GOCE FLIGHT DYNAMICS OPERATIONS FROM AN ORBITAL PERSPECTIVE

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Abstract: *The Gravity Field and Steady-State Ocean Circulation Explorer mission GOCE was successfully launched on the 17th of March 2009 from the Plesetsk Cosmodrome on a Rockot launch vehicle and is since controlled from ESA's European Space Operations Centre (ESOC) in Darmstadt, Germany. The spacecraft is the first Earth Explorer Core Mission of the ESA Living Planet Program and its main objective is to obtain detailed measurements of the Earth's gravitational field to an unprecedented accuracy. The purpose of this paper is to report on the experiences of operating such an unique spacecraft from a flight dynamics point of view with an emphasis on the orbital aspects of the mission during the different phases of the mission (LEOP, commissioning, routine phases, and contingencies).*

Keywords: *GOCE, LEOP, routine operations, orbit control, SSTI.*

1 Introduction

The Gravity Field and Steady-State Ocean Circulation Explorer (GOCE) satellite that was successfully launched on the 17th of March 2009, from the Plesetsk cosmodrome, on a Rockot launch vehicle, is the first Earth Explorer Core Mission in a series of scientific Earth Observation missions the European Space Agency (ESA) is implementing in the frame of the ESA Living Planet Program [1,2]. An artist's impression of the GOCE spacecraft is shown in Figure 1.

1.1 Mission Objectives

The main objectives of the GOCE mission are to measure the Earth's gravity field anomalies with an unprecedented accuracy of 1 mGal (equals 10^{-5} m/s^2) and to provide a model of the geoid with an accuracy of 1 to 2 cm. Both objectives are to be met at a spacial resolution better than 100 km, which dictates how the orbit of GOCE should be maintained during routine operation phases.

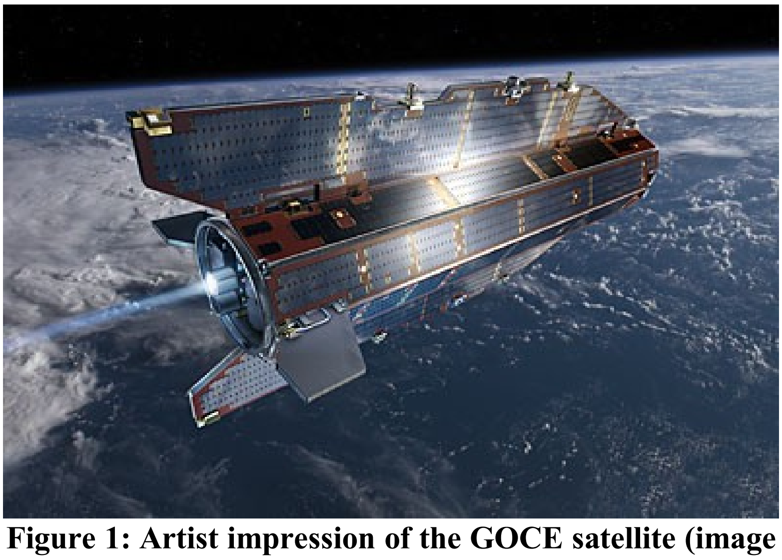

Figure 1: Artist impression of the GOCE satellite (image credit: ESA)

To achieve these objectives, GOCE has been orbiting the Earth in a sun-synchronous dusk-dawn orbit at an exceptionally low altitude of about 260 km, which is made possible by its aerodynamic shape and employing a sophisticated Drag-Free Attitude and orbit Control System (DFACS). The system uses an Ion Propulsion Assembly (IPA), in closed loop, to continuously counteract the drag caused by the residual atmosphere of the Earth. The high-resolution features of the gravity field are measured with a highly accurate Electrostatic Gravity Gradiometer (EGG) by measuring the acceleration differences over short baselines between proof masses of 3 pairs of accelerometers. The low-resolution data is obtained by measuring the spacecraft's drag-free orbit with a scientific, dual frequency (L1/L2), 12 channel Lagrange GPS receiver aboard the satellite, the Satellite-to-Satellite Tracking Instrument (SSTI). Both units are used in the DFACS control loop, making the GOCE spacecraft as a whole the gravity measurement device, with no clear distinction between spacecraft platform and payload. Figure 2 shows the main components of the GOCE satellite.

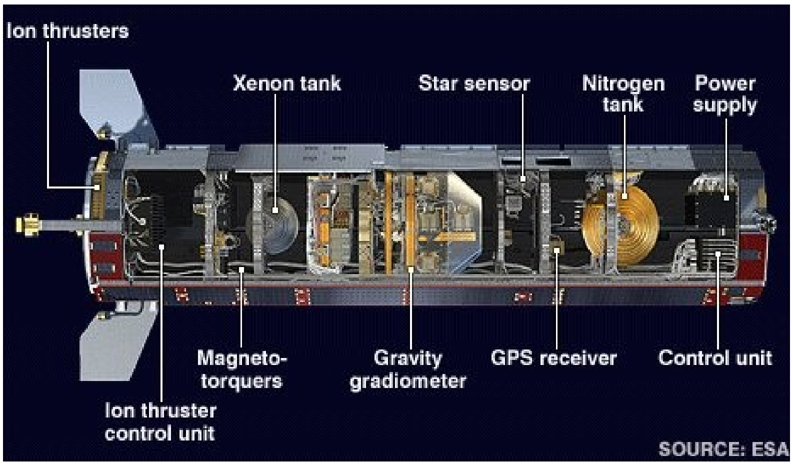

Figure 2: Illustration of the GOCE spacecraft and its main components (image credit: ESA)

The DFACS can operate in several modes, ranging from basic attitude stabilization modes up to full drag-free control modes. The modes for basic attitude stabilization with varying degrees of precision without orbit control (i.e. IPA and EGG not in the loop) are CPM, ECPM and FPM. The mode where in addition the altitude of the orbit is controlled, through the use of the IPA in open loop, is DFM_PREP. The modes for full drag-free control with both the IPA and EGG in the DFACS loop, are DFM_COARSE and DFM_FINE. The latter mode is the mode used during the scientific measurement campaigns. To maintain the spacial resolution during the measurement campaigns, the orbit altitude can be controlled by biasing the IPA thrust.

1.2 Flight Operations Segment

The GOCE spacecraft is controlled from the Flight Operations Segment (FOS) at ESOC. The FOS incorporates all systems required for operating GOCE and is implemented following the standard approach for ESA missions. The Flight Dynamic System (FDS) is part of that system and performs all those activities related to the determination and prediction of the GOCE orbit, the fuel bookkeeping, monitoring of the attitude, and the generation of commands for orbit and attitude related spacecraft operations. The FDS, based on ESOC's ORATOS platform, comprises the command generation, attitude monitoring, orbit , and test & validation subsystem.

The function of the GOCE command generation subsystem is to generate AOCS related commands and reports required by the Flight Control Team (FCT), where the function of the GOCE attitude monitoring subsystem is to process telemetry (TM) in order to derive flight dynamics related parameters for the monitoring of the spacecraft's behavior and health. The function of the GOCE orbit subsystem is to determine and predict the GOCE orbit, and provide orbital products daily to the other FDS subsystems, the FCT, the supporting ground stations, and the GOCE payload data ground segment at ESRIN. The Test and Validation subsystem (attitude and orbit) finally has the task to check all the products generated by the orbit subsystem and the command generation subsystem independently, before the FDS products can be distributed to other parts of the FOS.

This paper focuses on the orbital aspect of operating such a unique spacecraft. It mainly reports on the tasks of the FDS orbit subsystem and the experience gained during the different stages of the mission up the present time, covering almost 2 years of operation.

