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XMM-Newton Reaction Wheel-Based Attitude Safe Mode

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Abstract

XMM (X-ray Multi Mirror) Newton is a European space telescope that can observe objects in the X-ray and UV/visible wavelengths, launched in 1999 and currently in the extended mission phase. Keeping XMM-Newton in operations for another decade is of paramount importance for the scientific community: this requires the flight control team to be prepared to face the challenges posed by such an extended mission lifetime, e.g. the diminishing and/or depleting propellant. INTEGRAL (INTErnational Gamma-Ray Astrophysics Laboratory) features a similar platform and has already been operated for 3 years without using any propellant. This operational example proves that this concept can be implemented, representing a viable solution for the XMM-Newton case.

XMM-Newton’s thrusters are currently used for attitude safe mode, reaction wheel biasing, and orbit correction. This paper focuses on the building blocks required to design and develop an on-board reaction wheel-based attitude safe mode, without relying on the propulsion subsystem. As on-board memory and autonomy are limited for XMM-Newton, extending both requires the development of an initial series of patches to the on-board software. These modifications are extensively tested with the operational simulator, before uplink.

Consequently, the new safe mode is patched in the central computer, rather than in the attitude control computer, ensuring its independence from the attitude subsystem. This allows XMM-Newton to autonomously react to possible anomalies, taking the spacecraft in a Sun pointing orientation while waiting for the flight control team’s recovery actions. The safe mode is prototyped in JavaScript, to allow the flight control team to test and refine it against the operational simulator. The safe mode uses the Sun acquisition sensors to determine the spacecraft’s orientation, inertial measurement units to get the rate, reaction wheel control electronics for the wheel speed, and the control laws are defined accordingly to the Sun’s position. The software uses all these inputs to compute the torque to be commanded via attitude control computer to the wheels.

The source code is then delivered to industry for the patch creation and returned to the flight control team, to undergo uplink and functional validation within a realistic test environment based on the operational simulator. If the key safe mode functionalities are preserved, then the software is commissioned on board.

Depending on XMM-Newton’s future needs and the estimated available propellant, or because of possible failures, the decision on when making the reaction wheel-based safe mode operational will be made. Nonetheless, the enhanced autonomy can be immediately used, as rudimental failure detection isolation and recovery mechanism.

Keywords: safe mode, reaction wheel, XMM-Newton.

Nomenclature

A	Reaction Wheels orientation matrix in spacecraft reference frame
h	Angular momentum, [Nms]
w	Angular rate, [as/s]

Acronyms/Abbreviations

ACC	Attitude Control Computer
ADA	Programming language named after Ada Lovelace, mathematician and the first computer programmer

AOCS	Attitude and Orbit Control System
CDMU	Command and Data Management Unit
ESAM	Emergency Safe Attitude Mode
FCE	Failure Control Electronics
FDE	Failure Detection Electronics
FDCE	Failure Detection and Control Electronics
FoV	Field of View
FSS	Fine Sun Sensors
IMU	Inertial Measurement Unit
NSM	New Safe Mode
PROM	Programmable Read Only Memory
RW	Reaction Wheels
SAS	Solar Acquisition Sensor
SEU	Single Event Upset

1. Introduction

1.1 XMM-Newton spacecraft

XMM-Newton [1] was launched on Ariane-5 on 10 December 1999. As a corner stone mission of ESAs Horizon 2000 programme, it observes the hot X-ray universe with objects like neutron stars, black holes or active galaxies and has the largest X-ray collecting area of an X-ray observatory with a telescope ever launched [2]. The three-axis stabilized and 3.8 tons heavy spacecraft with a pointing accuracy of one arcsec consists of three main sections: a 7-meter-long telescope tube, a squarish service module also carrying three telescopes at its forward broader end and the focal plane assembly housing the detectors at its other extremity. This gives the spacecraft a total length of 10.8 m. Its pair of solar panels has a 16-metre span.

XMM-Newton was inserted into a highly elliptical orbit with a perigee around 20.000 km (now 22800 km) and an Apogee of 120000 km (now 98300 km) and a southern inclination of 40° (now 69°), [3]. Highly eccentric orbit offers the longest possible observation periods as XMM-Newton instruments need to work outside the radiation belts surrounding the Earth. The orbital period of XMM-Newton is exactly two times the Earth rotation period to maintain optimal contact between XMM-Newton and the ground stations tracking the satellite which is fundamental as it allows scientific data to be received in real-time (note that XMM-Newton has no onboard data storage capacity, so all data is immediately down-linked to the ground in real time).

The spacecraft was built by Dornier (now Airbus Defence and Space) from 1994-1999. Its main subsystems are the Attitude and Orbit Control System including the Reaction Control System (AOCS and RCS), On Board Data Handling System (OBDH), the Power and Thermal System (EPS, TCS), and the Radio Frequency System (RF). All subsystems have their own redundancy concept. The AOCS provides three-axis stabilisation during all modes. The AOCS architecture is formed around the Attitude Control Computer (ACC), running the software for mode control and the attitude and thrust control laws. The AOCS uses a Star Tracker and Fine Sun Sensor to provide the absolute reference. The star tracker is a small telescope with 3° x 4° field of view and a thermo-electrically cooled CCD detector. The Fine Sun Sensors deliver pitch and roll information, and their field of view is ±45° per sensor. Reaction wheels are the primary actuators for attitude control. In the classic 3-wheel mode operations scenario any 3 out of 4 reaction wheels can be used for active control, each one with a net torque of 0.2 Nm and 40 Nms momentum capacity. The reaction wheel that is not used for active control was originally off and only used as a cold redundancy unit. Spacecraft body axes orientation is shown in Fig. 1.

The thrusters use monopropellant propulsion system utilizing Hydrazine (N₂H₄) in blow down mode with Helium as pressurant. The propellant is stored in four surface tension tanks placed around the central cone element of the service module structure of the spacecraft. Eight monopropellant 20 N thrusters divided into two redundant branches each consisting of 4 thrusters are used for delta-V manoeuvres attitude control and reaction wheel desaturation. The functional objective of the OBDH subsystem is to provide command and telemetry capability allowing the overall spacecraft control for the operation centre and to provide clock and timing facilities for the other subsystems. It consists out of CDMU, two Remote Terminal Units (RTU) and six Digital Bus Units (DBU).

The EPS provides electrical power to all subsystems. During sunlight power is provided by a fixed, two-wing deployable Solar Array and in eclipse by two Nickel Cadmium batteries. Both energy sources are conditioned to provide a single 28 V DC regulated bus. The solar array generates a maximum power of 1.8 kW.

The TCS features a combination of active and passive thermal control systems originally without any on-board control software. This means that all the heater lines are either on-line controlled from ground or thermostat controlled. The ground commands open, or close transistor switches installed within the service module power distribution units, focal plane assembly power distribution units and mirror thermal control unit in the power lines between heater and latching current limiters. During ground contact outages, the heater lines are controlled by bi-metal mechanical thermostats in the satellite.

The Radio Frequency (RF) subsystem is composed of three main blocks which are two Low Gain Antennas, two transponders and a Radio Frequency Distribution Network with two switches to connect the transponders to the antennae. An S-Band transponder comprises three main modules: a diplexer, a receiver and a transmitter. The receiver assures the reception of signal in the range of 2025 to 2120 MHz (S- band) and the phase demodulation of the telecommand signal and the ranging tones. The transmitter performs the modulation of the telemetry video signal and the rang tones, as well as the power amplification of the output signal. The diplexer allows operating simultaneously the receiver and the transmitter with just a single RF connection. This configuration allows an effective data rate of 80 kb/s for downlink and 2kbs for uplink.

The European Space Operation Centre (ESOC) controls the mission 24/7, 365 days per year through a live ground station connection, since the spacecraft has only a limited amount of automation. However, over the years a lot of ground automation has been developed to operate it in a safe and efficient manner and to generate the highest possible science output.

