INTEGRAL End-Of-Life Disposal Manoeuvre Campaign

C. Dietze[(1)], A. Vasconcelos[(2)], G. Ziegler[(2)], A. McDonald[(3)], R. Southworth[(4)]
[(1)]CS GmbH at ESA/ESOC, Robert-Bosch-Str. 5, 64293 Darmstadt, Germany, phone: +49-6151-902257, email: claudia.dietze@esa.int
[(2)]SCISYS Deutschland GmbH at ESA/ESOC, Robert-Bosch-Str. 5, 64293 Darmstadt, Germany, phone: +49-6151-902314, email: andre.vasconcelos@esa.int, gerald.ziegler@esa.int
[(3)]CGI Deutschland Ltd. & Co. KG at ESA/ESOC, Robert-Bosch-Str. 5, 64293 Darmstadt, Germany, phone: +49-6151-902318, email: alastair.mcdonald@esa.int
[(4)]European Space Agency (ESA), ESOC, Robert-Bosch-Str. 5, 64293 Darmstadt, Germany, phone: +49-6151-903827, email: richard.southworth@esa.int

Abstract: *Gamma-ray observatory INTEGRAL is in an highly eccentric orbit and due to demand has been extended well beyond its nominal lifetime of 2.5+2.5 years. The initial 3 sidereal day orbit provided long periods of uninterrupted observation and continuous ground station support outside of Earth's radiation belts. Natural orbit evolution due to lunisolar perturbations causes variations in the perigee altitude leading to repeated crossings of the protected GEO and LEO regions in the next 200 years. An analysis of disposal options recommended the execution of an apogee-lowering manoeuvre in 2015 leading to re-entry in early 2029 via third body perturbations. In 2014 a target orbit acceptable for future operations was derived, fulfilling debris-avoidance requirements and maximizing station coverage outside the radiation belts. A manoeuvre campaign was designed considering all requirements regarding operations, spacecraft safety and maximal science observation time. The month-long campaign was executed beginning of 2015. This paper describes the preparatory analyses, manoeuvre execution and subsequent operations from Flight Dynamics point of view, and summarises the current status.*

Keywords: *End-of-Life Disposal, INTEGRAL, HEO*

1. Introduction

ESA's INTErnational Gamma-Ray Astrophysics Laboratory (INTEGRAL) is the most sensitive observatory in the hard X-ray to soft gamma-ray range and is operated from the European Space Operations Centre (ESOC), Darmstadt, Germany. Launched in October 2002 the mission was designed for a nominal lifetime of 2.5 years with a possible extension of another 2.5 years. Due to the accurate orbit insertion (large fuel reserve), flaw-less performance of the platform and instruments as well as continued high scientific interest the mission has regularly been extended, currently up to end of 2018 (subject to a review in 2016).

Figure 1: INTEGRAL artist's impression

The spacecraft was launched from Baikonur, Kazakhstan, into a highly eccentric orbit of 9,050 perigee and 153,660 km apogee altitude with an inclination of 52.25 degrees. This 3 sidereal day orbit ensured a repeating ground station pattern and the chosen phasing with respect to the Earth guaranteed continuous coverage originally from the Redu and since December 2013 from the Kiruna ground station for spacecraft heights above the Earth radiation belts. This is required due to the lack of data storage on-board: the scientific data - recorded continuously outside of the radiation belts - need to be sent instantaneously to ground or they are lost. Furthermore, the repeating event pattern eases mission planning, i.e. scheduling of scientific observations and platform operations, which is done on a revolution basis for INTEGRAL.

The natural orbit evolution mainly influenced by lunar and solar perturbations causes a variation of the perigee altitude of the spacecraft leading to repeated crossings of the protected GEO and LEO regions in the next 200 years as depicted in Fig. 2. Therefore in 2013/4, ESA's Space Debris Office (SDO) analysed options for a disposal of INTEGRAL with the available fuel, ideally maximizing the remaining science operations lifetime. Several possibilities were investigated either to force an atmospheric re-entry (directly or delayed) or to achieve a long-term raise above LEO. The outcome of this analysis was to perform an apogee-lowering manoeuvre in 2015 that would lead to an atmospheric re-entry in early 2029 due to the effects of third body perturbations [1]. It is the first time that a targeted disposal for a mission in such a highly elliptical orbit has been carried out, more than a decade in operations and to achieve a safe re-entry 15 years in the future while still continuing the mission after the de-orbiting manoeuvre.

In the course of 2014 the Flight Dynamics (FD) team at ESOC performed an analysis to determine a target orbit that would be acceptable for future operations and would fulfil SDO's requirements. FD then designed a manoeuvre campaign to achieve this target orbit considering operations, science observation time and spacecraft safety. This paper describes the detailed preparatory analyses, gives insight into the successful manoeuvre execution and subsequent operations from FD point of view and depicts the current status as well.

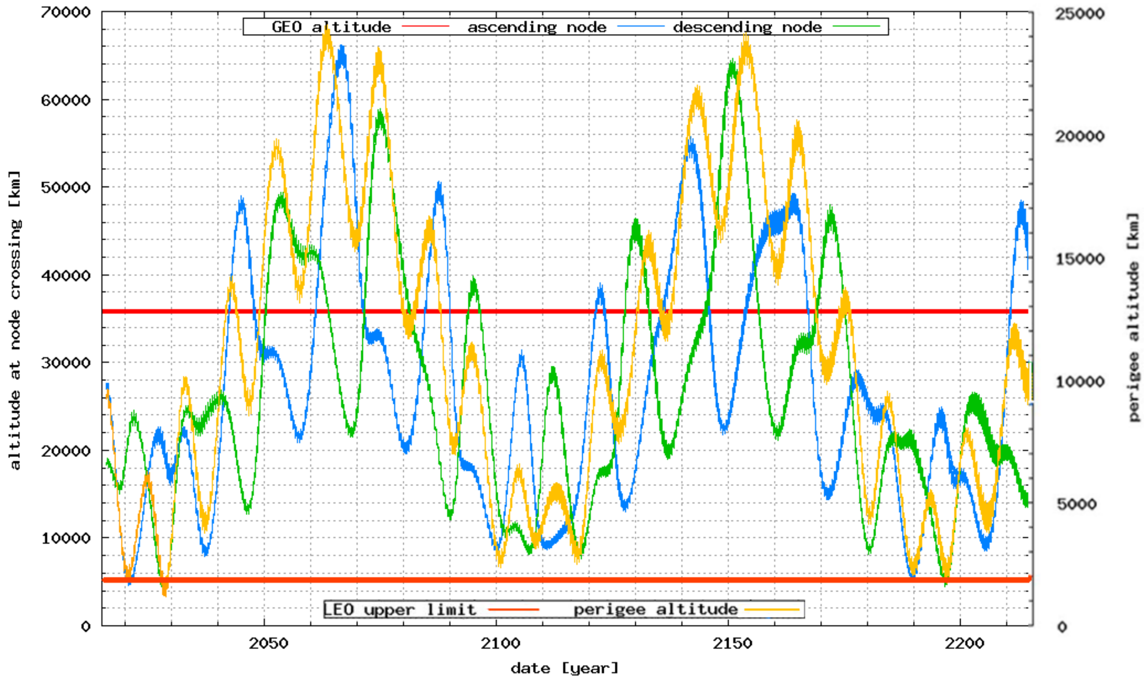

Figure 2: Spacecraft height at node crossings and at perigee in the next 200 years [1]

