WEATHERING THE STORM – GOCE FLIGHT OPERATIONS IN 2010

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ABSTRACT

ESA's Gravity Field and Steady-State Ocean Circulation Explorer (GOCE) was successfully launched on 17th March 2009. The mission is controlled by ESA's European Space Operations Centre (ESOC) in Darmstadt, Germany. Following completion of commissioning, routine operations started in September 2009, keeping the S/C in drag-free mode at an altitude of 259.6 km. Operations are driven by the unique aspects of the mission, in particular the very low altitude and the high complexity of GOCE's drag-free control system.

Following a general introduction, the main focus is put on the special events of 2010, when science operations were interrupted for several months due to problems with the main platform computer. These anomalies presented a major challenge, requiring to operate the spacecraft "in the blind" with no status information available, and extensive modifications of the on-board software to recover the mission.

1. THE GOCE MISSION

The Gravity Field and Steady-state Ocean Circulation Explorer (GOCE) was launched on 17th March 2009 as the first core mission of ESA's Living Planet Programme. For general information on the mission, see [1].

1.1 Mission Overview

The aim of GOCE is to measure the Earth's gravity field and to provide a model of the geoid with unprecedented accuracy, determining gravity field anomalies with an accuracy of 1 mGal (or 10^{-5} m/s^2), and the geoid to an accuracy of 1 to 2 cm at a spatial resolution better than 100 km.

Accurate knowledge of the gravity field has a wide range of applications. The high accuracy expected for GOCE's gravity field model is in particular essential for precise determination of ocean circulation. GOCE data will also be useful for leveling by GPS, navigation, continental lithosphere studies and for global unification of height systems, e.g. to establish a global sea-level monitoring system. See [2][3][4] for details about the scientific objectives of GOCE.

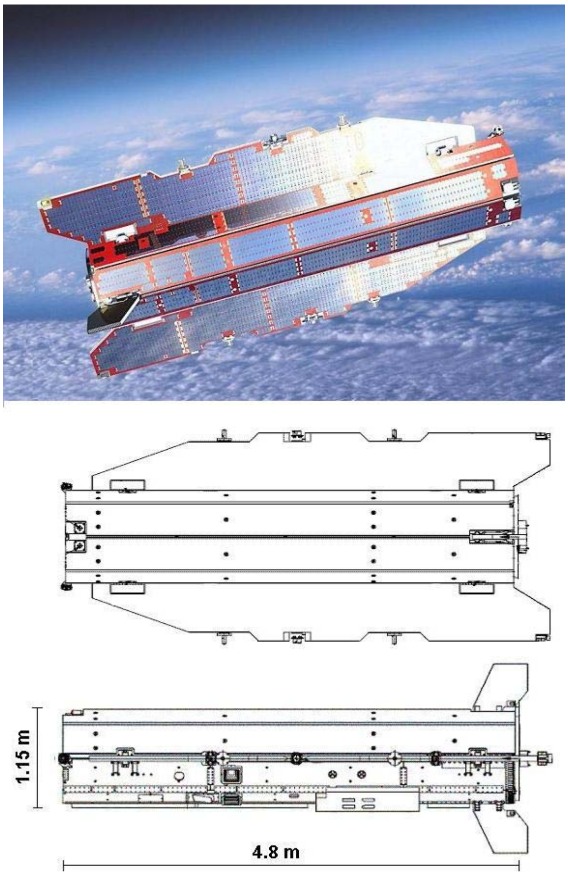

Figure 1. The GOCE spacecraft.

GOCE is the first spacecraft employing the concept of gradiometry, i.e. the measurement of acceleration differences over short baselines between proof masses of a set of accelerometers of the Electrostatic Gravity Gradiometer (EGG). The EGG is used to measure high-resolution features of the gravity field, while large-scale phenomena in the gravity field are obtained through analysis of GOCE's orbit as measured with a scientific GNSS receiver on-board the spacecraft, the Satellite-to-Satellite Tracking Instrument (SSTI).