1.3 FDS Orbit Subsystem

The FDS orbit subsystem makes use of the general purpose NAvigation Package for Earth Orbiting Satellites (NAPEOS) software to support the GOCE mission. NAPEOS has been developed in the nineties at ESOC and has been used ever since to provide support for all phases of ESA's Earth Observation missions in terms of mission preparation and operational support for orbit determination, orbit prediction and orbit control. The orbit determination element is designed to process the full range of the currently available measurement types, including different types of ground-based range, Doppler, and angular measurements, satellite-based GNSS measurements (generated from on-board receiver telemetry, today from the GPS system, later also from Galileo and possibly Glonass), height measurements from a radar altimeter, laser measurements and inter-satellite ranges and range-rates. The core of NAPEOS is the orbit determination suite BAHN. It is based on a high precision dynamic orbit integrator combined with a batch weighted least-squares estimator. The main role of BAHN is to generate accurate ephemerides for a spacecraft by minimizing the weighted difference between the real measurements and measurements computed using the best available parameter values and models, taking into account statistical uncertainties in the initial state estimate. To support the orbit modeling of GOCE in drag-free mode, in particular the feature of biasing the IPA thrust in this mode for orbit maintenance use, the NAPEOS software was extended by modeling and estimating the IPA thrust bias as a constant acceleration.

The models adopted for the orbit determination and prediction of GOCE are presented in Tab. 1. During LEOP and contingencies, the main sources of tracking data are the angular data, and S-band ranging and Doppler data from the ground station network supporting GOCE, when no SSTI data is available. During all other phases, the SSTI data is the main and often only source of tracking data for the operational orbit determination of GOCE. In the latter case, the angular data is not used in the orbit determination process directly, but used as an indicator for the proper functioning of the SSTI. The angular data residuals will increase when the orbit is based on incorrect SSTI data.

Table 1: Description of models used for the orbit determination and prediction of GOCE

Orbit models	
Geo-potential	EIGEN-GL05C degree and order 70
Third bodies	Sun, Moon (J2) and all planets (DE405)
Aerodynamics in decay or raise phase	Canon ball (constant area of 1.0352 m^2 or variable area table)
	Density (NRLMSISE-00)
	Wind (HWM93)
Aerodynamics in drag- free phase	None
Solar radiation pressure	Canon ball (constant area or variable area table), constant area: 11.2101 m^2
Albedo/IR radiation	None
Integrator	Multi-step Adams-Bashfort/Adams-Moulton predictor-corrector method of order 8, restarting at discontinuities using RK-8
Step size	120 steps per orbit
Measurement model	
S-band station position	ESA tracking directory [5], KSAT station ICD [6]
Weight of: Angular (az/el) data	10/10 mdeg (KIR-1) and 100/100 mdeg (SG3, TR1, AS1)
S-band ranging data	10 m (KIR-1) and 30 m (SG3, TR1 AS1)
S-band Doppler data	30 cm/s (KIR-1, SG3, TR1 AS1)
SSTI position data	30 m
Transponder delay	1.301 km
Estimated parameters	
Orbit determination arc	3 days
Drag-free phase	along track constant acceleration parameters bound by changes in the IPA thrust bias (maximum duration per parameter is one day) fixed solar radiation pressure coefficient per arc

Decay or raise phase + constant IPA thrust + SSTI	1 drag coefficient per day fixed along track constant acceleration parameters bound by thrust changes (maximum duration per parameter is one day) fixed solar radiation pressure coefficient per arc
Decay or raise phase + constant IPA thrust + S-band	1 drag coefficient per day fixed along track constant acceleration parameters bound by thrust changes (maximum duration per parameter is one day range bias per arc per station range-rate bias per arc per station
Decay phase + S-band	1 drag coefficient per day range bias per arc per station range-rate bias per arc per station
Decay phase + SSTI	1 drag coefficient per day
Prediction arc	30 days

The SSTI units aboard GOCE can provide positional data in either the Standard Positioning Service (SPS) mode (leased squares method) or in the Navigation Kalman Filter (NKF) mode. The latter mode provides more accurate positional information and is therefore preferred over the other mode. Both modes can provide positional data in either Earth-Centered-Inertial (ECI) True-Of-Date (TOD) or ECI J2000, or Earth-Centered-Earth-Fixed (ECEF) reference frame. The standard mode of operations is NKF, providing navigation solutions in the ECI J2000 reference frame through standard telemetry packages. The positional data is extracted from these packages by the software of the attitude monitoring subsystem before being used in the orbit determination process. Data taken in the other mode and other reference frames than ECI J2000, are only available through additional diagnostic telemetry packages. The 3-D, 3-sigma position error of the ECI J2000 NKF solution is around 30 meters (based on ground testing results of 2005 [3]).

2 Launch and Early Orbit Phase (LEOP)

The Russian Rockot launch vehicle, a derivative of the SS-19 intercontinental ballistic missile, supplied and operated by Eurockot Launch Services, was released from the launch pad of the spaceport at Plesetsk, Russia on March 17, 2009 at 14:21:13.776 UTC (epoch of lift-off contact). The spacecraft was injected quite accurately by the launcher into its sun-synchronous dusk-dawn orbit at an altitude of 283.2 km with a LTAN of 18:00. GOCE was injected at a higher altitude than the one foreseen for science operations to allow for the commissioning of the complex subsystems and units required to actually fly drag-free. The summary of the injection performance is presented in Tab. 2. The nominal values for the osculating orbital elements have been calculated based on the Rockot specifications [4]. The achieved values are based on an orbit determination done about 12 hours into the mission after separation, employing all S-band tracking data collected by the LEOP ground station network up to that point in time. The difference (achieved minus nominal) confirms the injection was well within the 3-sigma launcher injection uncertainties, indicated in the last column of the table.

Table 2: Summary of injection performance at separation (15:51:35.0 UTC)

Orbital element (osculating)	Nominal	Achieved	Difference [1]	Required accuracy (3-sigma)
Semi-major axis [km]	6656.400	6654.832	-1.568	± 5
Eccentricity [-]	0.00000	0.00019	0.00019	± 0.0025
Inclination [deg]	96752	96.762	0.010	± 0.05
Right Ascension of Ascending Node (RAAN) [deg]	85.227	85.225	-0.002	±0.25
Argument of Latitude [deg]	49.895	50.396	0.501	±5

[1] achieved minus nominal

The LEOP station network consisted of ESA's Kiruna ground station (KIR-1) in Sweden, the Svalbard ground station (SG3) in Svalbard and the Troll ground station (TR1) in Antarctica of the Kongsberg Satellite Services AS (KSAT), and the Alaska ground station (AS1) in Fairbanks of the Alaska Satellite Facility (ASF). The stations provided angular data, and S-band ranging and Doppler tracking data for the orbit determination of GOCE. The visibility of GOCE from these stations at an elevation of 5 degrees and the ground track of GOCE for the first 10 hours of the mission after separation are depicted in Fig. 3. Separation occurred shortly before AOS of the first Kiruna pass.