2. Definition of Target Orbit

The orbit change required to achieve re-entry in 2029 depends on the manoeuvre date, consequently the earlier the apogee can be lowered, the less fuel would be required. Considering operational and spacecraft constraints the first opportunity was beginning of 2015. The corresponding impulsive delta-v added up to at least 25 m/s when executed at perigee [1]. This manoeuvre, henceforth called disposal manoeuvre, would lower the apogee radius by approximately 12,500 km, from 160,500 km to approximately 148,000 km.

Other than a maximum apogee radius, no further requirement was put on the orbit after the disposal manoeuvre execution from the disposal point of view. Nevertheless a repeat orbit yielding a recurring station coverage pattern was thought desirable for mission planning purposes. In addition, with a repeat orbit an optimal phasing could be determined such that the station coverage above the radiation belts is maximized.

2.1. Choice of Repeat Orbit

Possible orbits with an apogee radius below the disposal apogee radius and with a period corresponding to a repeat orbit were analysed. The results are summarized in ascending delta-v order in Tab. 1. The perigee radius is assumed to be ~15,100 km both before and after the manoeuvre planned for January 2015.

Table 1: Possible repeat orbits after disposal manoeuvre

Disposal delta-v impulsive at perigee	Repeat pattern (orbits / sidereal days)	Apogee radius (km)	Semi-major axis (km)
0 m/s (original)	1/3 (original)	160,310	87,705
25.0 m/s	-	147,870	81,485
26.8 m/s	3/8	147,064	81,082
32.8 m/s	5/13	144,350	79,725
35.5 m/s	7/18	14,3178	79,139

The solution of 3 revolutions in 8 days (“3/8 repeat orbit”) was selected. This is the repeat pattern with the least number of cases (shortest repeat cycle), thus being simpler for mission planning. In addition, the required delta-v to achieve that orbit is the closest to the minimum delta-v for disposal, increasing the lifetime of the spacecraft in terms of fuel when compared with the other solutions.

2.2. Choice of Target Longitude

Once a repeat orbit was selected, the phasing of the orbit was tuned to maximize station visibility. The phasing can be expressed as a function of sub-satellite longitude at perigee λ for the first revolution of the three. Longitude λ should be selected such that Kiruna's station visibility above the radiation belts (assumed to be at a height of 40,000 km) is maximized over the three revolutions.

Figure 3 displays Kiruna ground station visibility relative to perigee crossing time as a function of longitude λ. Given that the orbit is a 3/8 repeat orbit with a period of 2 2/3 sidereal days the longitude at perigee for each of the three revolutions is shifted by 120 degrees with respect to the previous revolution. Hence the case of λ is equivalent to the case of λ + 120 degrees and λ + 240 degrees, and the ground station visibility of the three revolutions can be considered simultaneously for a λ of [0,120] degrees.

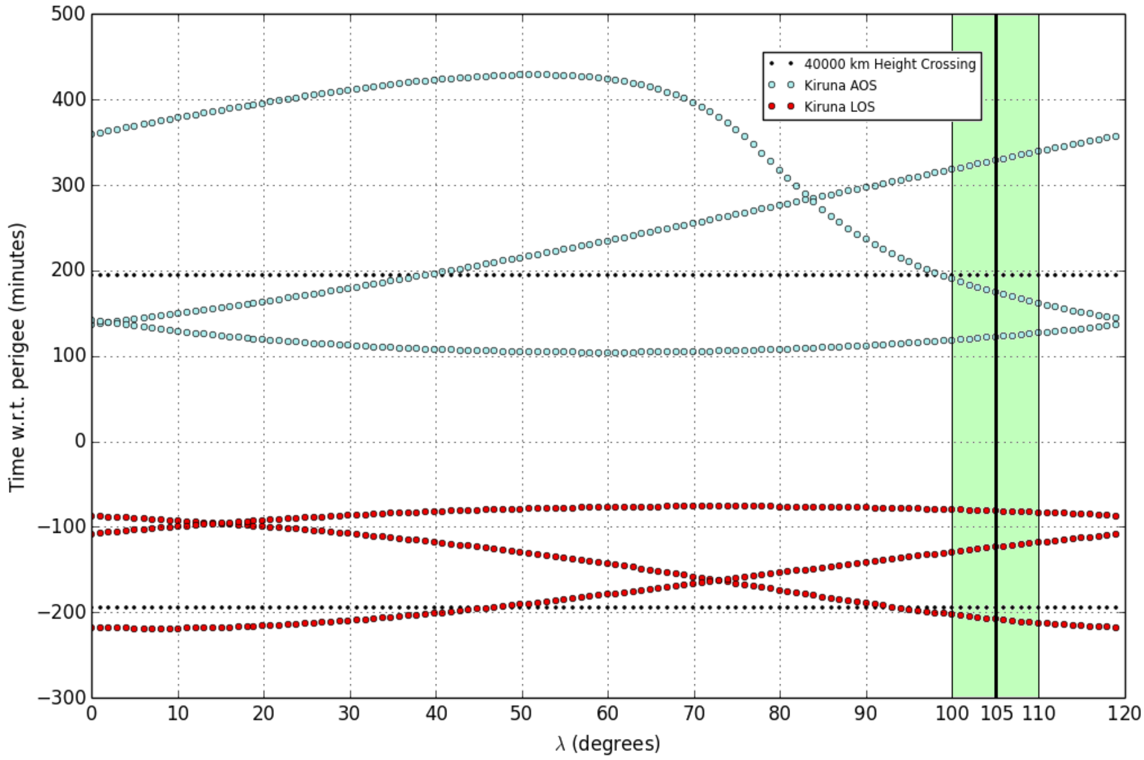

Figure 3: Kiruna ground station visibility in the three revolutions as a function of λ. The green region represents the target of λ = 105 degrees with a 5 degree band.

