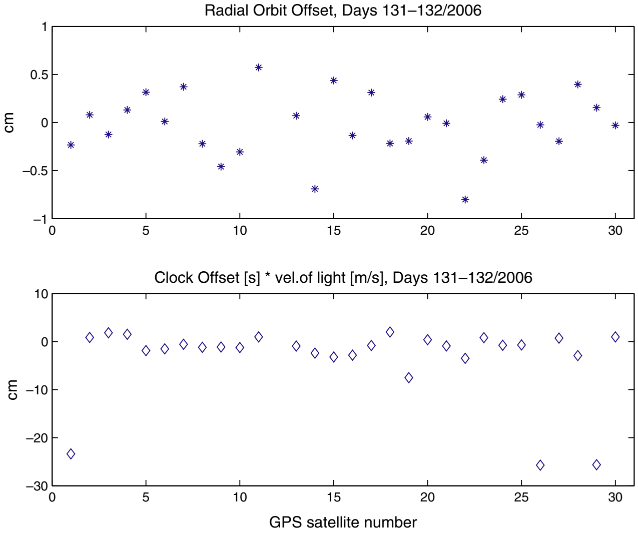

Fig. 6. Radial orbit (top) and clock (bottom) offsets for GPS satellites at midnight.

In the clock estimation procedure for the 5-s GPS clock corrections we also estimate the clock corrections for the midnight epoch of the following day. Therefore, we have two clock estimates for the midnight epoch available, one from day $n-1$ and one from day n. In order to use the clock corrections for the 30-h processing of day n we shift the corrections of day $n-1$ for each clock by an individual constant to match the midnight values with the corresponding clock corrections of day n. The same procedure is applied for the clock corrections of day $n+1$. They are shifted until they are connected with the corresponding clock corrections of day n. After this procedure the satellite clock corrections are continuous and connected in a phase-consistent way through the day boundary. The corresponding orbits are, however, not yet consistent. It is not possible to modify the orbits without deteriorating them. Therefore, we additionally correct the clock corrections of day $n-1$ and $n+1$ for the corresponding radial orbit offsets of the GPS satellites at midnight. Part of the inconsistency of the GPS satellite orbits at midnight can be accounted for by this correction.

In order to validate the described procedure we performed a simulation of error-free carrier phase observations using GPS orbits and clock corrections which are consistent over midnight together with an orbit representing the GOCE trajectory. Then we performed a kinematic point positioning for GOCE using the simulated data and GPS orbits and clock corrections which are not consistent at midnight similar as in reality. For the first solution we did not apply the above corrections and for the second solution we applied them. Fig. 7 shows the comparison of the two kinds of kinematic solutions with the "true" GOCE orbit for all three directions (radial, along-track, cross-track). On the left hand side one can see the solution

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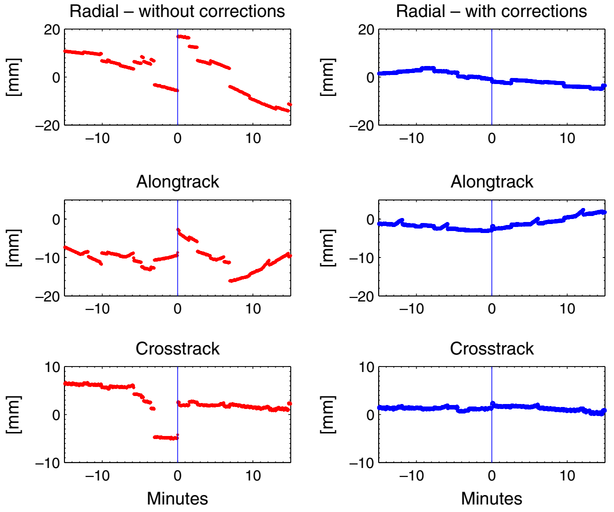

Fig. 7. Comparison of kinematic point positions with “true” GOCE orbit. Left: no corrections applied, right: corrections applied.