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To obtain a sufficiently strong gravity field signal, GOCE is in a sun-synchronous Earth orbit at an exceptionally low altitude of about 260 km, where the density of the Earth's atmosphere is significant. GOCE is specifically designed for minimising air drag forces and torques, possessing the capability to counteract the drag and cancel out non-gravitational forces. The actual altitude is chosen according to the current solar activity level, which is having a significant impact on the atmospheric drag forces encountered.

GOCE is operated by the European Space Operations Centre (ESOC) in Darmstadt, Germany. Science data is processed and archived by the Payload Data Ground Segment (PDGS) at ESRIN in Frascati, Italy. Further processing is done by the High-level Processing Facility (HPF), operated under ESA contract by the European GOCE Gravity Consortium.

1.2 The Spacecraft

GOCE was built under ESA contract by a consortium led by Thales Alenia Space Italy, with EADS Astrium Germany responsible for the platform, and Thales Alenia Space France for the gradiometer.

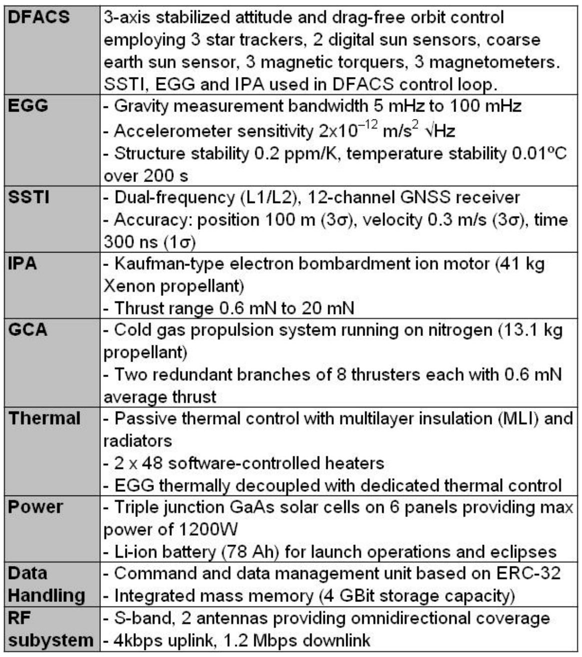
As non-gravitational forces like aerodynamic drag shall be minimised to not disturb EGG measurements, the structure is a slim, fully symmetric octagonal design with winglets for aerodynamic stability (Fig. 1).

Tab. 1 contains an overview of the characteristics of GOCE's subsystems. A summary of the major aspects is given here below; see [5] for more details.

Drag-free attitude and orbit control system (DFACS):

The DFACS provides 3-axis stabilised attitude control with magnetic torquers as actuators. An ion propulsion assembly (IPA) is used for continuous, closed-loop counteraction of atmospheric drag. To minimize internal disturbances, the satellite has no moving parts (like e.g. reaction wheels). The absence of strong actuators leads to complex attitude control laws sensitive to environmental changes. There is no clear distinction between platform and payload: SSTI and EGG are used in DFACS closed loop to measure (1) the non-gravitational forces acting on the spacecraft, allowing to counteract the air drag with the IPA; (2) the orbital position, allowing to orient the spacecraft according to its reference frame. The DFACS has several modes, ranging from basic attitude stabilization modes up to full drag-free control:

- CPM, ECPM and FPM: S/C attitude control with varying degrees of precision (i.e. no orbit control).
- DFM_PREP: orbit altitude control through usage of IPA in open loop (i.e. no drag-free control).
- DFM_COARSE, DFM_FINE: drag-free control with IPA and EGG used in closed loop.



