INTEGRAL Revisits Earth - Low Perigee Effects on Spacecraft Components

Jutta M. Hübner1
ESA/ESOC, Darmstadt, Germany

Richard T. Southworth2
ESA/ESOC, Darmstadt, Germany

Alastair McDonald3
Logica, Darmstadt, Germany

Peter Kretschmar4
ESA/ESAC, Madrid, Spain

Carmen Lozano5
VEGA Space GmbH, Darmstadt, Germany

Mike Walker6
SCYSIS Deutschland GmbH, Darmstadt, Germany

Since its launch in 2002, ESA's INTErnational Gamma-Ray Astrophysics Laboratory (INTEGRAL) has been observing astronomical objects simultaneously in gamma-rays, X-rays and visible light. Using its four instruments, it provides insight into the nature of sources of extremely high-energy radiation, and 9 years after its launch the scientific interest is still very high. The performance of INTEGRAL has far exceeded design specifications. To date, it is still the most sensitive gamma ray observatory in space, all prime units are still in use, no major failures have occurred and the degradation of spacecraft components is minimal. Last but not least, the nominal lifetime of two years has already been far exceeded, and the remaining fuel on board still allows for another decade of operations.

Major challenges the mission faces are the orbital evolution and the aging of spacecraft components: on October 25th 2011, INTEGRAL reached the lowest perigee altitude since its launch. This resulted in both increased exposure to proton radiation during perigee passage and an increased heating of the spectrometer’s cryocooler due to the Earth albedo, leading to a small reduction in payload performance. Furthermore, all electrical components will have reached their total dose qualification limit soon.

This paper summarizes the effects of the period of low perigee altitude on the degradation of the materials and spacecraft components. Furthermore, it presents the associated countermeasures, operational strategies as well as the impact on the fuel consumption and the science. Finally, the prospects for future INTEGRAL operations are summarized along with the lessons learned from the period of low perigee.

1 Spacecraft Operations Engineer, HSO-OAI, jutta.huebner@esa.int
2 Head INTEGRAL Spacecraft Operations Unit, HSO-OAI, richard.southworth@esa.int
3 Flight Dynamics Engineer, HSO-GF, alastair.mcdonald@esa.int
4 INTEGRAL Mission Manager, SRE-OOG, peter.kretschmar@esa.int
5 Spacecraft Operations Engineer, HSO-OAI, carmen.lozano@esa.int
6 Spacecraft Operations Engineer, HSO-OAI, mike.walker@esa.int
I. Introduction

ESA’s INTERnational Gamma Ray Astrophysics Laboratory (INTEGRAL), launched in October 2002, is designed to perform multispectral observations of the most violent and exotic objects in the universe, such as gamma ray bursts and supernova explosions. Its unique payload comprises the imager IBIS, the spectrometer SPI, as well as the complementary X-ray and optical cameras JEM-X and OMC. Furthermore, the INTEGRAL Radiation Environment Monitor IREM provides precise data on the local radiation environment around the spacecraft.

The nominal mission lifetime of two years and even the extended lifetime of another three years have already been far exceeded. However, to date INTEGRAL is still the most sensitive, accurate and advanced gamma ray observatory in space and the scientific return of INTEGRAL is excellent. INTEGRAL has operated almost perfectly throughout the mission, with no significant unrecoverable failures, and its overall performance is still far above design specifications: all prime units are still in use maintaining full redundancy, no major failures have occurred and the degradation of spacecraft components is minimal. The main challenge during the past years of INTEGRAL operations was to counteract the effects of the period of low perigee altitude and the associated impact by the passage of the satellite through the inner Van Allen proton belt. This paper summarizes the effects of the orbital evolution on the satellite, the degradation of the materials and spacecraft components, associated countermeasures and operational strategies.

II. INTEGRAL orbit evolution and its effects

A. Characterization of the INTEGRAL orbit after launch

INTEGRAL was launched into a highly elliptical, high inclination (52°) orbit with a perigee altitude of about 9000 km and an apogee altitude of about 153000 km. The orbital period of 3 sidereal days (about 71.8 hours) is controlled actively. This maintains the semi-major-axis at a constant value of around 87700 km.

Due to the high and eccentric orbit, INTEGRAL spends most of the time (>80 %) above an altitude of 60000 km well outside the trapped radiation of the Earth’s radiation belts (see section II.D). Therefore, long periods of uninterrupted scientific observation with nearly constant background are guaranteed. The instruments are only operated in their science modes above the Earth’s radiation belts. During the radiation belt passage, INTEGRAL is exposed to a high particle flux, which requires a specific safe configuration for the instruments.