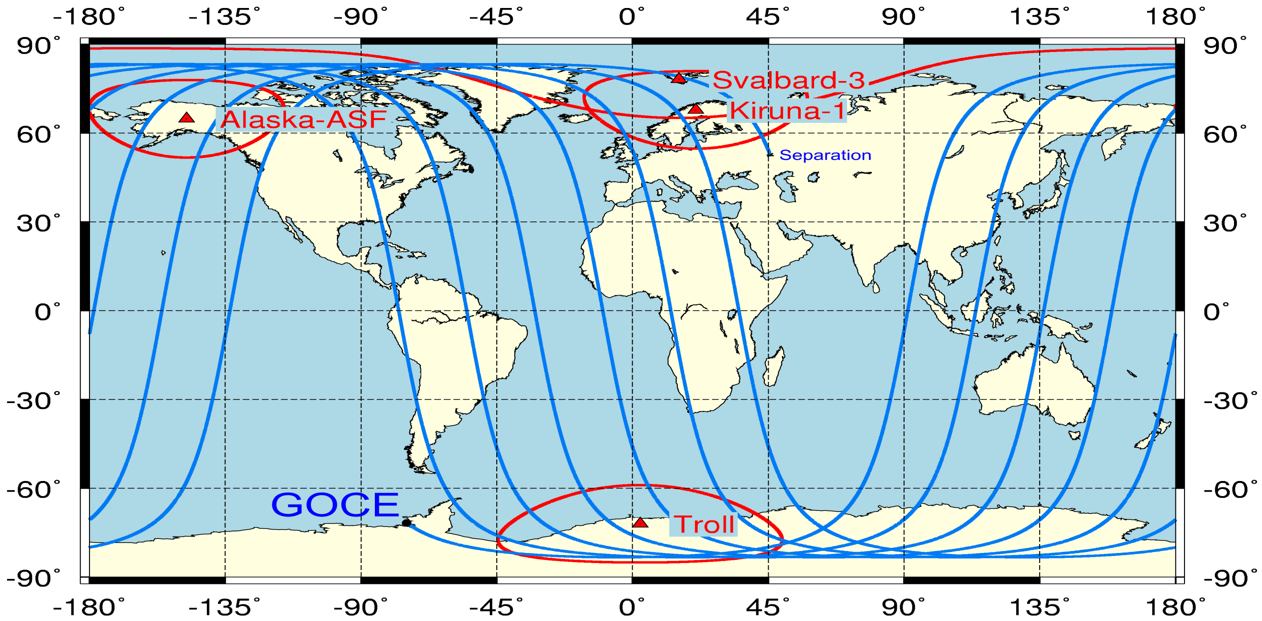

Figure 3: GOCE visibility from the LEOP station network at 5 degree elevation (red) and GOCE ground track (blue) for first 10 hours after separation.

The first acquisition over Kiruna was successfully performed based on the nominal orbit information provided by FDS before launch. The acquisition over the other stations did not pass off as easily. In the first few orbits these stations had some problems providing valid tracking data or tracking data at all for one pass. This improved slowly over the course of the LEOP. Fortunately, the orbit insertion was quite accurate, so no immediate update of the orbit information was needed. The about 7 seconds early Time Offset Value (TOV) reported by Kiruna at first acquisition matched reasonable well the TOV estimate of FDS, based on a first coarse orbit determination utilizing tracking data from the first Kiruna pass only. From this orbit, FDS predicted an increase in TOV of about 1.8 seconds early every orbit, corresponding to the 1.5 km lower than nominal orbit insertion (see Tab. 2), later confirmed by the stations. After 7 revolutions of GOCE the TOV had increased to about 20 seconds early. At this point in time the orbit of GOCE was updated, based on 2 Kiruna, 2 Svalbard, and 6 Troll passes with ranging and Doppler, and 1 Alaska pass with ranging only. New orbital products and commands were generated, successfully checked, and distributed to other parts of the FOS. Using the new predictions, the stations reported a TOV of 0 seconds as expected.

The LEOP lasted 3 days, where GOCE was operated from ESOC's main control room with 24/7 support in 12-hour shifts, with experts from the S/C manufacturer and from ESA's GOCE project team on site. During this time FDS support was provided in 9-hour shifts overlapping by 1 hour to allow for shift hand-over. The main operations during LEOP consisted of bringing the satellite into FPM - the mode foreseen for the orbit decay phase without use of the IPA - and initial check out of the SSTI. The activation of the more complex subsystems required for drag-free flying were done at a later stage. An important task of FDS during the commissioning of the SSTI was to evaluate the quality of the SSTI data and to determine whether the orbit determination of GOCE could be based on this tracking data type only. The importance being that without the SSTI data, the orbit determination would have to be based on S-band data only and this would seriously reduce the number of passes available for dumping the science data at a high data rate. Ground stations can no longer provide ranging to the satellite and take Doppler measurements when the satellite transponder is in high data rate mode. Besides, when the transponder is in this mode, the mass memory dump SSTI data covers the complete GOCE orbit and not just tracking over a station as is the case with S-band data and real time SSTI data. Real time SSTI data is taken from telemetry collected during the station pass.

The evaluation of the SSTI was done in two steps. In the first step, the collected real time SSTI data (transponder in low data rate mode) was compared to a GOCE orbit based on the S-band ranging and Doppler date from the LEOP ground station network only. The result of this comparison is depicted in Fig. 4. Shown are the real time ECI SSTI data residuals (in meters) of data collected over the Alaska and Troll ground station during two orbits.

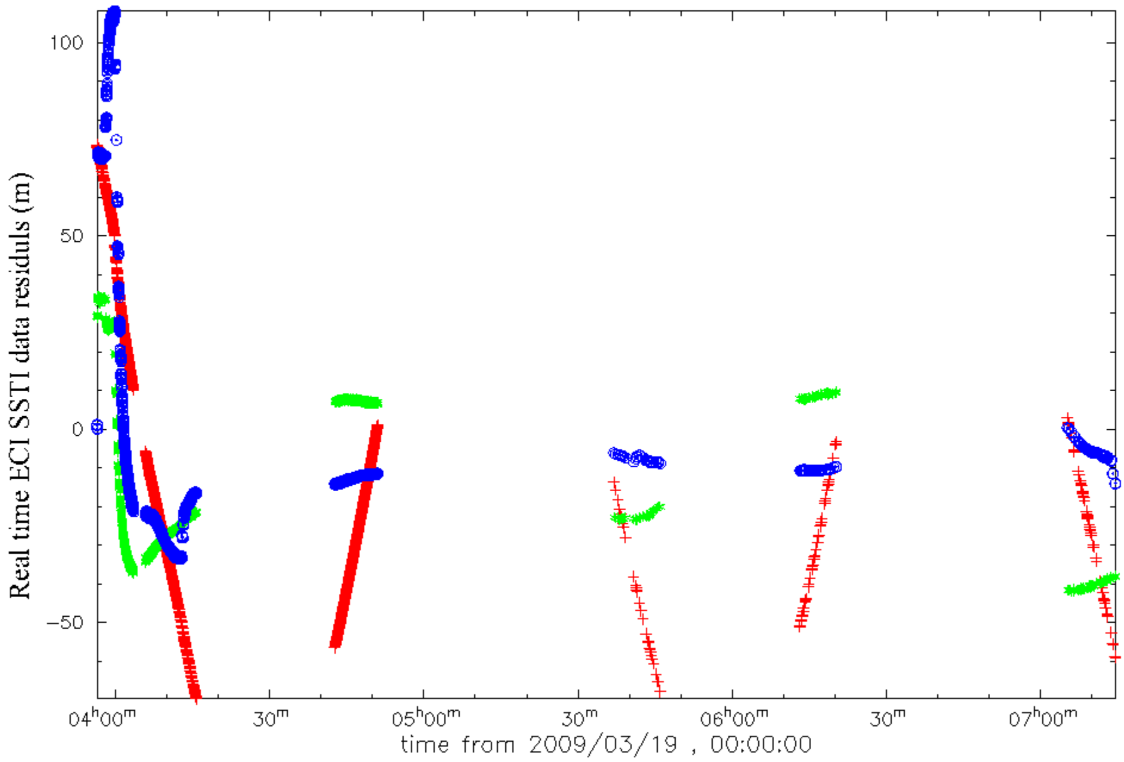

Figure 4: Residuals (in meters) of the real time ECI SSTI data, X (red), Y (green), and Z (blue), compared to a GOCE orbit based on S-band ranging and Doppler data only.

The residuals indicate that after the initial start up of the SSTI (left side of the graph) the solution converged to a consistent one, although slightly different from the S-band solution, but still within specifications. In the second step, the same comparison was made, but now with 13 hours of continuous SSTI data collected through mass memory dumps over Kiruna. The results of that comparison are presented in Fig. 5. Maximum residuals of about 160 m were found in X direction.

Comparing an orbit based on the SSTI data only with an orbit based on the S-band data only, revealed that the main difference between the two solutions is in cross track direction with the maximum deviation at the Equator, indicating that the Right Ascension of the Ascending Node (RAAN) is estimated differently for the two data types. Based on these results, the decision was made to start using the ECI SSTI data for the orbit determination of GOCE. After switching the transponder permanently to high data rate mode, the SSTI data was the main source of tracking data available for orbit determination.