DFACS	3-axis stabilized attitude and drag-free orbit control employing 3 star trackers, 2 digital sun sensors, coarse earth sun sensor, 3 magnetic torquers, 3 magnetometers. SSTI, EGG and IPA used in DFACS control loop.
EGG	- Gravity measurement bandwidth 5 mHz to 100 mHz - Accelerometer sensitivity 2×10^{-12} m/s^2 √Hz - Structure stability 0.2 ppm/K, temperature stability 0.01ºC over 200 s
SSTI	- Dual-frequency (L1/L2), 12-channel GNSS receiver - Accuracy: position 100 m (3σ), velocity 0.3 m/s (3σ), time 300 ns (1σ)
IPA	- Kaufman-type electron bombardment ion motor (41 kg Xenon propellant) - Thrust range 0.6 mN to 20 mN
GCA	- Cold gas propulsion system running on nitrogen (13.1 kg propellant) - Two redundant branches of 8 thrusters each with 0.6 mN average thrust
Thermal	- Passive thermal control with multilayer insulation (MLI) and radiators - 2 x 48 software-controlled heaters - EGG thermally decoupled with dedicated thermal control
Power	- Triple junction GaAs solar cells on 6 panels providing max power of 1200W - Li-ion battery (78 Ah) for launch operations and eclipses
Data Handling	- Command and data management unit based on ERC-32 - Integrated mass memory (4 GBit storage capacity)
RF subystem	- S-band, 2 antennas providing omnidirectional coverage - 4kbps uplink, 1.2 Mbps downlink

Table 1. Subsystem characteristics.

Electrostatic Gravity Gradiometer (EGG):

The EGG contains three accelerometer pairs mounted on an ultra stable carbon-carbon honeycomb support structure. For each accelerometer a proof mass is kept in the centre of the cage by electrostatic forces representative of the accelerations seen by the mass. The accelerations measurable are as small as one part in 10'000'000'000'000 of the gravity experienced on Earth, making these units about 100 times more sensitive than any accelerometers previously flown.

Control and Data Management Unit (CDMU):

The central computer is based on the TASI Milano LEONARDO computer (with ERC-32 single chip Atmel TSC695F). The CDMU is fully redundant; the processor of the unused CDMU side can't be accessed.

The Platform Application Software (PASW) running on the active CDMU side is in charge of all system-level functions, including data handling and drag-free control algorithms. The mass memory is also managed by the PASW, with the data being stored in a 4Gbit memory module. The PASW resides in the EEPROMs of the two processor modules in the CDMU [7].

2. SETUP AND APPROACH FOR GOCE FLIGHT OPERATIONS

2.1 FOS Systems and Interfaces

Fig. 2 shows the main facilities and interfaces of the GOCE Flight Operations Segment (FOS).

The SCOS-2000-based mission control system is running on Sun Solaris. The SIMSAT-based S/C simulator is executing the on-board platform software on an ERC-32 emulator, offering a very representative simulation environment. The flight dynamics system is based on ESOC's ORATOS platform and is used for orbit prediction and attitude monitoring activities.

GOCE's prime station in Kiruna (Sweden) is controlled remotely from ESOC's ESTRACK control centre. The SvalSat station in Svalbard of Kongsberg Satellite Services AS (KSAT) is used to augment the Kiruna contacts, while KSAT's Troll station in Antarctica is used for contingency support.

The main interface of the FOS is with the PDGS at ESRIN. The FOS provides all telemetry dumped in raw format; planning-related information is exchanged between the two entities. Further interfaces not indicated in Fig. 2 are with GOCE mission management (at ESRIN) and with the S/C manufacturer (for delivery of flight software patches).

2.2 Flight Operations Approach

Routine science operations are not complex, but rather consist of flying drag-free, with occasional minor altitude manoeuvres (in the order of a few metres) to correct for the residual bias in drag-free mode. However, the high S/C complexity implies that anomalies may quickly become quite demanding.

In routine, every day 6 Kiruna station passes are taken, augmented by 1 to 2 passes on the SvalSat station. Tab. 2 gives an example of the pass distribution and duration. Due to GOCE's low orbit, the pass durations are very short. Routine pass activities are automated as much as possible. Only ground station contacts during normal working hours are manned.

Mission planning is done once a week, with the output consisting of a set of command stacks (one for uplink to the S/C for time-tagged execution, one for the automatic release-based stack running on the MCS) covering all operations of the ensuing week.

The FOS has strict requirements on the completeness of science data. Playback telemetry is checked for gaps; missing data is redumped from the spacecraft.

Orbit determination and prediction is performed daily based on the S/C position vector in SSTI telemetry, with the prediction taking into account the S/C mode (drag-free or in decay). Deviations with respect to the planned S/C mode need to be immediately communicated to the orbit prediction system to generate new predictions. Orbit determination can also be based on radiometric data, requiring establishment of a special low bit rate telemetry mode.