There is a late AOS and early LOS in the first orbit, corresponding to the lowest and highest curve of AOS and LOS (i.e. Acquisition and Loss Of Signal), whereat both get shifted closer to perigee towards the second orbit. The second orbit shows the shortest coverage gap over perigee, corresponding to the innermost curves, while the gap is increasing again in the third orbit. For example, for λ = 330 degrees (that corresponds to λ = 90 degrees in Fig. 3), Kiruna LOS occurs 200 minutes before perigee, at the time of the 40,000 km height crossing, resulting in no loss of useful visibility. The AOS of Kiruna for the same longitude occurs 300 minutes after perigee, resulting in the loss of 100 minutes of visibility after the 40,000 km height crossing.

For values of λ above 100 degrees, AOS and LOS occur both below the 40,000 km height for two out of the three revolutions. If λ is kept in that region overall visibility is maximised. Within that region for increasing λ visibility time is reduced in the remaining revolutions, thus having to be kept as low as possible. Therefore it was decided that the target λ for the 3/8 repeat orbit should be set to 105 degrees, providing a 5 degree longitude band to account for deviations in the acquisition of the target longitude.

It should be noted that the visibility analysis was made assuming that the osculating Keplerian elements would remain stable for some time. With the secular evolution of these orbital elements other λ values may become optimal. As a result the target λ value might be updated in the future.

The Space Debris Office analysed the 3/8 repeat orbit with the selected phasing and confirmed that re-entry is achieved in 2029.

3. Manoeuvre Assessment

Ideally, the target orbit could be achieved with an impulsive manoeuvre of 26.8 m/s (from Tab. 1) executed at perigee with an attitude opposite to the velocity of the spacecraft. There are however restrictions to the manoeuvre placement and attitude that would render a single manoeuvre quite inefficient. As a result the manoeuvre had to be split into multiple burns.

3.1. Manoeuvre Efficiency

The actual manoeuvre requires a bigger delta-v due to non-optimal attitude and timing:

- The attitude close to perigee cannot be optimal due to attitude constraints;
- The mid-point of the manoeuvre cannot be at perigee due to missing station visibility;
- A manoeuvre of 26.8 m/s takes about 45 minutes to execute (gravity loss).

Figure 4 details the efficiency of the manoeuvre depending on the angle of attitude off-pointing and timing. It does not consider the additional effect of executing a long manoeuvre.

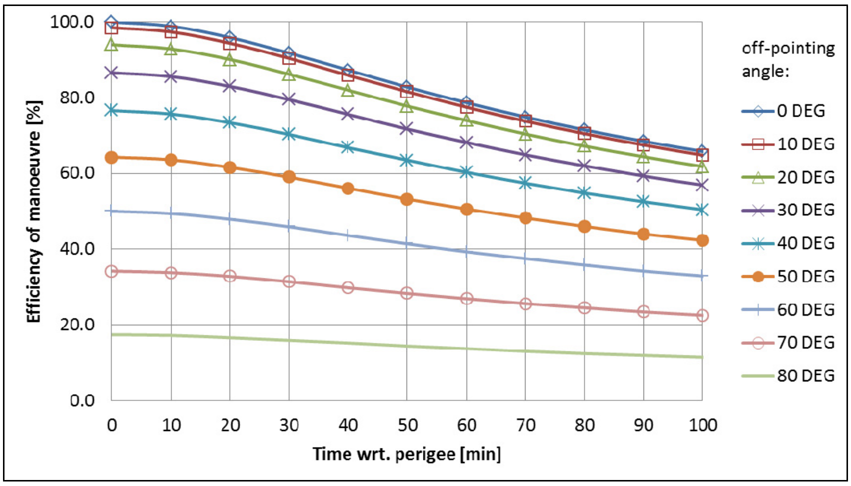

Figure 4: Efficiency of an impulsive manoeuvre with non-optimal attitudes and timing

3.1.1. Attitude Constraints

INTEGRAL's star trackers point in the delta-v direction and cannot be pointed at a bright body such as the Earth, Sun or Moon (would result in a blinding), which leads to a restriction of possible spacecraft attitudes. In addition, the solar aspect angle is restricted for power and thermal reasons. These pointing requirements lead to seasons when the disposal manoeuvre attitude is not reachable. To avoid operational complexity the spring and autumnal eclipse seasons had to be avoided as well. Also taking into account logistical limitations (e.g. periods with high work load or holidays) the remaining window for the disposal manoeuvre execution started in January and ended in March 2015.

The optimal manoeuvre attitude would lead to Earth blinding after perigee if the spacecraft did not slew away. To gain sufficient time for the post-manoeuvre activities, an off-pointing of about 10 degrees in the orbital plane (depending on the actual timing) is required to postpone the start of the Earth constraint. This leads to a loss of efficiency of at least 2%, with a rapid increase in loss of efficiency for a growing angle as depicted in Fig. 4. Figure 5 is an example case of how the start time of the Earth constraint can be delayed by increasing the angle to the optimal manoeuvre attitude at perigee away from Earth.

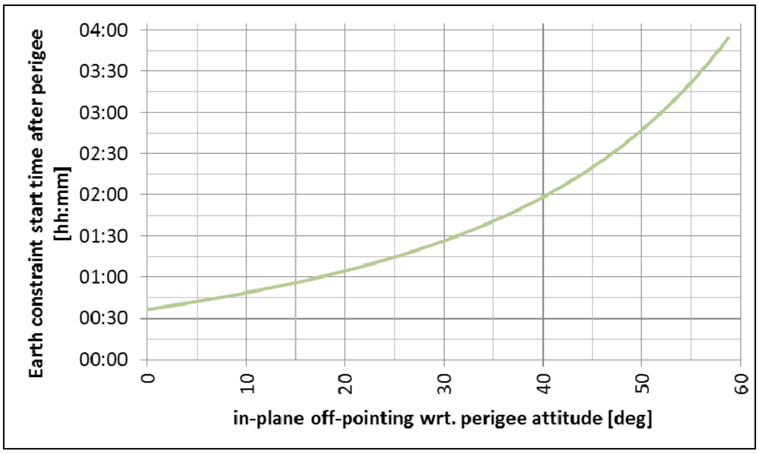

Figure 5: Earth constraint start time versus in-plane off-pointed attitude angle

3.1.2. Lack of Coverage

For safety reasons the manoeuvres had to be performed under station coverage, including preparatory and post-manoeuvre activities. After a manoeuvre the spacecraft needs to be reconfigured from thruster controlled manoeuvre mode to inertial pointing and slew mode such that it can leave the manoeuvre attitude, for which 30 min were scheduled. A complete avoidance of the Earth constraint requires a slew of about 40 degrees out of the orbital plane, which takes about 20 min. Therefore, the manoeuvre has to end either 50 min before LOS or before the Earth constraint start time, whatever is earlier. Unfortunately, within the available station network, station visibility (from the Kourou ground station) is possible only up to perigee. Therefore this implies that the manoeuvre mid-time (assuming a 45 min manoeuvre duration) is at ~75 min before perigee, which amounts to a loss of efficiency of around 25% (see Fig. 4).

