INTEGRAL operations and mission rescue without thrusters

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ABSTRACT

The International Gamma-Ray Astrophysics Laboratory (INTEGRAL) is a European space observatory mission that observes objects in gamma/X-ray and visible wavelengths. The spacecraft was launched in 2002, and has exceeded its original mission duration by a long margin. It is currently in its extended mission phase with observations approved to the end of 2024.

Anomalies in recent years have created interesting challenges for attitude control. In 2020 the fuel depleted unexpectedly earlier than predicted, making normal thruster-based momentum off-loading impossible. A workaround using solar radiation torque and slews was devised to manage angular momentum. ESOC and industry redesigned the slew algorithm to remove a constraint that previously required some additional momentum off-loading.

In September 2021 a major anomaly put the spacecraft into an uncontrolled tumbling state for several hours. This paper describes the context and the improvised recovery of attitude control using reaction wheels, and the subsequent development of procedures and a New wheel Safe Mode (NSM) to prevent a recurrence of loss of control. With NSM installed, the mission will operate safely without thrusters and with redundancy for any further unit failures until predicted re-entry in 2029.

1 INTRODUCTION

INTEGRAL is a European Space Agency scientific observatory dedicated to observing the high-energy universe in gamma and x-rays. The primary payload provides imaging and spectroscopy in parts of the x-ray and gamma ray part of the spectrum [1].

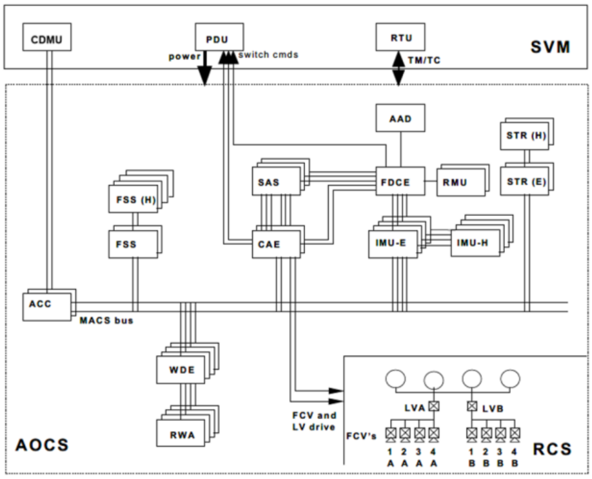
The spacecraft operates in an inclined eccentric orbit (initially 3-day period, later modified to 2.67 days), with observations conducted during the large fraction of the orbit period above the earth’s radiation belts. The orbit is inclined to provide long communications periods around apogee for northern hemisphere ground stations.

Matra Marconi Space Ltd. (now Airbus Defence and Space Ltd.) developed the INTEGRAL attitude and orbit control system (AOCS). The spacecraft prime contractor was Alenia Spazio (now Thales Alenia Space). Airbus has provided consultancy for the AOCS since fuel depletion in 2020.

Figure 1 Artist's impression of INTEGRAL in-flight. Image © Esa.

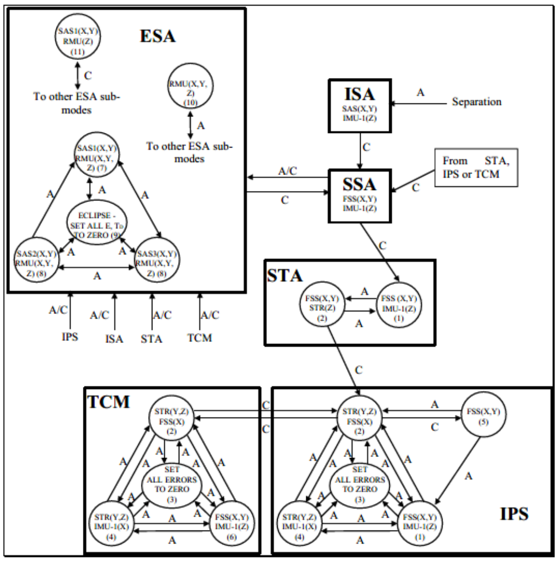
2 ORIGINAL AOCS DESIGN

The INTEGRAL AOCS is a subsystem with its own computers and software, unlike many modern spacecraft. The AOCS includes a set of attitude and rate sensors, reaction wheels, a computer for the nominal control laws (the Attitude Control Computer, ACC), and a hard-wired unit that contains failure detection functions and the safe mode (the Failure Detection and Control Electronics, FDCE). The ACC interfaces to the Command and Data Management Unit (CDMU) outside the AOCS in the service module (SVM), and the FDCE interfaces to the PDU.



Unit	Name
AAD	Attitude Anomaly Detector
ACC	Attitude Control Computer
FDCE	Failure Detection and Control Electronics
CAE	Control and Actuation Electronics
SAS	Sun Acquisition Sensor
FSS	Fine Sun Sensor
IMU	Inertial Measurement Unit
RMU	Rate Measurement Unit
RWA	Reaction Wheel Assembly
WDE	Wheel Drive Electronics
STR	Star Tracker
RTU	Remote Terminal Unit
CDMU	Command and Data Management Unit
PDU	Power Distribution Unit
RCS	Reaction Control System

Figure 2 AOCS Block Diagram, showing h/w interfaces



ESA Emergency Safe Attitude
ISA Initial Sun Acquisition
SSA Sun Sensor Acquisition
STA Star tracker Acquisition
TCM Thruster Control Mode
IPS Inertial Pointing and Slew

A = automatic transition
C = commanded transition

Figure 3 The Original AOCS modes, hosted in the ACC, and safe mode (ESAM) in the FDCE

The nominal modes for regular operations are; IPS, used for slews and fine pointing, and TCM, for momentum dumping using the thrusters. In case of failure, the FDE provides an alarm (automatic reconfiguration order, ARO) if it detects anomalous behaviour (such as loss of sun pointing or high rates), and triggers the safe mode, ESAM. ESAM, hosted in the FDCE, returns the spacecraft to a safe sun-pointing attitude using the thrusters, SAS and RMUs. Return from ESAM to ACC software control originally used a sequence of SSA (spin-up wheels and control using FSS), STA mode (the first mode to control attitude using wheels, and to control Z-axis using STR), followed finally by return to IPS (fine pointing using FSS and STR, with wheels for control).