2.3 Flight Operations in 2009

Following launch on 17th March 2009, commissioning lasted up to September 2009. To commission the complex subsystems needed to perform drag-free mode, GOCE was injected at an altitude higher than the one foreseen for science operations. The orbit was then lowered by not compensating the drag. Fig. 3 shows the S/C altitude from launch up to September 2009. The main activities were the following:

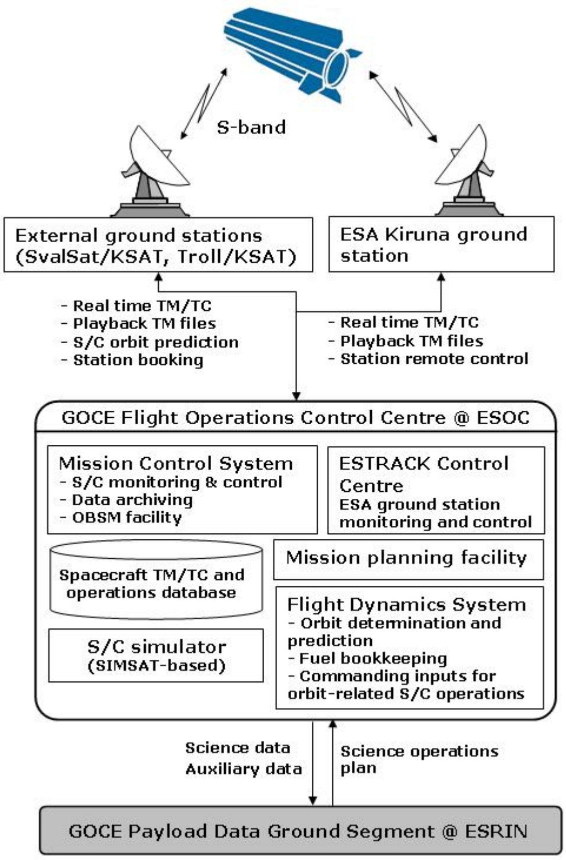


Figure 2. The Flight Operations Segment (FOS).

Ground station	Acquisition of signal [UTC]	Commanding duration [mm:ss]
Kiruna	04:31:34	04:21
Kiruna	06:00:22	05:52
Kiruna	07:29:29	04:31
Svalbard	11:53:41	05:20
Kiruna	13:21:47	02:09
Kiruna	14:48:54	05:20
Kiruna	16:17:26	05:41

Table 2. Example of daily station contacts.

Initial commissioning (17/03/2009 to 04/05/2009): Following completion of the LEOP, main activities were the commissioning of the ion propulsion system (Fig. 3, label 1) and the gradiometer while the orbit was left decaying.

Drag-free mode checkout (05/05/2009 to 22/06/2009): Drag-free mode was commissioned, with both IPA and EGG used in the DFACS control loop for the first time. This checkout was performed in two steps due to flight software problems (Fig. 3, labels 2 and 3).

Decay to science altitude (23/06/2009 to 14/09/2009): The orbit decay was resumed (Fig. 4, label 4) up to reaching an altitude of 259.6 km in September 2009 (Fig. 3, label 5). From that point onwards, the altitude was maintained in drag-free mode.

See [6][7] for more detailed information on the operations in the first year of the mission.

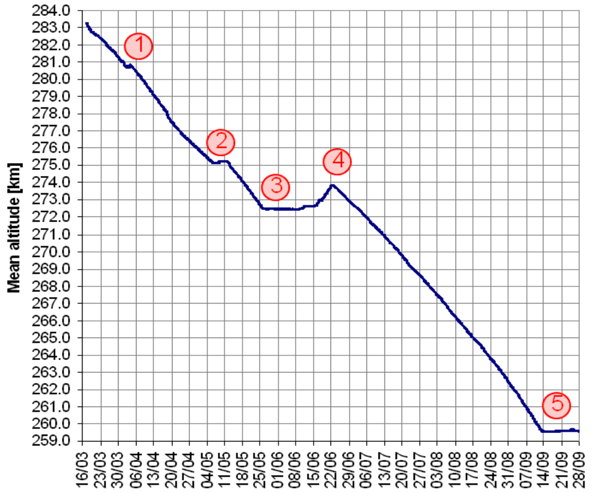


Figure 3. Altitude of GOCE from launch on 17/03/2009 up to stop of orbit decay on 14/09/2009.

