

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. 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 4 Gbit memory module. The PASW resides in the EEPROMs of the two processor modules in the CDMU⁴.

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 0.01°C 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 subsystem	- S-band, 2 antennas providing omnidirectional coverage - 4kbps uplink, 1.2 Mbps downlink

Table 1. Spacecraft subsystem characteristics.

II. Baseline Mission Profile and Flight Operations Approach

A. Original Mission Profile

GOCE was built to operate in a sun-synchronous, near-circular orbit with an inclination of 96.7 deg and ascending node at 18:00 local solar time. A peculiarity of the mission is that it has not been designed for a particular, fixed reference orbit. The selection of the altitude is driven by several factors: while a low altitude is in general beneficial for science, it is constrained by the higher atmospheric drag which shall not exceed the spacecraft's design limits. In addition, the ground track has to be such that the scientific objective of retrieving the Earth's geopotential at spatial scales down to 100 km can be reached around the globe, requiring to select an orbit with a sufficiently high repeat cycle.

Figure 2 shows the original mission profile of GOCE. Owing to the very low altitude of its sun-synchronous orbit, the S/C experiences 2 eclipse seasons per year, a long one and a short one. As there were concerns about the gradiometer data quality during the long eclipse season –it was expected that due to temperature gradients at entry

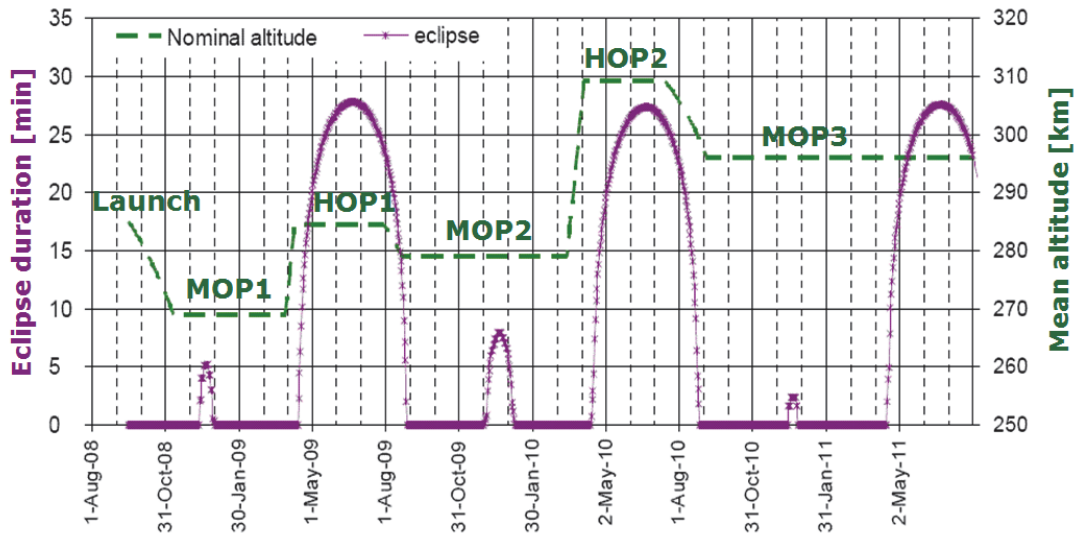


Figure 2. Baseline altitude profile and corresponding eclipse durations for launch on 10th Sept 2008 with measurement phases (MOP) only outside of the annual long eclipse seasons.

and exit of the eclipse, sudden release of mechanical stress would severely degrade EGG measurements– and due to the constrained power budget in eclipse, the plan was to interrupt science operations during the long eclipse season. Science operations in drag-free mode were only foreseen out of the long eclipse season in the so-called Measurement Operations Phases (MOP), while it was intended to raise the orbit to hibernate the mission (HOP = Hibernation Operations Phase) in the long eclipse season.

The first two measurement phases were planned to be done at 268 km and 278 km, respectively. A main driver for the altitude selection was to take into account the expected atmospheric density, which is highly dependent on the solar activity. These particular altitudes were selected since they yield a favorable repeat cycle of 61 days (979 revolutions) achievable with a relatively coarse altitude control of ± 1 km.