The INTEGRAL AOCS was derived from the design for XMM-Newton (X-ray Multi-Mirror Mission), with overlapping development schedules. Both missions use Sagem Regys 3S dynamically tuned mechanical gyroscopes (IMU). At the time of development in the 1990s gyro lifetime was a major concern, and the AOCS was designed to be ‘gyro-lean’ (i.e. almost ‘gyro-less’) with the gyros switched on only for specific short duration operations, in order to ration their on-time. Slews between science targets are frequently required, and so a gyroless slew algorithm was developed. The STR available in the 1990s did not provide star pattern recognition, and consequently gyroless slews were designed to use FSS for 2-axes closed loop control of the sun position, with spacecraft 3-axis momentum feedforward profiles, using wheel speed control, with speed loop in the ACC. The 3rd axis of the attitude is open loop, driven to the approximate target position by the momentum profiles. This algorithm has a non-obvious feature that some combinations of slew values and initial conditions give divergent behaviour for the uncontrolled axis. Within the original mission this behaviour was managed by an operating constraint that limited a component of momentum to avoid slew divergence.

The thruster modes operate a set of 2 branches × 4 thrusters/branch 20N (BOL) hydrazine thrusters, aligned for 3-axes torque, and operated together for delta-v. Consumables were sized for a 2.25-year nominal phase + 3 year extended phase, however the mission has far outlasted this.

3 ESAM8, and FUEL DEPLETION

In early 2020 all AOCS units were healthy, and fuel was predicted to last for several more years. On 16 May 2020 during a routine momentum dump, a part of the FDIR which monitors excessive thruster commanding was triggered, initiating ESAM#8 (the 8th safe mode since launch). ESAM recovered the attitude using the backup thruster branch. However, after settling, there was an anomalous large attitude transient, when the sun vector drifted ~70 deg, before ESAM self-recovered. This was later interpreted as showing that there was also an intermittent problem with the backup thruster branch; some of the ESAM thrusters underperformed, before recovering.

After return to normal AOCS operations the thruster performance was re-calibrated (commanding open loop pulses in IPS and measuring their impulses by the change of wheel momentum), and a large and variable loss of performance was discovered. The pressure in the RCS lines also showed strange behaviour, dropping significantly after thruster use, followed by very slow partial recovery.

Subsequent analysis has led to the hypothesis that the bladders of some of the 4 tanks were fully expanded, blocking the tank outlets and trapping remaining fuel. Additionally, nitrogen pressurant had diffused through the bladder over time into the downstream fuel that feeds the thrusters, contaminating it with gas bubbles and effecting thruster performance on both branches [2].

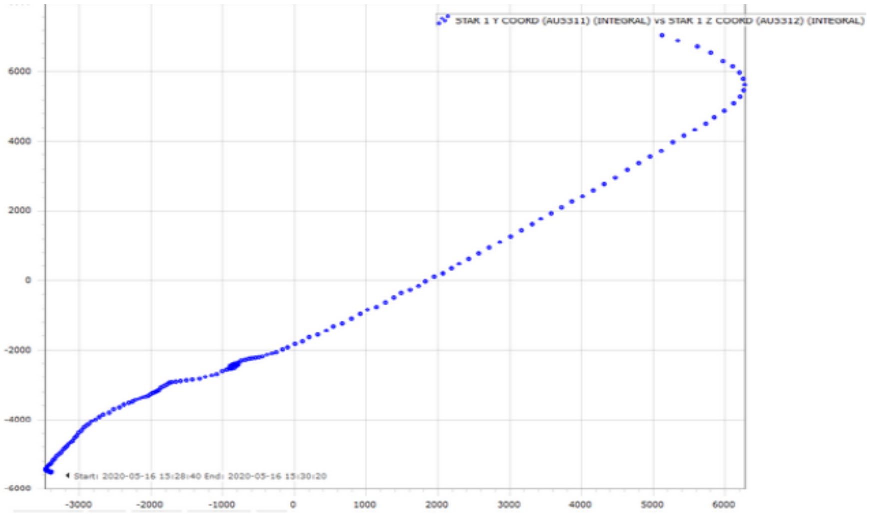


Figure 4 The guide star slews across the STR FOV (from left to right) during assymetic thruster performance during a momentum dump in 2020 immediately prior to ESAM8.

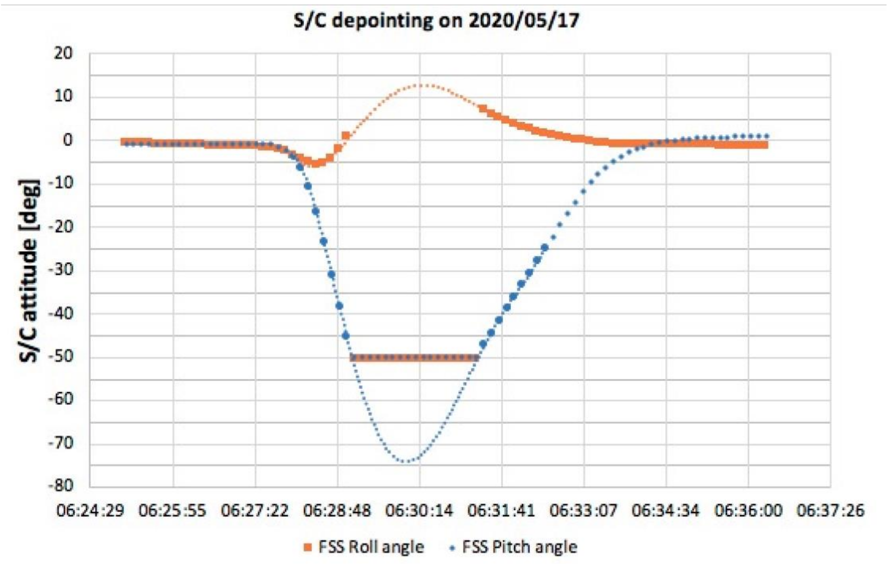


Figure 5 Large de-pointing and recovery during ESAM8.