3. FLIGHT OPERATIONS IN 2010

3.1 Overview

Following completion of commissioning in October 2009, the intention was to keep collecting measurement data at around 260 km altitude. As drag-free mode is not maintained and thus the altitude starts decaying whenever more severe contingencies occur (e.g. if the S/C enters safe mode), the plot of the S/C altitude shown in Fig. 4 gives a good overview of major special events. It can be seen that drag-free mode was interrupted in February 2010 and –during a longer period of time– in July/August 2010, including a major raise of the orbit commanded by ground.

Fig. 5 shows the thrust from the ion propulsion system throughout 2010:

- When in drag-free mode, the thrust level varies due to changes in the solar activity, impacting the atmospheric drag to be compensated.
- Owing to the low overall solar activity throughout 2010, the average thrust in drag-free mode is mostly between 1 mN and 3 mN, significantly lower than what had originally been assumed, thereby helping to conserve fuel.
- Fig. 5 also shows the special activities using the IPA in open loop in February/March 2010 to recover the altitude lost. The gap in data ranging from July to September is due to the lack of telemetry owing to the anomaly encountered (June/July) and due to the switch off of the engine in September to decay down to 260 km.

The two major problems encountered are described in more detail in the next sections.

3.2 The Failure of CDMU-A in February 2010

Safe mode was entered on 12th Feb, when an autonomous switchover to the redundant platform computer (CDMU-B) was triggered after two unsuccessful attempts to start the PASW on CDMU-A.

There were no signs of anomalous S/C behaviour prior to the first PASW restart. The PASW crash log available pointed to a problem during a floating point operation. Investigations were hampered by the following PASW/CDMU design features:

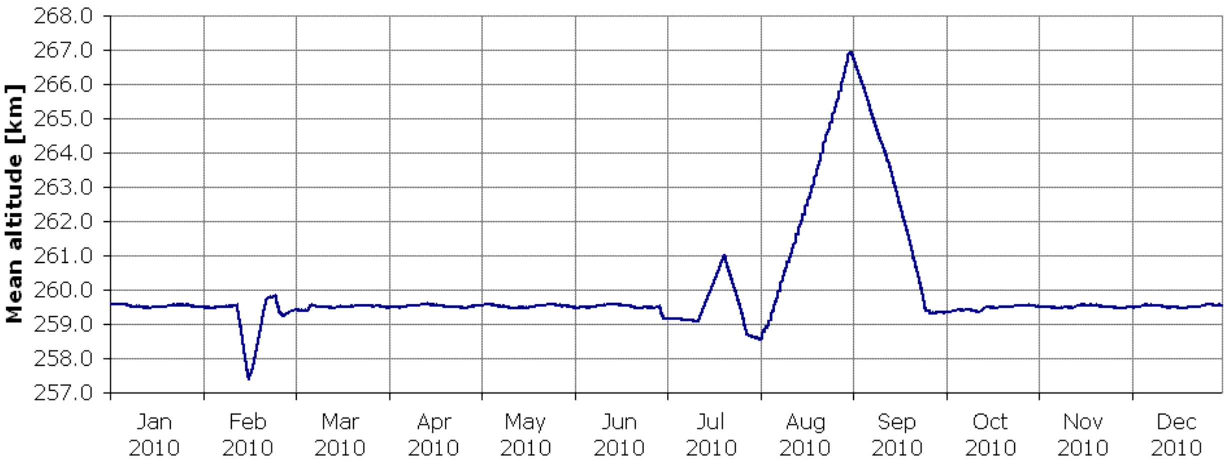


Figure 4. Altitude of GOCE in 2010, showing interruptions of drag-free mode at 260 km in Feb and July–Sept.