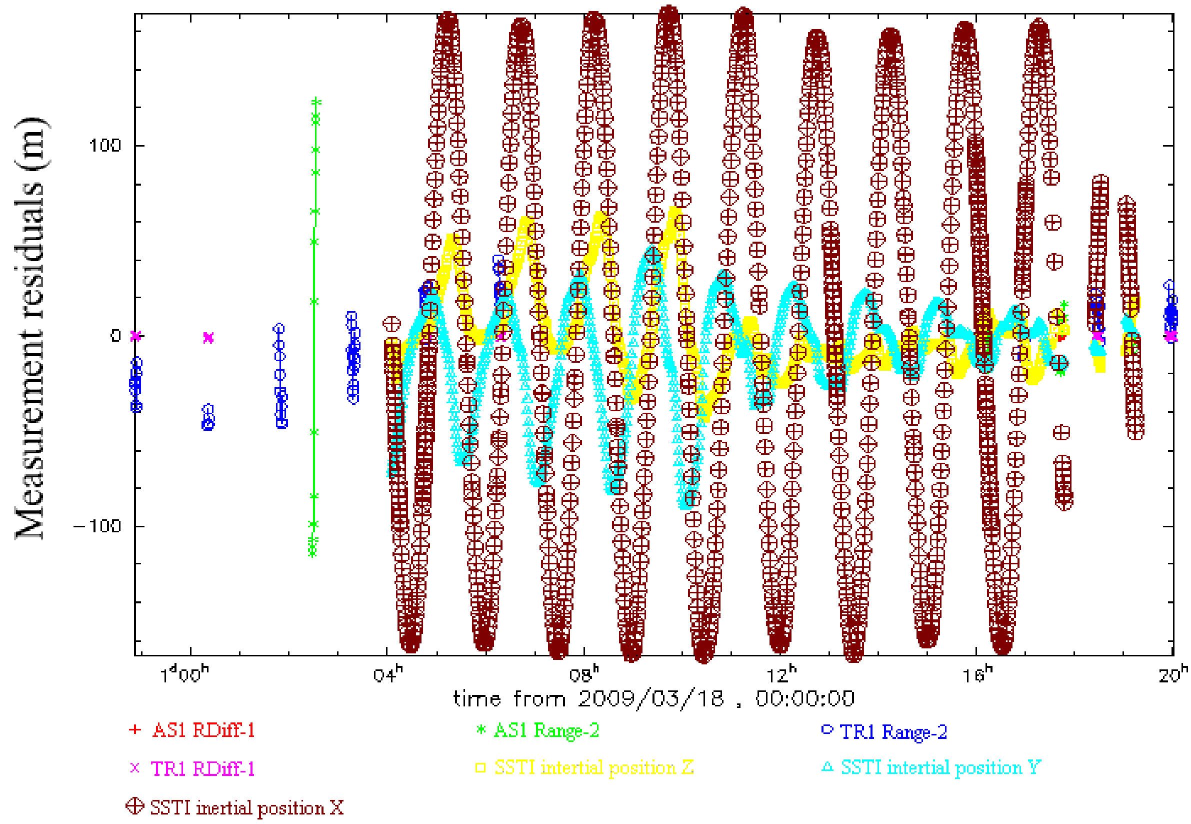

Figure 5: Residuals (in meters) of S-band ranging and range difference (Doppler) data, mass memory dump ECI SSTI data w.r.t orbit based on S-band data only.

Figure 6 shows the ECI SSTI data residuals after an orbit determination of GOCE based on SSTI data only. The SSTI data residuals were less than 30 m.

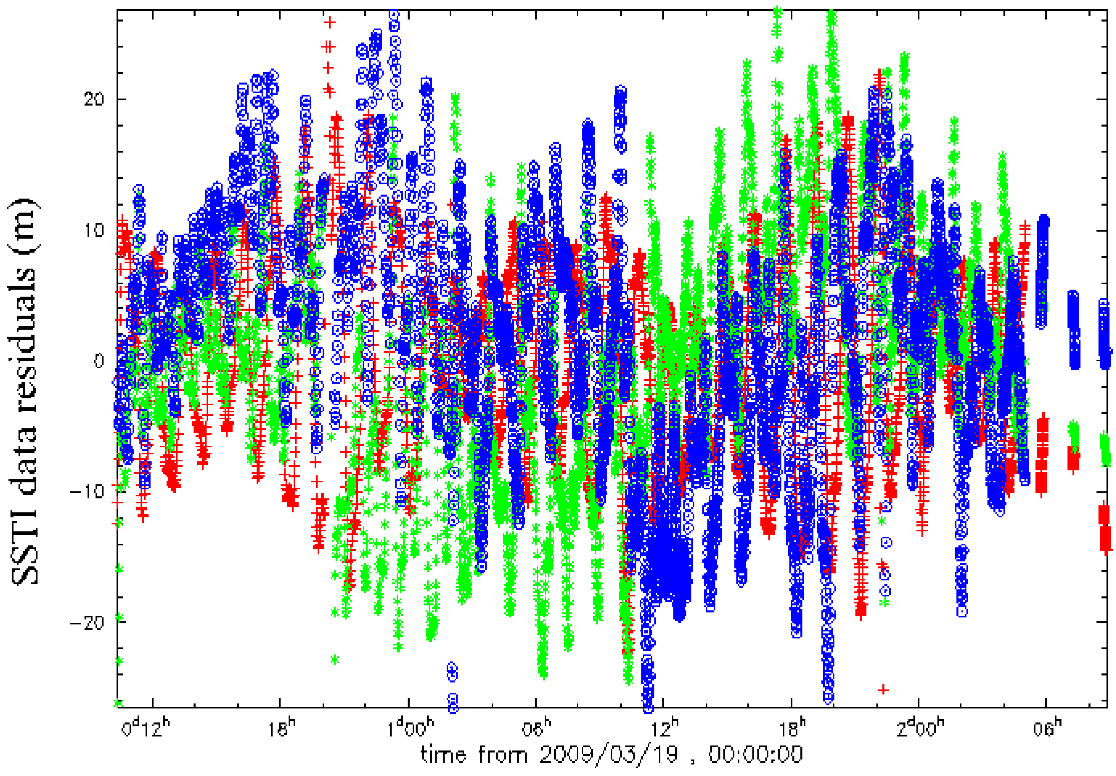

Figure 6: Residuals (in meters) of the ECI SSTI data, X (red), Y(green), and Z (blue), collected over almost 2 days, based on GOCE orbit determination using SSTI data only.

3 Commissioning phase

The commissioning of GOCE lasted from launch up to the start of the routine operations phase at the beginning of October 2009. During the commissioning, the orbit of GOCE needed to be lowered to the desired altitude, but because GOCE is not designed for performing orbit decay maneuvers, the lowering of the orbit is achieved by just not compensating the atmospheric drag. The decay rate is in the order of a couple of 100 meters per day at GOCE's altitude, depending largely on the activity of the Sun and to some extend the attitude control mode of GOCE. Figure 7 gives an overview of GOCE's mean altitude from launch up to the end of October 2009. It also indicates when specific events took place, like reaching the altitude that was selected for the routine science operation phase the middle of September 2009, but also when the DFACS commissioning started and ended. The events are described in more detail below.