Combined with the earlier failure detection during momentum dumping, the de-pointing showed that there were problems with both A and B-side thrusters. It is thought that the thrusters ingested a variable mix of fuel and pressurant, with random losses of performance. ESAM commands the thrusters in pairs, and bubbles would give asymmetric axis cross-coupling effects.

4 Z-FLIP ANGULAR MOMENTUM MANAGEMENT

Shortly after ESAM8 it was possible to improvise a manual thruster-based momentum dumping treating thruster performance as an unreliable random property. A longer-term fix was devised; to use solar radiation torque and slews to manage momentum.

INTEGRAL spends most of its time above geostationary altitude where the dominant external torque is solar radiation pressure. Due to its shape and centre of mass location, the radiation torque vector is close to spacecraft Y-axis. Hence during observation in a fixed inertial attitude using wheel control, momentum accumulates along the spacecraft Y axis. If the spacecraft is slewed about Z through 180 deg, the internal momentum must remain fixed in inertial space. The radiation torque direction is always fixed w.r.t. the spacecraft, and in the new attitude it therefore acts to reduce the stored momentum. This is 'Z-flip'; using periodic large angle slews to change the radiation torque vector direction relative to the stored momentum vector, to manage the momentum size. Z-flip is illustrated below.

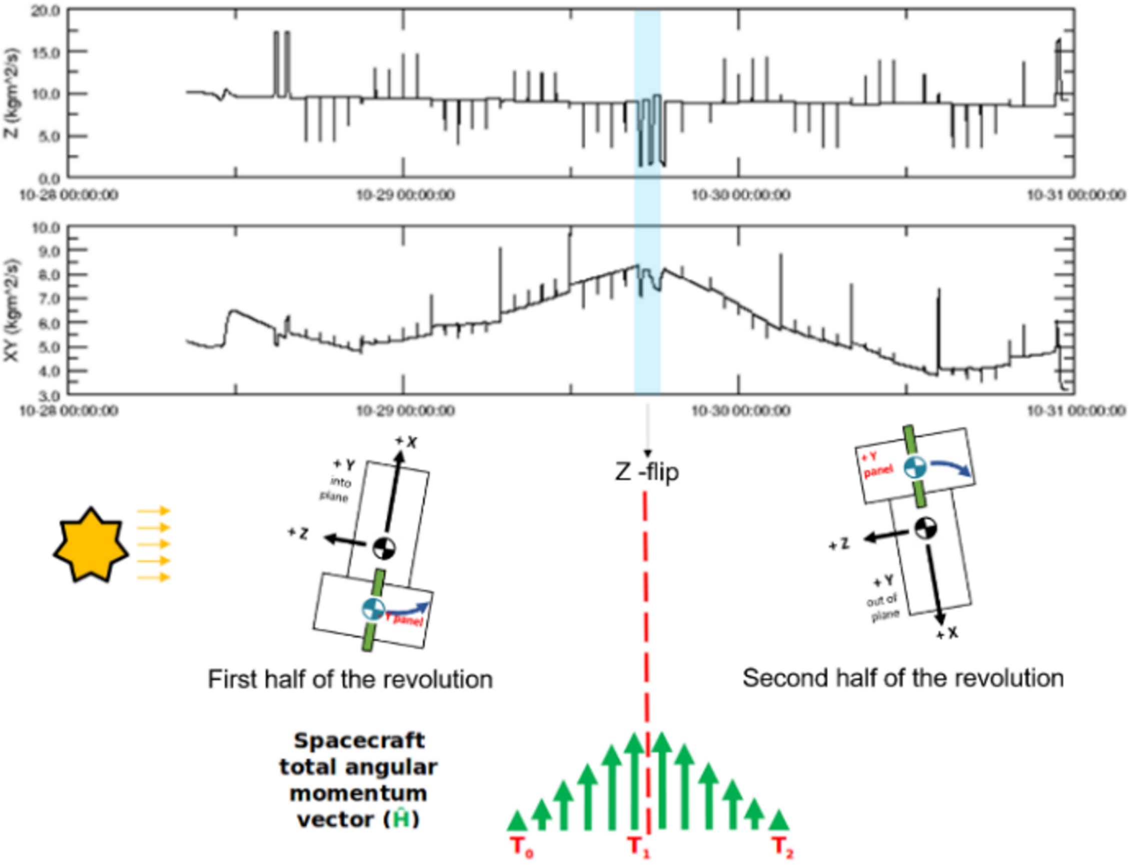


Figure 6 Wheel momentum components over time during 1 orbit
(Z axis component top, and XY plane middle), with slews showing as 'spikes'
(slews are almost instantaneous over the span of 3 days),
and the principle of Z-flip slews (bottom) [4]

Z-flip slew and observation sequences must be planned so that the long-term vector integral of torque to momentum is constrained, and the max short term excursion fits inside the wheel momentum limit. The graphic in the lower half of Figure 6 illustrates the simplest sequence with two attitudes separated by 180 deg, however other sequences separated by other angles are feasible. It was possible to retain the original operational range of roll and pitch angles for observing.

Initially after adopting the Z-flip strategy some periods in ‘dummy’ attitudes were required simply to manage momentum, effectively wasting some potential observing time. It was subsequently possible to design sequences of observations spread over the sky that also manage momentum and with a high efficiency for observing time.