B. Evolution of the INTEGRAL orbit

The highly eccentric orbit of the INTEGRAL satellite has evolved considerably throughout the mission and will continue to evolve over the next years. As a consequence, the perigee altitude and inclination will change significantly, which are important drivers for the passage through the radiation belts and the associated radiation environment encountered.

The perigee altitude varies enormously: after a maximum height of over 13000 km in 2006, the perigee dropped below 6000 km in 2010 and reached a minimum of just 2756 km on 25-10-2011 (Figure 1). Since the spacecraft was initially not intended to operate at such low altitudes and different radiation conditions, this marked a new scenario for the mission. Currently, the perigee altitude is increasing again: by late 2013, it is expected to be above 6000 km again, leading to a much more benign environment (see section II.C). A maximum value of about 9600 km is predicted to be reached in 2016. Unfortunately, starting in 2017 the perigee altitude will again reduce significantly and will reach its ultimate minimum of just 1900 km in 2020. On the other hand, the inclination will reduce from its maximum of 87° in 2008 to its minimum value of 48° in 2018 (Figure 1).

The main causes of the orbital evolution of INTEGRAL are the Earth's oblateness and the lunar gravitational perturbations, which act on all of the orbital parameters and are largely responsible for the variations in apogee, perigee and inclination. Other forces such as solar radiation pressure are small in comparison.
C. Negative aspects of the orbital evolution

*Evolution of the radiation belts passage of INTEGRAL: Passes through the inner proton belts*

Since INTEGRAL’s launch the characteristics of the passage through the Van Allen radiation belts have evolved significantly as a direct result of the orbital evolution. While the duration of the passage through the radiation belts remained more or less at a constant value of about 8 hours (i.e., about 10% of the orbital period) between launch and 2009, it decreased to about 5 hours afterwards (i.e., about 6%, see Figure 2).
Furthermore, the radiation belt entry and exit points as well as the shape of the radiation belt passage have changed dramatically (Figure 3): the INTEGRAL orbit progressively moved away from the inner proton belt between launch and 2006. A rapid approach towards the inner proton belts was again experienced starting 2007. In the second half of 2009, when the perigee altitude dropped below 6000 km, INTEGRAL started to pass through the inner proton belts. The significant proton fluxes are only experienced in the descending path of the orbit.

![Figure 3: Evolution of INTEGRAL’s passage through the radiation belts for one representative orbital period per year since launch, evenly distributed in time. The intensity of the trapped protons and electrons are mapped. The outer red semi-circle illustrates the 2D projection of the electron belts while the smaller inner red semi-circle depicts the proton belts (geomagnetic coordinates, units: Earth radii).](image)

**Increased heat input into the cryostat due to the Earth**

Due to the low perigee altitude, the heat input into the SPI cryocooler is increased by the Earth’s albedo. This is a seasonal effect and has the biggest influence on INTEGRAL during the Antarctic summer. There, the polar region, i.e., the region INTEGRAL is closest to at perigee, is lit up by the Sun. This leads to an increase in the SPI detector temperature during perigee and consequently to a small reduction in payload performance.

**Evolution of visibility**

The change in the orbital inclination will affect significantly the ground station coverage resulting in a change of visibility. Starting in late 2014, there will be a gap in visibility from Redu, INTEGRAL’s prime ground station in Belgium. It will appear about a quarter of the way through the “revolution” – the period of time from one perigee passage to the next – and will extend to about four hours. A similar gap will appear for the other European ground stations except Kiruna in Sweden. To fill this gap, coverage would be required from either Kiruna or a non-European station.
D. Evolution of the radiation environment around INTEGRAL

The evolution of INTEGRAL’s orbit strongly affects the radiation environment encountered by the spacecraft near Earth. In contrast, the radiation environment encountered outside the belts is independent of the orbital evolution. Nevertheless, the latter also will be characterized below to allow the contributions of the low perigee effects to be isolated.

Trapped particles in the Earth’s radiation belts

Energetic protons, electrons and heavy ions are trapped by the Earth’s magnetic field and form the so-called Van Allen radiation belts. They can be divided into two distinct belts: the outer belt is formed by energetic electrons of 0.1 – 10 MeV and the inner one by a combination of energetic protons of up to several hundred MeV energy and electrons with hundreds of keV. While the inner belt typically extends from 1.2 to 3 Earth radii and is reasonably stable in time, the outer belt extends to about 3 to 10 Earth radii and is highly dynamic due to storms and injected events by solar-terrestrial disturbances.