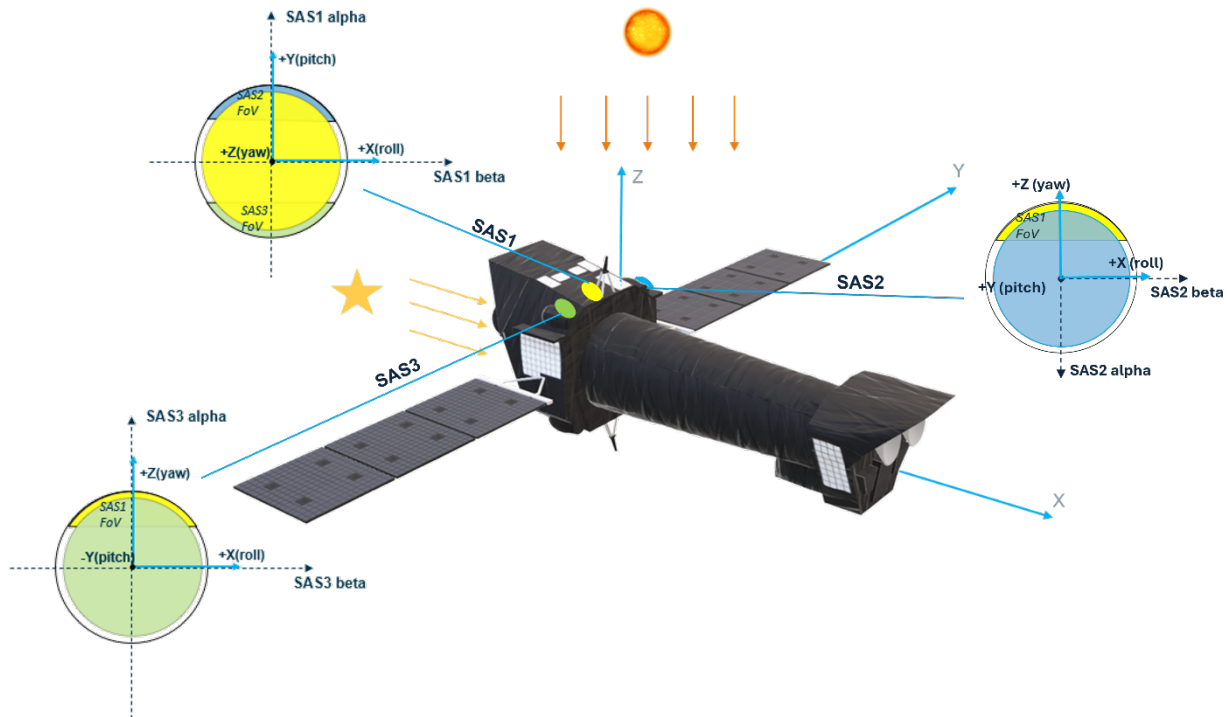


Fig. 1: XMM-Newton body axis. The observation direction, where scientific targets are located, is -X, while the Sun direction is +Z. Maximum excursion from the perfect Sun direction due to target location during nominal operations is $\pm 20^\circ$ on roll and pitch. Also Sun Acquisition Sensors are shown, together with their axes orientation with respect to the spacecraft body axes.

1.2 Towards the next decade

The XMM-Newton fuel was originally supposed to support the mission for 2+8 years. After a very good orbit injection by Ariane-5 not all expected fuel was needed to reach the final orbit. A change of orbit in 2003 to allow a full coverage of the orbit by the Santiago station caused a significant amount of fuel to be used. After that time various fuel saving activities have been put in place, the most effective being the usage of 4 wheels instead of 3. This changed the fuel consumption around 2014 from around 6 kg/year to below 2.5 kg/year. Fuel is used for the attitude safe mode (section 2) and for reaction wheel angular momentum off-loading, which is combined with small orbit correction to

keep the spacecraft ground track. Currently the estimates give a conservative approximation of availability of fuel until after 2034. It is currently not expected that fuel consumption can further be reduced as it is used also to keep the same ground track.

The current baseline targets to keep XMM-Newton operational ideally until NewAthena is launched (future X-ray mission, [4]) and therefore the Flight Control Team together with industry was asked to investigate on strategies to continue science operations after propellant will be over as currently this is the only major life-limiting factor. For this purpose, the Flight Control team used as a reference the strategies adopted by INTEGRAL (INTERNATIONAL Gamma-Ray Astrophysics Laboratory) that features a similar platform and has already been operated for 3 years without using any propellant, [5] [6]. As already mentioned, propellant is used for the attitude safe mode and to reduce the angular momentum accumulated by the reaction wheels. For this reason, a fuel-free reaction wheel based safe mode has been studied and implemented, main subject of this paper.

The strategy to cope with the reaction wheel angular momentum control, called Z-flip, is not subject of this paper. Z-flip operations use the effect of the solar pressure on the spacecraft solar panels to balance the accumulated angular momentum to avoid reaction wheel offloading [6], but it is still under investigation how it will impact science efficiency and orbit drift for XMM-Newton.

1.3 Emergency Safe Attitude Mode (ESAM)

The XMM-Newton spacecraft attitude is managed by the Attitude Control Computer, ACC, part of the Attitude and Orbit Control Subsystem (AOCS). The spacecraft is also equipped with a Failure Detection and Control Electronics unit (FDCE) that has the duty to evaluate if there is an attitude anomaly and recover from it. The FDCE unit is made by two parties: the FDE (detection) and the FCE (control).

The FDE monitors different attitude sensors readings and, in case it detects an attitude anomaly based on pre-defined criteria and thresholds, it will trigger an AOCS reconfiguration order, to re-configure it to allow the FCE to recover the attitude. This is the so-called attitude safe mode. At the end of the automatic reconfiguration the ACC is taken out from the control loop and the satellite attitude control is switched to the FCE which uses the thrusters to steer the satellite towards a Sun pointing attitude until the Flight Control Team intervene to manually recover back to ACC control. During this phase the attitude is read via the Sun Acquisition Sensors (SAS) and the rates are measured with Inertial measurements Units (IMU). XMM-Newton is equipped with three SASs, mounted on three different panels of the service model, respectively pointing toward to +X, +Y and -Y with a field of view of +/-97deg (their orientation ensures a certain level of overlap between them and minimise the blind spot of the back side of the service module, Fig. 1). At the beginning of life, maximum output current was ~33.33mA, and since then it is possible to observe an almost linear degradation, and it will not be a problem before at least 2040.

1.4 The XMM-Newton CDMU

The CDMU Software as delivered Pre-launch and burnt into PROM is divided into the Standard Application Software (SASW) for core services and the Mission Specific Software (MSSW) for XMM-Newton.

During the XMM-Newton Mission several patches have been built and uplinked to the CDMU onboard software, but all of them are lost in the event of a CDMU Processor Halt, or power cycle of the Central Terminal Unit (CTU), or switchover of the CTU from A to B. These patches include few bug-fixes uplinked to the CDMU onboard software, payload temperature control safety function and some additional software-based thermal control.

2. The NSM Patch

As already introduced, XMM-Newton has a limited on-board autonomy, which has been enhanced during its 25 years of operations with a mixture of ground-based automation and on-board computer patches (section 1.3). This section will cover only the latest of CDMU patches, the so called New Safe Mode (NSM) patch, which include three new features:

1. Extend the on-board memory
2. On board procedures
3. Reaction wheel-based attitude safe mode

Each of them is detailed in the next sections.

The NSM patch for XMM-Newton is based on the one uploaded on INTEGRAL [7]. It has been decided to upload it to the CDMU rather than the ACC (attitude-specific computer) to keep the attitude safe mode decoupled from the ACC itself, keeping the baseline implemented on the spacecraft, where the attitude safe mode uses the FCE for controlling purposes, and not the ACC (see section 1.3).

2.1 Extend on-board memory

On XMM-Newton all the CDMU software code runs in address state 0, but the full logical mapping for this address space which goes up to 128KWords (64KWords of code space, 64KWords of data) is currently not completely defined, with the potential to map 4 more code and 5 more data pages (respectively 16KWords and 20KWords).