3.1.3. Long Manoeuvre

A manoeuvre of at least 26.8 m/s takes more than 45 minutes to execute. It not only loses efficiency due to the manoeuvre not being executed at perigee (gravity loss), but also because the manoeuvre inertial attitude is fixed due to spacecraft limitations while the direction of the velocity changes during the manoeuvre. These two effects added together for a burn executed at perigee cause a loss of efficiency of about 2%.

3.1.4. Total Loss of Efficiency

Executing the disposal manoeuvre in one burn would require it to be executed outside perigee entailing a loss of efficiency of around 25% or a penalty of around 7 m/s for the planned manoeuvre, mainly due to the unfavourable placement of the manoeuvre. This corresponds to ca. 1.5 years of fuel usage for routine operations. Consequently, the disposal manoeuvre was split in order to minimize these losses of efficiency.

3.2. Disposal Manoeuvre Strategy

In order to mitigate the different losses of efficiency described in 3.1, a manoeuvre strategy was devised, in which the total delta-v was split in three main burns plus one touch-up burn.

3.2.1. Four Manoeuvre Strategy

The first burn that was required to be executed before perigee started a drift such that a favourable longitude at perigee was achieved four revolutions later, resulting in sufficient station coverage around perigee (from Perth) for the subsequent manoeuvres. A similar strategy was applied for the subsequent burns, while the final 3/8 repeat orbit was achieved with manoeuvre 4 (the touch-up manoeuvre) at the desired longitude at perigee of 105 degrees. Figure 6 illustrates the chosen burn strategy.

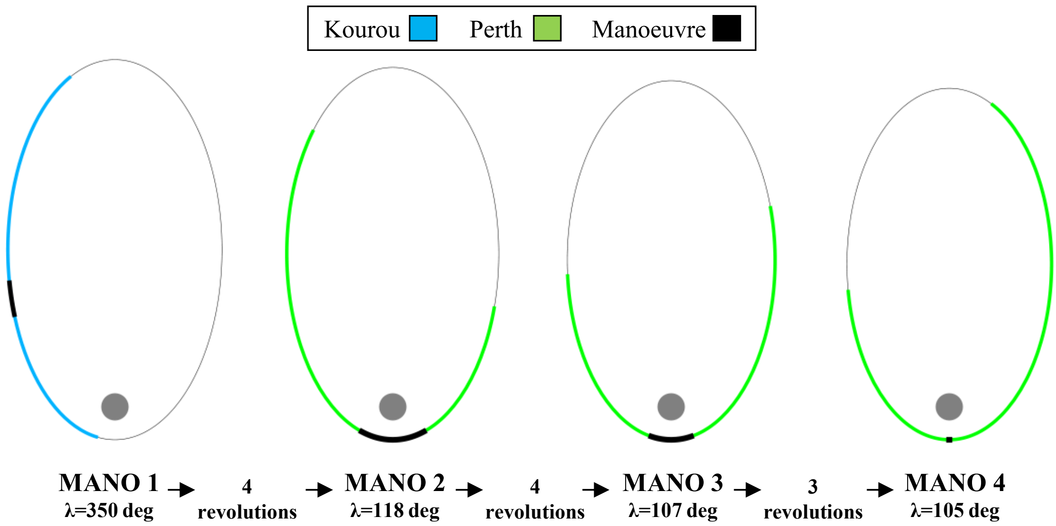

Figure 6: Station visibility, manoeuvre magnitude and longitude at perigee λ

In Tab. 2 the planned manoeuvres are detailed. The true anomaly is defined at manoeuvre mid-point and the attitude off-pointing is defined with respect to the velocity vector at manoeuvre mid-point. The biggest inefficiency lies in manoeuvre 1 due to its placement. With this strategy a total of 29.6 m/s was required to achieve the 3/8 repeat orbit, i.e. just 2.8 m/s (or 10%) above the ideal figure of 26.8 m/s. It corresponded to a saving of more than 4 m/s when compared to a single manoeuvre executed in the available slot.

Table 2: Planned disposal burns

	Mid-time (UTC)	Duration (min)	Delta-v non-impulsive (m/s)	In-plane off-pointing (deg)	True Anomaly (deg)	λ of initial orbit
Mano 1	2015/01/13-00:02	14	8.39	0	285.0	-10.0
Mano 2	2015/01/24-15:45	22	13.09	18	0.0	118.0
Mano 3	2015/02/04-15:44	14	8.02	16	0.0	107.0
Mano 4	2015/02/12-15:19	<1	0.09	12	0.0	105.0

3.2.2. Longitude Targets and Backup Strategies

Each manoeuvre was optimized to achieve a certain drift of the longitude at perigee (Δλ) in order to target a specific longitude at perigee for the next manoeuvre to be executed 4 or 3 revolutions later as outlined in Tab. 3.

Table 3: Manoeuvres and target longitudes at perigee

	Delta-v (m/s)	Accumulated Δλ / Rev (deg/rev)	Drifted revs / Target λ (deg)
Mano 1	8.39	32.0	4 / 118.0
Mano 2	13.09	87.3	4 / 107.0
Mano 3	8.02	119.3	3 / 105.0
Mano 4	0.09	120.0	3 / 105.0

The last manoeuvre had been executed more than a decade ago during the post-launch orbit acquisition, such that the effect of misperformances needed to be analysed. The actual performance of a manoeuvre had an impact on the arrival longitude at perigee and thus an impact on the station visibility at the perigee of the next burn. This can be seen in Fig. 7, which depicts the station visibility during manoeuvre 2 depending on the performance of manoeuvre 1, with the nominal case being represented by the vertical black line ("0%"). As outlined in 3.1.2, 50 min of station visibility were required after the burn end, which put a limit on the possible misperformance of the previous manoeuvre if the nominal plan was to be followed. For example, as seen in Fig. 7, manoeuvre 2 could still be executed at perigee for an overperformance of up to 5%.

Contingency plans were prepared for one-point failure cases in which manoeuvres were not performed or severely misperformed. As the intermediate orbits showed a drift of the longitude at perigee, a missed manoeuvre could be repeated after a certain drift time. Misperformances up to a certain amount could be compensated by performing the manoeuvre in another revolution and/or adjusting the manoeuvre magnitude. Other more complex or severe failures required a case-by-case analysis.