The average proton flux (E>10 MeV) encountered by the satellite within the radiation belts decreased during the early years of the mission, effectively disappearing during 2006 (Figure 4, left), when INTEGRAL passed only through the outer electron belt every perigee. However, in line with the sharp decrease of the perigee altitude from 2007 to October 2011, the exposure to proton radiation has increased substantially again starting in 2009. INTEGRAL started to also pass through the inner proton belt in the second half of 2009, which drastically increased the exposure to highly energetic trapped protons. In contrast, the averaged electron flux (E>0.5 MeV) has remained more or less constant throughout the mission and only shows a small variation with the solar cycle (Figure 4, right).

Radiation environment outside the Earth’s radiation belts and solar flares

The main contributor to the radiation environment outside the radiation belts are Galactic Cosmic Rays (GCRs) and Solar Particle Events (SPEs). The continuous low intensity GCRs with isotropic flux (83 % protons, 13 % α, 1 % heavier ions and 3 % electrons/positrons) are the dominant radiation source during quiet periods. Even though the flux levels are low compared to the trapped particles, they are hazardous to spacecraft electronics, since their high energies make them extremely penetrating: their spectrum covers a broad energy range from about 1 MeV up to 3x10^{20} eV and above. The typical energies per nuclei are about 100 MeV to 10 GeV.

The SPEs primarily consist of protons and light ions (α particles) with energies ranging from keV to GeV and beyond. They are sporadic in nature and generate high particle fluxes, so called solar flare events, of widely varying duration. Two distinct populations of SPEs exist with different characteristics: gradual proton-rich events with durations of the order of days (∼ 10 events/year) and impulsive electron-rich events with durations of the order of hours (∼ 1000 events/year). Indeed, the energies of the solar protons are basically lower than the GCR ones, but their particle fluxes in the 100 MeV range are on average about four orders of magnitudes higher.

Figure 4: Predicted trapped proton flux (E>10 MeV; left) and trapped electron flux (E>100 keV, >1MeV; right) on INTEGRAL (credits: SPENVIS and TEC-EES)
Both GCRs and SPEs are modulated by solar activity: the solar flux correlates with the solar cycle, whereas the GCR flux is anti-correlated. The reason for this is that the increased solar wind turbulences during the active phase leads to raised scattering of GCR and therefore a reduced GCR flux. The average solar cycle spans eleven years and can be divided into four inactive and seven active years.

The ongoing solar cycle #24 has started in January 2008 and is predicted to reach its peak early or mid-2013 (Figure 5). According to NASA’s predictions, it will be the least active cycle in the past hundred years. Up to 2006, 6 solar flare events have affected the INTEGRAL operations and already 6 since June 2011. INTEGRAL is equipped to cope with such events in terms of onboard functionality, ground operations procedures as well as mission performance margins.

E. INTEGRAL on-board Radiation Environment Monitor

The radiation environment around INTEGRAL is continuously monitored by the INTEGRAL Radiation Environment Monitor (IREM) mounted on-board INTEGRAL. It provides precise data on the local radiation environment at several energy levels by recording electrons, protons and cosmic rays and also measuring the absorbed dose along the INTEGRAL orbit. IREM data is used to monitor INTEGRAL’s passage through the radiation belts in different energy ranges (see Figure 2). The IREM count rates are also used to protect INTEGRAL’s scientific instruments by autonomously switching them to a safe configuration in case of high background radiation (e.g. due to a solar flare).

The IREM count rates outside the radiation belts increased steadily from the start of the mission until their maximum values in mid-2009 (Figure 6). Since the second half of 2009, a downward trend is experienced. The evolution correlates perfectly with the cosmic ray flux. The spikes correspond to solar flares.

![Cycle 24 Sunspot Number Prediction](image)

![Figure 5: Solar cycle #23 and #24 as predicted by NASA][11]

![Figure 6: Evolution of IREM count rates outside the radiation belts](image)
F. Overview of interactions of space radiation with the satellite material

The low energy plasma of electrons and protons (E < 0.1 MeV) in the outer regions of the magnetosphere and in interplanetary space is already stopped by thin layers of material and therefore does not pose any risk to most spacecraft electronics. However, it is damaging to surface materials and can contribute to spacecraft surface charging and discharging. In contrast, primary protons and particles with high energy and high charge which are less abundant possess significantly higher ionizing power and cause deep penetration damages. The secondary particle flux mainly consists of electrons created by ionization and photoelectric effect as well as protons and light ions due to inelastic interactions. The secondary particles are time coincident with the primary particles.