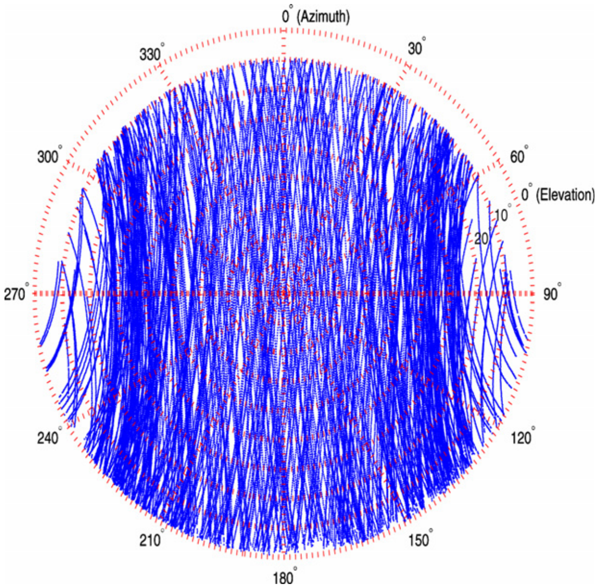

Fig. 8. Azimuth-elevation plot for GRACE A, azimuth of 0° represents the flight direction of the satellite. One data point stands for one L1 and L2 observation pair.

without corrections applied and on the right hand side the solution with corrections applied. Midnight is marked with a vertical line in all figures. The inconsistency of the used GPS orbits and clock corrections is obvious in Fig. 7 (left). Each of the jumps in the kinematic trajectory is caused by a constellation change of the GPS satellites tracked by the GOCE receiver. Due to the slightly inconsistent orbits and clocks, the phase observations are not connected correctly over midnight. In Fig. 7 (right) the jumps have been removed by our procedure and the comparison with the “true” GOCE orbit shows a very good agreement. The small remaining differences are caused by the fact that the inconsistency of the GPS satellite orbits cannot be accounted for completely by correcting for the radial orbit offset in the clock corrections.

6. Antenna characteristics

The 12-channel GOCE Lagrange GPS receiver will get its signals from a helix antenna. Compared to the receivers on CHAMP or GRACE this is a new receiver-antenna combination. So far, not too much is known about the data volume and data quality delivered by this combination. Some information is available in Zin et al. (2006). The phase center variations (PCVs) of the antenna are of particular interest. They were calibrated for an engineering model of the GOCE antenna with the Automated Absolute Field Calibration Technique by the Institut für Erdmessung of the University of Hannover. For details see Dilßner et al. (2006).

The acquisition of the signals for rising satellites is another important aspect. The elevation cut off angle is different for rising and setting GPS satellites. This asymmetry is encountered for other spaceborne GPS receivers, too, and it depends on the receiver setup and capabilities. Fig. 8 shows a typical example for an azimuth-elevation tracking behaviour for GRACE A. Obviously, the acquisition of the signals for rising satellites mainly in the upper hemisphere of the plot (flight direction) starts at about 10° and the setting satellites are tracked down to the local horizon or even below, i.e., until the signal is lost.

The impact of the elevation cut off angle on the estimated orbit results was studied by several data simulations. For simplicity we generated data with the same elevation cut off angle for rising and setting satellites. Six different sets of GOCE GPS observations with different elevation cut off angles (maximum of 12°) and a different maximum number of tracked satellites were simulated for 11 days:

(1) 0°, 12 satellites,
(2) 4°, 12 satellites,
(3) 8°, 12 satellites,
(4) 12°, 12 satellites,
(5) 12°, 10 satellites,
(6) 0°, 12 satellites, different observation noise.

The observation noise was set to 0.3 m for the pseudorange observations and to 1 mm for the carrier phase measurements (Simulations (1)–(5)) which is very optimistic (no systematic effects). Simulation (6) was based on an observation noises of 0.5 m for pseudorange and 2 mm for carrier phase. Simulation (1) (and (6)) is not realistic when considering a typical sky plot as shown in Fig. 8, but it is used as an “ideal” case for comparison purposes. Simulation (2) resembles CHAMP or GRACE tracking: If Fig. 8 is centered, a mean elevation cut off angle of 5° is obtained. Observe, however that the CHAMP and GRACE receivers are “only” configured to track 10 GPS satellites.