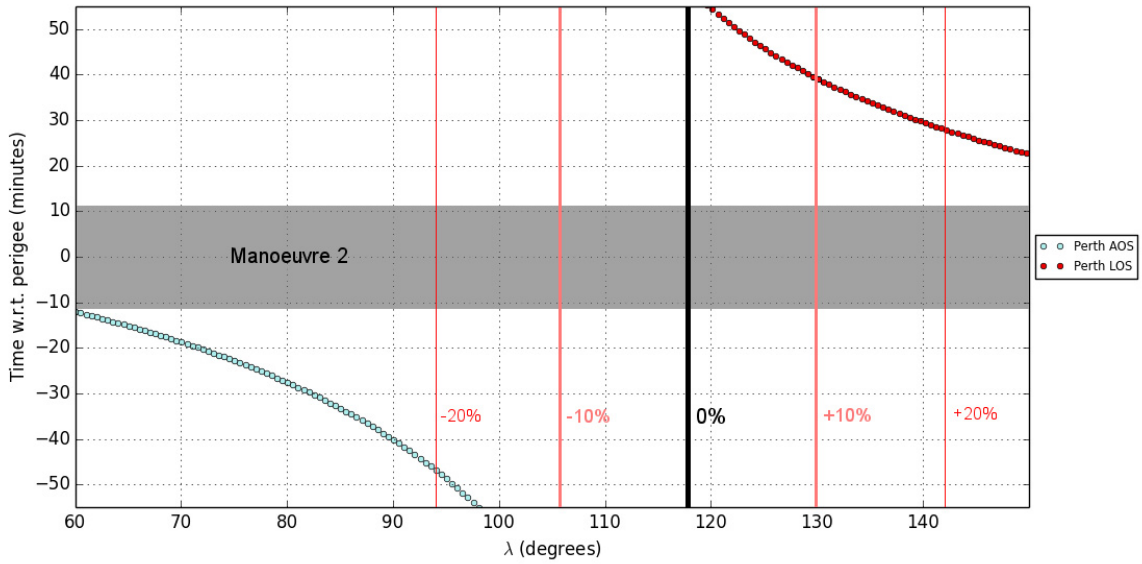

Figure 7: Perth station visibility for manoeuvre 2 depending on manoeuvre 1 performance

4. Manoeuvre Implementation

The implementation of the manoeuvre strategy required extensive mission and operational planning as well as prior testing as the last manoeuvres had been performed 12 years ago and also at apogee instead of perigee.

In addition, it had been decided to continue with the science observations during the manoeuvre campaign implying that the routine mission planning process needed to be performed but taking into account dedicating periods for manoeuvre execution and considering potential misperformances as described above in 3.2.2.

4.1. Mission Planning and Orbit Control for INTEGRAL

Mission planning is a cyclic process to define all activities during a planning interval, which is from one perigee passage to the next (a revolution) for INTEGRAL. The process starts with a planning skeleton file (PSF) generated by FD. It contains orbital and ground station coverage derived events, which are used to define operational actions for the platform or payload, or operational windows for activities such as a handover between stations. Periods without platform operations above the critical altitude, i.e. outside the radiation belts, are used by ISOC (INTEGRAL Science Operations Centre at ESAC) to schedule the scientific observations. FD processes this planned observation sequence (POS) to insert further platform command sequences (in particular AOCS related sequences) and their parameters according to the listed activities and events. The FCT (Flight Control Team) finally translates this enhanced POS (EPOS) into a timeline, which contains the individual commanding steps that will be executed by the real-time mission control system to operate the spacecraft and its instruments.

The slew requests from ISOC are used by FD to generate the speed profile of the reaction wheels, which are used for the rotation of the spacecraft. External torques (due to solar radiation pressure, gravity gradient effects) are taken into account, especially as they lead to an accumulation of angular momentum in the wheels. To reduce the angular momentum and thus ensure compliance with lower and upper speed limits reaction wheel biases (RWBs) are performed. As the thrusters are fired to keep the spacecraft attitude stable during these RWBs, a residual delta-v will be applied to the orbit. By choosing the attitude, in which these wheel off-loadings are executed, or the relative timing with respect to perigee for a given attitude, these delta-v's can be used for orbit control, i.e. to increase or decrease the semi-major axis to keep the desired relative phasing with respect to the Earth's surface.

4.2. Mission Planning for the Manoeuvre Campaign

The mission planning process and corresponding products had to be adapted to cope with the special requirements of the manoeuvre planning.

4.2.1. Mission Planning Process

Due to the various modifications required for the process, the planning of the manoeuvre campaign was started several weeks earlier than would be the case for routine products:

- PSF generation started beginning of December and finished for the entire manoeuvre period before the Christmas holidays 2014
- Corresponding POSs were expected back from ISOC in batches oriented on the manoeuvres, the first set had to be delivered before Christmas
- Test EPOSs were generated immediately to check the POSs
- Operational EPOSs were only generated shortly before the revolution start to ensure the accuracy of time-tagged commands and on-board broadcast packets
- No re-plans were allowed to avoid complication of the process or creation of additional workload

The orbit files used for mission planning had to be carefully chosen because the operational orbit didn't reflect the manoeuvre campaign until it did actually start. Therefore, a dedicated set of orbit files including the manoeuvres was distributed beforehand to be used by all parties in parallel to the files from the routine orbit determination.

Since different activities had to be scheduled, mission planning products were divided into three types: revolutions with a manoeuvre at the end of the revolution (i.e. before or at the perigee when the next one starts); revolutions directly after a burn; and revolutions without a manoeuvre.

4.2.2. Planning Approach for a Manoeuvre

An automatically planned timeline has to be constraint free as the planning systems check for constraints and reject products which violate them. Consequently, a planned timeline could not be used for the actual manoeuvre execution as the manoeuvre attitude becomes blinded as described in 3.1.1. As a result, the manoeuvre operations had to be performed manually and in real-time, overriding the automatic timeline. The latter could still be used in case of a manoeuvre cancellation.

This approach was implemented by creating a new planning window, which was scheduled to cover the entire manoeuvre activities and therefore blocked any other commanding. The preparatory activities comprised 1.5 hours for slewing to the manoeuvre attitude and ca. 3 hours for the manoeuvre preparation itself, which included spacecraft configuration and calibration of sensors needed during the manoeuvre. As outlined in 3.1.2, 50 min of coverage were required after the manoeuvre end. During this entire time frame coverage by two ground stations was scheduled for robustness. From the geometrical coverage two Australian stations were best suited to support the manoeuvres, Perth as prime and New Norcia was used as backup. After AOS in the next revolution, another 2 hours were blocked via the special manoeuvre window to monitor the spacecraft and re-join the automatic timeline.

The planned timeline and actual manoeuvre operations are outlined in Fig. 8.