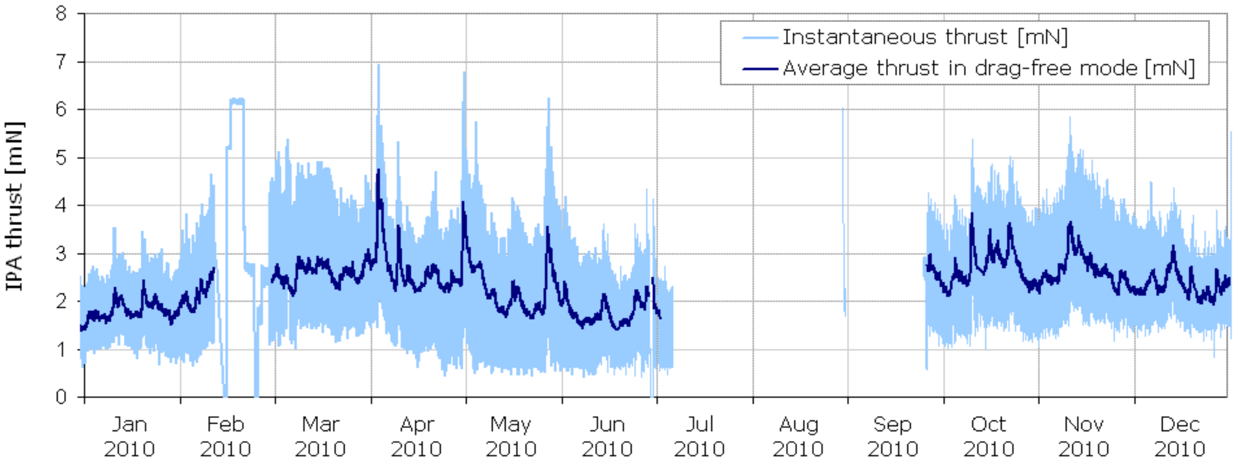


Figure 5. Ion propulsion thrust in 2010. The varying thrust level when in drag-free mode is due to changes in the solar activity. In February the IPA was fired in open loop to recover from the CDMU-A anomaly; in July/August no S/C telemetry is available due to the TM loss anomaly; in September the IPA was off to decay down to 260km.,

- The GOCE CDMU does not allow switching ON the unused processor module to a 'service mode' to check its status. Any attempt to check out PM-A requires a reconfiguration back to CDMU-A, entailing significant overhead and risk.
- PASW error logs –recorded when software execution stops anomalously– get overwritten in case of consecutive PASW restarts. Thus, out of the three PASW crashes on CDMU-A, only a single error log could be recovered.

Following initial operations on CDMU-B to recover the altitude lost, an unsuccessful attempt to manually switch back to CDMU-A was performed on 25th Feb, with the PASW not starting up on CDMU-A. Routine operations in drag-free mode on CDMU-B were then resumed in early March 2010. The flight operations concept and procedures were also updated for a permanent stay on CDMU-B.

Further investigations into the CDMU-A failure were undertaken in the mean time, including a check on possible problems during the manufacturing of the processor The outcome of the investigation was inconclusive. Based on the PASW crash log available, a random failure of the PM-A floating point unit is considered the most likely root cause.

The loss of CDMU-A after just one year of flight was undoubtedly a major setback for GOCE. Owing to the redundancy available, it was however possible to continue routine operations –as long as CDMU-B would work nominally, a condition soon to change.

3.3 TM Loss Anomaly in Summer 2010

Recovery from the CDMU-A failure was followed by the longest uninterrupted stretch of routine science operations from beginning of March up to 8th July, when an anomalous signal was received from the S/C. Following intense first troubleshooting activities including reconfigurations of the downlink chain (transmitter and telemetry modules), it was found that the S/C was in drag-free mode –thus the PASW was still running on CDMU-B–, however no telemetry generated by the PASW was received on ground. It was only possible to recover the reception of a small set of hardware-generated telemetry –the so-called high priority telemetry (HPTM)–, which gives basic status information on the CDMU and the transmitters. Taking into account these observables, the anomaly was determined to be related to the link between the processor module of CDMU-B and the CDMU telemetry modules (TMM).

