GOCE PRECISE ORBIT DETERMINATION FOR THE ENTIRE MISSION - CHALLENGES IN THE FINAL MISSION PHASE

A. Jäggi[1], **H. Bock**[1*], **and U. Meyer**[1]

[1]*Astronomical Institute, University of Bern, 3012 Bern, Switzerland*

[1*]*now at PosiTim UG, Germany*

ABSTRACT

The Gravity field and steady-state Ocean Circulation Explorer (GOCE), ESA's first Earth Explorer core mission, was launched on March 17, 2009 into a sun-synchronous dusk-dawn orbit and eventually re-entered into the Earth's atmosphere on November 11, 2013. A precise science orbit (PSO) product was provided by the GOCE High-level Processing Facility (HPF) from the GPS high-low Satellite-to-Satellite Tracking (hl-SST) data from the beginning until the very last days of the mission.

We recapitulate the PSO procedure and refer to the results achieved until the official end of the GOCE mission on October 21, 2013, where independent validations with Satellite Laser Ranging (SLR) measurements confirmed a high quality of the PSO product of about 2 cm 1-D RMS. We then focus on the period after the official end of the mission, where orbits could still be determined thanks to the continuously running GPS receivers delivering high quality data until a few hours before the re-entry into the Earth's atmosphere. We address the challenges encountered for orbit determination during these last days and report on adaptions in the PSO procedure to also obtain good orbit results at the unprecedented low orbital altitudes below 224 km.

Key words: GPS; Precise science orbit (PSO); Orbit determination before re-entry.

1. INTRODUCTION

The Gravity field and steady-state Ocean Circulation Explorer (GOCE, [12]) was the first Earth explorer core mission of the Living Planet Programme of the European Space Agency (ESA). The satellite was launched on March 17, 2009 from Plesetsk, Russia into a sun-synchronous dusk-dawn orbit with an inclination of 96.6°. It was equipped with six high-quality accelerometers [8] forming the GOCE core-instrument, the three-axis gravity gradiometer [24] for high-resolution recovery of the Earth's gravity field [7], three star cameras for attitude determination, as well as with two 12-channel dual-frequency Global Positioning System (GPS) receivers connected to helix-antennas [15] for precise orbit determination [6], instrument time-tagging, and the determination of the long-wavelength part of the Earth's gravity field [21].

The initial orbital altitude was 280 km, which was then lowered to 254.9 km (mean semi-major axis minus the Earth's radius at the equator) during the first months of the mission. This exceptionally low altitude was maintained at 254.9 km by the drag-free and attitude control system (DFACS), which compensated the non-gravitational forces acting in nominal flight direction by an ion propulsion assembly [1]. Since August 2012, the orbital altitude of the satellite was lowered stepwise by 30 km to about 224 km. In the first hours of October 21, 2013, the ion thruster ran out of fuel and the satellite could no longer be held on the measurement altitude. The official end of the mission was declared on this date and after a decay phase of 3 weeks the GOCE satellite re-entered the Earth's atmosphere in the first minutes of November 11, 2013.

2. ORBIT DETERMINATION FOR THE NOMINAL MISSION PHASE

As part of the European GOCE Gravity Consortium (EGG-C), the Astronomical Institute of the University of Bern (AIUB) was responsible for the generation of the official Precise Science Orbit (PSO) product within the GOCE High-level Processing Facility (HPF, [22]). Based on the methodology [16] and the experience gained from precise orbit determination (POD) of other low Earth orbiters (e.g., [17], [18], [20]), GOCE-specific adaptations were performed as documented in [3], [27].

The PSO product consists of a reduced-dynamic [16] and a kinematic [25] orbit. They were generated in one processing chain with an arc length of 30 h. The orbits were computed with a tailored HPF version of the Bernese GPS Software [9] using zero-difference GPS data collected by the onboard receivers. The 5 s GPS clock corrections [4] and the GPS final orbits from the Center

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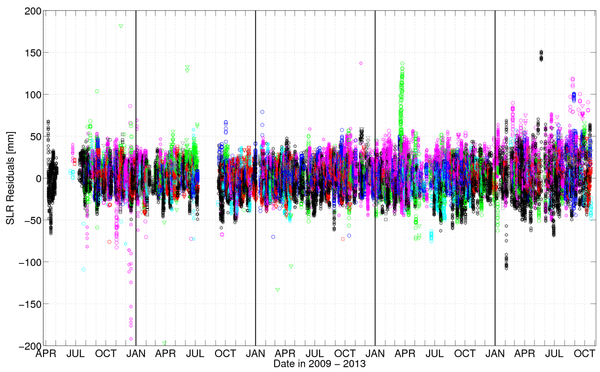

Figure 1. SLR residuals from April 10, 2009 until October 20, 2013 for the reduced-dynamic GOCE PSO solution.