The original mission duration was 20 months, comprising two measurement phases (MOP1 and MOP2) and one hibernation phase HOP1, with the mission to be launched at the start of MOP1. A further 10 month extension for a third measurement phase MOP3 (preceded by HOP2) was also foreseen as an option.

B. Flight Operations Setup and Approach

Figure 3 shows the main facilities and interfaces of the GOCE Flight Operations Segment (FOS) at ESOC.

The SCOS-2000-based mission control system (MCS) 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 Kiruna contacts, while KSAT's Troll station in Antarctica is used for contingency support. SSC's ESRANGE antennas located close to Kiruna are also used occasionally.

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. 3 are with mission management (at ESRIN) and with the S/C manufacturer (delivery of flight software patches).

Flight operations in the routine science phase are in principle not complex, consisting of flying drag-free with occasional altitude manoeuvres to correct for the residual bias in drag-free mode. However, the high S/C complexity implies that S/C anomalies may quickly become demanding.

In routine, every day 6 Kiruna station passes are taken, augmented by 1 to 2 passes on the SvalSat station. Due to the low orbit, pass durations are very short, with at most 6 min of commanding possible. 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 S/C.

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.

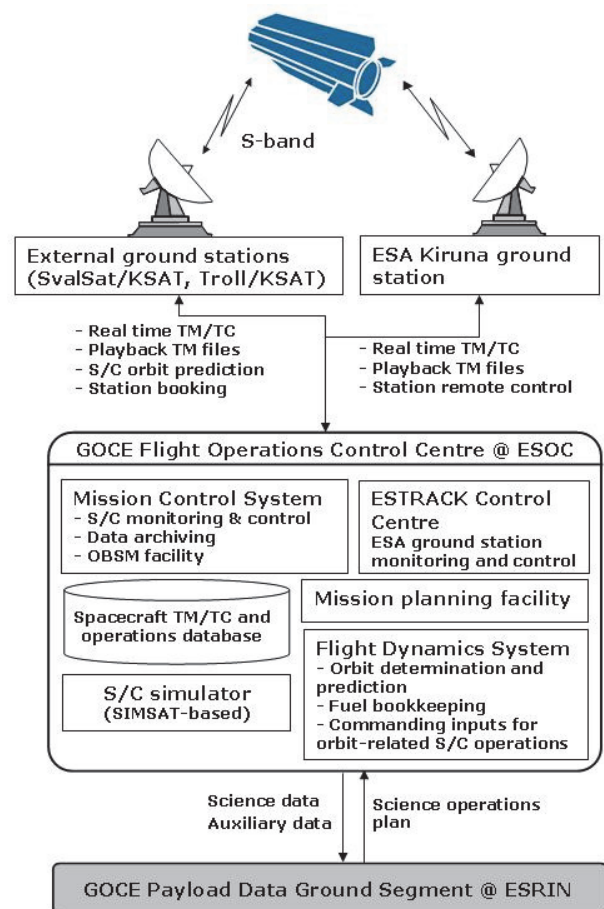


Figure 3. Overview of the GOCE Flight Operations Segment (FOS) at ESA/ESOC.

III. Evolution of Flight Operations throughout the Mission

A. Main Events throughout the Mission

Following launch on 17th March 2009 from Plesetsk Cosmodrome in Northern Russia, GOCE was injected into its sun-synchronous orbit at 283 km altitude, an altitude higher than the 268 km foreseen for science operations, giving enough time for commissioning the complex subsystems needed to perform drag-free mode. The major commissioning activities were completed by end of June 2009. The orbit was then left decaying further with the DFACS in FPM. Owing to the very low density environment encountered in-flight, it was decided to let the orbit decay further down to around 260 km. This altitude was reached in Sept 2009, when the decay was stopped and routine science operations began.

Since start of routine operations there were 7 interruptions of drag-free mode owing to various S/C anomalies, two of which were major problems in the on-board computer as described here below.

Routine operations were interrupted on 12th Feb 2010, when an autonomous switchover to the redundant on-board computer (CDMU-B) was triggered. An unsuccessful attempt to manually switch back to CDMU-A was performed on 25th Feb 2010. Science operations in drag-free mode with CDMU-B were then resumed in early March 2010. Owing to the very limited observables, the root cause could not be identified with certainty, but a failure of the floating point unit of the nominal processor module (PM-A) is considered the most likely failure scenario. As a consequence, CDMU-A was declared failed, and as from that point in time the mission was performed on CDMU-B with no redundancy left for the on-board computer.