Thus, the operations team found themselves in the difficult situation of having virtually no TM available to troubleshoot the anomaly, with the standard recovery activities already exhausted. This situation lasted for almost two months, requiring an exceptional amount of special operations to recover the mission. A brief account of the activities is given here below (see Fig. 4 for the impact the below activities had on the orbit):

Initial orbit raise (13/07/2010 to 22/07/2010):
To gain more margin, a first raise of the orbit was started by biasing the thrust in drag-free mode. With no direct observables from S/C telemetry obtainable, correct execution of the raise was carefully monitored by orbit determination based on radiometric data.

Safe mode commanded by ground (22/07/2010):
Initial investigations concluded that the only way to fully reinitialize the link between the processor module and the TMM was to restart the PASW, i.e. command

the S/C into safe mode. This was performed on 22nd July "in the blind", however the anomaly was still present after safe mode entry. The orbit was now decaying with the ion propulsion system off.

Stop of decay and step-wise orbit raise (29/07/2010 to 30/08/2010):
With the recovery by forcing a safe mode failed and still little to no observables on the S/C status, the orbital decay was stopped on 29th July by firing the IPA in open loop. A raise of the orbit of around 300 m per day was started on 3rd August, in such a way as to minimize the risk of having to search for the S/C in case of an anomalous interruption of IPA firing (see Fig. 6).

Preparations for S/C checkout (August 2010):
Much effort was put into getting information on the S/C status and the anomaly despite the unavailability of software TM. An intial check of essential parameters in software TM was done through using PUS services 12 and 19. An extensive PASW modification was then developed by the S/C manufacturer and installed on-board on 23rd August, allowing to downlink SW-generated TM in HPTM. The mechanism makes use of the fact that by default the PASW writes a register which is reported in HPTM. The PASW was thus modified such that specific software TM packets could be downlinked on request byte by byte in HPTM. A severe limitation of this is an excruciatingly slow downlink rate at 1.4 bytes per second: a full checkout of the S/C –i.e. getting a sample of the most important PASW housekeeping packets– takes more than a day given the short GOCE station contacts.

Recovery from the TM loss anomaly (30/08/2010):
With the means for thoroughly checking out the S/C finally avai1able, a series of investigation and testing operations on the failed link between PM-B and the TMMs was executed. In the frame of these activities, the temperature of the CDMU was raised by about 7 degrees. To the surprise of the operations team, this measure resulted in receiving good software telemetry when enabling the link on 30th August.

Resumption of routine mission operations (30/08/2010 to 05/10/2010):
Throughout September, the orbit was lowered to reach the desired altitude of 260 km for routine operations, with drag-free mode entered on 27th September. Routine mission operations were resumed as from 4th October following calibration of the gradiometer.

Needless to say, intense investigation activities into the problem have taken place offline starting in early July and lasting well beyond the in-flight recovery of the anomaly. While the problem could not be reproduced in a fully representative environment, indications for a possible temperature dependency of the LVDS receivers used for the failed link were found. As there were no further problems in the ensuing 6 months of operations with the CDMU temperature increased, there is growing confidence that this change may indeed prevent the problem from reoccurring. Nevertheless, all measures for dealing with a possible reoccurrence of the anomaly have been put in place, with the relevant special activities performed in summer 2010 now part of the FOS flight operations procedures.

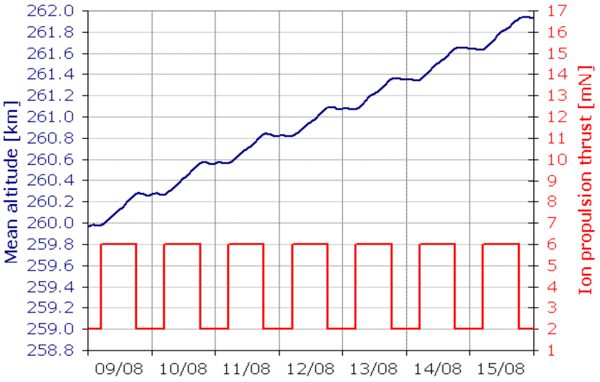


Figure 6. Excerpt of altitude and thrust profile during raise in August 2010. As an IPA failure when firing at high thrust may lead to differences between actual and predicted orbit –possibly requiring a search for the S/C–, the raise was only done under station coverage (low thrust in blind orbits at night)