Z-flip meant that the unreliable thrusters were no longer required for nominal operations. However if a further anomaly triggered safe mode, ESAM still depended on thrusters.

Industry proposed a new tuning of one of the original AOCS wheel modes, STA mode, as a partial solution to the now untrustworthy thruster safe mode. The new STA tuning modified the controller into a rate controller by using only a change of values, giving a larger convergence domain than the original STA mode (designed for initial conditions from steady sun pointing in thruster mode SSA). Although this was only a partial solution to the safe mode gap, as STA could not autonomously save the attitude (ground would need to react to a failure and command STA), this new tuning proved useful a few months later.

5 GYRO SLEW UPGRADE

The original design slew algorithm uses a combination of closed loop attitude control for 2-axes using FSS, and 3-axis feed-forward momentum profiles using closed loop speed control. The open loop attitude axis can be either stable or unstable with an exponential time constant as small as a few hundred of seconds, i.e. short enough that a large slew can last a few time constants. The original operating constraints limited the maximum value of a time-varying component of momentum during the slew, which prevented divergence. A momentum dump could be needed to meet this constraint before a large angle slew, and this was no longer possible after fuel depletion. The Z-flip strategy requires many large angle slews, and the only safe way to implement some of them was by breaking them into smaller angle slews, with additional operations and total slew time.

