Mem. S.A.It. Vol. 90, 26

Memorie della

The past, present and future of INTEGRAL operations

T. Godard[1], D. Salt[2], L. Toma[2], and R. Southworth[3]

[1] Rhea GmbH for ESOC, Spacecraft operation engineer, Robert-Bosch-Str. 5, Darmstadt, 64293, Germany, e-mail: thomas.godard@esa.int
[2] Telespazio Vega GmbH for ESOC, Spacecraft operation engineer, Robert-Bosch-Str. 5, Darmstadt, 64293, Germany
[3] ESA-ESOC, INTEGRAL Spacecraft operation manager, Robert-Bosch-Str. 5, Darmstadt, 64293, Germany

Abstract. Designed for an operational life of only five years, INTEGRAL celebrated its 16th birthday on 17th October, 2018, with the potential to operate until its re-entry in February, 2029. Within this context, the paper first reviews past actions to ensure a safe disposal while enabling continued operations until then, which have been achieved via significant reductions in propellant consumption. It then discusses the current activities that are ensuring maximum use of available observation time to return science data, which are being achieved by automation of both routine and contingency recovery operations. Finally, it outlines preparations underway to ensure rapid reaction to a Target of Opportunity in support of multi-messenger astrophysics, which will require preemptive slewing to the required observation attitude.

Key words. INTEGRAL – Disposal – End of life – Fuel – Propellant – Astrophysics – Multi-messenger

1. Introduction

INTEGRAL (Winkler et al. 2003) was launched in its initial orbit in 2002. After that time, the orbit was allowed to evolve naturally and, to a large extent, this was very favourable for the mission operations. However, the INTEGRAL orbit is subject to considerable variation with its long-term evolution, being mainly driven by natural factors (i.e. Earth oblateness and luni-solar gravitational perturbations).

The perigee altitude and orbital inclination varies enormously, occasionally leading to perigee altitudes below 2000 km and to repeated crossings of the protected GEO and LEO regions. Analysis by the Space Debris group in ESOC showed this behaviour would continue for at least the next 200 years, resulting in both extremely low perigee altitudes as well as visibility changes affecting the ground station coverage (Armellin et al. 2015). Therefore, even though INTEGRAL is not covered by the space debris guidelines that came into force in 2008, investigations of disposal options for INTEGRAL were performed starting in 2013 with the goal of maximizing potential science operations lifetime while limiting the future risk to other spacecraft. These were based upon projections of the remaining propellant, the expected evolution of the orbit over time, along with the robustness and

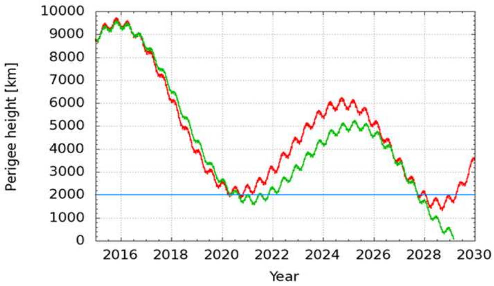

Fig. 1. INTEGRAL long-term evolution of the perigee altitude with (green) and without (red) the disposal manoeuvre performed in January 2015.

safety of each disposal option. Particular emphasis was paid to the risks on-ground from reentry debris and, to this end, a detailed breakup analysis was performed.

The option finally selected was to perform an apogee lowering manoeuvre at perigee in 2015 (Dietze et al. 2015) to amplify the natural orbital third body perturbation effects that lead to atmospheric re-entry in 2029, as shown in Fig.1. This disposal option would guarantee a safe re-entry while using less than half of the remaining propellant, ensuring continued science operations for a reasonable number of years thereafter. Both the date and latitude of re-entry are very predictable even more than ten years before the event, while the location of any surviving fragments after break-up will be in areas of very low population density and minimum land coverage over the Southern hemisphere between latitudes -45 and -70deg (Fig 3) with a casualty risk estimate several orders of magnitude below the ESA limit of 10^{-4} mentioned in ESA/ADMIN/IPOL (2014). The resulting orbit now has a period of 64 hours as compared to the 72 hours period prior to the delta-V.

2. Propellant consumption reductions

Fig. 4 shows propellant mass evolution from launch to the start of 2015, based upon book-keeping estimates from Flight Dynamics, which highlight the large reduction of propellant due to the series of delta-Vs that changed the orbit to ensure re-entry in 2029. However, it also suggested that the current consumption trend of 7.5 kg/year would limit the operational lifetime to around 2021.

The reason for this general trend in propellant consumption is because INTEGRAL performs at least one reaction wheel bias (RWB) at the beginning of each revolution using thrusters to reset the wheel speeds which ensure upcoming slews can be perform without violating wheel speed constraints. These RWBs compensate primarily for the cumulative effects of external torques due to solar photons pushing the spacecraft about its centre of mass, which must be absorbed by the reaction wheels in order to hold a fixed pointing attitude and so enable the instruments to perform their scientific observations.