The Fig. 2 shows a schematic of the XMM-Newton CDMU address state 0. There are some code and data areas that were already defined/mapped. To map the additional pages just mentioned (4 code and 5 data) it was necessary to create a low-level assembler instruction patch (in light blue in Fig. 2), place it in the memory area that is empty and execute it to have the new areas mapped and therefore usable (in Fig. 2 labelled as ‘new mapped area’). The new safe mode patch, including the on-board monitoring, the on-board procedure execution capability and the reaction-wheel based safe mode is loaded and executed in these new areas, as the memory originally used by the CDMU did not have enough space to allocate it.

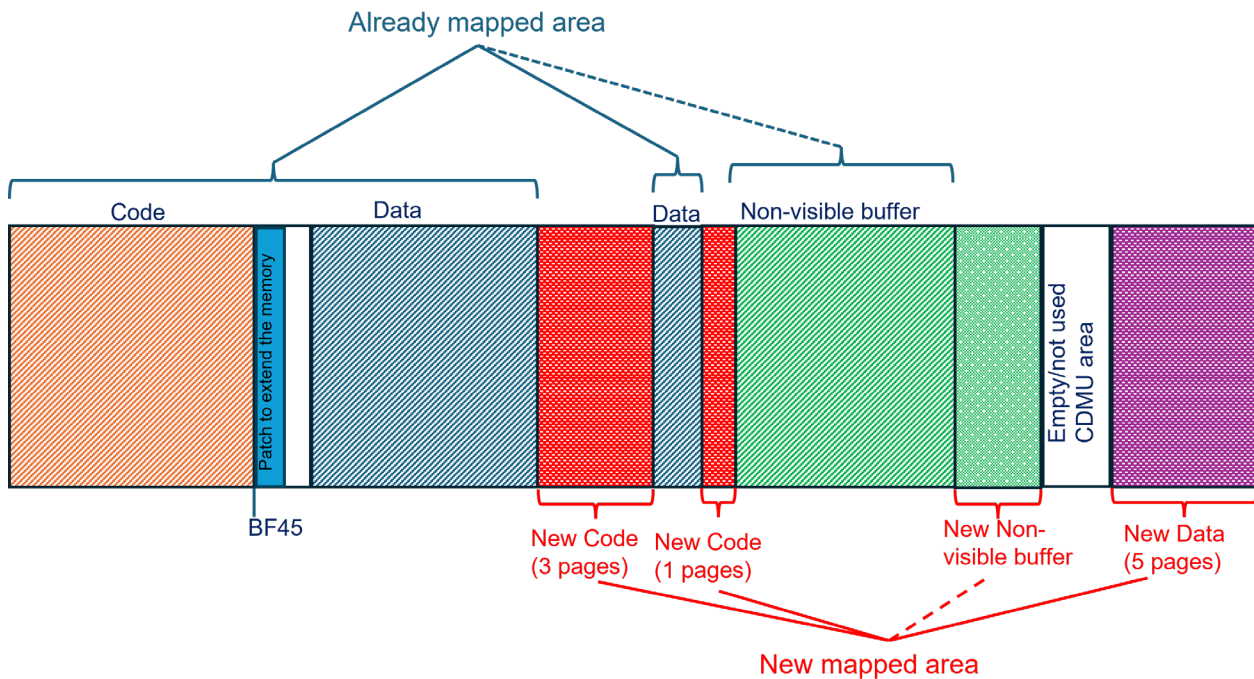


Fig. 2: XMM-Newton CDMU mapping schematic.

2.2 On-board procedures

To replicate the approach used by INTEGRAL and to use the reaction-wheel based safe mode, it was necessary to add to the spacecraft the feature to release on-board procedure in a rudimental form. These on-board procedures are triggered based on chosen parameters values or statuses and, once the procedures execution begins, all the commands contained in it are executed sequentially.

This mechanism of on-board procedure execution was not originally implemented for XMM-Newton, but it was a necessary addition to be able to reconfigure the AOCS subsystem to execute the reaction-wheel based safe mode. The AOCS reconfiguration is triggered by an attitude anomaly detected by the FDE, as it is for ESAM (thruster-based attitude safe mode), Fig. 3.

It should be noted that the XMM implementation of automatic on-board procedures as part of the NSM has extended the original INTEGRAL approach: the ability to release sequences of commands with command release relative timing, pre-transmission validation, and interlocking functions have been added to truly allow the term “on-board procedure” to be used.

As part of the AOCS reconfiguration sequence (i.e. AOCS reconfiguration 1 in Fig. 3), the prime ACC is powered OFF, together with all reaction wheels (RW), then the backup ACC is powered ON together with all RW. During normal scientific pointing, the ACC mode used relies on fine Sun sensor and star trackers to keep the spacecraft on target. The reconfiguration sequence changes the ACC mode to one where the wheels can be directly commanded

providing them with any target angular momentum. In case of the reaction-wheel based safe mode this is computed by the CDMU and provided then to ACC to the wheels. The last commands of the reconfiguration sequence are used to configure reaction wheel safe mode parameters (i.e. wheel/spacecraft inertia, convergence parameters, etc.).

In case any of the hardware used by the reaction wheel safe mode (NSM1) is failed, then the controller will fail, and this will trigger the execution of a second on-board procedure that will re-configure the AOCS subsystem (i.e. AOCS reconfiguration 2 in Fig. 3), to use different hardware (e.g. different ACC and IMUs) to recover the attitude (NSM2).

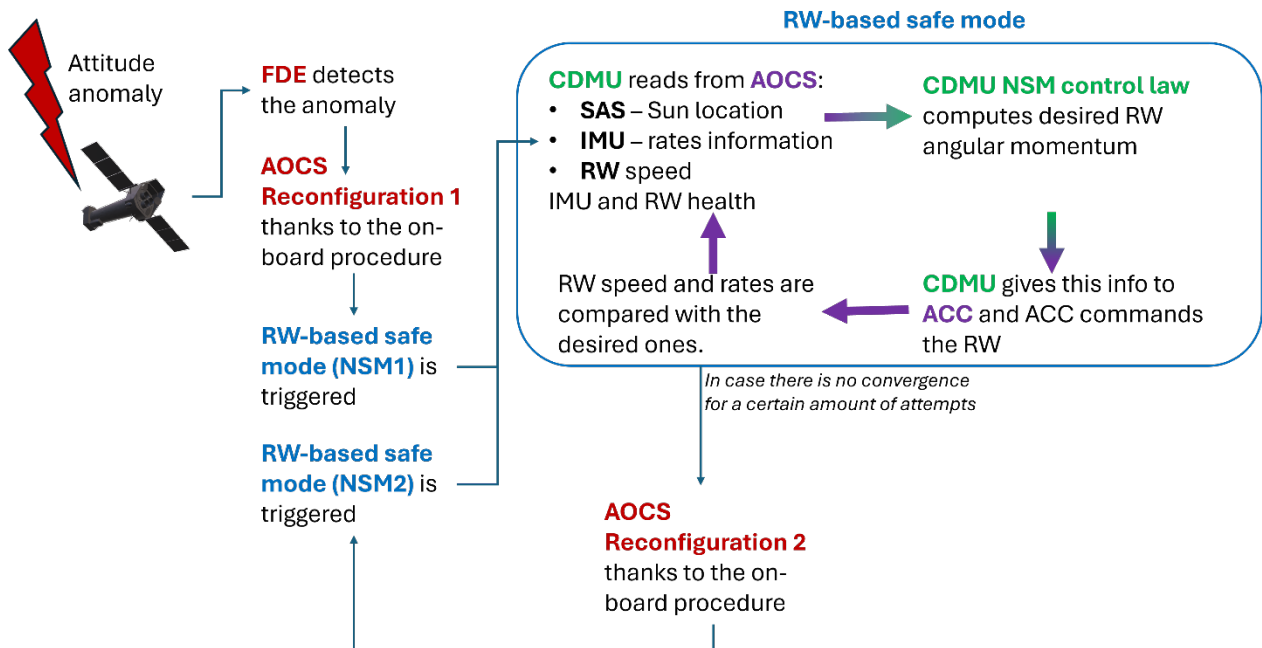


Fig. 3: NSM components with their functionalities.