4. CONCLUSIONS AND OUTLOOK

The GOCE spacecraft has encountered some major problems in 2010, which resulted in an interruption of routine operations for about 4 months in total. The anomalies were on GOCE's central platform computer (CDMU), with the nominal side presumably suffering a H/W failure in February 2010, and severe problems with the distribution of the telemetry data to the downlink chain in summer 2010.

Exceptional operations were needed to recover GOCE, including operating the S/C "in the blind" (i.e. virtually no observables available to ground) for extended periods of time. Major modifications of the on-board software had to be implemented, showing again the importance of post-launch OBSM for the mission [7].

The recovery activities in 2010 required close cooperation with all parties involved in the mission, comparable to the high level of interaction required during the early stages of a mission.

Despite the loss of CDMU redundancy, the spacecraft is in good health with an excellent margin in consumables. Consequently, following recovery from last summer's anomalies, in November 2010 the mission was extended by ESA up to the end of 2012.

ACRONYMS

CDMU	Control and Data Management Unit
CPM	Coarse Pointing Mode
DFACS	Drag Free Attitude and Orbit Control System
DFM	Drag Free Mode
ECPM	Extended Coarse Pointing Mode
EGG	Electrostatic Gravity Gradiometer
FCT	Flight Control Team
FOP	Flight Operations Plan
FOS	Flight Operations Segment
FPM	Fine Pointing Mode
GOCE	Gravity and Steady-state Ocean Circulation Explorer
HPF	High-level Processing Facility
HPTM	High Priority Telemetry
IPA	Ion Propulsion Assembly
KSAT	Kongsberg Satellite Services AS
LEOP	Launch and Early Orbit Phase
OBSM	On-board Software Maintenance
PASW	Platform Application Software
PDGS	Payload Data Ground Segment
PM-A	Processor module of CDMU-A
PM-B	Processor module of CDMU-B
PUS	Packet Utilisation Standard
SSTI	Satellite-to-Satellite Tracking Instrument
TMM	Telemetry Module

REFERENCES

[1] Haagmans, R., Floberghagen, R., Pieper, B., ESA's Gravity Mission GOCE, ESA, Noordwijk, The Netherlands, 2006.

[2] Drinkwater, M., Haagmans, R., Kern, M., Muzi, D., Floberghagen, R., "GOCE – Obtaining a Portrait of Earth's Most Intimate Features," *ESA Bulletin, No. 133*, February 2008, pp. 4 to 13.

[3] Floberghagen, R., 1Drinkwater, M., Haagmans, R., Kern, M., "GOCE's Measurements of the Gravity Field and Beyond," *ESA Bulletin, No. 133,* February 2008, pp. 24 to 31.

[4] Drinkwater, M.R., Haagmans, R., Muzi, D., Popescu, A., Floberghagen, R., Kern, M., and Fehringer, M., "The GOCE Gravity Mission: ESA's First Core Earth Explorer," *3rd International GOCE User Workshop, ESA SP-627*, ESA, Frascati, Italy, 2007.

[5] Fehringer, M., André, G., Lamarre, D., Maeusli, D., "A Jewel in ESA's Crown – GOCE and its Gravity Measurement Systems," *ESA Bulletin, No. 133*, February 2008, pp. 14 to 23.

[6] Steiger, C., Piñeiro, J., Emanuelli, P.P., "Operating GOCE, the European Space Agency's Low-flying Gravity Mission," *SpaceOps 2010*, Huntsville, USA

[7] Steiger, C., Lautenschläger, G., Weigl, A., Eilenberger, R., Väisänen, P., Maestroni, E., Da Costa, A., Emanuelli, P.P., "On-board Software Maintenance for GOCE, ESA's Gravity Mission," *Data Systems in Aerospace (DASIA) 2010,* Budapest, Hungary.