RAPID AND PRECISE ORBIT DETERMINATION FOR THE GOCE SATELLITE

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ABSTRACT

The ESA GOCE Core Explorer Mission carries a 12-channel, dual-frequency Global Positioning System (GPS) receiver for high-accuracy precise orbit determination. Precise GOCE orbit solutions are used to accurately geolocate the observations taken by the primary science instrument, the gradiometer, that aims at collecting medium to short wavelength gravity information. In addition, the orbit solutions provide complementary information for the long-wavelength gravity field part.

Precise orbit determination is an integral part of the GOCE High-Level Processing Facility (HPF) that produces the best gravity field model products possible. A rapid (RSO) and precise science orbit (PSO) determination chain are providing orbit solutions with a precision of about 10 cm at 1 day latency and 2-3 cm at 4 weeks latency, respectively. The 4 weeks latency for the PSO product holds for the final validated version. An interim PSO product with comparable precision is provided with a latency of 1-2 weeks.

Key words: GOCE; High-Level Processing Facility (HPF); Precise Orbit Determination.

1. INTRODUCTION

The Gravity field and stead-state Ocean Circulation Explorer (GOCE), launched 17 March 2009, is the first Core Earth Explorer Mission by the European Space Agency (ESA). It aims at mapping the static Earth's gravity field with a precision of 2 cm in terms of geoid and 1 mgal in terms of gravity anomalies for length scales down to 100 km [2]. The primary instrument to achieve these aims is a gravity gradiometer consisting of 3 orthogonal pairs of accelerometers. This primary instrument is amongst others supported by a high-quality, dual-frequency 12-channel Lagrange GPS receiver. This receiver allows a precise orbit determination (POD), which is one of the tasks of the High-Level Processing Facility (HPF) [4]. In addition, GOCE is equipped with retro-reflectors for Satellite Laser Ranging (SLR), which allows an independent check of the quality of the POD. Within the HPF, the Delft University of Technology FAE/A&S group and University of Bern AIUB institute are responsible for providing respectively low latency Rapid Science Orbit (RSO) and Precise Science Orbit (PSO) solutions. The validation is taken care of by IAPG of the Technische Universität München [10].

The low latency RSO solutions support GOCE mission operations. The RSO activities include format checks of the GPS Level 1b data, which are provided in RINEX format [8] and several quality checks of the GPS code and phase observations. In addition, the RSO orbit solutions serve as pseudo observations for quick-look gravity field estimation and are used for geolocating the GOCE Satellite Gravity Gradient (SGG) observations. Finally, a spin-off of the RSO orbit computations are time series of estimated non-gravitational accelerations that have been used to check the common-mode accelerations provided by the gradiometer. The PSO activities include GPS data format and quality checks as well, but are particularly essential for the final geolocation of the SGG observations and for use as pseudo observations in gravity field determination. A spin-off of the PSO activities is the prediction of GOCE orbits, which is crucial in the support of acquiring observations by the SLR tracking stations.

This paper provides a brief description of the POD instruments and a first assessment of their performance. This is followed by a short overview of the orbit products and also a first assessment of their quality.

2. PRECISE ORBIT DETERMINATION INSTRUMENTS

The 12-channel GOCE GPS receivers are attached with helix antennae opposed to e.g. patch antennae on-

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board CHAMP and GRACE [5]. In addition, GOCE is equipped with an SLR retro-reflector array (Fig. 1). The helix antenna proved to be very reliable and is mounted such on the GOCE satellites that in general 9 to 12 GPS satellites are tracked simultaneously.

GOCE GPS tracking data are provided with an interval of 1 s. Only for less than 0.2% of the epochs, less than 5 satellites are tracked allowing to perform a single point positioning for nearly all time instances. Using the tools outlined in [5], the noise levels of the several code observations could be estimated for the GOCE GPS receiver (Fig. 2). These noise levels are higher than for the CHAMP and GRACE BlackJack receivers, but when taking into account the higher sampling rate (1 Hz vs. 0.1 Hz leading to a reduction of the noise levels of about $\sqrt{10}$ when deriving normal points), the noise levels are comparable. The Root-Mean-Square (RMS) of fit of the ionospheric-free combination of phase observations for kinematic GOCE orbit solutions is about 5.6 mm, comparable to a value of 5.0 mm obtained for GRACE-A. It has to be noted that the noise level of the phase observations is in fact much lower, e.g. 2 mm for the BlackJack receivers [5]. The higher values of 5.0 and 5.6 mm are caused by the fact that use was made of preliminary, relatively low-rate, GPS clock products, requiring interpolation.