On 8th July 2010 a severe anomaly occurred, which prevented the correct transmission of software-generated telemetry to ground for almost 2 months. In the very difficult condition of having to operate the S/C “in the blind”, a wide range of investigation and troubleshooting operations were performed as part of a major effort jointly undertaken by ESA and industry. The anomaly was found to be on the communication link between the processor module and the telemetry boards. Such links employ low voltage differential signaling receivers that have proven to be prone to oscillate under certain conditions and temperature ranges. As part of various troubleshooting activities, it was decided to raise the operating temperature of the CDMU (though it had already been well within the allowed operating range), which in late August 2010 led to restoring TM downlink. The anomaly has not reoccurred since.

For a more detailed overview, see Ref. 3 for commissioning, Ref. 5 and 6 for 2010’s contingency operations.

B. Actual Mission Profile

The actual mission profile in terms of altitude and eclipse pattern is shown in Fig. 4. The entire routine science operations phase of the mission has so far been performed at 259.6 km altitude, which offers a repeat cycle of 61 days (979 revolutions) as at the baseline altitude of 268 km. Owing to the very low solar activity and consequent low atmospheric drag, there was no need to raise the orbit as originally foreseen. Only starting in 2011, the increase in solar activity towards the solar maximum expected in 2013 had a noticeable impact on the drag experienced by GOCE (see Fig. 5).

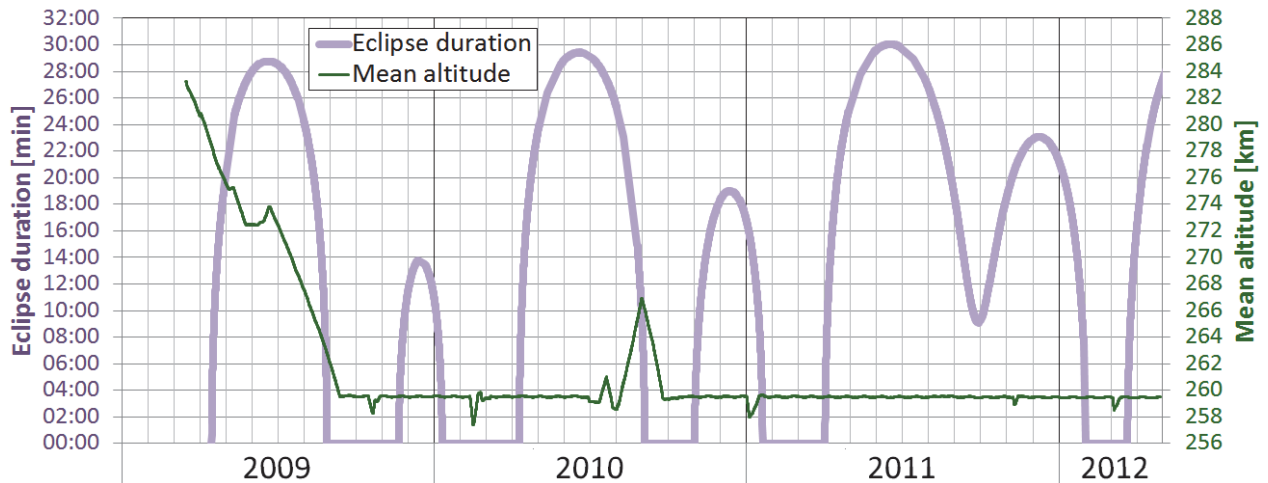


Figure 4. Altitude and eclipse pattern from launch up to present. The change in the eclipse pattern is due to drift of the inclination. Spikes in the mean altitude plot after September 2009 indicate interruptions of science operations in drag-free mode at 259.6 km (decay of the orbit due to uncompensated atmospheric drag).