It is foreseen to use the on-board procedure feature also to add additional on-board autonomous reaction not related with the safe mode.

2.3 The reaction-wheel based safe mode

This section focuses on the reaction-wheel based safe mode (NSM) control algorithm, which schematic is represented in the blue box in Fig. 3.

NSM foresees close interaction between CDMU and the AOCS:

- Information about satellite orientation, rotation rates, AOCS units’ health and reaction wheel speed is provided by the AOCS subsystem to the CDMU.
- With these data, the CDMU evaluates hardware health and computes which is the RW desired angular momentum to achieve a satellite rotation that will bring the satellite towards a Sun pointing attitude.
- This information is provided to the AOCS (ACC) that will then command the RW accordingly.
- The result is communicated to CDMU which will evaluate if the commands have been successful.

Each of these aspects is detailed in the following sections.

2.3.1 Inputs to the CDMU

The NSM, like the Emergency Attitude Safe Mode (ESAM), uses SASs to determine the relative position of the Sun with respect to the spacecraft. XMM-Newton is provided with three SASs:

- SAS1 is perpendicular to the +Z axis, which means that if Sun illuminates SAS1, then the solar arrays are illuminated (Fig. 1);
- SAS2 and SAS3 are perpendicular, respectively, to +Y and -Y axes (Fig. 1).

SASs outputs are expressed as α and β (measured in currents, mA) which are respectively the current components measured along SAS Y (α) axes and SAS X axes (β) respectively. The current along the two axis is generated by the

Sun when it is illuminating the SAS surface: depending on how the Sun vector is oriented, the two currents components along the sensor X and Y axis change.

Spacecraft rates are measured by gyroscopes (IMUs, from the FDE) while RW command and speed measurement are provided by the RW driving electronics. These inputs are used by the control algorithm to command the RWs to change the spacecraft orientation toward the Sun with zero residual rates.

RW and IMU health are assed based on LCL status and current flowing (IMU health is determined by FCE output).

2.3.2 NSM CDMU algorithm and control law

Once NSM trigger is set, at the end of the AOCs reconfiguration sequence, NSM algorithm will try to dump the rates as first action (Mode 0). Once this is completed then it will evaluate which RW angular momentum needs to be commanded to RW to steer the satellite towards a Sun pointing attitude (Modes 1-4).

Fig. 4 shows an overview of modes transition in NSM. Each mode is detailed hereafter. Indicatively, it is possible to have a mode change every NSM cycle, where the NSM cycle corresponds to the CDMU cycle that is 4s long.

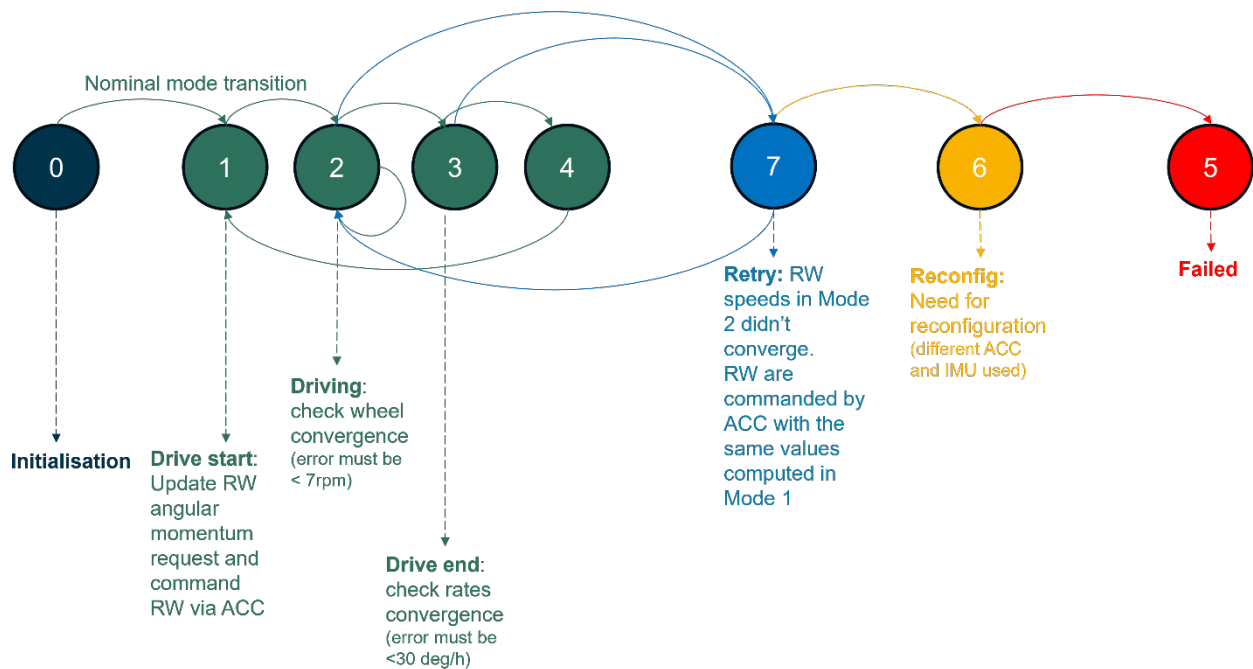


Fig. 4: NSM simplified mode transition.

0 - Initialization: initialize NSM configuration variables. The initial control law imposes to reduce rates to zero. NSM will stay in this mode unless "Triggered" to drive wheels. From Mode 0 there is a transition to Mode 1.

1 - Drive Start: different control laws are applied based on Sun position. Different control laws are described later in this section. Control laws are used to determine which is the target/final angular momentum rate that the spacecraft should have to achieve a Sun pointing attitude. This information is used to compute the corresponding final spacecraft angular momentum, $\mathbf{h}_{f,SC}$. This value is then used in Eq. (1) to compute the target/final wheel angular momentum to be given to the ACC which then commands the wheels.

2 - Driving: checks that wheel speeds converge within ~ 7 rpm (6.7 rpm). If convergence is not achieved in that CDMU cycle, a *timer* increases by one. If the wheel speeds do not converge in the following cycle, then the *timer* increases again. The *timer* can increase up to 30 (timeout): at this point the *number of retries* increases by 1 and Mode 7 (retry) transition is commanded. A maximum of 4 *retries* are allowed, and just before the *number of retries* would become 5, the mode transition to Mode 6 (Reconfiguration) would happen.

3 - Drive End: when wheels speeds are met then spacecraft rates are checked against the expected ones (allowed error is equal to 30°/h). If there is no convergence, transition to Mode 7 (Retry) is commanded and the *number of retries* increases by one unit.

4 - Wait: all convergence criteria are met (i.e., wheels speed and spacecraft rates converge) and the algorithm waits a certain number of seconds (currently set to 0s) to go back to Mode 1 (Drive Start) mode. This mode has been included to cover the case in which RW are commanded too often.

5 - Failed: if target momentum or rates are not achieved after the reconfiguration flag is set. Reconfiguration flag is set if there is one Mode 6 transition (Reconfiguration) and at the end of the second NSM attempt (NSM2, section 2.2) there is no convergence.

6 - Reconfigure: this mode is entered after the *maximum number of retries* of 4 is reached. The software assumes that there are faulty/unresponsive units therefore it configures AOCS to use different ones: the NSM2 is triggered (section 2.2) which uses ACC-A, redundant IMU set.

7 - Retry: retry driving the wheels with last control law output (do not select new one). Currently up to 4 *maximum number of retries* are allowed before entering Mode 6 (Reconfigure).

This is summarised in Fig. 5.