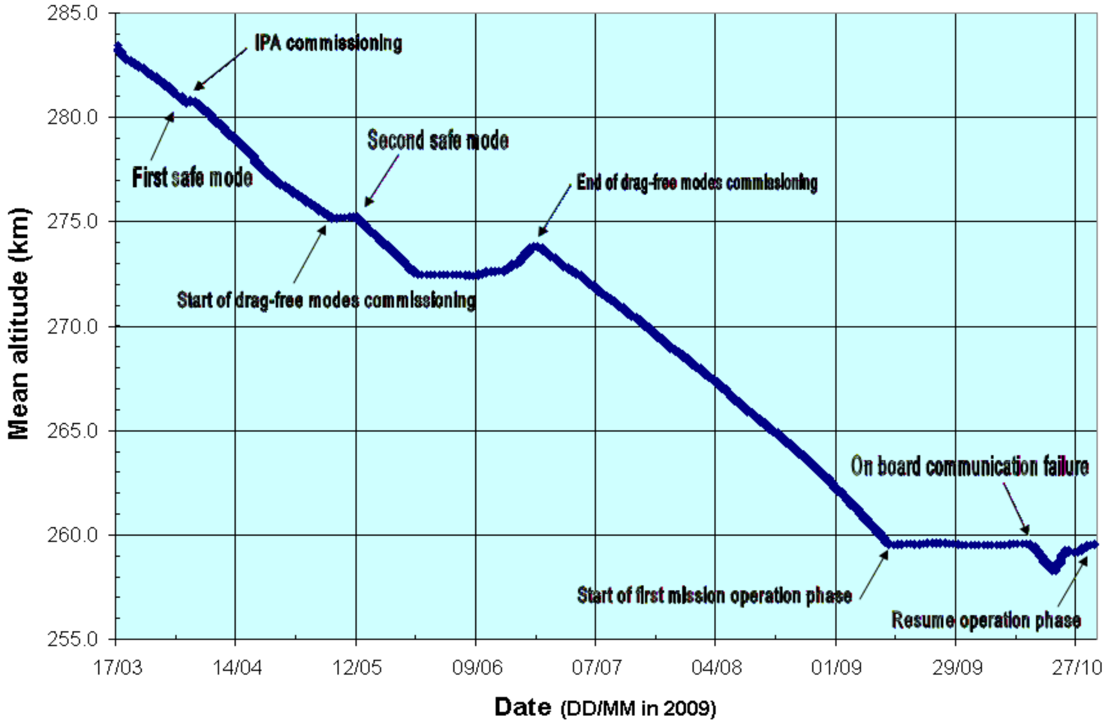

Figure 7: Mean altitude (in km) of GOCE during decay phase, from launch date to the start of the first mission operation phase.

The days immediately after LEOP were dedicated to the unit-level commissioning of the DFACS, whereas the commissioning of the IPA system only started 10 days after (see Fig. 7) to allow for complete out-gassing of the unit. During the 4 days of IPA commissioning, the engine was fired at a wide range of thrust levels (including the maximum available thrust of 19 mN). To properly reflect the orbit changes in the orbit prediction used for pointing the ground station antennas, a close coordination with the FCT was required.

At this stage of the mission, the FDS system was set up to run automatically once a day, however this turned out to be less automatic than expected due to the first safe mode of the mission on the 1st of April 2009. The safe mode was caused by an attitude controller problem in the FPM mode of the DFACS. It turned out the FPM controller settings, as established before launch, were inadequate for controlling the spacecraft in an environment, where the level of atmospheric drag was lower than foreseen due to the exceptionally low solar activity at the time, and the spacecraft atmospheric properties were actually different from what had been assumed. The problem was in the end solved by redesigning the FPM controller gains. The new set of gains for the FPM mode, but also the higher DFACS modes, were installed aboard the spacecraft on the 22nd of April. The next day FPM was entered successfully and the commissioning of the higher DFACS modes commenced.

On 5th of May GOCE entered the drag-free modes DFM_COARSE and DFM_FINE for the first time, stopping the orbit decay as can be seen from Fig. 7. However, on the 12th of May, the commissioning of the drag-free modes was interrupted by the second safe mode of the mission, caused by a flight software problem when performing the EGG K2 calibration in DFM_FINE for the first time. While the anomaly was investigated and fixed, the spacecraft decayed further with the DFACS in FPM mode until the 26th of May when the transition back to DFM_FINE was performed.

On the 23rd of June the orbit decay was resumed (see Fig. 7) after successfully completing the commissioning of the DFACS drag-free modes. One insight that resulted from the commissioning was that the routine science operation phase should take place at a lower altitude than foreseen before launch in order to experience a drag force higher than the minimum IPA thrust level of 0.6 mN over the complete orbit. If the drag force would drop below this level, GOCE would not be flying completely drag-free and would be providing unreliable science measurements. After some analysis of the expected drag level at different altitudes and different levels of solar activity, it was decided to stop the decay at a mean altitude of 259.6 km. In addition to having enough air drag at this altitude, this altitude also provides a better spacial resolution of more accurate measurements than would be possible at the originally foreseen 268 km altitude. This target altitude was finally reached on 13th of September when the DFACS mode was changed to DFM_FINE and the first routine operations phase started in the first half of October 2009. However, this was interrupted on the 16th of October, when a communication failure on board forced the DFACS to fall back to FPM, switching off the IPA. The IPA was switched on again 4 days later after patching the platform software RAM. Science was resumed on the 26th of October after a short raise phase (see Fig. 7).

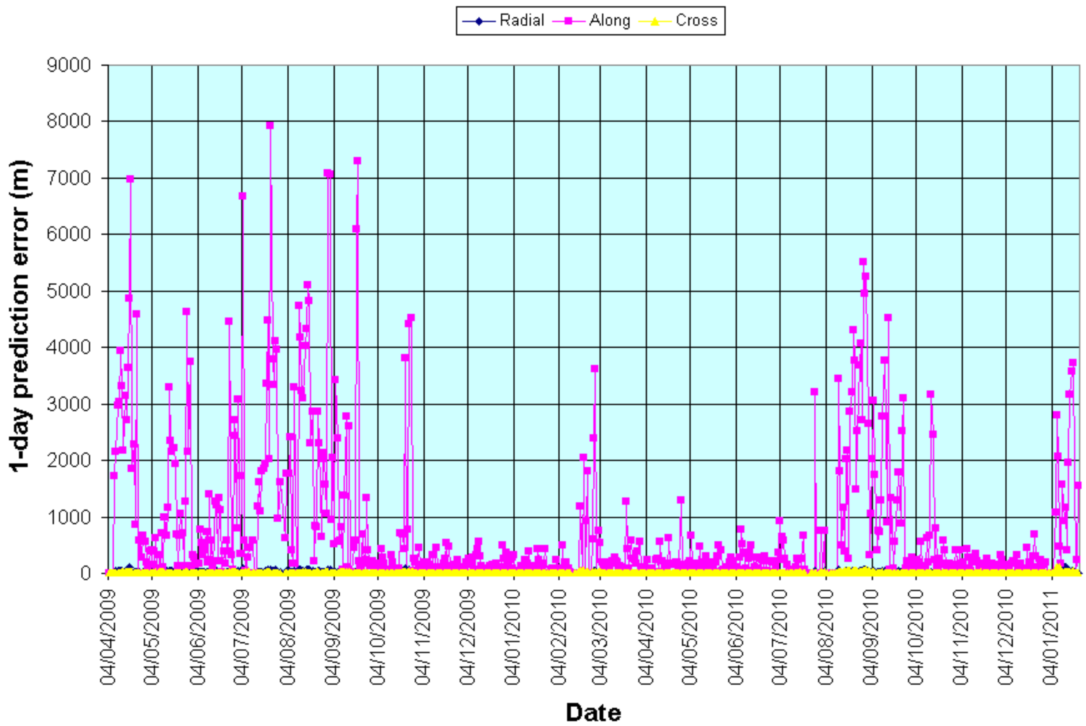

Figure 8: 1-day prediction error (in meters) since the start of the mission. Maximum along track prediction error is about 1 second TOV

Throughout the decay phase the accuracy of the orbit predictions were not within requirements, which states the orbit predictions over a 3-day period should be better than 100, 9000, and 100 meters in respectively radial, along, and cross direction when not in drag-free mode. The main reason for the inaccurate predictions can be traced back to the unpredictable variation in the attitude around yaw that was observed in FPM, with attitude errors ranging from 5 up to 20 degrees [7], and errors in the solar prediction. These large variations in attitude and atmospheric density cause a significant fluctuation of the orbit decay rate and thus impact the accuracy of the orbit prediction. As can be seen from Fig. 8 already 1-day predictions can violate the orbit prediction requirement.

