GOCE FLIGHT DYNAMICS SUPPORT TO THE LOW ORBIT AND DEORBITING OPERATIONS

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Abstract: *Since its launch in March 2009 until August 2012 the ESA mission GOCE successfully achieved its scientific mission of mapping the Earth's gravity field with an unprecedented accuracy at a mean altitude of 260 km. To maximize the scientific return of the mission prior to its end of life, in the summer of 2012 a special low orbit operations campaign started, resulting in GOCE being operated at mean altitudes between 260 and 230 km. In October 2013 fuel depletion caused the start of GOCE's final decay. The inevitable destructive re-entry occurred in the early hours of 2013/11/11, 1.5 hours after its last contact with ground (Troll in Antarctica) when GOCE was showing an almost nominal behaviour. This paper presents a summary of the preparatory work and the operational support provided by the ESOC Flight Dynamics team, which led to the successful completion of the GOCE low orbit, final decay and re-entry operations.*

Keywords: *GOCE, LEO, re-entry, drag force, density.*

1. Introduction

The paper is divided into three sections. Section 1 is this introduction, where the GOCE nominal mission is briefly described. Special low orbit operations are covered in Section 2 and de-orbiting and re-entry operations are addressed in Section 3.

1.1. GOCE scientific mission overview

The Gravity Field and Steady-State Ocean Circulation Explorer ESA mission GOCE was the first mission of the ESA's Living Planet Programme. GOCE's scientific objective was to measure the Earth's gravity field and provide a model of the geoid with extremely high accuracy never achieved before.

GOCE was 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). This instrument was used to measure high-resolution features of the gravity field, while large-scale phenomena in the gravity field were obtained through analysis of the spacecraft's orbit as measured with a scientific GNSS receiver on-board the spacecraft.

1.2. GOCE spacecraft design

In order to map the Earth's gravity field at a high accuracy and with a fine spatial resolution, GOCE had to orbit at the lowest possible altitude where the drag force and torques encountered by the spacecraft are significant. On the other hand, the main scientific instrument required a quiet environment to perform its measurements, ideally free of any disturbances from non-gravitational forces. These demanding requirements led to a unique platform design, which embarked several novel technologies; one can say that GOCE was designed to be a spaceborne gravimeter. The spacecraft was equipped with a new and sophisticated Drag Free Attitude and Orbit Control System (DFACS) that provided 3 axis stabilized attitude using magnetotorquers as actuators and an Ion Propulsion Assembly (IPA) that, working in close-loop with the EGG, continuously counteracted the atmospheric drag and kept the satellite flying undisturbed and drag-free along the flight direction.

The satellite body was symmetrical along its flight direction and contained no moving parts in order to minimize mechanical disturbances. Two winglets provided additional passive aerodynamic stability (see Figure 1). The spacecraft attitude was kept Sun and nadir pointing, with the same side of the spacecraft (where the solar panels were mounted) always facing the Sun.

Figure 1. GOCE artist's impression. Image credit: ESA

In addition to the EGG and the GNSS receiver, the DFACS received inputs from the following sensors: coarse combined sun and earth sensor unit, three redundant star trackers, three redundant magnetometers and two digital sun sensors. The DFACS had several modes, ranging from basic attitude stabilization modes up to full drag-free control, with both IPA and EGG used in the DFACS loop. When GOCE was in drag-free mode, the orbit altitude could be adjusted through biasing the IPA thrust. This design did not cover the possibility to perform orbital plane orientation direct control. For more detailed information about the GOCE spacecraft and missions design see [2].

1.3. GOCE operational orbit

The requirements that dictated the basic design of the GOCE operational orbit were the following:

- Low altitude. The effect of higher degree terms of the gravity field decreases rapidly with distance from the Earth surface.
- Safe altitude. The role of the IPA was not only to make the scientific measurements possible. The instantaneous compensation of the drag force was a key factor to achieve a reasonable mission duration at low altitude, avoiding an early re-entry. The expected performance of the IPA, the corresponding Xenon consumption budget and envisaging a safe recovery margin in case of IPA outages were the main drivers involved in the selection of the original operational altitude. They were all dependent on the levels of solar and geomagnetic activity throughout the mission lifetime, which determine to the largest extent the atmospheric drag force encountered by the spacecraft.
- Orientation of the orbital plane with respect to the Sun. GOCE had solar panels only on one side of the spacecraft and this should be continuously orientated towards the Sun. No out of plane control was possible.
- Short repeat cycles were to be avoided in order to ensure a good coverage of the complete Earth surface.

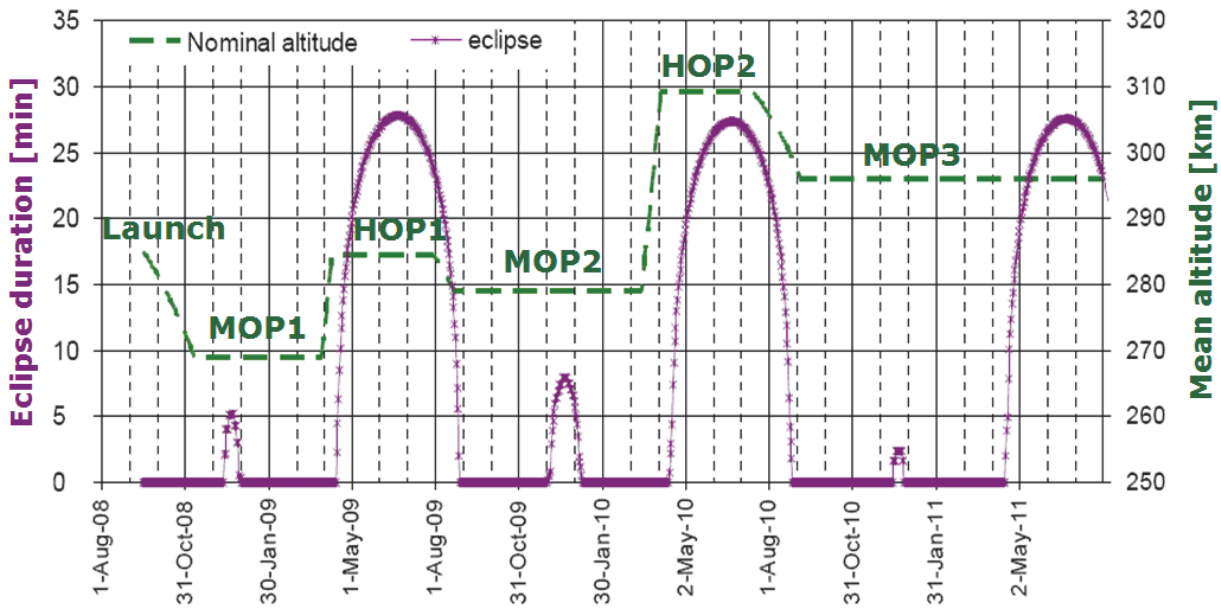

Figure 2. Original Mission mean altitude profile before launch

In response to these requirements the following operational orbit basic design was selected before launch:

Near polar, Sun-synchronous orbit with Mean Solar Local Time of the Ascending Node (MSLTAN) at 18:00 hours. The selection of the MSLTAN was subject to the launch date. The original mission profile design contemplated the possibility to have alternating Measurements Operational Phases (MOP) and Hibernation Operational Phases (HOP), when the satellite was taken to a higher altitude coinciding with the start of the long eclipses season (see Figure 2). The long eclipses season distribution throughout the year depended on the selection of a dawn-dusk or a dusk-dawn orbit. Since the intention was to match the end of the spacecraft's Commissioning Phase with the start of the first MOP, the consolidation of the launch date was an input to the final selection of the MSLTAN.
The rationale behind the MOP/HOP alternating approach was twofold: on the one hand it was expected that the EGG performance suffered degradation due to thermal disturbances during periods of long eclipses at the times of entering and exiting eclipses, on the other the power budget could become an issue during long eclipses, especially in scenarios of high drag force requiring strong IPA thrusting to compensate its effect on the orbit altitude.
Since no inclination manoeuvres were going to be performed, the Sun-synchronism could not be maintained, leading to a drift in MSLTAN. This drift had no significant impact on the short/long eclipse pattern during the 20 months of the nominal GOCE mission.

Low orbit, 268 km mean altitude. This altitude was providing a long repeat cycle of 61 days and it was a safe selection from the point of view of the expected drag force. This altitude ensured that in case of a contingency affecting the IPA, the Flight Operations Segment (FOS) had 8 days to restart the thrusting before the increase in drag force due to the altitude decay led to an unrecoverable state. The assumptions on the solar activity were a conservative combination of the predictions published by Marshall Flight Space Centre (Ap and F10.7 values corresponding to the 95th percentile) and the observed values during the previous solar cycle (cycle 23). The atmospheric air density model used was the MSISE-90 (MSISE-00 was not available at the time the mission analysis was carried out)

1.4. GOCE Routine Phase operations at 260 km mean altitude: 2009 to 2012

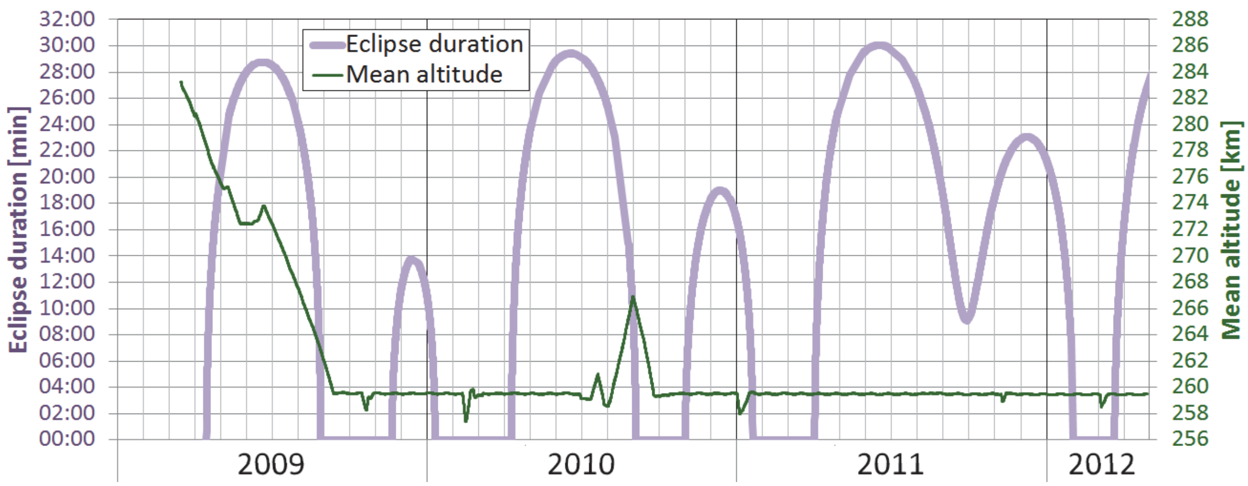

Figure 3. GOCE mean altitude profile during the extended Routine Phase

GOCE was launched on the 17th of March 2009 from the Plesetsk Cosmodrome on a Rockot launch vehicle. It was injected on a near polar, dusk-dawn Sun-synchronous orbit at an approximate mean altitude of 283 km. The Commissioning Phase operations were conducted as GOCE semi-major axis decreased due to the effect of the atmospheric drag force. In June 2009 the originally planned operational altitude of 269 km was reached. However, in view of the low levels of solar activity and the corresponding low drag force encountered by GOCE, it was decided to continue the decay towards a lower operational altitude, with the consequent benefit for the Mission's objectives.