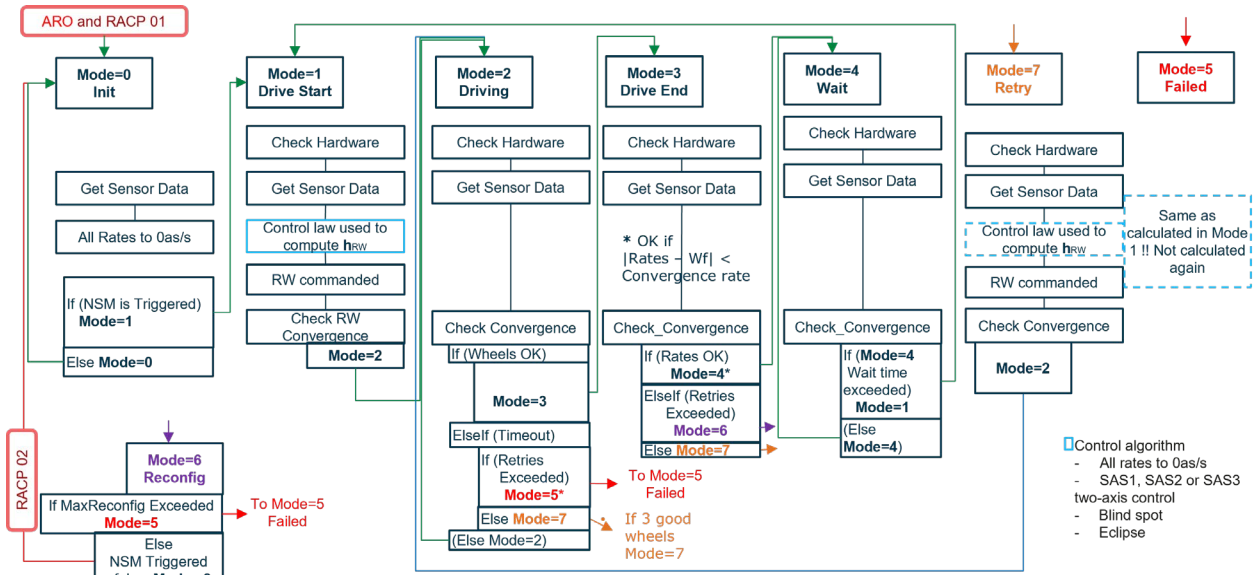


Fig. 5: NSM detailed mode transition.

NSM baseline foresees to use all 4 RWs to perform these actions, this configuration is automatically changed if one of the units is identified as faulty or if ground control decides to use a different subset of RWs. The basic equations used are reported below.

$$\mathbf{h}_{f,RW} = \mathbf{h}_{i,RW} + \mathbf{h}_{i,SC} - \mathbf{h}_{f,SC} \quad (1)$$

The Eq. (1) uses the conservation of angular momentum to determine the final RW angular momentum ($\mathbf{h}_{f,RW}$) to be commanded to the wheel (via ACC) to reach the desired attitude. $\mathbf{h}_{f,RW}$ is expressed in spacecraft reference frame but the command given by the ACC to the RW to force a certain angular momentum requires this quantity to be expressed in RW reference frame (i.e., inputs to the telecommand are one angular momentum value for each wheel).

Using the RW orientation matrix, \mathbf{A} , it is possible to obtain the RWs angular momentum values to be commanded to the RW to obtain the desired final spacecraft angular momentum ($\mathbf{h}_{f,SC}$), needed to drive the spacecraft towards the correct attitude.

$$\mathbf{h}_{f,RW,RWframe} = \tilde{\mathbf{A}}^{-1} \mathbf{h}_{f,RW} \quad (2)$$

\mathbf{A} is a 3x4 matrix which columns represents the orientation of each RW rotation axis with respect to spacecraft body frame. Matrix is shown in Eq. (3).

$$\mathbf{A} = \begin{bmatrix} \cos 60^\circ & -\cos 60^\circ & -\cos 60^\circ & -\cos 60^\circ \\ 0 & \sin 60^\circ & 0 & -\sin 60^\circ \\ \sin 60^\circ & 0 & \sin 60^\circ & 0 \end{bmatrix} \quad (3)$$

In case the recovery is executed using three RWs, then $\tilde{\mathbf{A}}$ is equal to \mathbf{A} without the column corresponding to the RW that is not use (the result is a 3x3 matrix). In case four RW are used then $\tilde{\mathbf{A}} = \mathbf{A}$ (3x4 matrix) and $\tilde{\mathbf{A}}^{-1}$ is \mathbf{A} pseudo-inverse matrix.

Going back to Eq. (1), terms $\mathbf{h}_{i,RW}$ (initial RW angular momentum) and $\mathbf{h}_{i,SC}$ (initial spacecraft angular momentum) are determined, respectively, from RW speeds measurements and IMUs body rates readings, multiplying both terms by the respective inertias (i.e., RW and spacecraft inertias).

The final spacecraft momentum ($\mathbf{h}_{f,SC}$) it is obtained multiplying the desired final spacecraft body rates (\mathbf{w}_f , provided by the NSM control law based on SAS readings) by the spacecraft inertia. This value is computed in Mode 1 (Drive Start) based on different control laws are applied, based on Sun position, to determine how the spacecraft shall rotate (i.e. rates, direction): the control law selection logic is summarised in Fig. 6.

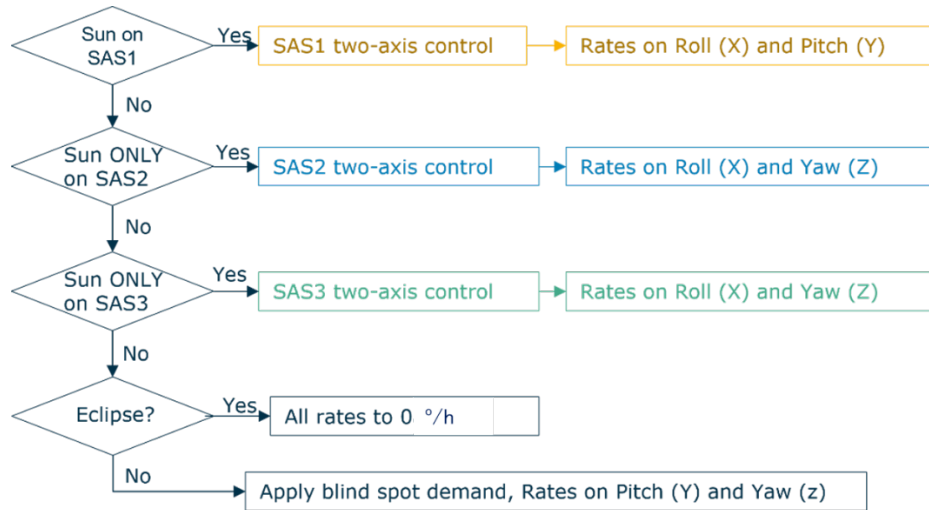


Fig. 6: NSM control laws selection logic.

The NSM algorithm in Mode 1 checks first Sun is on SAS1. Sun is on SAS1 if:

- Sun present on SAS1 (Sun presence current lower threshold for all SASs is 10.4mA) or
- one of the SAS1 output currents is higher than a certain value I_D (configurable) and currently set to 5mA.

Sun is on SAS2 or on SAS3 if:

- Sun is not on SAS1 and
- Sun present on SAS2/3 only or
- one of the SAS2/3 outputs currents is higher than a certain value I_D (configurable) and currently set to 5mA.

The two- axis control algorithm consists in reading SASs output and using them to provide variable rates around two axes. Based on this, four different two-axis control laws are identified:

1. SAS1 two-axis control law, if Sun is visible on SAS1;
2. SAS2 two-axis control law, if Sun is visible only on SAS2;
3. SAS3 two-axis control law, if Sun is visible only on SAS3;
4. Blind spot control law.