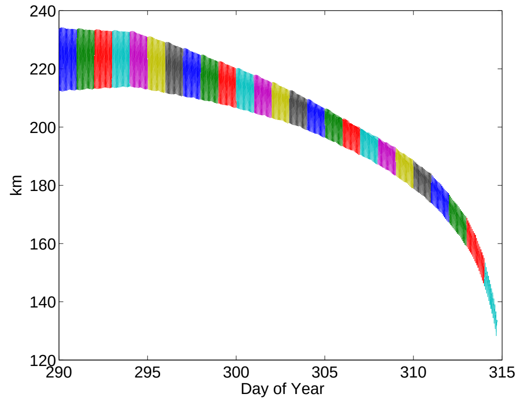

Figure 2. Evolution of the GOCE orbital height in the final phase between October 17 and November 10, 2013.

of Orbit Determination in Europe (CODE, [10]) were used to process the full amount of 1 s GPS data for kinematic POD and 10 s GPS data for reduced-dynamic POD. The parameters of the reduced-dynamic orbit of the PSO product are the six initial osculating elements, three constant empirical accelerations acting over the entire 30 h arcs in the radial, along-track, and cross-track directions, and piecewise-constant accelerations over 6 min acting in the same directions. No use was made of the GOCE common-mode accelerometer data or non-gravitational force models for the official PSO solutions, which implies that the piecewise constant accelerations mainly compensate the not explicitly modeled non-gravitational accelerations. Due to the neglected accelerometer data and due to the low orbital altitude, only rather weak constraints were imposed on the piecewise constant accelerations. The GOCE PSO generation is described in full detail in [3], [5].

The PSO is available since April 7, 2009 and was continuously delivered based on the same parameter settings as long as GPS data were available. Except for some days in early 2011, the main receiver (SSTI-A) was running in nominal operation. Independent SLR measurements may be used to compare the computed ranges between the GPS-based GOCE orbit trajectories and the SLR ground stations of the International Laser Ranging Service (ILRS, [23]) with the directly observed ranges. Figure 1 shows the SLR validation for the reduced-dynamic PSO solutions since April 10, 2009 for the entire nominal mission period. Thanks to the availability of dedicated orbit predictions for SLR tracking [19], a considerably large amount of SLR measurements may be used to independently assess the quality of the GOCE PSO solutions. The RMS of the SLR residuals over the entire mission is at a level of 1.84 cm for the reduced-dynamic PSO with only a small bias of 0.18 cm. A more detailed discussion on the excellent quality of the GOCE PSO product over the entire mission and possibilities for further improvements may be found in [6].

3. ORBIT DETERMINATION FOR THE FINAL PHASE

Operational orbit determination was continuously performed at AIUB from April 2009 until the official end of the mission in the early morning of October 21, 2013 (day 294), when the Xenon gas tank got empty and the drag-free flight could no longer be maintained. Consequently also the orbital height could no longer be maintained and the decay phase began. Figure 2 shows the evolution of the orbital height until November 10, 2013, when the last GPS data was recorded at 17:15:20 UTC. As predicted by Celestial Mechanics [2], the orbit got more and more circularized by the different magnitudes of atmospheric drag acting at perigee and apogee (note the faster decrease of the apogee height than the perigee height in Fig. 2). Moreover, the decay rate was significantly accelerating with decreasing orbital height. On November 09, 2013, the last day which is fully covered with GPS data, a decay rate as large as about 10 km per day is observed.