G. Overview of radiation induced damages

The radiation induced damages to INTEGRAL’s subsystems and components can be divided into long term and transient effects, which may lead to induced signals, latch-ups, upsets, burnouts, gate ruptures or bit flips. The main contributor to the long term effects is the total ionizing dose, which accumulates from the incident particles and leads to a degrading performance of the satellite’s subsystems. For INTEGRAL, most electrical components have already exceeded their total dose qualification limit by up to 10%.[13]

Transient effects can be generated by the whole spectrum of particles penetrating the satellite. The effects are threefold: (1) Temporary activation, i.e., re-emission of absorbed radiation by the payload material, which may cause loss of resolution and periods of inoperability. This is mainly caused by high-energy proton impacts. (2) Increased probability of temporary problems to critical equipment, e.g., temporary star tracker blinding. (3) Degraded unit performances, which might even lead to a permanent unit malfunction.

The degradation at software and hardware level experienced by INTEGRAL is described in the following sections. Furthermore, it is discussed whether the effects are caused by the passage through the proton belts due to the orbital evolution.

III. Recoverable degradation

A. Single Event Upsets (SEU)

Some recurring single anomalies experienced by INTEGRAL’s subsystems that are most probably caused by unpredictable Single Event Upsets (SEU) comprise the following:
- Crash of the data processing electronics of instruments
- Subassembly unit reset and high voltage breakdowns
- Change in status of unit Latching Current Limiters (LCL)
- IREM crashes

Especially when affecting critical units, the consequences of these events may be quite serious with a considerable effect on operations. While the number of LCL SEU type events significantly increased in 2009, the number of IREM SEUs had their peak in late 2011 (Figure 7). Up to May 2012, 130 IREM resets have been reported. These anomalies trigger an automatism to switch the instruments IBIS and OMC into a safe configuration and therefore have an impact on the operation of both instruments. The likelihood of such real time spontaneous events is increased due to the effect of the perigee reduction and the associated subsequent passage through the proton belts starting in 2010.

Changes in the status of the Main bus Regulation Unit (MRU) due to SEUs, possibly caused by electrostatic discharge, occurred regularly until late 2007. Since then no further events have been recorded, the reason for this change in behavior is unknown.

Figure 7: History of SEUs in events per year (top) and accumulated (bottom) (note: for 2012, only events until May are taken into account)
B. Instrumental background outside the radiation belts

INTEGRAL’s radiation environment has evolved dramatically since the start of the mission. The evolution of the background count rates as seen in all detector types and across the broad energy bands correlates perfectly with the cosmic ray flux and consequently with the IREM counts outside the radiation belts (see Figure 6): a steady increase of the mean count rates for all detectors has been experienced over the mission until the second half of 2009 upon resumption of the new solar cycle. Afterwards, a downturn has been observed in all count rates (Figure 8). No effects due to the change in perigee passage and the resulting increased exposure to highly energetic protons in the inner Van Allen belts have been observed. Furthermore, the instrumental background of all instruments is not affected by any activation: the count rate due to delayed emission from the spacecraft and detector materials as a result of activation (e.g., see non-vetoed count rate, i.e., the light green curve in Figure 8) has been observed to decrease in line with the total count rate.

C. Star tracker blinding and loss of guide star during perigee

The star tracker CCD is aging with, up to now, 5 lit pixels having been identified. Through the perigee passage, a fixed attitude is maintained and care is taken to select from ground a guide star for attitude control by the star tracker which is isolated from any such “blemish” pixels. Nevertheless, with decreasing perigee altitude, the losses of guide star at perigee occurred more frequently due to the higher radiation environment affecting the overall star tracker performance. From 2011 onwards, loss of guide star started to occur during most perigees. This has an impact on the inertial measurement unit usage (see section V.B) and operations immediately post perigee (see section V.C).
IV. Non-recoverable degradation & failures

A. Solar array degradation

The solar arrays and the two batteries are absolutely critical components without redundancy. While for the batteries no degradation is experienced so far, the degradation of the solar arrays is twofold: a continuous, slow long term gradual degradation, as well as unpredictable degradation steps, caused by solar flares or micro-meteorites. While the degradation rate amounted to about 1-2%/year until 2010, a significant loss of array output power by 5-7%/year was experienced after 2010, most likely due to the increased exposure to proton radiation when the perigee dropped below 6000 km (Figure 9). Still, INTEGRAL is generating enough power to operate the entire payload with sufficient margin, even at the maximum allowed solar aspect angle of 40 degrees.