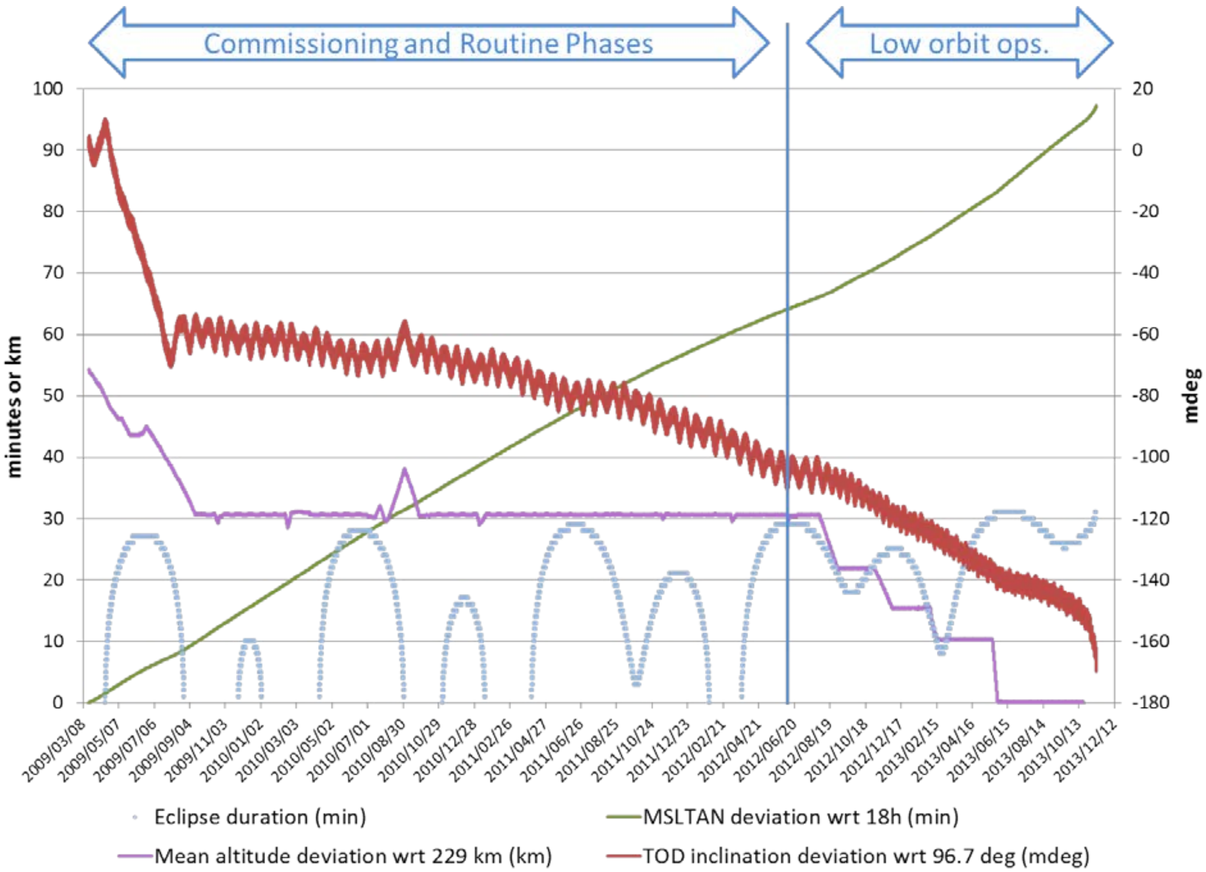

Figure 4. Evolution of the TOD inclination, mean altitude, MSLTAN and eclipse duration throughout the entire GOCE mission

GOCE reached a mean altitude of 260 km in September 2009. From that moment and until July 2012 GOCE was successfully operated at this mean altitude during its extended Routine Phase. The analysis of the EGG performance during the Commissioning showed little measurement's degradation due to the start and end of the eclipses. This together with the in-flight confirmed margin in the power budget and the low levels of solar activity resulted in abandoning the original mission altitude profile. HOPs were removed from the operational orbit control concept and science measurements in drag-free mode were performed irrespective whether the spacecraft was in eclipse season or not (see Figure 3). Beyond its intended 20 months of mission lifetime GOCE was operated for a much longer period, being this considerable mission extension possible thanks to the excellent scientific results, the good status of the satellite, and the large margin in the fuel budget for the IPA.

The Sun-synchronism achieved at the injection was gradually lost due to the contribution of the inclination drift (inclination was not controlled) and the semi-major axis being lower than the sun-synchronous one since the beginning of the mission. In Figure 4 this effect can be observed, especially the changes in the MSLTAN drift rate due to changes in altitude. As expected the eclipse pattern evolved into a continuous eclipse state at the end of the extended Routine Phase, when the MSLTAN had grown above 19:00 h.

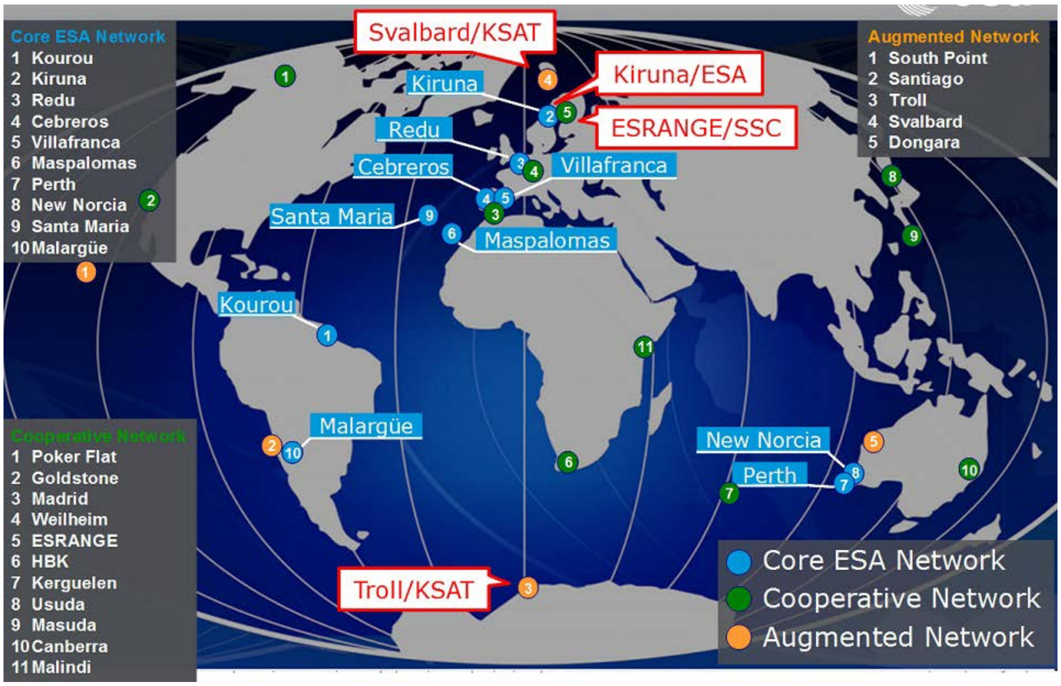

Figure 5. GOCE Ground stations network during Routine, Low orbit and De-orbiting operations (red boxes). Image credit: ESA

During the whole duration of the GOCE Mission, the GOCE Flight Dynamics (FD) Orbit Determination and Control team (OD&C) was in charge of performing orbit determination and trajectory propagation. The orbit determination was based on the data provided by the GNSS receiver on-board extracted from telemetry. During periods when this telemetry was not available, the orbit determination was performed using S-band radiometric data, requiring establishment of a special low bit rate telemetry mode. This telemetry mode did not allow transmission of science data to ground, therefore the provision of S-band radiometric data to the FD OD&C team during periods of telemetry loss was kept to a minimum of four passes per day: two ascending arc and two descending arc passes.

The GOCE Ground Stations Network during the Routine Phase consisted of three stations located in Kiruna (Sweden), Svalbard (Norway) and Troll (Antarctica). Every day six Kiruna station passes were taken, augmented by one to two passes on the Svalbard station. There was a significant coverage gap during the night, typically 10 hours. Troll was only used for additional support in recovery/contingent activities.

The orbit determination was performed once per day during the Routine Phase (for more detailed description of the FD orbit determination setup see [3]). The GOCE trajectory was then propagated forwards in time taking into account the expected spacecraft mode (usually drag-free mode) to generate a set of products to support the Mission Planning activities and pointing elements to support the acquisition of signal (AOS) at the stations. The spacecraft modes that could be modeled by the FD OD&C team to propagate the GOCE trajectory were:

- Drag-free mode: The IPA compensates continuously the atmospheric drag force encountered by the spacecraft in a close loop with the EGG. No drag force is considered in the propagation.
- Drag-free mode + constant thrust: A bias can be commanded on-board so that the action of the IPA results on compensating the drag force and exerting a constant acceleration on the spacecraft, achieving this way the orbit control. No drag force is considered in the propagation. A constant acceleration aligned with the inertial velocity is applied.
- Constant thrust: The IPA is used in open loop to provide a constant thrust on the spacecraft. The drag force is considered in the propagation as well as a constant acceleration aligned with the inertial velocity.
- Free-drift: The IPA is inactive. This corresponds to a free drift propagation.

The accuracy of the propagated GOCE trajectory depended obviously on the mode the spacecraft was operated in. During periods of drag-free mode the predictions were extremely accurate. When GOCE was not in drag-free mode, the prediction of the drag force encountered by the spacecraft was rather inaccurate due to the difficulties to model the spacecraft attitude, due to the atmospheric density model intrinsic error and above all, due to the poor predictability of the solar and geomagnetic activity.

If at any point in time GOCE exited the flying mode that had been assumed for the generation of trajectory predictions, the FD OD&C team had to be immediately informed to assess the impact on the predicted ground stations visibility times. Typically when GOCE left drag-free mode due to an unexpected spacecraft reconfiguration event, the stations started to observe that AOS was occurring earlier than expected. This was the effect of the semi-major axis decay (decreasing orbital period) that followed the exit of drag-free conditions, which was not accounted for in the predictions sent by FD to the stations. This difference between the expected AOS time at the station and the actual one was measured in terms of time offset value (TOV). The TOV is the time offset that, when applied to the spacecraft's trajectory predictions available at the station, minimizes the pointing error with respect to the actual spacecraft trajectory as observed from the station (see Figure 6).

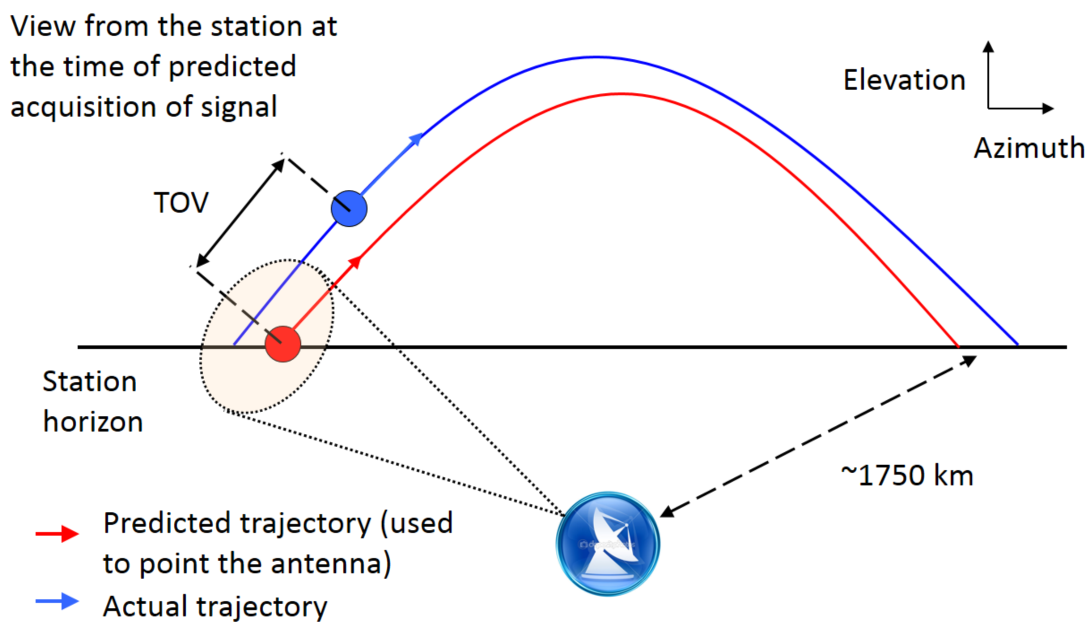

Figure 6. TOV definition

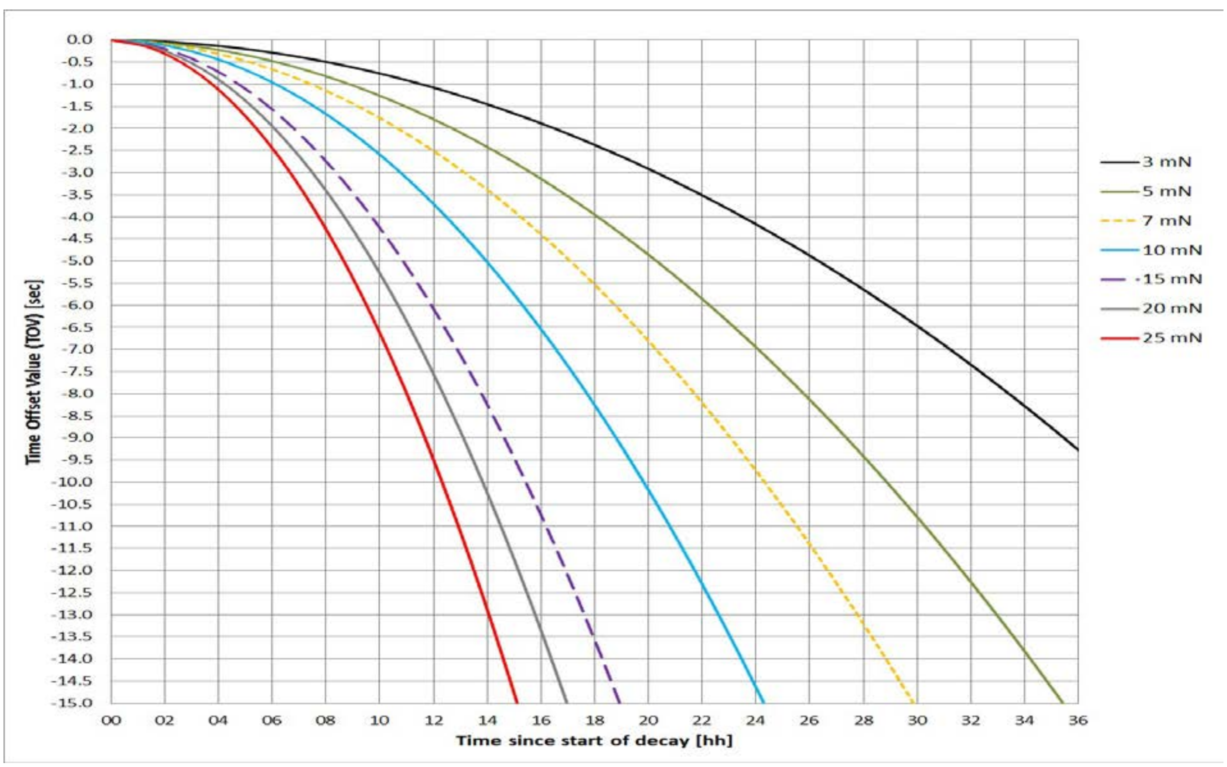

Figure 7. Evolution of the TOV at Kiruna (Sweden) in case of exiting drag-free mode depending on the averaged drag force encountered by GOCE