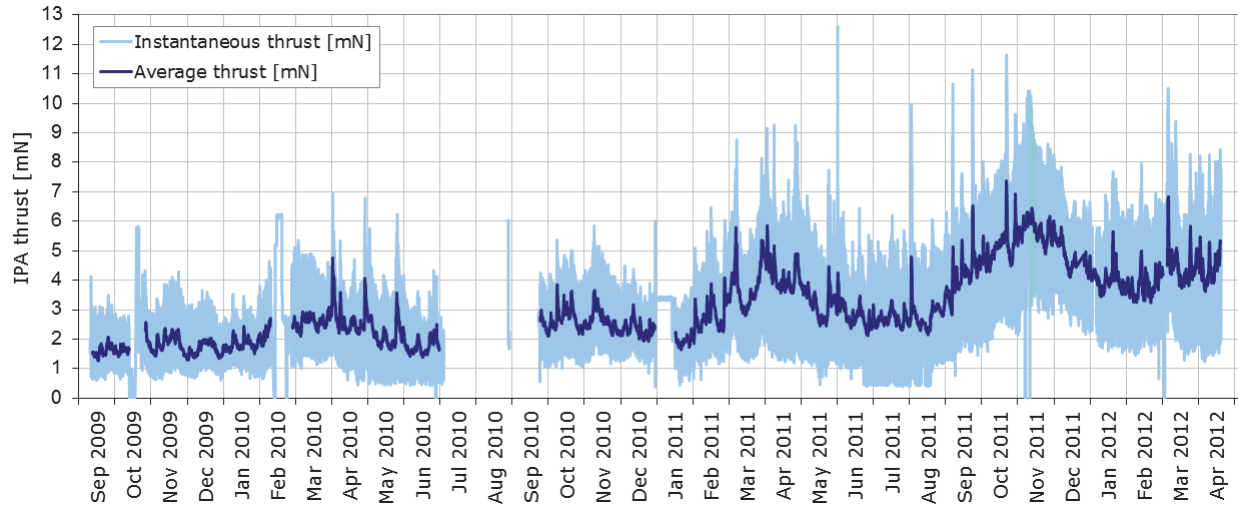


Figure 5. IPA thrust in routine operations to compensate the air drag, showing instantaneous thrust and thrust averaged over each orbit. The variations are caused by changes in solar and geomagnetic activity.

Throughout commissioning operations during 2009’s long eclipse season, the performance of the gradiometer was analysed in great detail, concluding that data quality was little impacted by thermal effects when entering or exiting an eclipse. In combination with good margin in the power budget and very low solar activity, this allowed to abandon the concept of hibernation phases: consequently science operations in drag-free mode were performed throughout the year, irrespective of whether the S/C was inside or outside of eclipse season.

Figure 4 also shows a significant evolution in the pattern of eclipses. The S/C design does not allow performing out-of-plane manoeuvres to control the inclination, only in-plane manoeuvres can be done to control the semi-major axis (i.e. the altitude). The Local Time of Ascending Node (LTAN) of GOCE’s orbit is hence left drifting throughout the mission. As a consequence, the duration of the short eclipse season has increased significantly. As of 2011, there is no eclipse-free period between the former two eclipse seasons, and the S/C is in eclipse season for the major part of the year. As the maximum duration of eclipses has only increased marginally (from 28.6 min to slightly above 30min), the S/C design and budgets are compatible with this new eclipse pattern.

C. Orbit Control

Altitude control of GOCE’s orbit is crucial to achieve the desired ground coverage for global mapping of the Earth’s gravity field. The original requirement was to control the S/C altitude such that each of the 979 ascending node crossings in a 61-days repeat cycle would fall into a bin of 40 km width (corresponding to a spacing of approximately 0.4 deg).

In practice, GOCE’s drag-free control system was found to perform to a very high precision, with a residual drift in altitude of a few tens of centimetres per day. The spread around the targeted equator crossing could be kept to less than ± 3 km (far better than the required ± 20 km) by performing small altitude adjustment manoeuvres in the order of no more than ± 20 m altitude raise/lowering every few weeks. These manoeuvres are implemented without interrupting science operations, by introducing a small