![Figure 9: Solar array output current evolution since launch normalized to the maximum permitted pitch angle of 40° (worst case scenario) and to the mean Earth-Sun-distance. A clear correlation between the unit degradation and strong solar events (e.g., Nov 2003) can be seen.](image)

B. Degradation of the sun acquisition sensor

The ageing of the photovoltaic cell of the Sun Acquisition Sensor (SAS), which provides information on the position of the Sun in the sensor FoV, results in a lower output current for a given Sun position. Therefore, the angular threshold has to be lowered to compensate for this effect and to keep the allowed Sun excursions constant (Figure 10, see section V.D). Until 2010, a degradation of about 1.2%/6 months has been experienced, less than expected by the manufacturer (2%/6 months). However, from 2010 onwards, a drastically increased degradation of about 2.7%/6 months has been observed, which correlates with INTEGRAL passing through the proton belts. The aging of the SAS correlates linearly with the accumulated dose. The evolution of the SAS degradation due to the low perigee altitude is consistent with the one observed in the solar arrays.
C. Permanent detector degradation and failures, sensitivity of instruments & imaging performance

To date, the instruments’ degradation, i.e., neither the energy resolution, spectral response, hot pixels, dead pixels/change in the sensitive area, spectral gain, sensitivity and imaging capabilities, nor the JEM-X’s anode degradation as well as the dark current increase, degradation of the charge transfer efficiency and the evolution of the flatfield of OMC could be associated with the low perigee altitude. The effects are rather related to the flux of rare heavy (and thus very energetic) ions in the cosmic ray flux. The changes are gradual and close to expectations. They can be compensated by detector annealing,[14] in-flight calibrations and improvements in the ground processing and therefore have no impact on the scientific return.

The permanent failures of four out of 19 SPI Germanium detectors and two out of 91 SPI anticoincidence subassembly front end electronics are not connected to the low perigee altitude and the associated radiation effects, since they occurred when INTEGRAL had not yet passed the inner proton belts. To avoid further failures in SPI detectors, modifications of the annealing procedure[14] to reduce the thermal stress on the detector pre-amplifiers as well as changes to the initial radiation belt passage strategy have been implemented. Due to the redundancy concept, some of the failures did not have any impact on the performance at all.

The analysis of the failures of the preamplifiers’ DC output voltage indicates that they could have been caused by a destructive flash of high voltage, partially destroying the preamplifier. As a preventive action to decrease the risk of further detector failures, the SPI Germanium detectors are operated at a reduced voltage. The effect of this reduction on the instrument’s sensitivity was minimal as the characteristics of the detectors have changed during the mission. Therefore, the scientific performance is still guaranteed.

V. Impact on operations and resources

Some effects of the period of low perigee altitude can be compensated for by minor changes in INTEGRAL operations. The implemented countermeasures as well as the preventive actions are discussed below.

A. Perigee raising maneuvers as possible countermeasures

As a possibility to mitigate the risk of the exposure to proton radiation at perigee, perigee raising maneuvers were analyzed.[10] Since it is very expensive in terms of fuel, it was agreed to follow a step-by-step strategy: the instruments’ health is continuously monitored jointly by the flight control team and the PI teams. In case an effect on the instrument performance is noticeable, a moderate perigee raise maneuver will be performed during the densest part of the proton belts to raise the perigee out of the core of the proton belts. This uses only some of the available fuel. When the next radiation effect is noticed, another small maneuver will be implemented and so on. To date, no such perigee raising maneuver was necessary.
B. Star tracker blinding: impact on the inertial measurement unit usage

Whenever the guide star is lost, the control will be switched from the star tracker to the inertial measurement unit (IMU). The IMU provides angular and rate information by means of a gyroscope which spin axis keeps a constant direction in inertial space. Therefore, the loss of a guide star has a direct impact on the IMU usage. Up to now, the IMU has been switched on for a duration of about 1800 hours in total. Since the guaranteed lifetime is 4000 hours, the effect of the IMU-ON time due to the loss of guide star during the proton belt passage is not critical.