ESTEC determined that the original qualified lifetime of the DTG gyros was very conservative, as seen by the long-term behaviour of the same model on other spacecraft, and it was therefore acceptable to have gyros permanently switched on and used for slews, a big change to the original design philosophy. The Gyro Slew (GSL) slew software patch to ACC software modifies the original slew so that in addition to X and Y closed loop control using FSS, the Z-axis is controlled using integrated Z-rate. The gyro slew avoids the divergent behaviour of open loop slews, and this enables large angle slews to be commanded in a wider range of conditions. The gyro upgrade to slewing made the Z flip strategy far more practical, and allowed full recovery of observing efficiency. Work on the gyro slew software update was close to completion when ESAM9 occurred.

```
  AG2990   RATES FROM FDE IMU 360 as/s   KIR1        65535   D200001_1_2     11524    2021.313.11.29.15.509
X-GRID INTERVAL    000.00.15.00 AUTO HARD COPY    OFF
NAME     DESCRIPTION       VALUE         UNIT VLDITY SAMPLE TIME           MIN          MAX          LINE
A9234    TM ROLL RATE           2.40     as/s VALID  2021.313.11.29.16.509 -360.00      360.00
A9232    TM PITCH RATE         -2.40     as/s VALID  2021.313.11.29.16.509 -360.00      360.00
A9241    TM YAW RATE            0        as/s VALID  2021.313.11.29.16.509 -360.00      360.00
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Figure 7 Gyro-slew, plot of angular rate TM during GSL commissioning, Nov 2021

6 ESAM9, and RECOVERY from TUMBLING

In 22 September 2021 an SEU switched off an LCL, powering-off one of the 3 active reaction wheels, which caused loss of attitude control [2]. The attitude diverged and triggered ESAM9. ESAM was briefly able to control the attitude ('flying on fumes') before losing thrust, whilst the wheels started to spin down. An attempt to reacquire attitude using the normal recovery sequence from ESAM failed, and the spacecraft started to tumble (with ACC now in STA mode). Without reliable thrusters and a working safe mode, the spacecraft was in a dangerous state.

The spacecraft was tumbling with a peak rate of order 1000"/s (equivalent to a period of ~20 minutes, but the state was not a simple spin). The solar arrays received varying illumination during parts of the tumble, but overall the battery was slowly discharging. The normally sun pointing SAS1 provided measurements whilst it was illuminated during parts of the tumble (and the other 2 SAS, aligned on +Y and –Y showed the sun during other parts of the tumble). The narrower FOV FSS (+/-50 deg/axis) provided measurements less often, when +Z was near the sun.

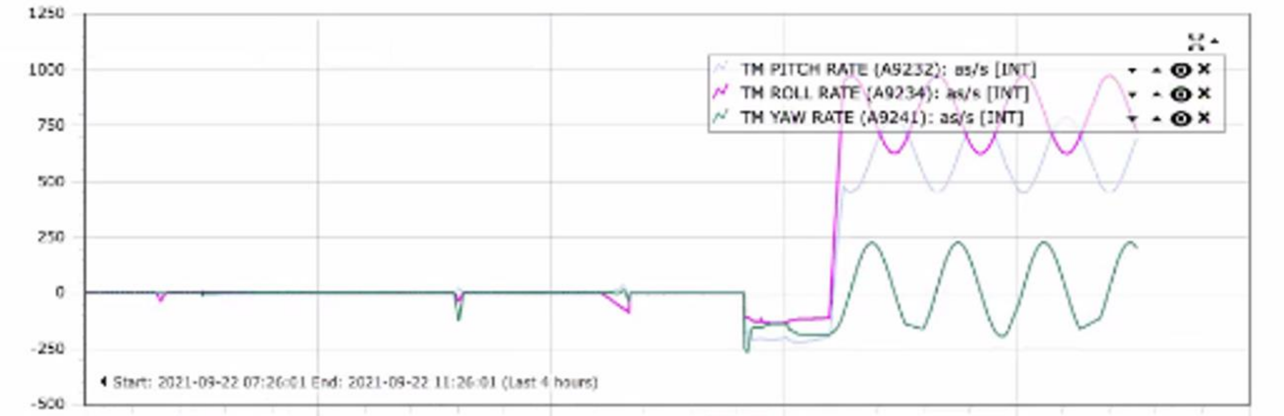


Figure 8 TM of angular rates ("/s) from ESAM9, showing entry to tumbling state (sinusoidal tumble rates include some gaps from TM outages, due to comms aspect angles)

The tumble motion meant that the pattern of sun angles varied from one 'spin' to the next. The angular rate was above the STR tracking rate, but FDE TM provided 3-axis rates from the IMUs. The IMUs were already permanently on in preparation for deploying GSL.

ESOC and industry debated how to recover by WebEx, with some discussion about trying one of the thruster branches. In parallel, the payload was commanded off to conserve power. With battery charge running out, we decided to command the ACC to SSA mode, which has the functionality to command changes of wheel speed directly from ground. SSA mode is a thruster mode, designed to operate using the FSS, and only when the sun is in the FSS FOV. The RCS was isolated to prevent thruster pulses (with unpredictable performance). With the RCS isolated, the only active actuation capability of SSA mode is closed loop control of the wheel speeds to ground-commanded values. In SSA the ACC also provides useful TM, in this case principally the wheel speed.

During the earlier recovery attempt from ESAM, STA mode had diverged, leaving 3 wheels running at the maximum speed allowed by a software saturation limit. It was recognised that additionally spinning up the 4th wheel (normally cold redundant) near to its max speed would balance the total momentum and reduce the angular rates. The 4th wheel was commanded to spin up, and had the hoped-for effect, significantly reducing the rates. All 4 wheels were now near to +/-max speed, and the spacecraft was now slowly rolling around X, with smaller Y and Z components.

It was realised that the wheel 4-momentum was near to a null vector, and all 4 wheels could be spun-down to zero RPM. This would have little effect on the spacecraft body rate (since it was a null space change), but would provide the benefit of giving wheel speed headroom for subsequent control efforts. The spin-down was commanded, leaving the wheels at zero speed, and with the same slow roll rate giving varying illumination.

At this point the authors started to coordinate changes of angular rate by generating specific wheel speed vectors. TM values from ESOC were shared by WebEx, the next wheel speed values were computed in Matlab by Airbus, and sent back by to ESOC, all by the WebEx chat function. The next change of wheel speeds was designed to reduce the angular rates to zero. Rate changes were computed using conservation of total momentum and knowledge of the wheel alignment matrix,

$$A\underline{h}^{RW} + J\underline{\omega} = constant \tag{1}$$

$$\Delta\underline{h}^{RW} = A^{-1}\left(-J\Delta\underline{\omega}\right) \tag{2}$$

where A is the wheel alignment matrix, h is momentum, J is spacecraft inertia, and ω is the body rate. The normal 3-wheel set of wheels was used.

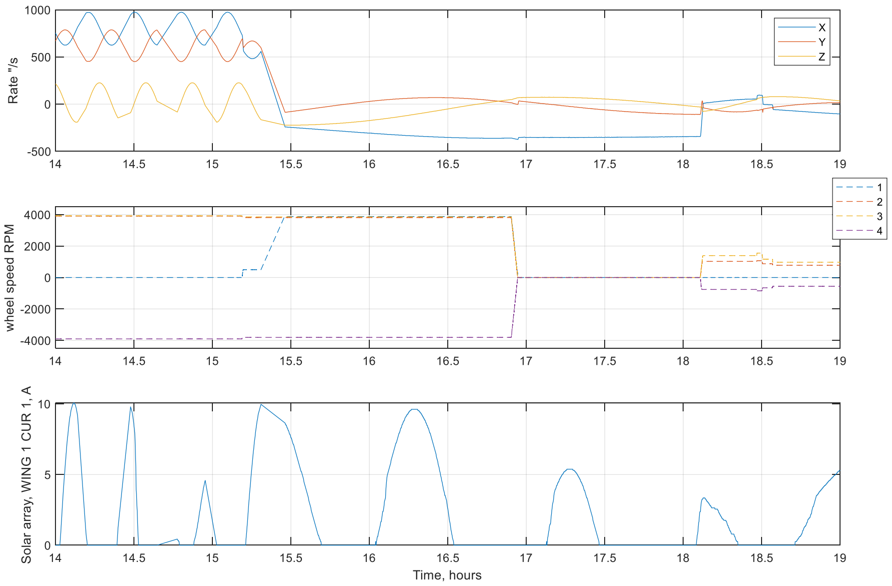
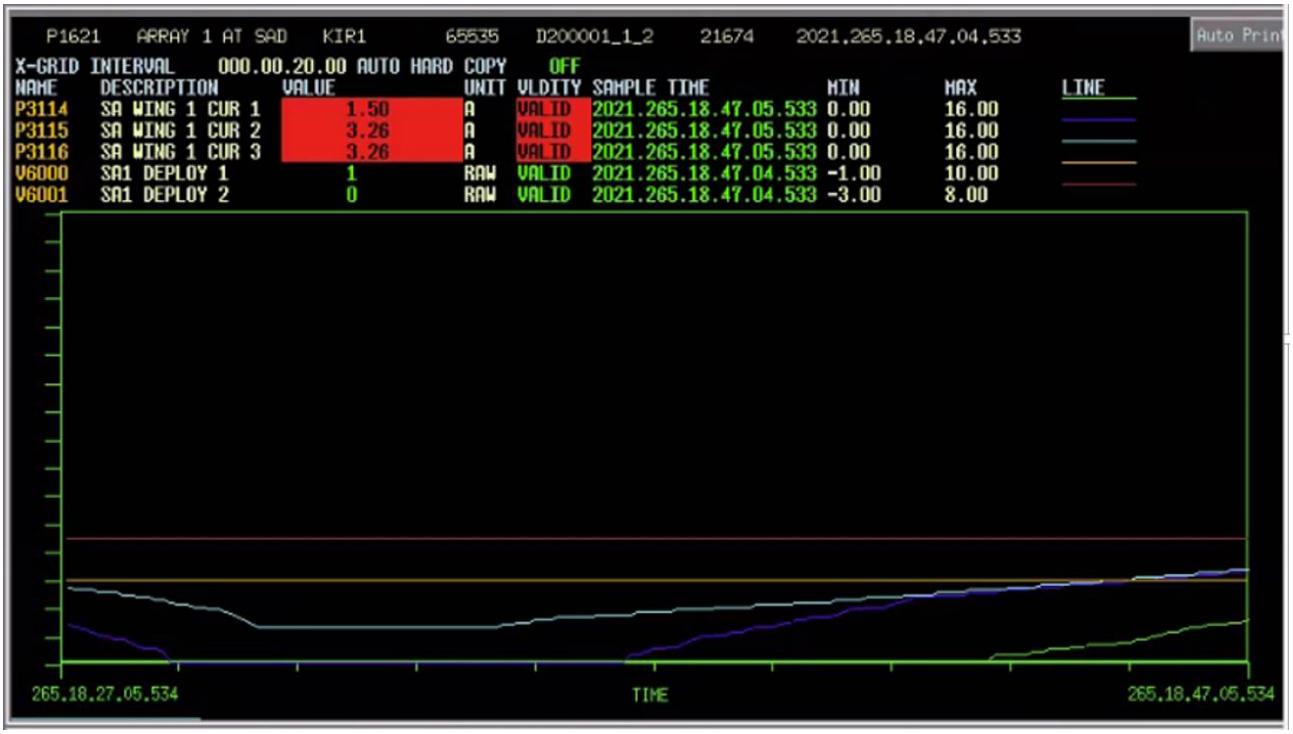


Figure 9 TM from the end of tumbling phase, when the first open loop changes of wheel speed were commanded in SSA mode.
Angular rates (top), wheel speeds (middle) and solar array current (bottom)

The next wheel speed changes were computed to reverse the roll rate and then stop again, to improve the array current (which was at a low value at high incidence, with one array partly in shadow of the spacecraft). For the first time in some hours there was a kind of attitude control, and the batteries were permanently being charged!



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  P1621    ARRAY 1 AT SAD    KIR1        65535    D200001_1_2     21674     2021.265.18.47.04.533
X-GRID INTERVAL    000.00.20.00 AUTO HARD COPY    OFF
NAME    DESCRIPTION     VALUE           UNIT VLDITY SAMPLE TIME           MIN     MAX       LINE
P3114   SA WING 1 CUR 1         1.50    A    VALID  2021.265.18.47.05.533 0.00    16.00
P3115   SA WING 1 CUR 2         3.26    A    VALID  2021.265.18.47.05.533 0.00    16.00
P3116   SA WING 1 CUR 3         3.26    A    VALID  2021.265.18.47.05.533 0.00    16.00
V6000   SA1 DEPLOY 1            1       RAW  VALID  2021.265.18.47.04.533 -1.00   10.00
V6001   SA1 DEPLOY 2            0       RAW  VALID  2021.265.18.47.04.533 -3.00   8.00
```