From Fig. 8, 9, and 10 we see that over the mission the orbit prediction error along track has been below the 8, 120, and 800 km for respectively 1-day, 3-day, and 6-day predictions during FPM. However, because the orbit predictions are generated on a daily basis, the predictions have been accurate enough to ensure correct pointing of the station antennas for acquiring the spacecraft.

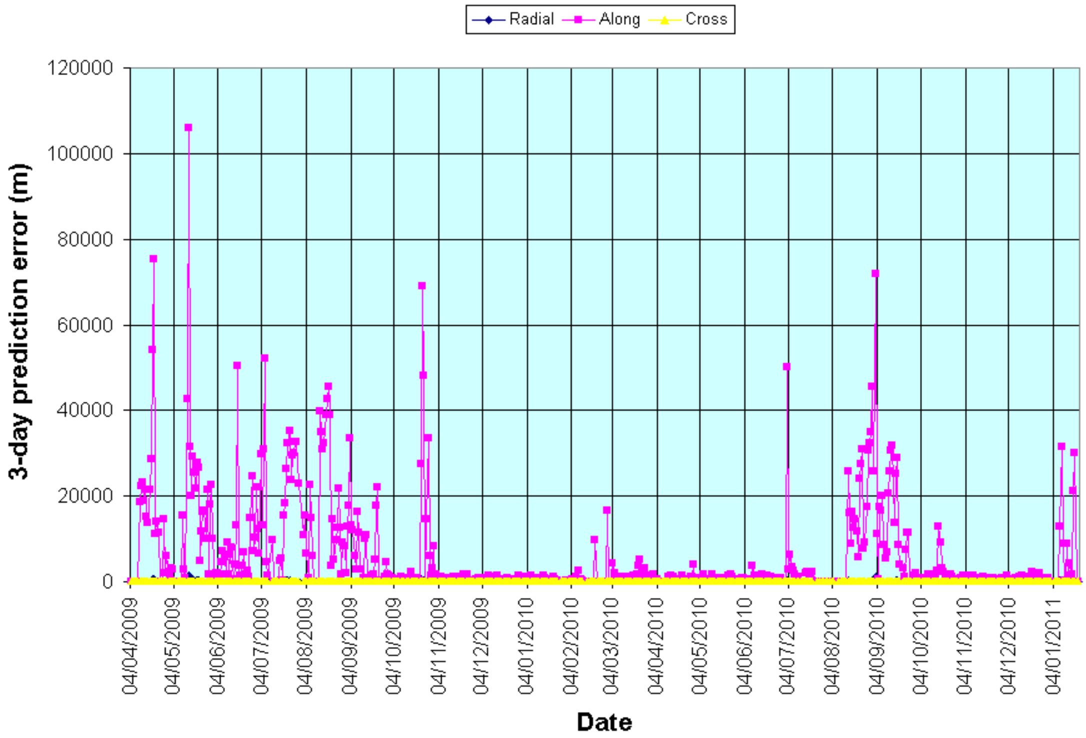

Figure 9: 3-day prediction error (in meters) since the start of the mission. Maximum along track prediction error is about 16 second TOV

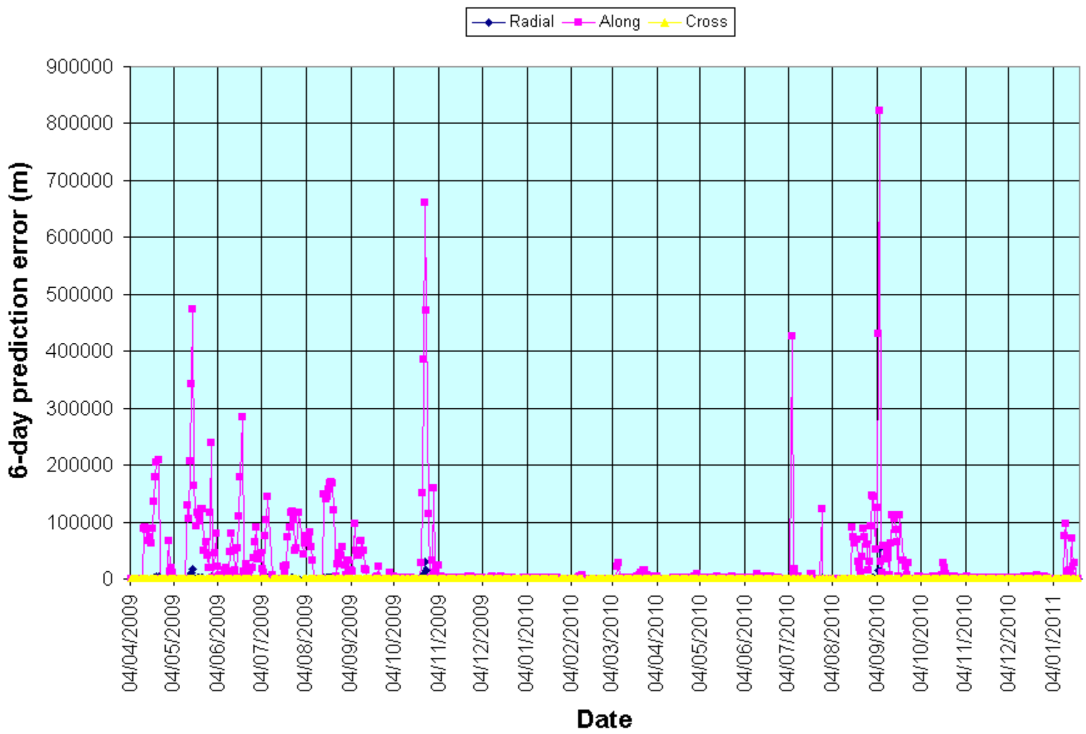

Figure 10: 6-day prediction error (in meters) since the start of the mission. Maximum along track prediction error is almost 2 minutes TOV

Note that during drag-free phases the predictions have been much more accurate.

4 Routine operation phases

The orbit determination and prediction is performed daily and is based on the spacecraft position data as obtained in the SSTI telemetry. The models used are as defined in Tab. 1 with the spacecraft being in drag-free mode. The orbit prediction takes into account the current and planned spacecraft mode (drag-free, decay or raise). In true drag-free mode the IPA thrust bias is set to 1.87E-7 m/s^2 and the constant acceleration parameters, estimated per day, are around 0 ± 30 nm/s^2 (see Fig. 11).