2.1. Removal of RWB tranquilization phase

RWB operations are performed autonomously by the Attitude Control Computer (ACC) after it has been commanded into Thruster Control Mode (TCM). The key function of the associated sub-modes and stages are shown in Fig. 2 and consist of six stages; the first five using thrusters to change the wheel speeds and also control the attitude, while the sixth takes over control of the attitude using wheels.

The command that performs the bias always sets the Stage-5 'tranquilisation' time to 100 seconds in order to minimize pointing errors when transitioning from thruster control back to wheel control, in order to continue science operations. However, analysis of the propellant used during the RWB has shown that typically more than 50% is taken for tranquilisation. Its removal, by simply setting the value within the command to zero, would therefore reduce consumption significantly and thereby increase the operational lifetime.

Analysis by industry, XMM in-flight experience and INTEGRAL in-flight testing showed no significant impacts on attitude control and pointing stability of removing the RWB tranquilisation phase. Its subsequent implementation within routine operations at the

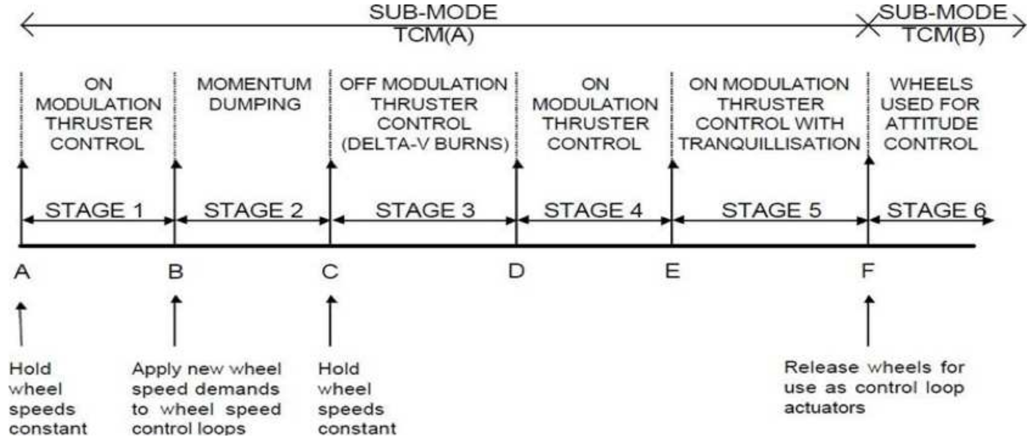

Fig. 2. Thrust Control Mode (TCM) sub-mode/stage functions.

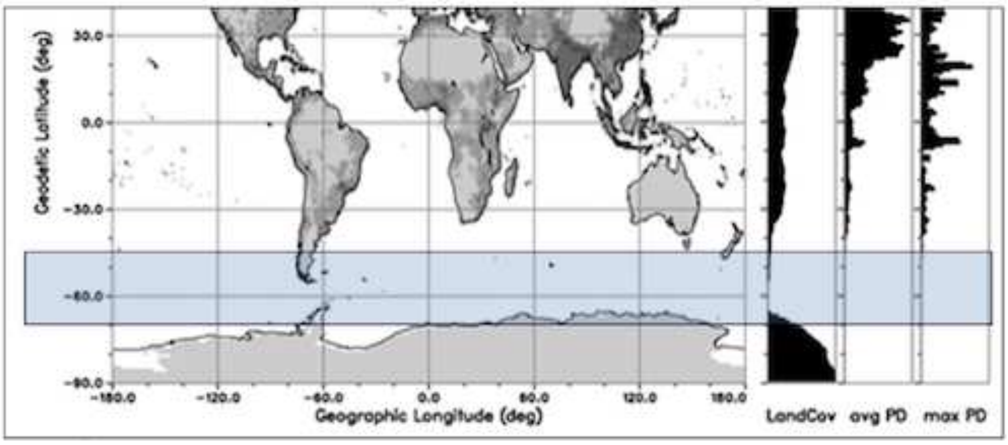

Fig. 3. Potential location of ground impact of INTEGRAL fragments following re-entry. The targeted latitude makes sure to minimize both the land coverage and the population density.

start of February, 2016, resulted in an immediate reduction in propellant consumption of around 50% or more with no significant impact on spacecraft stability, pointing and wheel speed margin. This meant that the average consumption rate was down to around 3.5 kg/year, extending the operational lifetime by around six years to the start of 2027 (i.e. just over two years before re-entry, in 2029).