In case the Sun is visible on SAS1 (no matter if it is also visible on SAS2/SAS3), the two-axis control is applied on roll and pitch. The control law reads the current output from SAS1 (in terms of α and β angles expressed as a function of the current read from the SAS, [mA]) and brings the Sun in the centre of SAS1 field of view. The rotation rate around the two axis is progressively reduced once the Sun gets close enough to the SAS1 FoV centre. The rotation rate starts decreasing when SAS1 readings are lower than 10mA (configurable, expressed as $i_{\text{threshold}}$ in Eq.(4)). Rates decreases proportionally to α/β readings. Maximum rotation rates around both axis is 90°/h (configurable, expressed as w_{max}). The value 90°/h is the one used to execute slews during routine operations. SASs-local axes α and β are reported in Fig. 1 with respect to the spacecraft body axes.

In the XMM-Newton NSM version of the algorithm, when both α and β are within the 5° on FSS (called Sun safe window), there is an option to dump the rates and if it is enabled then the rates are stopped immediately otherwise they

are simply reduced until α and β are equal to 0mA (i.e. 0°, perfectly Sun pointing attitude). Control law is reported in equations (4) and (5). Yaw rate is 0°/h.

$$w_x = -\text{sign}(\alpha) * \left(\frac{\min(i_{\text{threshold}}, |\alpha|)}{i_{\text{threshold}}} \right) * w_{\text{max}} \quad (4)$$

$$w_y = -\text{sign}(\beta) * \left(\frac{\min(i_{\text{threshold}}, |\beta|)}{i_{\text{threshold}}} \right) * w_{\text{max}} \quad (5)$$

When Sun is visible only on SAS2, the two-axis control algorithm brings the Sun towards the area of SAS2 FoV, where Sun would also be visible on SAS1 thanks to the large field of view of the sensors. At this point the SAS1 two-axis control law would take over the spacecraft attitude control. The SAS2 two-axis control law applies rates on roll and yaw bringing the β angle reading to 0mA (yaw rotation) and the α reading towards SAS2 area where Sun is also visible on SAS1. Also, in this case the rotation rate around yaw decreases proportionally with SAS2 β readings when less than $i_{\text{threshold}}$ (10mA, i.e., Sun is getting closer to SAS2 $\beta = 0$ mA). Maximum rotation rates around both axis is 90°/h (w_{max} , configurable). Control law is reported in equations (6) and (7). Pitch rate is 0°/h.

$$w_x = -w_{\text{max}} \quad (6)$$

$$w_z = \text{sign}(\beta) * \left(\frac{\min(i_{\text{threshold}}, |\beta|)}{i_{\text{threshold}}} \right) * w_{\text{max}} \quad (7)$$

Similarly, when the Sun is visible only on SAS3 (Fig. 6), the two-axis control law brings the Sun towards the area of SAS3 FoV where Sun would also be visible on SAS1 (target is to bring β reading to zero and modify α angle reading towards SAS3/SAS1 overlap region). Also in this case, a constant rate on roll is applied, while the yaw rate is progressively reduced as the Sun is approaching the area where it is visible also on SAS1. Maximum rates are 90°/h (w_{max} , configurable). Control law is reported in equations (5) and (6). Pitch rate is 0°/h.

$$w_x = w_{\text{max}} \quad (8)$$

$$w_z = -\text{sign}(\beta) * \left(\frac{\min(i_{\text{lim}}, |\beta|)}{i_{\text{lim}}} \right) * w_{\text{max}} \quad (9)$$

In case of a blind spot (Sun non-present in any of the SASs but no Eclipse), fixed rates are applied, equation (10).

$$\mathbf{w}_f = [0, +w_{\text{max}}, -\frac{w_{\text{max}}}{2}] \quad (10)$$

In eclipse no rates are applied. The spacecraft AOCs subsystem knows that an eclipse is coming thanks to three different timers that are placed around the real eclipse: one applies on FDE, one on FCE and the last one on ACC, as summarized in Fig. 7.



Fig. 7: XMM-Newton eclipse timers.

NSM considers eclipse if the FCE ECLIPSE timer is running, and Sun is on none of the SASs.

During the NSM design and implementation the term 'Drift Proposal' is often used as synonym of control law. They have minor differences, which are reported hereafter for clarity. The Drift Proposal is a quick way to understand where Sun is located, and which control law is applied.

- Drift Proposal 3 means different conditions depending on the case.
 - o Mode 0 is entered, and rates are commanded to 0°/h (first NSM action is to dump any rate)
 - o Sun is +/-5° on FSS on both axis (Sun close to SAS1 field of view, called 'Sun safe region'). In this case:
 - Rates can be dumped if the 'dump rate' option is enabled.

- Or rates just decrease proportionally to the SAS readings.

Drift Proposal 3 transition when Sun enters the Sun safe region is used to start incrementing the Sun Safe Count, thanks to which a yaw rate is applied when Sun Safe Count = Sun Safe Threshold (currently set to 100, configurable). Yaw rate on 10°/h is currently set as default and it is used to help with the RW angular momentum balancing while waiting for the Flight Control Team to recover the satellite to mode used for scientific observations.

- Drift Proposal 4: if Sun is only on SAS2, SAS2 two-axis control is applied.
- Drift Proposal 5: if Sun is only on SAS3, SAS3 two-axis control is applied
- Drift Proposal 6: if spacecraft is in eclipse, all rates are commanded to 0as/s
- Drift Proposal 7: Sun is in the blind spot and blind spot control law is applied
- Drift Proposal 8: if Sun on SAS1 but above +/-5° on FSS. SAS1 two-axis control is applied.

Fig. 8 shows Drift Proposal (DP) transitions.

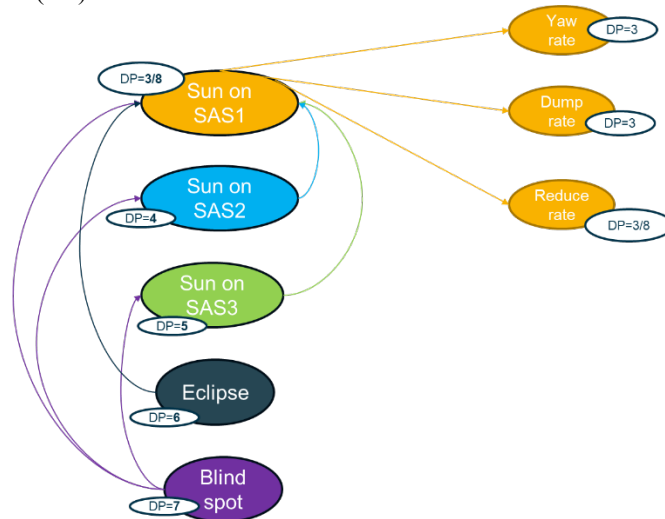


Fig. 8: NSM Drift Proposals (DP) transitions.

3. The development and test approach

As already introduced, the CDMU patch comprises two main parts: the enhanced on-board monitoring and reaction procedures and the reaction wheel based safe mode. The development and testing approach of each part was different.

The on-board monitoring and reaction procedure has been developed directly by industry starting from requirements provided by the Flight Control Team in ESOC. The patch has been directly delivered to the Flight Control Team and underwent component and system level tests developed in JavaScript, language that can be used directly with the operational simulator in an automated way. With this method, it was possible to perform all sets of tests multiple times once a new version of the patch was delivered. This approach, based on fast and automatic tests, led to the provision of almost immediate feedback to industry, leading to an agile approach that was fundamental to obtain rapid improvements or fixes. Tests aimed to evaluate if the old CDMU capabilities were kept and if the new augmented feature were developed as per need. This part of the patch was the first one to be delivered and it did not include the reaction-wheel based safe mode.

In parallel a JavaScript version of the reaction-wheel based safe mode was developed, starting from the INTEGRAL code, with some XMM-Newton only improvements. The algorithm was tested and validated with the operational simulator in an automatic way to be able to run different recovery scenarios and failures.