In order to ensure the timely reaction of the FD OD&C team an on-call approach was in place. During the Routine Phase, the combination of moderate levels of solar activity and the operational altitude close to 260 km, resulted in a FD OD&C on-call schedule covering only weekends and bank holidays. Kiruna and Svalbard stations are 13 m. antennae, which translates into a half beam width of 0.35 deg for S-band acquisition configuration. GOCE AOS occurred typically at 1750 km from the station. This means that the spacecraft always crossed the antenna's beam as long as the TOV was below 3 seconds (colored area in Figure 6). Considering that the typical averaged drag forced at 260 km mean altitude was below 7mN, any exit of drag-free conditions right after the end of the working day did not result in TOVs larger than 2 seconds at the time of the first pass on the next morning (10 hours later), as can be observed in Figure 7.

2. GOCE low orbit operations from 260 km to 230 km mean altitude: July 2012 to October 2013

At the beginning of 2012 a review of the GOCE operational concept was initiated, aiming at maximizing the scientific return of the mission prior to its end of life. The main objective of this review was to assess the feasibility of lowering the GOCE operational orbit, with the consequent improvement in the resolution of the gravity measurements.

The GOCE Flight Operations Segment (FOS) had been designed, as described in the introductory chapter, to conduct safely operations at a mean altitude of 260 km. This design responded primarily to a safety requirement: the FOS operational concept was ready to cope with IPA outages of up to 8 days, meaning that in case of interruption of the drag-free conditions the FOS had to resume the IPA thrusting within 8 days before reaching an altitude and drag levels where the satellite could not be recovered any longer. For the low orbit operations phase this time was reduced to 4 days and later on to 2 days, putting the corresponding measures in place to be able to react more quickly to contingencies on the ion propulsion system.

The FD OD&C team performed the required analysis to find the minimum mean altitudes that were compatible with safe conduction of operations assuming maximum IPA outages during 8, 4, and 2 days. Additionally FD provided assessments of the orbit prediction accuracy. This assessment had to take into account the expected errors in the prediction of the solar and geomagnetic activity, the air density model errors and the behaviour of the spacecraft attitude. The assumptions made for this analysis and the results, together with the corresponding measures put in place to mitigate the risks of not acquiring the spacecraft signal when operating out of drag free mode are summarized in the following subsections.

2.1. Assumptions to the FD orbit lowering analysis

2.1.1. Atmospheric air density

As for the mission analysis work before launch mentioned in the introduction, FD used the NASA MSFC predictions to model the expected evolution of the solar activity. The predictions available at the time of the analysis were the March 2012 release (Figure 8). The resulting air density at altitudes ranging from 260 to 240 km computed using MSISE-00 is shown in Figure 9.

A conservative approach was taken: the various decay trajectory analysis assumed the maximum expected density in 2012 at 95th percentile levels of solar activity (density peaks marked in Figure 9). On top of this, a geomagnetic storm was included in the first days of the decay.

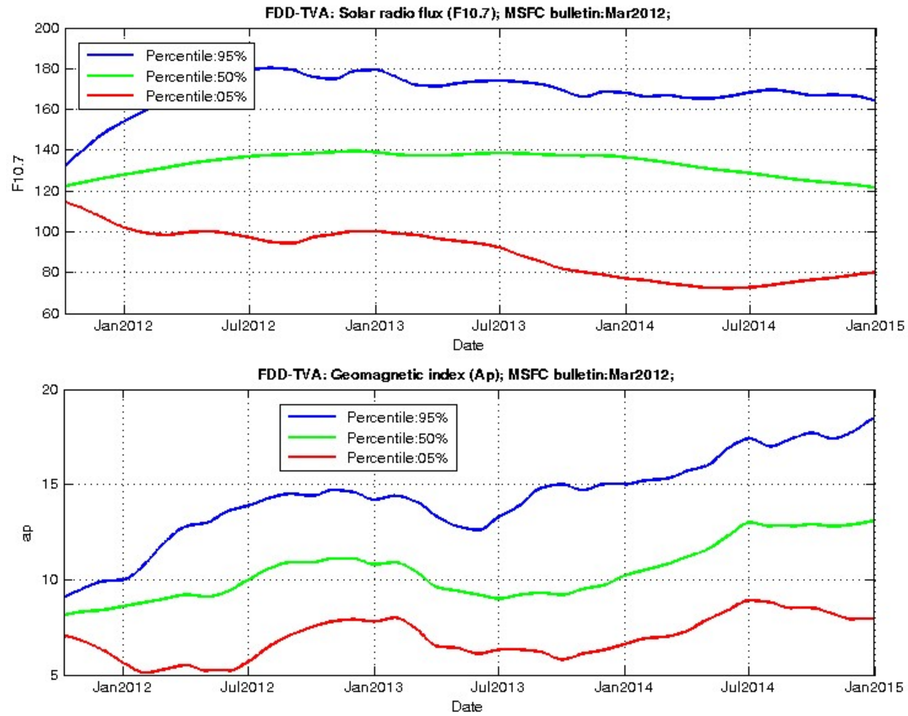

Figure 8. MSFC Ap and F10.7 predictions in March 2012

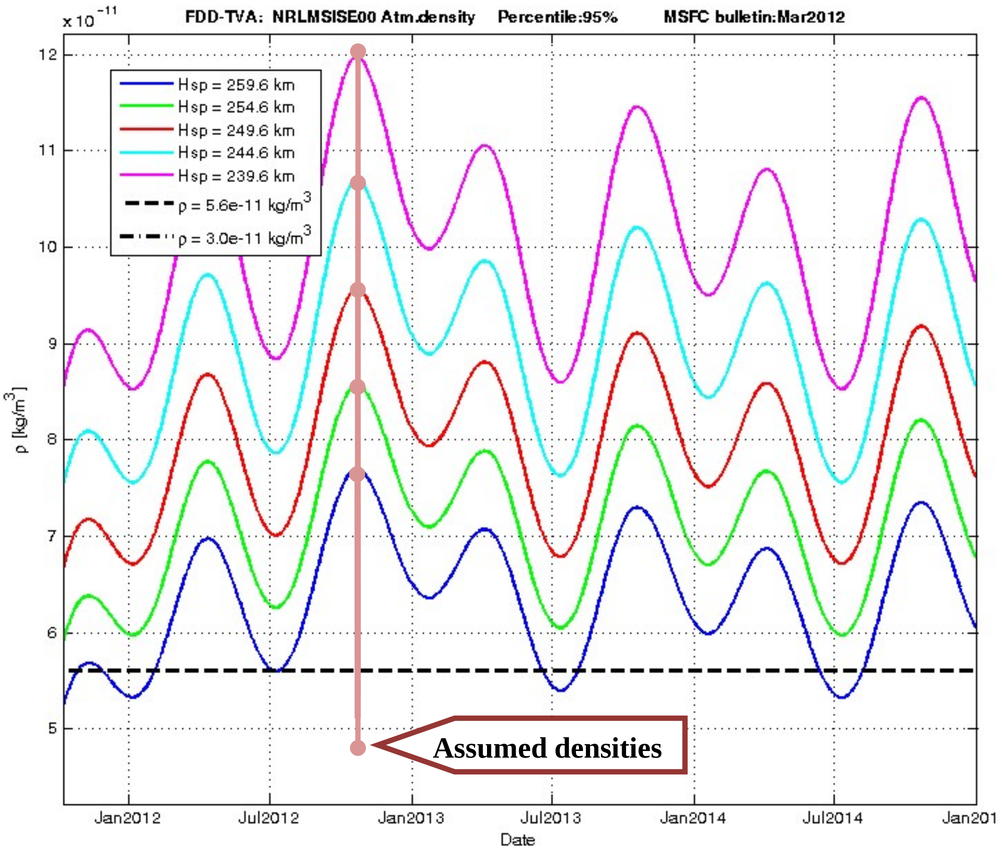

Figure 9. MSISE-00 computed density for several mean altitudes based on the solar and geomagnetic activity predictions from the MSFC March 2012 at the 95% confidence.

2.1.2. Maximum thrust available to perform the altitude recovery

As part of the preparations for the orbit lowering, the power budget established before launch was re-evaluated by the Flight Control Team (FCT). Operations in a high drag environment required higher thrust levels, with the consequent impact on the overall spacecraft power consumption. When in sunlight, the power budget allowed to fire the IPA at the maximum thrust level (20 mN). When in eclipse season the maximum possible IPA thrust while still keeping a balanced power budget was dependent on the eclipse duration. The reviewed budget allowed to have approximately 6 mN additional thrust as can be observed in Figure 10.

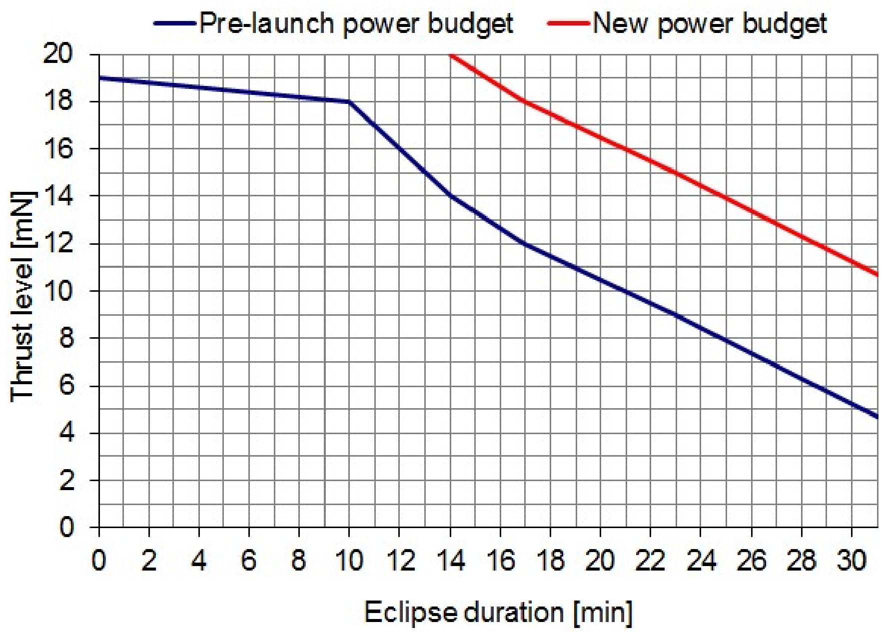

Figure 10. IPA available thrust vs eclipse duration after power budget re-evaluation

As already remarked in the introductory section (see again Figure 4), from the start of the mission the MSLTAN drifted away from 18:00 h due to the inclination and semi-major axis being different from the Sun-synchronous values. At the end of the extended Routine Phase (July 2012) the MSLTAN was 19:06 h, leading to Sun eclipses in every orbit. Having a close look at the evolution of the eclipse duration from August 2012 onwards (Figure 11), a maximum recovery thrust of 15 mN was assumed, corresponding to a maximum eclipse duration of 23 minutes. At this time it was agreed that this assumption could imply reviewing the final selected altitude around April 2013 when the eclipses duration was going to increase significantly above 23 minutes.

2.1.3. Spacecraft attitude evolution after exiting drag-free mode

When the spacecraft exits drag-free mode the pointing stability depends on the DFACS mode. The autonomous mode sequence that follows the exit of drag-free mode goes from Coarse Pointing Mode (CPM) with large variations of the spacecraft pointing to Fine Pointing Mode (FPM) and Drag-Free Mode Prep (DFM-P), where the attitude control thresholds are narrower. This DFACS mode sequence has a significant impact on the drag force experienced by the spacecraft and it has to be properly modelled when propagating the decay after leaving drag-free mode.