Table 1 lists for one particular day the percentage of epochs with a specified number of tracked satellites (5 to

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Table 1
Simulated GOCE observations – percentage of number of tracked satellites per epoch – example for one day

Sim.	Number of tracked satellites per epoch								% of obs.
	5	6	7	8	9	10	11	12	
(1)	0.00	0.00	0.25	2.30	8.63	24.92	30.63	**33.28**	100.00
(2)	0.00	0.00	1.93	11.11	24.35	**29.45**	22.56	10.61	91.52
(3)	0.08	1.40	9.63	25.58	**27.96**	22.21	10.95	2.20	83.21
(4)	1.19	8.05	20.33	**33.42**	21.83	10.83	3.98	0.38	75.42
(5)	1.19	8.05	20.33	**33.42**	21.83	15.19	–	–	75.00

12) for simulations (1) to (5). Bold numbers indicate the peaks of the histograms. As to be expected the largest percentage shifts more and more to a smaller number of satellites when the elevation cut off angle grows. For simulation (1) at 33% of all epochs 12 satellites are tracked simultaneously and for simulation (3) the largest percentage is 28% for nine simultaneous tracked satellites.

In the last column the overall percentage of observations is given with respect to the amount of observations for simulation (1). We see that for the simulations (4) and (5) with an elevation cut off angle of 12° the number of tracked satellites is reduced by 25% with respect to simulation (1) with a cut off elevation angle of 0°. The differences between simulations (4) and (5) are not significant because the percentage of epochs for which 11 or 12 satellites are tracked is already very low for simulation (4).

What is the impact on precise orbit determination of the significant loss of data when rising the elevation cut off angle from 0° to 12°? We focus on the kinematic orbit solution to answer this question, because the reduced-dynamic orbit solution is less sensitive to epochs with few or missing observations.

We compare the kinematic point positioning solutions computed with data from the six simulations with the "true" orbit used for the simulations. Fig. 9 shows the differences for the radial component (left ordinate) for 5 h of a particular day for simulations (1) and (4). The RMS error is a measure of the quality of the kinematic position results with respect to the "true" orbit. The solid line included in the plots gives the z-coordinate of the near-polar satellite orbit (right ordinate). Near the poles, at extremal z-coordinate, the GPS satellites are only visible within a band from the horizon to an elevation of 45° due to the satellites orbital inclination of 55°. An elevation cut off angle imposed by the antenna therefore has the largest impact on the positioning results in polar regions. This effect is clearly visible on Fig. 9.

Table 2 summarizes the RMS errors of the orbit differences for all six simulations. The RMS error for sim-

Table 2
Simulated GOCE observations – RMS errors (mm) for orbit differences – example for one day

Sim.	RMS errors (mm)			
	Radial	Along-track	Cross-track	All
(1)	3.9	1.9	1.7	2.7
(2)	4.5	2.1	1.8	3.1
(3)	5.2	2.3	2.0	3.5
(4)	6.2	2.7	2.2	4.1
(5)	6.3	2.7	2.2	4.1
(6)	7.9	3.7	3.3	5.4