The test campaign has the purpose to verify that:

- All mode transitions were correctly executed
- All control law were correctly implemented
- Capability to limit single wheels angular momentum to a maximum value configurable (usually set to value very close to the RW mechanical limit, i.e. 39Nms)
- Robustness against wheel SEU
- Robustness against permanent wheel failure (i.e. attitude recovery can be performed also with three wheels)

- Capability of changing wheel sets immediately if during the recovery one of the wheels is powered off (SEU)

The test campaign proved that the attitude could be recovered from extreme pointing (close to the operational edges of $\pm 20^\circ$ on roll/pitch) and with various total angular momentum, starting from 7Nms (very common), going to 21 Nms (high total angular momentum, but realistic in case of a target of sudden interest and no reaction wheel bias capabilities), up to 27Nms (extreme case).

Once the JavaScript was validated successfully, the algorithm was handed over to industry which created the patch in ADA code ((language used by the on-board software). After the patch was delivered it was necessary to perform the test campaign once again, to prove that all functionalities of the JavaScript prototype were kept.

One NSM recovery example used during the test campaign is hereafter reported, which overview is visible in Fig. 9. The chosen starting attitude is $\sim 20^\circ$ on both roll and pitch (i.e. FSS angles in Fig. 9, leftmost side), starting rates were set to 0as/s (equivalent to $0^\circ/h$) and initial reaction wheel speeds were [-384.31, -316.13, 1046.36, -485.81] rpm.

The chosen injected failure in this case was the wheel with highest angular momentum (RW3) switch off.

The total angular momentum stored in RW3 is first transferred to the other wheels and then to the spacecraft rates, as shown in Fig. 9, ‘failure propagation’ side on RW speed and spacecraft rates plots. RW3 speed is shown as frozen value even if the power switch is opened (i.e. no current is flowing). The additional rates cause an attitude change (FSS plot in Fig. 9): the oscillations start small and then increase in amplitude until it causes an attitude anomaly (i.e. one of the FDE criteria being violated, section 1.3). The FSS angles oscillations in terms of α and β is also displayed in the left side of the Fig. 10.

When FDE detects the attitude anomaly, the AOCs subsystem and NSM are configured by the on-board automatic procedures, as summarised in Fig. 3 and in section 2.2, after this action is completed NSM is triggered and the recovery can start (green area in Fig. 9). The on-board automatic procedure also executes a power cycle of RW3, so that the wheel can be used for the NSM recovery as the anomaly was not caused by a permanent failure (Fig. 9, RW plot).

Fig. 11 shows the NSM recovery in a more detailed way, together with NSM modes and control law (i.e. drift proposal), introduced in section 2.3.2.

After NSM trigger is set (Fig. 11, TM *NSM TRIGGERED* = 1), the NSM mode is Mode 0 (Fig. 11, TM *NSM RECOVER MODE* = 0): NSM parameters are initialised with values defined by the on-board automatic procedure (section 2.2). Immediately after it transit to Mode 1 (Fig. 11, TM *NSM RECOVER MODE* first transition to 1) where it first tries to dump the rates: the NSM controller in the CDMU computes the angular momentum to be commanded to the RW (commanded via ACC) to bring all rates to $0^\circ/h$, TM *NSM DRIFT PROP* = 3 in Fig. 11 (introduced in section 2.3.2). The wheels are commanded in Mode 2 (Fig. 11, TM *NSM RECOVER MODE* first transition to 2) and this mode is maintained for few cycles until RW speed convergence is reached and Mode 3 transition is allowed. Afterwards also spacecraft rates convergence is reached, and Mode 4 transition is permitted: only at this point the Drift Proposal changes to the value 8 (Fig. 11, TM *NSM DRIFT PROP* transition from 3 to 8) and Mode 1 is again entered.

As in this case the Drift Proposal is 8, this indicates that Sun is on SAS1 and the NSM controller will compute the RW angular momentum to rotate the satellite towards a perfectly Sun pointing attitude (as the option to dump rate once in the 5° region was disabled for this example, together with the yaw rate). The used control law is detailed in 2.3.2.

Also in this case, Mode 2 where wheels are driven to the desired attitude, is maintained for few cycles until RW speed convergence is reached (Fig. 11, TM *NSM RECOVER MODE* second transition to 2). The second transition to Mode 4 is permitted only when also spacecraft rates converge.

After this point Modes 1-2-3-4 transitions are repeated until the end of the recovery.

When the spacecraft reaches the 5° region on both FSS roll and pitch, the Drift Proposal changes from 8 back to 3 (Fig. 11, TM *NSM DRIFT PROP* transition from 8 to 3), but this does not cause a change in the control law applied as for this example the feature to dump the rates within the 5° region is disabled (rates would have gone to $0^\circ/h$ if would have been enabled).

Perfect Sun pointing attitude (FSS α and β angles equal to 0°) is reached in ~ 35 minutes and it is possible to observe in the right plot in Fig. 10 that, after the transition to Drift Proposal (DP) 8 the Sun ‘moves’ towards the centre of the FSS field of view with the most direct and efficient pattern (straight line).

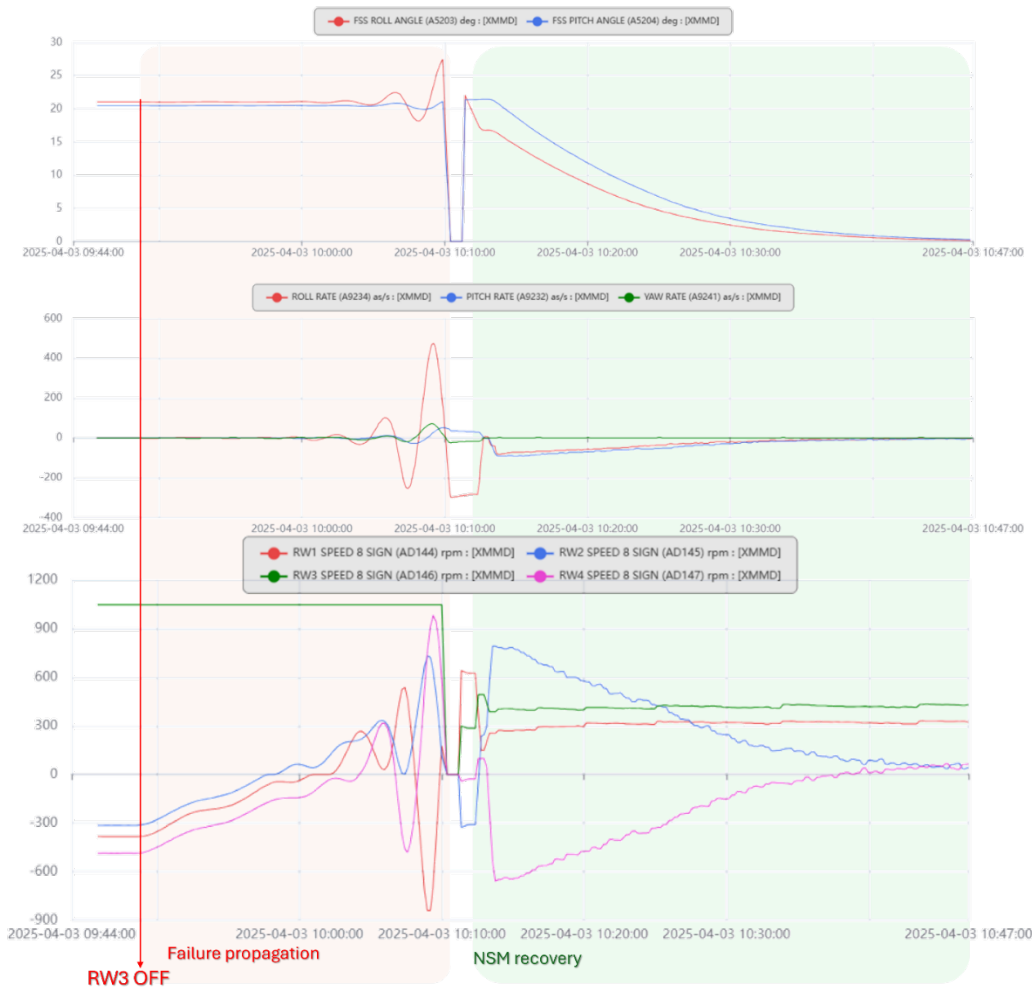


Fig. 9: Recovery example from RW3 switch OFF due to SEU.