The transition between the drag-free flight and the decay phase on October 21, 2013 is also prominently seen in the estimated piecewise constant accelerations. Figure 3 shows that in the early morning hours of the day a sudden jump in the mean level of the along-track accelerations occured due to the presence of atmospheric drag. Figure 3 illustrates that from this moment onwards significantly different accelerations were acting on the satellite. It is worth mentioning that essentially no adaptions were needed in the PSO procedure to compute reduced-dynamic orbital solutions for this particular day. In order to get optimal orbital fits, however, the changed characteristics of the expected accelerations need to be taken into account.

3.1. Modifications of the POD procedure

Dynamic POD is a challenge for satellites at low orbital altitudes due to unavoidable deficiencies in the non-

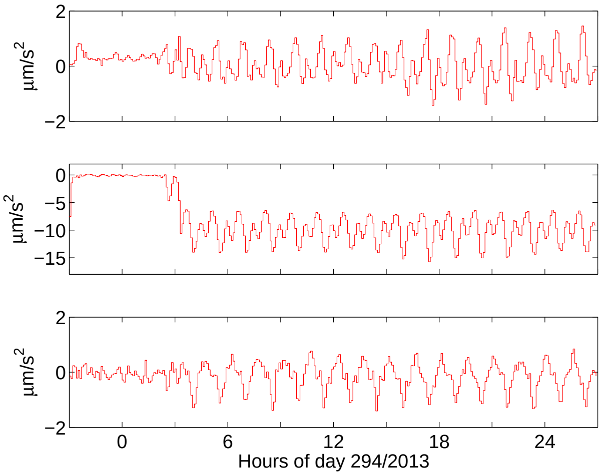

Figure 3. Piecewise constant accelerations estimated on October 21, 2013 in the radial (top), along-track (middle), and cross-track (bottom) direction of the local orbital frame. Note the transition into non-drag-free flight and the different scale for the along-track component.

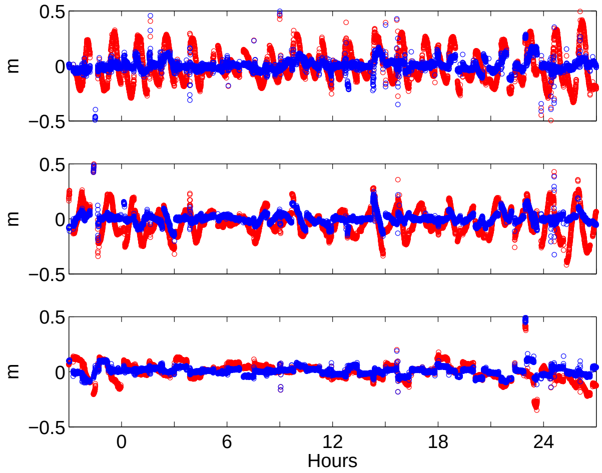

Figure 4. Differences between reduced-dynamic and kinematic orbits on October 31, 2013 in the radial (top), along-track (middle), and cross-track (bottom) directions. Differences based on original POD settings are displayed in red, differences based on reduced-dynamic orbits with adapted constraints are displayed in blue.

gravitational force models such as atmospheric drag models [26]. For GOCE POD the dynamic models were fixed by the GOCE standards [11], implying that also the used gravitational models are no longer optimal for the very low orbital altitudes due to the use of rather old models, e.g., the gravity field model EIGEN-5S [13]. If dense and continuous tracking data such as GPS measurements are available, however, use may be made of their geometric strength by adopting reduced-dynamic orbit determination techniques [28]. At AIUB, so-called pseudo-stochastic parameters, e.g., realized as piecewise constant accelerations, are adopted to realize reduced-dynamic POD [16]. Since pseudo-stochastic parameters are primarily intended to compensate for force model deficiencies, they are characterized by a priori variances which constrain them to zero. If dense tracking data are available, pseudo-stochastic parameters may be set up frequently and may even replace deterministic force models to a certain extent by relaxing the a priori variances accordingly.

In order to minimize the accumulation of orbital errors, the GOCE orbital arc-length was not kept fixed for the final phase of the mission as it was the case for the nominal mission phase. 30 h arcs were still generated for days 294-304, but were shortened to independent arcs of 15 h for days 305-309 with new initial conditions set up at 12:00:00. A further reduction to 10 h was performed for the days 310-313, where the GPS data were processed in independent intervals of 21:00:00-06:59:59, 07:00:00-16:59:59, and 17:00:00-02:59:59. For the very last day, where GPS data are only available until 17:15:20, the three independent arcs were chosen from 21:00:00-04:00:00, 03:59:59-10:59:59, and 11:00:00 to 17:59:59.