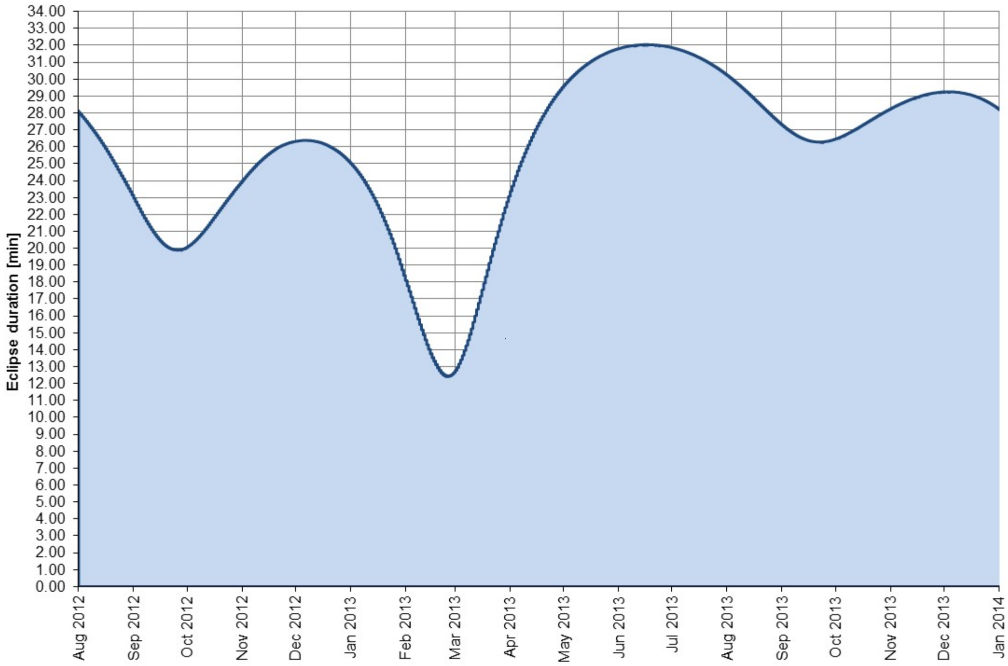

Figure 11. Evolution of the eclipse duration after the extended Routine Phase

The FD OD&C model of the drag force assumes a constant drag frontal area without applying any attitude law. Instead the orbit determination estimates the value of the drag coefficient (CD) that provides the best fit to the input tracking data (either GPS or radiometric data) in a configurable time interval. Based on the observed estimation of CD profiles when leaving drag-free conditions during the 3 years of mission a CD profile was generated assuming that the spacecraft followed its autonomous mode transition from CPM to FPM and it stayed in this mode for the rest of the decay (see Figure 12).

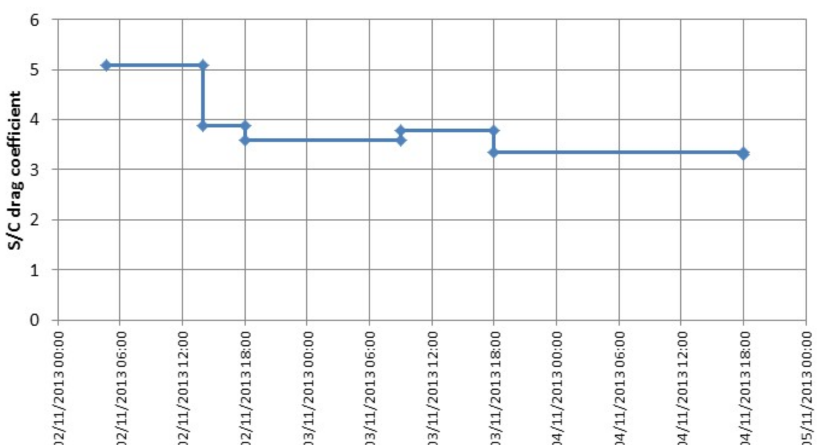

Figure 12. Drag coefficient profile depending on the DFACS mode changes

The recovery is performed by commanding a constant thrust of 15 mN. The spacecraft mode is DFM-P. The IPA provides a force aligned with the spacecraft X axis. The direction of the X axis is controlled around the inertial spacecraft velocity at a threshold that is dependent on the DFACS mode. Since the FD OD&C models the constant acceleration as parallel to the spacecraft velocity, a reduction of the thrust force module was applied to the acceleration input to the propagation. This reduction factor was $(2/\pi) * Sin(w)$, where w is the maximum yaw de-pointing angle along the orbit.

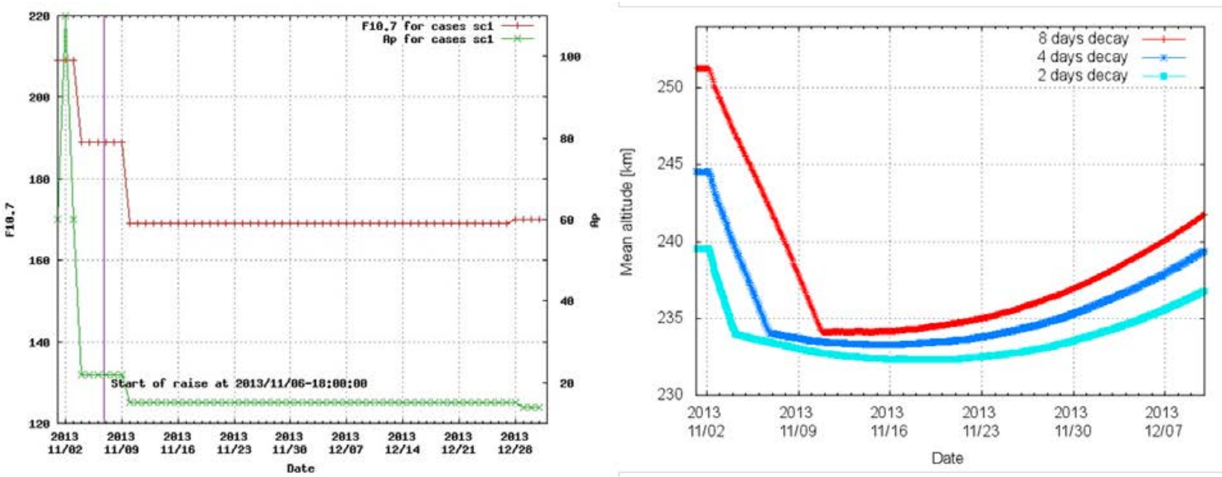

Figure 13. Solar and geomagnetic profile used in all cases (left). Mean altitude evolution during decay and recovery for the cases starting at 251, 244.6 and 239.6 km (right)

2.2. Results of the FD orbit lowering analysis

Several decay trajectories starting at different altitudes and respecting the assumptions listed in the previous subsections were propagated. The minimum altitudes that allowed recovery after a decay of 8, 4 and 2 days were found to be 251, 244.6 and 239.2 km respectively. Figure 13 shows the evolution of the mean altitude for these cases.

At these altitudes the maximum expected drag force were observed to be always below 25 mN (plots not included). Looking at the evolution of the expected TOV at the Kiruna station (Figure 7) it could be concluded that there was always going to be a more than 6 hour time interval before the TOV grows above 3 seconds, which was the limit for safe acquisition at the stations without having to go on a search. It was decided to reduce the 10 hours gap in coverage during the night by adding a daily Troll pass close to 02:00 UTC. The FD OD&C team on-call schedule was extended to start at 05:00 local time every day. This way in case a fall-back out of drag-free mode was detected during the Troll pass over night the FD team could be on-console to generate and deliver new station predictions on time.

2.3. Execution of the low orbit operational campaign

The actual altitude profile during the low orbit operations campaign is shown in Figure 14. Thanks to lower than expected drag levels owing to low solar activity, the altitude could be lowered by another 10 km, down to about 229 km mean altitude.

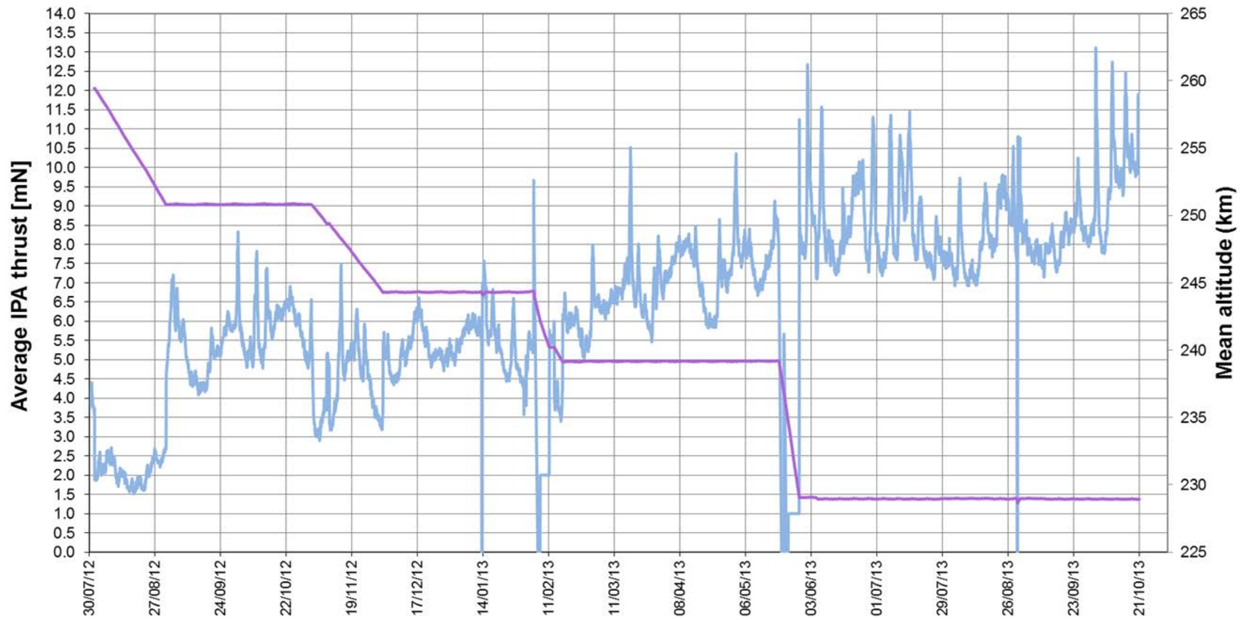

Figure 14. Mean altitude profile during the low orbit operations campaign and averaged IPA thrust force over one orbit (when the spacecraft was in drag-free mode)

The orbit lowering took place in the several steps, which allowed the FOS to complete all the preparatory activities to operate GOCE at a progressively lower altitude. Complete 61 day measurement's campaigns were carried out at every intermediate altitude.

From 260 km to 251 km mean altitude. August 2012.
251 km was the lowest altitude that was determined by the FD analysis to still be compatible with the setup of the ground segment for the routine mission. The orbit lowering was not conducted with the spacecraft in free drift. GOCE was kept in drag-free mode with a negative constant acceleration bias corresponding to a 2 mN thrust bias against the flight direction. This approach was safer than a free-drift since it did not involve switching the IPA off and on again after the decay and provided a confortable scenario in terms of spacecraft predictions accuracy for Mission Planning and station acquisition. Additionally it allowed to continue acquiring science data during the decay.

Unfortunately when in drag-free mode, the IPA minimum thrust level was 0.6 mN, meaning that for segments of the orbit where the drag force was below 2.6 mN the DFACS could not provide drag-free conditions with a 2 mN negative bias, but the drag force + 0.6 mN. This effect had to be modeled by the FD OD&C team for the propagation of the predicted trajectory during this decay. The selected approach was to use a lower acceleration against the flight direction for the trajectory propagation. The process to find this acceleration encompassed:

- Estimation of the predicted drag force during the propagation period (red curve in Figure 15). Special care was taken to tune all parameters involved in the modeling of the drag force to the best extent possible, taking as reference the IPA thrust level from the previous days extracted from telemetry.

- Averaging the predicted resulting thrust force, assuming the DFCAS behavior mentioned in the paragraph above (green curve in Figure 15).

This approach was successful: no re-planning of activities or station acquisition issues were reported during the duration of this decay phase (1 month).