Figure 10 Solar array currents from the 3 panels of wing 1, at start of manual speed commanding
The TM display shows red warnings, indicating array outputs below the normal range.

Figure 10 shows the wing 1 currents as the spacecraft slowly rolls back towards a better illuminated attitude, just avoiding a complete loss of array power. Wing 1 was partly shadowed by the spacecraft body, accounting for the different values from the different panels.

There were some hours of trial and error wheel speed commanding, which eventually reached a state where the sun was at small sun alpha angle and large beta angle, as shown by SAS1. In order to return to normal on-board closed loop attitude control using the wheels, we needed the sun in the FOV of the FSS.

Using equations (1) and (2) above provides a definite means to change the rate, however as soon as the spacecraft starts to rotate, the internal momentum bias causes a gyro-dynamic torque, causing angular acceleration. This changes the rate, and so only small steps can be commanded before the rate changes significantly from the commanded one, and the change in attitude starts to change direction.

It was realised that to account for gyroscopic torques, the software used for planning slews could be used to generate the speed profile for a slew to pitch the spacecraft towards reacquiring the sun in the FSS. The speed values could be commanded in a timed sequence, approximating the slew, and this would generate the intended angular rate profile. The slew was planned, and the speed values were painstakingly commanded in sequence, with a 2 minute sampling of values. The sequence had the desired effect, the spacecraft slewed, mainly in a +Y sense as intended, and the sun re-entered the FSS FOV.

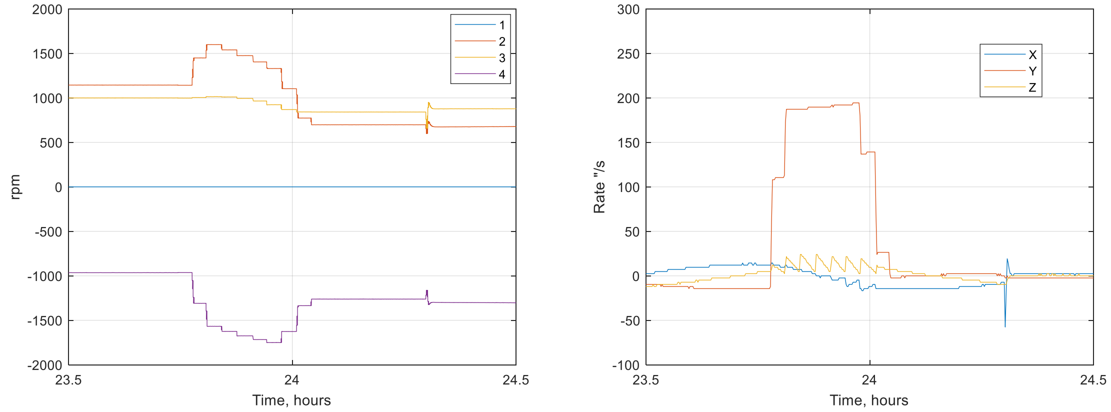

Figure 11 Piecewise ground-commanded slew, wheel speeds (left) and angular rates (right)
The final transient on the right side of the plot is the STA mode settling transient,
where closed loop control was finally restored

The modified STA mode was now used to resume closed loop attitude control at the current FSS position. The ACC mode was commanded from SSA to STA, and STA settled the rates.