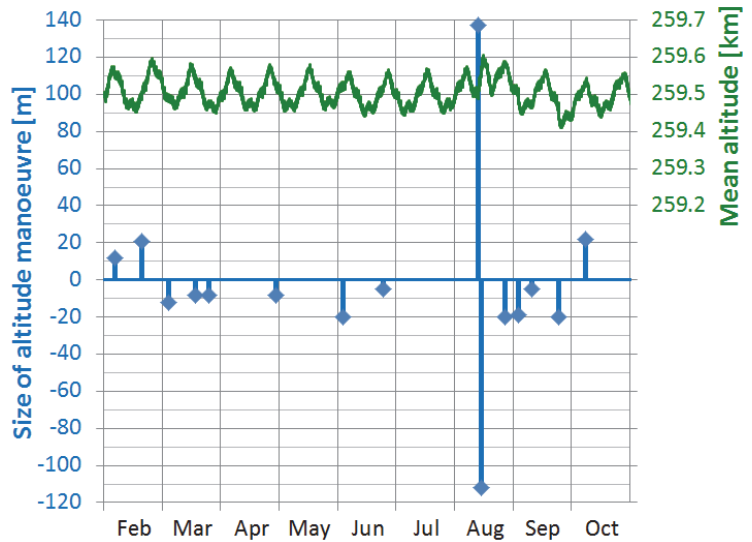


Figure 6. Altitude manoeuvres in drag-free mode from Feb to Oct 2011. The pair of large manoeuvres in August was to shift the ascending node crossings following completion of a repeat cycle.

acceleration bias (usually corresponding to less than 0.2 mN thrust) in drag-free mode for the desired duration of time. See Fig. 6 for an overview of the manoeuvres needed in the longest uninterrupted period spent in drag-free mode from Feb to Nov 2011. The very precise altitude control allowed to improve the 0.4 deg spacing of subsequent ascending node crossings at the equator inherent to a 61 days cycle: occasionally the repeat cycles were slightly rotated with respect to each other, with the aim to achieve a homogeneous coverage of 0.1 deg longitudinal spacing at the equator by the end of the nominal mission.

Despite operating in a drag environment, thanks to the excellent drag-free mode the orbit prediction accuracy for GOCE is comparable to what is achieved for missions on more conventional orbits at 700 km altitude. Only when not drag-free, prediction accuracy is heavily impacted by the highly variable drag environment³.

D. On-board Software Maintenance (OBSM)

In the first year of the mission, an unexpectedly high number of anomalies in the flight software were discovered. As a consequence, a large number of OBSM activities were needed. A total of 15 distinct PASW patches had to be installed, some to correct major problems. Most notably, two distinct cases of a loss of attitude control caused by deficiencies in the PASW code were encountered in commissioning⁴.

Another major software-related anomaly occurred in January 2011, when a gradual loss of correct pointing was observed owing to the SSTI providing an incorrect state vector to the DFACS, caused by a problem in the SSTI application software and hence requiring replacement of this software.

Fortunately the PASW offers sophisticated means to install patches for the existing software image in permanent memory. It is possible to install chains of patches to be applied on top of the compressed default PASW image, rather than having to replace the full PASW image, which would require a large operational overhead⁴.

Another lesson learnt on GOCE concerns the installation of patches in RAM on the running software: for the PASW this turned out to be a rather common activity, as the overhead of installing a patch in permanent memory and then activating it through putting the S/C into safe mode would have been very large. While this holds for most current ESA missions, it is particularly true for GOCE, in which case the orbit is heavily affected by entering safe mode (interruption of drag-free control).

E. Contingency Operations

S/C Contingency Acquisition in Case of Drag-free Mode Interruption:

A unique characteristic of GOCE is that significant S/C anomalies (e.g. safe mode entry) all lead to a rapid change of the orbit, as drag-free mode can't be maintained and the S/C is left decaying. Depending on the atmospheric drag, this can easily lead to losing 1–2 km altitude per day. Special measures have to be taken to ensure the S/C is successfully acquired at the next ground station pass in such a case, despite the station using old orbit predictions assuming the S/C to be drag-free. Figure 7 shows the evolution of the along-track error in case of drag-free mode interruption for high atmospheric densities similar to what was experienced late in 2011. Depending on the geometry of the specific ground contact, the S/C signal will be out of the antenna beam for Time Offset Values (TOV) bigger than 3-4 sec, which can happen as early as 9 hours after drag-free mode interruption.