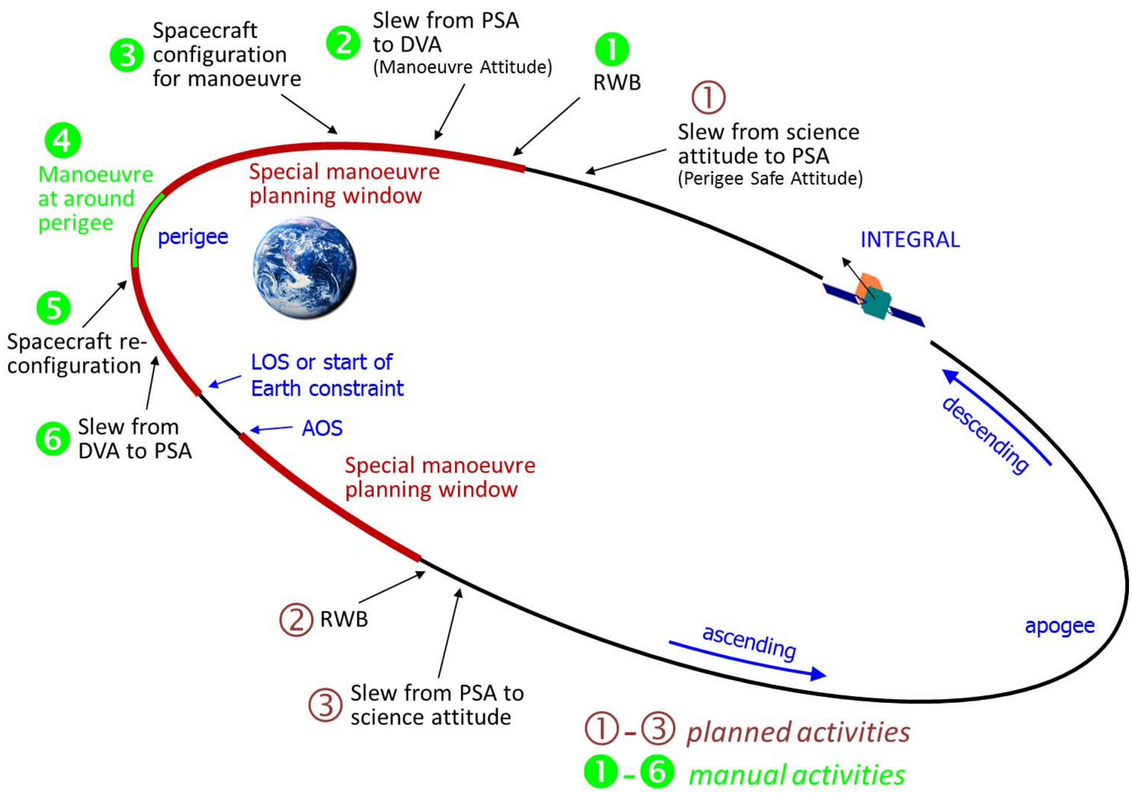

Figure 8: Operational planning (red numbers) and manual execution of activities (green numbers) for a manoeuvre

The nominal timeline contained the slew to the perigee safe attitude (PSA) at the end of the revolution including the manoeuvre, and at the beginning of the following revolution a RWB to set the planned reaction wheel speeds plus the slew from the PSA to a science pointing. The PSA was defined by FD as the optimal manoeuvre attitude rotated out-of-plane to avoid the Earth constraint completely (see 3.1.2). The actual manoeuvre attitude (DVA) is the optimal attitude, which is opposite to velocity direction at manoeuvre mid-point, rotated away in the orbital plane to postpone the start of the Earth constraint as described in 3.1.1.

The nominal timeline was augmented via manual operations:

- a RWB to set the reaction wheel speeds as required for the manoeuvre operations plus the slew from the PSA to the manoeuvre attitude before the burn
- afterwards the slew from the DVA back to the PSA.

The wheel speeds were automatically corrected by the RWB at the beginning of the revolution after the manoeuvre. Due to the deviation from the planned attitude the active on-board antenna may change as well.

4.2.3. Necessary Modifications of Mission Planning Products

As coverage is essential for commanding and telemetry, a margin is applied to ground station related events during routine planning: e.g. LOS and AOS times around coverage gaps are buffered during routine operations by 25 and 35 min, respectively. Due to the increased pre-planning time for the manoeuvre campaign and possible misperformances of manoeuvres large discrepancies between planned and actual times of orbital events may occur. As the time between two burns is too short to replan, it was decided to generate the PSFs with an increased margin to cover for a reasonable range of misperformance (as described in 3.2.2, severe over- or underperformances, or manoeuvre cancellations would need to be assessed on a case by case basis). The buffer was expanded to 150 min for all revolutions between the first and the last burn. This covered a shift of ground station times of up to 30 min per revolution for the pre-planned batch of 5 revolutions up to and including the next manoeuvre. For the first revolutions after the fourth and much smaller burn this buffer was reduced to 60 min.

In addition, the perigee attitude, usually defined by ISOC, was provided by FD for all revolutions to enable the manoeuvre operations as outlined in 4.2.2 also in case of a delay. For the first set of revolutions after the last burn the perigee attitudes in the PSF were changed to two attitudes that were optimal for orbit control. After manoeuvre 3 it could be decided depending on its performance if it was necessary that ISOC uses these attitudes to support the final target orbit acquisition via routine RWBs. After these revolutions the routine mission planning rules applied again.

4.3. Preparatory Activities

The complex mission planning process described above in 4.2 had been necessary to ensure maximum science observations throughout the entire manoeuvre campaign. In total just over 68 hours of science time had to be sacrificed, which is less than one pre-manoeuvre orbit, whereby the majority was required for the post-manoeuvre calibrations. To ensure the successful execution of the planned manoeuvre operations several tests were executed.

4.3.1. Test Manoeuvre

A test manoeuvre was scheduled for September 9th, 2014 to exercise the complete preparatory process, the manual operations and post-burn activities, as well as to check the spacecraft and ground tools performance. The burn was planned with a delta-v of 1 cm/s, which corresponds to a burn duration of ca. 8 sec. The test manoeuvre was executed without anomalies and a manoeuvre magnitude of 1.2 cm/s was estimated afterwards. The gained experience was used to update the timing of the manoeuvre execution timeline.

4.3.2. Mission Planning Test and Improvements

The whole mission planning cycle was exercised beforehand using three test revolutions after the actual campaign to ensure that the mission planning systems can cope with the shorter post-disposal revolution length. Minor issues were encountered and fixed.

In addition, the planning modifications lead to the following issues that were encountered during actual mission planning:

- The increased margin on ground station AOS and LOS times resulting in a large commanding gap over perigee had to be considered for activities that need regular execution in a certain time interval;
- As ISOC was not allowed to schedule activities inside the special manoeuvre window, FD had to add a ground station handover window manually during POS import;
- Care had to be taken in the scheduling of commands released and/or executed relative to perigee time or related events due to the possible shift of times during the planning.