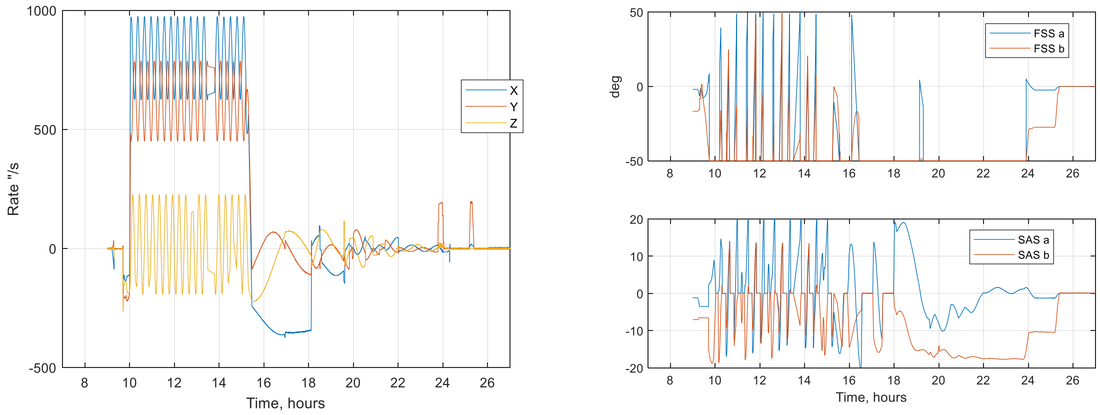

Figure 12 TM through whole of ESAM9 recovery, including tumbling phase (t~10 to 15 hours). Angular rates (left), and FSS angles and SAS1 sun sensor current (mA) outputs (right)

With the ACC now performing closed loop control using wheels, it was possible to command a further transition from STA to IPS. In IPS a conventional slew was used to return the sun the rest of the way to +Z, seen in Figure 12 as FSS angles and SAS1 outputs going to zero on all axes.

7 GROUND BASED SAFE MODE

After recovery from ESAM9, work on the gyro slew update was resumed, and it was successfully commissioned on the spacecraft in Nov 2021. GSL enabled large angle slews to be commanded as single manoeuvres for a wider range of initial momentum.

ESOC developed an automated ground-based procedure to automate a future recovery using the wheels. This would perform slews similar to the ESAM9 manual recovery in a systematic way. This procedure was hosted in the Mission Operations Information System (MOIS). The MOIS safe mode uses spacecraft TM of the SAS outputs, wheel speeds and IMU rates to generate sequences of wheel speed commands, with the ACC in SSA mode. The ground based mode will perform a sequence of single axis rotations, or drift proposals described in [4], to return the sun to +Z. INTEGRAL has almost continuous ground station visibility, and thus a ground based safe mode provides safety for most of the orbit, but not all of it. This gap motivated the development of a new safe mode on-board the spacecraft.

8 NSM, THE NEW SAFE MODE

NSM was developed from the MOIS procedure algorithm to provide a similar safe mode, able to acquire sun-pointing from any starting attitude. The CDMU was chosen as the host processor for NSM since it is independent of the AOCS and can thus theoretically recover any AOCS anomaly (including failed ACC). Conversely, if the CDMU fails the AOCS continues to function nominally, hence we have a system which is completely single failure tolerant. The original attitude role for the CDMU was only to act as a TM/TC pipeline to the AOCS functions housed in ACC and FDCE.

It was possible to modify the CDMU "TM Monitoring" functions to read wheel speed data directly from ACC TM, and in addition IMU angular rate and SAS Alpha/Beta angle data from FDE TM. It was then possible to modify further the CDMU to add the NSM algorithm for computing momentum changes to implement rate changes. NSM initialises AOCS to a known starting condition and forces the payload to a safe configuration. NSM commands the ACC into SSA mode and commands it to implement wheel speeds, using all 4 wheels if all are healthy, or 3 otherwise. The NSM control algorithm is derived from ESAM and from the wheel speed commanding used by MOIS. NSM is able to use the three SAS to efficiently recover from a random starting attitude (although it is expected that the most probable initial conditions for NSM will be close to sun pointing already). NSM contains FDIR functions to isolate various possible failures, such as a wheel failure (identified by failure of wheel speed TM to reach a commanded value).

NSM was developed in slightly more than 1 year during 2022-2023. More detail on NSM is provided in [4]. NSM was commissioned in March 2023, [5]. The software patch was installed in the CDMU, de-installed to validate the removal procedure, and then re-installed. A MOIS procedure was used to slew away from sun pointing to a set of different starting attitudes, before NSM was triggered to validate recovery using different wheel sets. NSM successfully returned +Z to sun pointing from each starting condition. If a future anomaly triggers the FDE anomaly detection, NSM will recover a safe attitude without ground assistance.