The ground antennas were originally foreseen to await GOCE in a mode which would allow picking up the S/C signal and following it automatically in case the S/C appeared earlier than expected. However, this turned out to be infeasible, as the Kiruna antennas used for GOCE could not move fast enough out of their parking position at the horizon in that case. The solution chosen instead was to have special contingency procedures for the station operators, instructing them to perform a “directed search” along track for GOCE in case of no acquisition. This involves offpointing of the antenna along track up to when the S/C is acquired. A search along

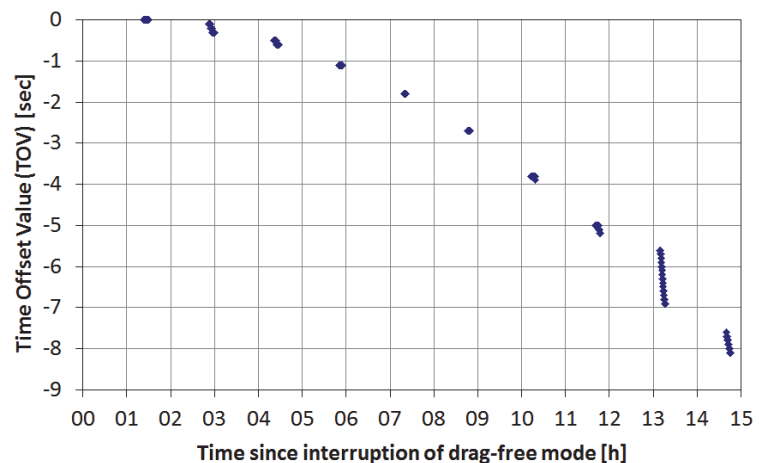


Figure 7. Evolution of the along-track error if drag-free mode is interrupted. The along track error is measured in terms of the Time Offset Value (TOV), i.e. the time difference between the expected and actual acquisition of the S/C.

track is in general sufficient, as the across-track error grows much slower and would only lead to no acquisition after a few days.

Failure of CDMU-A in February 2010:

The failure of the prime on-board computer constituted a major loss of on-board redundancy. A range of measures was taken to update the S/C configuration and operations concept following to event.

The CDMU has a sophisticated and fully configurable reconfiguration scheme, which in case of a safe mode foresees a number of restarts with different unit selections first on CDMU-A, then on CDMU-B. This was revised following the CDMU-A failure, enabling the maximum number of recoveries on CDMU-B prior to entering the “last chance” configuration (all redundant units selected and FDIR disabled globally), and adapting the unit selections to provide full flexibility.

Another measure was to improve ground coverage, scheduling an additional SvalSat/KSAT pass every day late in the evening, shortening the number of blind orbits with no ground contact overnight and thereby reducing the reaction time in case of on-board anomalies.

TM Loss Anomaly in July 2010:

Following reception of an erroneous S/C signal on 8th July 2010, troubleshooting of the anomaly started immediately. Reconfigurations of the downlink chain led to the recovery 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. However, still no software-generated telemetry was received, despite the PASW running on CDMU-B and correctly performing drag-free mode (as observed indirectly by measuring the TOVs at the ground station). The operations team was hence stuck in a very difficult situation, having virtually no TM available to further investigate the problem and to execute the routine S/C operations. Complex operations had to be performed in this condition, including forcing the S/C into safe mode to attempt to recover. To make this possible, the following special contingency operations to get more information on the S/C status were performed:

- An initial check of essential parameters in software TM was done through reusing Packet Utilisation Standard (PUS) monitoring and event action services 12 and 19 of the PASW. These services are normally employed for FDIR purposes. In this case, they were used to checkout software TM parameters by defining a S12 entry to monitor a parameter against an expected value, with the event action performing an activity visible in HPTM (e.g. switch off of ranging in the transmitter). Owing to the high overhead, this method was used only for checking out key software parameters.
- In the meantime, a sophisticated PASW modification was developed by the S/C manufacturer to allow the downlink of SW-generated TM in HPTM. The mechanism makes use of the fact that by default the PASW can write a 16 bit 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. The basic principle is shown in Fig. 8. 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.