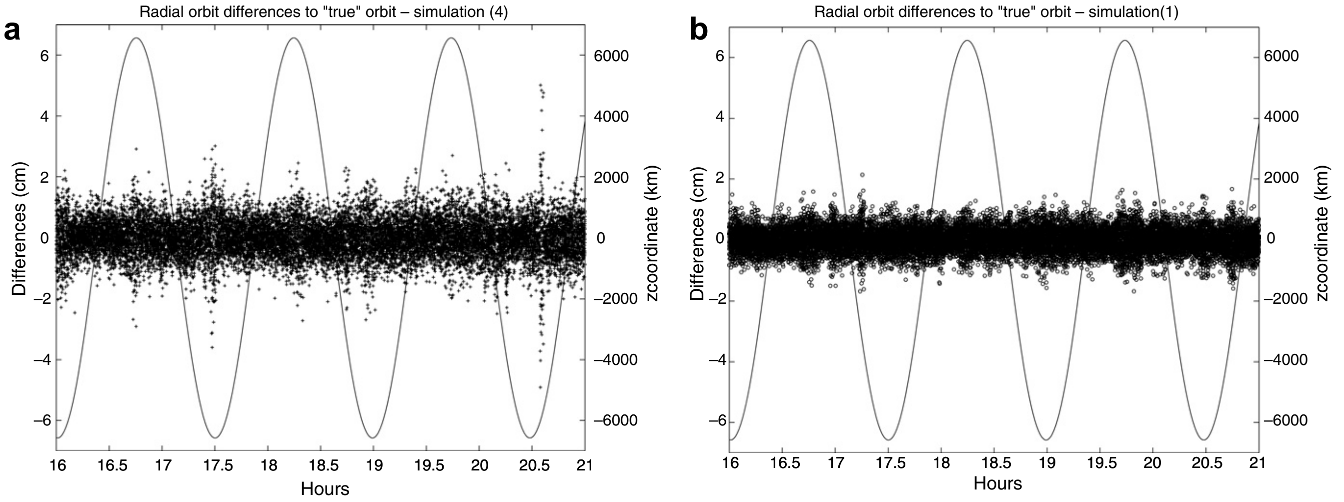

Fig. 9. Radial orbit differences of kinematic positions obtained with simulated observations with respect to the "true" orbit. Z-coordinate of orbit position overlayed.

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ulation (2) is only slightly larger than for simulation (1) and the orbit differences show no obvious degradation of the kinematic orbit result, confirming that the missing observations in simulation (2) have no significant impact w.r.t. simulation (1) on the kinematic orbit solution. For simulation (3) the impact of about 17% of missing observations w.r.t. simulation (1) is already visible in the quality of the kinematic orbit positions. Mainly over the polar regions the noise in the orbit differences becomes larger, but the degradation of the orbit quality is not yet alarming. The kinematic solutions for simulations (5) and (4), however, suffer from the satellite coverage over and near the polar regions (see Fig. 9a). The quality of the kinematic solutions for simulations (4) and (5) is degraded w.r.t. simulation (2), the simulation comparable to the CHAMP and GRACE performance. The accuracy requirements are still be met with such an – admittedly – pessimistic receiver/antenna performance. Considering, on the other hand, that the simulation represents an ‘‘ideal’’ case without cycle slips, multipath, and outliers, the real situation might be worse. If we should have such a high percentage of epochs (more than 50%, see Table 1) with eight or fewer tracked satellites (as found for simulations (4) and (5)) the loss of one or two observations could be critical for the quality of the kinematic positions.

If the observation noise of the phase carrier measurements is multiplied by a factor of 2 (simulation (6)), the differences between the kinematic positions and the ‘‘true’’ positions are doubled, as well (RMS error 5.4 mm instead of 2.7 mm). An observation noise of 2 mm would be more realistic considering systematic effects but it poses still no problem to meet the requirements.

7. Summary and conclusions

The GOCE satellite, as the first ESA Earth Explorer Core Mission, will be launched in December 2007 and HPF, as part of the ground segment, will process Level 1b data and generate Level 2 products. A central part of the HPF is the determination of precise orbits using GPS measurements deliverd by the dual-frequency Lagrange GPS receiver. The PSO is generated at AIUB and is based on a zero-difference approach. It is realized in one procedure for both the reduced-dynamic and the kinematic orbit solution. The generation of high-rate GPS clock corrections needed for the PSO solutions is also part of the HPF processing at AIUB. The procedure developed for the GOCE PSO processing has been applied for the two GRACE satellites. We showed that the procedure is suitable for GOCE and that the accuracy requirements of 2 cm (1-dimensional) can be met.

The PSO is generated in a 30-h overlap processing. Due to the 24-h processing scheme for the generation of the GPS orbits and clock corrections, they show small discontinuities (orbits: few millimeter, clocks: few centimeter) at the day boundaries. We described a procedure to connect the GPS orbits and clock corrections at midnight in a phase-consistent way. The POD results are much improved by this procedure.

The receiver/antenna configuration for GOCE is new and there is so far only little information available concerning the quality and amount of data. We therefore studied the impact of different elevation cut off angles on the kinematic point positioning results and have seen that even in a worst case (cut off between 10° and 15°) the required accuracy can still be met.

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