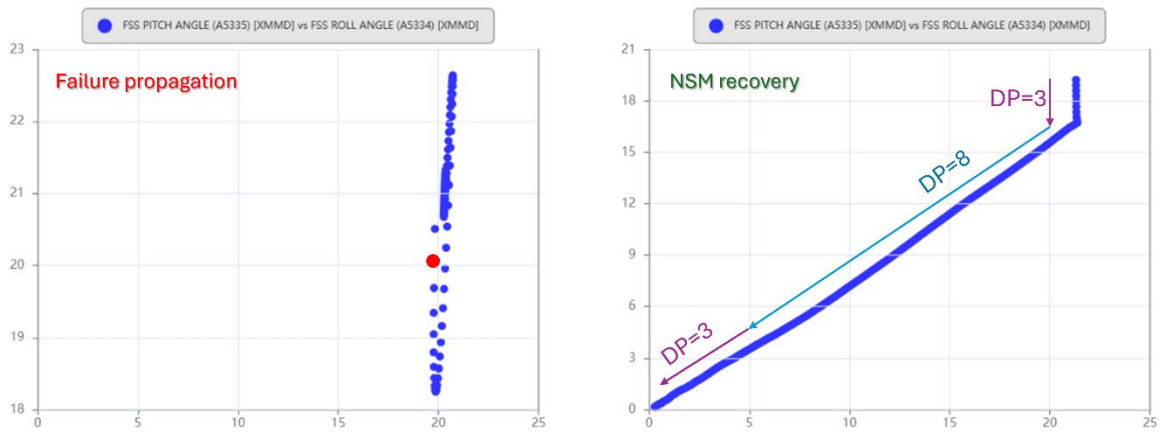


Fig. 10: FSS α versus β during propagation of the failure (left plot, starting point in red) and NSM recovery (right plot, direction shown by the arrows).

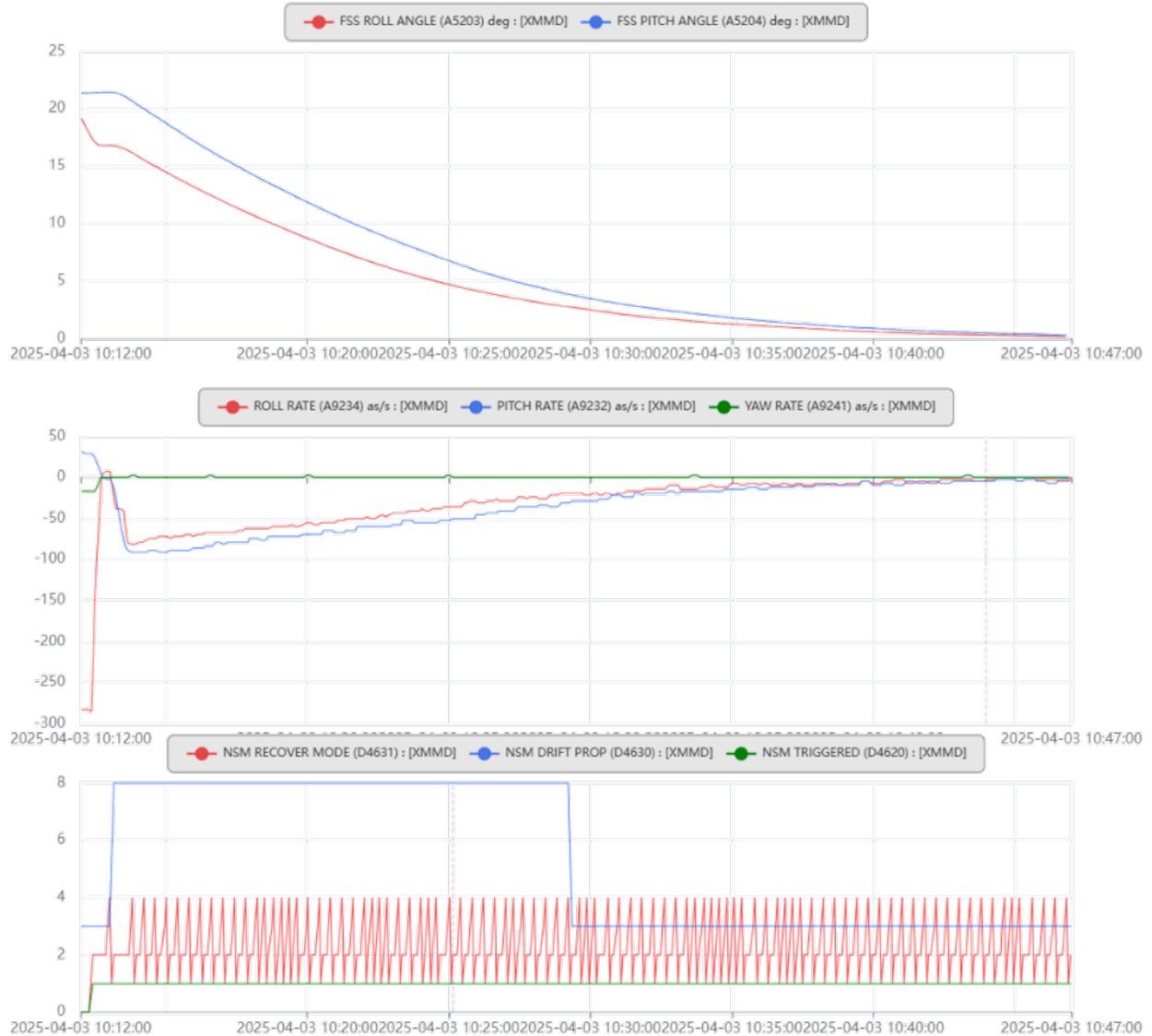


Fig. 11: NSM recovery, attitude, rates and NSM modes.

4. Conclusions

The XMM-Newton CDMU patch that enables a reaction-wheel based attitude safe mode (NSM) project was kicked off in October 2023, with the aim to use INTEGRAL NSM development and commissioning expertise [7] to prepare XMM-Newton for the case where the propellant is depleted. The project went through all nominal phases from requirements definition (concluded in November 2023), preliminary design (concluded in February 2024), final design (concluded in September 2024) and final acceptance (January 2025).

During this time frame industry delivered four different patches which were progressively extending the spacecraft on board software capability. The first three patches are listed below.

- 1) Patch to extend the memory, section 2.1. This was immediately uploaded to the spacecraft at the beginning of 2024.
- 2) Patch to extend the monitoring function capability and allow automatic on-board procedure execution (section 2.2).
- 3) Patch to allow the CDMU software to read telemetry from the AOCS (section 2.3.1).

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In the meantime, the NSM controller and algorithm, subject of section 2.3.2, was developed using JavaScript and tested directly with the simulator, using many different starting conditions and failure scenarios (section 3) until the final design review, where the script was handed over to industry for direct implementation in the CDMU on board software. This constitutes the last patch delivered, the number 4.

Every time a new patch was received, it underwent component level and system level validation from the Flight Control Team, mostly via automatic script.

The patch was successfully commissioned in late February 2025: the NSM recovery was forced by direct command and not with attitude failure, for safety reason. During the commissioning the recovery from four different corners was tested to test in-flight attitude recovery from close to extreme pointing and all sign combination of roll and pitch with magnitude of $\sim 16^\circ$. NSM was using both four and three wheels, to simulate also the case of a permanent wheel failure.

Currently the patch is loaded and activated on-board, foreseen to be used soon together with the thruster-based attitude safe mode (ESAM, baseline for XMM-Newton) with the purpose to save propellant, using NSM to recover the attitude in some specific cases and ESAM in other. This approach will be used until first signature of thruster failure, after which the NSM will replace fully the ESAM.

The additional feature of the patch that allows the execution of the on-board procedure will be exploit to increase automation on-board.

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