5. Execution of Manoeuvre Strategy

The manoeuvre campaign lasted one month from 12^{th} of January to 12^{th} of February 2015.

5.1. Manoeuvre Operations

A detailed timeline comprising all pre-, manoeuvre, and post-burn activities was derived from the automatic timeline events and the manual activities. This was critical to check the timing and coordinate the contributions of the different teams involved. Dedicated FCT and FD team members were either on-site or on-call to support the schedule.

Besides the activities already mentioned in 4.2.2 the following manual operations were executed:

- Generation of the command file for the manoeuvre a few days in advance
- Gyroscope sensor calibration and update of corresponding on-board parameters
- Execution of the manoeuvre commands by FCT, monitoring by FD and FCT
- Evaluation of the thruster firings by FD and FCT to assess the actual delta-v
- Orbit determination to update ground station predictions if necessary
- Attitude history file generation including the attitude deviations from planned timeline

5.2. Manoeuvre Performance

In this section the execution and performance of the manoeuvres are described, as well as the resulting changes in the planning of the remaining manoeuvres.

5.2.1. Manoeuvre 1

The first manoeuvre was optimized as discussed in section 3.2.

Manoeuvre 1 lowered the apogee by 9% less than expected. This was due to an under-performance of 7% in the thrusters coupled with a mistake in the manoeuvre execution time. The burn was commanded 5 minutes earlier, which is 2% less efficient than the manoeuvre at the originally planned time. This caused a drift of 10 minutes per revolution with respect to the planned orbital event times. In addition, an off-modulation effect caused the manoeuvre to last for 19% longer than expected. This did not have a noticeable effect in the efficiency of the manoeuvre, but was taken into account for the following manoeuvres in order to centre them around perigee. Figure 9 shows thruster monitoring plots for burn 1.

The execution of manoeuvre 1 was therefore declared nominal and the nominal plan followed.

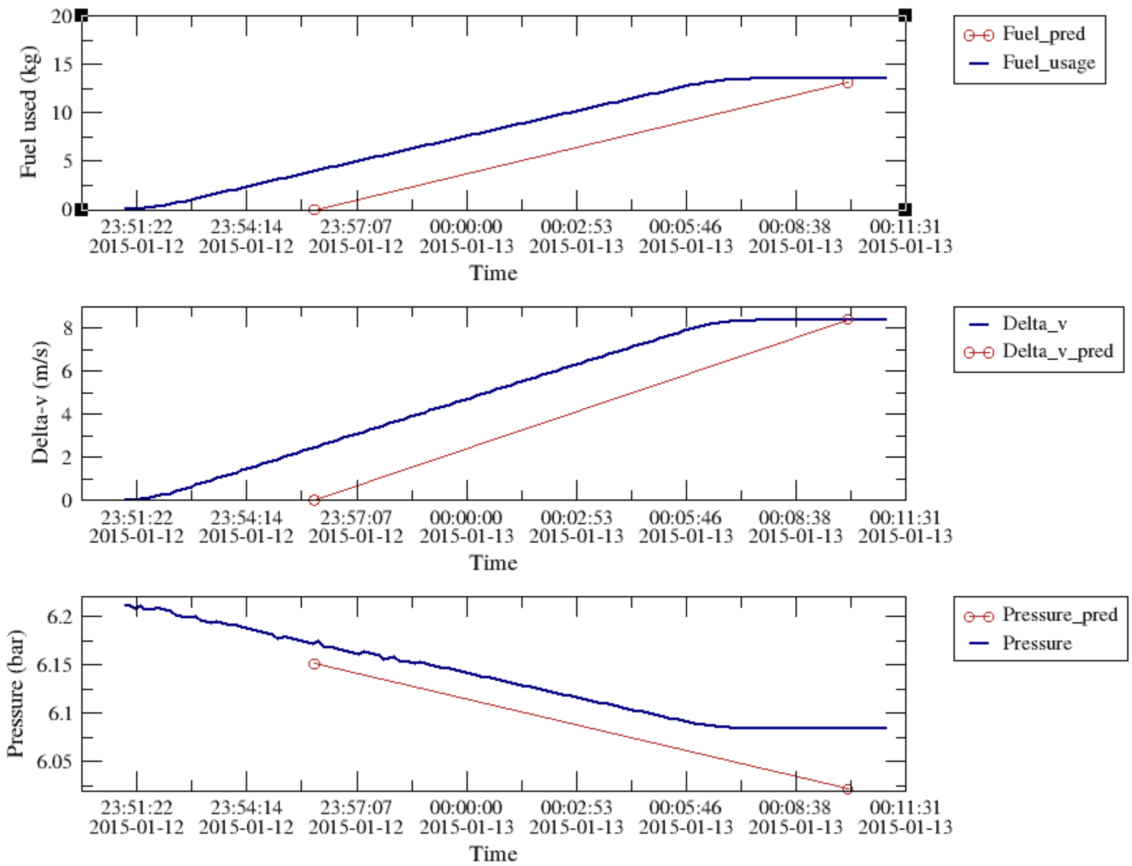

Figure 9: Thruster monitoring plot from manoeuvre 1; predicted values are in red, measured in blue

5.2.2. Manoeuvre 2

The underperformance of burn 1 required an adjustment of the other manoeuvres' magnitudes. As manoeuvre 1 had underperformed by 7%, it was decided that the strategy for manoeuvre 2 and beyond had to take into account also the possibility of an underperformance of burn 2 of up to 5%.

The longitude target for manoeuvre 3 was consequently increased to 112.2 degrees. In this way an underperformance of manoeuvre 2 of 5% would result in a longitude at perigee of 105 degrees at the time of execution of manoeuvre 3, at which point the drift would be stopped. If the longitude at perigee is less than 105 degrees at manoeuvre 3, this would require manoeuvre 3 to be stronger to reverse the drift and that manoeuvre 4 is executed in the direction of the velocity. This would not only lead to waste of fuel, but would be more difficult to prepare from the attitude point of view, because it was an initial assumption that all manoeuvres would be executed roughly with the same attitude.

When implementing manoeuvre 2, the expected thrust was adjusted by -7% due to the observed behaviour of the thrusters during burn 1, and the start time had to be adjusted as well to account for an off-modulation of around 15%, such that the burn was as centred as close as possible to perigee.

In spite of the increased duration due to lower thrust, increased delta-v, and off-modulation, there was still sufficient station coverage for manoeuvre 2 to be executed nominally.

Manoeuvre 2 had an almost nominal performance. The thrust was higher than expected by 0.3%, while the off-modulation was slightly higher than expected.