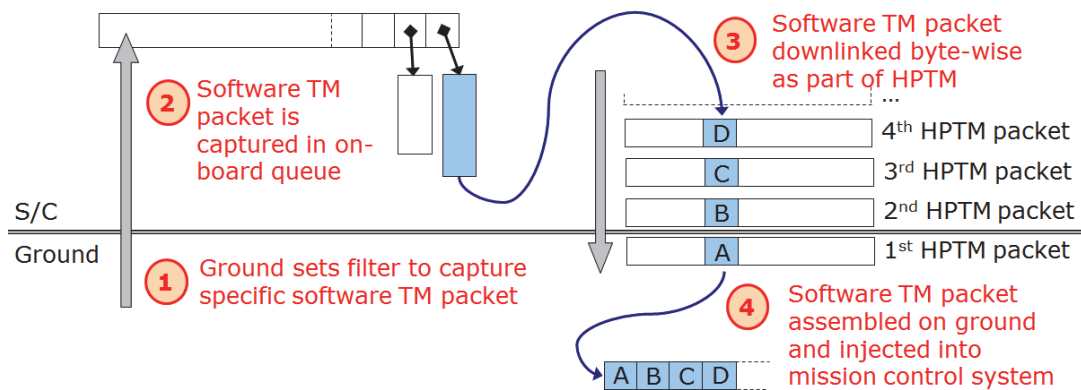


Figure 8. Illustration of the principle for downlinking software-generated telemetry packets byte-wise in a register reported in High Priority Telemetry (HPTM). A packet downlinked by these means has to be reassembled on ground. Owing to the fixed HPTM packet generation rate, the resulting net downlink rate for software telemetry packets is very slow at around 1.4 Bytes per second.

IV. Conclusion and Outlook

Operating in a drag environment at an extremely low altitude of 259.6 km, GOCE has a unique mission profile and highly complex spacecraft design, which presented a special challenge for flight operations. Owing to the many firsts of the mission and hence many uncertainties before launch concerning the spacecraft performance, significant changes to the mission profile and operations concept were needed in flight. This included selection of a new, lower altitude for routine operations, abandoning the concept of hibernation phases in eclipse season, and a new approach for orbit altitude control.

The high complexity of the spacecraft and its flight software also led to an exceptional number of on-board software changes, in particular in the first year of the mission. Last but not least, GOCE experienced some major anomalies related to the central on-board computer, requiring a large range of special contingency operations to recover the mission.

GOCE has already operated longer than the originally foreseen 20+10 months. Despite the loss of the prime on-board computer, the S/C is in an excellent condition. The quality of the science data is outstanding. It is expected that all original mission objectives can be met by the end of 2012, when the currently approved mission ends. As there is still enough fuel for about 1 additional year of operations, preparations are currently ongoing for another mission extension. Rather than continuing to operate at the current altitude of 259.6 km, it is considered to further lower the orbit. This would allow significantly reducing the error at high spatial resolutions of up to 80 km and possibly even discovering new gravity features, which no other mission would be able to accomplish in the years to come.

Appendix A Acronym List

CDMU	Control and Date Management Unit
CESS	Coarse Earth Sun Sensor
CPM	Coarse Pointing Mode
DFACS	Drag Free Attitude and Orbit Control System
DFM	Drag-free Mode
DSS	Digital Sun Sensor
ECPM	Extended Coarse Pointing Mode
EGG	Electrostatic Gravity Gradiometer
FCT	Flight Control Team
FDIR	Failure Detection, Isolation and Recovery
FOP	Flight Operations Plan
FOS	Flight Operations Segment
FPM	Fine Pointing Mode
GCA	Gradiometer Calibration Assembly
GOCE	Gravity and Steady-state Ocean Circulation Explorer
HOP	Hibernation Operations Phase
HPF	High-level Processing Facility
HPTM	High Priority Telemetry (i.e. GOCE telemetry generated by hardware)
ILRS	International Laser Ranging Service
IPA	Ion Propulsion Assembly
KSAT	Kongsberg Satellite Services AS
LEOP	Launch and Early Orbit Phase
MCS	Mission Control System
MOP	Measurement Operations Phase
OBCP	On-board Control Procedure
OBSM	On-board Software Maintenance
PDGS	Payload Data Ground Segment

PM	Processor module (of the Control and Data Management Unit)
PUS	Packet Utilisation Standard
RAM	Random Access Memory
S/C	Spacecraft
SSC	Swedish Space Corporation
SSTI	Satellite-to-Satellite Tracking Instrument

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