2.2. Removal of 'zero' speed wheel operation constraints

XMM-Newton has significantly reduced RWB propellant consumption by operating with all four reaction wheels while INTEGRAL uses only three in the current configuration. This allows adjustment of individual wheel speeds without changing the total angular momentum of the spacecraft. Unfortunately, due to cost

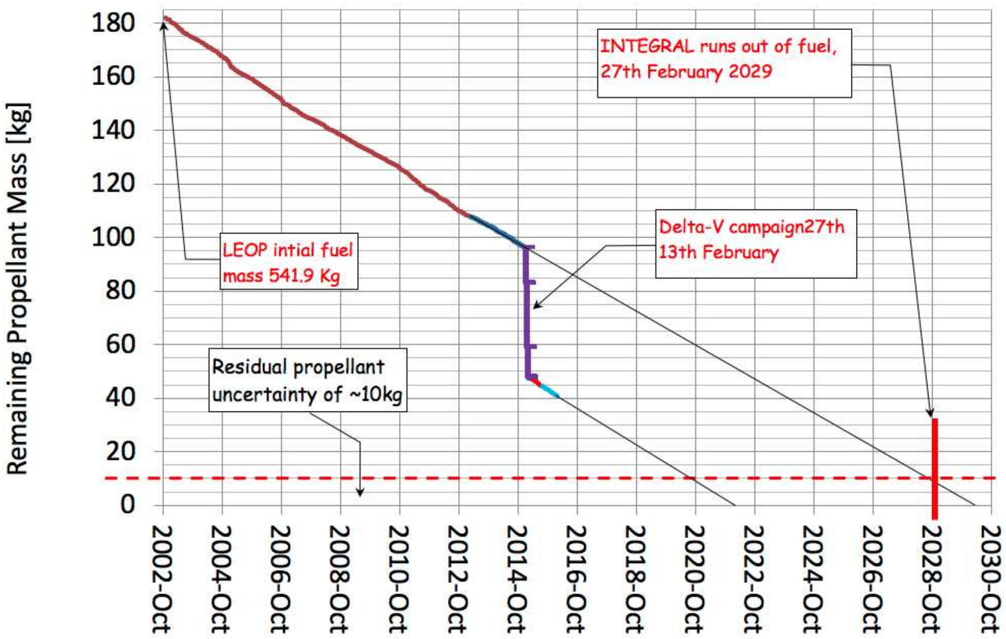

Fig. 4. INTEGRAL propellant bookkeeping history and consumption trends from launch to start of 2015, after the disposal manoeuvre.

constraints, this approach could not be adopted by INTEGRAL and the only remaining option was to relax wheel speed constraints about the 'zero' region. This increases the range of possible angular momentum vectors, enabling to be unload the accumulated external forces by a single bias while also reducing the expected range of speeds.

To clear concerns over wheel health and spacecraft pointing stability, a series of in-flight tests were performed in 2015 (Huebner et al. 2016) that showed no attitude control issues with all three wheels operating within the low speed region (i.e. +/-4rpm). In addition, a series of laboratory tests performed at ESTEC on a 'flight spare' reaction wheel, which have been ongoing since 2015, have shown no discernible signs of distress or degradation. Finally, a modified version of the Flight Dynamics mission planning software was developed, tested and validated for operational use in September, 2017.

Fig. 5 shows the propellant mass evolution since 2012 and highlights the reductions due to both the removal of RWB tranquilisation and removal of the 'zero' wheel speed constraints, which has reduced the observed rate by around 15%. The overall result is that it INTEGRAL may have an operational lifetime up to its re-entry in February, 2029, with sufficient residual propellant to control the re-entry longitude and target a region with minimum land coverage and population density.

This would be the first 'controlled' re-entry ever performed by a mission in such a highly elliptical orbit as well as by an ESA astronomy satellite.

2.3. Fast re-planning for multi-messenger astrophysics

A fast re-planning process will be needed for future Target of Opportunity (ToO) requests that support multi-messenger astrophysics (e.g. Gravitational waves). However, such requests may require extremely large slews to the new target attitude that may take