In addition to the reduced arc-length, thresholds in the GPS carrier phase data screening (which relies on intermediate reduced-dynamic orbit solutions) and the number of iterations in the orbit determination procedure had to be adapted due to inferior qualities of the underlying a priori orbits which are based on only a small number of orbital parameters. Most importantly, however, the a priori standard deviations of the empirical parameters of the final solutions had to be adapted as discussed in detail in the following paragraph.

3.2. Comparison RD-KIN

For all days from 294 to 314 reduced-dynamic solutions with different a priori standard deviations imposed to the 6-min piecewise constant accelerations were computed and eventually compared with the kinematic orbits. It has to be emphasized that the kinematic solutions are completely independent of the GOCE orbital dynamics. Apart from potential issues in GPS data screening, which relies on intermediate reduced-dynamic solutions, kinematic orbits are therefore not further affected by the very low orbital heights. The agreement between both orbit types may therefore serve as a measure for the quality of the reduced-dynamic orbits in the final phase. Provided that good dynamic models are available, this is as opposed to the nominal mission phase where it is usually the quality of the kinematic orbits which is assessed by comparing them with the more robust reduced-dynamic solutions [6].

Figure 4 shows the differences between the reduced-dynamic and the kinematic orbit solution for one particular day in the local orbital frame when using either the original POD settings as they were adopted throughout the entire nominal mission phase, or when using ten times weaker constraints imposed on the piecewise constant accelerations estimated in the reduced-dynamic orbit deter-

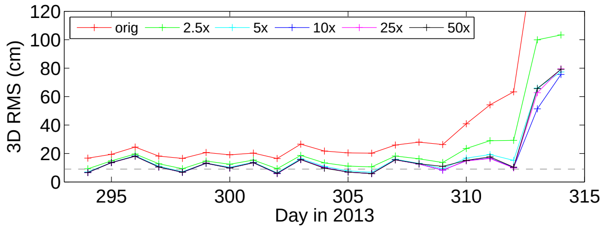

Figure 5. 3D RMS of differences between reduced-dynamic and kinematic orbits when adopting different constraints for the reduced-dynamic POD wrt the original settings.

mination. Obviously the reduced-dynamic solution based on weaker constraints agrees significantly better to the kinematic solution.

Figure 5 shows the 3D RMS values of the differences between the kinematic and the reduced-dynamic solutions for different constraints. The dashed line at 9 cm indicates a pessimistic estimate of the consistency achieved during the entire nominal mission phase when the drag-free flight was still active. Adopting the nominal POD settings for the final decay phase obviously yields a much degraded consistency. Significant improvements may be achieved by adopting much weaker constraints, where a factor of ten seems to be reasonable. Figure 5 also shows that good solutions may be obtained for all days of the decay phase, apart from the very last two days where still somewhat larger differences between the reduced-dynamic and kinematic solutions occur.

3.3. Comparison with accelerometer data

The common-mode GOCE accelerometer data provide a measure of the non-gravitational forces acting on the satellite. Because the reduced-dynamic PSO solutions did neither make use of the common-mode accelerations, nor of models describing the non-gravitational forces, the common-mode accelerometer data may be compared with the piecewise constant accelerations estimated in the course of the reduced-dynamic orbit determination from the GPS data. Assuming that the neglect of non-gravitational force models represents the largest source of mismodeling also at very low orbital altitudes, an agreement between the independent common-mode accelerometer data and the estimated accelerations from orbit determination is expected.