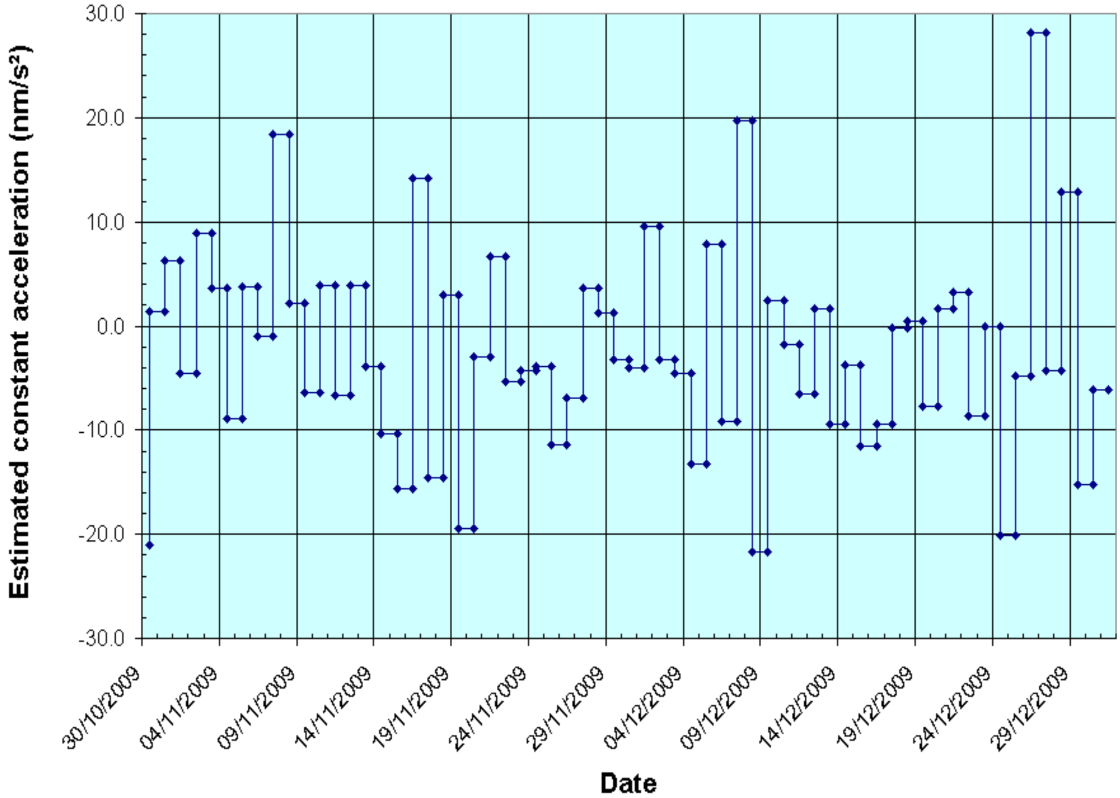

Figure 11: Estimated constant acceleration (in nm/s^2) for the first measurement phase (30/10/2009 till 31/12/2009). The average value is very close to 0 nm/s^2.

The mean altitude shows a constant pattern that repeats itself ever 20 days, which is the sub-cycle of the 61 day repeat orbit GOCE is kept in (see Fig. 12). The objective of the orbit control is to maintain the long term ground track as close as possible to the reference defined by the scientists and minimize the deviation rate [8]. If the ground track starts drifting to the East, which is equivalent to GOCE's altitude being too low, the altitude of GOCE can be raised by increasing the nominal IPA thrust bias on board the satellite. When this is required, the difference in IPA thrust bias is taken into account in the orbit prediction and is estimated during the orbit determination process. If on the other hand, the ground track of GOCE drifts to the West, i.e. the altitude of GOCE is too high, the altitude of GOCE can be reduced by decreasing the IPA thrust bias on board. When this is required, again the difference in IPA thrust bias is taken into account in the orbit prediction. Please note that in this case the drag is still compensated by the DFACS and thus no drag is modeled and no drag coefficients are estimated.

In the mission time line it was foreseen that the altitude of GOCE would be raised to a so called hibernation altitude just before the start of the eclipse season and would be lowered to routine operations altitude again after the eclipse season (twice a year). In the end it turned out that this was not necessary because the energy demand of the IPA was low enough to continue the science operations phase during the eclipse season, mainly due to the low solar activity.

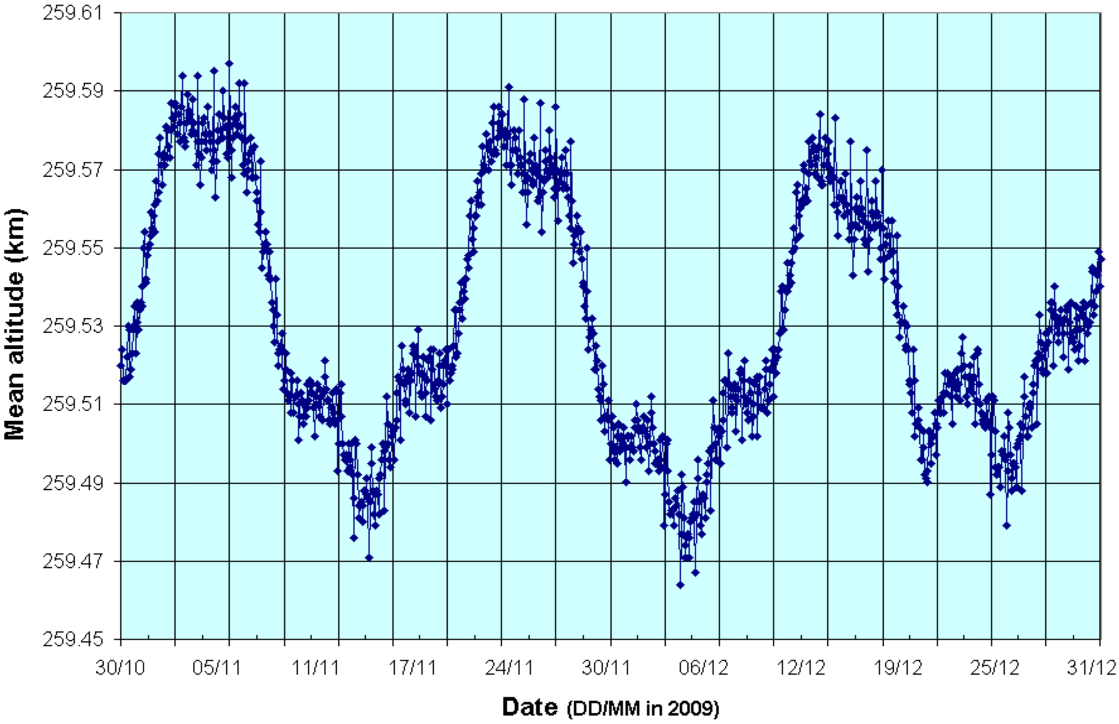

Figure 12: Mean altitude (in km) of GOCE starting on the 30th of October 2009, at the start of the first mission operations phase.

The science operation phase was interrupted again on the 12th of February 2010 by a complete failure of the CDMU-A unit (see Fig. 13), which could not be fixed any more. The satellite has since been working with only one CDMU, unit B. Around the 20th of March 2010 the gradiometer failed. As with each of the events where the IPA is turned of, the initial decay is followed by a raise phase to reach the operational altitude again. Each time this happens, it requires the manual intervention of the FD team to change the estimation strategy (see Tab. 1) and to reflect the unforeseen changes in the orbit as accurate as possible. After changing to CDMU-B and fixing the gradiometer problem, the science operation phase continued until the IPA failed on the 30th of June, followed by a major contingency on the 9th of July 2010. On that day the stations stopped receiving SW-generated telemetry. Only the hardware generated telemetry could still be retrieved, providing very limited information on the status of the satellite. Apparently, the IPA was still working (confirmed by FDS through constant acceleration estimates) and it was therefore decided to command a change to drag-free mode in the blind. A raise was initiated at the 17th of July, followed by a complete system reboot on the 22nd of July to force a reactivation of the telemetry unit. Still not receiving telemetry it was decided to start raising the altitude of GOCE by 5 to 10 km, from the 2nd of August onwards, to gain 30 days of margin in case of IPA failure. Per day a continuous IPA thrust of 4.33 mN was required to raise the satellite by 10 km in 30 days. With such a thrust level there was a genuine concern that the stations might not find the spacecraft at the first pass of the morning in case the IPA would fail at the start of the blind orbits taking place during the night. To reduce the risk, it was decided to split the required thrust in 2 parts, i.e. a continuous 6 mN thrust over 9 orbits during the day, where an IPA failure would be noted immediately, and a continuous lower thrust of 2 mN during the rest of the night. An integer number of orbital periods was selected to avoid changing the eccentricity while raising the orbit. On the 31st of August the SW-generated telemetry was unexpectedly received again after a slight warm-up of the processor module (see Fig. 2). Right after, a natural decay was initiated and science operations was resumed again on the 26th of September (see Fig. 13).