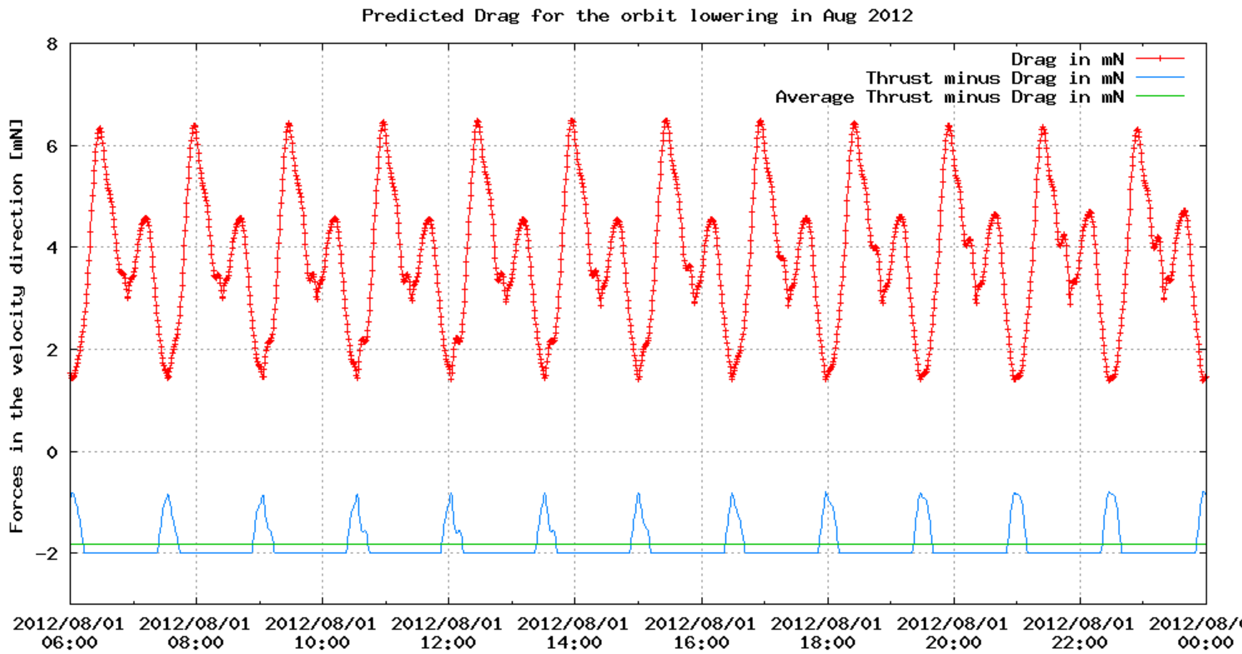

Figure 15. One day modeling of the IPA thrust as an averaged constant acceleration along the orbit during the decay in August 2012

From 251 km to 244.3 km mean altitude. November 2012.
At this point in time the special measures for the low orbit operations campaign were already in place. As in the previous orbit lowering, GOCE stayed in drag-free mode with a commanded constant acceleration negative bias corresponding to a negative thrust bias of 1.5 mN. With this bias the IPA was not reaching its minimum thrust level (0.6 mN) at any point in the orbit, which made the generation of predictions by FD easier than in the previous decay.

From 244.3 km to 239.2 km mean altitude. February 2013.
This orbit lowering was not performed in drag-free mode as the spacecraft had fallen out of drag-free mode due to an on-board anomaly, which meant a much faster decay.

After arriving at 239.2 km mean altitude, a reassessment of the situation aiming at a fourth lowering took place. The levels of solar activity and with them the observed air density were at much lower levels than assumed in the 2012 predictions. A further orbit lowering was decided to a final mean altitude of 229 km in May 2013. This lowering was performed out of drag-free mode to arrive at the final altitude as soon as possible. Science operations in drag-free mode at 229 km were conducted up to running out of fuel in October 2013.

3. GOCE de-orbiting and re-entry operations

After completion of the orbit lowering operations down to 230 km mean altitude, the preparatory work for the GOCE re-entry started. Following a decision from Mission management, the FOS teams set as goal to operate the spacecraft down to the lowest possible altitude. A thorough assessment of the expected Space and Ground Segments performance was initiated that resulted in an operations concept and the definition of activities for the de-orbiting phase of GOCE. The de-orbiting phase was defined as the operational phase spanning the end of the scientific mission, when the IPA stops compensating the atmospheric drag force due to fuel depletion and the satellite starts its final decay, to the point when contact with the spacecraft through the radio frequency system can no longer be uphold and the final re-entry phase starts.

During the re-entry phase GOCE was a passive body without any ground control capability. The GOCE re-entry was selected by the Inter-Agency Space Debris Coordination Committee (IADC) to conduct an observation campaign. Thanks to this international campaign the GOCE re-entry was to be monitored not only by the ESOC Space Debris Office (SDO), but also by the members of the IADC. This would allow having the best possible means available for monitoring the re-entry and predicting the re-entry location. In particular the FD OD&C team was supposed to provide their orbit solution based on either GPS or S-band tracking data to the centralized IADC observations repository up to the point when contact with GOCE was lost.

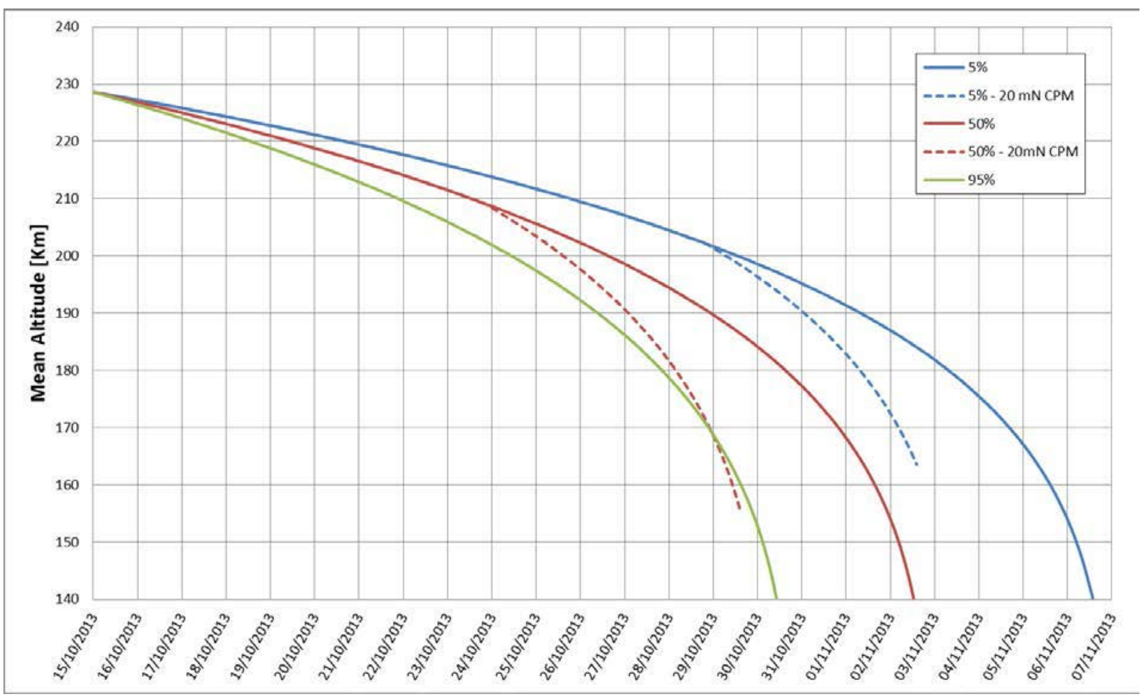

Figure 16. Reference de-orbiting trajectories based on MSFC predictions from March 2013

3.1. FD mission analysis studies to support the de-orbiting preparations

This subsection summarizes the results of the Flight Dynamics investigations that contributed to the GOCE de-orbiting operations concept that was adopted, together with the major modifications introduced in the FD System to support these critical operations.

3.1.1. GOCE de-orbiting reference trajectories

Once the satellite exited drag-free conditions when running out of Xenon, the decay rate depended on the DFACS mode and on the air density level, which is driven by the solar activity.

As for the mission analysis work done for the operational orbit lowering presented in section 2, FD used the NASA MSFC predictions to model the expected evolution of the solar activity. Reference trajectories were generated based on the MSFC predictions from March 2013 at the 5%, 50% and 95% confidence bounds. The start altitude for the decay was 230 km. Two different attitude profiles were considered:

- DFACS mode during decay is FPM. This profile is represented by a constant CD value of 3.5 for the entire decay.
- DFACS mode during decay is FPM down to an altitude corresponding to a drag level of 20 mN and from that point onwards CPM is assumed, which is represented by a larger CD of 5.5, since the attitude control is less stable in this mode.

Simulations provided by the GOCE manufacturer concluded that these two attitude profiles were the most likely ones to happen during the de-orbiting. Figure 16 shows the evolution of the mean altitude for every trajectory created. The solid lines show the altitude profile assuming the attitude control is achieved in FPM throughout the entire decay. The dashed lines show the steeper decay due to the increase in the drag levels caused by the higher attitude pointing errors. The de-orbiting phase was therefore estimated to last between two and three weeks.

3.1.2. Estimation of Xenon tank depletion

The end of the GOCE drag-free operations and start of the de-orbiting and re-entry phases was determined by the depletion of the Xenon tank. It was consequently important for planning purposes to have a good estimate of when this was going to occur.

The FD Attitude Monitoring System (AMS) was in charge of the Xenon bookkeeping during the whole GOCE mission. The bookkeeping was performed based on two different methods: the PVT and the mass flow integration method (integrating readings from the mass flow sensor of the IPA since the beginning of the mission). The PVT method was based on a gas state equation that accounted for the compressibility of the Xenon. The method had to be adequate for a range of tank's pressures going from an initial level of 125 bars at launch to 5 bars at the end of the mission. As seen in Figure 17 both methods were showing very consistent results for the remaining Xenon in the tank at the beginning of 2013.

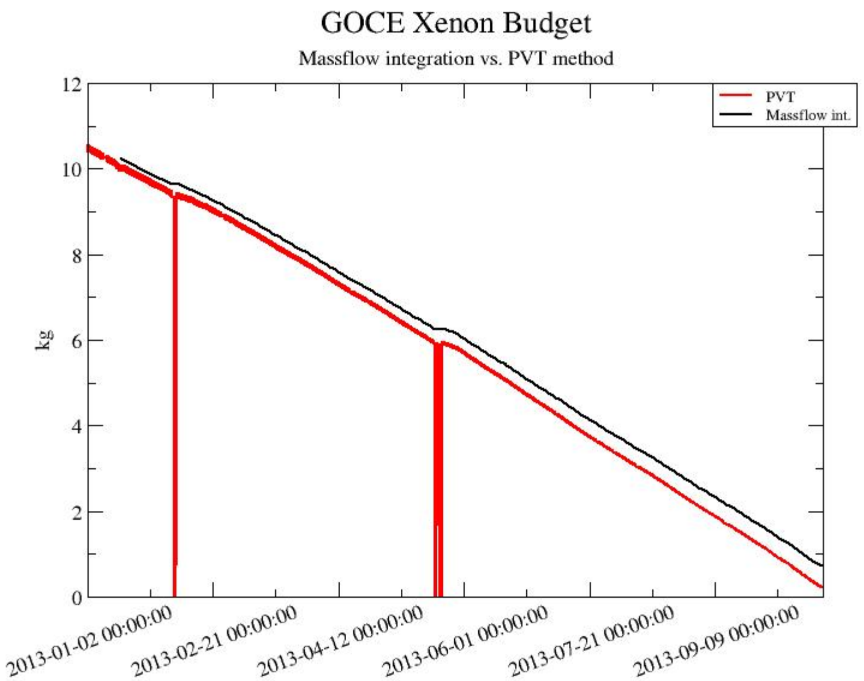

Figure 17. Xenon bookkeeping. PVT and mass flow integration methods

Since the PVT method was expected to be more accurate during the remaining of the mission in 2013, as from mid-May 2013 this method was used to estimate the remaining Xenon mass instead of the mass flow integration method (which is affected by an error accumulated in more than 4 years of operations). It had to be considered that the PVT method was affected by the errors in the pressure and temperature sensor readings (± 1.1 bar and ± 1.5 C respectively), introducing worst case inaccuracy of ±300 grams. Also from May onwards the FD AMS team provided on a daily bases estimations of the Xenon tank depletion date based on a linear extrapolation of the daily Xenon consumption, taking the ± 300 grams uncertainty into account.

The estimation of the earliest and latest dates for the start of the de-orbiting phase was assessed regularly by combining the following input elements: predicted solar activity (minimum=MSFC at 5%, maximum=MSFC at 95%), Xenon mass inaccuracy (± 300 grams), minimum operating pressure for the IPA pressure regulator. A pressure regulator was responsible for providing a constant pressure in the Low Pressure Section of the IPA. Following the manufacturer's specifications, the pressure regulator should provide this constant pressure for values of the tank's pressure down to 5 bars. It was not known whether the IPA was going to continue working for tank's pressures lower than this. If so, once reaching a tank's pressure of 2.5 bars the effect of the pressure regulator should be none, leading to the same pressure in the High and the Low Pressure Sections of the IPA.

3.1.3. Accuracy of the orbit predictions

One of the crucial aspects of the FD support during the de-orbiting phase was providing orbit predictions accurate enough to successfully acquire the spacecraft signal.