Figure 6 shows the comparison of the measured non-gravitational accelerations with the estimated accelerations in the local orbital frame for one particular day. The local orbital frame is represented by the radial, along-track, and cross-track direction. It has to be emphasized that the transformation from the gradiometer instrument frame, to which the common-mode accelerometer data are referring, to the local orbital frame significantly changes the characteristics of the accelerations due to

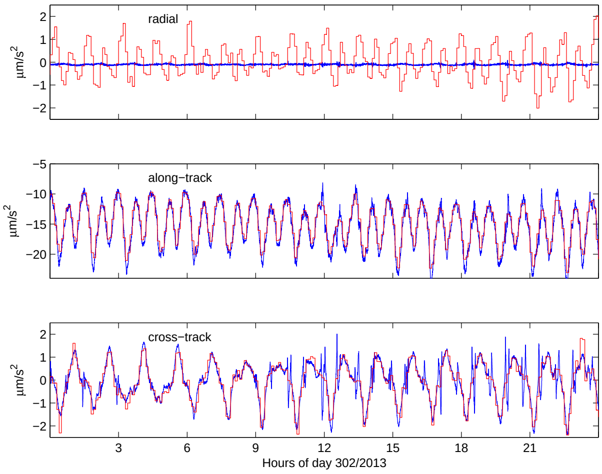

Figure 6. Piecewise constant accelerations (red) compared with measured accelerometer data (blue) on October 29, 2013.

the attitude motion, which particularly affects the cross-track direction. Figure 6 confirms a good agreement for both the along-track and the cross-track direction, where the estimated piecewise constant accelerations are indeed dominated by non-gravitational accelerations. For the radial direction, however, the measured accelerations are much smaller and do not match with the estimated piecewise constant accelerations. Further tests will be needed to check whether this is due to the gravitational force model which is inadequate at this low orbital altitude, or due to a non-optimal constraining of the empirical accelerations in the radial direction.

3.4. The very last day before re-entry

Figure 7 shows the differences between the reduced-dynamic and the kinematic orbit solution for the very last day in the local orbital frame when using the original POD settings or when using ten times weaker constraints imposed on the empirical accelerations. Despite the generally larger differences and a significant number of jumps in the kinematic positions, a surprisingly good agreement is observed even at the extremely low orbital altitude of 140 km. Some larger differences are only observed for the last couple of hours before GPS tracking ended.

4. CONCLUSIONS

Operational determination of the GOCE PSO was continuously performed at AIUB from April 2009 until the official end of the mission in the early morning of October 21, 2013. Accuracies of better than 2 cm were achieved for the reduced-dynamic solutions. Thanks to the continuously running GPS receivers, orbits could still be determined during the final decay phase until a few hours

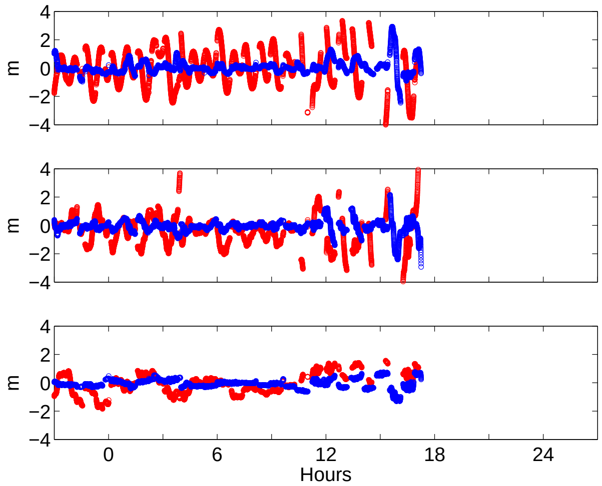

Figure 7. Differences between reduced-dynamic and kinematic orbits on the very last day (November 10, 2013) in the radial (top), along-track (middle), and cross-track (bottom) directions. Differences based on original POD settings are displayed in red, differences based on reduced-dynamic orbits with adapted constraints are displayed in blue.

before the re-entry into the Earth's atmosphere. The strong accelerations caused by the no longer compensated non-gravitational accelerations asked for adaptions in the POD settings for the reduced-dynamic orbit computations. Based on relaxed constraints of the estimated empirical accelerations good orbit results could still be achieved. This is confirmed by a comparable consistency between kinematic and reduced-dynamic solutions as achieved for the nominal mission phase, as well as by a good agreement between estimated and measured accelerations in the along-track and cross-track directions. Reasonable solutions could even be achieved at unprecedented low orbital altitudes down to about 140 km until the very last GPS measurements were collected on November 10, 2013 at 17:15:20 UTC.

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