The first GOCE SLR observations were acquired by the Australian Yarragadee station at the end of March 2009 (Tab. 1). Up to 22 stations have been able to track GOCE until June 2010 leading to a total of 888 passes and 15703 normal points (on the average about 5 passes and 100 normal points per day). A significant increase in the number of passes was obtained after orbit predictions were provided by the HPF (AIUB) to the International Satellite Laser Ranging (ILRS) community around DOY 200 of 2009 (Fig. 4, [3]). The SLR observations form a valuable data set for checking the quality of GPS-based GOCE orbit solutions (Section 3).

3. PRECISE ORBIT DETERMINATION PRODUCTS

The HPF orbit products include low-latency RSO and more precise PSO products. Both the RSO and PSO products are composed of orbit solutions based on the reduced-dynamic and kinematic orbit techniques [10]. These products include time series of positions and velocities (reduced-dynamic only) in SP3 format [9], additional files for quality analysis and files in support of SGG observation checking and gravity field determination. The precision requirement for the RSO orbit solutions is 50 cm 1-dimensionally (1D) with a latency of 1 day after GPS data availability. For the PSO, the precision requirement is 2 cm 3-dimensionally (3D) and the typically latency is 1 week. The RSO and PSO orbit solutions are computed with different software systems allowing cross-verification and inter-comparisons. The different software systems are GEODYN (RSO reduced-dynamic), GHOST (RSO kinematic) and Bernese (all PSO solutions) [7, 6, 1]. The time interval for the time series of orbit position and velocity solutions is equal to 1 s and 10 s for kinematic and reduced-dynamic orbit solutions, respectively.

Table 2. Mean and RMS of fit of SLR observations (November 2009 - January 2010).

	Orbit solution	Mean (cm)	RMS (cm)
RSO	reduced-dynamic	1.29	4.10
	kinematic	0.53	7.14
PSO	reduced-dynamic	0.88	2.05
	kinematic	0.88	2.23

The latency of the RSO product is displayed in Fig. 5. In fact, this figure represents the latency with respect to the last time epoch that is covered by the computed orbit. For example, if the orbit covers 0:00 - 24:00 of DOY 100, 2010, then a latency of 1 day means the RSO product is provided before 24:00 of DOY 101, 2010. However, the RSO orbits are nominally computed within 12 hours after the availability of the last required RINEX files. In case the latency requirement is not met, this is due to hick ups in the delivery of the required products. The consistency between all RSO and PSO orbit solutions is nominally better than 10 cm 3D (Fig. 6). The consistency between PSO kinematic and reduced-dynamic orbit solutions is generally even better than 2 cm 3D, indicating that all requirements are met. This is also reflected y the RMS of fit of SLR observations, which is of the order of 2 cm for the PSO and 4-7 cm for the RSO orbit solutions (Tab. 2).

Finally, the reduced-dynamic orbit determinations provide time series of non-gravitational accelerations which, when estimated in the instrument frame of the gradiometer, would ideally coincide with the common-mode accelerations (after correcting for a bias). In general, a high level of consistency is observed between the variations of these accelerations (Fig. 7), indicating that the scale factors of the accelerometers are properly calibrated. The orbit computations thus also support the validation of the gradiometer observations.

4. CONCLUSIONS

The Lagrange receiver onboard GOCE is a high-quality, dual-frequency GPS receiver that, together with a helix antenna, provides continuous tracking by 9-12 GPS satellites most of the time. The GOCE GPS observations allow the computation of rapid (1 day latency) and precise (4 weeks latency) orbit solutions with a 3D precision of nominally better than 10 and 2 cm, respectively, well within the prelaunch requirements.