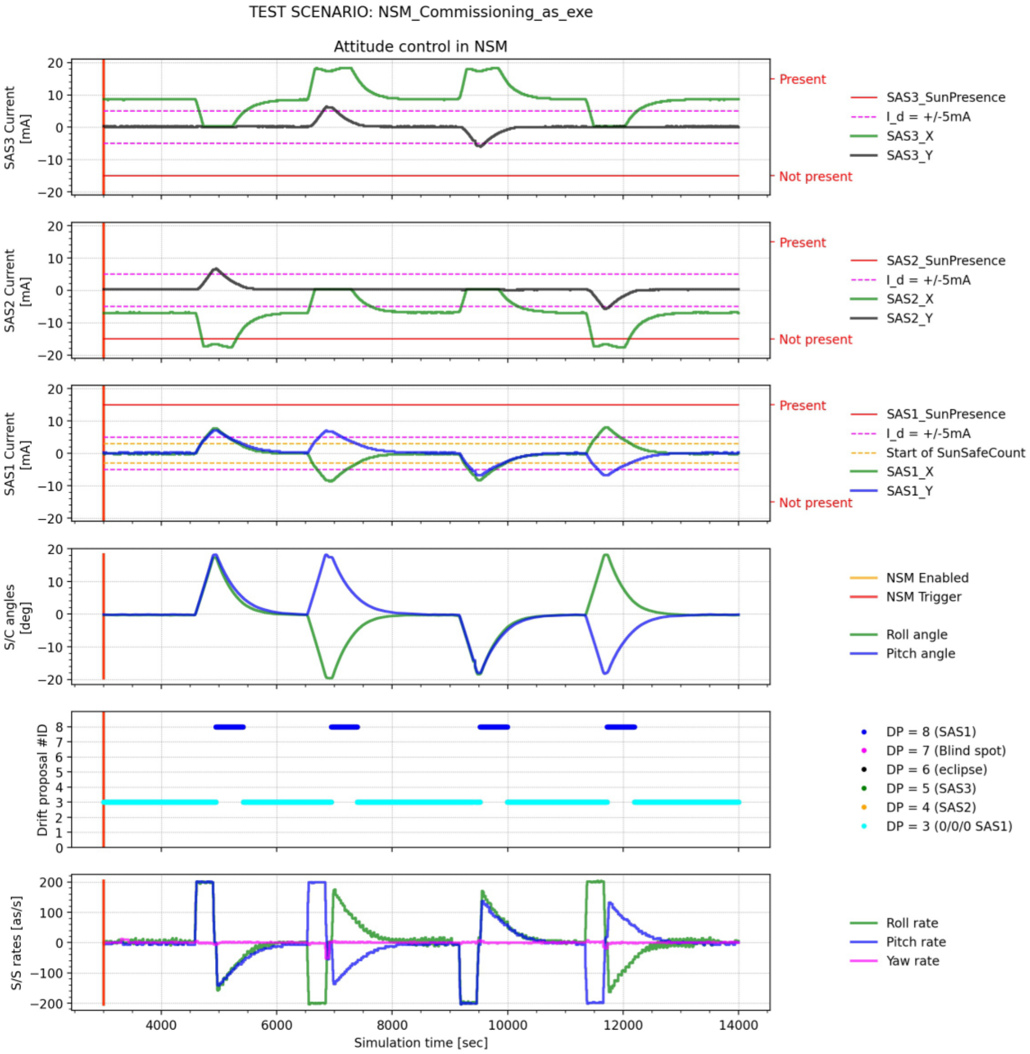

Figure 13 NSM commissioning TM: NSM was executed from 4 different initial attitudes, using a different wheel set for recovery each time.
Plots (from top to bottom); SAS currents (sun position) from the 3 SAS units, sun angles (roll and pitch, where sun pointing = (0,0)), NSM states, and angular rates

9 CONCLUSION

ESOC and industry have redesigned and extended the INTEGRAL AOCS to operate under conditions never considered before launch, to provide firstly nominal operations without using thrusters, and later a wheel-based safe mode. Separate upgrades to both ACC and CDMU software have added new functionality, taking advantage of unused memory space and spare processing power. Angular momentum management (‘momentum dumping’), regularly used the thrusters up to 2020. Since fuel depletion, ‘Z-flip’ slews, solar radiation torque and careful observation sequencing have eliminated the need for thrusters.

The ESAM9 mission critical anomaly came close to ending the mission, but dedicated teamwork improvised a recovery just in time to avoid battery depletion, in part by ground commanding wheel speed values to perform a series of slews to return the sun into the FSS FOV, allowing a return to normal AOCS modes.

A ground based safe mode was developed after ESAM9 to automate slewing using wheel speeds commanded from ground, and this provided a partial safety net (for most of the orbit, when there was ground contact), whilst the fully automated on-board recovery solution NSM was developed. ESOC successfully commissioned NSM in March 2023. Since the upload of NSM the INTEGRAL spacecraft once again has a fully operational on-board Safe Mode that can recover all single failures to AOCS units (including the type of LCL switch-off single event upset that caused ESAM9), multiple AOCS unit resets triggered by spurious PDU initialisation (ESAM7) and any attitude/rate anomaly detectable by FDE. All attitude control, both nominal and safe mode is now via wheels. A new constraint is the need to operate within the momentum range recoverable by NSM.

At the time of writing INTEGRAL has operated without nominal commands to the thrusters for almost 3 years. In March 2023 ESA approved a further extension of observations to the end of 2024 [6], which will mark 22 years of operations.

10 REFERENCES

[1] E. Kuulkers, “INTEGRAL reloaded: spacecraft, instruments and ground system,” New Astronomy Reviews, no. 93, p. 101629, 2021.

[2] T. Godard, “The New Life of ESA’s INTEGRAL Spacecraft Without Propulsion System,” Journal of the British Interplanetary Society, vol. 75, no. 3, 2022.

[3] “Three hours to save Integral,” ESA, 18/10/2021. [Online]. Available: https://www.esa.int/Enabling_Support/Operations/Three_hours_to_save_Integral. [Accessed 10/4/2023].

[4] G. De Marco, “New Safe Mode for INTEGRAL Mission”, presented at Space Ops 2023

[5] “Safe at last”, ESA, 03/04/2023. [Online]. Available: https://www.esa.int/Enabling_Support/Operations/Safe_at_last [Accessed 10/4/2023]

[6] “Extended Life for ESA's Science Missions”, ESA, 7/3/2023. [Online]. Available: https://sci.esa.int/web/director-desk/-/extended-life-for-esa-s-science-missions [Accessed 10/4/2023]