5.2.3. Manoeuvre 3

Manoeuvre 3 also had to be planned accounting for off-modulation. Manoeuvre 3 was planned in such a way that a nominal execution would not require the execution of manoeuvre 4, with the final drift being adjusted by the routine RWBs.

Manoeuvre 3 under-performed by 1.3% and the off-modulation was slightly higher than expected. Due to the under-performance a fourth touch-up manoeuvre was required to achieve the target longitude at perigee as is shown in Fig. 10.

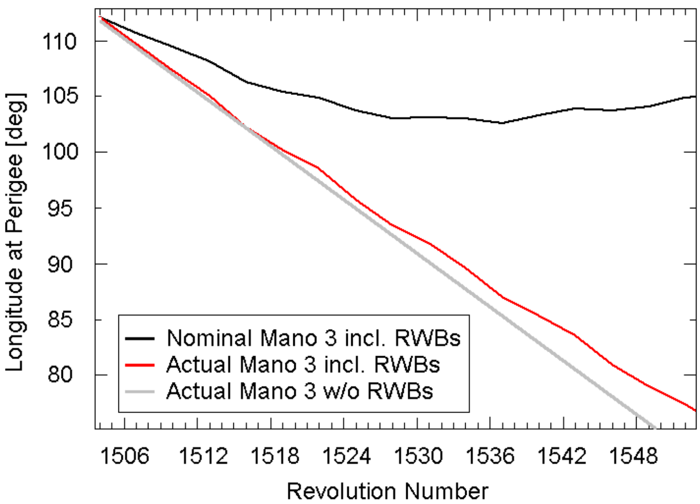

Figure 10: Evolution of longitude at perigee over revolutions after manoeuvre 3 execution

5.2.4. Manoeuvre 4

Burn 4 was designed to compensate for the underperformance of burn 3. The manoeuvre duration derived from the required delta-v was 16 sec. Considering the ramp function for thrusting and the off-modulation a total duration of 78 sec was estimated.

The magnitude of manoeuvre 4 is in the order of 10 RWBs and the overall performance (including nearby RWBs) provided a slight overperformance of 6%, which could be compensated by the routine orbit control. Therefore, ISOC was not required to use the recommended perigee attitudes that were optimized for orbit control, but could continue with routine science planning after the calibration revolution following this last manoeuvre.

5.3. Summary

Table 4 outlines the parameters of the planned and actual execution of the four disposal burns.

Table 4: Planned and actual execution of the disposal manoeuvres

	Mano 1	Mano 2	Mano 3	Mano 4
Start time (UTC)	2015-01-12 23:56:00	2015-01-24 16:17:00	2015-02-04 15:15:55	2015-02-12 15:02:06
End time w/o off-modulation (UTC)	2015-01-13 00:10:00	2015-01-24 16:44:11	2015-02-04 15:28:43	2015-02-12 15:02:22
Duration w/o off-modulation (s)	840	1631	768	16
End time w/ off-modulation (estimate, UTC)	Off-modulation not considered	2015-01-24 16:49:00	2015-02-04 15:31:29	2015-02-12 15:03:24
Duration w/ off-mod. (estimate, s)	Off-modulation not considered	1920	934	78
Actual duration (s)	1001	1869	944	75
Target longitude at perigee (deg)	118.0	106.1	112.2	105.0
Achieved longitude at perigee (deg)	106.0	112.2	109.2	(*)
Mid-time True Anomaly w/ off-modulation (deg)	285.0 (w/o off-modulation)	0.0	0.0	0.0
Mean thrust (N)	34.1	31.0	30.3	30.1
Planned delta-v (m/s)	8.393	14.913	6.896	0.146
Actual delta-v (m/s)	7.733	14.964	6.817	0.158
Measured propellant use (kg)	13.0	23.7	10.9	0.3
Right Ascension (J2000, deg)	9.835	51.095	47.588	44.302
Declination (J2000, deg)	40.926	-5.105	-1.123	2.844
Off-pointing (at mid-time, deg)	0	18	13	8
Post-burn apogee height (km)	150,824	143,877	140,883	140,679
Post-burn orbital period (hh:mm)	69:52	65:41	63:54	63:49

(*) The final target longitude at perigee of 105 degrees was achieved by a combination of manoeuvre 4 and the subsequent routine RWBs (similar to the case depicted in Fig. 10 by the black line, i.e. the evolution of λ for the planned manoeuvre 3).

6. Post-manoeuvre Operations and Current Status

The performance of each manoeuvre was assessed via thruster on-time evaluation and orbit determination, which was used to update the manoeuvre strategy as described in 5.2. After each burn a thruster torque re-scaling was performed and the mission planning process as outlined in 4.2 was continued. In total 47.9 kg of fuel were used, which changed the spacecraft mass distribution and so a spacecraft inertia and external torque calibration as well as a full thruster torque calibration were performed in the revolution after the fourth burn.

The disposal manoeuvres have shortened the orbital period by ca. 8 sidereal hours, which results in a loss of science time of ca. 3% per revolution [2]. As mentioned in 2.2, one out of three revolutions shows a shorter coverage period. To simplify mission planning the critical altitude at radiation belt entry was raised to ensure safe instrument closure also for the revolution with earlier LOS. The instrument activation after perigee is performed after crossing the critical altitude ascending or AOS, whatever is later, so that no modification is required. Accounting for the final revolution length the scheduling rules for activities that require periodic execution in the revolution were adjusted, as well as computations in the mission planning software, auxiliary tools or scheduling of automatic jobs that are based on the orbital period.

Performing routine RWBs the final target longitude was reached and since then controlled within the 5 degree band.

7. Outlook

The final achieved orbit was analysed by ESOC's Space Debris Office assuming that the 3/8 repeat pattern is kept and the longitude of perigee at every third orbit is at 105 +/-5 degrees. The long-term propagation shows that the re-entry of INTEGRAL will occur at the end of February 2029. A dedicated breakup analysis shows a minimal on-ground casualty risk due to the southern impact latitude range [1].

The underperformance of manoeuvre 1 caused an increase of the estimated propellant usage by ca. 3 kg. After the disposal campaign approximately 47.8 kg of fuel were left, which at the current average rate of consumption would support further operations up to October 2021. If other factors, like power or fiscal constraints, limit the spacecraft's lifetime, the remaining propellant could be used to 'trim' the orbit in order to better constrain the re-entry conditions and thereby further reduce the on-ground expected casualty risk [2].

8. References

[1] Merz, K. et al. "Orbit Aspects of End-Of-Life Disposal from Highly Eccentric Orbits." Proceedings 25th International Symposium on Space Flight Dynamics – 25th ISSFD. Munich, Germany, 2015.

[2] Salt, D., Southworth, R. "INTEGRAL Disposal Strategy & Scope for Future Science Operations." TN, issue 2, revision 0, 28/04/2015.