On the 2nd of January 2011 the science operation phase was interrupted again due to both SSTI units providing erroneous state vectors. It turned out that the conversion from ECEF SSTI to ECI SSTI was failing due to a problem in the computation of the Greenwich Apparent Sidereal Time (GAST) that goes directly into the rotation matrix used for the conversion. Initially S-band data was used from the Kiruna, Svalbard and Troll ground stations for the orbit determination. It turned out that the ECEF SSTI was not erroneous, so these data were collected through diagnostic telemetry packages and used instead. After updating the look-up table on board, operations turned back to normal and science operations were resumed on the 17th of January 2011.

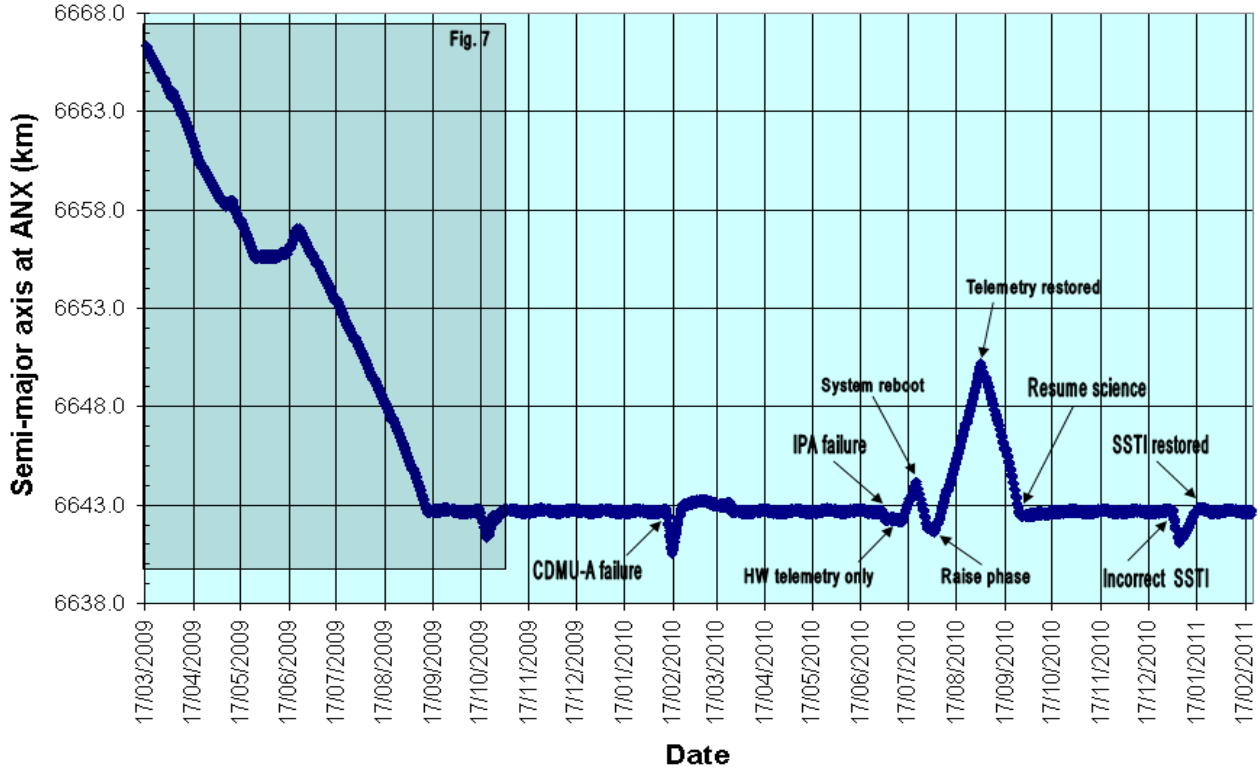

Figure 13: Evolution of the semi-major axis since the start of the mission. Significant events that effected the routine operations are indicated in the graph. The first 6 months of the mission are covered by Fig. 7.

The following graph (Fig. 14) shows the evolution of the inclination since the start of the mission.

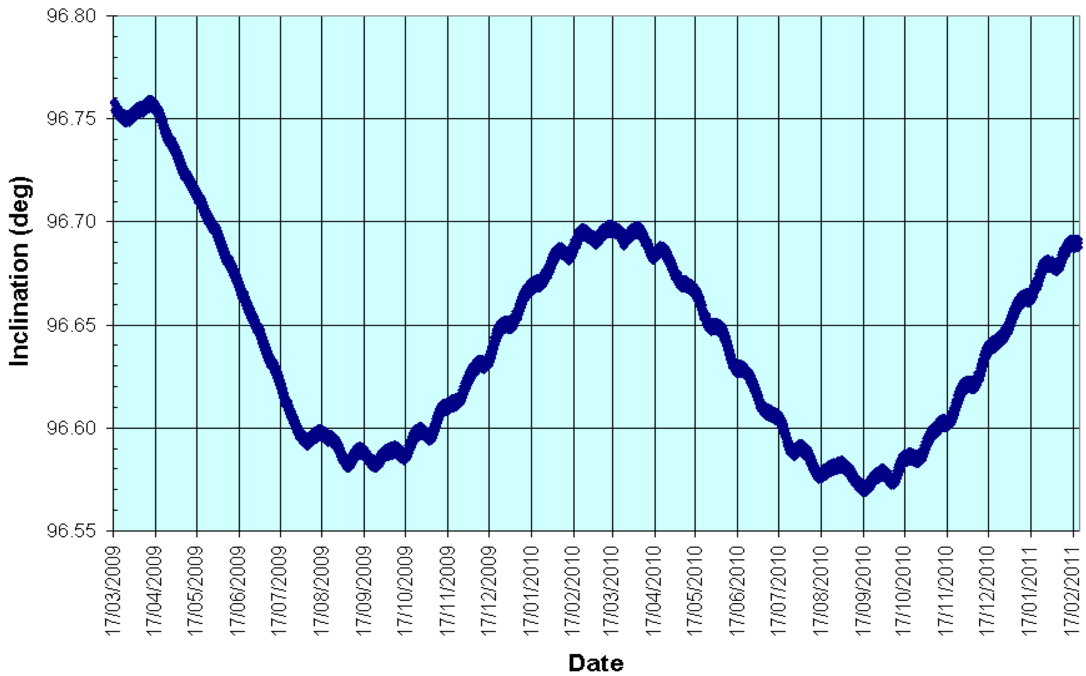

Figure 14: Evolution of the inclination (in degrees) since the start of the mission.

As expected, the inclination is hardly changing for an orbit with a Local Time of Ascending Node (LTAN) of 18:00. It only fluctuates by about 6 mdeg around an inclination of 96.64 degrees. The LTAN was very close to 18:00 at the start of the mission, 18:00:10 to be exact, and has since been increasing with more or less a constant rate of about 3.5 seconds per day. Constant, mainly because GOCE has been flying at more or less the same altitude since September 2009. After almost 2 years of mission the LTAN has shifted about 42 minutes. In about a years time, the LTAN will have shifted another 20 minutes, moving GOCE into a situation where eclipses will occur every orbit. This will however not have a serious impact on operations, as long as the solar activity does not increase significantly and eclipse times stay within limits.

The satellite is currently in good health, flying drag-free at a mean altitude of 259.6 km, increasing the coverage by GOCE, adding more measurements to the already collected measurements.

5 Conclusions and outlook

The last 2 years of the GOCE mission have been a special experience in many was. This paper conveys this experience from a flight dynamics point of view with an emphasis on the orbital aspects of the mission. After almost 2 years of mission the GOCE satellite is still alive and in good health despite some serious contingencies that were in the end solved successfully.

The nominal GOCE mission will end in April 2011, but because of the excellent spacecraft health and the low consumption of the xenon by the ion propulsion system (well below the budget due to the low solar activity), the mission has been extended up to the end of 2012 beyond its nominal lifetime. The FD team at ESOC will continue supporting this unique mission with great interest.

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