C. Star tracker blinding: recovering from loss of guide star events during perigee

To give the spacecraft controller more time to recover from a loss of guide star experienced during perigee before the start of the instrument window and to avoid knock on effects on subsequent attitude and orbit control system operations, an additional 10 minutes were given at the start of the revolution. The additional time did not have any impact on the science and remaining instrument operations.

D. Calibration of the sun acquisition sensor

Due to the increased degradation of the SAS since 2010, the calibration of the SAS is performed twice per year since 2011 instead of annually. The calibrations are performed to evaluate the output current for different Sun aspect angles to recalculate the SAS window thresholds and to re-adjust the angular threshold in line with the recommended 2% threshold variation. The angular threshold is lowered accordingly to keep the allowed Sun excursions constant.

E. Special perigee attitude and higher fuel consumption

The decreasing perigee altitude lead to an increased heat input into the SPI cryocooler due to the Earth's albedo, in particular by the (illuminated) polar region. As countermeasure, a special perigee attitude was selected for certain periods of the year to shelter the spectrometer cooler from the Earth’s albedo. This minimized the heating of the spectrometer but has led to an increase in fuel consumption, since (additional) changes to the INTEGRAL attitude before perigee were necessary. However, due to the faultless injection into its final orbit back in 2002 as well as the efficient fuel usage strategies and a minimum number of emergency safe modes, the remaining fuel on board INTEGRAL still allows for another 10-12 years of operations.

F. Reaction wheel momentum changes with thruster firing

Three reaction wheels are the actuators which maintain routine three-axis attitude control. Typically around 100 attitude maneuvers are carried out every orbital period. These maneuvers combined with the external disturbance torques acting on the spacecraft make it necessary to perform pre-planned momentum changes to the wheels by firing the thrusters. The higher the number of maneuvers and the higher the external torques, the higher the likelihood that such adjustments in the wheel speeds are necessary. With the lowered perigee passage altitude, the dominant disturbance torque due to gravity gradient increases. Therefore there is a small penalty in fuel usage corresponding to the increased likelihood in commanding significant changes in wheel speeds to avoid them saturating or remaining close to zero. Nevertheless, the fuel penalty is small and, as stated in the previous section, the remaining fuel on-board means that this is not a significant problem.

G. Radiating at perigee

Due to the evolving perigee altitude, INTEGRAL approached regulations limits from the International Telecommunication Union for radiating at perigee in 2010. To avoid violating these regulations, the transmitter has been switched off below an altitude of 5000 km since mid-2010.

VI. Conclusion and outlook

The orbital evolution of INTEGRAL has led to greatly increased exposure to proton radiation close to perigee after early 2010. So far, significant effects of this have only been observed for the solar arrays and the sun acquisition sensor. Other effects of the passage through the proton belts could be compensated for by minor changes in operations. Most critical subsystems (e.g., batteries, cryocooler performance) have not been affected at all by the low perigee altitude. The scientific performance of the instruments remains excellent. In particular, there have been significant improvements in the sensitivity and imaging capabilities over the mission especially for IBIS due to in-flight calibrations and improvements in the ground processing and SPI due to the implementation of on-board data
compression algorithms allowing much higher data rates. However, the effect of the changing radiation belt characteristics and the changing environment at perigee on the spacecraft subsystems will be carefully monitored and continuously reviewed during the coming years. An automated warning system for the early detection of degradation effects is in place at the INTEGRAL mission operations center. The current high radiation condition during the perigee passage will probably persist until late 2013, when INTEGRAL’s perigee altitude is above 6000 km again, where a much more benign environment is expected.

Since the total dose accumulated by the units and electronic components has already exceeded the qualification limits, there is an increased likelihood of more real time spontaneous effects as well as failure or degradation of units. However, possible effects may be partially mitigated by the use of redundant units. Since all prime units are still in use, full redundancy is still available. There are no open issues for the continued successful operation of the instruments (also see [9]). Due to its very good margin on consumables and all limited-life components, INTEGRAL has the potential to provide excellent scientific data well into the next decade.

Acknowledgments

The authors would like to thank J.P. Roques (IRAP Toulouse), G. La Rosa (INAF-IASF Palermo), S. Brandt (DTU Space, Copenhagen), M. Mas Hesse (CAB Madrid) and W. Hajdas (PSI Villigen) for the fruitful discussions as well as the combined INTEGRAL/XMM flight control team for their dedicated work and invaluable effort. INTEGRAL is an ESA Science Mission in cooperation with Russia and the United States with instruments and contributions directly founded by ESA Member States.

References