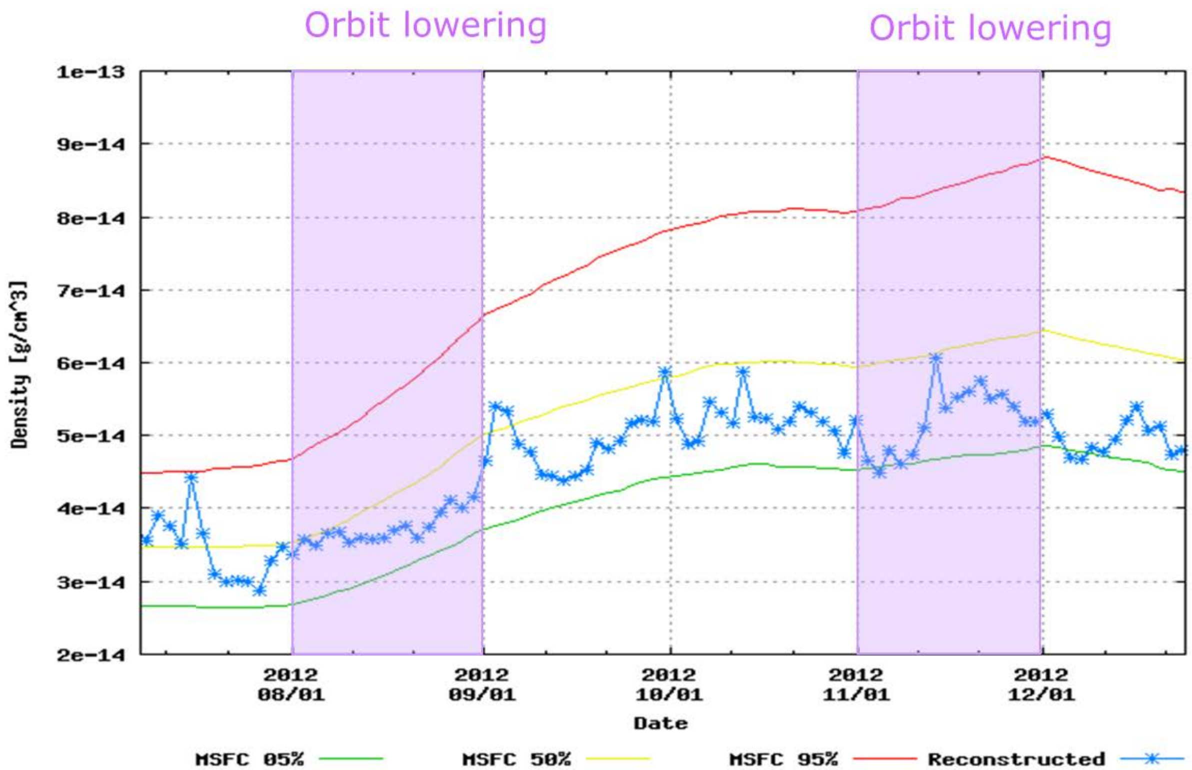

Figure 18. Comparison of the air density based on the MFSC predictions from March 2012 and the observed solar activity on the second half of 2012. Reconstructed GOCE orbit input to the density computation

As mentioned already in the introduction, predicting the drag force for GOCE at such low altitudes becomes rather inaccurate, due to the very poor predictability of the solar activity which is responsible to the largest extent of the changes in atmospheric air density. The analysis of the expected accuracy of the FD predictions during the de-orbiting had to use as primordial assumption a realistic scenario for the levels of solar and geomagnetic activity. When FD started the preparations of the de-orbiting campaign at the beginning of 2013 it was noticed that the MSFC predictions at the 95% confidence that had been used as input for the preparations to the low orbit operations (see Figure 8) had turned out to be extremely conservative. Figure 18 shows the computation of the air density for the reconstructed GOCE trajectory based on the MSFC predictions from 2012 and also on the real observed solar activity during the second half of 2012. The density that GOCE encountered during that period was between the 5^{th} and the 50^{th} percentile. Therefore it was decided to base the study of the FD predictions accuracy for altitudes below 230 km on a medium to low solar activity scenario.

Table 1. Solar and geomagnetic indexes reference values and expected short term error

	F10.7	F10.7 error	Ap	Ap error
Medium	140	20	15	8
Low	95	10	7	5

The analysis was performed by propagating pairs of trajectories, one of them representing the actual spacecraft trajectory and the other one representing the predicted trajectory generated by FD. The drag force is computed using constant values of the F10.7 and the Ap indexes for both trajectories. For one of them these constant indexes are values representative of a medium (or low) solar activity regime. For the other trajectory the indexes are modified with the expected short term error that will affect the FD prediction of these indexes. In a more concrete example and for a medium solar activity case, the real GOCE trajectory is propagated assuming 140 and 15 for the F10.7 and Ap indexes respectively whereas the predicted FD trajectory is propagated using 120 and 7 for the F10.7 and Ap indexes respectively.
The reference values for the F10.7 and Ap and the short term error (extracted from the previous solar cycle, as the difference of the daily observations of the indexes to the 81 days average) used in the analysis are shown in Table 1.

The pairs of propagated trajectories start at the same orbital position. As time evolves the two trajectories start drifting apart. The separation between the two propagations is measured in terms of TOV (see definition in Figure 6). The resulting TOVs for a range of altitudes from 230 to 120 km are listed in Table 2. For mean altitudes down to 210 km the TOV is not expected to grow above 3 seconds (limit for the station to acquire without going on a search). This meant that for the first de-orbiting week and independently of the level of solar activity the transition from drag-free mode conditions to free drift could be handled without any changes with respect to the low orbit operational approach. However, once going below this altitude FD had clearly to increase the frequency of orbit determinations performed per day. It was decided to go from one orbit determination every 24 hours to one orbit determination every 12 hours, in order to ensure that the TOV would stay below 3 seconds in case of bad solar activity predictions.

Table 2. Evolution of the maximum expected TOVs after the first pass of the day (05:00 UTC app.) Low and medium solar activity scenarios and decreasing altitudes

	Low/Medium solar activity results			
Altitude (km) / TOV(s) after	**0 hrs**	**12 hrs**	**24 hrs**	**36 hrs**
230	0.1/0.1	0.6/0.7	1.4/1.8	2.8/3.5
220	0.1/0.1	0.7/0.8	1.8/2.2	3.4/4.2
210	0.1/0.1	0.9/1.0	2.2/2.7	4.3/5.2
200	0.2/0.2	1.1/1.2	3.0/3.5	5.5/6.5
190	0.2/0.2	1.5/1.6	4.0/4.6	7.3/8.5
180	0.3/0.3	1.9/2.1	5.6/6.3	10.5/12.0

Regarding Mission Planning activities, the extrapolation of the TOVs in Table 2 covering more than one week is shown in Figure 19. This indicated that the mission planning and the station bookings activities had to be performed at a higher frequency than the one applied so far, which was once a week. The corresponding parts of the FOS were modified to cover the planning and booking activities under these high orbit prediction uncertainties. The pre and post station pass times were augmented, daily monitoring by the FCT of the deviation of the stations visibility times with respect to the station booked times was foreseen. FD products for Mission Planning were modified to cover two weeks instead of one.

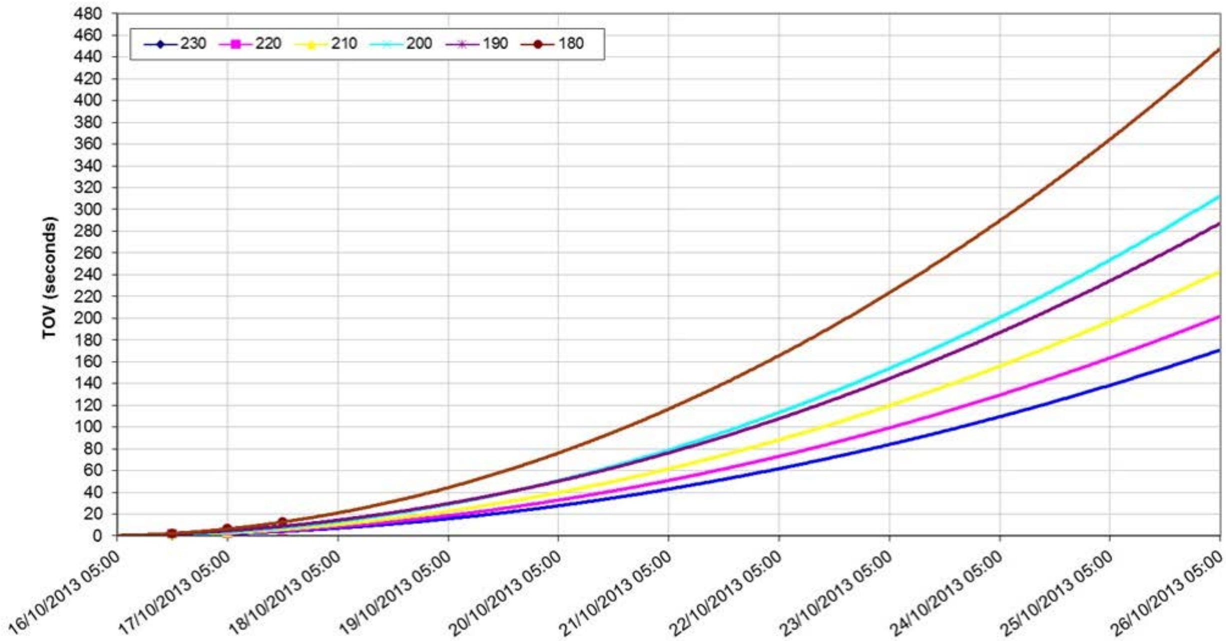

Figure 19. Maximum expected TOV evolution (10 days) at Kiruna during de-orbiting

The FD OD&C setup for the generation of Two Line Elements (TLE) to support the acquisition at Svalbard and Troll was modified to reduce the time interval for the TLE model fit, in order to ensure good pointing accuracy.

3.1.4. Tracking campaign and orbit determination schedule

Even though the GOCE manufacturer did not foresee any issue related to the GNSS receivers working at low altitudes, the FD System had to be prepared to base their orbit solution on S-band data in case of not having any GPS data available in telemetry.

A tracking campaign was conducted prior to the start of the orbit lowering operations and it was complemented with a second campaign before the start of the de-orbiting. The intention of this campaign was to ensure the correct configuration of all ground stations and tracking units (Cortex and IFMS) providing support to GOCE in an end to end test involving FD.

The schedule of the two orbit determinations was chosen in a way that it was valid independently of the type of tracking data used as input. As mentioned in the introductory section, a quick analysis performed by the FD OD&C team concluded that in case of running orbit determinations based on S-band data a minimum of 4 passes (ideally two in the first half of the day and 2 in the second) were sufficient to determine GOCE's orbit with sufficient accuracy. This analysis assumed:

- Range and 2-way Doppler data are available (establishment of low bit rate telemetry mode required to make ranging possible).
- No systematic errors in the tracking data.
- Initial guess for the state vector with a maximum error of 300 m in semi-major axis and 4 degrees in argument of latitude.

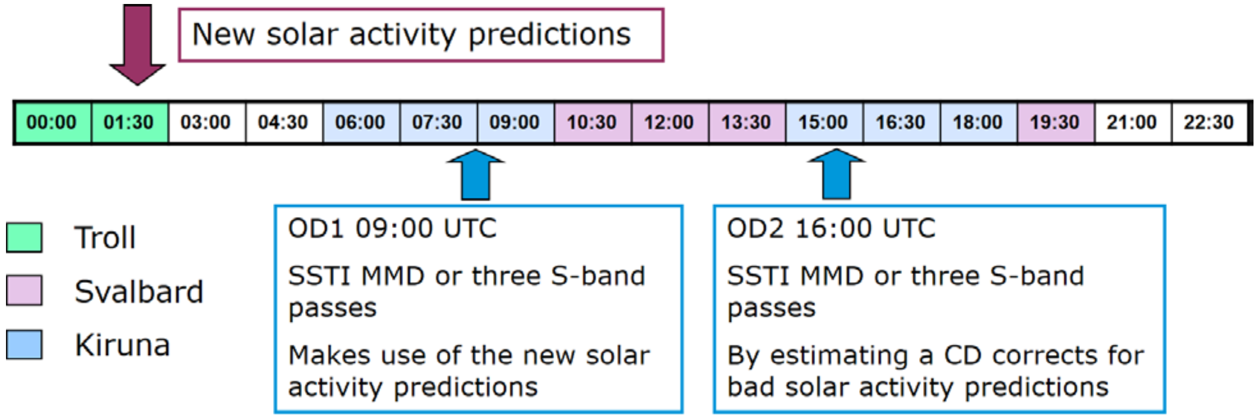

Figure 20. Orbit determination schedule for the GOCE de-orbiting phase. SSTI (Satellite to Satellite Tracking Instrument) refers to GPS data

Taking into account the distribution of passes and the time of the day when the solar and geomagnetic predictions were updated (see Figure 20) the two orbit determinations were placed at 09:00 UTC and 16:00 UTC. Ideally they should have been 12 hours apart, but the selected approach was a good compromise between keeping the required accuracy for the GOCE orbit predictions and having most part of the FD activities reasonably within normal working hours.