In addition, the delivery of predicted GOCE orbits supports tracking of GOCE by SLR stations, leading to typ-

Figure 1. GPS and SLR antennae

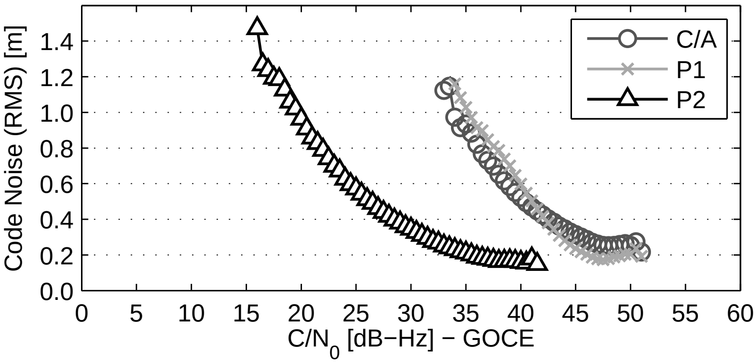

Figure 2. In-flight GOCE GPS receiver performance

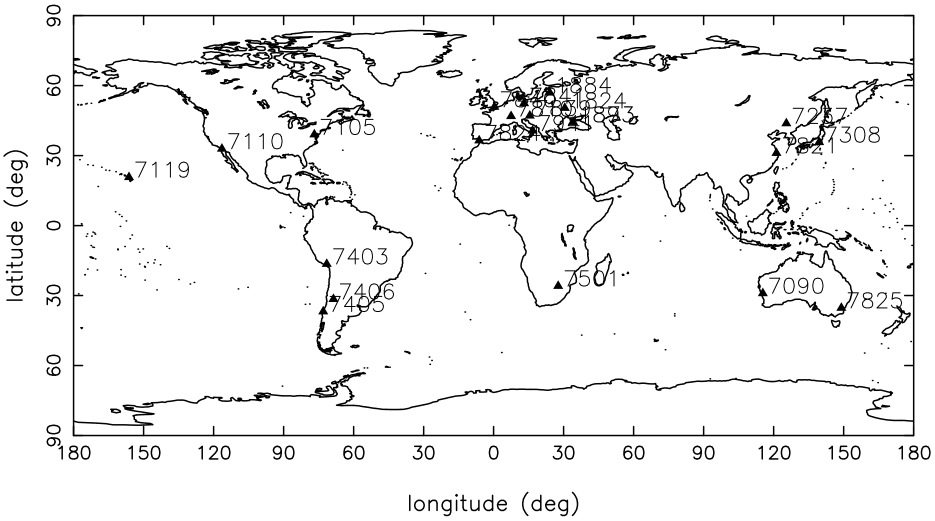

Figure 3. Geographical distribution of SLR tracking stations (31 May 2009 - 13 June 2010)

Table 1. SLR tracking stations (31 May 2009 - 13 June 2010).

Tracking period	Station	#passes	#obs	
090331 21:42:33 - 100613 11:20:01	7090	286	6333	Yarragadee, Australia
090821 08:56:08 - 100605 09:13:32	7237	114	1265	Changchun, China
090828 05:58:13 - 100611 06:10:42	7839	85	2092	Graz, Austria
090621 22:05:58 - 100428 22:25:55	7105	64	1508	Greenbelt, Maryland
090729 17:14:28 - 100609 06:19:23	7810	51	1078	Zimmerwald, Switzerland
090730 17:15:18 - 100613 17:38:33	7840	47	562	Herstmonceux, United Kingdom
090615 08:17:52 - 100604 08:58:11	7825	38	144	Mt Stromlo, Australia
090924 18:43:08 - 100201 06:43:44	7824	33	540	San Fernando, Spain
090824 06:08:29 - 100606 16:39:56	7841	29	604	Potsdam, Germany
090817 14:01:44 - 100601 14:26:01	7110	25	316	Monument Peak, California
090430 23:06:51 - 100523 23:19:47	7406	24	392	San Juan, Argentina
091013 15:52:18 - 100126 04:06:59	1893	18	208	Katzively, Ukraine
091006 16:26:04 - 100123 15:58:30	1884	15	151	Riga, Latvia
090729 04:26:09 - 100202 03:54:38	7501	14	153	Hartebeesthoek, South Africa
091007 16:18:24 - 100407 16:28:12	7941	10	61	Matera, Italy
090907 10:11:52 - 091125 10:28:37	7405	8	77	Concepcion, Chile
091013 08:21:55 - 100204 09:02:54	7308	7	68	Koganei, Japan
090628 04:02:09 - 100205 04:25:58	7119	7	42	Haleakala, Hawaii
100323 10:42:38 - 100610 10:59:35	7403	6	33	Arequipa, Peru
091122 09:52:28 - 100104 09:46:21	7821	5	64	Shanghai, China
100119 16:14:01 - 100119 16:14:37	1824	1	7	Golosiiv, Ukraine
091201 15:15:55 - 091201 15:18:31	1873	1	5	Simeiz, Ukraine