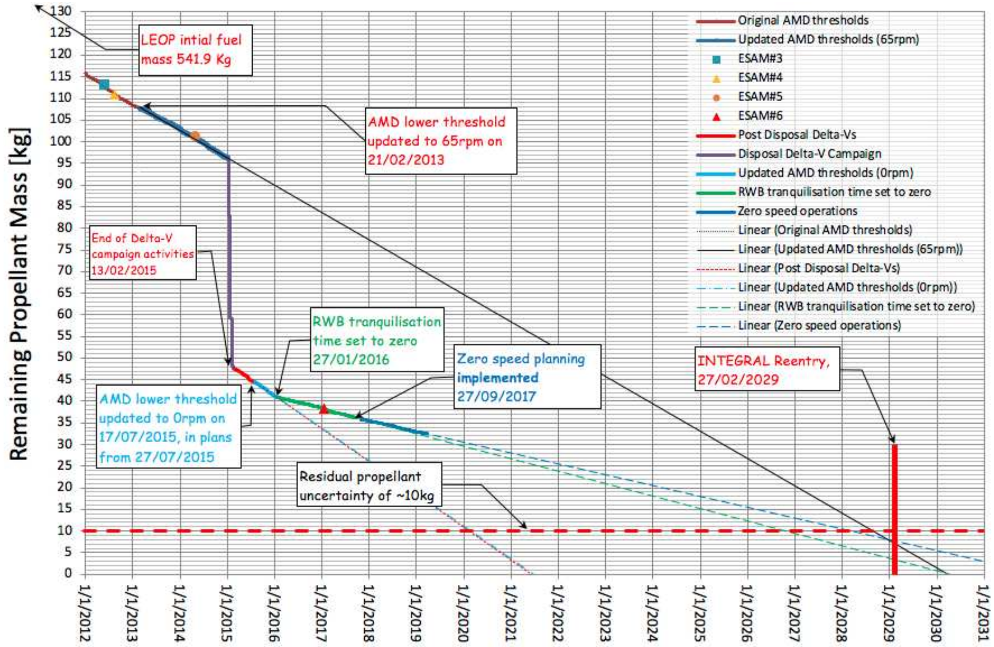

Fig. 5. INTEGRAL propellant bookkeeping history & consumption trends since 2012. The various implementation to optimize the fuel usage allowed to extend the potential mission lifetime after the disposal manoeuvre from 2020 to 2029.

up to eight hours to complete due to constraints imposed by the issues explained below and related to spacecraft dynamics, attitude pointing and on-ground processing. 1) The INTEGRAL maximum slew rates is 200 arcsec/sec. 2) To avoid pointing at bright objects during the slew (e.g. Sun, Earth, Moon, Planets), up to five Open Loop Slews may be performed, each taking around 10 minutes to generate. The first slew (less than 80 degrees) is around the pitch axis at lasts around 27 minutes maximum. Four yaw slew may be needed, bringing a maximum and total slew angle of 270 degrees, taking around 25 minutes to generate and execute. 3) A final Closed Loop Slew, with a maximum duration of around 10 minutes, to arrive precisely on-target and thereby enable the start of scientific observations. In addition, we must assume that a reaction wheel bias will be required after each slew to unload the wheel momentum. This takes another 25 minutes. Finally, a change of guide star, lasting 15minutes, might be needed after each RWB.

As the goal is to reach the ToO attitude as fast as possible, the fast re-planning process aims to commence any large slew(s) as soon as possible and thereby enable the more detailed science activities to be planned in parallel, since these need only be available once the spacecraft has reached the target attitude. Due to the constraints previously mentioned, it is though that in the worse case scenario (e.g. pointing attitude very far from each other), the satellite could point to its new attitude within eight hours. To this end, the science planners at ISOC will first alert ESOC mission planners that a ToO has been received, giving specific details of the target attitude. ESOC planners will then check the current attitudes safety (e.g. no imminent eclipse, perigee or other risks of sensor/instrument blinding) and then authorize the spacon to stop timeline. Flight Dynamics will then assess the slew size and duration and communicate this to the ISOC planners, who will then decide if the slew(s) should commence immediately or are small enough to be implemented by the normal re-planning process. In either event, the ISOC planners will then prepare a new plan, beginning at either the current attitude or the new target attitude, which they will then forward to the ESOC planners for final implementation and execution. This procedure is being developed jointly by ISOC and ESOC and is expected for operational use in the course of 2019.

3. Conclusion

After more than 16 years in orbit, INTEGRAL's performance remains excellent and still far above design specifications. There have been no significant unrecoverable failures. The satellite still uses all of its prime units and overall degradation of both the platform and the payload is minimal. The effects of aging are not critical and can be compensated for by modest operational countermeasures, resulting in very good margins on consumables and all limited-lifetime components.

Continued significant interest in INTEGRAL's science data is demonstrated by a healthy over-subscription at each announcement of opportunity and an undiminished rate of target of opportunity requests. With continued interest by scientific community, INTEGRAL has the potential to provide excellent scientific data well into the next decade. Additionally, INTEGRAL will provide a baseline in support of the International Astronomical Consortium for High Energy Calibration Standards for high-energy calibration while enabling cross calibrations with currently operating missions such as XMM, Chandra, NuSTAR, Swift and Suzaku.

References

Armellin, R., et al. 2015, Adv. Space Res., 56, 479

Dietze, C., et al. 2015, Proceedings of 25th International Symposium on Space Flight Dynamics ISSFD

ESA 2014, Space Debris Mitigation Policy for Agency Projects, ESA/ADMIN/IPOL(2014)2

Huebner, J. M., et al. 2016, AIAA SpaceOps2016 Conference Proceedings, 2359, 1838

Winkler, C., et al. 2003, A&A, 411, L1