3.2. FD support to the de-orbiting operations

Operations at 230 km mean altitude continued practically undisturbed, with the IPA providing a stable thrust beyond the specifications of the pressure regulator (5 bars in the High Pressure Section), which were reached on the first half of October 2013. The FD AMS team monitored closely the evolution of the High and Low Pressure Sections of the IPA. On the 2013/10/18 the tank's pressure reached 2.5 bars.

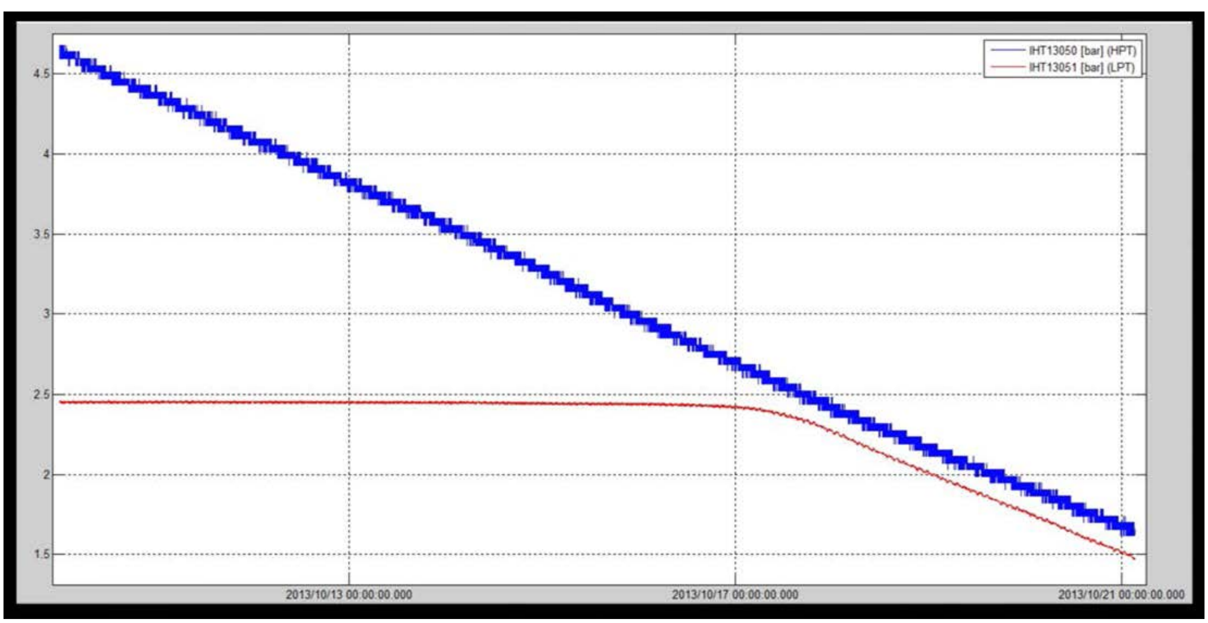

Figure 21. Readings of the High an Low Pressure Sections of the IPA

As expected, from that moment the readings in telemetry showed equal pressure in the High and Low Pressure Sections of the IPA (Figure 21). On the 2013/10/20 a “noisy” thrust was observed in the IPA thrust values in telemetry but the estimation of residual accelerations as part of the orbit determination did not show any conclusive results about the thrust being underperforming. On the 2013/10/21-03:16 UTC GOCE left drag free mode marking the start of the de-orbiting phase.

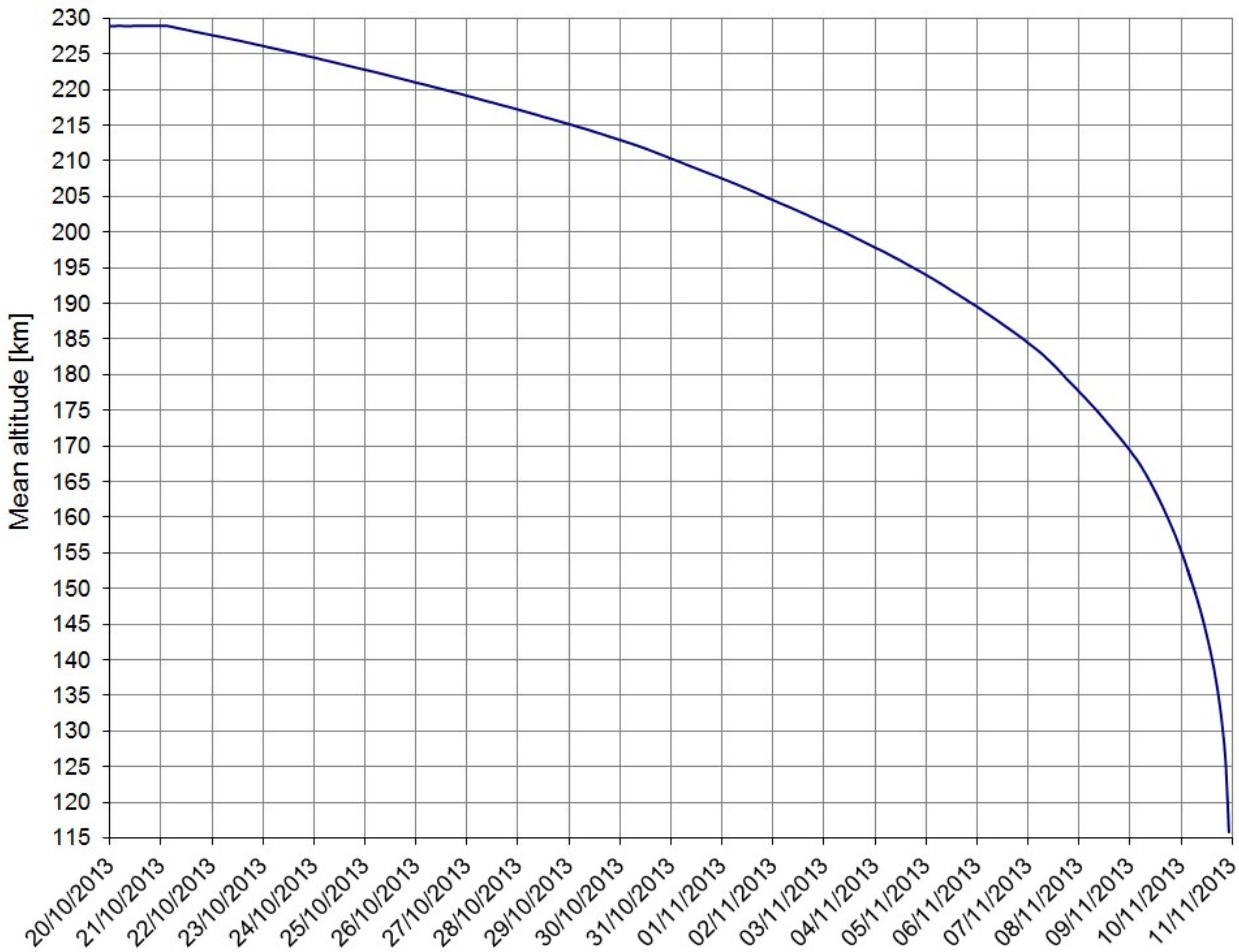

Figure 22. Mean altitude evolution during GOCE de-orbiting phase

Exceeding all expectations on both space and ground segments, GOCE was operated up to 1.5 hours before its final destructive re-entry on the early hours of the 2013/11/11 with the DFACS remaining in FPM until the end. The evolution of the mean altitude during the decay is shown in Figure 22. Compared to the reference decay trajectories showed in Figure 16, the de-orbiting duration was close to the maximum foreseen duration: three weeks.

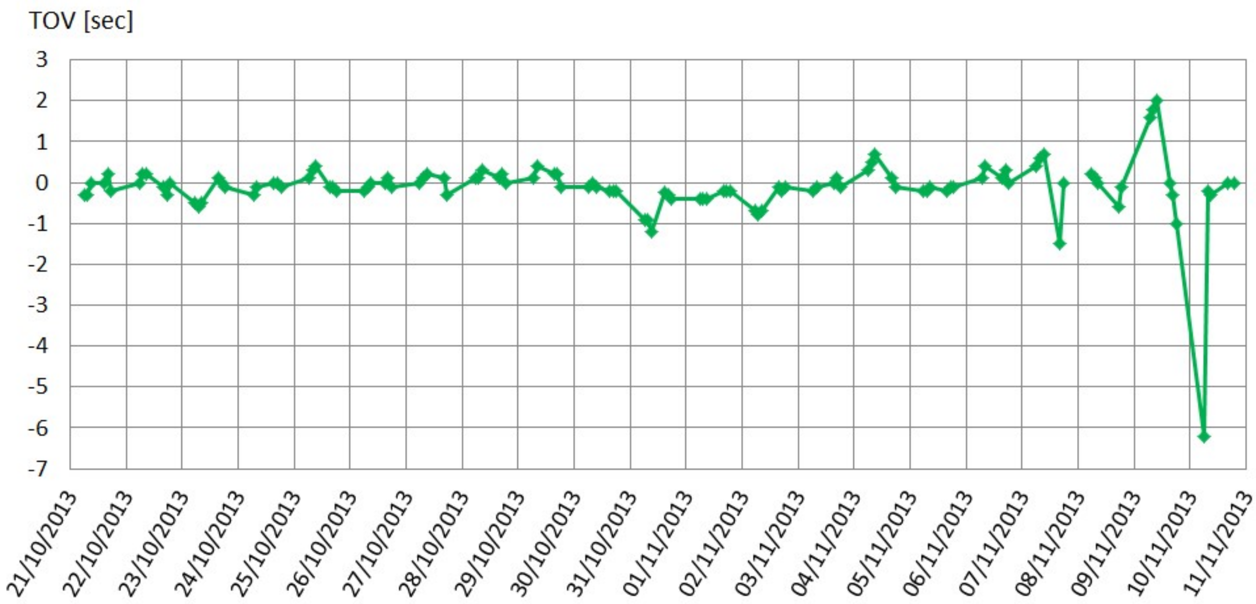

Figure 23. Kiruna reported TOVs during the de-orbiting

The FD predictions proved to be exceptionally accurate during the three weeks of decay operations thanks to the adopted approach of performing two orbit determinations per day. The stations acquired the signal in every pass without having to perform searches. The evolution of the TOVs reported by Kiruna during the de-orbiting is shown in Figure 23. In the morning of the last day of GOCE operations on the 2013/11/10, Kiruna reported its largest TOV during the decay phase. GOCE AOS happened 6 seconds earlier than predicted. The monitoring of the orbit decay evolution during the night passes at Troll had already provided a warning and Kiruna took the pass without having to search for the spacecraft.

The TOV values reported by Kiruna were a valuable source of information about the daily actual decay in semi-major axis with respect to the predicted decay after the two daily orbit determinations. One of the sanity checks part of every orbit determination was to check that the new determined orbit was in good agreement with the latest TOVs reported by Kiruna.

The FD OD&C team changed the CD estimation time interval to 6 hours, in order to improve the modeling of air density changes, since daily values of the solar activity were input to the computation of the density. Figure 24 shows the 6 hour CD estimations responding to the changes in density due to variations in the geomagnetic activity. For periods when the predictions available at the time the orbit determination took place were bad, the estimation of a higher or lower CD provided atmospheric density values that allowed to have a good fit of the GPS data. The estimated extended state vector together with the predictions up to the re-entry point were generated twice a day and provided to the ESOC SDO, which made them available to the IADC campaign.

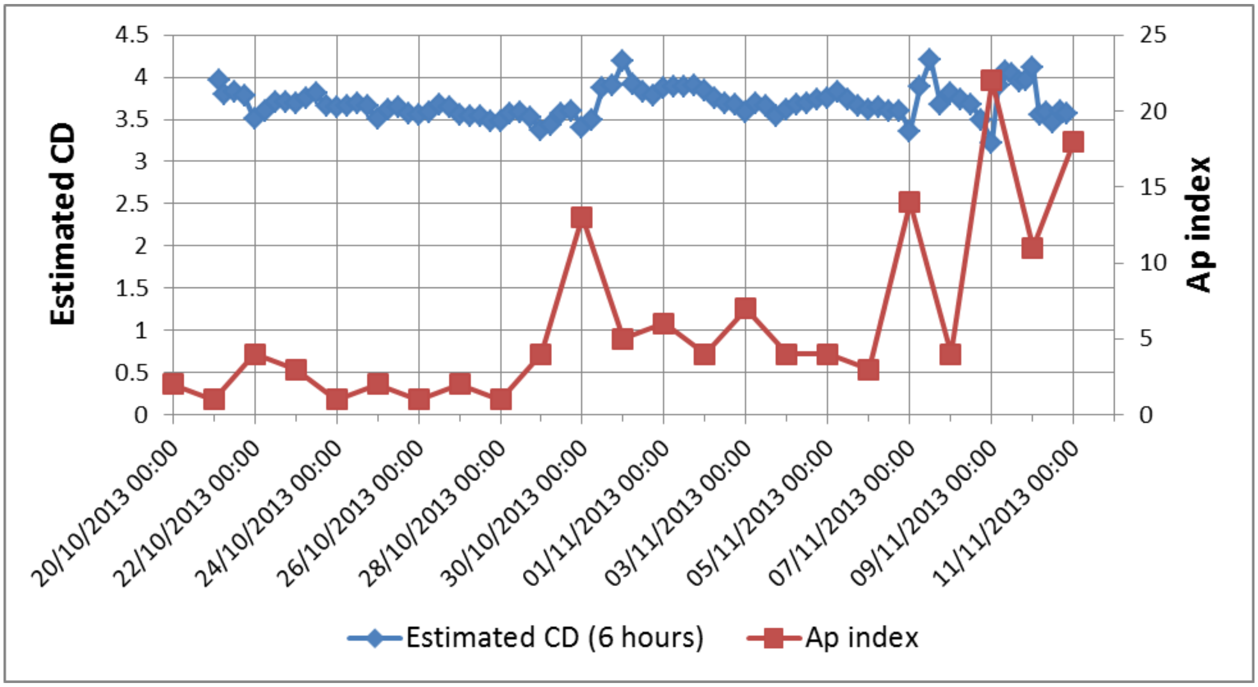

Figure 24. History of estimated 6-hours CD values during the GOCE final decay vs changes in the daily geomagnetic index Ap

With every orbit determination the FD OD&C team provided a set of monitoring products covering the remainder of the decay phase. The mean altitude, averaged density and drag force were some of the monitored parameters (Figure 25).