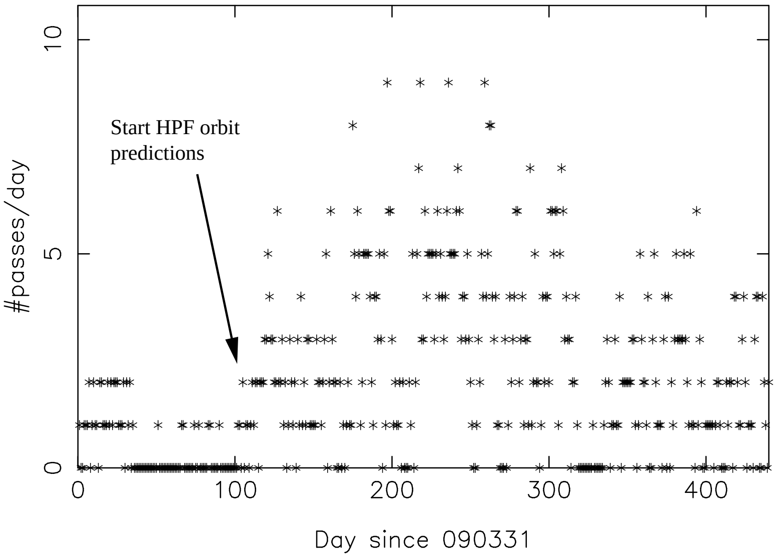

Figure 4. Number of SLR passes per day (31 May 2009 - 13 June 2010)

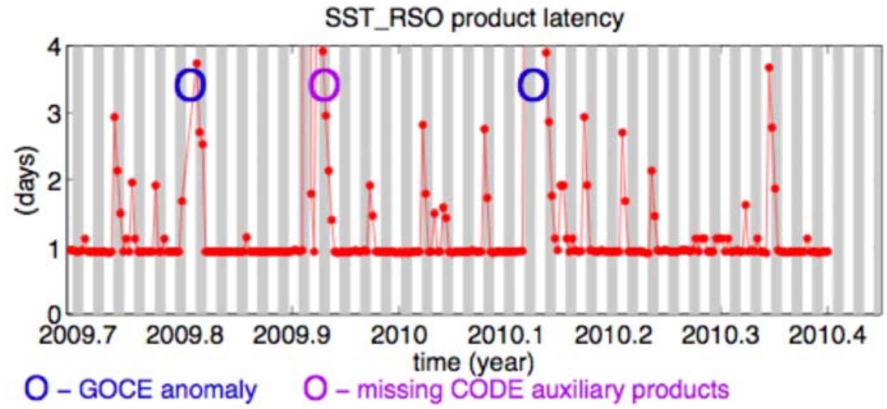

Figure 5. Latency of RSO product

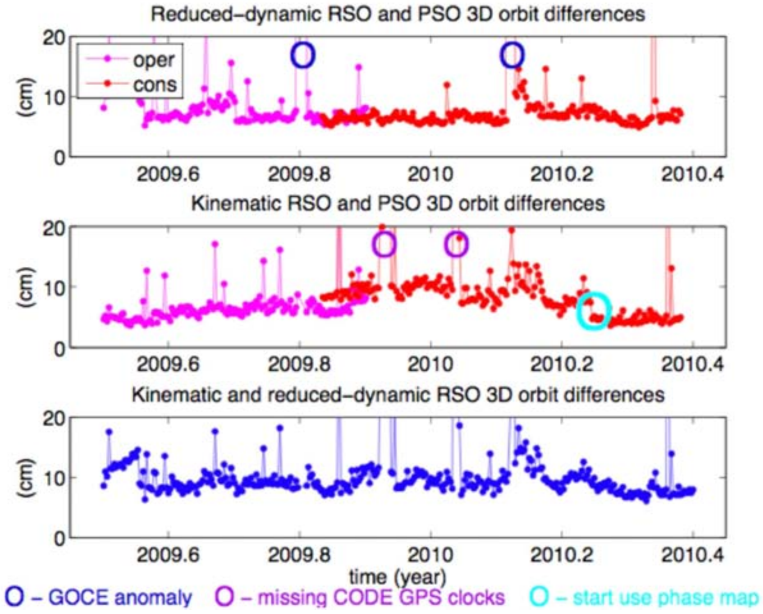

Figure 6. Comparison between RSO and PSO orbit solutions

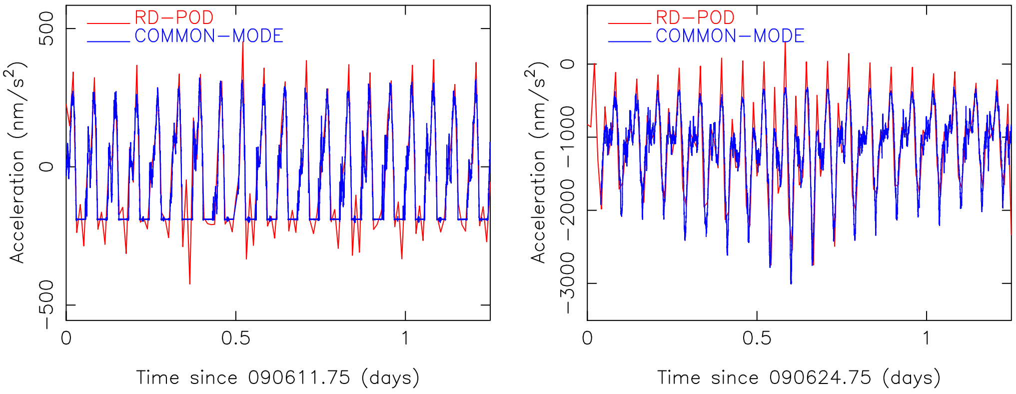

Figure 7. Common-mode accelerations vs. estimated non-gravitational accelerations from the reduced-dynamic RSO solution in flight direction: drag free control on (left: 11 June 2009) and off (right: 24 June 2009)

ically 5 passes or more per day. The confrontation of GPS-based RSO and PSO orbit solutions with these observations, with an RMS of fit of 4-7 and 2 cm, indicate as well that the orbit solutions are of high quality and meet the requirements.

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REFERENCES

[1] Dach, R. & Hugentobler, U. & Fridez, P. & Meindl, M. (2007). Bernese GPS Software, *Version 5.0”*, University of Bern

[2] Drinkwater, M. & Haagmans, R. & Muzzi, D. & Popescu, A. & Floberghagen, R. & Kern, M. & Fehringer, M. (2007). The GOCE gravity mission: ESA’s first core explorer, in *3^{rd} GOCE User Workshop, 6-8 November 2006, Frascati, Italy*, pp. 1–7, ESA SP-627.

[3] Jäggi, A. & Bock, H. & Floberghagen, R. (2010). GOCE orbit predictions for SLR tracking. GPS Solutions, DOI 10.1007/s10291-010-0176-6

[4] Koop, R. & Gruber, T. & Rummel, R. (2007). The status of the GOCE high-level processing facility, in *3^{rd} GOCE User Workshop, 6-8 November 2006, Frascati, Italy*, pp. 199–205, ESA SP-627, 2007.

[5] Montenbruck, O. & Kroes, R. (2003). In-flight Performance Analysis of the CHAMP BlackJack Receiver, GPS Solutions 7, 74-86, DOI 10.1007/S10291-003-0055-5

[6] Montenbruck, O. & Andres, Y. & Bock, H. & et al. (2008). Tracking and Navigation Performance of the GRAS Instrument on MetOp-A, *GPS Solutions*, *12*(4), 289–299, doi: 10.1007/s10291–008–0091–2

[7] Pavlis, D.E. & Poulouse, S. & McCarthy, J.J. (2006). GEODYN Operations Manual, *Contractor report*, SGT Inc., Greenbelt, MD

[8] RINEX (2001). RINEX: The Receiver Independent Exchange Format Version 2.20, ftp://cddisa.gsfc.nasa.gov/pub/reports/formats/rinex220.format, last accessed, 30 June 2008.

[9] SP3c (2007). The Extended Standard Product 3 Orbit Format (SP3-c), ftp://igscb.jpl.nasa.gov/igscb/data/format/sp3c.txt,last accessed, 30 June 2008

[10] Visser, P.N.A.M. & van den IJssel, J. & Van Helleputte, T., Bock, H. & Jaeggi, A. & Beutler, G. & Hugentobler, U. & Svehla, D. (2006). Rapid and Precise Orbit Determination for the GOCE Satellite, in *3^{rd} GOCE User Workshop, 6-8 November 2006, Frascati, Italy*, pp. 235–239, ESA SP-627.