On the morning of the 2013/11/10, Sunday and last day of GOCE operations, the FD OD&C on-call engineer was called in due to an observed large TOV of 6 seconds early during the first Kiruna contact of the day. From that moment the OD&C team stayed at ESOC providing onsite support. Orbit determinations took place after every pass, using the real time GPS data retrieved from the S-band telemetry. The orbit determination and generation of products setups were adapted to this special support which aimed at providing new predictions to the stations from one pass to the next. Support continued in this fashion up to the last contact with the spacecraft from Troll (Antarctica) at 2013/11/11-22:43 UTC. The GPS residuals of the last orbit determination run after this pass are shown in Figure 26, using continuous GPS data extracted from the dump of the on board mass memory and the real time data obtained in the last six contacts with the spacecraft. The reconstructed drag force based on the MSISE00 air density model, observed solar activity and wind model HWM93 is shown in Figure 26.

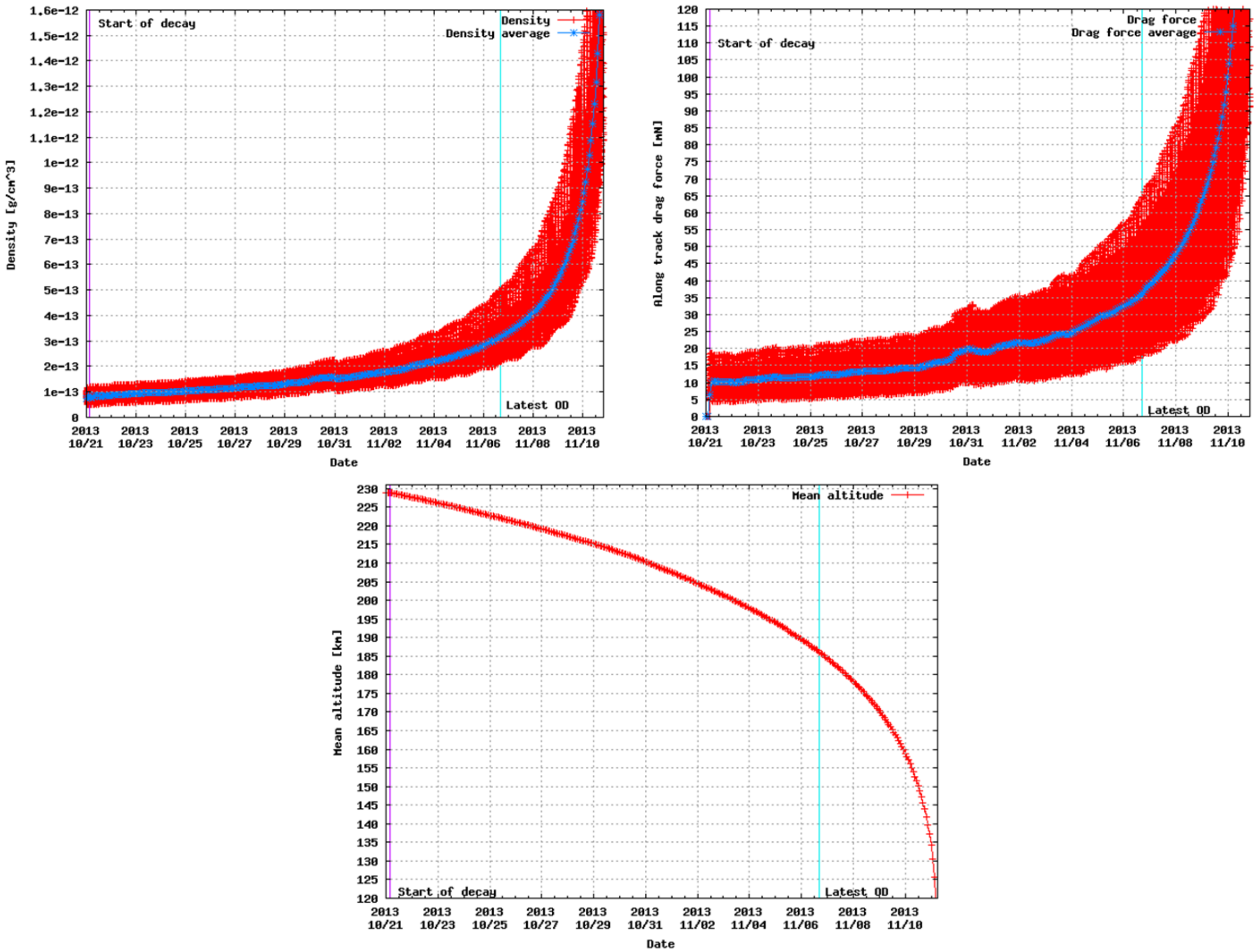

Figure 25. Evolution of the air density, drag force and mean altitude report provided during the decay phase. 2nd orbit determination on the 2013/11/06

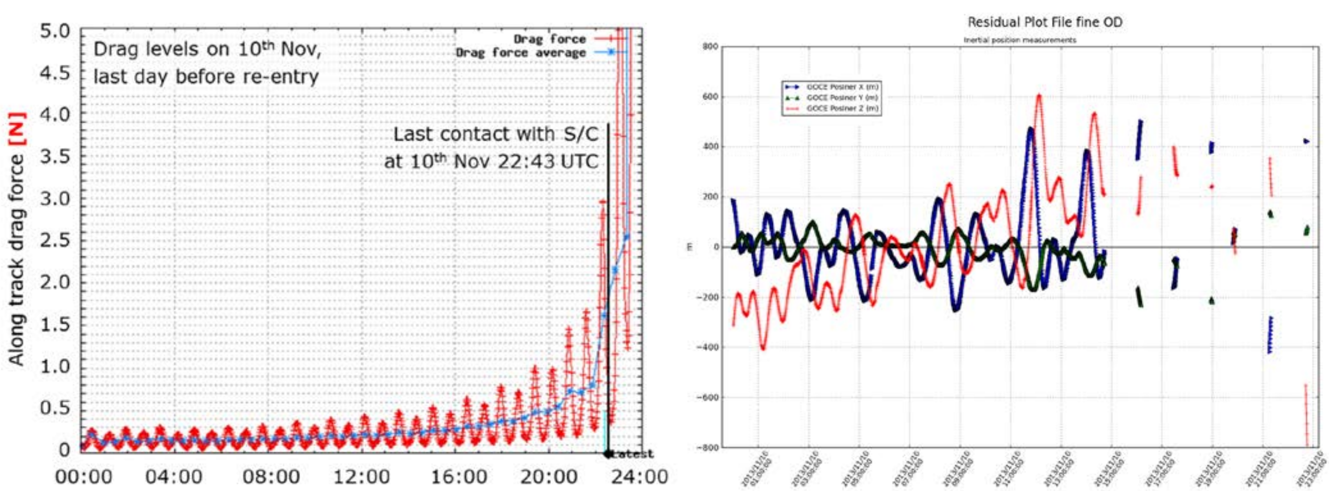

Figure 26. Drag force based on the reconstructed GOCE trajectory during the last day of operations (left) and last orbit determination GPS inertial positions residuals (right)

The propagation of the state vector after the last orbit determination, still assuming a 3.5 CD corresponding to FPM showed a final destructive re-entry (80 km altitude) over the Indian Ocean, west to the Australian coast at 2013/11/10-23:54 UTC. This was approximately the final predicted re-entry location obtained by the IADC campaign with an uncertainty of ± 0.5 hours.

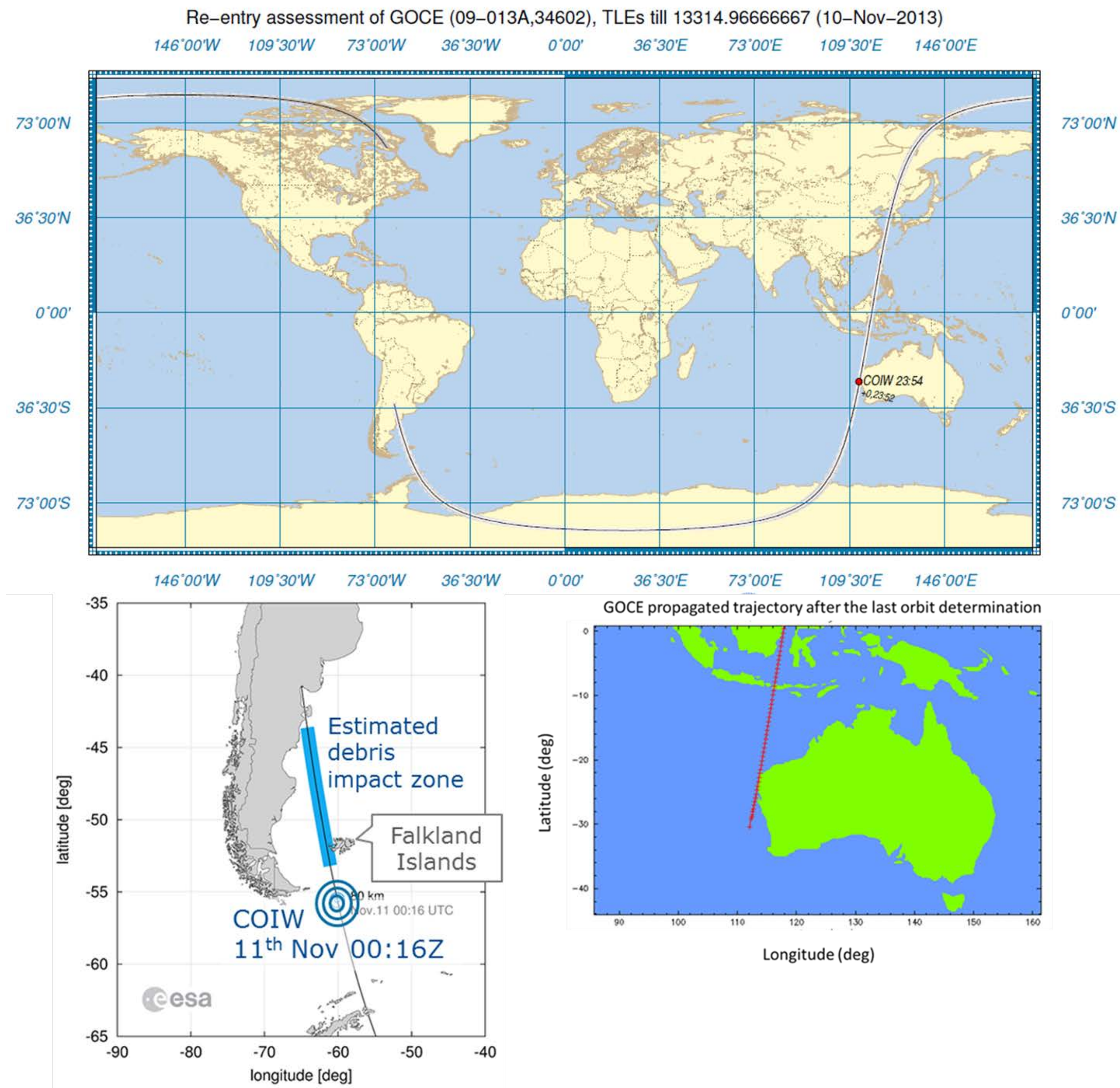

Figure 27. IADC predicted COIW (top). ESOC FD OD&C propagated trajectory after the last operational orbit determination (bottom right). Final COIW east to the Falklands (bottom left).

GOCE final Centre Of Impact Window (COIW) location was close the Falklands at 2013/11/11 00:16 UTC, within the ESOC FD and IADC predicted re-entry window (see Figure 27).

4. References

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